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HEINRICH - HERTZ - INSTITUT

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REPORT 1997



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## **HHI REPORT 97**

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## **FOREWORD**

In a future information society, nations which are strong in the area of information technology will be able to assure jobs and to create new and innovative work places. Information technology is crucial for economic competitiveness on world markets. Germany has a strong information technology industry, and it is the mission of the HHI to contribute to the strengthening of this industry's competitiveness.

A fundamental goal of information technology is to give users easy access to all present and future information and communication services. Efficient networks and terminal systems are the technological pre-conditions for this. In these areas the HHI focuses on Photonic Networks, Mobile Broadband Systems and Electronic Imaging Technology for Multimedia.

In order to improve the transfer of the results to industry, and also because of the increasing tendency of industry to contract out its research, the HHI is at present in a reorientation phase. Previously the Institute's objective was mainly to perform advanced research ahead of industrial development, but now the HHI aims to do application-oriented research in direct cooperation with industry or through research contracts. The HHI also endeavours to make its potential available to firms which work in areas not directly related to those of the HHI, particularly to small and medium enterprises.

In spite of the change of direction towards applications, the Institute must not lose sight of its original mission for advanced research. In fact, through closer contact with the applications and by working with industrial partners, it is possible to focus better on areas of future fundamental research.

Here we would like to thank all supporters and friends of the HHI, as well as all partners from industry and research, for their valued help and for their trust in us. The management would like to thank in particular the staff, who must be given credit for the productivity of the Institute.

Berlin, January 1998  
Clemens Baack, Wolfgang Grunow

## **VORWORT**

In einer zukünftigen Informationsgesellschaft werden die Nationen in der Lage sein, Arbeitsplätze zu sichern und neue innovative Arbeitsplätze zu schaffen, die eine starke Position auf dem Gebiet der Informations-technik einnehmen. Die Informationstechnik ist entscheidend für die Wettbewerbsfähig-keit der Wirtschaft auf internationalen Märkten. Deutschland verfügt über eine leistungs-fähige informationstechnische Industrie. Es ist Aufgabe des HHI, einen Beitrag zur Stärkung der Wettbewerbsfähigkeit dieses Industriebereichs zu leisten.

Ein wesentliches Ziel der Informationstechnik ist es, alle heutigen und zukünftigen Infor-mations- und Kommunikationsdienste den Nutzern problemlos zur Verfügung zu stellen. Technische Voraussetzungen dazu sind lei-stungsfähige Netze und Endsysteme. Auf die-sen Gebieten arbeitet das HHI in seinen Schwerpunkten Photonik-Netze, Mobile Breit-bandssysteme und Elektronische Bildtechnik für Multimedia.

Zur Verbesserung des Ergebnistransfers zur Industrie, aber auch in Hinblick auf die Tendenz der Industrie, Forschung in zunehmendem Maße auszulagern, befindet sich das HHI in einer Umorientierungsphase. War es bislang Aufgabe des Instituts, im wesentlichen im Vorfeld der Industrieforschung zu arbeiten, so versucht das HHI nun, eine anwendungsnahen Forschung durch direkte Ko-operation mit der Industrie und durch Auftragsforschung zu betreiben. Das HHI ist bemüht, sein Potential auch solchen Firmen nutzbar zu machen, deren Tätigkeitsfelder nicht unmittelbar die des HHI berühren; dies gilt insbesondere für KMU's.

Trotz dieser Hinwendung zur Anwendungs-nähe darf das Institut seine ursprüngliche Mission der Vorfeldforschung nicht aus den Augen verlieren. Durch größere Anwendungs-nähe wird es jedoch möglich, zusammen mit den Industriepartnern die Felder zukünftiger Vorfeldforschung schärfer zu fokussieren.

Allen Förderern und Freunden des HHI so-wie allen Kooperationspartnern aus Industrie und Forschung sei an dieser Stelle für die ge-währte Unterstützung und das Vertrauen, das sie uns entgegengebracht haben, gedankt. Die Leistungsfähigkeit des Instituts ist das Verdienst der Mitarbeiter, ihnen gilt der be-sondere Dank der Geschäftsführung.

Berlin, im Januar 1998  
Clemens Baack, Wolfgang Grunow



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**Portrait of the Institute · Porträt des Instituts**



## **Mission, Activities, Personnel and Financing**

Information technology is of overriding importance for the development and strength of the economy. It is the key technology on the road from an industrial society to an information society, and is itself a leading branch of the economy, with high growth rates world-wide. It is of crucial importance as the basis of global commercial and private communications and for the development of innovative multimedia products for the information society.

The aim of research and development activities at the Heinrich-Hertz-Institut (HHI) is to further develop the principles of information technology and to demonstrate, in partnership with industry, new applications for new products.

The research areas pursued at the Institute derive from the following considerations. Telecommunication applications and infrastructure stimulate each other. The present situation is characterized by an explosive increase in the use of the Internet and mobile communication systems, both by commercial users and increasingly by private users. As a result we can assume that by the year 2010 the traffic in data and image services will be ten times greater than the telephone traffic, which will remain approximately steady. If this is to come about, the capacity of the present telecommunication infrastructure must be enlarged significantly. Related to this, existing networks will be modernized using more efficient technologies. Optical communication technology must be considered for the installed network for technical reasons, especially because of the enormous transmission capacities of glass fibres. The resulting challenge is to exploit the possibilities of optical communication technology in application areas, and to turn research results and pilot projects into industrial products. The HHI meets this challenge through its projects centred on the area of **Photonic Networks**.

Mobile communication is at present still limited to narrowband applications, in contrast to communication on the wired network. But here too a need for broadband transmission systems is developing. The challenge for research is to develop suitable system concepts, to establish the technological principles, and to work

## **Ziel, Aufgaben, Personal und Finanzierung**

Die Informationstechnik spielt eine herausragende Rolle für die Entwicklung und Leistungsfähigkeit der Volkswirtschaft. Sie bildet die Schlüsseltechnologie auf dem Wege von der Industriegesellschaft zur Informationsgesellschaft und ist selbst einer der führenden Wirtschaftszweige mit weltweit hohen Wachstumsraten. Herausragend sind ihre Funktion als Basis für die weltumspannende geschäftliche und private Kommunikation und ihre Bedeutung für die Entwicklung innovativer Multimedia-Produkte für die Informationsgesellschaft.

Das übergeordnete Ziel der F&E-Arbeiten des Heinrich-Hertz-Instituts ist es, die Informationstechnik in ihren Grundlagen weiterzuentwickeln und, in Abstimmung mit der Industrie, neue Anwendungen für neue Produkte zu erschließen.

Die Forschungsthemen des Instituts ergeben sich aus den folgenden Überlegungen. Informationstechnische Anwendungen und Infrastruktur befruchten sich wechselseitig. Derzeit ist die Situation durch eine explosionsartige Zunahme der Nutzung des Internet und mobiler Kommunikationssysteme durch geschäftliche und in steigendem Maß auch durch private Anwender gekennzeichnet. Auf der Basis dieser Entwicklung ist davon auszugehen, daß das Verkehrsaufkommen von Daten- und Bilddiensten im Jahr 2010 um das zehnfache über dem etwa konstant bleibenden Telefon-Verkehrsaufkommen liegen wird. Um diese Entwicklung zu ermöglichen, ist eine erhebliche Kapazitätsvergrößerung der bestehenden Telekommunikationsinfrastruktur erforderlich. Damit verbunden ist die Modernisierung bestehender Netze durch den Einsatz leistungssteigernder Technologien. Für die Festnetze kommt hierfür wegen der enormen Übertragungskapazität der Glasfaser im wesentlichen die optische Nachrichtentechnik in Betracht. Daraus ergibt sich die Herausforderung, die Anwendungsmöglichkeiten der optischen Nachrichtentechnik auszuloten und die in der Forschung und in Pilotanwendungen erzielten Ergebnisse in Industrieprodukte zu überführen. Diese Herausforderung greift das HHI mit den Projektarbeiten im Schwerpunkt **Photonik-Netze** auf.

Im Gegensatz zur Kommunikation über

## **Corporate Bodies**

The corporate bodies of the HHI are the General Meeting, the Supervisory Board, the Managing Directors and the Scientific Technical Committee.

Members of the **Supervisory Board** for this report period are:

**Prof. Dr. J. Hesse**, (chairman), Carl Zeiss, Oberkochen  
**MinDirig Dr. K. Rupf**, (1st vice-chairman), BMBF, Bonn  
**SenR P. Schuhe**, (2nd vice-chairman), SenWissForsch und Kultur, Berlin  
**MinR J. Claus**, Deutsche Telekom AG, Bonn  
**Prof. Dr. H. Berger**, Technische Universität Berlin  
**ORR H.-D. Götze**, SenFin, Berlin  
**Dr. H. Roehle**, HHI, Berlin  
**MinDirig Dr. J. Sander**, BMPT, Bonn  
**Dr. H. Venghaus**, HHI, Berlin

The **Scientific-Technical Committee** is comprised of heads of departments and an equal number of elected members from the Institute, and advises the Supervisory Board and the Managing Directors on all important scientific and technical matters.

Further, the HHI has appointed a **Scientific Advisory Committee** of experts from industry, the Deutsche Telekom AG and the academic sector. Members of the Scientific Advisory Committee for this report period are:

**Prof. Dr. G. Kohn**, (chairman), Universität Stuttgart  
**Prof. Dr. J. Eberspächer**, Technische Universität München  
**Dr. H. Eisele**, Alcatel-SEL AG, Stuttgart  
**Dr. H.-G. Junginger**, Sony Europe GmbH, Fellbach  
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**Werner Späth**, Siemens AG, Regensburg  
**Dr. K. U. Stein**, Siemens AG, München  
**MinR W.-P. Ottenbreit (guest)**, Deutsche Telekom AG, Bonn

## **Organe und Gremien**

Die Organe der HHI GmbH sind die Gesellschafterversammlung, der Aufsichtsrat, die Geschäftsführer und der Wissenschaftlich-Technische Rat.

Dem **Aufsichtsrat** gehörten im Berichtsjahr folgende Mitglieder an:

Der **Wissenschaftlich-Technische Rat** ist paritätisch mit Abteilungsleitern und gewählten Mitarbeitern des Instituts besetzt und berät den Aufsichtsrat und die Geschäftsführung in allen wichtigen wissenschaftlichen und technischen Fragen.

Die Gesellschaft beruft außerdem einen **Wissenschaftlichen Beirat** aus Experten der Industrie, der Deutschen Telekom AG und des Hochschulbereichs. Dem Wissenschaftlichen Beirat gehörten im Berichtsjahr folgende Mitglieder an:

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**R & D Activities · F & E Aktivitäten**



## R&D FIELDS

### Photonic Networks

#### Topics and Results

Photonic networks are the backbone of high capacity communication networks. The photonic network is expected to exploit the enormous bandwidths available in optical fibres by the use of optical frequency-division multiplexing (OFDM) and optical time-division multiplexing (OTDM) techniques. Together with optical switching, optical signal transmission will be able to realize transparency and therefore service independence in the network. The photonic network offers extremely broadband transmission paths for all current and future services.

The main objective of research in the area of photonics at the HHI is to make substantial contributions to the development of photonic networks. The following main areas are being addressed:

- Development of network concepts for the various layers of photonic networks – the core, access and customer networks.
- Identification of the requirements for the network elements and their photonic components, and also for the equipment needed to supervise the network.
- Investigation of the potential of optical multiplexing techniques such as OFDM and OTDM. The optimum combination of both is of paramount importance.
- Determination of the length limitations of the optical transmission paths in photonic networks due to signal degradation by the non-ideal network components.
- Investigations into the supervision and control of the network (operation, administration and maintenance – OAM).
- Development and fabrication of photonic components and subsystems.

The research area of photonic networks is divided into the specialist areas Access and Customer Network and Core Network.

#### Access and Customer Network

Research and development activities in this area are concentrated on the use of WDM techniques in the access network.

The goal is to develop and investigate system concepts and components for WDM applications in the access network.

Research and development activities for a WDM upgrade of an existing passive optical network (PON) are being carried out. Work in this area is based on a system concept which gives a capacity increase without changing the glass fibre network structure between the central office and the Optical Network Units (ONUs) near the subscribers. A WDM overlay of permanent wavelength paths in the region of 1.5 µm is added to the passive optical access network. This also considerably improves the protection against interference and eavesdropping. The key elements used are arrayed waveguide gratings (AWGs) for various multiplexing, demultiplexing and routing functions of the different wavelength signals. In an experimental system AWGs are used with the 100 GHz channel spacing proposed by the International Telecommunication Union (ITU).

The HHI is developing and fabricating such filters with various specifications using SiO<sub>2</sub>/Si technology. For example, 16 channel AWGs at 100 GHz channel spacings with fibre-to-fibre insertion losses of 5 dB and crosstalks of less than -25 dB were realized. Also, an 8 channel AWG with a so-called flat top design was developed, which is better suited for cascading because of its nearly rectangular transfer characteristic. The optical star coupler is another key component needed for the system concept introduced above for a WDM upgrade of a PON, in addition to the WDM multiplexer/demultiplexer. A concept for combining both functions in one component has been developed and first devices have been fabricated. This device functions as an AWG in one wavelength region and has the distribution function of a star coupler in another region.

For the upgrade of optical transmission systems using WDM techniques it is necessary to use transponders to interface to an existing system environment. A transponder consists of an optical receiver and an optical transmitter which transmits at a given wavelength. Depending on input sensitivity and optical output power, signal gain as well as wavelength conversion can be achieved with such an electro-optical wavelength converter. In cooperation with

industry, a modular bitrate-transparent transponder without temporal regeneration which works over the range 100 Mbit/s to 2.5 Gbit/s has been developed. For operation at fixed bit rates (e.g. SDH, STM-16), electronic signal regeneration and clock recovery circuitry can be added. Furthermore, the transponder can also be used in optical cross-connects and optical add/drop multiplexers. The transponder is provided with appropriate control and supervisory functions for inclusion in a TMN system.

Drop filters, which separate signals at different carrier frequencies, are further key elements in WDM systems. Such a component, in the form of active monolithically integrated optoelectronic InP elements, is being developed under the framework of an ACTS project. The device consists of a tunable, polarization-independent optical filter, an optoelectronic detector and an electronic preamplifier. A transfer characteristic with a bandwidth of 400 GHz (3.2 nm) and a tuning range of 25 nm was obtained with 20 dB crosstalk.

Bidirectional optoelectronic transceivers are being developed for access network applications. The overall objective is a compact design suitable for mass production using monolithic integration techniques. This project is being carried out in close collaboration with partners from industry. The HHI transceivers will also be used in OFDM field trials in an ACTS project under the general direction of CNET (France) and Telenor (Norway).

The use of selective area epitaxy technologies is indispensable for the application of integration technologies based on InP. To this end metalorganic (MO) MBE technique is being further developed and optimized in collaboration with a partner from industry, the Walter Schottky Institute in Munich, and the University of Ulm.

A four channel WDM transmitter with 200 GHz channel spacings is being developed and fabricated, using technologies mentioned above, to satisfy the requirements of a partner from industry. The device is to operate at 2.5 Gbit/s and the channel frequency allocation scheme is based on ITU proposals. During the past year the main work was the development of strained layer multi-quantum-well lasers with high output powers.

Long wave DFB lasers are being fabricat-

ed using solid source MBE for an R&D contract with an industrial partner. The subject of this technology-oriented contract is the development of DFB laser diodes for use in bidirectional optical access networks.

A system test using new components is only possible if these are available as complete modules. Mounting and connection technology is therefore another important focus of the technological activities.

## Core Network

Work in this research area is concentrated on high bitrate time division multiplexing (TDM) techniques, optical crossconnects and optically transparent networks. With the high bitrate TDM technique, multiplexing and demultiplexing may be performed either electrically (ETDM) or optically (OTDM). Important issues are the generation, modulation, detection and synchronization of the optical signals. Other topics for investigation are the impacts of the photonic components and fibre nonlinearities on the quality of the optical signals and techniques for dispersion compensation.

Transmitters with integrated laser/modulators (low chirp) and receivers with integrated waveguide diodes and high electron mobility transistors (HEMT) for optimal impedance matching are being developed for ETDM at 40 Gbit/s, mostly using the NRZ modulation format. A laser/modulator module which can be tuned over several nanometres and which has a 3 dB frequency of 18 GHz was built.

High bitrate receivers have been developed for the wavelength region 1.3 to 1.5 µm. They consist of waveguide-integrated PIN photodiodes and HEMTs to amplify the electrical signals. The methods used can in principle be used for the further development of optoelectronic integrated circuits (OEICs) up to the 100 Gbit/s region. The OEIC receiver module was successfully tested in a 20 Gbit/s system experiment by an industrial partner. In a further development in cooperation with an industrial partner, 40 Gbit/s detection experiments have also been carried out successfully.

The optical time division multiplexing (OTDM) work includes the investigation and realization of optical subsystems which

can multiplex 1 to 10 Gbit/s optical signals together to form 40 to 160 Gbit/s signals (MUX), and subsequently demultiplex them (DEMUX). RZ data signals generated using modelocked lasers are generally used for transmission.

Experiments in combining WDM and TDM technology in a transmission system with a total capacity of 160 Gbit/s gave the following result. Four 40 Gbit/s signals, which were generated from 10 Gbit/s data streams using optical time division multiplexing, were transmitted in four WDM channels over 100 km of standard fibre at a wavelength of 1.55 µm. Dispersion compensation of all four WDM channels using a common dispersion compensating fibre was all that was needed for error-free transmission.

Furthermore, comparative investigations for 40 Gbit/s OTDM transmission at a wavelength of 1.55 µm via different types of fibre (standard, "true wave", dispersion compensating and dispersion shifted fibre) have been carried out. Large distances could be bridged without optical amplification by a combination of standard fibre and dispersion compensating fibre.

Demultiplexing and "add-drop" functions in OTDM systems were successfully performed with various nonlinear interferometric arrangements (Mach-Zehnder, Michelson and Sagnac interferometers). Monolithically integrated symmetrical Mach-Zehnder interferometer components with two additional branches for optical signal control were successfully fabricated. Optical semiconductor amplifiers are used as nonlinear elements in the two branches of the interferometer. These components (PIC) have also been used for purely optical wavelength conversion. BER measurements demonstrated error-free functioning.

As an alternative for optical demultiplexing, the use of electro-optical Mach-Zehnder structures which use the quantum confined stark effect (QCSE) in MQW structures is also being investigated. Polarization-independent switching was demonstrated in a strained quantum well structure involving tunnel barriers for the light holes. Capacitively loaded travelling wave structures, which are suitable for demultiplexing up to 40 Gbit/s, are planned for microwave control. This combination is presently under development.

Signal degradation in optical networks limits the transmission lengths of the optical paths. Complete regeneration of digital signals (3R – reamplification, reshaping and retiming) can remove this limit. We are working on methods and components for partial regeneration (2R – reamplification and reshaping) or complete regeneration (3R) using optical signal processing. Key components for 3R regeneration are clock recovery and decision stages. Three-section RWG lasers have bistable characteristics if appropriately designed. A module for clock recovery was built which operates from below 5 to more than 20 Gbit/s. The clock rate is continuously adjustable by means of an electric current. Additionally, we are investigating how specially developed three-section RWG lasers may be used as decision units. Because of the common fabrication technology of the amplifier, clock recovery unit and decision unit, it will be possible in the future to monolithically integrate a 3R regenerator.

The exchange equipment for future communication systems must be able to switch optical frequency multiplexed signals with very high bit rates. For this purpose suitable optical spatial, frequency, and time switching stages are required. The aim of this research work is exchange equipment which allows the signals to be switched by optical means. Optoelectronic conversion in the signal path must be avoided in order to overcome the speed limits of electronic signal processing.

The properties of regenerator-free optical communication networks are being investigated theoretically as well as experimentally under a contract with a network provider. The essential elements in the transport layer of such networks are the transmission lines, fibre amplifiers, and optical crossconnects. Non-ideal properties of these components limit the transmission lengths in the optical networks because of signal degradation. The corresponding transparency length diagrams can be used to plan the transport layer of optically transparent networks. The experimental tests are in an eight channel WDM loop test bed in which data packets at transmission rates of up to 10 Gbit/s per wavelength channel circulate around a fibre loop. Cascades of several transmission sections, together with optically transparent crossconnects, can be modelled with this

test bed, and the signal quality can be measured as a function of the number of crossconnects and of the fibre link lengths. Methods for simulating signal propagation in an optical path are being developed and tested against the experimental measurements. For this we use the program package BroadNeD, which will soon be commercially available.

Different realization strategies are being investigated for the spatial switches in the optical crossconnects or for protection switching. One approach is based on the use of liquid crystals in combination with SiO<sub>2</sub>/Si waveguides. The goal is the realization of total internally reflecting switches which can be made in small sizes, which need negligible control power and which have digital switching characteristics. Another strategy is to develop thermo-optically controlled switches using polymers. Polymer materials are especially suitable because of their large temperature coefficients for the optical refractive index and their low thermal conductivities, properties which result in low switching powers. During the past years various types of switches have been developed, especially interferometric directional coupler switches (2 x 2) and switch matrices (4 x 4) as well as digital optical switches (1 x 2 and 2 x 2) with very low optical crosstalk values. Fabrication was based essentially on PMMA material, which however has a low temperature stability and a relatively large optical loss. Work is therefore concentrated on the characterization and technology of new polymer materials with hopefully improved properties.

Polymers were also investigated as potential materials for electro-optical and nonlinear optical components. They might be used for optical functions such as all-optical switching, frequency conversion and parametric optical amplification. Activities concluded during the reporting year have shown that polarized polymers with electro-optical coefficients of about 15 pm/V at 1.5 µm and with adequate long-term stability, and which are suitable for the production of high frequency modulators, can be fabricated. However, the investigated polarized materials have not yet proved so far to be suitable for all-optical components based on phase matched frequency doubling for signal wavelengths around 1.5 µm.

Optical frequency converters can be used in crossconnects in WDM systems to minimize blocking and as interfaces between the access and core networks. A study entitled "Operation and Supervision of Optical Frequency Converters in the Frequency Stage of Optical WDM Crossconnects" was made as part of a commission by a network provider. In this study the costs of operation and supervision of transponders and optical frequency converters based on cross gain modulation and cross phase modulation were analyzed. This topic is closely connected with the problems of operation and maintenance (OAM) of the components and subsystems in optical networks. An important problem in this case is that the possibilities for controlling the signal quality are very limited, even when there are only very low demands on the transparency of the optical networks.

The application of WDM technology in the core network with optical crossconnects at data rates up to 10 Gbit/s per WDM channel is being investigated in the ACTS project PHOTON, which is led by Siemens. The HHI is responsible for the development and construction of a wavelength reference for the demonstrator as well as for system studies in this project.

The work towards high bit rate TDM and WDM transmission technology is supported by analytical investigations of the signal quality as a function of the optical path length in the photonic network. A series of new program modules, which were verified by comparison with system experiments, has been developed to model and simulate the optical paths. First simulations of optical crosstalk in crossconnects have been successfully carried out.

Planning data for a photonic network have been worked out in cooperation with an industrial partner, who also commissioned this study. In order to clearly represent all relevant system aspects, a network model was developed which is well suited for investigating physical and functional properties and with which the efficiency of a photonic network can be shown. From this we can conclude that it is possible to completely connect all nodes of a network the size of Germany in an optically transparent manner with individual wavelength channels at up to 10 Gbit/s per channel. However, the development step from

WDM point-to-point transmission to a switchable WDM network is so large that further development of the current glass fibre networks must occur in a number of phases: point-to-point one channel, point-to-point multichannel with WDM, network with fixed routing of WDM channels, network with protection switching capabilities in the WDM domain, and finally a flexible network with switching functions for all channels in WDM crossconnects.

Most of the above activities are carried out under the national research program Photonik II, which is supported by the Federal Ministry for Education, Science, Research and Technology. Between 1994 and 1998 the focus is essentially on optical communication systems and techniques, key components and key technologies. The various topics are investigated by the communications industry in cooperation with research institutions and universities. The scientific leadership of the research program is shared between the Fraunhofer Institute for Applied Solid-State Physics (FhG-IAF) in Freiburg and the HHI.

## Competencies

Investigation and development of architectures for photonic networks, development of planning guidelines and studies of specific problems of photonic networks

Characterization and testing of optical networks and network components, including experiments on fibre loops, transmission experiments over large distances and field trials

Development of high rate optical WDM systems (10 Gbit/s per channel) and the corresponding measurement methods

Investigation, design and development of optical WDM LANs/MANs, optical access networks and passive optical networks

Development of methods for the control and supervision of networks

Development, application and verification of simulation software for optical transport networks

Design and development of optical systems using heterodyning

Development of wavelength conversion methods for WDM systems

Investigation and development of high rate OTDM subsystems (10 to 40 Gbit/s and above), including multiplex/demultiplex and add/drop techniques

Development of methods for purely optical clock recovery and signal regeneration (2R and 3R)

Development of methods for the generation of ultra short optical pulses

Optimization of methods of dispersion management

Design and development of optical frequency reference equipment

Design and fabrication of transponders and optical SDH front ends

Development, fabrication and characterization of fiberoptic components

Development, fabrication and characterization of methods and devices for PMD compensation

Development, fabrication and characterization of opto-electrical components and photonic integrated circuits based on InP:

- Tunable lasers (DFB, DBR)
- Multi-wavelength laser arrays
- Optical amplifiers
- Fast laser/modulator transmitters
- Wavelength converters
- Wavelength drop filters
- Demultiplexers and add/drop multiplexers for OTDM applications
- Components for optical clock recovery and signal regeneration (self pulsating lasers)
- Integrated transceivers
- Ultra-fast photodetectors (70 GHz)
- High bit rate optical receivers with integrated MMIC preamplifiers
- Optical microwave generators

Development and fabrication of thermo-optical switches and switch matrices with minimal crosstalk using polymers.

Development and fabrication of planar waveguide components in SiO<sub>2</sub>/Si (e.g. waveguide grating filters)

Development and fabrication of passive and of electrically controllable diffractive optical components in SiO<sub>2</sub>

Modelling of photonic components and integrated circuits

Development, optimization and application of component technologies:

- Clean room laboratories (class 10/1000)
- Epitaxy (MOVPE, MBE, MOMBE) and the characterization of InP-based semiconductor materials
- Secondary ion mass spectroscopy (SIMS)
- CAD/CAM of photolithography masks
- Electron beam lithography and optical lithography
- Dry etch processes (reactive ion etching, ion beam etching) with endpoint detection
- Rapid thermal short time processing
- Deposition of metal and dielectric layers (evaporation, sputtering, plasma deposition)
- Optical coatings
- Characterization and technology of optical polymer materials
- High resolution scanning electron microscopy

Development and application of electrical and optical mounting and connection methods for components (flip chip bonding, high frequency packaging, laser welding, fibre-chip coupling)

## Mobile Broadband Systems

### Topics and Results

Wireless broadband communication technology is presently of growing importance because of the increasing demand for mobility and the emergence of network providers without direct access to the customers (the last mile problem). In addition to the already established mobile radio networks, there is increasing interest in small size cellular systems, wireless local loops and wireless local area networks (LANs). These systems with data rates up to 155 Mbit/s should be compatible with ATM (asynchronous transfer mode). Because of the existing frequency allocation schemes, these new systems require higher carrier frequencies, ranging from the lower GHz range up several hundred THz. The HHI believes that the importance of mobile broadband communications in the access and customer spheres will match that of wired broadband links.

A main objective of research at the HHI is to make substantial contributions to the development of mobile broadband communication systems. The work concentrates on the transport layer of communication networks, i.e. on transmission and system-oriented aspects. Broadband wireless local loops are being investigated as well as broadband wireless LANs and in-house systems. In detail, the following topics or projects are under investigation.

The HHI participates in the joint project Integrated Broadband Mobile Communication System (IBMS) under the framework of the BMBF key development program ATMmobil. The aim of this project is to develop a concept for future ATM-based multimedia communications that includes both indoor and outdoor environments in a unified approach. This system should be flexible with respect to the interfaces and technologies and should allow various access types (e.g. cable, radio, infrared). It should also offer variable bit rates and scalable Quality of Service (QoS) according to demand. The HHI is responsible for the design of the inhouse network component of this project.

Since ATM has its origin in wired environments, some effort is necessary to maintain the QoS contract between user

and network during connection over time-varying wireless channels. Thus, the main objectives include the development of suitable concepts for QoS maintenance by combining adaptive forward error correction coding schemes with appropriate wireless infrared and radio interfaces, as well as the design of inhouse backbone architectures and access schemes for wireless ATM.

- A novel approach for an inhouse system combining wired and wireless access has been proposed. This takes advantage of optical microwave generation techniques and at the same time permits wired connections at low additional cost.
- To maintain the agreed QoS parameters over time varying channels, a radio frequency (RF) modem that adapts to both service and channel has been conceived. Thus, a nearly constant transmission quality can be obtained by continuous adaptation of the modulation and forward error correction methods in conjunction with automatic packet retransmission requests. Some aspects of this concept have been theoretically analyzed and simulated.
- A software demonstrator of the physical transmission layer has been developed to determine the influence of the RF transmission on the bit error rate. This takes into account the various channel parameters, modulation methods and forward error correction techniques.

For wireless infrared (IR) communications, two approaches are presently under investigation which exploit direct beam line-of-sight and spot diffusing links. The aim is to realize inexpensive and power-efficient transceivers for data rates up to 155 Mbit/s. Both base station oriented systems and ad hoc LAN systems with spot diffusion are under consideration. The system performance and the power budget are considerably improved by using a tracked architecture. Array technologies for receiver and transmitter will supersede the use of mechanically moved optics.

- First laboratory experiments on an IR ad hoc LAN have been carried out. The distribution of the transmitter power across the cell was realized by diffuse reflection from the ceiling (spot diffusion with diffusion angle about 100 degrees). The receiver optics (field of view less than one degree) was directed towards the diffusing spot. Error-free digital video transmission

(140 Mbit/s, CMI) could be obtained over a distance of 2 m with 20 mW transmitter power and -39 dBm receiver sensitivity.

Well known principles in the area of optical frequency division multiplexing are being applied to broadband mobile communication systems operating in the 60 GHz band. These investigations are being carried out within the framework of the BMBF program Photonik II. The aim is to combine fibre-based low loss distribution of broadband signals between control and base stations with remote, cost-effective microwave generation in low-cost base stations. Using optical heterodyning and the sideband injection locking technique, low phase noise microwave signals can be generated at very precise frequencies (accuracies in the Hertz range) and with great frequency flexibility. In contrast to other optic/microwave techniques, external optical modulators and amplifiers are not required.

- Bidirectional transmission experiments with a simplified mobile communication system have been carried out at the HHI in cooperation with our industrial partner Bosch Hildesheim. The components of a digital radio relay system were used and two microwave carriers with high spectral purity were generated simultaneously and remotely by optical heterodyning, using the above-mentioned principle. One of the carriers at 62.2 GHz was OQPSK modulated by the 155 Mbit/s data signal for the down link, while the second carrier at 64 GHz was unmodulated and was used as an LO signal for the uplink mixer in the base station. This mixer was employed for the down conversion of the uplink signal coming from the mobile station at 65.2 GHz, so that conventional fiberoptic transmission back to the control station can be used. The connection between control station and base station was a 12.8 km standard single mode fibre, and the span of the radio link was about one metre.
- For two-channel transmission experiments the setup was augmented by a further injection locked laser. Two signals were generated in the 62 GHz band, each carrying a 155 Mbit/s OQPSK modulated data signal. BER measurements at different channel spacings showed that a minimum spacing of less than 140 MHz was possible, due to the high spectral efficiency (greater than unity).

- Highly efficient optic/microwave converters containing photodetectors and MMIC amplifiers were developed in hybrid technology for the 60 GHz band. This work was carried out at the HHI in cooperation with FhG-IAF Freiburg, DASA and the Hahn-Meitner Institute. Several converter modules with different MMIC amplifier chips have been completed for the frequency range from 50 to 70 GHz, and have been tested in the experimental system.

## Competencies

Design and development of optical microwave generation systems

Development of optical millimetre wave techniques for mobile communications in the 60 GHz range

Design and development of IR inhouse mobile communication systems

Development of hybrid concepts for integrated mobile communication systems

Sequence and system design for optical CDMA

Design of combined channel coding and equalization concepts for wireless ATM systems

## **Electronic Imaging Technology for Multimedia**

### **Topics and Results**

The R&D contributions of the HHI to this research area are in the areas of Image Processing and Terminal Systems and Applications.

### **Image Processing**

The HHI activities in the field of image processing are concentrated on signal processing and coding for image services for various applications and at various resolutions, on the realization of hardware demonstrators, and on the design of VLSI components. The image formats range from QCIF (Quarter Common Image Format) with 144 x 180 pels up to HDTV with 1152 x 1920 pels. Typical applications are VLBV (Very Low Bitrate Video) for multimedia communication at low bit rates, TV and HDTV distribution and communication, as well as studio applications for TV, HDTV and VLTV (VisionLike TeleVision). One emphasis is on Multimedia Communication on Integrated Networks and Terminals (MINT), which is a collaborative project sponsored by BMBF. Main topics of this project are mobile communications and terminals for mobile and stationary multimedia services. The development of the MPEG-4 standard for image and sound compression plays a central role in MINT.

Pixel-oriented and block-oriented coding methods, as standardized by MPEG (Moving Pictures Expert Group), have reached a certain degree of saturation in performance. Substantial improvements can only be obtained by applying "intelligent" coding schemes which use image analysis and synthesis methods.

Such object and model based techniques are being initially developed for VLBV coding (8-64 kbit/s), though with certain restrictions on the image material (e.g. the picture phone). However, these techniques will also be applied to general video sources in order to support wideband broadcast services. The results of this work have been presented to ISO-MPEG as contributions to the specification of the forthcoming MPEG-4 standard.

In addition to the development of compression algorithms themselves, the applications of these methods in new interactive services is of crucial importance. Thus the HHI is developing applications using MPEG-4 for broadcast services via DAB/DMB (Digital Audio/Multimedia Broadcasting) and for interactive services via ISDN or the Internet.

- A Netscape application was developed using JAVA for interactive scene manipulation based on object-oriented MPEG-4 coding. This application supports user functions such as remote loading of compressed video objects, showing the objects in the local browser window, generation of new video scenes by copying the objects into a compositor window, and editing (cut, paste, copy, magnify, etc.) of video scenes in the compositor window. This application was exhibited at IFA '97 and CeBIT '97, where it was awarded the second prize of a renowned computer magazine.
- A system for teleshopping in a virtual shop was developed, in which the user can click real video objects (sales objects) on the screen and call for additional information about them (price, size, colour, etc.). The user can also view the objects from all sides (3D models) or can request on-line advice about them. This system was exhibited at IFA '97.

In the field of processing of moving 3D sequences, the emphasis at the HHI is on combined motion and disparity estimation and compensation. These techniques can be applied in the studio (3D production, depth keying) as well as for communication purposes (3D video conferencing). In particular, software and hardware development is being carried out for autostereoscopic multi-viewpoint systems. These will be applied in fields such as communication, medicine, 3D program production and industrial automation. As well as general algorithmic investigations for disparity estimation and intermediate image interpolation, a real time system for the generation of intermediate views is under development, in cooperation with other partners.

- A new method for the simple 3D representation of video objects was developed. This "incomplete 3D" system transforms the object photographed with two or more cameras into a 2D object which can

be compressed using the MPEG-4 standard. The reconstruction at the receiver can be achieved with a disparity map, which can be transmitted as mask data in an MPEG data stream. Thus an elegant system for 3D coding has been created which can be applied within the existing MPEG-4 syntax.

The development of methods for image processing in the studio and in TV receivers using computer simulations has played an important role in the HHI over many years. Important topics have been motion estimation, interpolation of intermediate pictures, format conversion and noise reduction. Advances in algorithms and microelectronics now allow these methods to be integrated onto a single chip.

- A method of motion estimation and format conversion which is outstanding for its high performance and low complexity has been developed. It allows the conversion of 24/25 Hz (film) or 50/60 Hz interlaced (video) input sequences to output sequences at arbitrary frame rates up to 120 Hz, in either interlaced or progressive formats. This achievement forms the basis of joint chip developments with semiconductor manufacturers.

Interactive search and selection of video and audio information will be of great importance for the successful introduction of future multimedia services. In order to make it possible to search for non-text-based content, for instance over the Internet, a standardized Multimedia Content Description Interface (MPEG-7) is to be developed within the MPEG framework. Work has started on image analysis, image characterization and image indexing.

The development of new transmission concepts and methods for mobile multimedia communication and the development of new concepts, features and user interfaces for stationary and mobile terminals play central roles in work under the framework of the collaborative project Multimedia Communication on Integrated Networks and Terminals (MINT).

It is the objective of the work carried out at the HHI to contribute major components to the collaborative MINT demonstrator, including an MPEG-4 decoder with the system demultiplexer, an MPEG-4 system multiplexer as well as systems for decoding and displaying 3D images.

Furthermore, these components must be integrated into the terminals, which may be based on PCs (laptops or notebooks), workstations, set-top units or mobile DAB receivers built into cars. Also, laboratory tests and field trials must be carried out.

To achieve this objective, concepts for the realization of the above components must be developed taking into account future technologies and products. Since signal processing, such as image compression and format conversion, will eventually be done using audio/video (A/V) processors, investigations are underway into how these algorithms can be performed on such processors, possibly together with co-processors. The results of these investigations will also benefit the EUREKA/MEDEA project MPEG fo(u)r Mobiles, which began in 1997.

Moreover, for all types of terminals user-friendly graphical interfaces are under development. These interfaces include conventional remote control devices as well as speech input.

- The initial concepts and prototypes ("Objects on Demand", MPEG-2 compressed 3D video on CD-ROM, and an interactive user interface including speech input) were presented to the general public at IFA '97.

Recent advances in image compression (MPEG-2) and in digital transmission methods (DVB standards) allow the introduction of cinema-like film and video distribution services over satellite and cable. These services include movies, live events and commercial presentations, which may be transmitted to small electronic cinemas, ordinary cinemas, entertainment centres, universities, hotels and possibly to individual subscribers. DVB techniques will be used for transmission over satellite and cable, and MPEG-2 will be used for image and sound compression. In particular, the HHI is providing an MPEG-2 HDTV decoder, which involved the development of a 1-chip decoder. The decoder is to be presented to the general public in Europe (within the framework of the ACTS project CINENET), as well as in Japan and the USA, at the beginning of 1998.

## Terminal Systems and Applications

Multimedia techniques should enable the interactive and simultaneous access to information in different modalities (image, audio, text, etc.). As a consequence, multimedia user interfaces should be designed to support natural and familiar forms of information exchange. Here the task is to develop new concepts for the realization of novel, useful, user friendly, attractive and non-tiring multimedia applications, which might then find their way into the marketplace.

R&D work at the HHI in this field covers the development of interactive 3D user interfaces and the user-oriented design and evaluation of selected communication and information services. Other work is devoted to the development of new display technologies, especially autostereoscopic image reproduction methods and full colour light emission using electroluminescence. Also included is the development of a read/write head for high rate data transmission using the new storage medium DVD.

The efficiency of user interfaces for information-rich applications benefits from the use of 3D imaging technologies. The HHI is therefore developing autostereoscopic displays for the reproduction of 3D scenes that allow the unlimited presentation of information in a way that is matched to the human eye.

Three basic functions in natural viewing must be involved when viewing the display – i.e. the limited depth of focus, the coupling between accommodation and convergence of the lines of sight, and the change of perspective with a change of viewing position (dynamic perspective). To do this it is necessary to introduce a synthetic depth of focus, coupled with a dynamic adaptation of the focal plane to the plane of fixation. Moreover it is necessary to provide intermediate views in proper perspective. The positions of the eyes and of the fixation point in space must be known to control these functions. Image processing algorithms as well as special optical components and video-based measuring methods have been developed for these purposes. The functions mentioned above have been implemented and demonstrated in an autostereoscopic workstation display with a gaze-controlled

user interaction space instead of a mouse-controlled user surface.

- The user friendliness of the concepts "virtual communication space" and "gaze control" has been demonstrated.
- New measuring methods to determine eye position and line of sight were developed. These meet the practical requirements for measurement speed and precision.
- First steps for the construction of a "Depth of Interest Display" using synthetic depth of focus were undertaken.
- A platform-independent visual operating system ("virtual communication space") was conceived and partially implemented using JAVA and VRML.
- A novel 3D operating system with gaze control based on the workstation operating system UNIX and the Virtual Reality Software dVS was conceived and successfully implemented. The system was presented to the public at IFA '97 and has had a very positive response in the technical press.

A high degree of user friendliness in an information application can only be achieved if the design of the user interface is based on a reliable analysis of user requirements. Methods for analyzing user requirements and determining usability were further developed and are available to the public, and especially to the ACTS project groups.

- The HHI offers this service in cooperation with its partners in the ACTS project Usability in ACTS (USINACTS). The HHI has implemented a help service with a bulletin board on human factors topics in the Web.

3D imaging has proved to be a very useful technology in studio-based video conferencing. Similar advantages may also be expected for desktop multipoint conferencing, which is a particularly appropriate form of conferencing for dispersed workgroups in an organization. We have therefore also investigated the benefits of specific 3D technologies for workplace systems, in particular undistorted reproduction of motion parallax and object geometry, eye contact, perceptually correct 3D image mixing, and remote 3D pointing.

- A perceptual experiment has shown that the divergence between accommodation and convergence that arises with stereoscopic methods hardly influences the representation of motion parallax.

- Initial experiments with mixing 3D images show that images with greater depth should be positioned in the upper part of the screen and images with less depth in the lower part.
- Several different methods for remote 3D pointing have been developed and tested for user friendliness. It was shown that with these methods a conventional computer mouse can be used for pointing in stereoscopic presentations.

One important aspect of interpersonal communication is informal communication. This term refers to the spontaneous and usually confidential chats held outside structured conferences, e.g. at coffee breaks or at other accidental meetings. Since informal communications have a positive significance for both the individuals and the organization, there is a need to find ways of providing technological support for informal communication in dispersed workgroups. It is especially important to find ways of representing non-verbal signals such as eye contact or similar non-verbal interactions.

- A survey of potential users of telecooperation systems has shown that informal communication is regarded as indispensable in many work-related situations.
- A limited inhouse field experiment with an Internet relay chat system resulted in a list of requirements for technical systems to support informal communication.
- A multipoint workplace video conferencing system was implemented which makes it possible to have individual eye contact between all partners.

R&D work at the HHI on autostereoscopic displays concentrates on the lenticular screen method, but the field lens principle is also being investigated. The developmental goals are to create compact displays based on either matrix panels (for desktop applications) or large format back projection displays (for simulators or other special applications). Both types are intended for single users. In an autostereoscopic display the direction of the light beams must change as the user moves, and new tracking principles are being developed to achieve this.

- In the past, direct view display panels combined with lenticular sheets had to be used in the portrait orientation, which makes image conversion necessary. This was required because only in this orienta-

tion were the three colour sources for each pixel vertically aligned, thus making it possible to project their light through the corresponding lenslet into the eye of the user. We have eliminated this restriction by a new lenticular lens structure (the "colour multiplex method"). Standard landscape format images can now be presented.

- A prototype of a new large screen back projection display was constructed. The screen consists of a sandwich arrangement of a single lenticular sheet and a diffusing plate. The lenticular screen uses the colour multiplex method. A movable projection system, which can change the positions and relative distances of the projected image points, is used for tracking.
- The light bundles in a lenticular screen display are separately aligned for each pixel column. By contrast, the field lens principle aligns the light in a global fashion through a single large field lens, with an individual LC panel for each eye. A display based on this principle was set up. Its high resolution is very attractive, as is its large crosstalk attenuation. Naturally, the thickness of a field lens display is considerably greater than that of a lenticular display. This display is being tested in a 3D multipoint communication experiment.
- The spatial resolution of autostereoscopic lenticular displays is limited by the achievable precision in registering the image and lens rasters. If tracking is done by moving a lenticular screen relative to the display panel, the achievable registration precision is reduced compared to that of a fixed arrangement. In order to combine the advantages of a fixed arrangement with the possibility of tracking, a robot arm has been developed which adjusts the entire display as the viewer moves in such a way that its position and orientation relative to the viewer remain constant.
- In cooperation with a partner from industry, the HHI has developed a prototype of a very compact high resolution autostereoscopic display with lens raster tracking for medicinal applications. This system was demonstrated at the HHI stand at IFA '97.

In the search for new display principles, the HHI is concentrating on high voltage electroluminescence. In spite of the very promising results obtained in the past using the "colour-by-white" principle, optimization of the blue primary colour is still

needed, since it still does not match the required EBU primary value.

• Improvements of SrS:Ce thin film electroluminescent device performance were achieved by applying a new charge compensation method for Ce<sup>3+</sup> dopants in the phosphor layer preparation process. The result is a blue shift of the emission spectrum of about 10 nm, together with an increased luminous efficiency of up to 2 lm/W. Initial white emitting SrS:Ce/ZnS:Mn display prototypes, of size 10 cm x 10 cm and with a resolution of 128 x 128 pixels, demonstrated the potential of colour-from-white display applications.

As well as display technology, data storage is also an essential component of multimedia systems. The Digital Versatile Disk (DVD), which has just started to go to market, is based on the principle of the optical disk, but has a considerably larger storage capacity (currently 9 GB) as well as fast data access (exceeding 10 Mbit/s) and the option of re-writability.

• In order to extend the conventional optical reading head of a CD player for simultaneous reading and writing of information on a DVD with several storage layers, the possible replacement of the conventional optics by light, multifunctional Diffractive Optical Elements (DOEs) is under investigation. These are computer generated and are produced by microstructuring techniques.

Analysis and optimization of communication terminals and services on the basis of human factors criteria

Development of video-based pattern recognition and photogrammetry methods

Modelling and development of integrated circuits for image processing

Design and construction of experimental systems for the development of video-based communications applications and for testing and demonstrating new communication technologies and hardware architectures

Analysis of human sensory and sensorimotor functions in relation to communication applications

Expertise in desktop computer graphics design

Research in the area of high voltage electroluminescence (SrS:Ce, ZnS:Mn)

Development of multilayer electroluminescent structures, blue-emitting phosphors, full colour flat displays and transparent displays

Development of diffractive optical elements for read/write heads of optical disks

## Competencies

Development of algorithms and hardware architectures for image and sound compression (MPEG-2, MPEG-4)

Development of algorithms and hardware architectures for 2D and 3D image analysis and synthesis using motion and stereo information

Development of applications based on MPEG-2/4/7 and JAVA for interactive services over the Internet, DVB/DAB/DMB or ISDN

Development of 3D display technologies

Conception and evaluation of user interfaces for multimedia applications using VRML, JAVA, and dVS

## F & E-SCHWERPUNKTE

### Photonik-Netze

#### Themen und Ergebnisse

Basis leistungsfähiger Kommunikationsnetze sind photonische Netze, die mit Hilfe von optischen Frequenz- und Zeitmultiplextechniken die außerordentlich hohe Bandbreite von Lichtwellenleitern nutzen. In Verbindung mit dem optischen Schalten der Transportwege ermöglicht die optische Nachrichtenübertragung transparente und damit dienstunabhängige Netze. Mit einem Photonik-Netz werden also für alle heutigen und zukünftigen Dienste sehr breitbandige Transportwege bereitgestellt.

Ziel des HHI ist es, mit seinen Forschungsarbeiten maßgeblich zur Entwicklung des Photonik-Netzes beizutragen. Folgende Themen werden schwerpunktmäßig behandelt:

- Entwicklung von Netzkonzepten für die verschiedenen Ebenen des Photonik-Netzes, nämlich Core Network, Access Network und Customer Network.
- Ermittlung der Anforderungen an die Netzelemente und deren photonische Komponenten sowie an Einrichtungen zur Überwachung des Netzbetriebs.
- Untersuchung des Potentials optischer Multiplexverfahren wie der Frequenz- und der Zeitmultiplextechnik, wobei der optimalen Kombination beider Multiplexverfahren eine besondere Bedeutung kommt.
- Ermittlung der Längenbegrenzung optischer Pfade in photonischen Netzen, die durch nichtideale Netzkomponenten und die daraus resultierende Signaldegradation begrenzt wird.
- Untersuchungen zur betrieblichen Überwachung, Steuerung und Regelung von Netzen (Operation, Administration and Maintenance: OAM).
- Entwicklung und Herstellung zugehöriger photonischer Komponenten und Subsysteme.

Der Forschungsschwerpunkt Photonik-Netze gliedert sich in die Fachgebiete Access und Customer Network sowie Core Network.

### Access und Customer Network

Die Forschungs- und Entwicklungsarbeiten konzentrieren sich auf den Einsatz der WDM-Technik im Access Network. Ziel ist es, Systemkonzepte und Komponenten für WDM-Anwendungen im Access-Network zu entwickeln und zu untersuchen.

Es werden Forschungs- und Entwicklungsarbeiten zum WDM-Upgrade eines bestehenden passiven optischen Netzes (PON) durchgeführt. Hierbei wird auf einem Systemkonzept aufgebaut, das eine Kapazitätserweiterung ohne Änderung der Glasfasernetzstruktur zwischen der Zentrale und den teilnehmernahen Optical Network Units (ONU) erlaubt. Das passive optische Zugangsnetz wird mit einem WDM-Overlay von permanenten Wellenlängenpfaden im Bereich 1,5 µm versehen, was gleichzeitig den Schutz gegen Störungen und Abhören erheblich verbessert. Zentrales Bauelement ist ein Arrayed Waveguide Grating (AWG), das zum Multiplexen, Demultiplexen und zum Routen der Signale unterschiedlicher Wellenlänge eingesetzt wird. In einem Experimentalsystem werden AWGs entsprechend dem von der International Telecommunication Union (ITU) vorgeschlagenen 100-GHz-Kanalraster verwendet.

Derartige Filter werden im HHI mit unterschiedlichen Spezifikationen auf der SiO<sub>2</sub>/Si-Materialbasis entwickelt und hergestellt. So wurden 16-Kanal-AWGs mit einem Kanalabstand von 100 GHz, einer Einfügedämpfung von Faser zu Faser von 5 dB und einem Nebensprechen von < - 25 dB realisiert. Des Weiteren wurden ein 8-Kanal-AWG mit einem sogenannten Flat-Top-Design entwickelt, dessen angehert rechteckförmige Durchgangskarakteristik besser für eine Kaskadierung geeignet ist. In dem zuvor dargestellten Systemkonzept für den WDM-Upgrade eines PONs ist neben dem WDM-Multiplexer/Demultiplexer der optische Sternkoppler eine weitere Schlüsselkomponente. Es wurden ein Konzept zur Vereinigung beider Funktionen in einer Komponente, d.h. der Funktionen eines AWGs für den einen Wellenlängenbereich und die Verteilfunktion eines Sternkopplers für einen anderen Wellenlängenbereich, entwickelt und erste Komponenten hergestellt.

Bei dem Upgrade von optischen Übertragungssystemen mit Hilfe der WDM-Technik ist es notwendig, diese mit Hilfe von Transpondern an eine bereits existierende Systemumgebung zu adaptieren. Ein Transponder besteht aus einem optischen Empfänger und einem optischen Sender, der auf einer vorgegebenen Wellenlänge sendet. Je nach Eingangsempfindlichkeit und optischer Ausgangsleistung kann mit einem solchen elektro-optischen Wellenlängenkonverter neben der Wellenlängenumsetzung auch eine Signalverstärkung erreicht werden. In Kooperation mit der Industrie erfolgte die Entwicklung eines modularen Transponders, der ohne zeitliche Regeneration bittransparent von 100 Mbit/s bis 2,5 Gbit/s arbeitet. Für den Betrieb bei festen Bitraten (z.B. SDH, STM-16) kann eine elektronische Signal- und Taktrückgewinnung eingefügt werden. Weiterhin ist der Transponder auch in optischen Cross-Connects und optischen Add/Drop-Multiplexern einsetzbar. Für die Einbindung in ein TMN-System ist der Transponder mit entsprechenden Steuer- und Überwachungsfunktionen versehen.

Eine weitere zentrale Komponente in WDM-Netzen sind 'Drop' Filter, die einzelne Wellenlängenkanäle aus dem Kanalensemble herausfiltern können. Eine solche Komponente in Form eines aktiven, monolithisch integrierten optoelektronischen Bauelements auf InP-Basis wird im Rahmen eines ACTS-Vorhabens entwickelt. Sie besteht aus einem abstimmbaren, polarisationsunabhängigen optischen Filter, einem optoelektronischen Detektor und einem elektronischen Vorverstärker. Für eine Durchlaßcharakteristik mit 20 dB Nebensprechen wurde eine Filterbreite von 400 GHz (3,2 nm) und ein Durchstimmbereich von 25 nm erreicht.

Für den Einsatz im Access-Bereich werden bidirektionale optoelektronische Wandler (Transceiver) entwickelt. Dabei wird ein monolithisch integrierter, kompakter und für die Massenfertigung geeigneter Aufbau angestrebt. Das Vorhaben wird in enger Zusammenarbeit mit Industriepartnern durchgeführt. Darüber hinaus sollen Transceiver des HHI im Rahmen eines ACTS-Projekts unter Federführung von CNET (Frankreich) und Telenor (Norwegen) in OFDM-Feldversuchen eingesetzt werden.

Für die Integrationstechniken auf InP-Basis stellt die flächenselektive (lokale) Epitaxie einen unverzichtbaren Herstellungsschritt dar. Deshalb wird hierfür das metallorganische (MO)MBE-Verfahren in enger Zusammenarbeit mit einem Industriepartner sowie der Universität Ulm und dem Walter-Schottky-Institut München weiterentwickelt und optimiert.

Ferner wird, basierend auf obiger Technologie, nach Spezifikationen eines Industriepartners, ein WDM-Transmitter mit 4 Kanälen im Abstand von 200 GHz entwickelt und hergestellt. Die Lage der Frequenzkanäle entspricht den ITU-Vorschlägen, die Bitrate soll bei 2,5 Gbit/s pro Kanal liegen. Arbeitsschwerpunkt war im vergangenen Jahr die Entwicklung von Strained-Layer Multi-Quantum-Well Lasern mit hoher Ausgangsleistung.

In einem F&E-Auftrag eines Industriepartners werden langwellige DFB-Laser auf der Basis der Feststoffquellen-MBE hergestellt. Gegenstand dieses technologieorientierten Auftrages ist die Entwicklung von DFB-Laserdioden für den Einsatz in bidirektionalen optischen Anschlußnetzen.

Ein systemmäßiger Test und Einsatz von Bauelementen ist nur möglich, wenn diese in Form von kompletten Modulen vorliegen. Die Aufbau- und Verbindungstechnik ist daher ein weiterer bedeutender Schwerpunkt der technologisch orientierten Arbeiten.

## Core Network

Die Arbeiten in diesem Fachgebiet sind auf die Themen höchstbitratige Übertragung im Zeitmultiplex (TDM), optischer Crossconnect und optisch transparentes Netz ausgerichtet. Für die höchstbitratige Übertragung (TDM) kann das Multiplexen und Demultiplexen sowohl elektrisch (ETDM) als auch optisch (OTDM) erfolgen. Wichtige Aufgaben sind dabei die Generierung, Modulation, Detektion und Synchronisation der optischen Signale. Weitere Untersuchungspunkte sind der Einfluß von photonischen Netzkomponenten und Faser-Nichtlinearitäten auf die Qualität der optischen Signale sowie die Techniken der Dispersionskompensation.

Für die ETDM-Technik bei 40 Gbit/s werden Transmitter mit integriertem Laser/Modulator (geringer Chirp) und

Empfänger mit integrierten Wellenleiterdioden und High-Electron-Mobility-Transistoren (HEMT) für die optimale Impedanzanpassung entwickelt. Die Übertragung erfolgt vornehmlich mit NRZ-Signalen. Ein Laser/Modulator-Modul, das im Bereich einiger nm abstimmbar ist und eine 3 dB-Grenzfrequenz von 18 GHz aufweist, wurde aufgebaut.

Hochrate Empfänger werden für den Wellenlängenbereich 1,3 bis 1,55 µm entwickelt. Sie bestehen aus wellenleiter-integrierten PIN-Photodioden und HEMTs zur Verstärkung der elektrischen Signale. Das dafür verwendete Bauelementkonzept erlaubt prinzipiell eine stetige Fortentwicklung der zugrundeliegenden optoelektronischen integrierten Schaltung (OEIC) bis in den 100 Gbit/s-Bereich. Die als Modul aufgebauten Empfänger-OEICs wurden in 20 Gbit/s-Systemexperimenten eines Industriepartners erfolgreich getestet. In einem weiteren Schritt sind zusammen mit einem Industriepartner erfolgreiche 40 Gbit/s-Detektionsexperimente durchgeführt worden.

Die Arbeiten zur optischen Zeitmultiplextechnik (OTDM) beinhalten die Untersuchung und Realisierung optischer Subsysteme, die in der Lage sind, optische Signale von 1 bis 10 Gbit/s zu einem 40 bis 160 Gbit/s-Signal zusammenzufassen (MUX) und anschließend wieder rein optisch zu demultiplexen (DEMUX). Zur Übertragung werden hier vornehmlich mit modengekoppelten Lasern generierte RZ-Signale verwendet.

Experimentelle Untersuchungen zur Kombination von WDM- und TDM-Technik in einem Übertragungssystem mit der Gesamtkapazität von 160 Gbit/s zeigten folgendes Ergebnis. 40 Gbit/s-Signale, generiert aus 10 Gbit/s-Datenströmen im optischen Zeitmultiplex, wurden in 4 WDM-Kanälen über 100 km Standardfaser bei einer Wellenlänge von 1,55 µm übertragen. Dabei war eine gemeinsame Dispersionskompensation für alle 4 WDM-Kanäle mittels dispersionskompensierender Faser ausreichend, um eine fehlerfreie Übertragung zu gewährleisten.

Ferner wurden vergleichende Untersuchungen zur 40 Gbit/s OTDM-Übertragung bei einer Wellenlänge von 1,55 µm über verschiedene Fasertypen (Standardfaser, "True-Wave"-Faser, dispersionskompensierender Faser und dispersionsverscho-

bene Faser) durchgeführt. Ohne optische Zwischenverstärkung konnten die größten Entfernungsmit einer Kombination aus Standardfaser und dispersionskompensierender Faser überbrückt werden.

Für Demultiplex- und "Add-Drop"-Funktionen in OTDM-Systemen wurden verschiedene nichtlineare Interferometeranordnungen (Mach-Zehnder-, Michelson-, Sagnac-Interferometer) mit optischen Halbleiterlaserverstärkern als monolithisch integrierte Komponenten hergestellt und erfolgreich eingesetzt. Monolithisch integrierte symmetrische Mach-Zehnder Interferometer Bauelemente mit zwei zusätzlichen Abzweigen zur optischen Signalkontrolle wurden erfolgreich hergestellt. Als optisch nichtlineares Element werden optische Halbleiterverstärker in jedem der zwei Arme des Interferometers eingesetzt. Diese Bauelemente (PIC) wurden weiterhin für eine rein-optische Wellenlängenkonversion eingesetzt. BER Messungen zeigten eine fehlerfreie Funktion.

Alternativ werden zum optischen Demultiplexen elektro-optische Mach-Zehnder Strukturen untersucht, in denen der Quantum Confined Stark-Effekt (QCSE) in MQW-Strukturen ausgenutzt wird. Für eine verspannte Quantenfilmstruktur mit Tunnelbarrieren für die leichten Löcher wurde polarisations-unabhängiges Schalten demonstriert. Für die Mikrowellensteuerung sind kapazitätsbelastete Lauffeldleitungen vorgesehen, die für das Demultiplexen bis 40 Gbit/s geeignet sind. Die Kombination wird zur Zeit bearbeitet.

Die Signaldegradation in optischen Netzen führt zu einer Längenbegrenzung der optischen Pfade. Durch vollständige Regeneration der digitalen Signale (3R, re-amplification, reshaping, retiming) kann diese Begrenzung überwunden werden. Mit Hilfe der optischen Signalverarbeitung werden Verfahren und Komponenten entwickelt, die es erlauben, digitale optische Signale teilweise (2R, reamplification, reshaping) oder völlig (3R) zu regenerieren. Schlüsselkomponenten der 3R-Regeneration sind die Taktrückgewinnung und Entscheiderstufen. 3-Sektions-RWG-Laser zeigen bei geeignetem Design eine bistabile Charakteristik. Es wurde ein Modul zur Taktrückgewinnung aufgebaut, das im Bereich von unter 5 bis über 20 Gbit/s arbeitet. Die Taktrate ist über einen Strom kontinuierlich einstellbar.

Darüber hinaus wird untersucht, inwie weit speziell entwickelte 3-Sektions-RWG-Laser auch als Entscheider verwendet werden können. Die technologischen Gemeinsamkeiten dieser Verstärker, Taktextraktions- und Entscheiderstufen ermöglichen in der Zukunft die monolithische Integration eines optischen 3R-Regenerators.

Die Vermittlungseinrichtungen zukünftiger Kommunikationssysteme müssen optische Frequenzmultiplexsignale und sehr hochratige Signale durchschalten können. Hierzu sind entsprechende optische Raum-, Frequenz- und Zeitstufen erforderlich. Ziel der Forschungsarbeiten sind Vermittlungseinrichtungen, die eine Durchschaltung der Signale mit optischen Mitteln ermöglichen. Hierdurch sollen zum einen optoelektrische Wandlungen im Signalweg vermieden und zum anderen Geschwindigkeitsgrenzen überwunden werden, die die elektronische Signalverarbeitung setzt.

Im Auftrag eines Netzbetreibers werden die Eigenschaften von regeneratorfreien optischen Kommunikationsnetzen sowohl theoretisch als auch experimentell untersucht. Die wesentlichen Elemente in der Transportebene solcher Netze sind die Übertragungsstrecken, Faserverstärker und optischen Crossconnects. Nichtideale Eigenschaften dieser Komponenten führen, bedingt durch Signaldegradation, zu einer Begrenzung der Übertragungslänge im optischen Netz. Entsprechende Transparenzlängendiagramme können als Grundlage für die Planung der Transportebene optisch transparenter Netze dienen. Die experimentelle Überprüfung erfolgt in einem achtkanaligen WDM-Ringtestbed, in dem Datenpakete mit einer Übertragungsrate von bis zu 10 Gbit/s pro Wellenlängenkanal in einem Faserring umlaufen. Mit dem Ringtestbed kann die Kaskadierung mehrerer Übertragungsabschnitte in der Zusammenschaltung mit optisch transparenten Crossconnects nachgebildet und die Signalqualität als Funktion der Anzahl der durchlaufenen Crossconnects und der Faserstreckenlänge bestimmt werden. Es werden Methoden zur Simulation der Signalausbreitung im optischen Pfad entwickelt und mit den experimentellen Messungen überprüft. Dafür kommt das Programm paket BroadNeD zum Einsatz, das demnächst kommerziell erhältlich sein wird.

Bei der Entwicklung von Raumschaltern für optische Crossconnects oder für das Schalten von Ersatzwegen werden unterschiedliche Realisierungswege verfolgt:

Ein Ansatz basiert auf der Verwendung von Flüssigkristallen in Verbindung mit SiO<sub>2</sub>/Si-Wellenleitern. Ziel ist die Realisierung von Totalreflexionsschaltern, die kompakt aufgebaut werden können, quasi leistungslos steuerbar sind und eine digitale Schaltcharakteristik aufweisen. Als zweiter Weg wird auf der Basis von Polymeren die Entwicklung thermo-optisch steuerbarer Schalter verfolgt. Polymermaterialien eignen sich hierfür besonders wegen ihres großen Temperaturkoeffizienten des optischen Brechungsexponenten und der geringen Wärmefähigkeit. Dies sind Eigenschaften, die insgesamt zu kleinen Schaltleistungen führen. In den zurückliegenden Jahren wurden unterschiedliche Schaltertypen, namentlich interferometrische Richtkopplerschalter ( $2 \times 2$ ) und -matrizen ( $4 \times 4$ ) und digital optische Schalter ( $1 \times 2$ ,  $2 \times 2$ ), mit sehr niedrigen optischen Crosstalk-Werten entwickelt. Die Herstellung basierte dabei im wesentlichen auf dem Material PMMA, das eine geringe Temperaturstabilität und eine relativ hohe optische Dämpfung aufweist. Deshalb konzentrieren sich die Arbeiten nun mehr auf die Charakterisierung und Technologie neuer Polymermaterialien, von denen verbesserte Eigenschaften erwartet werden.

Polymere wurden auch als potentielle Materialien für elektrooptische und nichtlineare optische Bauelemente untersucht. Damit könnten optische Funktionen wie optisch-optisches Schalten, Frequenzumsetzung oder parametrische optische Verstärkung realisiert werden. Die Arbeiten, die im Berichtsjahr abgeschlossen wurden, haben gezeigt, daß gepolte Polymere mit elektro-optischen Koeffizienten von etwa 15 pm/V (@1,5 μm) und ausreichender Langzeitstabilität hergestellt werden können, die zur Herstellung hochfrequenter Modulatoren geeignet sind. Für optisch-optische Bauelemente auf der Basis phasenangepaßter Frequenzverdopplung erwiesen sich jedoch die bisher untersuchten Polungsfarbstoffe für Betriebswellenlängen um 1,5 μm als ungeeignet.

Optische Frequenzumsetzer können für Crossconnects in WDM-Systemen zur Verminderung der Blockierung und als Interface zwischen Access- und Core-

Network eingesetzt werden. Im Rahmen eines Auftrages eines Netzbetreibers wurde eine Studie mit dem Titel "Betrieb und Überwachung von optischen Frequenzkonvertern in der Frequenzstufe optischer WDM-Crossconnects" angefertigt. In der Studie wurde der Aufwand für Betrieb und Überwachung von Transpondern und optischen Frequenzkonvertern analysiert, die auf Kreuzverstärkungsmodulation bzw. Kreuzphasenmodulation (XPM) basieren. Die Aufgabenstellung steht in engem Zusammenhang mit der Problematik von Betrieb und Wartung (Operation and Maintenance (OAM)) der Komponenten und Subsysteme in optischen Netzen. Als wichtiges Problem erweist sich hier, daß selbst bei sehr geringen Anforderungen an die Transparenz der optischen Netze die Möglichkeiten zur Kontrolle der Signalqualität sehr stark eingeschränkt sind.

Die Anwendung der WDM-Technik im Core Network mit optischen Crossconnects bei Datenraten bis zu 10 Gbit/s pro WDM-Kanal wird in dem von der Firma Siemens geführten ACTS-Vorhaben PHOTON untersucht. Das HHI ist mit der Entwicklung und dem Aufbau der Wellenlängenreferenz für einen Demonstrator sowie mit Systemstudien an dem Vorhaben beteiligt.

Die Arbeiten zur höchstbiträtigen TDM- und zur WDM-Übertragungstechnik werden unterstützt durch analytische Untersuchungen der Signalqualität als Funktion der optischen Pfadlänge im photonischen Netz. Für das Modelling und die Simulation von optischen Pfaden wurden eine Reihe von neuen Programmmodulen entwickelt, die im Vergleich mit Systemexperimenten verifiziert werden konnten. Erste Simulationen zur Untersuchung des optischen Nebensprechens in Crossconnects wurden erfolgreich durchgeführt.

Im Auftrag und in Kooperation mit einem Industriepartner wurden Planungsdaten für ein Photonisches Netz erarbeitet. Für eine übersichtliche Darstellung aller relevanten Systemaspekte wurde ein Netzmodell entworfen, an dem sich physikalische und funktionale Eigenschaften gut untersuchen lassen und mit dem die Leistungsfähigkeit eines photonischen Netzes gezeigt werden kann. Zusammenfassend kann der Schluß gezogen werden,

daß die optisch transparente Vollvermaschung aller Knoten eines Netzes mit der Flächenausdehnung Deutschlands über einzelne Wellenlängenkanäle mit bis zu 10 Gbit/s pro Kanal möglich ist. Der Entwicklungsschritt von einer WDM-Punkt-zu-Punkt Übertragung hin zu einem schaltbaren WDM-Netz ist allerdings so groß, daß die Weiterentwicklung von derzeitigen Glasfasernetzen in folgenden Phasen geschehen wird: Punkt-Punkt einkanalig, Punkt-Punkt mehrkanalig mit WDM, Netz mit starrem Routing von WDM-Kanälen, Netz mit Ersatzschaltungen im WDM-Bereich und schließlich ein flexibles Netz mit Schaltfunktionen für alle Kanäle in WDM-Crossconnects.

Ein Großteil der oben beschriebenen Aktivitäten wird im Rahmen des nationalen Forschungsprogramms Photonik II, gefördert vom Bundesministerium für Bildung, Wissenschaft, Forschung und Technologie, durchgeführt. Während der Laufzeit 1994 – 1998 zählen optische Kommunikationssysteme, die optische Verbindungs-technik sowie Schlüsselkomponenten und -technologien zu den wesentlichen Schwerpunkten. Die Themen werden von der nachrichtentechnischen Industrie zusammen mit Forschungseinrichtungen und Universitäten bearbeitet. Die wissenschaftliche Federführung des Forschungsprogramms teilen sich das Fraunhofer Institut für Angewandte Festkörperphysik (FhG-IAF), Freiburg, und das HHI.

## Kompetenzen

Untersuchung und Entwicklung der Architekturen photonischer Netzwerke, Erstellung von Planungsrichtlinien und Studien zu spezifischen Problemen photonischer Netzwerke

Charakterisierung und Test von optischen Netzwerken und Netzwerkelementen einschließlich Experimenten an ringförmigen Fasertrassen, Übertragungsexperimente über große Längen und Feldversuche

Entwicklung von hochratigen optischen WDM-Systemen (10 Gbit/s pro Kanal) und entsprechenden WDM-Meßtechniken

Untersuchung, Entwurf und Entwicklung von optischen WDM-LANs/MANs, opti-

- schen Netzen im Teilnehmerbereich und passiven optischen Netzwerken
- Entwicklung von Verfahren zur Steuerung und Überwachung von Netzwerken
- Entwicklung, Anwendung und Verifikation von Simulations-Software für optische Transportnetzwerke
- Entwurf und Entwicklung von auf Heterodyn-Techniken beruhenden optischen Systemen
- Entwicklung von Verfahren der Wellenlängenkonversion für WDM-Systeme
- Untersuchung und Entwicklung von hochratigen OTDM-Subsystemen (10 bis 40 Gbit/s und höher) einschließlich Multiplex/Demultiplex- und „Add/Drop“-Techniken
- Entwicklung von Verfahren zur rein optischen Taktrückgewinnung und Signalregeneration (2 R und 3 R)
- Entwicklung von Methoden zur Erzeugung ultrakurzer optischer Pulse
- Optimierung von Verfahren zum Dispersionsmanagement
- Entwurf und Entwicklung von optischen Frequenzreferenz-Geräten
- Entwurf und Herstellung von Transpondern und optischen SDH-Frontends
- Entwicklung, Herstellung und Charakterisierung von faseroptischen Komponenten
- Entwicklung, Herstellung und Charakterisierung von Verfahren und Geräten zur PMD-Kompensation
- Entwurf, Herstellung und Charakterisierung von optoelektronischen Bauelementen und photonisch integrierten Schaltungen auf der Basis von InP:
- abstimmbare Laser (DFB, DBR)
  - Multi-Wellenlängen-Emitter (Laser-Arrays)
  - optische Verstärker
  - schnelle Laser/Modulator-Transmitter
  - Wellenlängen-Konverter
  - Wellenlängen-“Drop“-Filter
- Demultiplexer und „Add/Drop“-Multiplexer für OTDM-Anwendungen
- Bauelemente zur optischen Taktrückgewinnung und Signalregeneration (selbstpulsierende Laser)
- integrierte Transceiver
- ultra-schnelle Photodetektoren (70 GHz)
- hochbiträtige optische Empfänger mit integriertem MMIC-Vorverstärker
- optischer Mikrowellengenerator
- Entwicklung und Herstellung von thermooptischen Schaltern und Schaltmatrizen mit geringem Nebensprechen auf der Basis von Polymeren
- Entwurf und Herstellung von planaren Wellenleiterkomponenten in SiO<sub>2</sub>/Si (z.B. Wellenleitergitter-Filter)
- Entwurf und Herstellung von passiven und von elektrisch steuerbaren diffraktiven optischen Elementen in SiO<sub>2</sub>
- Modellierung von photonischen Bauelementen und integrierten Schaltungen
- Entwicklung, Optimierung und Anwendung von Bauelement-Technologien:
- Reinraumlabore (Klasse 10/1000)
  - Epitaxie (MOVPE, MBE, MOMBE) und Charakterisierung von InP-basierenden Halbleitermaterialien
  - Sekundärionen-Massenspektrometrie (SIMS)
  - CAD und Herstellung von Photolithographie-Masken
  - Elektronenstrahl-Lithographie und optische Lithographie
  - Trockenätzprozesse (reaktive Ionenätzung, Ionenstrahlätzung) mit Endpunkterkennung
  - thermische Kurzzeitprozessierung
  - Deposition von Metall- und Dielektrika-Schichten (Aufdampfung, Sputtern, Plasma-Deposition)
  - optische Beschichtungen
  - Charakterisierung und Technologie von optischen Polymermaterialien
  - hochauflösende Rasterelektronenmikroskopie Entwicklung und Anwendung von elektrischen und optischen Aufbau- und Verbindungstechniken für Bauelemente (Flip-Chip-Bonden, Hochfrequenz-Gehäusung, Laserschweißen, Faser-Chip-Kopplung)

## Mobile Breitbandsysteme

### Themen und Ergebnisse

Mit dem Wunsch nach verstärkter Mobilität einerseits und mit dem Auftreten neuer Netzbetreiber ohne direkten Zugang zu den Teilnehmern andererseits gewinnt die Mobilkommunikationstechnik stark an Bedeutung. Neben den bekannten Mobilfunknetzen rücken zunehmend die kleinzelligen Mobilfunksysteme, der drahtlose Teilnehmeranschluß sowie drahtlose Inhousekommunikationssysteme in das Blickfeld des Interesses. Derartige Systeme mit Übertragungsraten bis zu 155 Mbit/s müssen ATM-tauglich sein. Unter Berücksichtigung des bestehenden Frequenzverteilungsplanes führt dies zu höheren Sendefrequenzen, die sich ausgehend von den heutigen Frequenzen im unteren GHz-Bereich bis zu einigen 100 THz (Licht) erstrecken können. Das HHI geht davon aus, daß die breitbandige Mobilkommunikation im Access- wie auch im Customer-Bereich eine ebenso große Bedeutung wie die breitbandige leitungsgebundene Kommunikation erlangen wird.

Ziel des HHI ist es, mit seinen Forschungsarbeiten zur Entwicklung breitbandiger Mobilkommunikationssysteme maßgeblich beizutragen. Die Arbeiten sollen sich hauptsächlich auf die Transportebene, d.h. auf die Übertragungstechnik und Systemtechnik konzentrieren. Dabei werden sowohl der breitbandige drahtlose Teilnehmeranschluß als auch breitbandige drahtlose LANs und Inhouse-Systeme betrachtet und folgende Themen bzw. Vorhaben bearbeitet:

Im Rahmen des BMBF-Förderschwerpunktes ATMmobil ist das HHI an dem Verbundvorhaben Integriertes Breitbandiges Mobilkommunikationssystem (IMBS) beteiligt. In dem Vorhaben wird ein Systemkonzept für künftige ATM-basierte Multimediamkommunikation entwickelt, das die Bereiche innerhalb und außerhalb von Gebäuden (indoor und outdoor) in einem gemeinsamen Ansatz betrachtet. Das System soll flexibel bezüglich der eingesetzten Technologien sein, eine Vielzahl an Zugängen (z.B. Kabel, Funk oder Infrarot) erlauben und je nach Bedarf verschiedene Bitraten und Quality-of-Service (QoS) Parameter bereitstellen. Unter Leitung des

HHI wird der Inhouse-Systemanteil entwickelt. Da ATM ursprünglich für die drahtgebundene Übertragung entwickelt wurde, müssen bekannte Konzepte erweitert werden, um die zu Beginn einer Verbindung zwischen Nutzer und Netzwerk ausgehandelten QoS-Parameter auch über zeitvariable drahtlose Kanäle aufrechtzuerhalten. Die Projektziele beinhalten somit die Entwicklung geeigneter Konzepte zur Sicherung der Übertragungsgüte auf den Funkstrecken durch günstige Kombination von adaptiven Kanalcodierungen mit angepaßten Modulations- und Zugriffsverfahren für Infrarot- und Funkübertragung sowie die Entwicklung der Inhouse-Netzarchitektur.

- Es wurde ein neuer Ansatz für ein Inhouse-System mit drahtlosen und leitungsgebundenen Zugängen vorgeschlagen, das die Vorteile einer optischen Erzeugung der Funksignale nutzt und darüber hinaus auch leitungsgebundene Interfaces bei geringem zusätzlichen Aufwand integriert.
- Zur Gewährleistung der vereinbarten QoS-Parameter wurde ein dienste- und kanaladaptives Funkmodem konzipiert, das durch ständige Anpassung von Modulation und Fehlerschutz sowie ggf. durch Paketnachforderungen eine weitgehend konstante Übertragung sichern soll. Teilspekte des Konzepts wurden theoretisch und simulativ untersucht.
- Ein Software-Demonstrator für den physical layer wurde geschaffen, mit dem der Einfluß von Funkkanälen auf die Bitfehlerwahrscheinlichkeit unter verschiedenen Randbedingungen (Kanalparameter, Modulation, Fehlerkorrektur) untersucht werden kann.

Bezüglich drahtloser Infrarotkommunikation werden derzeit zwei Ansätze untersucht, die auf Konzepten mit direkter Strahlausbreitung und diffuser Strahlausbreitung mit direkter Sichtverbindung basieren. Es ist das Ziel, kostengünstige und leistungseffiziente Transceiver zu realisieren, wobei Datenraten von 155 Mbit/s angestrebt werden. Es werden sowohl Systeme mit Basisstation als auch ad-hoc LANs betrachtet, die ohne Basisstation auskommen und auf der diffusen Reflexion eines Lichtflecks beruhen. Die Systemeigenschaften und die Leistungsbilanz werden beträchtlich durch Anwendungen eines Nachführsystems verbessert. Array-Tech-

nologien der Sende- und Empfangselemente können später mechanisch bewegte Teile ersetzen.

- Für ein ad-hoc LAN wurde in einem ersten Laborversuch die Verteilung des Sendesignals durch diffuse Reflexion an der Decke realisiert (Spot Diffusing mit einem Streuwinkel = 100 Grad). Die Empfängeroptik (Gesichtsfeld < 1 Grad) wurde auf den Reflexionspunkt ausgerichtet. Mit 20 mW Sendeleistung und einer Empfängerempfindlichkeit von -39 dBm konnte ein Videosignal (140 Mbit/s, CMI codiert) fehlerfrei übertragen werden.

Für die kostengünstige Erzeugung und Verteilung von Mikrowellensignalen in zellulären Breitband-Funknetzen werden im Rahmen des BMBF-Förderschwerpunktes Photonik II Methoden der optischen Frequenzmultiplextechnik untersucht. Das Ziel ist, neben der verlustarmen glasfasergebundenen Übertragung von Breitbandsignalen zwischen den Kontroll- und Basisstationen auch die für die Funkübertragung erforderlichen Mikrowellensignale im 60 GHz-Band in aufwandsarmen Basisstationen mit optischen Mitteln zu erzeugen. Für die Mikrowellenerzeugung wird das optische Heterodynprinzip angewandt, wobei die optischen Signale zweier DFB-Laser überlagert werden. Mit Hilfe der „Seitenband Injection Locking“-Technik werden quarzstabile, phasenrauscharme Mikrowellensignale mit einer Einstellgenauigkeit im Hertz-Bereich generiert. In der Kontrollstation werden nur wenige Mikrowellenkomponenten benötigt, die auf Grund des optischen Vervielfachungsprinzips lediglich für moderate Mikrowellenfrequenzen (bis 4 GHz) ausgelegt sein müssen. Im Gegensatz zu anderen Verfahren zur optischen Mikrowellenerzeugung werden keine externen Modulatoren und optischen Verstärker benötigt.

- Am HHI wurden in Kooperation mit unserem Industriepartner Bosch-Hildesheim bidirektionale Übertragungsexperimente mit einem vereinfachten experimentellen Mobilfunksystem durchgeführt. Dafür wurden Komponenten eines kommerziellen Digitalrichtfunksystems eingesetzt und mit dem genannten optischen Verfahren die Mikrowellenträger erzeugt. Ein Mikrowellensignal bei 62.2 GHz wurde für die Übertragung von 155 Mbit/s Datensignalen im OQPSK-Format von der Basisstation zum Teilnehmer (Downlink) generiert und ein

zweites bei 64 GHz für den Rückkanal-Mischer in der Basisstation. Mit diesem Mischer wurde das von der Mobilstation kommende Datensignal bei 65.2 GHz (Uplink) auf eine niedrige Trägerfrequenz umgesetzt, so daß eine einfache optische Übertragung von der Basisstation zurück zur Kontrollstation möglich ist. Kontroll- und Basisstation wurden mit einer 12.8 km langen Standard Monomodefaser verbunden, mit der Funkstrecke wurde = 1 m überbrückt.

- Für Zweikanaluntersuchungen wurde der experimentelle Aufbau mit einem zusätzlichen Laser erweitert. Damit wurden zwei Mikrowellensignale im 62.0 GHz Band erzeugt. Jedes war mit 155 Mbit/s Datensignalen im OQPSK-Format moduliert. Fehlerratenmessungen bei variablem Kanalabstand ergaben wegen der hohen spektralen Effizienz > 1 minimale Abstands-werte von < 140 MHz.
- Am HHI werden in Kooperation mit der FhG-IAF-Freiburg, der DASA und dem Hahn-Meitner Institut Optik/Mikrowellen-Konverter als hybrid integrierte Module für das 60 GHz-Band mit hoher Konversions-effizienz entwickelt. Es wurden mehrere Konvertermodule mit unterschiedlichen MMIC-Verstärkern im Frequenzbereich 50 bis 70 GHz fertiggestellt und bei Übertragungsversuchen im Experimentalsystem eingesetzt.

## Kompetenzen

Entwurf und Entwicklung von Systemen zur optischen Mikrowellenerzeugung

Entwicklung von optischen mm-Wellen-Techniken für die Mobilkommunikation im 60 GHz-Bereich

Entwurf und Entwicklung von IR-Mobil-kommunikationssystemen für den Betrieb innerhalb von Gebäuden

Entwicklung von hybriden Konzepten für integrierte Mobilkommunikationssysteme

Sequence-Entwurf und Systementwicklung für optisches CDMA

Entwurf von kombinierten Kanalcodie-rungs- und Entzerrungskonzepten für drahtlose ATM-Systeme

## **Elektronische Bildtechnik für Multimedia**

### **Themen und Ergebnisse**

Die F&E-Beiträge des HHI zu diesem Schwerpunkt sind den Fachgebieten Bildsignalverarbeitung und Endsysteme und Anwendungen zuzuordnen.

### **Bildsignalverarbeitung**

Die Aufgaben im Themenbereich Bildsignalverarbeitung sind auf Signalaufbereitung, -verarbeitung und Codierung für Bilddienste unterschiedlichster Auflösungen und Anwendungen sowie auf die Realisierung von VLSI-Komponenten und Hardwareaufbauten (Demonstratoren) ausgerichtet. Die Bildformate reichen vom QCIF (Quarter Common Image Format) mit 144 x 180 Bildpunkten bis hin zum HDTV mit 1152 x 1920 Bildpunkten. Typische Anwendungen sind VLBV (Very low bitrate video) für niedrigratige Multimediamarkommunikation, TV- und HDTV-Verteil- und Kommunikationsdienste sowie Studioapplikationen für TV, HDTV und VLTV (VisionLike TeleVision). Ein Schwerpunkt der Arbeiten liegt bei der Multimediamarkommunikation auf integrierten Netzen und Terminals (MINT), einem vom BMBF geförderten Verbundprojekt. Die Hauptziele dieses Projekts liegen bei der Mobilmarkommunikation sowie bei den Benutzerplattformen für mobile und stationäre Multimediadienste. Dabei steht der sich z.Z. entwickelnde Bild- und Tonkompressionsstandard MPEG-4 im Mittelpunkt.

Bildpunkt- und bildblockbasierte Codierverfahren, wie sie z.Z. beispielsweise bei MPEG-2 zur Anwendung kommen, haben eine gewisse Sättigung ihrer Leistungsfähigkeit erreicht. Wesentliche Verbesserungen können nur von den sogenannten intelligenten Codierverfahren erwartet werden, die sich Methoden der Bildanalyse und Bildsynthese bedienen.

Solche objekt- und modellbasierten Techniken werden einerseits für die Bildübertragung mit extrem niedrigen Datenraten (8... 64 kbit/s) entwickelt, wobei das Bildmaterial jedoch eingeschränkt ist (z.B. auf Bildtelephonie). Andererseits sollen solche Techniken auch für allgemei-

nes Bildmaterial eingesetzt werden, um auch breitbandigere Videoverteildienste mit abzudecken. Die Ergebnisse dieser Arbeiten werden bei ISO-MPEG (Moving Pictures Expert Group) eingebracht, wodurch Beiträge zur Spezifizierung des zukünftigen MPEG-4 Standards geleistet werden.

Neben der Entwicklung der Kompressionsalgorithmen spielt die Anwendung dieser Verfahren für neue interaktive Dienste eine entscheidende Rolle. So werden im HHI auf MPEG-4 basierende Applikationen für Broadcast-Dienste über DAB/DMB (Digital Audio/Multimedia Broadcast) und für interaktive Dienste über ISDN sowie über das Internet entwickelt.

- Unter Verwendung von JAVA wurde eine Netscape-Applikation für die interaktive Szenenmanipulation auf Basis der objektbasierten MPEG-4 Codierung entwickelt. Diese Applikation unterstützt Nutzerfunktionen wie das „Fernladen komprimierter Videoobjekte“, das „Anzeigen der Objekte im lokalen Browser-Fenster“, die „Generierung neuer Videoszenen durch Kopieren der Objekte in ein Compositor-Fenster“ und das „Editieren (Cut, Paste, Copy, Magnify etc.) der Videoszenen im Compositor-Fenster“. Diese Applikation wurde auf der IFA '97 und auf der CeBIT '97 ausgestellt und erhielt dort den 2. Preis einer renommierten Computerzeitschrift.

- Es wurde ein System zum Teleshopping in einem virtuellen Laden entwickelt, in dem reale Videoobjekte (Verkaufsobjekte) vom Nutzer auf dem Bildschirm angeklickt werden können. Auf diese Weise kann der Nutzer Zusatzinformationen (Preise, Größe, Farbe usw.) zu den Objekten abrufen, sich die Objekte von allen Seiten betrachten (3D-Modelle) oder eine On-line-Beratung für diese Objekte aufrufen. Dieses System wurde auf der IFA '97 ausgestellt.

Im Bereich der Verarbeitung bewegter 3D-Sequenzen liegt der Schwerpunkt bei der kombinierten Bewegungs- und Disparitätsschätzung sowie -kompensation. Anwendungen für diese Techniken ergeben sich sowohl im Studiobereich (3D-Produktion, depth-keying) als auch bei der Bildkommunikation (3D-Videokonferenz). Im speziellen werden Soft- und Hardwareentwicklungen für ein autostereoskopisches Multi-Viewpoint-System durchgeführt, das für die Bereiche Kommunikation,

Medizin, 3D-Programmproduktion und Automatisierung im industriellen Bereich eingesetzt werden soll. Neben grundlegenden algorithmischen Untersuchungen im Bereich Disparitätsschätzung und Zwischenbildinterpolation soll in Zusammenarbeit mit einigen Kooperationspartnern ein Gerät zur Echtzeit-Zwischenperspektivenberechnung aufgebaut werden.

- Ein neues Verfahren zur einfachen 3D-Darstellung von Videoobjekten wurde entwickelt. Dieses „Incomplete 3D“ genannte System wandelt das mit zwei oder mehreren Kameras aufgenommene Objekt in ein 2D-Objekt um, das dann entsprechend dem MPEG-4 Standard komprimiert werden kann. Die Rekonstruktion in ein 3D-Objekt ist empfangsseitig mit Hilfe einer Disparitätsmappe möglich, die als Maskendaten innerhalb eines MPEG-4-Datenstroms übertragen werden kann. Somit wurde ein elegantes System zur 3D-Codierung geschaffen, das sich innerhalb der bestehenden MPEG-4-Syntax anwenden lässt.

Im Rahmen langjähriger Arbeiten wurden am Heinrich-Hertz-Institut wesentliche Komponenten für die Bildsignalverarbeitung im Studio und in Fernsehempfängern auf der Basis von Rechnersimulationen entwickelt. Wesentliche Arbeitspunkte betrafen die Bewegungsschätzung, die Zwischenbildinterpolation, die Formatumsetzung und die Rauschreduktion. Fortschritte bei der Algorithmenentwicklung und in der Halbleitertechnologie erlauben es nun, derartige Systeme auf einem Chip zu integrieren.

- Es wurde ein Verfahren zur Bewegungsschätzung und Formatkonversion entwickelt, das durch seine hohe Leistungsfähigkeit und durch seine geringe Komplexität besticht. Mit dem entwickelten Verfahren können ausgehend von 24/25 Hz (Film), 50 Hz oder 60 Hz (Video) Eingangssequenzen im Zeilsprung Ausgangssequenzen mit beliebigen Bildwiederholfrequenzen  $\leq$  120 Hz in progressiver oder in Zeilsprungdarstellung erzeugt werden. Die erreichten Ergebnisse bilden die Grundlage für gemeinsame Chipentwicklungen mit Halbleiterherstellern.

Für die erfolgreiche Einführung zukünftiger Multimedien dienste wird die interaktive Suche und die Auswahl von Video- und Audioinformationen eine entscheidende Bedeutung gewinnen. Um nun die Suche

nach nicht textbasierten Inhalten z.B. über das Internet zu ermöglichen, soll im Rahmen von MPEG ein standardisiertes „Multimedia Content Description Interface (MPEG-7)“ geschaffen werden. Erste Arbeiten zur Bildanalyse, Bildcharakterisierung und Bildindizierung wurden aufgenommen.

Im Rahmen des BMBF-Verbundprojekts Multimediakommunikation auf integrierten Netzen und Terminals (MIINT) stehen die Entwicklung neuer Übertragungskonzepte und -verfahren für die mobile Multimedia-kommunikation und die Entwicklung neuer Konzepte, Features und Bedieneroberflächen für stationäre und mobile Multi-media-Benutzerplattformen im Mittelpunkt.

Ziel der Arbeiten im HHI ist es, Kernkomponenten zum Gesamtdemonstrator des Verbundprojekts zu liefern. Solche Kernkomponenten sind Einrichtungen zur MPEG-4-Decodierung inklusive Systemdemultiplex, ein MPEG-4 Systemmultiplexer sowie Einrichtungen zur Decodierung und Darstellung von 3D-Bildern. Darüber hinaus müssen alle o.g. Einrichtungen in die zu entwickelnden Plattformen, die auf Basis von PCs (Laptop/Notebook), Workstations, Set-Top-Units oder mobilen DAB-Empfängern im Fahrzeug bestehen, integriert werden, und es müssen Systemtests im Labor und im Feld durchgeführt werden.

Hierfür sollen Konzepte zur Realisierung dieser Komponenten unter Berücksichtigung zukünftiger Technologien und Produkte entwickelt werden. Da langfristig Signalverarbeitungsverfahren wie Bildcodierung und Formatkonversion auf sogenannten A/V-Prozessoren (Audio/Video) ablaufen werden, sollen Untersuchungen vorgenommen werden, wie sich die genannten Verfahren auf solchen Prozessoren bzw. in Verbindung mit Co-Prozessoren realisieren lassen. Die Ergebnisse dieser Untersuchungen sollen auch in das EUREKA/MEDEA-Projekt „MPEG fo(u)r Mobiles“, das in 1997 begonnen wurde, einfließen.

Darüber hinaus sollen für alle Terminaltypen bedienfreundliche graphische Benutzeroberflächen geschaffen werden, die auch die Verwendung von Fernbedienungen und Spracheingabe mit berücksichtigen.

- Erste Konzepte und Prototypen („Objects on Demand“, „MPEG-2 kompri-

mierter 3D-Video von der CD-ROM", „interaktive Benutzeroberfläche incl. Spracheingabe“) wurden auf der IFA '97 der breiten Öffentlichkeit präsentiert.

Die Fortschritte bei der Bildkompression (MPEG-2) und bei den digitalen Übertragungsverfahren (DVB-Standards) erlauben die Einführung kinoähnlicher Film- und Videoverteildienste unter Verwendung der Satelliten- und Kabelübertragung. Zu den Programmarten gehören Spielfilme, Live-Übertragungen und kommerzielle Präsentationen, die an elektronische Kleinkinos, an Kinos, an Unterhaltungsstätten, an Universitäten, an Hotels und u.U. an individuelle Teilnehmer übertragen werden sollen. Für die Übertragung über Kabel und Satellit sollen Techniken entsprechend den DVB-Standards eingesetzt werden und für die Bild- und Tonkompression MPEG-2-Verfahren. Das HHI hat den Aufbau des MPEG-2 HDTV-Decoders übernommen, wobei insbesondere ein 1-Chip-Decoder entwickelt wurde. Der Decoder soll Anfang 1998 sowohl in Europa (im Rahmen des ACTS-Projekts CINENET) als auch in Japan und den USA der breiten Öffentlichkeit präsentiert werden.

## Endsysteme und Anwendungen

Die Multimediatechnik soll den interaktiven und gleichzeitigen Zugriff auf Informationen in unterschiedlichen Modalitäten (Bild, Ton, Text etc.) ermöglichen. Multimediale Benutzerschnittstellen sollen dadurch besonders für natürliche Formen des Informationsaustauschs geeignet sein. Hier stellt sich die Aufgabe, technologische und anwendungspraktische Konzepte zu erarbeiten und zu realisieren, mit denen neue multimediale Anwendungen möglich werden, die zweckmäßig, benutzerfreundlich, attraktiv und ermüdungsfrei sind und somit den Weg in den Markt finden können.

Die F&E-Arbeiten des HHI zu diesem Themenbereich umfassen die Entwicklung interaktiver 3D-Benutzerschnittstellen und die nutzergerechte Gestaltung und Erprobung ausgewählter Kommunikations- und Informationsdienste. Sie umfassen weiter die Entwicklung von Displaytechnologien zur autostereoskopischen Bildwiedergabe und zur vollfarbigen Lichtemission auf der Basis von Elektrolumineszenz und die Entwicklung eines Schreib-/Lesekopfes für

die hochratige Datenübertragung des neuen Speichermediums DVD.

Die Effizienz von Benutzerschnittstellen für informationsreiche Anwendungen lässt sich durch die Verwendung von 3D-Bildtechniken steigern. Für die Reproduktion dreidimensionaler Szenen werden deshalb am HHI autostereoskopische Bildwiedergabeverfahren entwickelt, die eine uneingeschränkte und augenverträgliche Informationsdarstellung ermöglichen.

Die natürlichen Funktionen der begrenzten Schärfentiefe und der Kopplung zwischen Akkommodation und Konvergenz der Blicklinien sowie die Aspektveränderungen bei Änderungen des Betrachterstandortes (Dynamische Perspektive) müssen auch bei der Displaybetrachtung wirksam werden. Diese Forderung lässt sich mithilfe einer synthetischen Schärfentiefe, verbunden mit einer dynamischen Anpassung der Schärfenebene an die Ebene des Fixationspunktes sowie mit der Darstellung perspektivisch korrekter Zwischenansichten erfüllen. Zur Steuerung dieser Funktionen müssen die Positionen der Augen und des Fixationspunktes im Raum bekannt sein. Die hierzu erforderlichen Bildsignalverarbeitungsverfahren sowie spezielle optische Komponenten und videobasierte Meßverfahren wurden entwickelt. Eine Demonstration der genannten Funktionen erfolgt auf einem autostereoskopischen Arbeitsplatz-Display, bei dem statt einer Maus gesteuerten Benutzeroberfläche ein Blickpunkt-gesteuerter Benutzer-Interaktionsraum verwendet wird.

- Die Benutzerfreundlichkeit der Konzepte „virtueller Kommunikationsraum“ und „Blicksteuerung“ wurde nachgewiesen.
- Neue Ansätze zur Messung von Augenposition und Blickrichtung wurden entwickelt und den praktischen Erfordernissen hinsichtlich Meßgeschwindigkeit und Genauigkeit angepasst.
- Erste Schritte zum Aufbau eines „Depth of Interest Display“ mit synthetischer Schärfentiefe wurden unternommen.
- Ein plattformunabhängiges auf JAVA und VRML basierendes Betriebssystem („virtueller Kommunikationsraum“) wurde konzipiert und zum Teil implementiert.
- Auf Basis des Workstation-Betriebssystems UNIX und der Virtual Reality Software dVS wurde ein neuartiges 3D-Betriebssystem mit Blicksteuerung konzipiert und lauffähig implementiert. Das System

wurde auf der IFA '97 der Öffentlichkeit präsentiert und fand eine sehr positive Resonanz in der Fachpresse.

Eine hohe Benutzerfreundlichkeit einer informationstechnischen Anwendung setzt u.a. voraus, daß der Entwurf der Benutzerschnittstelle auf Ergebnissen einer zuverlässigen Analyse der Benutzerbedürfnisse basiert. Die erforderlichen Analysemethoden sowie Methoden zur Ermittlung nutzungsrelevanter Merkmale (Usability-Test) wurden weiterentwickelt und stehen der Öffentlichkeit, vor allem den ACTS-Projektgruppen, zur Verfügung.

- Diesen Service erbringt das HHI gemeinsam mit Partnern des ACTS-Vorhabens "Usability in ACTS (USINACTS)". Das HHI hat einen Help Service mit einem Bulletin Board zu Human Factors Themen im WWW eingerichtet.

Im Rahmen von am HHI durchgeführten Kommunikationsexperimenten mit Studio-Videokonferenzen haben sich 3D-Bildtechniken als nützlich für die Erhöhung der Telepräsenz und Effektivität erwiesen. Entsprechende Vorteile werden auch bei Multipoint-Desktop-Konferenzen erwartet. Diese Kommunikationsform bietet sich vor allem bei räumlich verteilten Arbeitsgruppen an. Da diese Kommunikationsform in Zukunft weiter an Bedeutung gewinnen wird, wurde der Nutzen von 3D-Techniken auch für Arbeitsplatzsysteme untersucht. Dabei ging es u.a. um eine unverzerrte Wiedergabe von Bewegungsparallaxe und Objektgeometrie, um wahrnehmungsmäßig konfliktfreie Bildmixschung sowie um 3D-Fernzeigen.

- Ein Wahrnehmungsexperiment ergab, daß die bei stereoskopischen Verfahren auftretende Trennung von Akkommodation und Konvergenz kaum Einfluß auf die Wiedergabe der Bewegungsparallaxe hat.
- Erste Versuche zur Mischung von 3D-Bildern zeigten, daß Bilder mit größerem Tiefenvolumen im oberen und Bilder mit geringerem Tiefenvolumen im unterem Bildschirmbereich positioniert werden sollten.
- Es wurden verschiedene Verfahren zum 3D-Fernzeigen entwickelt und in Nutzerexperimenten hinsichtlich ihrer Benutzerfreundlichkeit überprüft. Es zeigte sich, daß beim Einsatz solcher Verfahren eine normale Computermaus zum Zeigen in stereoskopischen Darstellungen verwendet werden kann.

Ein wichtiger Aspekt zwischenmensch-

licher Kommunikation ist die informelle Kommunikation. Gemeint sind damit die spontanen und überwiegend vertraulichen Gespräche z.B. am Rande von Konferenzen, bei Kaffeepausen oder bei anderen zufälligen Begegnungen. Da diese Formen der Kommunikation eine positive Bedeutung für den einzelnen Mitarbeiter ebenso wie für das Unternehmen haben, wird für verteilte Arbeitsgruppen nach technischer Unterstützung der informellen Kommunikation gesucht. Besondere Bedeutung hat dabei die Wiedergabe non-verbaler Signale, wie z.B. Blickkontakt, oder entsprechender Surrogate.

- Eine Befragung potentieller Nutzer von Telekooperationssystemen ergab, daß informelle Kommunikation in vielen Arbeitszusammenhängen als unverzichtbar angesehen wird.
- Ein kleiner Inhouse-Feldversuch mit Hilfe eines Internet-Relay-Chat-Systems führte zu einer Liste von Anforderungen an technische Systeme zur Unterstützung informeller Kommunikation.
- Es wurde ein Multipoint-Arbeitsplatz-Videokonferenzsystem aufgebaut, das individuellen Blickkontakt zwischen allen Gesprächspartnern ermöglicht.

Die F&E-Arbeiten des HHI an autostereoskopischen Displays konzentrieren sich auf Linsenrasterverfahren. Als Nebenthema wird auch das Feldlinsenverfahren untersucht. Entwicklungsziele sind der Aufbau kompakter Displays auf der Basis von Matrixdisplay-Panels für Desktopanwendungen und von großformatigen Rückprojektionsdisplays für Simulatoren oder andere Spezialanwendungen. Die Verfahren sind jeweils für einen Betrachter vorgesehen. Bei autostereoskopischen Displays müssen die Strahlenbündel bei Betrachterbewegungen nachgeführt werden. Dazu werden neue Trackingverfahren entwickelt.

- Bisherige Direktsichtdisplay-Linsenrasteranordnungen mußten im Hochformat betrieben werden (dabei ist Bildsignalkonversion erforderlich), damit die dann untereinanderliegenden drei Farbpunkte eines Pixels mithilfe des zugeordneten Linsenelements in das Betrachterauge abgebildet werden können. Diese Einschränkung konnte jetzt durch eine neue Linsenrasterstruktur ("Farbmultiplex-Verfahren") überwunden werden. Es können jetzt normgerechte Querformat-Bilder dargestellt werden.

- Der Prototyp eines neuen Großbild-Rückprojektionsdisplays wurde aufgebaut. Der Bildschirm besteht aus einer Sandwich-Anordnung aus einem Einfach-Linsenrasterschirm und einer Streuscheibe. Das Linsenraster arbeitet nach dem Farbmultiplex-Verfahren. Zum Tracking dient eine bewegliche Projektionsoptik, mit der die Lage und der gegenseitige Abstand der projizierten Bildpunkte verändert werden kann.
- Während die Linsenrastertechnik auf einer bildpunktweisen Ausrichtung des Beleuchtungsstrahlenganges auf das Betrachterauge basiert, erfolgt beim Feldlinsenprinzip die Lichtausrichtung global durch eine große Feldlinse. Ein solches Verfahren wurde aufgebaut; es besticht durch eine hohe Auflösung (für jedes Auge ist ein individuelles LC-Panel vorhanden) und durch hohe Übersprechdämpfung. Naturgemäß ist die Bautiefe bei Feldlinsendisplays jedoch erheblich größer als bei Linsenrasterdisplays. Das Display wird z.Z. in einem 3D-Multipointkommunikationsexperiment getestet.
- Die örtliche Auflösung autostereoskopischer Linsenrasterdisplays ist durch die beherrschbare Präzision der Registrierung von Bildpunkt- und Linsenrastern begrenzt. Verwendet man zum Tracken ein Linsenraster, das gegenüber dem Displaypanel bewegt werden kann, so verringert sich die erreichbare Registrierungsgenauigkeit verglichen mit einer starren Anordnung. Um die Vorteile der starren Anordnung mit einer Trackmöglichkeit zu verbinden, wurde ein Robotarm entwickelt, der bei Betrachterbewegungen das gesamte Display so nachführt, daß dessen Position und Orientierung relativ zum Betrachter konstant bleiben.
- Die Zusammenarbeit des HHI mit einem Industriepartner resultierte im Aufbau des Prototypen eines sehr kompakten, hochauflösenden autostereoskopischen Displays mit Linsenrastertracking für medizinische Anwendungen. Eine Demonstration erfolgte am HHI-Stand auf der IFA '97.

Bei der Erforschung neuer Displayprinzipien konzentriert sich das HHI auf die Hochfeldelektronolumineszenz. Obwohl in der Vergangenheit mit dem „Farbe aus Weiß“-Konzept vielversprechende Resultate erzielt werden konnten, ist noch eine Optimierung des Blaufarbtons, der noch nicht den geforderten EBU-Werten entspricht, erforderlich.

- Verbesserungen des Verhaltens von SrS:Ce Dünnfilm-Elektronolumineszenz-Strukturen konnten durch Anwendung eines neuen Verfahrens zur Ladungskompensation von Ce<sup>3+</sup> Dotierungen im Präparationsprozeß der Phosphorschicht erreicht werden. Damit wird eine Blauverschiebung des Emissionsspektrums um ca. 10 nm bei gleichzeitiger Erhöhung der Lichtausbeute auf 2 lm/W erreicht. Erste weiß emittierende SrS:Ce/ZnS:Mn-Display-Prototypen mit 10 cm x 10 cm Größe und einer Auflösung von 128 x 128 Pixeln demonstrierten das Anwendungspotential von Farbe-aus-Weiß-Displays.

Neben der Displaytechnologie ist die Datenspeicherung eine wesentliche Komponente in Multimediasystemen. Hier steht die auf dem Prinzip der optischen Disk beruhende Digital Versatile Disk (DVD) mit deutlich erhöhter Speicherkapazität von derzeit 9 GB bei schnellem Datenzugriff (> 10 Mbit/s) und der Option der Wiederbeschreibbarkeit vor der Markteinführung.

- Für die Erweiterung des herkömmlichen optischen Lesekopfes eines CD-Spielers auf das simultane Auslesen und Einschreiben der Informationen einer DVD mit mehreren hintereinanderliegenden Speicherschichten wird der Ersatz konventioneller Optiken durch leichte, multifunktionale „Diffraktive Optische Elemente“ (DOEs) untersucht. Diese werden computergeneriert durch Mikrostrukturierungstechniken hergestellt.

## Kompetenzen

Entwicklung von Algorithmen und Hardwarearchitekturen zur Bild- und Tonkompression (MPEG 2, MPEG 4)

Entwicklung von Algorithmen und Hardwarearchitekturen zur 2D- und 3D-Bildanalyse und Synthese auf der Grundlage von Bewegungs- und Stereoinformation

Entwicklung von Anwendungen auf Basis von MPEG-2/4/7 und JAVA für interaktive Dienste im Internet, über DVB/DAB/DMB oder über das ISDN

Entwicklung von 3D-Displaytechnologien Konzeption und Bewertung von Benutzerschnittstellen für Multimediaanwendungen

auf der Basis von VRML, JAVA, MSDL und dVS

Analyse und Optimierung von Kommunikations-Endgeräten und -Diensten nach anthropotechnischen Kriterien

Entwicklung von videobasierten Mustererkennungs- und Photogrammetrieverfahren

Modellierung und Entwurf von integrierten Schaltkreisen für die Bildsignalverarbeitung

Entwurf und Aufbau von Experimental-systemen für die Entwicklung von videobasierten Kommunikationsanwendungen und für Test und Demonstration neuer Kommunikationstechnologien und neuer Hardwarearchitekturen

Analyse sensorischer und sensomotorischer Funktionen des Menschen mit Bezug zu Kommunikationsanwendungen

Expertise in Desktop Computer Graphics Design

Forschung auf dem Gebiet der Hochfeld-Elektrolumineszenz (SrS:Ce, ZnS:Mn)

Entwicklung von Vielschicht-Elektrolumineszenzstrukturen, blau emittierenden Phosphoren, vollfarbigen Flach-Displays, transparenten Displays

Entwicklung von Diffraktiven Optischen Elementen für den Schreib-/Lesekopf einer Optischen Disk

## R & D PROJECTS · F & E-PROJEKTE

Project	Projekt	Project Manager · Projektleiter phone · Telefon email	Provider of Grant/Contractor · Förderer/ Auftraggeber Period · Laufzeit
<b>Photonic Networks</b>		<b>Photonik-Netze</b>	
OFDM-LAN with Optical Filters, PHOTONIK II, 2 Subprojects:	OFDM-LAN mit optischer Filtertechnik, PHOTONIK II, 2 Teilprojekte:	Godehard Walf +49(0)30-31002-455 walf@hhi.de	BMBF 4/94 – 3/98
1) OFDM-LAN/MAN	1) OFDM-LAN/MAN	Fritz-Joachim Westphal +49(0)30-31002-288 westphal@hhi.de	
2) Optically Transparent Interconnection of OFDM Networks	2) Optisch transparente Zusammenschaltung von OFDM-Inselnetzen	Jürgen Saniter +49(0)30-31002-288 saniter@hhi.de	
Frequency Selective Tunable Receiver OEICs Based on Indiumphosphide for OFDM Systems, PHOTONIK II	Frequenzselektive abstimmbare Empfänger-OEICs auf Indiumphosphid-Basis für OFDM-Systeme, PHOTONIK II	Helmut Heidrich +49(0)30-31002-538 heidrich@hhi.de	BMBF 4/94 – 3/98
Broadband Lightwave Sources and Systems, ACTS BLISS	Broadband Lightwave Sources and Systems, ACTS BLISS	Niraj Agrawal +49(0)30-31002-510 agrawal@hhi.de Helmut Heidrich +49(0)30-31002-538 heidrich@hhi.de	EU 9/95 – 8/98
WDM Transmitter PIC for Industrial Applications	WDM-Transmitter-Chip für den industriellen Einsatz	Frank Fidorra +49(0)30-31002-538 fidorra@hhi.de	HHI 5/96 – 4/97
Selective Area MOMBE for Laser/Waveguide Integration, PHOTONIK II	Flächenselektive MOME für die Laser/Wellenleiter Integration, PHOTONIK II	Harald Künzel +49(0)30-31002-546 kuenzel@hhi.de	BMBF 1/95 – 3/98
Fabrication of Long-Wavelength Lasers Using Solid Source MBE	Herstellung langwelliger Laser auf der Basis der Feststoffquellen MBE	Agnostis Paraskevopoulos +49(0)30-31002-527 paraskevopoulos@hhi.de	Industry 7/95 – 12/97
Integrated Waveguide Components on SiO <sub>2</sub> /Si for OFDM Systems	Integrierte Wellenleiterkomponenten auf SiO <sub>2</sub> /Si-Basis für OFDM-Systeme	Berndt Kuhlow +49(0)30-31002-448 kuhlow@hhi.de	HHI 4/94 – 3/98

Plasma Etching Techniques for Micro-Optical Elements with Highly Precise Profiles for Micro Systems	Plasmastimulierte Ätztechniken für mikrostrukturierte optische Elemente mit hoch präzisen Profilen für die Mikrosystemtechnik	Margit Ferstl +49(0)30-31002-430 ferstl@hhi.de	State of Berlin 10/96 – 5/98
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2) Semiconductor Laser Amplifier Components for OTDM Applications	2) Halbleiterverstärkerkomponenten für OTDM-Anwendungen	Niraj Agrawal +49(0)30-31002-510 agrawal@hhi.de	
Photonic Technologies for Ultra High Speed Information Highways, ACTS HIGHWAY	Photonic Technologies for Ultra High Speed Information Highways, ACTS HIGHWAY	Detlef Hoffmann +49(0)30-31002-454 hoffmann@hhi.de	EU 9/95 – 8/98
High Bit Rate Receiver OEICs Based on InP, PHOTONIK II	Höchstfrequente Empfänger-OEICs auf InP-Basis, PHOTONIK II	Heinz-Gunter Bach +49(0)30-31002-503 bach@hhi.de	BMBF 4/94 – 3/98
Investigations on a Regenerator Free Optical Network	Untersuchungen zu einem regeneratorfreien optischen Netz	Bernhard Strelle +49(0)30-31002-586 strelle@hhi.de	Industry 5/96 – 4/97
Frequency Stage in the Optical WDM Crossconnect	Frequenzstufe im optischen WDM-Crossconnect	Erwin Patzak +49(0)30-31002-514 patzak@hhi.de	Industry 5/96 – 4/97
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Metropolitan Optical Network, ACTS METON	Metropolitan Optical Network, ACTS METON	Dirk Trommer +49(0)30-31002-526 trommer@hhi.de	EU 9/95 – 8/98
Nonlinear Optical Polymers for Waveguide Devices: Optimisation of Poling and Electrical and Optical Characterization, MaTech	Polungsoptimierung sowie elektrische und optische Grundlagenuntersuchungen für nichtlinear optische Polymerwellenleiterbauelemente, MaTech	Simona Bauer-Gogonea +49(0)30-31002-447 sbauer@hhi.de	BMBF 5/94 – 4/97

SiO <sub>2</sub> /Si Waveguide Switches Using Liquid Crystal Layers	SiO <sub>2</sub> /Si-Wellenleiter- schalter mit LC-Schichten	Elmar Schulze +49(0)30-31002-522 schulze@hhi.de	HHI 1/97 – 12/98
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Transponders for 2,5 Gbit/s	Transponder für 2,5 Gbit/s	Jürgen Saniter +49(0)30-31002-288 saniter@hhi.de	Industry 12/97 – 10/98
Development of Basic Technological Processes and Components	Entwicklung technolo- gischer Basisverfahren und Bauelemente	Helmut Heidrich +49(0)30-31002-538 heidrich@hhi.de	Industry 3/97 – 12/04
Arrayed Waveguide Grating Filters	Arrayed Waveguide Grating-Filter	Berndt Kuhlow +49(0)30-31002-448 kuhlow@hhi.de	Industry 7/97 – 12/98
Active Resonant Grating-Waveguide Structures for Rapidly Tuning Semiconductor Lasers with no Moving Elements	Gitterwellenleiter-Struktur für den Einsatz in einem modengekoppelten Halbleiterlaser mit Wellen- längendurchstimmbarkeit ohne mechanisch bewegliche Elemente	Hans-Georg Weber +49(0)30-31002-443 hgweber@hhi.de	BMBF 7/97 – 6/00
Planning Guidelines for Photonic Networks	Planung Photonisches Netz	Ernst-Jürgen Bachus +49(0)30-31002-457 bachus@hhi.de	Industry 7/96 – 3/98
Mobile Broadband Systems	Mobile Breitbandsysteme		
Integrated Mobile Broadband System  2 Subprojects:	Integrierendes breit- bandiges Mobilkommu- nikations-System,  2 Teilprojekte:	Godehard Walf +49(0)30-31002-455 walf@hhi.de	BMBF 10/96 – 6/00
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2) Broadband Mobile Communication System Based on IR	2) Breitbandiges Mobil- kommunikationssystem auf Infrarotbasis	Clemens v. Helmolt +49(0)30-31002-506 helmolt@hhi.de	

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Optoelectronic Converter OEIC for 38/60 GHz as Component for Future Integrated Antenna Base Stations for Mobile Communication	Optoelektronischer Wandlerschaltkreis für 38/60 GHz als Bestandteil zukünftiger integrierter Antennenbasisstationen für die Mobilkommunikation	Heinz-Gunter Bach +49(0)30-31002-503 bach@hhi.de	NaFöG 4/97 – 4/99
Optical Time Delay Network	Optische Verzögerungsnetzwerke	Erwin Patzak +49(0)30-31002-514 patzak@hhi.de	Industry 7/97 – 1/99
<b>Electronic Imaging Technology for Multimedia</b>		<b>Elektronische Bildtechnik für Multimedia</b>	
Decoding and Signal Processing Systems for Network Independant Multimedia Communication	Decodier- und Signalverarbeitungseinrichtungen für die netzübergreifende Multimedialkommunikation	Peter Stammnitz +49(0)30-31002-570 stammnitz@hhi.de	BMBF 1/96 – 12/98
AV Processors for Network Independant Multimedia Communication	AV-Prozessoren für die netzübergreifende Multimedialkommunikation	Maati Talmi +49(0)30-31002-293 talmi@hhi.de	BMBF 1/96 – 12/98
VLBV for Multimedia Services over Mobile and Data Networks	VLBV für Multimediadienste in Mobilfunk- und Datennetzen	Thomas Sikora +49(0)30-31002-622 sikora@hhi.de	BMBF 7/94 – 6/97
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Mobile Multimedia Systems, ACTS MOMUSYS	Mobile Multimedia Systems, ACTS MOMUSYS	Minhua Zhou +49(0)30-31002-616 zhou@hhi.de	EU 10/95 – 8/98
Architectures, Software and Hardware for MPEG4 Systems, ACTS EMPHASIS	Architectures, Software and Hardware for MPEG4 Systems, ACTS EMPHASIS	Thorsten Selinger +49(0)30-31002-404 selinger@hhi.de	EU 10/95 – 9/98
Realisation of 3D Environments with Integrated Streaming Objects	Realisierung von virtuellen 3D-Umgebungen mit integrierten Objekten	Peter Kauff +49(0)30-31002-615 kauff@hhi.de	Industry 11/96 – 10/97
Package for New Operational Autostereoscopic Multiview Systems and Applications, ACTS PANORAMA	Package for New Operational Autostereoscopic Multiview Systems and Applications, ACTS PANORAMA	Jens-Rainer Ohm +49(0)30-31002-617 ohm@hhi.de	EU 9/95 – 8/98

Cinema Films and Live Events via Satellite and Cable Networks, ACTS CINENET	Cinema Films and Live Events via Satellite and Cable Networks, ACTS CINENET	Ulrich Höfker +49(0)30-31002-569 hoefker@hhi.de	EU 9/95 – 8/97
Object Based Motion Estimation for Up-Conversion and Image Quality Improvement	Objektorientierte Bewegungsvektorschätzung für Up-Conversion und Bildqualitätsverbesserung	Jens-Rainer Ohm +49(0)30-31002-617 ohm@hhi.de	Industry 8/96 – 7/97
Videocompression and -Presentation for Interactive Services (VPID)	Videokompression und -präsentation für interaktive Dienste (VPID)	Peter Kauff +49(0)30-31002-615 kauff@hhi.de	BMBF 1/97 – 12/99
Integration and Optimization of the MPEG-4 Video Verification Model of MOMUSYS	Pflege und Optimierung des MPEG-4-Videoverifikationsmodells von MOMUSYS	Minhua Zhou +49(0)30-31002-616 zhou@hhi.de	Industry 4/97 – 1/98
MPEG-4 Fo(u)r Mobile Communications – M4M	MPEG-4 Fo(u)r Mobile Communications – M4M	Ralf Schäfer +49(0)30-31002-560 schaefer@hhi.de	Industry 7/97 – 6/98
MPEG-4 for Mobile Multimedia Service	MPEG-4 für Mobile Multimedia-Dienste	Thomas Sikora +49(0)30-31002-622 sikora@hhi.de	BMBF 7/97 – 6/00
Virtual Interactive Video Shop - VITO -	Virtueller T-Punkt mit Online-Fachberater im Internet-VITO	Peter Kauff +49(0)30-31002-615 kauff@hhi.de	Industry 10/97 – 5/98
Coding of Contour- and Surface Data Using Wavelets	Codierung von Kontur- und Oberflächendaten unter Verwendung von Wavelets	Jens-Rainer Ohm +49(0)30-31002-617 ohm@hhi.de	DFG 10/97 – 9/99
Development of an Evaluation Board	Erstellung eines Evaluierungsboards	Matti Talmi +49(0)30-31002-293 talmi@hhi.de	Industry 9/97 – 6/98
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Approaches for Gaze-Controlled Interactions with Autostereoscopic Multimedia-Displays	Verfahren zur blickgesteuerten Interaktion mit autostereoskopischen Multimedia-Displays	Siegmund Pastoor +49(0)30-31002-345 pastoor@hhi.de	BMBF 1/95 – 12/98
Telepresence in the Workplace	Telepräsenz am Arbeitsplatz	Lothar Mühlbach +49(0)30-31002-237 muehlb@hhi.de	BMBF 8/94 – 6/98

User Interfaces for Cross-Network and Cross-Service Multimedia Applications, MINT	Benutzerschnittstellen für netz- und diensteübergreifende Multimedia-anwendungen, MINT	Thomas Meiers +49(0)30-31002-218 meiers@hhi.de	BMBF 1/96 – 12/98
Usability in ACTS, ACTS USINACTS	Usability in ACTS, ACTS USINACTS	Lothar Mühlbach +49(0)30-31002-237 muehlb@hhi.de	EU 7/96 – 12/98
Autostereoscopic Single User Monitors with Tracking Systems	Autostereoskopische Einpersonen-Monitore mit Trackingsystem	Reinhard Börner +49(0)30-31002-259 boerner@hhi.de	BMBF 4/96 – 3/00
Evaluation of the Global Learning Platform of the Deutsche Telekom AG	Evaluation der Global Learning Plattform der Deutschen Telekom AG	Jens Faber +49(0)30-31002-235 faber@hhi.de	Industry 5/97 – 1/98
Full Colour Electroluminescence Based on IIa-Vla Compounds	Vollfarb-Elektrolumineszenz auf der Basis von IIa-Vla-Verbindungen	Karl-Otto Velthaus +49(0)30-20377-326 velthaus@hhi.de	BMBF 7/95 – 6/98
Next Generation Colour Electro-luminescent Displays, ESPRIT ELDISP	Next Generation Colour Electroluminescent Displays, ESPRIT ELDISP	Karl-Otto Velthaus +49(0)30-20377-326 velthaus@hhi.de	EU 11/96 – 10/99
New S+S:Ce,Mn,Ag multi-source deposition process for Active-Matrix Electro-luminescent-Devices	New S+S:Ce,Mn,Ag multi-source deposition process for Active-Matrix Electro-luminescent-Devices	Karl-Otto Velthaus +49(0)30-20377-326 velthaus@hhi.de	Industry 10/97 – 9/98
Diffractive Optical Elements for a Write/Read Optical Pickup of a Disk	Diffraktive Optische Elemente für den Schreib/Lesekopf einer optischen Disk	Berndt Kuhlow +49(0)30-31002-448 kuhlow@hhi.de	TH Darmstadt 10/96 – 12/99



## **Selected Achievements**



H.-G. BACH, D. HOFFMANN  
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## PROGRESS IN 40 Gb/s TDM TECHNIQUES

### Abstract

Key aspects of the progress in 40 Gb/s TDM techniques are reviewed. The further development of electrical TDM is demonstrated in the light of a monolithic InP-based photoreceiver for  $\lambda = 1.55 \mu\text{m}$ . Its optoelectronic conversion capabilities for 40 Gb/s RZ and NRZ modulated PRBS data streams are demonstrated. In addition, a combination of optical TDM and WDM with four wavelength channels each carrying 40 Gb/s, giving a total bitrate of 160 Gb/s, is presented.

### 1. Introduction

Consumers will make increased use of multimedia with the transition to the information age. The demand for more information such as video, text, images and voice will result in an explosion in traffic. This development can already be observed in the growing traffic on the Internet. Based on this observation, technology roadmaps which have been developed in Japan forecast transmission rates of 100 Mb/s to the home and 5 Tb/s for the backbone network systems by the year 2010. The total capacity of all installed fibres will rapidly be exhausted. To fill the gap between this enormous bandwidth demand and the data rates now installed (64 kb/s to homes and 622 Mb/s to 2.5 Gb/s in the network), a large amount of research and development is required.

Different approaches are possible for upgrading the existing networks. They can be categorized in terms of multiplexing type (Time division Multiplexing (TDM) and Wavelength Division Multiplexing (WDM), signal format (RZ and NRZ), single channel bitrate, dispersion accommodation and fibre types. An optimum combination of advanced photonic and electronic processing technologies must be found. A future network will in principle consist of the parts sketched in Fig. 1. The individual channels are in electronic format

and at a moderate bitrate. Using TDM techniques, data channels are transported and switched on the basis of time slots. This requires switching and signal processing in the picosecond range for high-speed TDM systems. Current research is trying to determine the optimum bitrate at which the transition from electrical TDM (ETDM) to optical TDM (OTDM) should take place. The TDM channels at different wavelengths can further be combined by WDM. At the receiving end a corresponding demultiplexing operation must be performed.

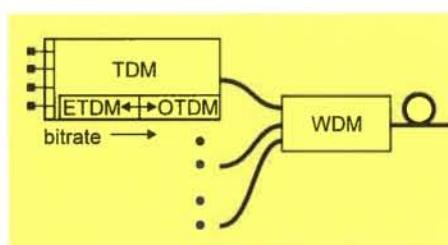


Fig. 1.  
Schematic of the  
transmission system  
at the transmitter  
end. The receiver  
reverses these  
operations.

This paper focuses on two aspects of the progress towards high capacity and high speed transmission systems. Firstly, a monolithic InP-based photoreceiver for  $\lambda = 1.55 \mu\text{m}$  is presented and its optoelectronic conversion capabilities for 40 Gb/s RZ and NRZ PRBS data streams are demonstrated. With such a device the applicability of ETDM, which is a standard technique in lower bitrate systems, is extended to higher bitrates which actually can only be achieved by OTDM. Secondly, a combination of OTDM and WDM is presented that allows a total bitrate of 160 Gb/s.

Such an OTDM approach is presently the only way to investigate 40 Gb/s TDM transmission. It allows us to make initial studies of transmission-related aspects and of the limitations of high speed RZ transmission over long fibre links. The question about which kind of multiplexing is best can not be answered yet. It depends on the properties of the devices and their interactions in the chosen system.

## **2. Ultra-Broadband InP-Based Photoreceiver for 40 Gb/s Detection**

### **2.1 Background**

Advanced TDM transmission systems operate at bit rates up to 40 Gb/s to manage increasing traffic on fibre-based communication networks. Although non-return to zero (NRZ) coding is widely applied [1], return to zero (RZ) modulation promises advantages with respect to the achievable transmission length with standard fibres [2]. In either case ultra-broadband front-ends are needed for optoelectronic (OE) signal conversion.

A monolithic InP-based optoelectronic receiver (Rx) is presented. It replaces a commercially available photodiode in a 40 Gb/s detection experiment in a step towards a 40 Gb/s opto-electronic integrated circuit (OEIC) technology. The receiver OEIC comprises a waveguide-integrated photodiode and a travelling wave amplifier (TWA) providing additional signal amplification. Its OE power transfer function includes the spectral range of a 40 Gb/s NRZ data stream. In a detection experiment with an OTDM RZ PRBS modulated source, direct detection of the received 40 Gb/s pulse sequence by the InP-based photoreceiver is demonstrated. The design of the complete receiver module is described as well as its signal conversion properties for 40 Gb/s TDM applications.

### **2.2 Optoelectronic receiver design for fast TDM systems**

For TDM transmission systems which support the synchronous digital hierarchy (SDH) standard, photoreceivers are needed which exhibit a flat gain characteristic down to some 10 kHz to ensure the transmission of the frame synchronization of the synchronous transport modules. The components of a photoreceiver (photodiode and amplifier stage) should have both good power linearity and flat conversion properties within the frequency span of the bit rate. Furthermore a group delay time scatter within  $\pm 15\%$  of the bit period and an output reflection factor less than -10 dB over the full bandwidth are desirable [3]. The polarization sensitivity should

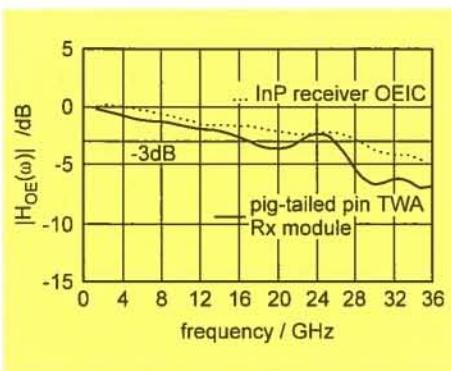
not exceed about  $\pm 1$  dB, to compensate for the loss of polarization orientation in standard fibres and to allow for some polarization scrambling of stringed bits in optical multiplexing experiments.

### **2.3 Monolithic photoreceiver**

The photoreceiver OEIC comprises a photodiode with integrated optical waveguide [4] and a HEMT-based travelling wave amplifier, both monolithically integrated on a semi-insulating InP substrate [5]. The layer stack of the evanescent field coupled GaInAs pin-photodiode is optimized to achieve an internal quantum efficiency of about 85 % for photodiodes with a size of  $5 \times 20 \mu\text{m}^2$ . The electrical 3 dB bandwidth, which is limited by the transit time, amounts to 35 GHz. Optical measurements show an overall external quantum efficiency of 30 % with almost polarization-insensitive behaviour (within  $\pm 1$  dB). The AlInAs/GaInAs HEMT layers are regrown by MBE after locally removing the photodiode layers [5]. Further technological details of the fabricated photoreceiver OEIC, with dimensions approximately  $1 \times 3 \text{ mm}^2$ , are provided in [3].

The amplifier stage is built according to a travelling wave scheme for the envisaged 40 Gb/s applications. The TWA has a fifth order lowpass transimpedance function similar to a Bessel filter, which satisfies the demands of digital system applications. The amplifier has a transimpedance of 40  $\text{dB}\Omega$  and a bandwidth of 28 GHz [6]. The photoreceiver OEIC is mounted in a one square inch pigtailed module. It is operated with a 2 V TWA drain voltage and a photodiode reverse bias of 1 V.

Fig. 2 shows the power transfer frequency response of the receiver module as well as of the receiver OEIC, as determined by optical heterodyne measurements at a wavelength of 1.55  $\mu\text{m}$ . The OEIC has a bandwidth of about 28 GHz, while the Rx module has a slightly smaller bandwidth of about 26 GHz. This demonstrates the good transmission behaviour of our coplanar packaging technology, which provides nearly flat gain characteristics up to the range of 28 to 36 GHz (cf. Fig. 2). High-power saturation of the dc and RF photocurrent responses is not observed up to photocurrents of 1.5 mA [4].



## 2.4 Signal detection capability for NRZ modulation at 40 Gb/s

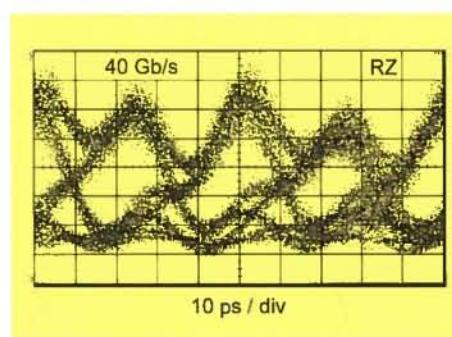
In order to demonstrate the signal conversion capability of the receiver OEIC for 40 Gb/s NRZ data, the spectral energy contents of an input optical PRBS of 128 bit length was determined by an FFT. The most important spectral information for 40 Gb/s data reconstruction are contained in frequencies up to 27 GHz. Thus, the original optical and the converted optoelectronic spectra are fairly close to each other. By integration of the noise up to 40 GHz, the  $1.55 \mu\text{m}$  sensitivity of the Rx OEIC to the optical power inside the feeding waveguide is calculated to be -14 dBm, including a chip-internal photodiode conversion efficiency of 75 %.

## 2.5 OTDM RZ modulated signal source and detection experiment at 40 Gb/s

To demonstrate experimentally the high-speed optical signal conversion properties of the photoreceiver, the Rx module was fed by the signal from an OTDM source setup, which was originally developed for 10 and 40 Gb/s RZ test signal generation and subsequently extended to a 40 Gb/s OTDM transmission system. A mode-locked erbium fibre ring laser (ML-EFRL) served as a 10 GHz optical pulse source (8 ps full width half maximum (FWHM) pulse width) at  $\lambda = 1548 \text{ nm}$  [7]. The output pulse train was connected to a lithium niobate Mach-Zehnder interferometer (MZI), which was used as the data modulator. The modulator was driven by a 10 Gb/s NRZ pattern generator. At the MZI output the 10 Gb/s RZ signal (PRBS,

length  $2^{27}-1$  to  $2^{31}-1$ ) is either used directly as a test pattern or is connected to an optical fibre delay-line multiplexer (OTDM) to interleave the pulses to create a 40 Gb/s RZ signal. The multiplexer consisted of three cascaded optical 1:1 fibre splitters forming two Mach-Zehnder interferometers with a three bit period (75 ps at 40 Gb/s) and a six bit period path difference. Due to the use of splitters, which do not preserve the polarization state, the 40 Gb/s signal was formed by bit pulses with four different states of polarization (SOP).

Fig. 3 shows the eye pattern of our monolithic InP-based photoreceiver module at 40 Gb/s when receiving the RZ modulated  $2^{31}-1$  PRBS data pattern. The average optical input power was approximately +3 dBm. The eye pattern is inverted to be comparable to a standard photodiode detection scheme. The TWA gain block exhibits about 6 dB insertion gain. A conversion factor of the Rx module of about 30 mV/mW is achieved. Furthermore, the bit pattern is changed to NRZ type due to the receiver bandwidth limitation in relation to the bit rate of 40 Gb/s. However, this facilitates threshold detection when the decision circuit receives an appropriate lowpass filtered NRZ signal. Some residual polarization sensitivity of the receiver is observed according to the different states of polarization in the bit stream. The eye pattern quality turned out to be almost insensitive to the PRBS pattern length up to a length of  $2^{31}-1$ , which proves that the Rx module and bias T have corners at sufficiently low frequencies.



**Fig. 2.**  
Frequency responses of the InP receiver OEIC (dotted line) and the pig-tailed pin TWA Rx module (full line).

**Fig. 3.**  
Measured eye pattern of the photoreceiver module at 40 Gb/s receiving an RZ modulated PRBS data pattern of length  $2^{31}-1$ .  
1. Scales:  
x-axis 10 ps/div,  
y-axis 20 mV/div.

### 3. 4 Channel x 40 Gb/s unrepeated OTDM transmission over 100 km of standard fibre

We describe in the following 4 channel x 40 Gb/s unrepeated OTDM transmission over 100 km of standard fibre. This technique, which uses a combination of TDM and WDM, seems to be more advantageous than pure TDM transmission in increasing the transmission capacity of standard fibre. To compensate chromatic dispersion of the fibre (about 16 ps/nm/km at 1.55  $\mu$ m) one may use dispersion compensating fibre (DCF) [8–10], chirped fibre gratings [11] or mid-span spectral inversion [12]. In this experiment we use DCF for compensating the fibre chromatic dispersion.

The experimental set up is shown in Fig. 4. The four WDM channels  $\lambda_1$  to  $\lambda_4$  were generated by two modelocked semiconductor lasers (FWHM = 1.3 ps) and a spectral slicing technique based on an arrayed waveguide grating (AWG). The AWG was fabricated in our laboratory (channel spacing 2 nm, FWHM = 0.9 nm). Using this technique, optical pulses (FWHM = 4.0 ps) at four different wavelengths  $\lambda_1$  to  $\lambda_4$  with a wavelength spacing of 2 nm were generated. The four pulse trains were coupled together into one intensity modulator (10 Gb/s, PRBS, length 2<sup>7</sup>-1 and 2<sup>31</sup>-1). Each of the four 10 Gb/s data signals was then multiplexed four times by a fibre delay-line multiplexer. To ensure a 40 Gb/s PRBS 27-1 data stream, the bit sequences were shifted against each other by 63.5 and 31.75 bit periods in the multiplexer. Finally we obtained four 40 Gb/s OTDM single polarization WDM channels at wavelengths  $\lambda_1$  to  $\lambda_4$ .

The 4 x 40 Gb/s data signal was then transmitted over 100 km of standard fibre ( $D_{SMF} = 17$  ps/nm/km at  $\lambda = 1551$  nm,  $\alpha = 0.25$  dB/km,  $dD/d\lambda = 0.07$  ps/nm<sup>2</sup>/km). The dispersion compensating fibre ( $L = 17.5$  km,  $D_{DCF} = -97$  ps/nm/km at  $\lambda = 1551$  nm,  $\alpha = 0.5$  dB/km,  $dD/d\lambda = -0.28$  ps/nm<sup>2</sup>/km) was placed at the receiver. A tunable optical filter (FWHM = 2 nm) followed the DCF to select one of the four 40 Gb/s WDM channels. Note that no individual dispersion compensation of the WDM channels was applied.

Fig. 5 shows the optical spectra of the four WDM channels at the output of the transmission line. The widths (FWHM) of the optical pulses at the input of the demultiplexer (semiconductor laser amplifier in a loop mirror–SLALOM) varied between 4.5 ps and 8 ps depending on how close a channel was to the optimum wavelength for dispersion compensation. This optimum wavelength was chosen to be at about 1551 nm. A comparison of the measured pulse widths with the calculated pulse broadening over the fibre span verified the total fibre dispersion and its slope. The selected channel was then demultiplexed in the time domain using a SLALOM-based all-optical demultiplexer [13], and the demultiplexed 10 Gb/s data signal was fed into the 10 Gb/s receiver.

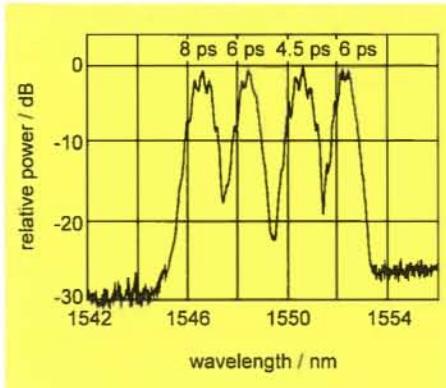
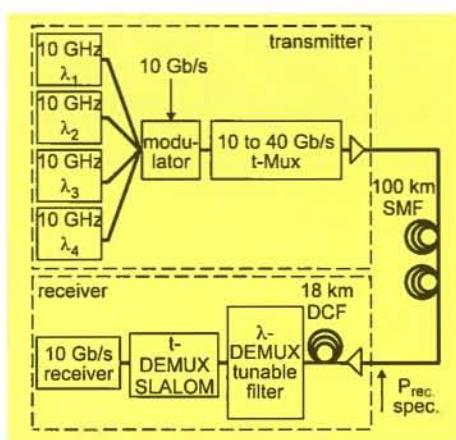


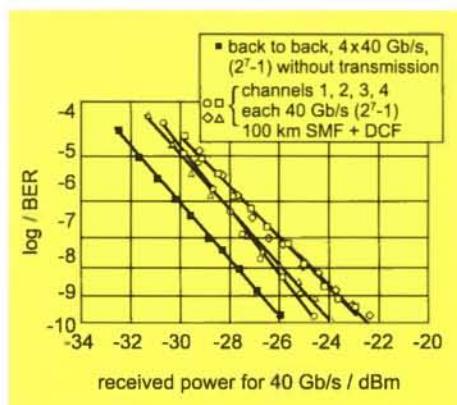
Fig. 6 shows the BER measurements for each of the four WDM channels. The received power was measured at the output of the 100 km transmission line as indicated in Fig. 4. The data presented were taken for a PRBS of length 27-1 for comparison with the simulations. However, the performance exhibited minimal pattern

**Fig. 5.**  
Optical spectra of the four WDM channels, each at 40 Gb/s. The measured pulse widths at the output of the transmission line are also shown.

**Fig. 4.**  
Setup for the 4 x 40 Gb/s experiment.



length dependence (within 1 dB) for lengths up to 231·1 [9]. From the error rate performance of the system, both before and after the transmission, we can see that the transmission penalty (at BER = 10<sup>-9</sup>) is about 3 dB. This penalty was attributed to the dependence of the demultiplexer on the pulse width and on the variation in the performance of the receiver due to the spectral shape. The demultiplexer had an optimum performance for pulse widths less than 4 ps. As in [9], the penalty was investigated as a function of the optical power at the input of the SMF. As compared to single channel transmission, there was no additional penalty due to nonlinear effects for four channel transmission with a total fibre-coupled input power up to 20 dBm.



#### 4. Conclusions

Two key aspects of 40 Gb/s TDM techniques were investigated. Firstly, an InP-based monolithically integrated photoreceiver module for  $\lambda = 1.55 \mu\text{m}$  was successfully operated at a bit rate of 40 Gb/s in an OTDM generation and detection experiment. It replaced commercially available high-speed photodiodes and has the benefit of a 6 dB internal signal gain.

Secondly, we reported unrepeated data transmission of four WDM channels, each carrying a 40 Gb/s OTDM signal, over 100 km of standard fibre (non-dispersion-shifted fibres). A single piece of dispersion compensating fibre was used for dispersion post-compensation of all four WDM channels. Both experiment and numerical calculation showed that inter-channel crosstalk due to four wave mixing (FWM) is negligible.

#### 5. Acknowledgments

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Fig. 6.  
Measured bit error rates for the four WDM channels, each at 40 Gb/s.

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## APPLICATION OF WAVELENGTH MULTIPLEXERS IN WDM NETWORKS

### Abstract

Optically transparent WDM networks need wavelength multiplexers and demultiplexers for combining and splitting the optical channels. The HHI has developed 8 and 16 channel AWG WDM multiplexers with flattened transmission characteristics. They are compared with different types of commercially available wavelength multiplexers and demultiplexers with regard to their amplitude and group delay characteristics. The bit error rate performances of 10 Gbit/s NRZ signals are measured after cascading these devices 30 times in an optical loop testbed. Furthermore, in a four channel 10 Gbit/s transmission experiment the penalty increase caused by crossconnects containing AWGs is investigated.

### 1. Introduction

Transparent optical networks [1] use the wavelength division multiplex (WDM) technique for a high transmission capacity and an effective network restoration capability. The individual channels carry information with bit rates of up to 10 Gbit/s. The routing of data streams is performed in optical crossconnects (OXC). Within the OXC the signal paths are routed in the space and wavelength domains in a circuit switching manner.

A WDM signal traverses a series connection of fibre trunks and crossconnects in the core network until arriving at the destination point. This leads to a cascade of OXC paths, consisting of multiplexers, demultiplexers, space switches and wavelength converters. The cascability performance of these OXC paths and their components is evaluated here, both experimentally in a loop testbed and theoretically using numerical simulation software.

### 1. Transparent optical crossconnects

OXC are allocated at the nodes of transparent core networks. The architectures of these OXC have been investigated worldwide. Fig. 1 shows one scheme for a transparency-supporting OXC.

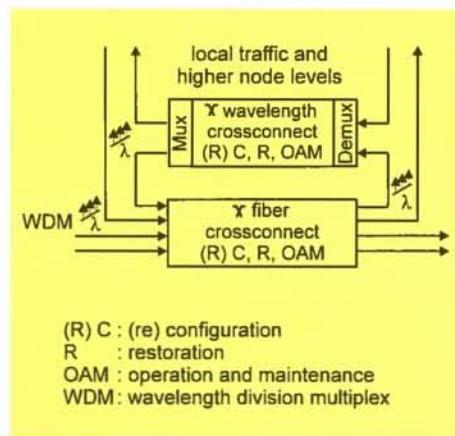


Fig. 1:  
Transparency-  
supporting  
crossconnect.

The OXC has two levels. The lower one is the so called fibre OXC, which consists of space switches used for routing complete optical carrier bundles for reconfiguration and restoration. Switching of the individual optical carriers in the wavelength domain and connecting to the local and higher node levels is performed at the second node level, called the wavelength OXC. Multiplexers and demultiplexers are positioned at the input and output to split the carrier bundles into the individual carriers and to combine them again. This leads to the OXC architecture shown in Fig. 2, which is being researched at the HHI.

Input WDM signals are demultiplexed and routed in a central space switching matrix. After an (optional) wavelength conversion and a power levelling stage, the signals are combined to form new carrier bundles. This architecture exhibits good modularity and scalability for the realization of nodes of medium size.

The input carrier splitting in a WDM crossconnect is performed in wavelength demultiplexers, and the output carrier bundling is done by wavelength multiplexers. Multiplexers and demultiplexers are commonly built of arrayed waveguide grating (AWG) filters [2, 3] or multilayer interference (MI) filters [4]. A signal in the core network traverses a cascade connection of crossconnects until arriving at the

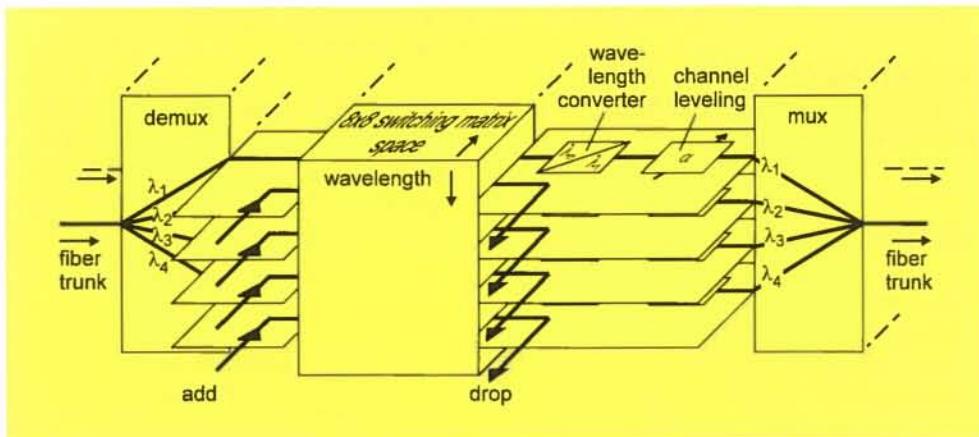


Fig. 2:  
The HHI  
crossconnect.

destination point. This leads to a cascade of multiplexers and demultiplexers in a transparent optical network, giving for example a passband narrowing effect [5, 6] and therefore resulting in transparency length limitations [7].

## 2. WDM multiplexers with optimized transmission characteristics

Wavelength multiplexers and demultiplexers (MUX/DEMUX) are the fundamental components for WDM network systems and have attracted considerable research interest. A most promising solution for such devices is the phased array invented in 1988 by M.K. Smit [8]. Basically it is an optical grating spectrograph realized with planar waveguides. It consists of an arrayed waveguide grating (AWG) connected to input and output waveguides through focussing slab regions on both sides in a Rowland circle configuration, as shown in Fig. 3.

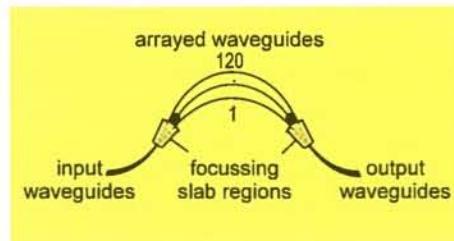


Fig. 3:  
Layout of an arrayed  
waveguide grating  
filter.

The grating is realized by monomode channel waveguides with constant path length (phase) difference  $\Delta L = m \cdot \lambda_c$  between adjacent waveguides, where  $\lambda_c$  is the device central wavelength in the grating waveguides and  $m$  is the grating order,

which is typically in the range of 80 to 240 for WDM AWGs with 100 GHz or 200 GHz channel spacing.

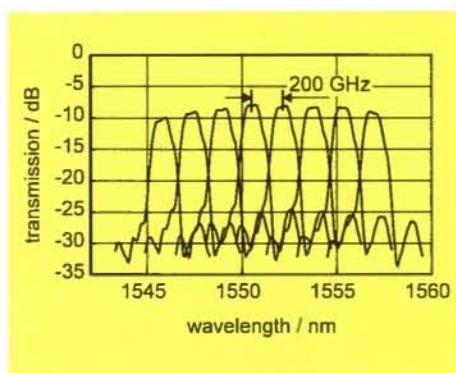
The AWG reproduces the input field with a wavelength dependent shift at one of the output waveguides, which correspond to the different wavelength channels. Therefore, the spectral response of the DEMUX is the convolution of the input image at the output side with the output waveguide mode (and vice versa for the MUX). A Gaussian response results if monomode input and output waveguides and stigmatic imaging are used. This layout has the lowest possible transfer loss and the lowest crosstalk. But from the point of view of system applications it has some important drawbacks, e.g. wavelength fluctuations will lead to signal level fluctuations in the net. A solution which guarantees cascadability must first of all exhibit a flattened spectral response.

Various approaches to flattened filter characteristics have been published. Some approaches use multimode waveguides at the input and/or output or multimode interference (MMI) structures including horn structures [9, 10] or a Y-junction [11], and some use various methods of image blurring, either by small modulations of the grating path lengths or by varying the grating end positions in order to form multiple separated images at the output waveguides [12, 13]. All these methods are inherently accompanied by a certain amount of additional loss, which is proportional to the desired passband broadening.

We have investigated various flattened AWGs as well as standard AWGs with Gaussian filter characteristics for 8 and 16 channels with 200 GHz and 100 GHz channel spacings, respectively. All were

fabricated in silica technology on PIRI substrates.

A very promising solution for flattened filter characteristics is the use of MMI structures at the AWG input. Fig. 4 shows the transmission behaviour of an eight channel 200 GHz AWG with MMI structures at all eight input waveguides, which generate the next higher symmetric waveguide mode as well as the fundamental mode. Compared with the Gaussian filter, the flattened filter has an increased 3 dB bandwidth (about 120 GHz instead of about 65 GHz), but at the expense of a greater insertion loss (9 dB instead of 6 dB). Crosstalk is also slightly increased.



modulated in an external Mach-Zehnder modulator with a 9.953 GHz sine wave and sent to the multiplexer input. The multiplexer output is connected to a high speed direct-detection receiver. After detection and amplification the envelope signal is narrowband filtered. The amplitude and phase  $\varphi(\lambda)$  of this sine wave are compared to a reference signal in a microwave transition analyzer working as a high speed vector voltmeter. The phase shift of this wave is directly proportional to the group delay  $\tau(\lambda)$  of the multiplexer:

$$\tau(\lambda) = -\frac{\varphi(\lambda)}{360 \cdot 9.953 \text{ GHz}} = -0.2791 \text{ ps} \cdot \varphi(\lambda)$$

The cascadability of multiplexers is measured in the fibre loop testbed shown in Fig. 6. Here an externally modulated 10 Gbit/s ASK NRZ 215-1 PRBS signal is cut into data bursts and fed into a loop consisting of 75 km of dispersion-shifted fibre (DSF), two EDFA's and the wavelength multiplexers and demultiplexers. After each round trip a part of the data signal is coupled out for bit error rate (BER) measurement.

Fig. 4:  
Transmission  
characteristic of a  
flattened eight  
channel 200 GHz  
AWG.

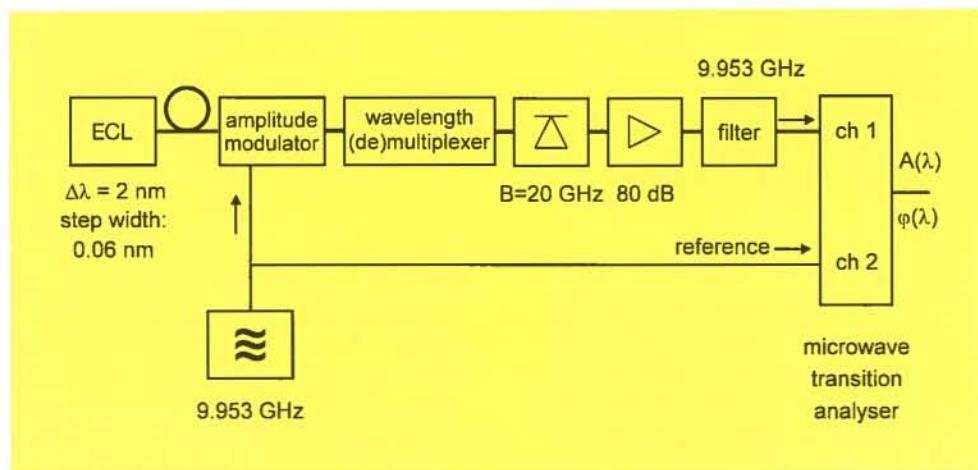


Fig. 5:  
Setup for measuring  
the amplitude and  
group delay of  
multiplexers.

### 3. Measurement of multiplexer transmission characteristics

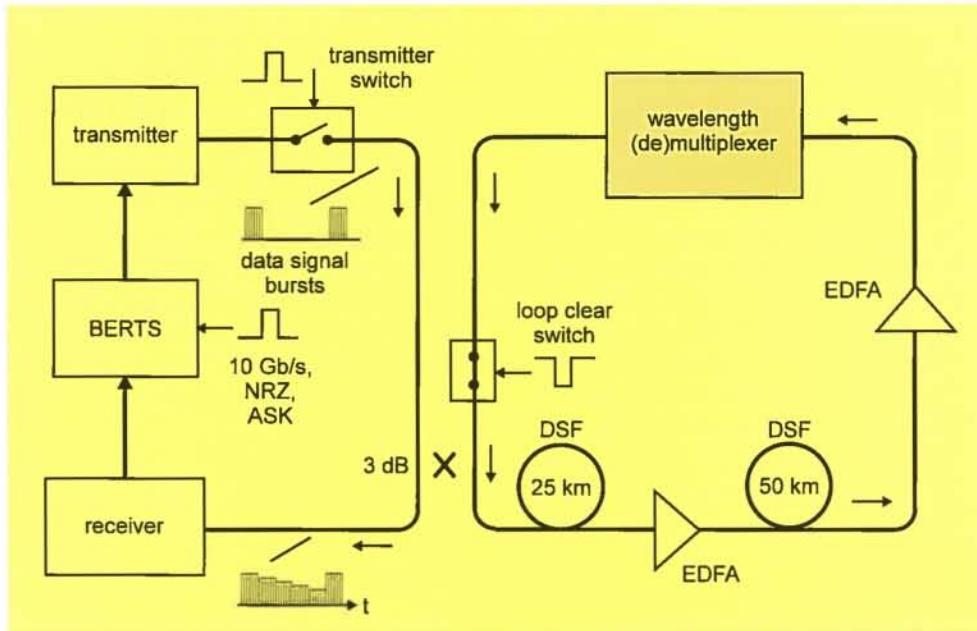
For the initial characterization of multiplexers, the amplitude and group delay characteristics are measured as a function of wavelength detuning from the passband centre frequency. The measurement setup is shown in Fig. 5. Light delivered by an external cavity laser (ECL) is amplitude

### 4. Transmission characteristics of different multiplexers

Four different types of multiplexers and demultiplexers (Fig. 7) have been tested with a 10 Gbit/s NRZ data signal in a loop testbed. The results are compared after 30 round trips.

The multiplexer performances (Figs. 8a-d) show the relative optical amplitude

**Fig. 6:**  
Optical loop for  
testing the  
cascadability of wave-  
length  
multiplexers and  
demultiplexers.



**Fig. 7:**  
Technical data of the  
tested wavelength  
multiplexers and  
demultiplexers.

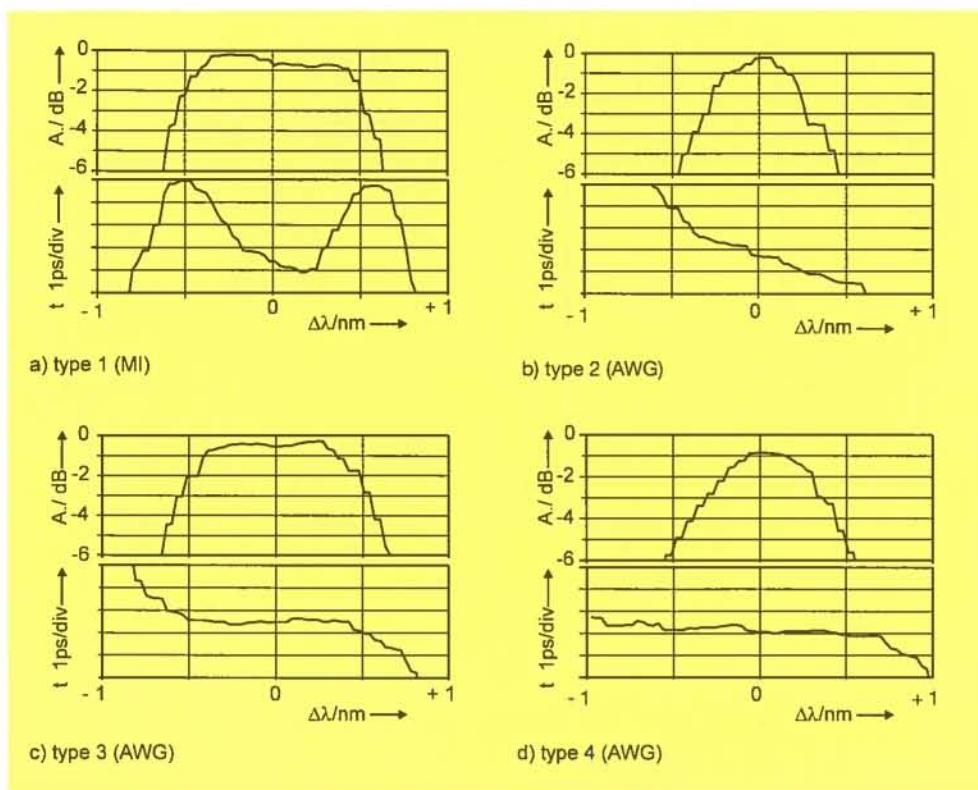
	type 1 (MI)	type 2 (AWG)	type 3 (AWG)	type 4 (AWG)
channel spacing	1.6 nm	1.6 nm	1.6 nm	2 nm
bandwidth	1 dB 3 dB	0.88 nm 1.10 nm	0.41 nm 0.60 nm	0.82 nm 1.12 nm
insertion loss	2.5 dB	3.4 dB	9.6 dB	4.0 dB
polarization dependent shift of center frequency	$\pm 0.05$ nm	$\pm 0.05$ nm	$\pm 0.02$ nm	$\pm 0.21$ nm

MI : multilayer interference  
AWG : arrayed waveguide grating

transfer characteristics  $A(\Delta\lambda)$  in the upper graph and the group delay  $\tau(\Delta\lambda)$  as a function of wavelength detuning  $\Delta\lambda$  in the lower graphs. The MI (de)multiplexer has a nearly flat 3 dB pass band greater than 1 nm, but its group delay has positive and negative slope regions (dispersion). This property makes a cascade of these devices very sensitive to transmitter wavelength variations. The AWGs have either constant (Fig. 8b) or nearly zero group delay slopes (Figs. 8c,d). Therefore the amplitude characteristic of an AWG cascade determines its sensitivity to transmitter wavelength variations, since a constant dispersion can be compensated.

BER curves at 10 Gbit/s were measured as a function of the wavelength detuning of the signal (relative to the filter centre

frequency) for back-to-back and 30 loop round trips, both with and without multiplexers. The resulting penalty (Fig. 9) shows that the signal degradation is influenced not only by the amplitude behaviour of the device, but also by its group delay. Type 3 has a broad amplitude passband characteristic and a constant group delay slope compared to those of type 2, which result in a greater detuning tolerance. By contrast, type 1 has nearly the same amplitude passband as type 3, but has two different group delay slopes with opposite signs, which results in only half the detuning tolerance. The penalty curve of type 4 cannot be directly compared to those of the other filters because of its wider channel spacing and a polarization-dependent centre frequency shift of  $\pm 0.21$  nm. Since



**Fig. 8:**  
Amplitude and group delay curves of four different wavelength multiplexers and demultiplexers.

the polarization was adjusted for optimum transmission during the loop experiment, type 4 only appears to be more tolerant of wavelength detuning.

## 5. WDM transmission over optical crossconnects

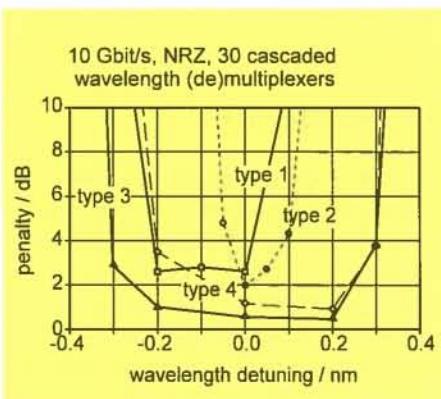
In another loop experiment a four channel 10 Gbit/s WDM transmission over 15 OXCs separated by 78.3 km dispersion-compensated standard single-mode fibre trunks was demonstrated. The OXC path consisted of a  $1 \times 8$  AWG demultiplexer and multiplexer, an  $8 \times 8$  fibre switching matrix and variable attenuators. The AWGs are characterized by a constant group delay slope of -2 ps/nm and a 1 dB bandwidth of 90 GHz.

The loop included 78.3 km of standard single mode fibre (SMF), 12.8 km of dispersion-compensated fibre (DCF) and the OXC path (Fig. 10a). The transmitter signals ( $\lambda = 1549.32$  to  $1554.13$  nm with 200 GHz spacing, 10 Gbit/s NRZ,  $2^{15}-1$  PRBS) were decorrelated by 20 km SMF and then fed into the loop. The SMF, DCF and OXC input powers were adjusted to 0 dBm, -2 dBm and +3 dBm per channel, respectively. The BER was measured after

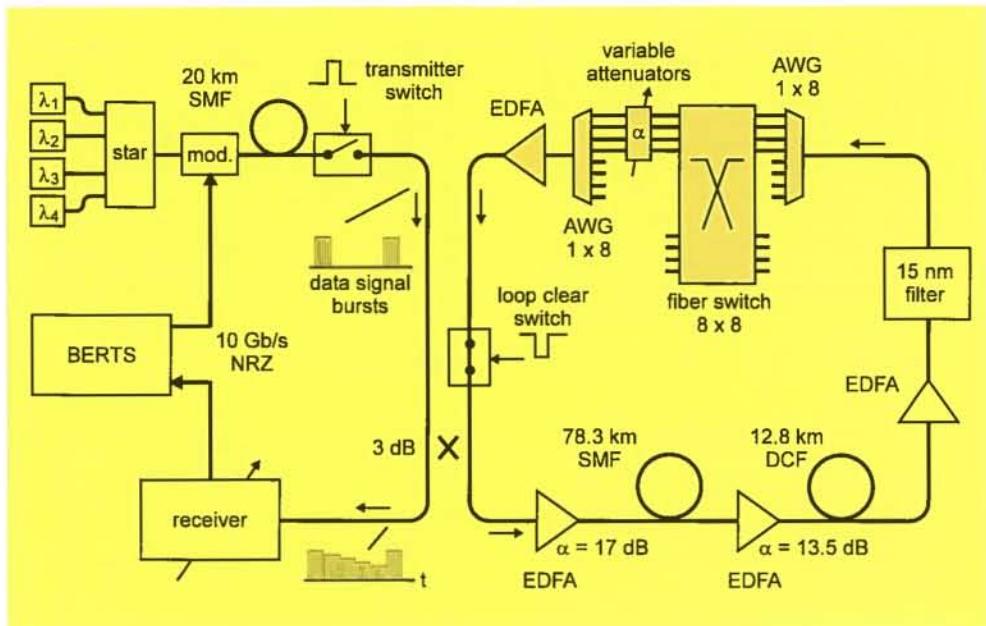
5, 10 and 15 round trips. Penalties at  $BER = 10^{-9}$  with and without OXCs are shown for up to 15 round trips with a total trunk length of 1175 km in Fig. 10b. The average penalty caused by inserting the OXCs in the transmission line is less than 0.2 dB per OXC, mainly caused by the broadband noise due to the additional EDFA gain in the loop.

## 6. Conclusions

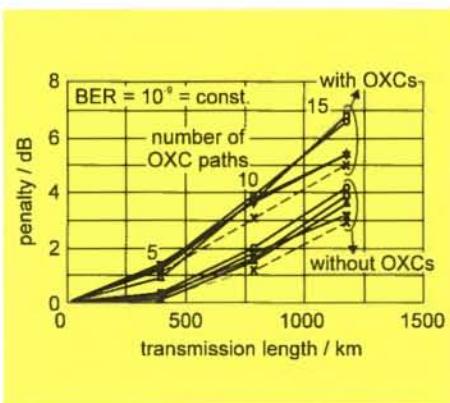
Multiplexing in WDM crossconnects for splitting up optical carrier frequency bundles and for combining them is best performed by AWGs. AWGs exhibit the best



**Fig. 9:**  
Penalty of 30 cascaded multiplexers versus detuning for  $BER = 10^{-9}$ .



**Fig. 10:**  
10 Gbit/s  
transmission over a  
four channel fibre link  
with OXCs.  
(a) Loop setup;  
(b) Penalty as a  
function of the trans-  
mission length and  
OXC number.



group delay characteristics, which is important for cascading them in transparent optical networks. In a cascade of crossconnects containing these AWGs a penalty of less than 0.2 dB per OXC was found, mainly caused by EDFA noise. Up to 15 crossconnects could be inserted in a fibre trunk with a length of 1200 km, which is sufficient for an average nation-wide transparent optical network in Europe.

### Acknowledgments

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publish the results is gratefully acknowledged. The responsibility for the contents rests exclusively with the authors.

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## OPERATION, ADMINISTRATION AND MAINTENANCE (OAM) IN PHOTONIC NETWORKS

### Abstract

The problems of Operation, Administration and Maintenance (OAM) of optical networks and their relationship to the transparency of these networks are discussed. As an example of how complex the operation of network elements can be, the necessary monitoring and control units for the operation of interferometric optical frequency converters are described.

### Introduction

There is no doubt that optical frequency division multiplexing (OFDM) will form the backbone of the next generation of optical networks world wide. This technique makes it possible to meet the requirements for higher capacity for the foreseeable future while retaining the currently installed fibres. At the same time it increases the importance of automatic failure recovery and maintenance, since the breakdown of an OFDM link even for a short time can cause huge economic losses.

The situation is even more serious because the demands of users for quality and reliability of transmission services have grown, and also because there is an aspiration towards bit rate transparency or even complete independence from modulation format, line coding, clock frequency and transmission format.

For the network operator this means that all cost savings gained by OFDM will be eaten up by the extra costs of operation and maintenance unless there is an automatic fault recovery system installed which can monitor and restore every decline in signal quality or every breakdown of an optical channel. There is an absolute urgency for international standardization of operation and maintenance procedures because the network operators want to be independent of special suppliers.

### 1. Problems of OAM in transparent photonic networks

The supervision of a maintenance entity in a photonic network is quite a difficult task, and the difficulties will increase with the degree of transparency. We define transparency as the ability of the network to transport specified classes of signals. The fewer restrictions there are, the more transparent is the network. A clear description of the concept of transparency is given in an article by Bischoff [1].

Ideal photonic paths would be completely transparent and all possible kinds of optical signals could be transmitted through the network. Short optical fibres are quite close to this ideal. At longer lengths the transparency of the fibre is limited due to losses, dispersion, polarization mode dispersion and non linear effects (e.g. self phase modulation, cross phase modulation and four wave mixing), and perhaps also by the noise of the optical amplifiers that may be necessary.

It is nevertheless desirable to extend the high degree of transparency of the fibre itself to the whole network, but network elements like optical amplifiers, add/drop multiplexers and optical crossconnects will put limits on the transparency. It is therefore necessary to decide early on which signals are allowed in the network. This decision determines which components can be implemented and it also determines which methods for supervision of the network and for failure detection and localization are available. A proposal for which signals transparency has to be guaranteed is shown in figure 1. It represents a possible compromise between transparency and OAM requirements.

According to this proposal the signal in the network is restricted in the following ways:

- The signals are digital, binary, ASK modulated.
- All bitrates up to a maximum bitrate are allowed. The maximum bit rate defines a bit rate class.
- The wavelength is restricted to the gain range of fibre amplifiers.
- The signals are continuous (no burst-like signals).

Several authors have recently discussed the problems of OAM in photonic networks [2], [3], [4].

**Figure 1:**  
**Allowable signals in an optical network.**  
**The transparency is restricted to the free choice of the transmission format and the maximum bitrate.**

optical window	OFA-band	1480 - 1580 nm	1300 + ... nm	850 + ... nm
type of signal	digital	analog		
modulation levels	binary	ternary	multi-level	
modulation formats	ASK	FSK	PSK	
line coding	numbers of 0 and 1 equal	CMI	5B / 6B	numbers of 0 and 1 not equal
bit rate	< 700 Mbit/s	< 2,5 Gbit/s	< 10 Gbit/s	> 10 Gbit/s
type of transmission	continuous signals	burstwise signals		

 transparent

OFA: optical fiber amplifier

 not transparent

ASK: amplitude shift keying

FSK: frequency shift keying

PSK: phase shift keying

CMI: coded mark inversion

A maintenance philosophy for telecommunication networks is given in the ITU Recommendation M.20 [5]. Operation and maintenance of optical networks must also follow these guidelines. The problems of operation and maintenance in optical networks are strongly linked to the requirement of transparency of the network. A direct measurement of the signal quality is the best way to detect any degradations in the network. Even rather modest requirements on transparency of the optical network reduce the possibilities of controlling the signal quality. Methods such as estimation of bit error rate by parity bits, as used in digital networks, are not possible.

This imposes stringent requirements on the operational reliability of all parts of the equipment. The components have to be so reliable that the few possible measurements of signal quality (power, wavelength) and control of the operational parameters must be sufficient to guarantee proper operation. Active components such as optical amplifiers and frequency converters are especially critical elements. They may fail because of ageing, for example, in which case control parameters have to be readjusted or the component has to be replaced.

One can distinguish between three situations for digital signals:

- The bit stream cannot be observed and the bit rate is not known. In this case only analogue optical quantities, such as optical power, optical spectrum or optical signal-to-noise ratio, can be observed. This situation arises with the proposed degree of transparency allowing bit rate classes (< 0.7, 2.5 or 10 Gbit/s).
- The bit rate is known and timing recovery can be performed. Then the bits can be synchronously sampled and the extinction ratio and signal-to-noise ratio at the bit centre can be measured. Also the complete eye diagram can be recorded. It is even possible to estimate the error rate, using assumptions about the probability distributions of the pulse fluctuations.
- The transmission format is known (e.g. SDH), as in digital networks. In this case additional information can be added to the signal to estimate the error rate. In principle this works as follows: The transmitter counts the zeros and ones in a certain time interval (block) and sends this information as part of a header to the receiver. The receiver also counts and compares the results.

To improve the operational safety we

could consider introducing test signals in paths in the crossconnect which are currently not in operation. Nevertheless the evaluation of signal quality in transparent networks is very indirect and rough. Whether it is adequate is still not clear.

## 2. Cross phase modulation frequency converters

There have been many review articles on optical frequency converters [6], [7], [8], [9], so we omit here detailed descriptions of their characteristics.

Figure 2 shows the structure of a Mach-Zehnder Interferometer (MZI) frequency converter that was developed and built at the HHI. In this configuration there is an optical amplifier in each interferometer arm and the MZI is formed with symmetric couplers. The input data signal is coupled via one of the outer couplers in one of the two amplifiers, which changes its index of refraction and detunes the interferometer. The probe signal at the desired output wavelength is thereby modulated. Because the modulation is performed by optical data light due to the phase modulation of the probe light, frequency converters like this one are called "cross phase modulation" (XPM) converters.

By a suitable selection of the amplifier operation point there will be nearly zero output power if no signal power is injected, and the interferometer will be switched to transparent if there is signal power.

Apart from the transponder, which is described in more detail in a separate contribution to this report, only frequency converters based on cross gain modulation (XGM) and cross phase modulation (XPM) in semiconductor optical amplifiers are

close to implementation in optical WDM networks. These optical frequency converters process only intensity modulated digital signals, with a maximum bit rate of 10 Gbit/s. This is the degree of transparency proposed in figure 1.

Any further extension of the transparency (e.g. allowing frequency modulated signals) excludes the implementation of XGM and XPM frequency converters or direct detection transponders. It would be necessary either to exclude frequency conversion completely or to use coherent frequency converters based on four wave mixing, difference frequency generation or similar effects.

## 3. Optical crossconnects with frequency converters

The possible expenditure for surveillance and control of a technical entity depends on its location. The number of optical crossconnects will be low, with a spacing of possibly more than a hundred kilometres, and they will be situated at the main switching nodes of the network. The frequency converters in optical WDM crossconnects will be located in an environment where complex measurement equipment is locally available, so that the supervisory system can be situated near the crossconnect. This is in contrast to the operation of optical "in-line" amplifiers, which have no direct access to the supervisory system via electrical interfaces. In this case additional supervisory channels must be provided, but these are not necessary for the frequency converters.

For the discussion of the XPM frequency converter we will assume that it is implemented in a crossconnect, like the one

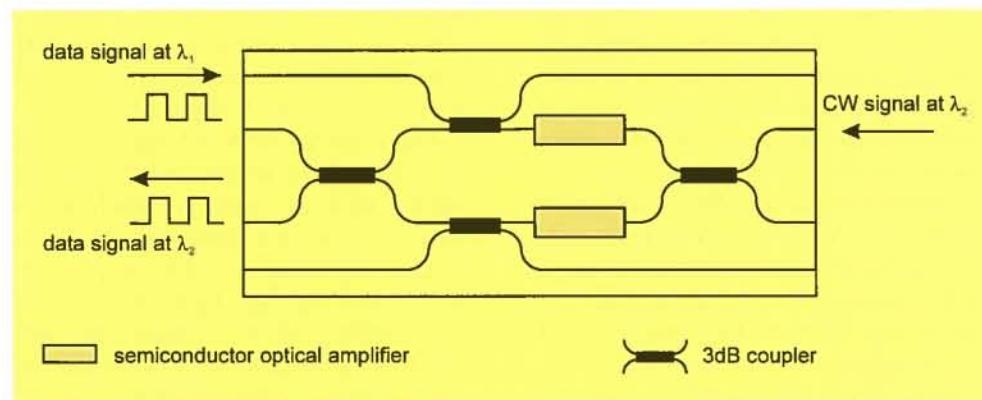
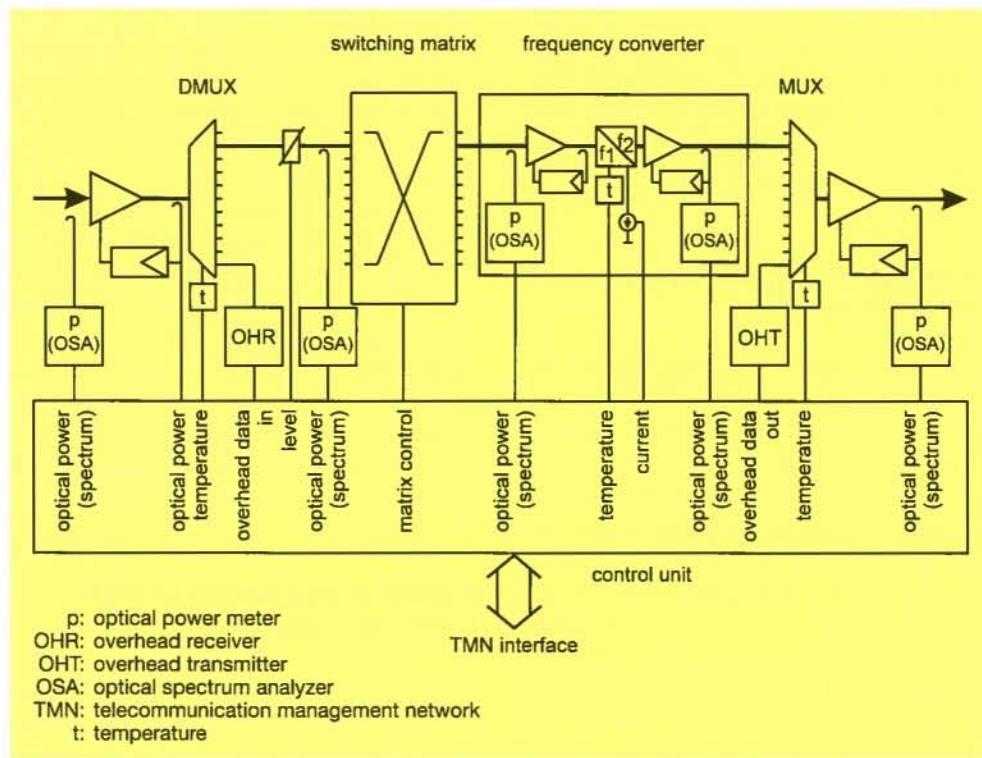


Figure 2:  
Structure of an MZI frequency converter developed at HHI.



depicted in figure 3, which consists of the following components:

- Input amplifier
- Optical wavelength demultiplexer
- Power adjustment
- Space switching matrix
- Frequency converter
- Optical wavelength multiplexer
- Output amplifier

At the input and output of the crossconnect there are controlled fibre amplifiers, which compensate for losses on the link or in the crossconnect. Following the input amplifier the wavelengths are separated by a demultiplexer. The powers in the single carriers are then equalized, to compensate for different channel powers. They are then switched to the correct output port of the switching matrix. Either each output is connected to a frequency converter (as in the figure) or the crossconnect has a pool of frequency converters which are switched into the signal path as required. The single carriers are again wavelength multiplexed and then fed into a controlled output amplifier, which amplifies the power to the prescribed level.

Control and supervision of all functions in the crossconnect are performed in a control unit. There are three main tasks of the control unit:

- Monitoring of the integrity of the input

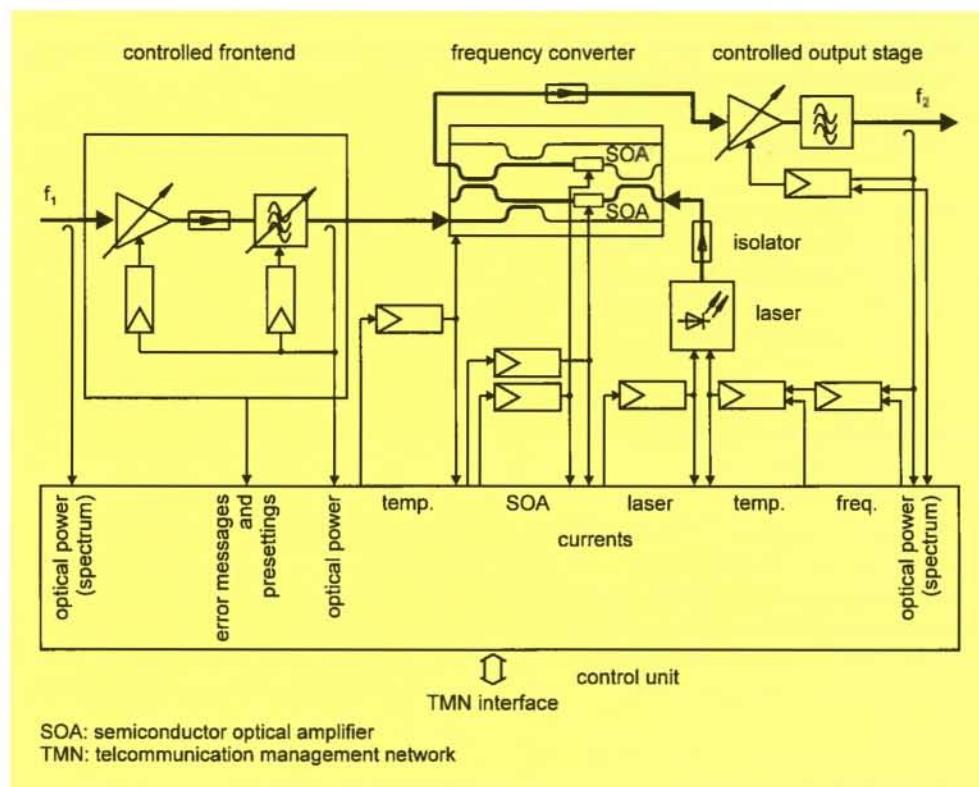
and output data streams.

- Extraction, interpretation and processing of the overhead channels.
- Control of the complete hardware of the crossconnect, monitoring of its proper operation, display of malfunctions, and delivery of status information to the TMN system.

#### 4. Operation of a Mach-Zehnder interferometer frequency converter

Fig. 4 shows a MZI frequency converter together with the necessary equipment for monitoring and controlling its operation. The basic point is that the complete frequency converter consists of many more elements than just the frequency converter chip. The figure demonstrates that many parameters have to be monitored and controlled to operate a frequency converter.

This converter does not have the main drawbacks of the simpler cross gain modulation frequency converter, which are inversion of the data signal and a large frequency chirp. But it needs extra control and monitoring units, especially for the input amplifier, which is indispensable with this form of frequency converter because of its small input dynamic range (< 3 dB).



**Figure 4:**  
**A XPM frequency converter with all essential components for OAM.**

In addition the gain of the amplifier has to be adjusted for an optimum operating point, depending on the input wavelength. For each input wavelength the control unit has to read the control value for the gain from a table and send it to the controller. For each input and output amplifier a tracking filter for the ASE also has to be provided and controlled.

At least one of the currents through the optical amplifiers on the converter chip must be adjusted according to the input wavelength. This also has to be automatically performed by the control unit. The input power has to be controlled according to the dynamic range requirements. The temperature and currents of the converter chip and the current of the pump laser also have to be controlled. Finally, the power and the optical frequency of the output signal have to be tuned via the temperature of the pump laser. All controlled parameters, as well as the input wavelength, have to be monitored.

## Conclusion

We have tried to explain the problems of operation and maintenance in transparent optical networks, using the MZI frequency

converter as an example of how complex the monitoring and control of a single element can be. It is shown that the MZI frequency converter needs optical pre and post amplifiers, which have to be adjusted for each individual input wavelength. Also, the adjustments of currents and temperature of the converter chip itself increase the complexity of the practical operation. Taking all this into account, it seems that the transponder is a less costly solution.

The problem of operation and maintenance in optical networks does not depend on the type of frequency converter, but is due to the difficulty or impossibility of direct measurement of the signal quality, which in turn is caused by the required transparency. Frequency converters as active components are especially critical elements in this respect.

## Acknowledgment

Parts of this article are taken from a study done by the HHI under a contract with the Deutsche Telekom AG. Their agreement to publish the results is gratefully acknowledged. The responsibility for the contents rests exclusively with the authors.

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## NUMERICAL SIMULATIONS OF OPTICAL PATHS AND VERIFICATION BY EXPERIMENT

### Abstract

The main steps in the numerical simulation of optical paths are discussed. Verification of the numerical methods by fibre loop measurements shows that modelling has to be done in close interplay with measurements of the important parameters of the various network components. Furthermore, simulation of the signal degradation along the optical path requires efficient numerical tools for estimation of the bit error rate.

### Introduction

Numerical simulation of optical transmission lines is of increasing importance for the design and understanding of optical telecommunication systems. During recent years a number of numerical simulation tools have been developed and are used worldwide to study the numerous effects found in optical fibre propagation and to give guidelines for the design of the optical paths. The central feature of all these programs is an efficient numerical solution of the nonlinear Schrödinger equation to simulate light propagation along the fibre. In addition, a large variety of numerical models has been developed to simulate optical transmitters, receivers, amplifiers, filters, switches, crossconnects and wavelength converters.

An example of such a simulation tool is BroadNeD, which is a software simulation tool for the analysis and optimization of broadband communication systems. It is currently used by major telecommunication providers as well as system manufacturers, and is developed and marketed by

BNeD GmbH, a spin-off of HHI. BroadNeD supports the physical level simulation with a module library, including models for all components that are necessary to simulate an optical WDM core network. These models are carefully tested and evaluated in order to deliver results that are comparable to experimentally obtained ones. The simulation environment Ptolemy is used as a platform for BroadNeD. This environment offers a huge number of different simulation paradigms that can be mixed within one overall simulation. Ptolemy has the potential to become the standard simulation environment in the future.

In this article, we will show the interplay between numerical simulation and experimental verification, ranging from measurements and modelling of the individual components to a description of a complete optical transmission experiment.

### 1. Numerical simulation of optical paths

Fig. 1 shows in schematic form the three main blocks of a typical optical transmission system.

The transmitter consists mainly of the laser, modulator and bit generator. The receiver includes the photodiode, optical and electrical filters and amplifiers. The centre box shows the optical transmission path including fibres, fibre amplifiers and filters.

A fundamental problem of all simulations of an optical path is insufficient knowledge of the performance of its individual components. The component parameters may sometimes be taken from data sheets, but most of them have to be extracted from specific measurements. The main task of numerical simulation is to find out which are the decisive parameters of a component that limit its transmission properties. In order to have an efficient numerical simulation, the numerical model of each component has to be powerful enough to include all relevant effects, but

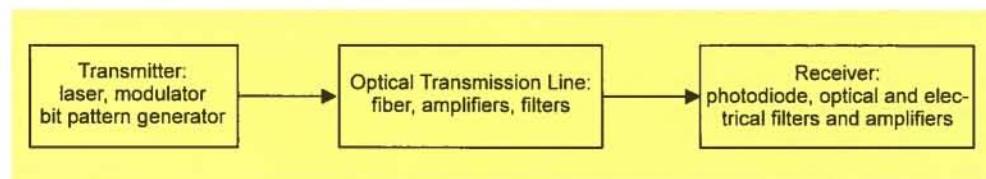
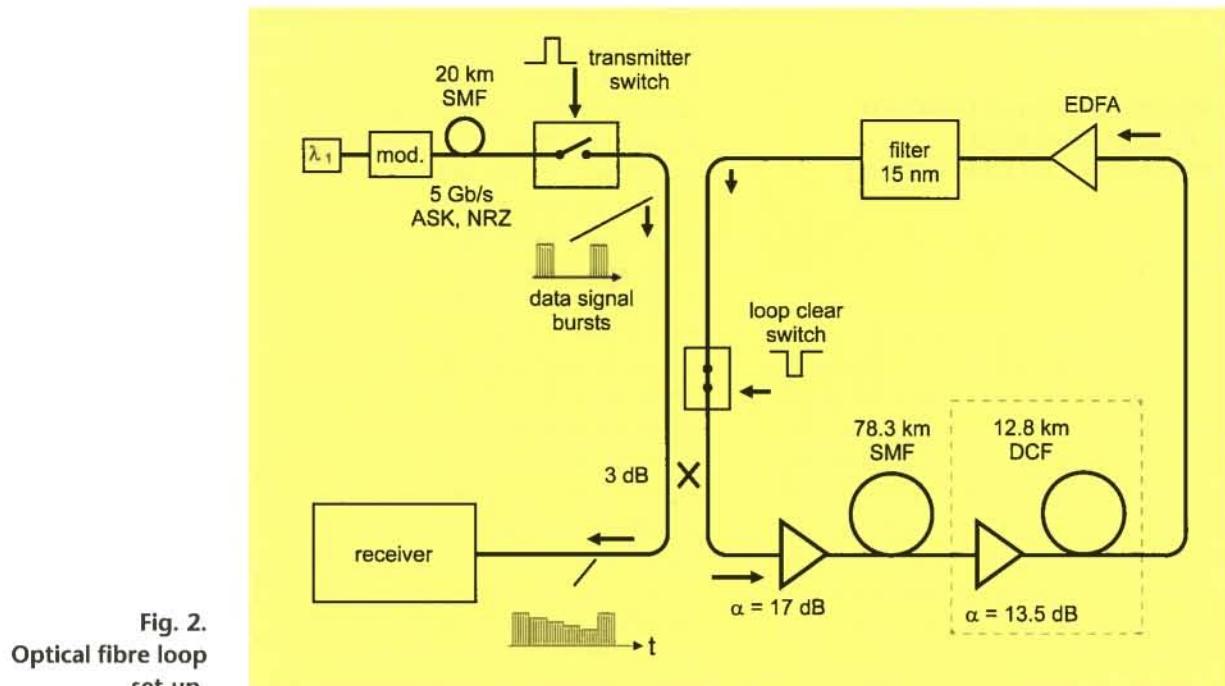


Fig. 1.  
Schematic of an  
optical transmission  
system.



**Fig. 2.**  
Optical fibre loop  
set-up.

simple enough to guarantee a fast simulation of the total optical path. In addition, reliable and simple measurement techniques are needed for characterizing the individual components.

Laboratory transmission experiments supported by a numerical simulation are important steps towards the design of optical transmission systems. The last phase will be a field experiment to validate the rules derived from laboratory experiments and simulations. A problem of higher complexity is the design of a complete optical network, since it also includes, besides the optical transmission behaviour, the dynamic properties induced by the switching of optical channels as well as the operation and maintenance functions. Here we will focus on laboratory experiments, mainly made with a loop set-up, and the accompanying numerical simulations.

## 2. Optical loop experiments

Experiments for characterizing the transmission in an optical path are performed with a fibre loop set-up [2]. Fig. 2 shows the configuration for a single channel experiment with bit rates up to 10 Gbit/s. The carrier wave is modulated by a PRBS NRZ signal, split into signal bursts and injected into the fibre loop. The loop consists of two EDFA, a 15 nm filter and

78.3 km standard single-mode fibre (SMF) with a dispersion of  $D = 17 \text{ ps/nm/km}$ . The fibre input power is 0 dBm. For a comparison between uncompensated and compensated fibre trunks, an additional dispersion compensating fibre (DCF) of 13.8 km length and a further EDFA delivering a DCF input power of -2 dBm could be inserted.

## 3. Component parameters

In a first step all network components are measured separately by standard methods for obtaining the parameters which describe the operation of the isolated component. Some results are collected in Table 1. The amplitude and time delay characteristics of the filters are also measured for inclusion in the calculations. The modulator chirp parameter  $\alpha$  is determined by connecting the modulator to SMF sections of different lengths, since the chirp together with dispersion results in a pulse steepening or pulse broadening. Thus, the pulse evolution is observed during transmission experiments and fitted to numerically calculated pulse evolutions to obtain the chirp parameter.

Wavelength	1554.13 nm
Linewidth of the external cavity laser	0.1 MHz
Extinction ratio of the modulator	13 dB
Rise time of the pulse	32 ps
Chirp parameter of the modulator	-0.43
Signal to noise ratio after the modulator	38 dB
SMF fibre dispersion	17 ps/nm/km
SMF fibre dispersion slope	0.072 ps/nm <sup>2</sup> /km
DCF fibre dispersion	-96 ps/nm/km
DCF fibre dispersion slope	-0.21 ps/nm <sup>2</sup> /km
EDFA noise figure	5 dB
Nonlinear fibre index	2.6 10 <sup>-16</sup> cm <sup>2</sup> /W

Table 1:  
Parameters for the  
simulation of a  
10 Gbit/s fibre loop.

#### 4. Back-to-back experiment and numerical BER estimate

In the second step, simulations and measurements of back-to-back bit error rates (BER) are compared. In this case the receiver is directly connected to the transmitter, and the validity of numerical models containing the previously extracted component parameters of the transmitter and receiver components can be tested.

The BER is the most important parameter for characterizing the quality of digital transmission. It is defined as the number of incorrectly detected bits divided by the total number of detected bits. Therefore, numerical simulations of BER are a fundamental problem of simulation, since the BER requirements for an optical path are expected to be between 10<sup>-9</sup> and 10<sup>-12</sup>. Direct simulation of these small bit error rates requires bit streams with huge lengths. Even the fastest current computers would take weeks of computation time for handling such data.

For a less time consuming simulation, the BER is estimated by the Q-factor method [1]. The principle is shown in Fig. 3, where the current distribution at the photodiode output is drawn separately for the "0" and "1" bits. The variances  $\sigma_0$  and  $\sigma_1$  are caused by degradation of the binary signal during transmission. These distributions can be approximated in many cases by probability density functions which are described by only a few parameters. For example, probability density functions like those in Fig. 3 can be assumed to be Gaussian, which are defined by their

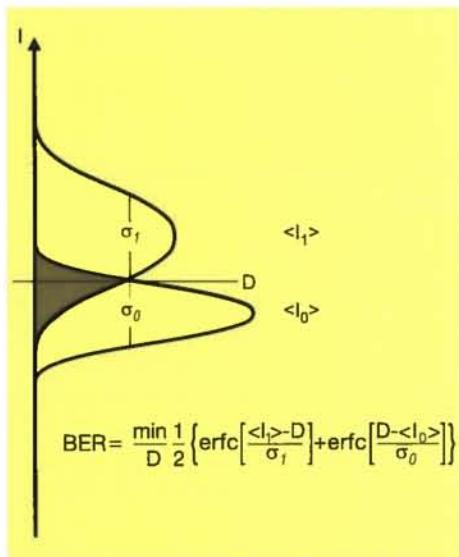


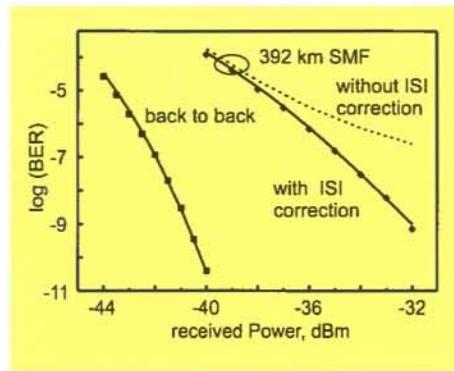
Fig. 3.  
BER estimation by the  
Q-factor method.

means and standard deviations. These parameters can be evaluated with sufficient accuracy from only 10<sup>3</sup> – 10<sup>4</sup> samples. Then the optimum decision value D, the minimum BER and the corresponding Q-factor can be estimated.

Obviously, for a Q-factor estimate the physical processes leading to the signal degradation must be known in order to estimate accurately the shape of the probability density function. If, for example, the main disturbance is amplifier noise, a Gaussian probability distribution is a good approximation. From this example it becomes apparent that the assumptions underlying a simulation have to be verified by comparing an experiment with the numerical simulation.

The Q-factor method was tested by simulation of the BER dependence of a 5 Gb/s

**Fig. 4.**  
Measured (squares) and simulated (solid lines) BERs for the back-to-back experiment. Also shown (at right) are the results of a five round trip experiment.



back-to-back transmitter-receiver combination. Fig. 4 shows that the measured results (squares) and the simulation (continuous line) are in very good agreement. This shows that the assumption that the main source of degradation is white Gaussian noise in the amplifier results in a good description of the noise process.

## 5. Simulation of the fibre loop experiment

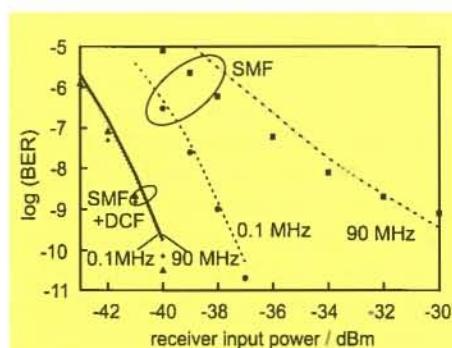
In the final step the complete fibre loop is simulated. The results for an amplitude shift keyed (ASK) directly detected transmission experiment at 5 Gbit/s after five round trips are shown on the right side of Fig. 4. Again the squares indicate the measured BER, and the dashed curve shows the BER calculated using the Q-factor method discussed in the foregoing.

In this case we obtain poor agreement between the calculated and measured results, with the calculations indicating a BER floor. This is because of the erroneous application of the Q-factor method to NRZ bit strings in dispersive transmission lines. Short pulses are more affected by dispersion than longer pulses, so that in the case of NRZ coding a 1-bit bordered by two 0-bits is broadened more than a 1-bit that has another 1-bit as a neighbour. These effects lead to bit pattern dependent intersymbol interference (ISI). It has been shown [3] that for a correct application of the Q-factor method the pattern dependent ISI has to be considered; i.e. the noise probability density calculation has to be done separately for 8 different patterns of a central bit with its nearest neighbours (000, 100, 001, 101, 010, 110, 011, 111). The solid curve in Fig. 4 includes this ISI correction and exhibits good agreement with the experimental results.

## 6. Signal degradation due to transmitter properties

Transmitter parameters such as laser linewidth and transmitter chirp are a source of signal degradation during propagation. Minimum degradation is obtained with narrow linewidths and a small or negative chirp parameter  $\alpha$ . Transmitters consisting of ECLs (External Cavity Lasers) and an external MZI modulator (Mach-Zehnder Interferometer) meet these requirements, but are very expensive. It is therefore desired to use low cost transmitter components such as directly modulated lasers or lasers with integrated electroabsorption modulators (EAM).

The intensity modulated signal suffers additional frequency modulation because of phase noise and chirp. Fibre dispersion converts this frequency modulation (FM) into amplitude modulation (AM), which leads to an additional system penalty. However, theory predicts that the undesirable effects on the signal vanish if the fibre dispersion is compensated.

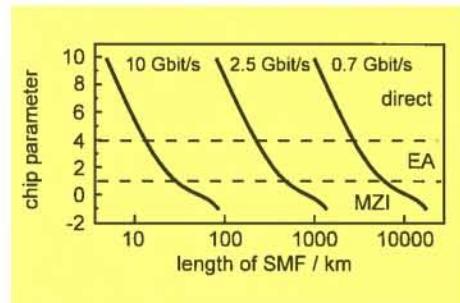


Laser frequency noise is proportional to the laser linewidth [4]. This laser linewidth was measured for two lasers, and was 0.1 MHz for the ECL and 90 MHz for a DFB laser. Using these lasers together with an external modulator, 5 Gbit/s transmission experiments were performed with the fibre loop setup. The BER curves for 313 km of SMF (symbols are measured data, lines show the simulation). It is seen that for a BER of  $10^{-9}$  the DFB laser leads to an additional penalty of more than 7 dB.

We also show in Fig. 5 the results of measurement and simulation for four round trips of SMF with dispersion compensation by 13.8 km of DCF. As predicted

by theory, no penalty due to the laser linewidth is observed. It follows that for dispersion compensated fibre trunks, lasers with large linewidths suffer no signal degradation in directly detected ASK transmission systems.

Next, the effect of chirp has been investigated by numerical simulation. In Fig. 6 the maximum chirp parameter tolerable for SMF transmission is shown as a function of SMF length, with bit rate as parameter. In addition, ranges for the chirp of a directly modulated laser, an EAM and an MZI modulator are shown. It is seen that 10 Gbit/s transmission with directly modulated lasers is only possible over a distance of less than 20 km.



In the case of dispersion compensation, the chirp is also no limitation for the transmission length. For single-channel transmission there remain limitations due to the combined effects of amplifier noise and the nonlinear effect of self phase modulation. For multichannel WDM transmission an additional degradation results from nonlinear cross phase modulation and from four wave mixing.

## Conclusion

Because of the high complexity of optical paths, a step-by-step strategy for the design and numerical simulation of optical transmission lines has to be developed. We have discussed the three main steps of such a simulation: parameter extraction and modelling of the isolated components, simulation of the back-to-back measurement, and simulation of the complete optical path.

Furthermore, we have shown that an error estimate by the Q-factor method is the only efficient simulation method if the measured BER is to be compared with the

calculations. For this method it is necessary to make assumptions about the probability density functions describing the distributions of the 0-bits and 1-bits, and it is essential to verify these assumptions by comparing the simulation with an experiment.

The numerical simulation strategy has been verified by comparison with 5 Gbit/s loop measurements. Furthermore, the effects of transmitter frequency noise and chirp on signal degradation in directly detected ASK transmission systems have been investigated. Increased laser linewidths and chirp parameters lead to additional system penalties for propagation in the standard SMF trunk, but do not affect dispersion-compensated fibre trunks.

## Acknowledgment

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**Fig. 6. Required chirp parameter for a given length of SMF transmission line and different bit rates.**

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## TRANSPONDERS FOR WDM SYSTEMS

### Abstract

A modular transponder for multi-channel optical systems up to 2.5 Gbit/s has been developed and realized at the Heinrich-Hertz-Institut (HHI) Berlin. The transponder is controlled and supervised by a processor and can be integrated into existing Telecommunication Management Networks (TMNs). Various applications and specifications for transponders are discussed. Experimental results are given for the operation of the transponder in a system environment.

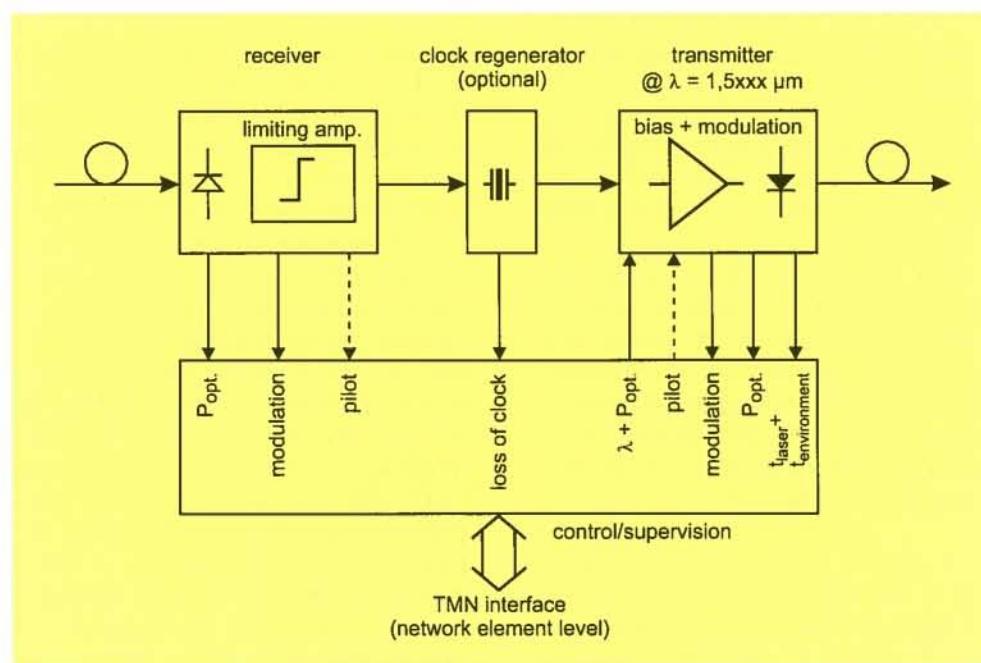
### Introduction

WDM technology is becoming of increasing importance in the core network of public telecommunication systems. The possibility of creating flexible, efficient and economic networks by integrating WDM technology into existing fibre infrastructures is already being taken advantage of in countries where limited transmission capacities exist. Yet even in countries where existing fibre infrastructures have proven

sufficient in the past, foreseeable transmission capacity bottlenecks caused by increasing communication traffic require technical solutions, which WDM technology provides.

The use of transponders as network elements, as well as the implementation of WDM technology in optical transmission systems, is of increasing significance. Transponders, also called translators, allow for the adaptation of signals of arbitrary wavelengths to those used by the WDM system. Optical solutions for wavelength conversion are currently the topic of global research [1, 2], yet it is difficult to estimate how soon prototypes fit for production will emerge. Instead, the telecommunication industry has taken a strong interest in optoelectronic transponders because of their ready commercial availability. They can be optimized for various applications and can be easily integrated into network monitoring and management systems.

The basic principle of an optoelectronic transponder is illustrated in figure 1. An optical signal of arbitrary wavelength is received by an optoelectronic receiver. After being regenerated electronically, the signal is then routed to a transmitter that retransmits the signal using a fixed and stabilized wavelength. This process is monitored by electronic controlling and supervision circuits. The functionality provided by these circuits, including an appropriate microcontroller, is also called OAM functionality



**Figure 1:**  
**Block diagram of an optoelectronic transponder with 2R or 3R regeneration**

(Operation, Administration and Maintenance). These circuits are connected to the Telecommunication Management Network (TMN). As a result, the TMN can directly monitor and control the transponder as a network element.

Transponders are used in various applications:

- As mentioned above, when undergoing an optical point-to-point WDM upgrade, the specified optical interfaces of the WDM system must be maintained. In most cases the existing terminal equipment has to be integrated into the new WDM system, for economic reasons. Optical signals in this terminal equipment are frequently not compatible with the optical interfaces of WDM systems and must therefore be converted using a transponder.
- Topologies for the most efficient upgrading of existing point-to-point connections to future optical networking standards are currently being discussed. With ring topologies, such as those under discussion for implementation in city and urban areas, individual access networks are connected to the ring network using optical add/drop multiplexers. By installing transponders between these add/drop multiplexers and the access networks, the optical interfaces of these multiplexers can be maintained.
- Optical cross connects (OXCs) for transparent WDM systems are under investigation in first field trials. An OXC for a transparent optical network essentially contains a spatial stage and a frequency stage. As long as no reliable optical solutions are available for frequency or wavelength conversion, transponders can be used to perform these functions in the frequency stages of OXCs.
- Wide area or international optical networks operated by different network providers will probably be divided into subnetworks. This will ease the operation and management of networks. If signal regeneration or wavelength conversion is required at interfaces between subnetworks, transponders can be used.

Because of the relevance of transponders for the short term implementation of advanced optical transmission systems and optical networking, a modular transponder

concept suitable for system experiments has been developed and realized in the Photonik II project BP 437/2 at the Heinrich-Hertz-Institut.

## Transponder developed at HHI

From a system engineering and economic point of view, a multitude of different variations is possible in the applications mentioned above. Individually optimized solutions are appropriate for each case. The three separate functional blocks of a transponder (receiver, electronic regenerator and transmitter) are therefore realized as individual modules. The most significant specifications of the developed transponder are:

- Input Sensitivity: The optical input sensitivity and the dynamic range of the transponder are important system parameters. For most applications a receiver sensitivity in the order of -20 dBm and a dynamic range of approximately 20 dB is sufficient. For an application in a ring network, a HHI transponder equipped with an APD receiver achieved a sensitivity of -30 dBm.
- Bitrate: Depending on the application, either a fixed bitrate or a bitrate range must be specified. The HHI transponder can be operated either within a bitrate range ("bitrate-transparent" between 100 Mbit/s and 2.5 Gbit/s) or at a fixed bitrate according to the SDH hierarchy. Electronic data and clock regenerator modules, which can be inserted between the receiver and the transmitter modules, are available for SDH bitrates of 622 Mbit/s and 2.5 Gbit/s.
- Transmitter Specifications: The most important parameter for the transmitter specification is the wavelength of the output signal. Currently, two types of laser modules are commercially available that comply with the proposed 100 GHz optical frequency spacing recommended by the ITU. One uses the laser current for direct modulation, and can be used for "long haul" (80 km) or "very long haul" (120 km) transmission without in-line amplifiers at data rates up to 2.5 Gbit/s. Another available type is an electroabsorption laser module with an integrated electroabsorptive modulator. This laser is

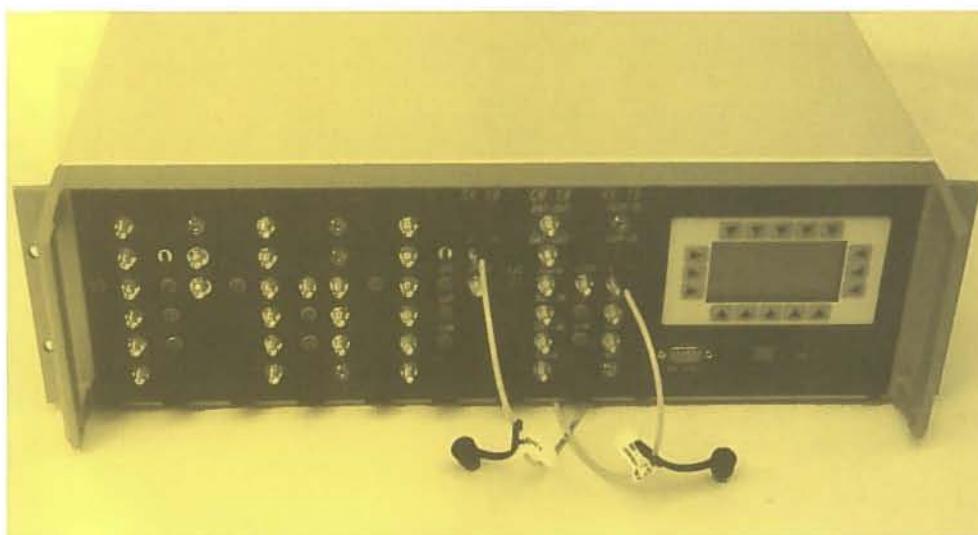


Figure 2:  
Photo of the modular  
rack-mounted  
transponder.

suitable for multi-channel systems with in-line amplifiers and allows transmission distances above 120 km. The transponders developed at the HHI are operated with directly modulated DFB laser diodes.

By using control and supervision circuits in modules which are interconnected to a central processor, the HHI transponder can be controlled as a network element by a TMN. Because the optical input power of the receiver module is supervised, it is possible to implement Automatic Power Shutdown (APS), as recommended by the ITU. In the receiver and transmitter modules the processing of pilot tones (useful for the identification of optical channels) is possible, but has not yet been implemented.

Up to eight receiver, regenerator or transmitter modules can be placed in a 19" rack in arbitrary combinations. Additionally the rack contains the central processor and a local panel for operating the transponder (see figure 2). All basic operational parameters of the modules are preset by hardware which predefines points of operation. If the communication between the central processor and the modules is interrupted, these predefined points of operation are used and basic operation is guaranteed.

The transponders were tested and characterized at 2.5 Gbit/s with PRBS sequences with a length of  $2^{23}-1$ . The following results were obtained at a BER of less than  $10^{-9}$ :

- Optical input power: < -33 dBm.
- Optical output power: > 0 dBm.
- Dynamic range: > 20 dB.
- Penalty after 106 km,

compared to back-to-back with clock recovery:	0.4 dB.
• Penalty after 106 km, compared to back-to-back without clock recovery:	1.8 dB.

## Conclusion

These results show that the transponders built at the HHI are very well suited for long-haul multi-channel WDM systems with target distances up to 120 km. If the transponder were to be used in larger quantities, it is possible to integrate all modules onto a single board.

## Acknowledgment

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AND R. KAISER

## PHOTONIC APPLICATION SPECIFIED INTEGRATED CIRCUITS (PHASICs) FOR PHOTONIC NETWORKS

### Abstract

PHASICs encompass optical, optoelectronic, electro-optic, and electronic building blocks forming a new category of ICs with broad innovative and economic potential. HHI's approach to the development of a generic, extendable integration process for the fabrication of various possible PHASIC architectures is summarized. Using this concept, not only high volume components such as bi-directional WDM transceivers for FSAN applications can be produced, but also lower volume devices for diverse high performance applications.

### 1. A new category of ICs: PHASICs

The implementation of Full Services Access Networks (FSAN), including optical paths to the subscribers such as FTTC/B/H (Fibre-To-The-Curb/Building/Home), will demand the availability of high volume, low cost photonic modules for the subscriber links, as well as lower volume products for optical functions in the optical nodes. Special high performance photonic modules will be required in the core network, e.g. for WDM functions, ultra-high bitrate TDM optical multiplexing or de-multiplexing, or 3R regenerator operation.

Ongoing cost reductions are envisaged, starting from current commercially available micro-optic or fibre optic versions (1<sup>st</sup> generation), continuing through hybrid assemblies on a Planar Lightwave Circuit (2<sup>nd</sup> generation), and finally ending with monolithic versions as the 3<sup>rd</sup> generation. The potential cost reduction with monolithic versions is mainly determined by their low packaging effort, which in the long term is the essential cost minimizing factor in photonic module fabrication.

The optical and electronic properties of semiconductor compound materials based on InP can be "engineered" to form various kinds of components which can perform optoelectronic/electronic-optic con-

version, passive or electrically controllable waveguiding, and all optical functions. More than that, the technology offers the ability to integrate monolithically on a single chip a selected mixture of all of the different basic building blocks. A new category of ICs with broad innovative and economical potential arises: Photonic Application Specified Integrated Circuits (PHASICs).

Of course – as in Si ASIC technology – one advantage is that the chip processing costs can be shared by the available dices on a wafer, so that PHASICs are an economical solution for smaller chip sizes. But furthermore, both medium sized PHASICs and also larger optical board setups become attractive – in the latter case, the photonic and/or optoelectronic functions are concentrated in the PHASICs and the purely optical interconnections are on the optical board. The reason for this is that the optical coupling effort to the "outside single mode fibre world" is much greater than the electronic packaging effort.

The development of a potentially high volume PHASIC, an optical bi-directional WDM transceiver, has started to evaluate its feasibility for future mass production. This PHASIC processing will be based on a generic integration process with the potential to be extended to the open family of PHASICs at lower production volume with higher performance specifications. It could also be extended to realize special functions, such as high performance ultra-high bitrate devices and all optical signal processing functions which are physically restricted to PHASICs. Of course, these lower volume PHASICs will have a chance of becoming products only after the establishment of production facilities for high volume fabrication.

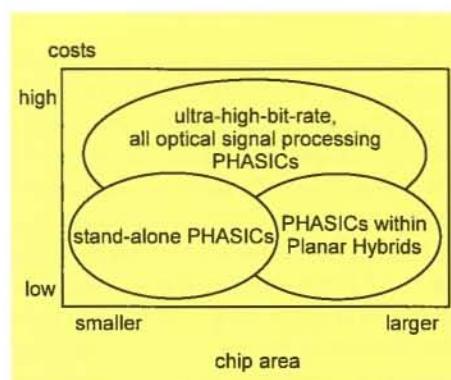


Fig. 1.  
Application fields  
of PHASICs.

## 2. PHASIC development at HHI

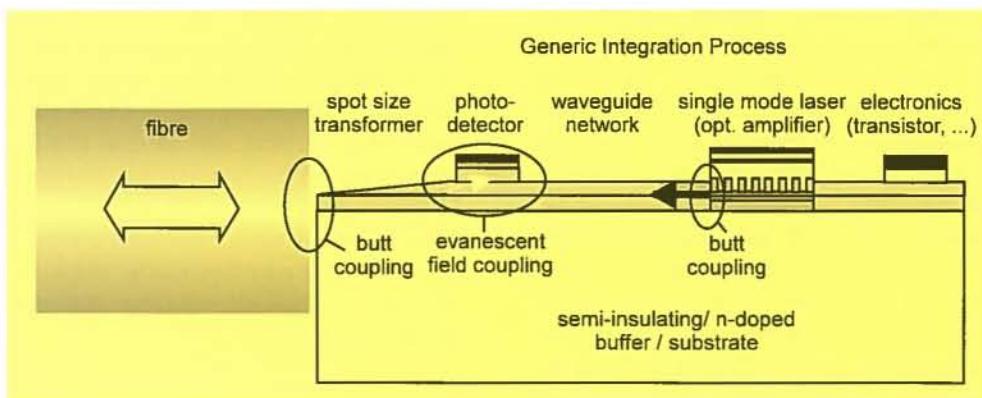
Based on its broad experience in InP technology, HHI is developing key III-V semiconductor components based on indium phosphide for implementation in optical telecommunication networks. Two main activities in this work package are: (1) the development of different PHASIC architectures to explore their physical feasibility and their potential for economical commercial fabrication, and (2) to develop reproducible technological tools and integration concepts for economical parallel full-wafer processing (this is analogous to the activities in microelectronic Si ASIC technology).

A variety of PHASICs is currently under development at HHI, including wavelength multiplexers and demultiplexers, converters, bi-directional optical WDM transceiver components [1], functional devices including multi-gain sections for use as 3R regenerators etc. [2], optical millimeter-wave generators [3], laser modulator components for transmission up to 40 Gbit/s, waveguide-integrated 70 GHz PIN photodiodes [4], 40 Gbit/s photodetector/amplifier devices [5], and optical multiplexers and demultiplexers for applications up to the 0.1 Tbit/s range [6].

semiconductor device fabrication. Such a versatile process enables the fabrication on each wafer of either many of the same kind of chips or of a variety of customer-designed chips. Thus, it will also be possible to reduce both the development effort and the time schedule for new application-specific components.

### 2.1 HHI's advanced generic PHASIC process

The basic idea of a "generic, extendable integration concept" means the availability of a single, economical and simply upgradable fabrication process for the integration of different optical, optoelectronic, electro-optical and/or electronic building blocks into different high performance PHASICs with diverse functionalities. A PHASIC fabrication technology based on a first generation of such a generic integration process was demonstrated at HHI in 1994/1995 with the parallel fabrication of polarization-insensitive (polarization diversity) heterodyne receiver PHASICs, optical microwave generator PHASICs, simple bi-directional optical transceiver PHASICs and discrete tunable 4-section DBR lasers on a single semi-insulating InP wafer [7].



**Fig. 2.**  
Schematic showing  
PHASIC building  
blocks (optical spot  
size transformer,  
photodetector,  
waveguide network,  
DFB laser, and  
electronics).

For future economical fabrication of potentially high volume PHASICs (e.g. bi-directional optical transceivers and optical millimeter-wave generators), as well as for the fabrication of various high performance, lower volume candidates (e.g. wavelength multiplexers and demultiplexers, and lasers with integrated modulators), HHI is developing a generic, extendable integration process based on standard equipment generally used for commercial

Since then, HHI's generic integration concept has been updated in terms of process effort, flexibility, performance, and yield, relying on a practical technology with the following key features:

- Versatility to enable the fabrication of various PHASICs with different functionalities, including spot size transformers for optimum fibre/chip coupling.
- Flexible, widely independent choice and

optimization of the integrated subelements or building blocks.

- Integration of a ridge waveguide laser instead of a buried heterostructure laser by using a butt coupling scheme and selective area epitaxial regrowth.
- Integration of photodetectors in the IC waveguide by utilizing evanescent field coupling (chosen because of its technological simplicity).
- Use of semi-insulating, Fe-doped GaInAsP/InP waveguide layers and InP substrate material in order to minimize parasitic capacitances and leakage currents, and thus electrical crosstalk.
- Application of "light baffles" for optical crosstalk suppression.
- Application of thin etch stop layers or etch control layers for accurate dry and wet chemical etching.
- Minimum number of semiconductor layer growth steps.
- Largely simultaneous processing of the IC building blocks.
- Device and technology development in close cooperation with industrial partners (Siemens, Bosch Telecom) to benefit from the existing commercial fabrication of qualified discrete lasers and photodetectors.

All regrowth steps for the required semiconductor layers – including the selective

area regrowth steps – have so far been performed by MOVPE. It is well known that selective area MOVPE produces enhanced regrowth ("rabbit ears") and variations in the material composition in the vicinity of masked areas. These effects depend strongly on the geometric dimensions of the masked areas and degrade the optical and electrical device properties and cause problems with microstructuring. During the past year it became evident that the MOMBIE growth technique will be the better choice for future economical PHASIC fabrication (whenever butt coupling schemes utilizing selective area regrowth techniques are applied). By using MOMBIE, the problems with MOVPE that are described above are almost eliminated (cf. Fig. 3).

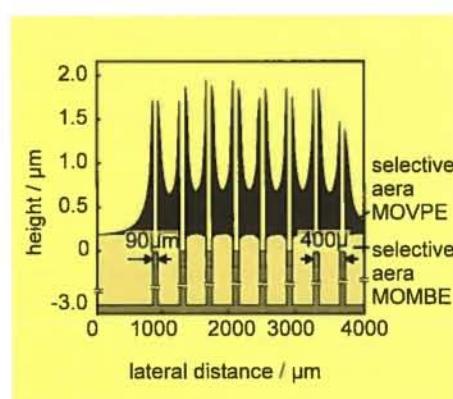


Fig. 3.  
Typical enhanced regrowth in the vicinity of masked mesas with selective area MOVPE, compared with nearly ideal growth behaviour with selective area MOMBIE.  
(Dimensions of masked areas: 90 μm x several 100 μm.)

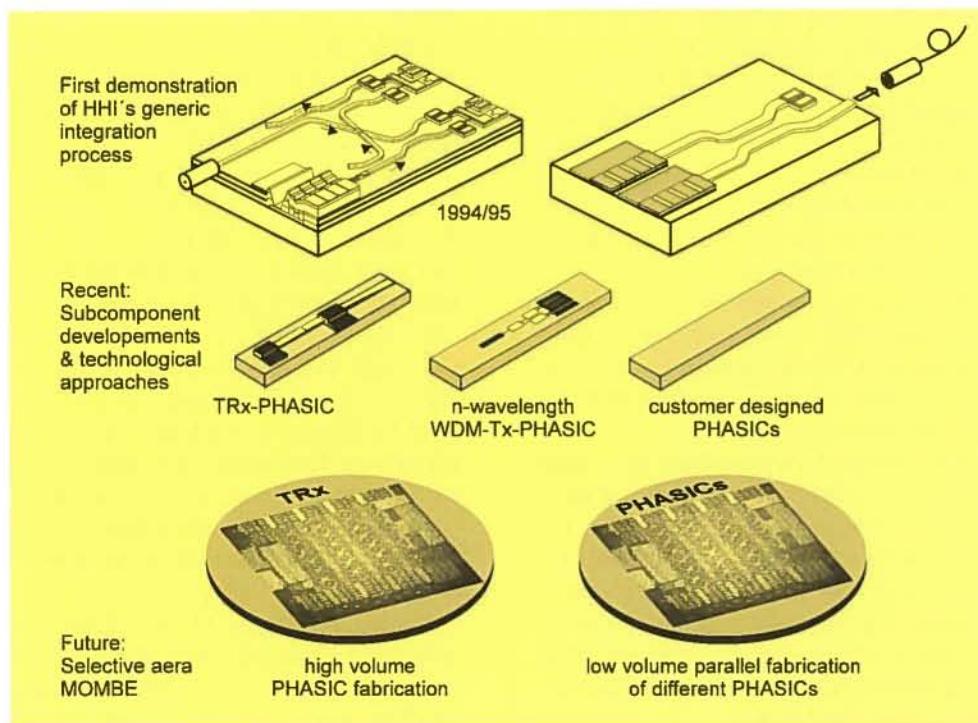


Fig. 4.  
Technology implementations from first demonstration to future exploitation.

Furthermore, MOMBE enables better uniformity in layer thickness and material composition, higher doping concentrations in regrown semiconductor layers and considerably lower regrowth temperatures, reducing the dangers of degradation (e.g. in strained layer MQW sections) and of diffusion between previously grown doped layers. More details on MOMBE are given in the article "Selective MOMBE: Improved Fabrication Technology for PHASICs".

## 2.2 Building blocks for PHASIC fabrication based on a generic integration process

**INTEGRATED LASER:** In the earlier PHASIC approach, based on the first generation of a generic integration concept, 4-section planar buried heterostructure (PBH) DBR tunable lasers were integrated. For the integration of a BH laser by butt coupling, the IC waveguide layers have to be grown selectively around the masked laser stripe. If the regrown IC waveguide layers have to be semi-insulating, there is a danger of degradation of the BH laser performance by aging effects – possible long-term migration effects of Fe ions into the active laser section may cause reduced laser performance. In order to circumvent these aging effects, a process was developed for the integration of a ridge waveguide (RW) laser structure. However, this process had to be modified for the application of selective area MOVPE because the masked laser areas are much larger than those for BH lasers. Nevertheless, by using a novel etching process to form the larger masked RW laser areas, good waveguide layer regrowth suitable for integration applications has been achieved.

An ideal lateral alignment of the RW laser ridge with the IC waveguide is guaranteed by a special formation process using the laser metallization and a dielectric as mask materials.

The validity of the developed integration process was demonstrated with the fabrication of integrated 1.5 µm and 1.3 µm Strained Layer (SL) MQW Fabry-Perot (FP) lasers consisting of an active and a passive section. The RW laser ridge in the active section is butt coupled to a semi-insulating Fe-doped rib waveguide in the passive section, as described above.

Measurements on discrete 1.3 µm FP SL MQW RW lasers fabricated by this process, but consisting only of the active laser section, and also on the same RW laser structures fabricated using our conventional technology (for comparison), have shown that the subsequent selective area MOVPE process has almost no influence on the basic laser characteristics (threshold current, output power, external quantum efficiency). The basic laser layers were grown at Siemens in Munich. The characteristics of the FP lasers including both the active and the passive section are only slightly different from those of the discrete devices described earlier, indicating the quality of the butt joint interface.

In addition, the generic character of the integration process was verified by the integration of Complex Coupled (CC) DFB lasers by Siemens. The basic characteristics of the DFB lasers including the butt joint and a semi-insulating passive waveguide section are again comparable to those from which the butt joint was cleaved off.

Furthermore, initial 1.5 µm FP RW SL MQW lasers have been successfully integrated by using the same processing but utilizing selective area MOMBE. Butt coupling efficiencies of 50 to 74% between the active FP laser and the passive section have been achieved, according to first measurements. A performance degradation due to the integration was not observed.

**WAVEGUIDE-INTEGRATED PHOTO-DETECTOR:** The benefits of waveguide-integrated photodetectors with evanescent field coupling are a relatively simple integration process and small size, which results in good RF characteristics. Areas in the range of some 100 µm<sup>2</sup> and fabrication on a semi-insulating waveguide and substrate platform give the lowest possible capacitances ( $\leq 60$  fF), and consequently very large possible electrical bandwidths [4] (c.f. the article "Progress in 40 Gbit/s TDM Techniques"). In addition to the benefit of large bandwidth, fabrication of balanced photodetectors is also possible, as demonstrated in the heterodyne receiver with integrated balanced photodetector and JFET amplifier units [7].

Another advantage of waveguide-integrated PIN photodetectors is the possibility of implementing a wavelength-selective function into such a component by

placing a waveguide absorber in front of the photodetector using a so-called "window effect" (cf. next section, Fig. 5b).

By proper choice of the absorber material in the photodetector and of the integrated waveguide absorber/filter, signals at two different wavelengths (with a separation greater than 0.1  $\mu\text{m}$ ) can be detected separately, or one of them can be suppressed. This new kind of device will be integrated in the optical transceiver described in the next section.

**OPTICAL SPOT SIZE TRANSFORMER:** The crucial requirement of chip area minimization for sharing factor maximization and thus processing cost optimization demands waveguides with highly confined optical fields in the waveguide network. These waveguides allow the incorporation of small bend radii within the PHASICs, but do not match the optical field of the fibre or the moderately confining waveguides of an optical board.

An integrated optical spot size transformer (SST) is indispensable for economical fibre/chip packaging as well as mounting of PHASICs on an optical board. The SST must be localized at the PHASIC interface due to the need to ensure horizontal and vertical alignment tolerances larger than  $\pm 1 \mu\text{m}$  for passive, reliable and thus economical single mode coupling of PHASICs to the external "single mode fibre world".

The adiabatic transformation of a single mode optical field is a challenging task. Depending on the type of PHASIC under consideration, the SST has to perform simultaneous mode matching, for either one or more closely spaced wavelengths (separated typically by a few nanometers) located within the same spectral window (2<sup>nd</sup> or 3<sup>rd</sup> optical window), or for different wavelengths lying in both spectral windows. In addition, polarization-insensitive operation has to be achieved for arbitrary states of polarization. The latter situation poses a demanding requirement for bi-directional optical WDM transceiver PHASICs using wavelengths of 1.3  $\mu\text{m}$  and 1.5  $\mu\text{m}$  for the upstream and downstream transmissions in optical access network links.

HHI's SST architecture uses a vertical ramp at the input/output port of the chip, in combination with the insertion of several thin layers (called "guiding layers") of quaternary GaInAsP material embedded in

InP beneath non-buried rib waveguides [8]. By properly adjusting the thicknesses of the layers and their separations, a waveguide may be formed which serves as a fibre-matched waveguide for both the 1.3  $\mu\text{m}$  and 1.5  $\mu\text{m}$  wavelengths. That is, an additional epitaxial regrowth step is not necessary, which would be a cost factor and which could also degrade previously fabricated building blocks, including pn-junctions.

Dry etching technologies for the fabrication of vertical waveguide ramps are under development, using either shadow-mask etching or a semi-transparent mask with varying density within a two-dimensional matrix with 0.08  $\mu\text{m}$  holes [9]. Fibre/chip coupling losses of -3 dB, including a -1 dB penalty for vertical and horizontal alignment tolerances of  $\pm 2 \mu\text{m}$ , have been demonstrated with both of these techniques. The process now has to be matured for inclusion into the generic integration process.

**ELECTRONICS:** Approaches for the integration of electronics, e.g. [5], are described in the article "Progress in 40 Gbit/s TDM Techniques".

### 3. Application of the generic integration process: bi-directional optical WDM transceiver PHASICs

A first candidate for a high volume fabrication is a bi-directional optical WDM transceiver PHASIC for the access network. The implementation of Full Services Access Networks (FSAN), including optical paths to the subscribers such as FTTC/B/H, will require millions of low cost bi-directional full-duplex WDM transceiver (TRx) components that are able to receive and transmit optical data via a single fibre [10]. Ongoing cost reductions are envisaged, starting from current commercially available micro-optic TRx devices (1<sup>st</sup> generation), continuing through hybrid assemblies on a Planar Lightwave Circuit (2<sup>nd</sup> generation), and ending up with the monolithic PHASIC version as the 3<sup>rd</sup> generation [11].

Bi-directional transceiver PHASICs will be a first vehicle to promote the installation of PHASIC production lines, with the potential for extension to the production of the open family of PHASICs with lower

production volumes and either higher performance specifications and/or special functions. The TRx PHASICs basically consist of a RW SL MQW DFB laser, a waveguide router network (duplexer), a photodetector with integrated waveguide absorber for residual light suppression, and a spot size transformer at the input/output port of the chip.

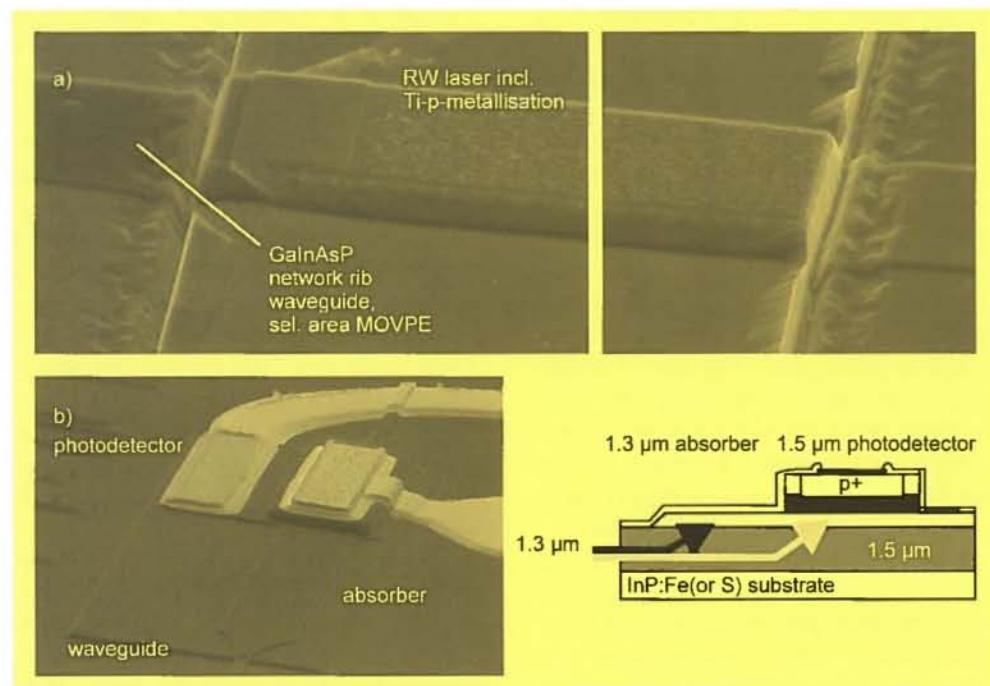
The demand to minimize the chip area for economical commercial fabrication increases the challenge to achieve the required electrical and optical crosstalk suppression. The electrical crosstalk is minimized by using semi-insulating substrate and waveguide material to avoid leakage currents and parasitic capacitances within the chip, and by ensuring sufficient on-chip distance between the laser and photodetector. On-chip light baffles are used to suppress the optical crosstalk due to residual unguided stray light from the integrated laser with its mW power level.

The waveguide router (duplexer) is used both to connect the laser and photodetector with the fibre port and to guarantee the required optical suppression of the residual light in the photodetector (e.g. the minimum targeted receiver power in the fibre is -34 dBm at a specified transmitter power in the fibre of -4 to +4 dBm).

The smallest, and thus most promising and economical solution at this time is an architecture including a wavelength-insen-

sitive Y-branch router in combination with a wavelength-selective photodetector building block. For a 1.5/1.3  $\mu\text{m}$  TRx, residual laser light suppression is performed by using a quaternary absorber material (Q-1.4) with a wavelength-equivalent bandgap of 1.4  $\mu\text{m}$  in the photodetector. Experimentally we achieved an extinction ratio of 27 dB. The complementary 1.3/1.5  $\mu\text{m}$  TRx has a Q-1.4 waveguide absorber located in front of the 1.5  $\mu\text{m}$  photodetector. An SEM photograph of such a structure is shown in Fig. 5b. The efficiency of this set-up is so large that crosstalk suppression data even greater than 40 dB have been verified.

With optimization of this concept, it will be possible to achieve small 1.3/1.5  $\mu\text{m}$  TRx devices with crosstalk suppression data meeting the FSAN specifications [12]. The target for the roadmap up to the year 2000 is the fabrication of small TRx PHASICs with a physical area in the range of 0.5  $\text{mm}^2$ . Under these circumstances the TRx PHASIC can exploit the advantages of sharing the processing costs by the parallel processing of two thousand chips per 2" wafer, as well as the minimization of packaging effort and improved reliability of the monolithic chip. Consequently, TRx PHASICs will reduce the photonic module cost compared to planar hybrid assemblies incorporating antireflec-



**Fig. 5.**  
SEM photographs of transceiver subcomponents:  
(a) Ridge waveguide (RW) MQW laser/network butt joints;  
(b) 1.5  $\mu\text{m}$  photodetector with integrated 1.3  $\mu\text{m}$  waveguide absorber.

tion coated (AR), flip-chip-mounted laser and photodetector chips with integrated SST on a Planar Lightwave Circuit.

## Conclusions

Do we need a PHASIC technology for the complete monolithic integration of all possible optical, optoelectronic, and electronic building blocks now that Photonic Lightwave Circuit technology is being implemented for production?

Of course we do, because in the long term the main cost driving factor in photonic module fabrication, the packaging effort, can be reduced essentially only by PHASIC technology. In addition, a large variety of PHASIC functions can be developed quicker and at reduced costs if the PHASIC fabrication is based on an optimized generic integration process.

HHI has demonstrated the versatility of its first generic integration process with the parallel fabrication of heterodyne receiver, millimeter-wave generator and plain transceiver PHASICs in 1994/95. Now, based on an updated generic integration process, the development of bi-directional optical transceiver PHASICs as initial high volume products has been started to evaluate its feasibility for future mass production as well as for the fabrication of high performance photonic modules at lower volumes.

## Acknowledgements

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H. KÜNZEL

## **SELECTIVE MOMBE: IMPROVED FABRICATION TECHNOLOGY FOR PHASICs**

### **Abstract**

MOMBE offers a combination of the characteristics of the MBE and MOVPE growth techniques. Under the framework of a collaborative project involving all major national research groups active in the field of MOMBE, including HHI, the potential of this technique for producing advanced InP-based photonic components was thoroughly investigated. Work at HHI has concentrated on embedded selective area growth, with the focus on the implementation of butt coupled laser-waveguide structures, which form a key integration cell for almost any photonic integrated circuit.

### **Introduction**

Metalorganic molecular beam epitaxy (MOMBE) represents the latest growth technology for III/V compound semiconductors and combines the advantages of both of the established epitaxial methods used today: molecular beam epitaxy (MBE) and metalorganic vapour phase epitaxy (MOVPE). As in MOVPE, gaseous sources, in particular metalorganic compounds of the group III elements, are employed which are practically non-exhaustible and which allow for an easy and accurate control of mass flows. These gases are converted into non-interacting atom beams in an ultra high vacuum environment, as in conventional MBE.

It is this combination of metalorganic precursors and MBE conditions which gives MOMBE its unique, nearly ideal growth performance for selective area deposition, a key growth step in the fabrication of photonic integrated circuits (PICs). Moreover, MOMBE offers distinct advantages from the economic point of view, partly because of its excellent growth uniformity and reproducibility, which results in high yields, and partly because of its exceptionally low consumption of source

materials. Associated with this are ecological advantages in terms of reduced working hazards and low amounts of toxic waste.

Under the framework of the national photonics program, all major German research groups active in the field of MOMBE have collaborated closely to investigate its potential for producing InP-based device structures. As well as demonstrating epitaxial material highly suited for advanced devices [1], the superiority of the MOMBE technique for selective growth in versatile and compact photonic application specified integrated circuit (PHASIC) designs has also been demonstrated.

Work performed at HHI in this joint project has focussed on the systematic improvement of selective area growth of InP/GaInAsP structures to achieve vertical sidewalls, suppressed irregular vertical growth and controlled lateral growth. In particular, work has concentrated on the selective deposition of Fe-doped semi-insulating waveguides (WG) and their integration with a ridge waveguide (RW) laser diode using the butt coupling scheme.

### **1. Selective area growth**

Selective area growth refers to a growth mode where layers are deposited in exposed areas on a wafer that is otherwise masked by a dielectric film on which no deposition is to occur. MOMBE offers practically ideal selective growth behaviour because of the absence of gas phase related diffusion effects. This kind of selectivity cannot be achieved with MBE because of the use of elemental source materials. MOVPE, on the other hand, suffers from diffusion effects giving rise to lateral non-uniformities in alloy compositions and growth rates near masked areas, extending over distances of up to several hundred micrometers.

Although the latter effects can be used to advantage for specific device applications, MOMBE is regarded as the technique of choice for selective material deposition whenever uniform layer growth up to the edges of the masked areas is required. This growth performance, being inherent to MOMBE, proves also to be independent of the mask geometry, thus making possible the compact integration

of various device structures on the same wafer. Furthermore, besides enabling the formation of InP/GaInAsP layer structures with excellent selectively grown lateral interfaces, the fairly low deposition temperatures, which are at least 100–200°C below those of MOVPE, help reduce dopant diffusion effects and temperature induced intermixing of multiple quantum wells (MQW).

Selective area epitaxy may be either planar selective area growth or embedded selective growth. In the former case selective deposition is performed onto a bare masked planar surface, whereas in the latter case selective infill growth (i.e. deposition into spatially very limited etched grooves) and the usual embedded growth (relatively large area selective deposition around structured devices) are of concern.

way local deposition of conducting semiconductor material in an otherwise semi-insulating matrix is possible. This can be used in novel design concepts to achieve highly doped buried contact layers, electrical isolation of different integrated optoelectronic devices, or a reduction of parasitic elements.

Recently, the large potential of selective MOMBE growth has been proven by the successful application to new device structures. MQW stripe lasers were selectively deposited side by side using planar selective growth, and the characteristics of the processed devices appeared to be comparable to those fabricated from conventionally grown material deposited in the same run [2].

Selective infill growth was used to achieve low ohmic current access to the

**Fig. 1:**  
Scanning electron  
micrographs  
of the (01-1) cleavage  
plane of:  
(a) GaInAs deposited  
by planar selective  
MOMBE;  
(b) InP selectively  
infilled by MOMBE.

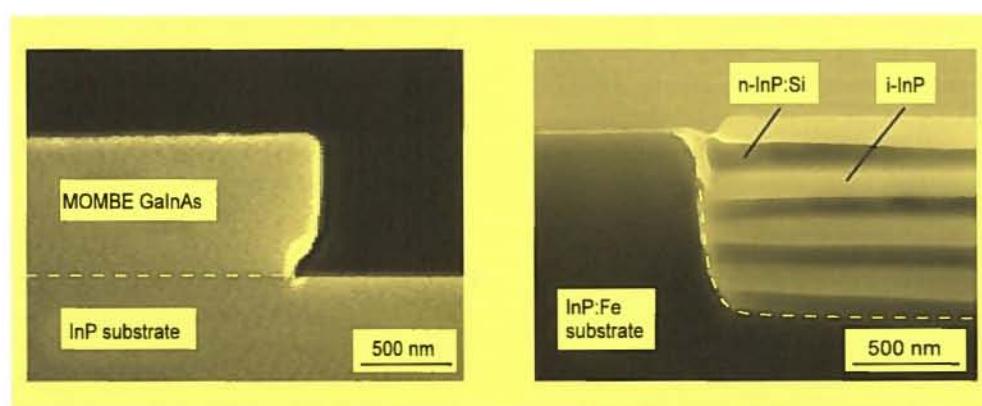


Fig. 1 represents the present status at HHI of selective MOMBE for these different types of locally restricted deposition. In Fig. 1a a representative rectangular cross-section of a planar selectively grown GaInAs layer is shown which features a perfect horizontal surface in conjunction with vertical sidewalls and a low vertical growth rate. Planar selective growth offers the possibility of depositing spatially isolated device structures to form, for example, arrayed devices.

In Fig. 1b selective infill growth of InP is depicted, and demonstrates nearly perfect flat growth contours in the whole grooved area, as indicated by the inserted marker layers. To this end, the lateral growth rate had to be reduced such that non-planar growth at the groove boundary is minimized, but at the same time preserving contact with the surrounding matrix to give a void-free vertical interface. In this

collector and base layers in heterostructure transistors (HBTs), and resulted in a fully planar device [3]. Moreover, infilled collector layers can help reduce the extrinsic capacitance associated with the base/collector overlap. This was demonstrated on DHBTs which were fabricated using MOMBE selective infill growth of the InP collector and MBE regrowth of the base and emitter. First functional devices have been presented [4].

Selective infill growth makes feasible laser formation inside optical waveguide structures in PICs. For demonstration, MQW lasers were realized which did not suffer from the infill growth process, and laser-waveguide butt joints were achieved [5] with characteristics equivalent to those made with the inverse integration scheme used at HHI, as described in the following.

## 2. Laser-waveguide butt joint

In PHASICs optical waveguides (WG) serve to interconnect optical devices on the chip. The butt joint concept has been favoured for connecting waveguides to these devices, since it allows independent optimization of the individual elements. Selective embedded MOMBE has been optimized in order to achieve continuous lateral contact of the regrown WG with the active devices as well as minimization of the spatial separation between neighbouring active and passive WG regions. It also completely suppresses irregular vertical growth at the mesa edges and eliminates enhanced growth in the butt joint region.

Fig. 2a shows the present status reached in the selective deposition of an InP-based WG structure adjacent to an ridge waveguide (RW) laser. It can be seen that a practically ideal growth profile with a continuous interface region has been achieved. Furthermore, uniformity of the alloy composition, even in the near vicinity of the vertical interface, has recently been verified [6].

More specifically, 1.55  $\mu\text{m}$  emitting MQW lasers were butt coupled to a selectively MOMBE-grown semi-insulating (Fe-doped) passive section [7]. Dopant incorporation was evaluated using spatially resolved secondary ion mass spectroscopy (SIMS). With the Fe concentration in the semi-insulating WG adjusted to be in the mid  $10^{16} \text{ cm}^{-3}$  range, the Fe incorporation at the laser site was deduced to be below the SIMS detection limit, thereby ruling

out any marked Fe movement towards the laser. Mapping of the Fe count rate reveals a sharp lateral doping interface between the laser and WG section.

500  $\mu\text{m}$  long laser diodes were coupled to passive sections of different lengths. Fig. 2b shows representative light output vs. laser current (P/I) characteristics for 380  $\mu\text{m}$  and 980  $\mu\text{m}$  long passive WGs, along with a reference curve of a laser without a WG section. The P/I characteristics show the expected trend of increasing thresholds with increasing WG length. While for the reference laser the threshold amounts to about 11 mA, an increase by some 30% to about 15 mA is obtained with a 600  $\mu\text{m}$  long passive section. Similar performance has been obtained as with recent results with lasers grown in a passive WG matrix [5], which shows that both approaches are equally suited for laser-waveguide integration.

## 3. Conclusions

MOMBE represents the preferred method for the selective growth of InP-based layer structures, unless specific features inherent in MOVPE are to be exploited. Practically ideal selective growth behaviour can be achieved, with no marked fluctuations of thickness or alloy composition near vertical regrowth interfaces. These features of MOMBE allow the implementation of compact and versatile device structures, even on the same chip.

Under the framework of a collaborative

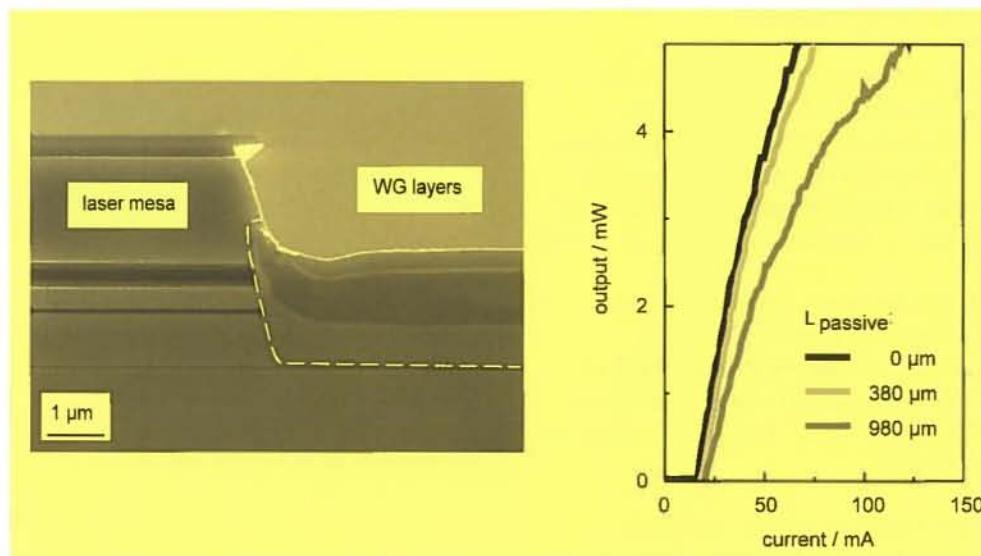


Fig. 2:  
Butt coupled  
laser-waveguide joint:  
(a) scanning electron  
micrograph of the  
(01-1) cleavage plane  
in the vicinity of the  
butt joint;  
(b) P/I characteristics  
of the integrated laser  
as a function of the  
length of the passive  
WG section.

project involving all major national research groups engaged in MOMB E, Fe doping to form semi-insulating layers and selective embedded growth have been intensively studied at HHI. The application of these processes to integrated laser-waveguide structures using the butt coupling scheme, which represents a crucial building block for PICs, has advanced to the stage that MOMB E can now be employed for the fabrication of demanding components such as monolithically integrated transceivers.

### Acknowledgments

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## BIDIRECTIONAL BROADBAND MOBILE COMMUNICATIONS AT 60 GHz USING OPTICAL SIDEband INJECTION LOCKING

### Abstract

Bidirectional 155 Mbit/s OQPSK signal transmission with remotely generated microwaves and optical heterodyning is reported. Two microwave carriers in the 62–64 GHz band are generated, one of which is modulated by the downlink data while the other is unmodulated and used as a local oscillator signal for the uplink mixer in the base station. Using sideband injection locking, the generated millimeter waves have quartz accuracy and low phase noise (<-100 dBc/Hz at 1 MHz).

A waveguide-integrated photodetector on InP with 0.3 A/W responsivity and approximately 70 GHz bandwidth was developed. It was used as an optic/millimeter-wave converter (OMC) in the BS. This has a bandwidth of more than 50 GHz and a wide dynamic range, thus minimizing the requirements for millimeter-wave amplification in the BS.

### 1. Introduction

Several millimeter-wave frequency bands between 26 and 70 GHz are being considered for broadband wireless access systems in order to avoid spectral congestion in lower frequency bands. These systems may employ a combination of optics and millimeter-wave techniques, which offers several advantages. Such optical millimeter-wave systems include millimeter-wave components in the radio link between the mobile station (MS) and the base station (BS). They also include optical components which are used in the BS and in the control station (CS) for the broadband low-loss connection and for generating millimeter-wave signals.

Especially in future cellular systems operating at frequencies in the 60 GHz band, the costs of the numerous base stations should be kept as low as possible [1].

Therefore the generation and control of the millimeter-wave signals for both the uplink and the downlink direction should be carried out in a centralized manner in the CS, thus obviating the need for millimeter-wave oscillators and modulators in the BSs. Instead, solely optoelectronic conversion is required to form a millimeter-wave signal by heterodyning the transmitted optical signals.

In this paper we report on experiments with optical heterodyning to generate the millimeter-wave signals. In general the resulting microwave carriers have phase noise due to the spontaneous emission and absorption of photons in the cavities of the semiconductor lasers. However, by applying sideband injection locking the phase noise of the optically generated microwave carriers was cancelled. Bidirectional 155 Mbit/s data transmission in the 60 GHz band was achieved using the offset quadrature phase shift keying (OQPSK) modulation format.

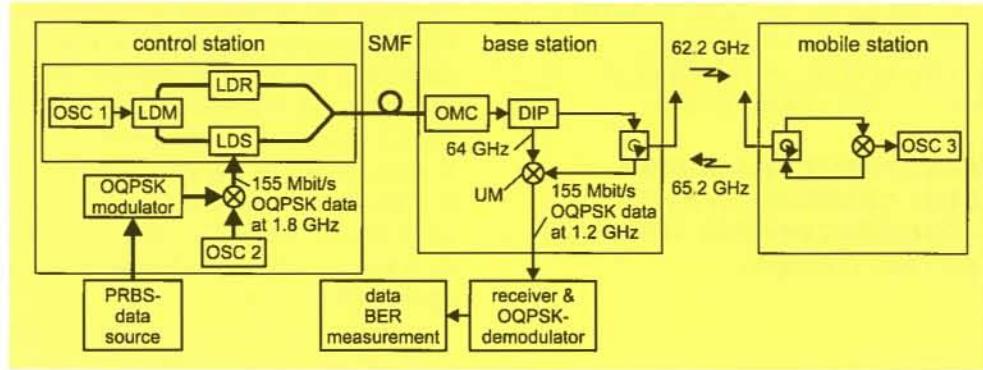
A photodetector was developed for the optic/millimeter-wave converter (OMC) in the BS. This has a bandwidth of more than 50 GHz and a wide dynamic range, thus minimizing the requirements for millimeter-wave amplification in the BS.

### 2. Stable optical source and transmission experiments

Various heterodyne methods have been investigated for the optical generation of millimeter-wave signals, since the transmission span of systems using intensity modulation is limited due to fibre dispersion. In principle the optical waves can be generated either by two separate lasers (multiple optical source technique [2]) or by one laser (single optical source technique). In the latter case special arrangements are needed; e.g. the modulation sideband technique [3], dual mode lasers [4], FM-modulated or externally phase-modulated lasers together with fibre dispersion, harmonic upconversion in nonlinear lasers [5], mode-locked lasers, or pulsed lasers [6, 7]. Simultaneous upconversion of several channels in millimeter-wave subcarrier systems using a single optical modulator is demonstrated in [8].

The experimental setup which we used for the bidirectional data transmission ex-

**Fig. 1.**  
**Experimental setup.**  
**Oscillators OSC1,**  
**OSC2, OSC3;**  
**Optic/millimeter-**  
**wave converter OMC;**  
**Standard single mode**  
**fibre SMF (12.8 km).**



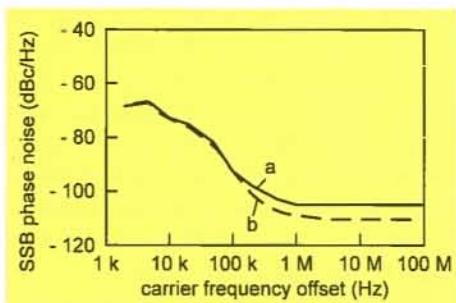
**Fig. 2.**  
**Single sideband (SSB)**  
**phase noise versus**  
**frequency offset at**  
**64 GHz.**  
**Curve a - optically**  
**generated carrier;**  
**Curve b - electronical-**  
**ly synthesized signal.**

periments in the 60 GHz band is shown Fig. 1. Two Distributed FeedBack (DFB)-lasers ( $\lambda = 1.54 \mu\text{m}$ ), designated as signal laser (LDS) and reference laser (LDR), were used for generating the millimeter-wave signal by optical heterodyning. The frequency spacing of the two lasers was 64 GHz. The two optical waves were combined and transmitted via a standard single mode fibre (SMF) to the OMC in the BS.

We developed and implemented two types of OMCs. A firstly hybrid integrated device [9] comprising a backside illuminated photodiode combined with a 60 GHz MMIC amplifier and secondly a p-i-n diode which was evanescently coupled to the feeding strip loaded waveguide, is described in section 3.

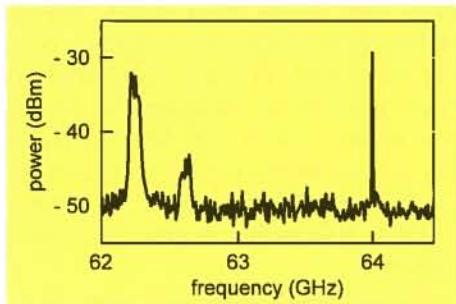
The lasers were frequency stabilized and the phase noise was cancelled by applying sideband injection locking [10, 11]. For this purpose a master laser LDM was modulated by a synthesizer signal (OSC1,  $f = 3.2 \text{ GHz}$ ) via its injection current, emitting a broad optical line spectrum. The slave lasers LDS and LDR were injection locked to the +10th and -10th modulation sidebands, respectively, with a frequency spacing equal to 64 GHz. Due to the correlation of the phase noise components, a millimeter-wave signal with high spectral purity and with very narrow linewidth ( $< 1 \text{ Hz}$ ) was obtained. Single sideband (SSB) phase noise measurements were carried out at 64 GHz using a spectrum analyzer (curve a in Fig. 2). For comparison, the phase noise of an electronically generated signal was also measured (curve b). The synthesizer signal which modulated the LDM at 3.2 GHz was upconverted to 64 GHz using an HP 50–75 mm wave source module. The results show that the phase noise of the optically generated

64 GHz signal is determined solely by the quality of the synthesizer signal.



For the data transmission experiments we used components of a commercially available digital radio-relay system (Bosch) containing OQPSK modulating and demodulating modules for 155 Mbit/s data signals and millimeter-wave components in the 62–66 GHz range. For the downlink at  $f_{\text{down}} = 62.2 \text{ GHz}$  the CMI coded data signals (pseudo random binary sequence PRBS, word length  $2^{23}-1$ ) were fed to the OQPSK modulator. The modulated output signal was upconverted to a 1.8 GHz carrier, which modulated LDS directly via its injection current. Due to the injection locking, LDS was modulated by its optical phase. After optoelectronic conversion in the BS we measured the OQPSK modulation spectrum and the residual carrier at the OMC output (Fig. 3).

Because the frequency spacing between LDS and LDR was 64 GHz, the lower modulation sideband appeared at the desired frequency for the downlink  $f_{\text{down}} = 62.2 \text{ GHz}$ . The residual carrier at 64 GHz was used as the local oscillator signal ( $f_{\text{MIX}}$ ) for the uplink mixer (UM) in the BS. The two signals were separated using a diplexer (DIP). The downlink signal spectrum shown in Fig. 4a was transmitted



to the mobile station (MS). It was converted to the uplink radio channel frequency at 65.2 GHz by a mixer and a synthesizer (OSC3,  $f = 3$  GHz) and retransmitted back to the BS. The spectrum of the uplink signal is shown in Fig. 4b. The UM converted the uplink signal down to 1.2 GHz using the optically generated LO signal from the second DIP output. This signal was applied to the receiver containing the OQPSK demodulator. This signal could be used to modulate a laser of a conventional fibreoptic transmission link from the BS back to the CS in a future complete radio-over-fibre system.

20 dB horn antennas (antenna spacing  $\approx 1$  m). The input powers at the OMC for the optical waves of LDS and LDR were -7.8 and -10.2 dBm, respectively. At a BER of  $10^{-9}$  only small penalties ( $< 2$  dB) for the receiver sensitivity were measured, and an error floor was not observed.

Sideband injection locking correlated the phase noise components of LDS and LDR. As can be seen in Fig. 6, a path difference between the signals of the two slave lasers caused a decorrelation of the noise terms, resulting in an increased BER. At optimum adjustment of  $\Delta L$  the phase noise was  $< -100$  dBc/Hz for offsets greater than 0.5 MHz, resulting in a  $BER < 10^{-9}$ . In millimeter-wave systems the chromatic fibre dispersion may limit the transmission length. Predistortion in the time domain, by matching  $\Delta L$  in the optical transmitter to the fibre dispersion, increases the transmission span. At 60 GHz the dispersion of 5 km SMF can be compensated by  $\Delta L = 1$  cm.

Fig. 3.  
Millimeter-wave  
spectrum at the OMC  
output.

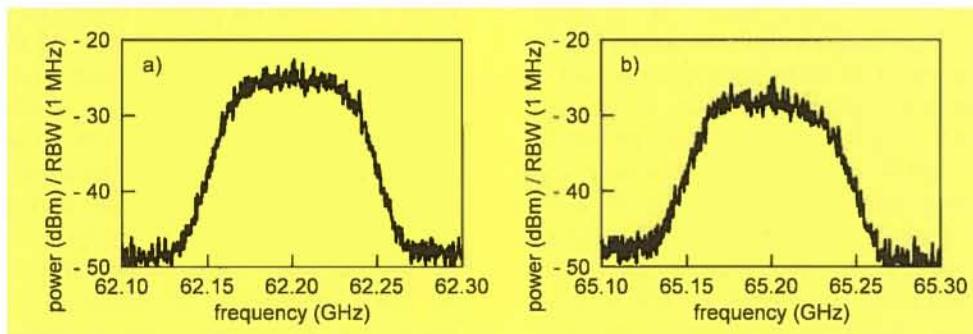


Fig. 4.  
(a) Downlink signal  
spectrum at 62.2 GHz  
measured at the  
mobile station.  
(b) Retransmitted  
uplink signal  
spectrum converted  
to 65.2 GHz measured  
at the base station.

In order to demonstrate the high quality of the optical microwave transmission and generation, bit error rate (BER) measurements were carried out (Fig. 5). The setup comprised a standard single mode fibre between CS and BS and a radio link using horn antennas or specially designed antennas for the indoor environment [12]. The BER is plotted as a function of the electrical power incident on the OQPSK demodulator, which was varied using an attenuator. Curve a shows the results of a back-to-back BER measurement when the OQPSK modulator and demodulator were connected directly by a coaxial cable. Curve b gives the BER values after transmission over 12.8 km of fibre plus the free space downlink and uplink between MS and BS using

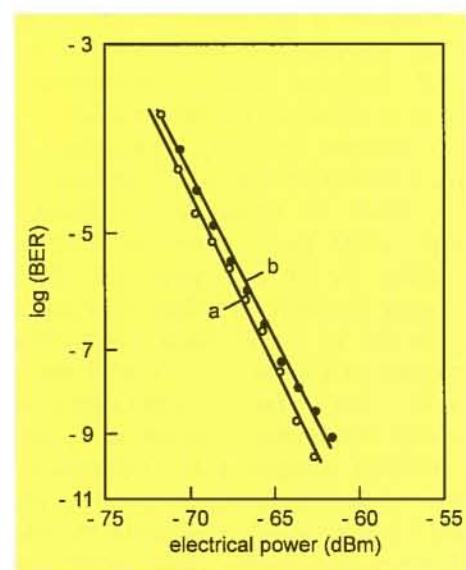
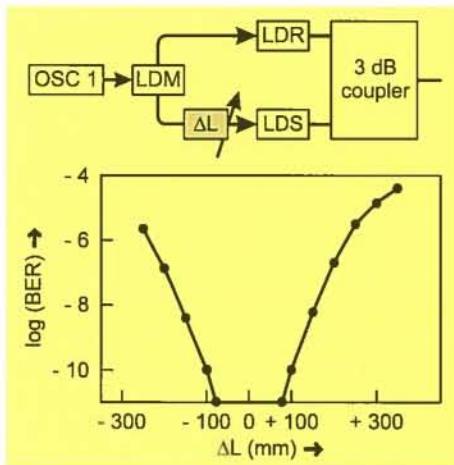


Fig. 5.  
BER versus electrical  
power at the OQPSK  
receiver input.  
Modulation:  
155 Mbit/s, PRBS.  
Curve a (open circles):  
back-to-back  
measurement.  
Curve b (filled circles):  
bidirectional  
transmission via the  
microwave links  
between BS and MS.  
Fibre length between  
CS and BS: 12.8 km  
(standard single  
mode fibre).

**Fig. 6.**  
BER versus path difference  $\Delta L$ , showing decorrelation of the phase noise terms of LDS and LDR.  
(OQPSK-signal,  
155 Mbit/s, PRBS,  
word length  $2^{23}-1$ .  
OSC1: oscillator,  
 $f = 3.2$  GHz).



### 3. Optic/millimeter wave converter

A key component of radio-over-fibre systems is the OMC, which dominates the cost of the BS. It consists of a high speed photodetector, a low noise preamplifier, filters, and a power amplifier for feeding the BS antenna. The photodetector must be able to detect the beat signal between the received optical waves. In the above mentioned experiments we used a hybrid integrated device comprising a backside illuminated photodiode and a 60 GHz MMIC amplifier. Due to the 20 dB gain of the MMIC amplifier, its responsivity was greater than 2 A/W at 62.5 GHz. A variety of problems concerning the millimeter-wave interconnections had to be tackled when packaging the hybrid OMC module, which would lead to increased costs in a practical system [9].

Therefore a photodetector was developed that offers the potential for monolithic integration together with millimeter-wave components on InP, and hence a cost effective packaging technology. In the following we describe the photodetector, which was fabricated from GaInAsP and GaInAs layers which were lattice-matched to InP and grown by Metal-Organic Vapour Phase Epitaxy. The device is formed by a p-i-n diode evanescently coupled to a feeding strip loaded waveguide. This concept has been proven to provide both a high bandwidth and a high conversion efficiency [13]. Furthermore, the uniform distribution of the light absorption over an extended region in these detectors leads to the capability of han-

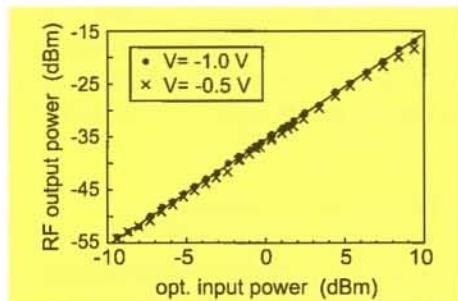
dling high optical input powers without suffering from carrier-induced field screening effects [14]. In order to reduce the requirements for the packaging, an on-chip bias network is built in an MMIC compatible process, which biases the photodiode without an external bias tee. An integrated  $50\ \Omega$  load resistor matches the system impedance.

The waveguide integrated photodetectors are characterized using on-wafer probing techniques under illumination by a lensed singlemode fibre. At a wavelength of  $1.55\ \mu\text{m}$  an internal quantum efficiency of 85 % was achieved. The polarization dependence of the responsivity is less than  $\pm 0.5$  dB. Taking into account the fibre-to-chip coupling and waveguide propagation losses, the resulting external responsivity amounts to  $0.3\ \text{A}/\text{W}$ .

The small signal equivalent circuit model elements of the photodetector were determined by S-parameter measurements in the frequency range from 45 MHz to 50 GHz. Due to the optimized contact layout the series resistance  $R_s$  is only  $3\ \Omega$ . The p-n junction capacitance  $C_{pd}$  amounts to  $40\ f\text{F}$ , whereas the parasitic capacitance of the contact pads is found to be  $18\ f\text{F}$ . Taking into account the  $50\ \Omega$  impedance of the system environment, these values lead to an RC bandwidth of 100 GHz. This value is almost equal to the bandwidth given by the transit time as given by the intrinsic layer thickness ( $f_{tt} = 110\ \text{GHz}$ ), so that an optimum overall bandwidth of 70 GHz is estimated. The frequency response was determined using a heterodyne setup. The electrical output signal is recorded with a 50 GHz spectrum analyzer and an additional external mixer for the range from 50 to 75 GHz. The frequency response turns out to be flat within the scatter of the data up to a frequency of 70 GHz, even at a low bias voltage of  $-0.5\ \text{V}$ .

This photodetector was used in the OMC system described above. Its system performance was demonstrated by the successful generation of a 64 GHz carrier modulated with a 155 Mbit/s OQPSK data load [15]. In the same setup, the power handling capability was evaluated using an additional EDFA. Fig. 7 shows the photodiode output power obtained after correction for losses in the electrical signal path to the spectrum analyzer. At a bias volt-

age of -0.5 V a slight compression of less than 1 dB can be observed at input power levels above +7 dBm. If the bias voltage is increased to -1 V, the microwave output signal increases linearly with the input power up to an optical power of +10 dBm.



#### 4. Conclusions

155 Mbit/s data signals in the OQPSK format were transmitted in both the downstream and upstream directions in a simplified experimental mobile communication system using optically generated microwave carriers in the 60 GHz band. Functions such as frequency generation, frequency selection, signal processing, and network management are remotely performed in the control station in this centralized concept of a broadband mobile communication system. Despite the possibly rough environment of the base station, millimeter-wave carriers with superior characteristics can be optically generated.

Fig. 7.  
Power linearity of the photodetector measured at 64 GHz.

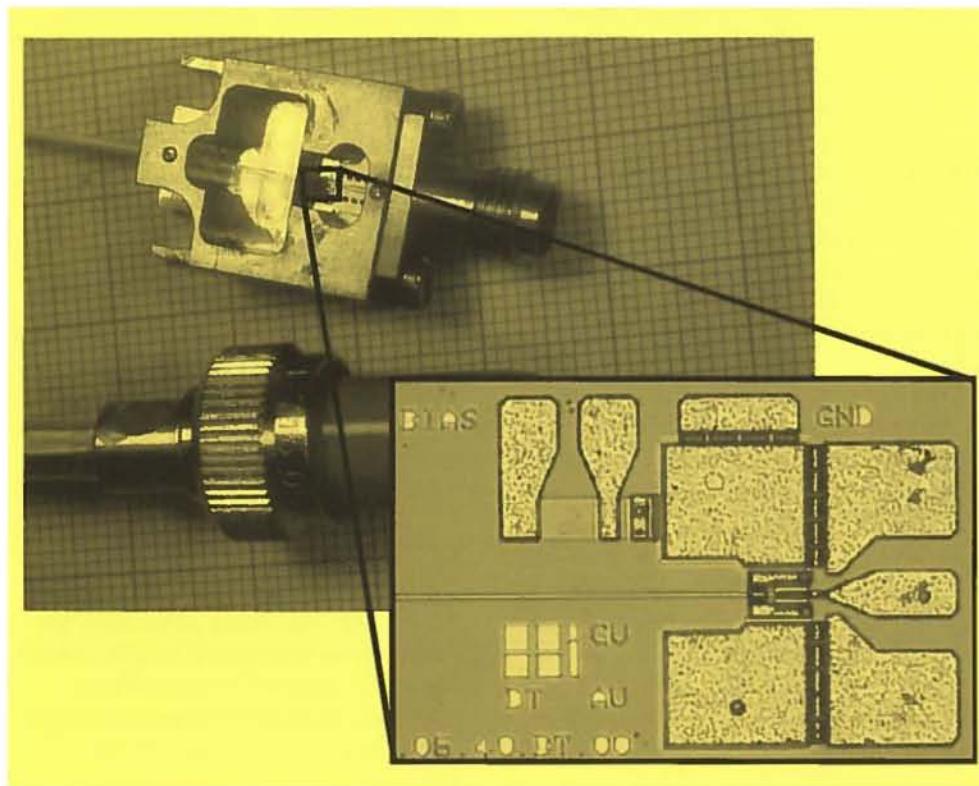


Fig. 8.  
Photograph of a photodetector module and micrograph of a detector die (not to scale).

A millimeter-wave compatible packaging technology was developed which consists of coplanar waveguides on TMM substrates, V-connectors at the output port, and a fibre pigtail at the input port. Fig. 8 shows a prototype module together with a micrograph of a photodetector die. The frequency response of the module is shown in Fig. 9. The 3 dB bandwidth is about 70 GHz, so that the detector module is capable of creating millimeter-wave signals over the entire frequency range of interest.

Hence very simple, low cost base stations can be built, and even the control station

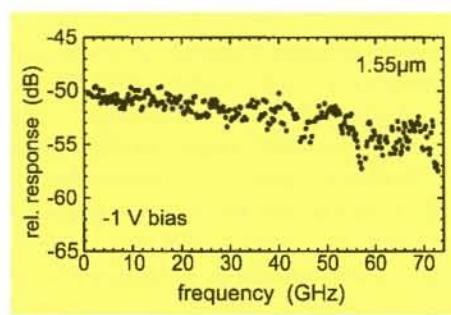


Fig. 9.  
Frequency response of a photodetector module measured with a heterodyne setup.

requires only cheap, standard components for moderate microwave frequencies.

Heterodyning the optical signals of two laser diodes offers great flexibility for the microwave frequency, which is simply given by the frequency spacing of the two lasers. Additionally, with sideband injection locking the slave lasers are multifunctional elements – they are used as an optical filter and an amplifier, and also act as a phase modulator whose required modulation rate is determined by the maximum system bitrate. Bandwidth-efficient broadband modulation can be applied because of the low phase noise. In contrast to other optical microwave generation techniques, e.g. optical harmonic upconversion or mode locking, the advantage of this technique is that the optical power is concentrated entirely in the two optical waves, so that it is a very efficient microwave generation technique which is also suitable for long distances without degradation due to fibre dispersion. The most important prerequisite for the implementation of pico-cellular mobile communication systems is the availability of low cost components, which is achieved by using photonic integrated circuits.

Furthermore a newly developed photodetector operating in the range from 0 to 70 GHz was presented. This has the potential for monolithic integration on InP together with a millimeter-wave amplifier, and was successfully tested in the system environment. Power linearity up to an input power of 10 mW was proven. This value is about a factor of ten higher than the maximum optical power which can be handled by commercially available high-bandwidth photodetectors with surface or backside illumination.

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technical support. The responsibility for the contents rests exclusively with the authors.

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## HEAD AND GAZE CONTROLLED INTERACTIONS WITH A 3D MULTIMEDIA COMPUTER

### Abstract

This article describes a new type of intelligent and interactive graphic human-computer interface for future multimedia computers. Key elements are a sophisticated 3D visual operating system, an autostereoscopic display and video-based head and gaze trackers. These enable intuitive, visually controlled (non-command) user interaction with a computer.

### Introduction

Graphical human-computer interfaces (HCIs) applying windows, icons, menus and mouse pointers have considerably simplified the use of computer programs compared with the use of purely text-oriented input and output techniques. However, strictly 2D surfaces present obvious restrictions; e.g. when several applications run simultaneously, overlapping windows make it more difficult to watch the screen and to follow its contents. In this context, 3D displays literally offer one more dimension to visualize the data flow and the interplay of programs, e.g. in complex multimedia applications. Humans are able to perceive and unambiguously interpret spatial structures without any additional mental effort. Thus, stepping into the third dimension will make it possible to provide documents, video images, application programs, databases, and networked computers with a clearer and more easily readable viewing structure.

To fully exploit the potential of 3D visualization techniques, we propose a novel intelligent and interactive HCI that "understands" the user's intentions and helps the user to navigate and manage his/her information resources intuitively. This means that we propose to give the computer "eyes" to watch the user and to anticipate his/her wishes immediately, without waiting for a direct command from the keyboard or mouse pointer (non-command based interaction).

The system's key elements are an autostereoscopic (free-viewing) 3D display, a graphical 3D user interface, a camera to sense the head's position and motion (head tracker), and equipment to measure the direction of the user's gaze (gaze tracker). The autostereoscopic display eliminates the need for 3D viewing glasses and gives the user a genuine representation of images produced either directly by the 3D visual operating system or by a stereo camera (for video conferences).

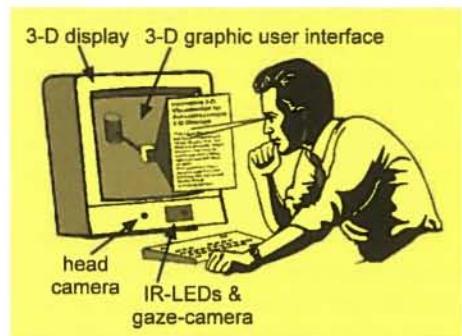
For example, with the head tracker a simple movement of the user's head could be sufficient to open the view of a document hidden behind a visually overlapping foreground object (dynamic perspective). Simultaneously, the gaze tracker determines the user's current point of fixation, so that looking at the formerly hidden document could, for example, pull it closer to the user so that its content becomes more easily readable. Moreover, the gaze tracker could adjust the process of image rendering so that only the object being looked at appears in full focus – objects out of the user's gaze would be temporarily considered unimportant and therefore shown out of focus to help them fade from the viewer's perception (active accentuation). This effect mimics the limited depth of focus range of the human eye. Human factors experiments have shown that viewing comfort is substantially improved when the depth of focus of the 3D representation is dynamically linked to the user's current point of fixation [1, 2].

In a current research project, a first prototype of the envisaged system was implemented and shown with its basic features running in full operation at the International Broadcasting Exhibition 1997 in Berlin.

### 1. System overview

Fig. 1 illustrates the basic arrangement of the system with the autostereoscopic display and interface components. Two video cameras are mounted at the front of the autostereoscopic display. One camera serves for the head tracking and video communication, and the other is used for sensing the user's gaze direction. A novel 3D visual operating system (VOS) supports the 3D representation of programs, data

and video images as well as the user's interactions with the system. The key components are discussed in detail in the following sections.



**Fig. 1.**  
Basic components of  
the proposed system.

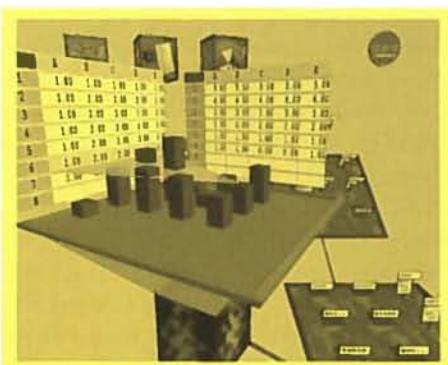
## 2. Visual operating system

A core element of the proposed user interface is a new operating system based on the concepts of both object-oriented programming (in terms of adaptation and the use of already available program functions) and visual programming (in terms of the display of software modules). This means that users can use a graphic editor to create and "program" their entire environment and applications by simply linking appropriate object-oriented software modules together. Compared to conventional visual programming tools, the proposed system builds on the advantages of 3D visualization to allow a clearly structured representation of the interconnected program modules.

By interpreting the user's point of fixation in the context of an application, the system can launch applications, show (or establish) connections between data objects, or download a hyperlinked document from the Internet. If the system answers quickly and precisely, the user will forget that the computer is watching him/her. The user gets the feeling of communicating with an intelligent and responsive system that reacts to his/her intentions even before they are expressed [3-6].

Imagine a file system where you see several boxes (directories) with files inside. The user looks at one of these boxes in the background, resulting in the creation of a pipeline connecting a "selector" to the relevant directory box. There is a tray above the selector where the user is able to view the table of contents of the selected direc-

tory box. Having read the file names, the user turns his/her view to one of the application program icons shown on rotating tool boxes (see upper part of the screen snapshot in Fig. 2). The relevant application program starts immediately (in this example it is a spreadsheet application). A long arm reaches out of the selector and at the end of this arm the spreadsheet appears, showing the data contained in the file where the user last looked. Viewing the spreadsheet makes the application come closer to the user. Its position and size can also be relocated by means of a conventional input device like a mouse. Looking at a graphic column in the 3D bar diagram causes its internal data structure and relationships to be illustrated and reflected in the content of the table (the marked line in the table at the left).



**Fig. 2.**  
Spreadsheet  
application  
under VOS.

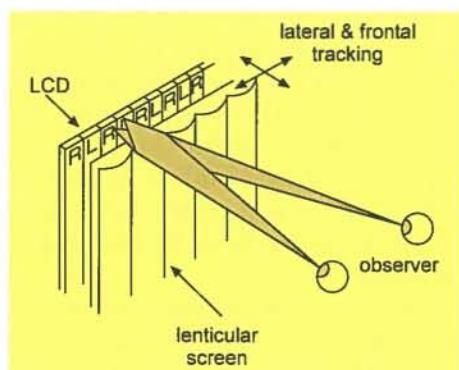
## 3. Autostereoscopic display

Because the computer evaluates the user's gaze, the proposed system requires a 3D display without polarizing glasses or any head gear occluding the user's eyes. Autostereoscopic 3D displays [7] are based on the concept of directional multiplexing, which means that the different perspective views are visible only from a limited number of fixed viewing positions. When the user positions his/her head so that the eyes are within the viewing zone, both views are immediately fused to create the illusion of a 3D space. For practical reasons, such displays must have a tracking mechanism to optically address the eyes, both at a fixed eye position and also when the user's head moves.

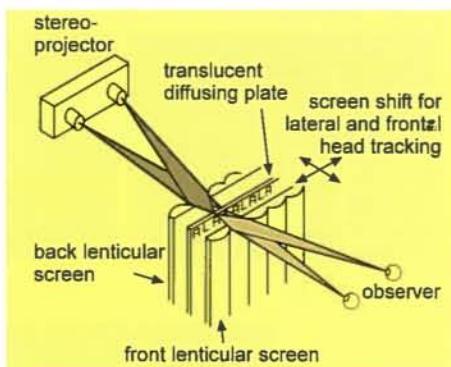
Fig. 3 shows the optical principle of a 3D display made in cooperation with Carl Zeiss. This display uses a movable lenticu-

lar screen to optically address the eyes over an extended viewing zone. The lenticular screen (made by Philips Optics) is placed in front of an LCD screen. The left and right image contents are simultaneously displayed in columns side by side. As a result, columns 1, 3, 5, 7, etc. (labelled "R" in Fig. 3), display the information for the right eye, while columns 2, 4, 6, 8, etc. (labelled "L"), display the information for the left eye. Since the lenticular screen has a directional selectivity in the horizontal plane, the colour primitives of the LCD panel have to be aligned vertically one above the other in order to avoid colour separation of the RGB components. Because in commercial LCD panels the colour primitives are aligned horizontally, the LCD panel used in this display is rotated by 90 degrees. The lenticular plate separates the two stereo pictures for the viewer's eyes. Depending on the user's head movements, the lens plate is mechanically adjusted to the left and right as well as in the frontal direction.

A high-resolution projection-type 3D dis-



play has also been developed in cooperation with Philips Optics and Cybertron GmbH. The display uses a dual lenticular screen with 1000 lenses each and two LCD projectors (Fig. 4). The cylindrical lenses of the back lenticular screen serve to form an array of left-right image stripes on an intermediate diffusing plate. The front lenticular screen has the same lens pitch as the back screen, which causes the two stereo half images to be channelled to the left and right eyes in specific viewing zones. Again, the front lenticular screen is shifted mechanically in the lateral and frontal directions to follow the head movement.



**Fig. 4.**  
Principle of a  
projection-type dual  
lenticular screen 3D  
display.

#### 4. Head tracker

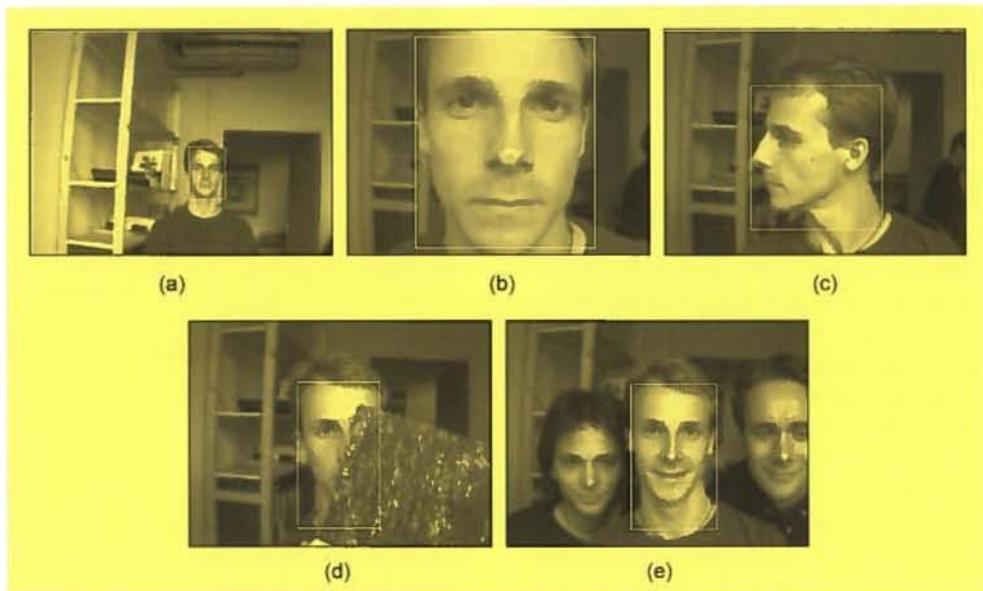
Fast and robust detection and tracking of the user's head position are required, both for optical addressing by the autostereoscopic display and for user interaction with the system. In this project, much effort has gone into realizing video-based non-intrusive head tracking methods [8]. The 3D head position (more precisely, the 3D positions of both eyes) is tracked continually using the video signals from the head camera. There are two essential steps in this process.

In the first step, the user's individual skin colour is learnt interactively by the computer and used as a basic feature for the detection of the face in the video image. After the facial region is located, the colour, foreground/background and motion information are combined and evaluated to keep track of the face when the user moves his/her head.

In the second step, the user's eyes must be found within the defined facial region. As humans periodically blink to lubricate their eyes, the natural, non-user-controlled closing of the eyelids is analyzed to locate the eyes. The eye regions are registered and stored as a reference pattern for the subsequent algorithm to use when tracking the eye positions after head movements. The darkest part in the eye pattern marks the position of the pupils.

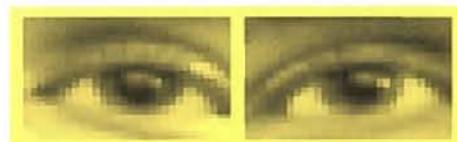
The performance of the head tracker is demonstrated in Fig. 5. Figs. 5(a) to (c) show some extreme conditions with strong variations in size and orientation of the head. Fig. 5(d) shows that the position of the head is correctly detected even when partially occluded, and Fig. 5(e) illustrates that the head is still correctly detected when additional persons enter the scene.

**Fig. 3.**  
A lenticular screen  
allows the separation  
of viewed 3D images  
created in a  
raster-scan mode.



**Fig. 5.**  
The video-based head tracker is able to cope with a range of difficult imaging conditions.

The use of user-specific skin colour in conjunction with appropriate scene analysis (separation of the foreground and background scenes) has been proven to be an appropriate technique for tracking the face in real time. In a working environment with near-constant lighting conditions, the face detection process can be terminated after both eyes have been found, and the information about the eye pattern is sufficient for tracking. Fig. 6 shows an example of the stored eye patterns.



**Fig. 6.**  
Eye patterns stored and used to find the eye positions in images.  
(The patterns have been enlarged for the purpose of printing.)

The tracking algorithm which was developed had to overcome difficulties such as high noise and poor camera resolution etc., since a special high-quality video camera is not used for head tracking in our system. A robust tracking result has been



**Fig. 7.**  
The eyes are detected and tracked in a sequence of video images.

achieved. The automatically detected eye regions are marked in the video image in Fig. 7. After localization of both pupils in an image, their positions in 3D space can be derived if the interocular distance of the user and the camera parameters are known.

The user's 3D eye positions must be known for three purposes: (1) for the autostereoscopic display to optically address the user's eyes; (2) to adapt the 3D perspectives of the graphic output to the user's view point; and (3) to aim the gaze camera at one of the user's eyes in order to get a zoomed image for precise gaze detection.

The accuracy of the head-tracking algorithm depends strongly on the resolution of the head camera and the tracking range (camera angle). The necessary tolerances are particularly small for the autostereoscopic display to correctly address the user's eyes. The accuracy of our system setup is about 2-3 mm in the lateral direction and about 1 cm in the frontal direction, which meets the requirements of the autostereoscopic display.

## 5. Gaze tracker

The gaze tracker measures the eye movements and estimates the user's current point of fixation [9]. The fixation point is defined as the intersection of the line of sight of one eye (gaze direction) with the surface of the object being viewed in

stereoscopic space. This information is used to interpret the user's intention for non-command interactions and to enable (fixation dependent) dynamic depth of focus.

We have opted for the cornea-reflex method because of its high precision and stability and because it is non-intrusive. The viewer's eye is illuminated with low-intensity infrared light. An array of infrared LEDs is mounted at a distance from the optical axis of the gaze camera. As a result, the pupil appears as a black circular region. The centre of the pupil and the reflection of the light from the cornea are found relatively rapidly due to a new algorithm that offers about 20 measurements per second on a standard SGI/O2 workstation without dedicated DSPs. There is a monotonic relationship between the vector pointing from the centre of the pupil to the centre of the light reflection (eye vector) and the user's gaze direction. After calibration, the gaze direction can be exactly derived from the eye vector.

Fig. 8 shows a prototype of the gaze camera used in our lab, which is based on the SONY EVI-D31 videoconference camera. The picture of the eye with marked positions of the pupil and the reflected light is illustrated in Fig. 9.



The gaze camera has to be tilted and panned to keep the eye being tracked at the centre of the image if there are head

movements. These movements cause changes of the eye vector and the calculated gaze direction, even when the user's absolute point of fixation remains unchanged. In order to ensure exact measurements for any head position, we have introduced a novel head-fixed transformation technique that compensates for measurement errors caused by head movements [10]. This way, the viewing direction can be estimated with a precision of about 0.4 degrees.

## Conclusions

We have designed and developed a powerful visual operating system running on a 3D multimedia workstation in combination with an autostereoscopic display. The system enables intuitive, non-command (visually controlled) interactions and hence opens for the user a totally new dimension in working with a computer. The first prototype has recently been demonstrated to the public. Our future work will focus on the optimization of the overall system performance and on extensions of the system's functionality. However, customized and application-specific low-cost versions (e.g. a down-scaled version for traditional 2D displays) are regarded as a means for speeding up the commercialization of the proposed concept.

## Acknowledgments

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**Fig. 8.**  
Gaze camera with infrared LEDs.

**Fig. 9.**  
Eye features used for gaze detection.

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R. SCHÄFER

## MPEG-4 – A NEW COMPRESSION STANDARD FOR INTERACTIVE APPLICATIONS AND SERVICES

### Abstract

The Moving Pictures Experts Group (MPEG), which produced the MPEG-1 and MPEG-2 video and audio compression standards, is at present developing the MPEG-4 standard. MPEG-4 targets interactive multimedia applications and will become a standard in early 1999. As well as an increased compression efficiency, MPEG-4 will also offer content-based functionality; i.e. the possibility of accessing and manipulating individual objects in the picture. Furthermore, MPEG-4 will offer possibilities for efficient video storage and for transmission over poor audio and video channels at bit rates between 5 kbit/s and 4 Mbit/s. This paper gives an overview of the state of the art of MPEG-4 development, concentrating especially on video content-based functionality, which is so important for interactive applications.

### 1. Introduction

Against the background of the rapid convergence of the telecommunications, computer and TV/film industries, and following on the successes of digital television, interactive graphic applications and the World Wide Web, the Moving Pictures Experts Group (MPEG) initiated the standardization phase of MPEG-4 in 1994. The target of this phase is to specify the algorithms and tools for the compression and flexible representation of audio-visual data, so as to fulfil the requirements of future interactive multimedia applications and services [1]. To achieve this, universal and efficient methods for coding audio-visual data, called audio-visual objects (AV objects or AVOs) are being developed. In particular, the future MPEG-4 standard should have the following features [2]:

- Universal accessibility and robustness in extremely error prone environments.
- New interactive functionalities, such as the possibility of user interaction when

presenting audio-visual material ("compositing").

- The hybrid coding of natural and synthetic AV objects (Synthetic Natural Hybrid Coding - SNHC).
- Increased compression efficiency compared to previous standardized methods.
- The possibility of "downloading" decoder tools.
- Simultaneous use of data from different sources.
- Support for communication between several participants.
- Integration of real-time applications and non-real-time (stored) applications.

To achieve these objectives, a set of coding tools for audio-visual objects supporting a great variety of functionalities is being developed. To complement these, a syntactic description of the coded objects is also under development.

Work in MPEG is distributed among the ten groups shown in Table 1 to finish The Committee Draft has been finished in November 1997 and it is planned to finalize the standard by the end of 1998. It should then become an International Standard in January 1999.

### 2. Requirements of the MPEG-4 standard

The so-called "requirements" underlie the entire MPEG-4 development process. These have been established for all aspects of the future MPEG-4 standards – i.e. for systems, audio, video and SNHC [3].

As an example, Table 2 gives the 16 systems requirements. These incidentally give an idea of the breadth in which systems aspects are covered. Compared with the first requirements document, most cuts have been made to the first point, flexibility – functionalities such as remote loading of composition scripts and the dynamic configuration of tools in the decoder, including their reconfiguration during the communication process, are no longer to be a part of the 1998 standard, but will be developed at a later stage. As regards system-level compatibility, backward compatibility to MPEG-1, MPEG-2 and H.324 is required, although at present it is not certain whether this can be achieved.

For each "profile" of MPEG-4 (see be-

1. Requirements	Requirements specification for the MPEG-4 (and MPEG-7) standard
2. DSM	Development of standards for interfaces between Digital Storage Media and servers or subscribers
3. Systems	Development of standards for multiplexing separately coded audio and moving picture data and associated information
4. Video	Development of standards for coding natural video
5. Audio	Development of standards for coding natural audio
6. SNHC	Synthetic Natural Hybrid Coding – development of standards for joint coding of natural and synthetic audio and video
7. Test	Subjective evaluation of the quality of coded audio and video material
8. Implementation	Evaluation of the complexity of coding methods and the establishment of limits of their realizability
9. Liaison	Relations with other committees
10. HoD	Head of Delegations – consulting committee for general questions

**Table 1:**  
Workgroups of the  
Moving Picture  
Experts Group.

low), an individual set of video, audio and systems requirements is set up, which this profile has to fulfil. MPEG-4 profiles are therefore defined in terms of their requirements.

- Flexibility
- Multiplexing of audio, video and other data
- Compositing of audio and video objects (AV objects)
- Remote loading of AV objects
- User interaction
- Interoperability between different media
- Compatibility
- Robustness with regard to transmission errors
- Object-based manipulation and editing at bit stream level
- Security and copy protection
- Multipoint operation
- Associated information for AV objects
- Delay times
- Configuration modes
- Prioritization of AV objects
- Dynamic resource management

**Table 2:**  
System  
requirements.

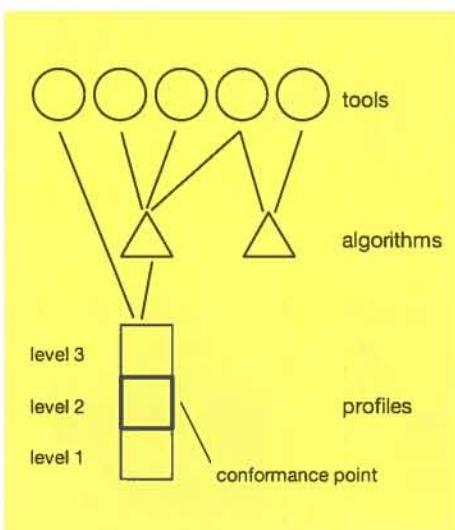
### 3. Building blocks of the MPEG-4 standard

The philosophy of the MPEG-4 standard is based on audio-visual objects (AV objects or AVOs). AV objects can be real or synthetically generated, and can in their turn consist of sub-objects. For instance, a person in a video scene may be a video object, while head and limbs could be sub-objects. The speech spoken by the person and the background noises can be audio objects.

“Tools” are defined for processing (e.g. compression). These tools can be applied using the MPEG-4 Syntactic Description Language (MSDL). Examples of tools include the DCT, motion compensation, and methods of synchronizing video and audio. Several tools can be combined to form “algorithms”, and an algorithm can also consist of several other algorithms (see Fig. 1). Examples of algorithms are hybrid DCT coding of video and Code Excited Linear Prediction (CELP) coding of audio.

A “profile” is a special set of tools and/or algorithms that fulfils a given set of requirements [4]. As with MPEG-2, there can be different levels within one profile (e.g. the maximum video resolution) – however, these are not yet completely defined. The specification of a profile at a particular level is called a

"conformance point". The specifications are thoroughly tested at the conformance points, and they then constitute the normative parts of the MPEG-4 standard. So far the "low delay profile" and the "main profile" for video, audio and systems have been defined for MPEG-4. There are also an "interactive profile" for video and a "speech profile" for audio.



### 3.1 Low delay profile

The low delay profile is intended mainly for real time communication and supervision applications. Level 1 and Level 2 of this profile have so far been defined at the system level. Level 1 supports only four AV objects, whereas Level 2 allows for 16 AVOs. For video a defined picture quality at least equal to that of H.263 is required at 24 kbit/s. At this data rate it must, for instance, be possible to recognize a face and its emotional expression, to recognize sign language, to read a text, and to lip-read. The video format QCIF/QSIF must be supported at Level 1. CIF/SIF should also be supported at Level 1, and CCIR 601 may be supported, whereas at Level 2 both CIF/SIF and CCIR 601 must be supported. For audio the sampling rate is 16 kHz, with the bandwidth of the (speech) signal between 50 and 7000 Hz. Up to 16 audio objects are supported. The sound quality is to be better than that of G.722, MPEG-1 or MPEG-2 under the same conditions, but the envisaged bit rates have not yet been stipulated.

### 3.2 Main profile

The main profile covers distribution services, and was therefore initially called the "broadcast profile". It supports up to 1024 objects and is to be compatible at the system level with MPEG-1 and MPEG-2 as well as with the relevant ITU standards for digital broadcast services. All video formats up to HDTV and all chrominance resolutions (4:2:0, 4:2:2, 4:4:4) are supported. Scanning can be done with or without line interlacing. At present 3 bitrate modes with limits of 1.5, 4 and 8 Mbit/s are proposed. However, on principle it should also be possible to use higher bit rates up to 100 Mbit/s for transparent quality, or for multiview or VR applications.

1.5 Mbit/s are intended for mobile multimedia services, 4 Mbit/s for TV (CCIR 601), and 8 Mbit/s for high quality applications or high resolutions.

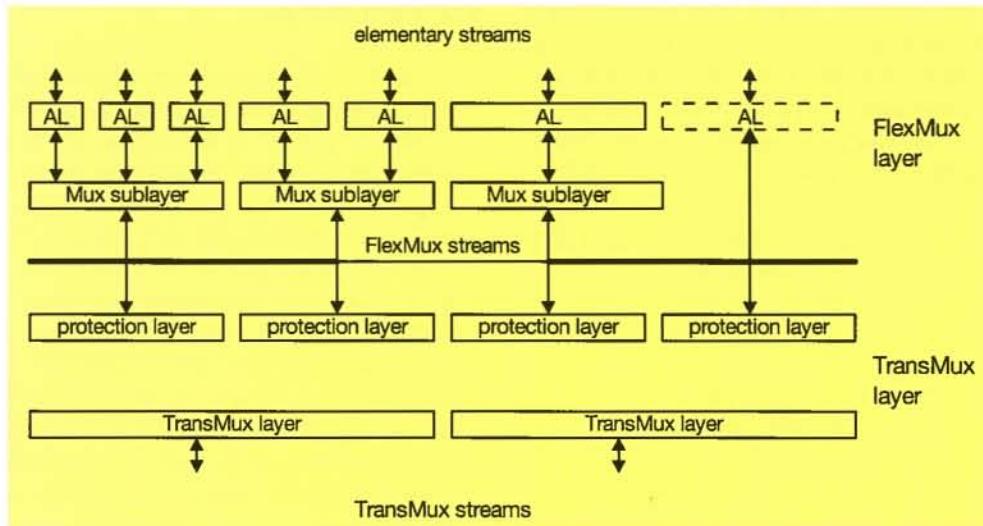
A picture compression efficiency at least twice that of all current standard methods (i.e. MPEG-1 and MPEG-2 [5]) is targeted. However, it is so far not certain that this can be achieved for arbitrary video material. Mono, stereo and multi-channel audio are supported, with planned bit rates up to 150 kbit/s per channel.

## 4. The system level of MPEG-4

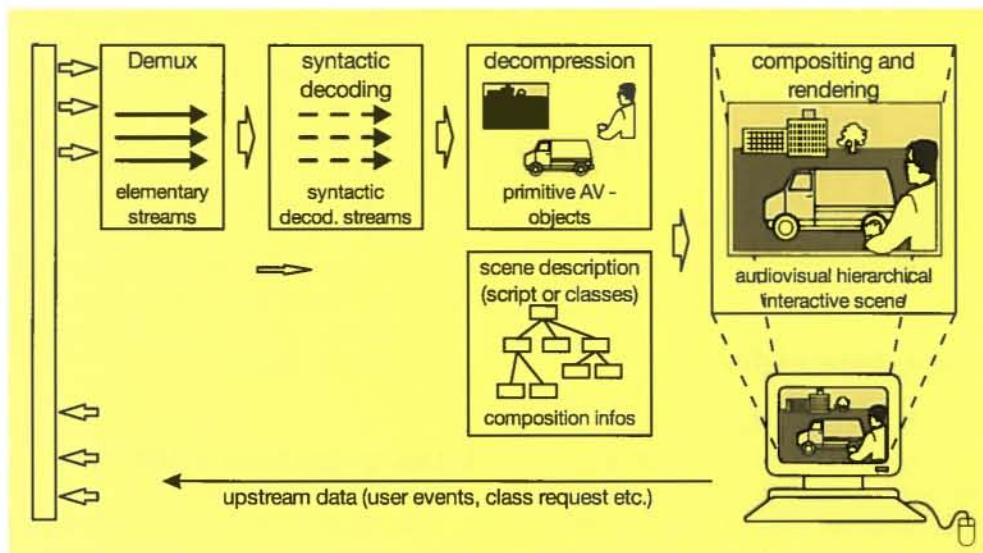
The systems part of the MPEG-4 standard describes a system for communication of audio-visual information. This means that on the transmission side such information is composed, compressed and multiplexed into one or several bitstreams, and on the receiver side these streams are demultiplexed, decompressed, assembled in a compositor and finally presented.

At the receiver it is possible for the user to influence the presentation interactively. For this purpose mechanisms are described which allow for the integration of natural and synthetic objects and which make it possible to multiplex and synchronize the individual AV objects. For this purpose a two layer multiplex system was introduced, as shown in Figure 2 [6]. An elementary stream (ES) is produced for each AV object. Elementary streams with the same service quality requirements (QoS) are combined in the FlexMux Layer to form FlexMux Streams. This layer also pro-

**Fig. 1.**  
Tools, algorithms,  
profiles, levels and  
conformance point.



**Fig. 2.**  
The two layer system  
level of MPEG-4.



**Fig. 3.**  
Processing steps in an  
MPEG-4 terminal.

vides mechanisms for clock recovery and for synchronization of the different AVOs.

The TransMux Layer is not specified in MPEG-4, but existing transport protocols, such as IP (UDP), ATM (AAL5) or MPEG-2 (TS), can be used. The DSM-CC (Digital Storage Media – Command and Control) Multimedia Integration Framework (DMIF) is being developed for connecting MPEG-4 terminals with each other and for connecting with or controlling storage media. DMIF offers a number of tools for operating MPEG-4 terminals over heterogeneous networks, including tools for navigation, for accessing tables of contents and data, for downloading applications, and for connecting with other terminals.

The main components of an MPEG-4 terminal are shown in Figure 3. Transport streams from the network are fed to suit-

able FlexMux Demultiplexers, which generate the elementary streams. These are the inputs to appropriate decoders, which reconstruct the AV objects. At the same time scene scripts are generated, which can be interactively changed by the user. Finally the scene on the display (video) or in the room (audio) is assembled with a compositor.

## 5. MPEG-4 audio

MPEG-4 will offer methods for the compression of natural (speech, sound) and synthetically generated audio signals. For bit rates of 2 to 6 kbit/s parametric coding schemes are used. For medium data rates ranging from 6 to 24 kbit/s, CELP technology will be used, and for higher data rates

(above 16 kbit/s) spatial frequency methods, such as vector quantization or AAC codes, will be used. Details of these methods can be obtained from the literature [7, 8].

## 6. Synthetic Natural Hybrid Coding

SNHC functionalities which the future MPEG-4 standard will support are for the present limited to:

- Animation of faces
- Integration of text and graphic overlays
- Text-to-speech (TTS) decoding
- Sound script based audio synthesis  
(e.g. MIDI based)
- Audio effects

In addition, at the system level there will be a "Binary Format for Scenes" (BIFS), which is based on VRML 2.0. BIFS is for the description of 2D or 3D scenes, and at first will consist of only a subset of VRML 2.0 which is relevant to MPEG-4, and which will possibly be modified or extended [9].

A set of animation parameters is defined for the animation of faces. This set is independent of the face models used, which are not standardized. Face definition parameters are specified to calibrate the models, such as "3D Feature Points", 3D nets, texture maps and personal features. A zero-tree based wavelet coding method [10], which allows for scalability up to 32 steps, is planned to compress the texture maps. Since block artefacts are avoided, this type of coding, which can also be used for the compression of individual images, offers a better quality than DCT, especially when bit rates are low.

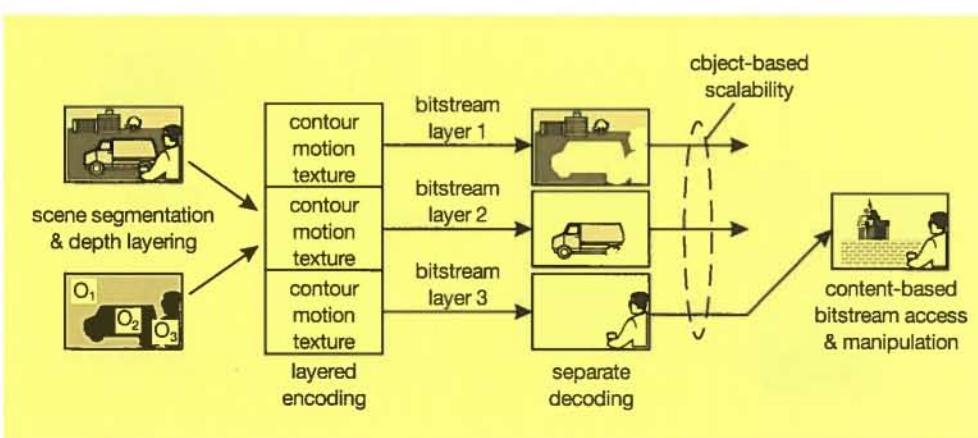
## 7. MPEG-4 video

MPEG-4 will offer not only efficient video compression, but also content-based functionalities not included in MPEG-1 or MPEG-2. The basic concept of these functionalities is illustrated in Figure 4. The scene consists of a background and several foreground objects, which are encoded in such a way that the receiver can decode the individual objects separately and manipulate them at presentation time. For example, they can be mixed with objects from a second scene, as also shown in Figure 4.

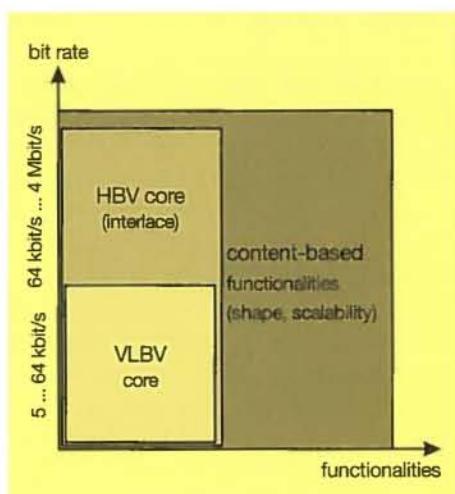
The MPEG-4 video algorithms will probably support all functionalities already in MPEG-1 and MPEG-2, in particular the possibility of efficiently compressing rectangular images.

A basic division into bit rates and functionalities, as offered by the current verification model of MPEG-4, is shown in Figure 5. At the lower end there is a VLBV (Very Low Bitrate Video) basic algorithm, which offers tools for applications between 5 and 64 kbit/s. This supports video-formats up to CIF and frame rates up to 15 Hz. The main applications for this basic algorithm are low delay real time communication, robust transmission over poor (mobile) channels and universal access to databases with fast forward and backward search operations.

The same functionalities are offered by the Higher Bitrate Video Core (HBV Core), which supports spatial and temporal resolutions up to CCIR 601, and which also provides additional tools for the coding of interlaced video. For the coding of rectangular images, tools similar to those of MPEG-1, MPEG-2 and H.263 are used



**Fig. 4.**  
**Basic concept of content-based image coding.**

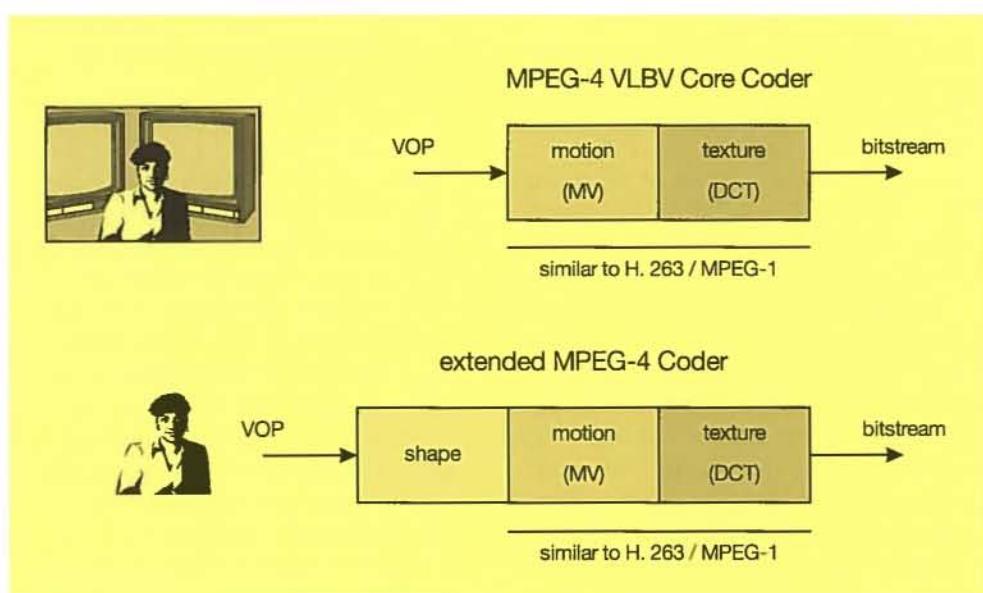


**Fig. 5.**  
Structure of the  
MPEG-4 video  
standard.

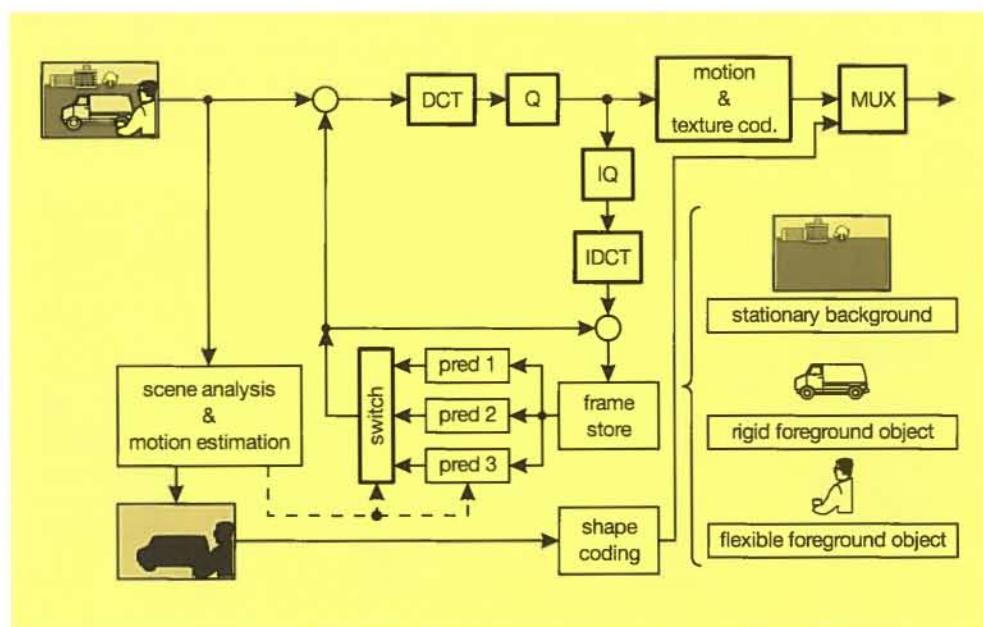
(upper part of Figure 6). Since it is necessary to code objects of arbitrary form for the content-based functionalities, coding tools such as Padding [11] and the Shape Adaptive DCT [12] are provided in the Extended Core (lower part of Figure 6).

Figure 7 shows a detailed block diagram of the current MPEG-4 video verification model. This is a conventional hybrid DCT structure, but augmented by further blocks. There is a block for contour coding and there are also a number of prediction modes supported:

- Conventional motion compensated and block-based ( $8 \times 8$  and  $16 \times 16$  blocks) prediction.



**Fig. 6.**  
VLBV core and  
extended core coder.



**Fig. 7.**  
Block diagram of the  
MPEG-4 video  
encoder.

- Global motion compensation using affine motion parameters.
- Static and dynamic sprite prediction for the background.

Although increased compression efficiency is not the main target of the MPEG-4 standardization, MPEG-4 will offer efficient coding at bit rates between 5 kbit/s and 4 Mbit/s or higher, so that a significantly larger range than with MPEG-1 and MPEG-2 will be covered. At low data rates between 5 kbit/s and 100 kbit/s the quality will be better than that of H.263, while at high data rates between 1 and 4 Mbit/s a quality better than that of MPEG-2 is targeted. This improved compression efficiency is mainly achieved by the following measures:

- Improved slice layer and macroblock layer syntax.
- Switched 8x8 and 16x16 motion compensation, which allows for more precise prediction.
- Block-overlapping motion compensation, which reduces block artefacts at low data rates.
- Global motion compensation for scenes with global camera motion.
- Postfiltering to avoid ringing and block artefacts.

In addition MPEG-4 supports so-called sprite prediction. If the background does not change for the entire coded scene, it is sufficient to transmit the background once at the beginning of the scene, and subsequently only the foreground objects need to be coded (static sprites). If the background changes slowly – for example, if new parts are added to the background, which need to be coded – one speaks of dynamic sprites. For some scenes these methods can achieve compression gains as high as 10 compared with MPEG-2.

Other techniques that are still being investigated within the framework of the core experiments, but which are not yet part of the verification model, concern:

- The 1/4 pel compensation, which provides a higher quality mainly at high data rates and with certain image types, but which requires considerably higher decoder complexity [15].
- The quadtree-based motion compensation method, which compensates for the motion of larger segments. This method

has advantages especially at low data rates, but is very costly to implement [16].

• Texture coding using matching pursuits, a method also suitable for low data rates. Instead of coding with a DCT, temporal prediction errors are decomposed into a set of separable Gabor functions, which are stored in a type of dictionary. This method therefore resembles vector quantization [17].

## 8. Summary

This article gives an overview of the state-of-the-art of MPEG-4 standardization in mid 1997. This standard supports algorithms and tools for the coding of natural and synthetic video, audio and speech as well as for the flexible representation of audio-visual data on terminals. The main application area of MPEG-4 will be interactive multimedia communication, for which a number of content-based functionalities are provided.

For video compression a basic algorithm based on a hybrid DCT with motion compensation, similar to MPEG-1 and MPEG-2, is provided. Furthermore, tools are provided which enable objects of arbitrary shape to be coded, as well as other tools for the efficient prediction of global motions as well as static and dynamic background scenes (sprites).

MPEG-4 will support video compression at data rates between 5 kbit/s and 4 Mbit/s, and so covers a larger application field than MPEG-1 or MPEG-2. While at low data rates it will be possible to obtain a better picture quality than with H.263, it is unlikely that it will be possible to code general TV material between 1 and 2 Mbit/s without loss of quality. It is therefore not expected that MPEG-4 will supersede the MPEG-2 standard which is now being introduced for digital TV. Instead, MPEG-4 will find its main applications in the mobile area (DAB/DMB, DECT, GSM, UMTS) and the Internet.

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## FORMAT CONVERSION FOR MULTIMEDIA TERMINALS

### Abstract

Format conversion of standard interlaced television signals is necessary for most multimedia terminal types. To render video signals with high quality on a PC or workstation monitor, a progressive display format is required, with a frame frequency equal to the frequency of the monitor. For flicker-free TV using advanced display types, either a conversion to progressive format or to a higher-frequency interlaced format is necessary.

High-quality format conversion must be based on motion-compensated frame interpolation techniques. HHI has developed low-complexity motion estimation and interpolation algorithms for this purpose. These methods are suitable for one-chip realization of realtime format conversion from CCIR 601 interlaced video input into either progressive or interlaced output signals, supporting a wide range of different frame rates.

For future interactive multimedia applications, it will be necessary to perform format conversion based on video objects instead of complete image frames. For this purpose, a scene segmentation must be performed, which can be used to enhance the quality of motion estimation and image interpolation.

### 1. Introduction

In conventional television, the video signal is recorded, transmitted and displayed using an interlaced scanning scheme, where the even and odd lines of an image frame are arranged in two successive fields (Fig. 1). This method is a compromise between bandwidth requirements and image quality, and is still the most common technique for video production, which means that literally all video signals come in this format. The field frequency is either 50 Hz (e.g. in Europe) or 60 Hz (e.g. in US/Japan). When the signal is displayed on a TV screen, the same temporal delay between even- and odd-line fields is ob-

served. Some well-known artifacts like line flicker and Moire patterns are only caused by the use of interlaced acquisition and display.

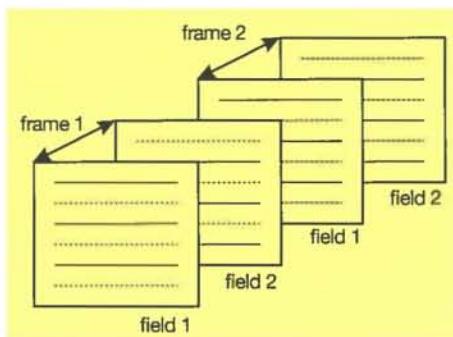


Fig. 1.  
Video scanning in an interlaced raster.

In a progressive video format, all lines of a frame are captured and displayed at the same time. There are good reasons to migrate from interlaced to progressive video, especially with the advent of digital television, where data compression and bandwidth reduction can be done by more sophisticated techniques than just omitting parts of the signal:

- Progressive displays are more comfortable for the observer ;
- Modern displays, like graphics-adapter driven computer monitors, flat-screen panel or projection displays, are progressive anyway;
- Graphics, that are now often mixed with video signals, are produced on computers with a progressive scan raster;
- Movie material has always been captured as a sequence of simultaneous full-image frames by film cameras;
- Interactive manipulation and mixing of video signals can be done with less artifacts;
- Extraction of still images from a video sequence is possible even when the scene is moving.

Format conversion is required in the following applications:

- For presentation on multimedia terminals (PC or workstation monitors), it is necessary to convert video signals to progressive format with frame frequency equal to the repetition frequency of the graphics adapter;
- For presentation on high-end TV sets, which also include wall-mounted flat-panel displays, a higher frequency than in conventional TV equipment is used. Again,

it depends on the type of the display whether format conversion to progressive or higher-rate interlaced signal is necessary;

- For standards independence (display/record of 50 Hz or 60 Hz video), any one of these formats must be convertible into the other;
- In multimedia, simultaneous presentation and also mixing of animated graphics and natural video is usual. In multimedia production, the complete presentation may consist of 50 Hz and 60 Hz video and graphics components. Before display, all signals must be converted to the same format.

It can be concluded that the display characteristics have most impact on the required format. On the other hand, unlike TV, where displays were at least nationally standardized, multimedia data will be presented on various displays with different resolution, repetition and raster characteristics. Hence, for representation of multimedia data, it is most convenient to retain the original format (the format in which data were captured) as long as possible, and perform conversion immediately before display is performed. This requires the realization of high-quality real-time format conversion devices. These should preferably be one-chip implementations in order to be integrated with low cost onto the graphics adapter board or into the TV chassis.

For the purpose of video signal format conversion, it is necessary to interpolate unknown samples from the available video signals:

- Deinterlacing leaves the repetition frequency as it is, and produces the missing lines (shown as dotted lines in Fig. 1) for a conversion to a progressive video signal (50 Hz or 60 Hz). In this case, it is possible to use samples which were taken by a camera exactly at the same time as the output line to be produced. However, even in this case it is useful to acquire information from temporally-neighborhood fields, because high vertical frequencies are not fully represented in the actual field. For best results, a motion-compensated deinterlacing filter should be applied, which takes into account the motion shift from one field towards another.

- In the case of frame or field interpolation, which is necessary when an upconversion of frame or field rate has to be performed, all the interpolated information has to be acquired from temporally-preceding or -succeeding fields. This cannot be performed without motion compensation, because a simple field or frame repetition is undesirable to avoid jerky movements. An example of interpolation with each two additional images between originally-captured image frames is shown in Fig. 2.

A motion-compensated format conversion system processes the interpolated information along the motion trajectory, which can be found by estimation of the displacement shift between the available fields. Hence, the two main components of such a system must fulfill the following requirements:

- The motion estimator must produce a highly-reliable dense motion vector field;

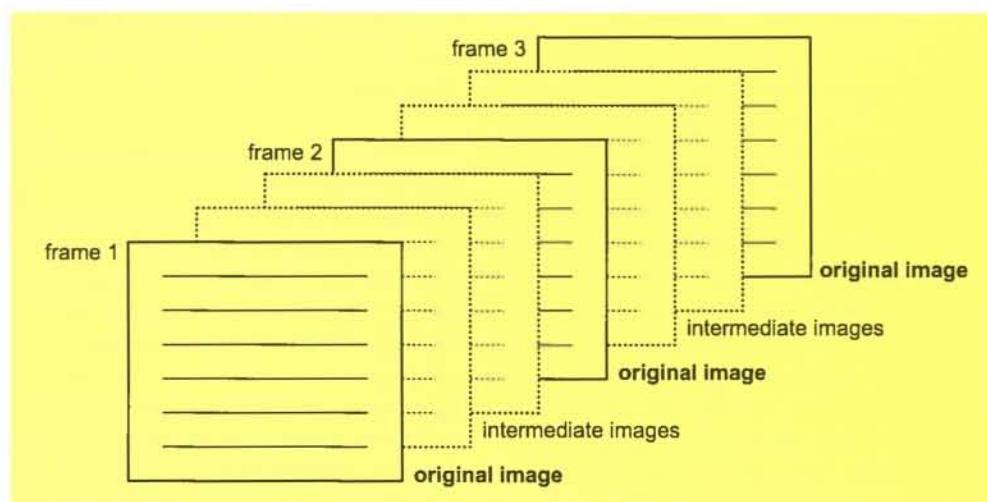


Fig. 2.  
Video presentation  
after format  
conversion.

however, no high-complexity algorithm can be used, because format conversion has to be performed in real time within the multimedia terminal.

- The interpolator should be able to tolerate occasional wrong results of the motion estimator. This can be done by application of error-tolerant filters, or by the introduction of a special fallback mode, which can be switched according to a reliability check.
- Because video can also contain material from a scanned movie film, where the temporal position within the video signal does not coincide with the real capture time, it is necessary to include a special movie mode detection.

For interactive applications, where the user can change the contents of the scene, and for scene mixing/composition from several video objects or graphics components, it is necessary to perform the format conversion separately for each video object. This can be accomplished either by using preliminary-available information, or by combination of the above-mentioned techniques with a segmentation procedure.

The organization of this contribution is as follows. Section 2 describes a new low-complexity motion estimation scheme, called hybrid recursive motion estimation, which was developed at HHI for the purpose of motion-compensated format conversion. Section 3 is about the error-tolerant techniques for deinterlacing and intermediate image interpolation, which are based on median filters with fallback switching capability. Section 4 is dedicated to the aspect of object-based format conversion. Section 5 shows some results and examples, and section 6 concludes.

## 2. Hybrid recursive motion estimation

Historically, there are two main approaches in motion estimation, namely block matching schemes [1] and schemes based on the optical flow principle [2]. In block matching, a sparse motion vector field is generated on a block-by-block basis. To select the best vector, the minimum of a cost function (e.g. the absolute-valued displaced block difference) is searched us-

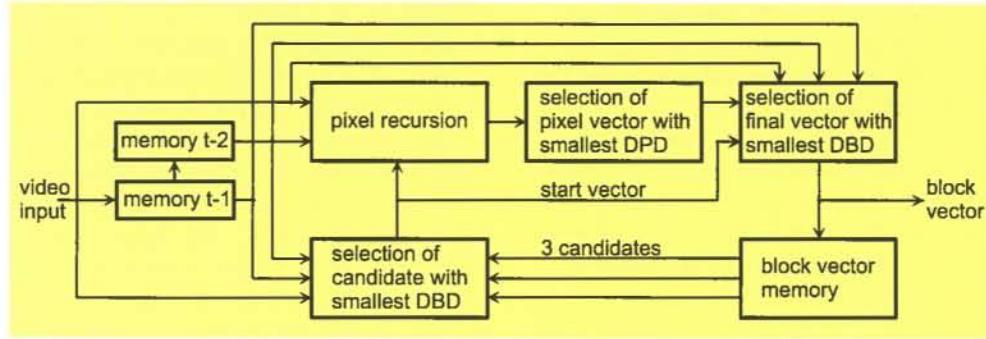
ing a set of candidate displacement vectors. The optical-flow principle is based on the analysis of spatial and temporal gradients in the video signal, which are used to solve a minimization problem, delivering the optimum motion vectors. Optical-flow based schemes are mostly applied on a pixel-by-pixel basis, and hence directly produce dense motion vector fields. For both classes of motion estimators, very efficient implementations exist, which are based on recursive techniques, exploiting the high coherence within the motion vector field. Block-recursive matching [3] uses block motion vectors already calculated (e.g. in the previous frame or at surrounding positions in the present frame) as candidates for the current search, allowing then some improvement by testing one or more additional vector(s). Pixel-recursive gradient-based motion estimation [4] takes the value at an adjacent pixel position as a starting point, and calculates an update term (possibly in an iterative procedure) to end up with the final motion vector.

For format conversion applications, the motion vector field produced by the estimator must obey the following constraints:

- It should be homogeneous, which means that abrupt changes should be avoided, unless an object border is present;
- It must be dense (pixel-wise defined).

Homogeneity of the field is a by-product of recursive schemes, if the recursion is based on immediate neighbors. Block matching, however, produces a sparse motion field (unless a strong overlap of blocks is used), and requires some minimum block size. On the other hand, block matching estimates are usually stable and reliable. The optical-flow field is dense by nature, which means that individual motion vectors are defined at each pixel position. Hence, optical-flow schemes have the potential to capture changes in the motion vector field, as they occur at object edges, with pixel accuracy; however, these schemes are quite sensitive to noise in many cases.

The hybrid recursive motion estimation developed at HHI is a combination of both estimator types. The goal is to retain the advantages of pixel-recursive and block-recursive approaches in order to obtain a low-cost estimator with high reliability and fast convergence of the recursive estima-



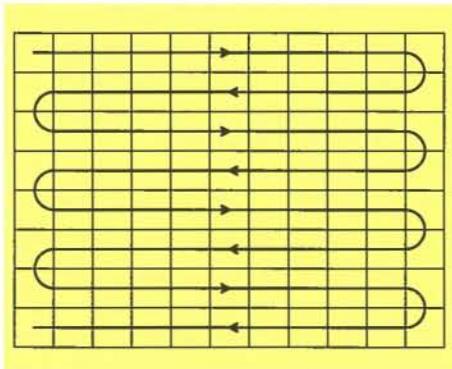
**Fig. 3.**  
Block diagram of the complete system.

tion process at object edges. As in block matching, a sparse block-based motion vector field is estimated, which is interpolated afterwards to calculate the dense field as required for format conversion filtering. The pixel-recursive technique is used to find an additional candidate vector for the recursive block matching, which helps to derive the correct motion shift at object edges, where discontinuities in the motion vector field are present. The main operation can be divided into four stages:

1. Determine an optimum start vector by block matching, comparing 3 candidate vectors from previously-processed blocks.
2. Use this start vector for the pixel recursion within the area of the block.
3. Select an additional update vector by performing a number of pixel recursions
4. Determine the best motion vector by block matching, comparing the start vector and the update vector.

Fig. 3 shows the block diagram of the complete system. The finally-selected vector is written into the vector memory, and then used as possible candidate for upcoming blocks.

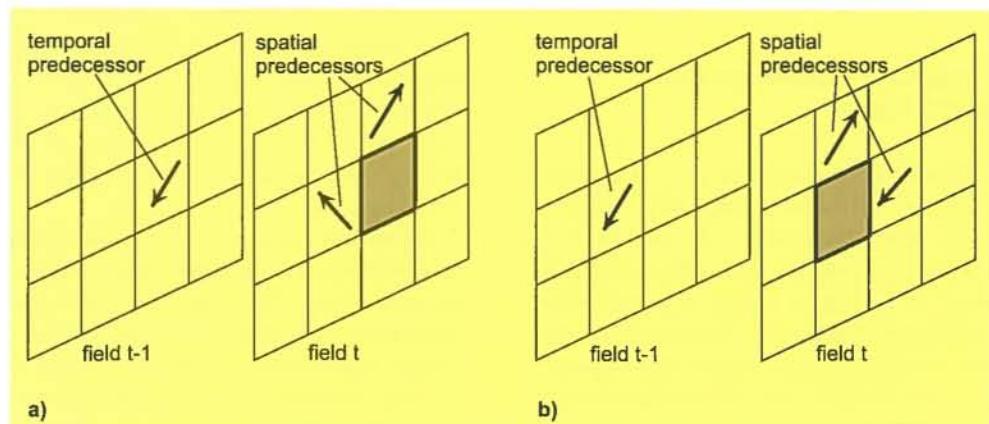
During block recursion, the blocks are processed in a meander-like scan, where



the recursion within the block slices alternates from left to right and from right to left (see Fig. 4). For estimation, three candidates are tested. These are (see Fig. 5):

1. A temporal predecessor, which comes from a position displaced by the motion shift estimated in the previous frame;
2. A vertical predecessor, which is a vector from the block immediately above;
3. A horizontal predecessor, which is in the left-to-right scan a left-neighbored vector, and in the right-to-left scan a right-neighbored vector.

As a criterion, we use the minimum absolute value of Displaced Block Difference (DBD) to select the candidate. If motion



**Fig. 5.**  
Vector candidates in  
a) left-to-right scan  
b) right-to-left scan.

estimation is applied on a field basis, as it is the usual case with interlaced video input, we use a combined DBD criterion, which takes into account the DBDs between the actual field and two predecessors. This measure helps to avoid wrong estimates caused by interlaced sampling, because the best correspondence for the actual field will be found either in a temporal-preceding field with same, or with opposite parity, depending on the amount of vertical motion.

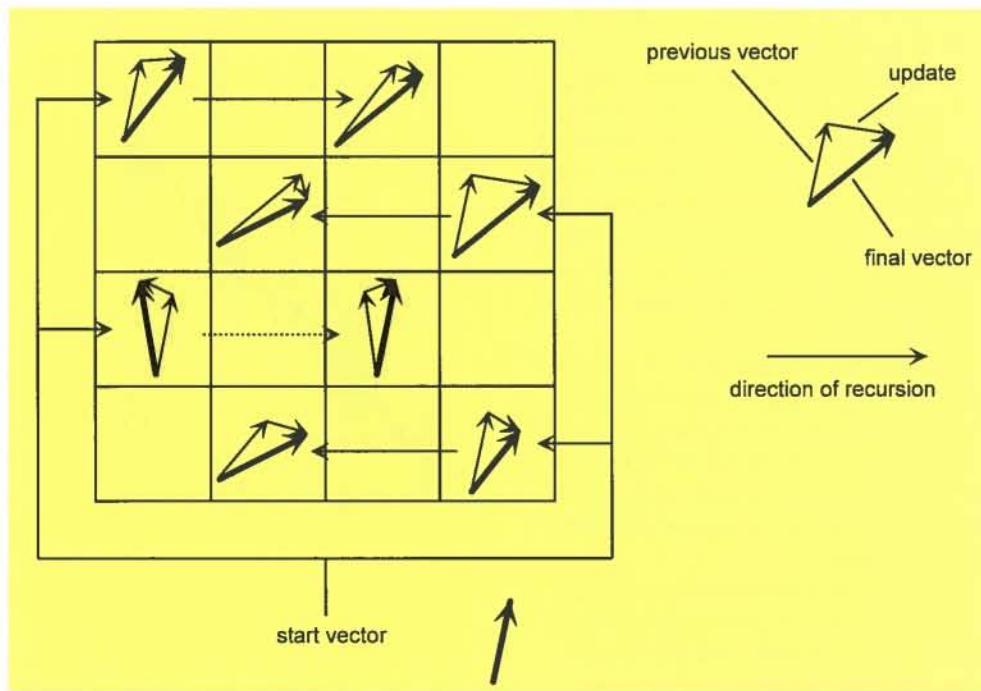
Among the vectors found by updates during pixel recursion, only one is selected, which within the block exhibits the smallest Displaced Pixel Difference (DPD) at its own position. Only for this one vector, the DBD is calculated over the whole block again. If that DBD is smaller than the one produced with the start vector, the vector selected from the pixel recursion update process will be the final vector for the whole block; otherwise, the start vector is retained. An example with block size  $4 \times 4$ , and pixel recursion updates performed at 8 positions, is shown in Fig. 6. A special low-complexity procedure for pixel-recursion update calculation was developed in this context, which makes the scheme a good candidate for low-complexity hardware realization.

The interpolation system described in the next section employs two fallback modes, which are global fallback and local

fallback. Basically, the action performed during interpolation is the same in both modes (repetition of the nearest 50/60 Hz frame instead of frame interpolation); however, the criteria for switching these modes are different. A simple fallback analysis is done already at the time of motion estimation, wherein the criterion used is the DBD obtained for the particular block with the finally-selected vector, which is compared to a specified threshold value.

Due to the recursive structure of the algorithm, scene changes need special attention, because false motion estimations may propagate temporally through several images of a sequence. If a scene change is detected, zero vectors are used instead of temporal predecessor candidates. Scene change and movie mode detection are based on the analysis of the Undisplaced Field Difference (UFD) between two adjacent fields.

The hybrid motion estimator generates a sparse block motion vector field with a grid spacing of  $M \times N$  pixels horizontally and vertically. In order to produce a dense (pixel-wise defined) vector field, as required by the motion-compensated up-conversion filter, a median-based erosion technique [5] is used. Herein, a value of the dense field is generated component-wise from the three nearest block vectors. The virtual position of the vectors is as-



**Fig. 6.**  
Pixel recursion within one block.

sumed to be at the center of the block, which is no true pixel position. Each step of median erosion generates a field with doubled number of vectors horizontally and vertically. In the case of  $4 \times 4$  blocks, the dense field is available after two steps. The first step produces a vector field with grid spacing of  $2 \times 2$  pixels as an intermediate result (Fig. 7a), which is then used to generate the pixel vectors (Fig. 7b). In Fig. 7, the positions marked with "\*" are from the lower-resolution input raster, while the pixels marked with "o" are the result of the erosion process. Three thin lines mark the values that are used for median calculation at a specific pixel position. Only at the last step, the generated values coincide with true pixel positions.

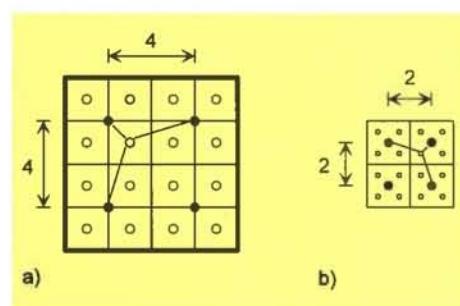


Fig. 7.

Values used in median interpolation for generation of dense vector field.

### 3. Error-tolerant upconversion filters

Upconversion performs generation of a frame or field sequence with higher frame or field repetition rate from an interlaced or progressive input sequence. The unknown data to be generated are most likely related to known data by the estimated motion trajectory. Hence, one of the most important measures in upconversion is the application of motion compensated filtering techniques. With respect to unknown data generation, two main tasks have to be fulfilled:

- Generation of unknown lines to convert an interlaced sequence to progressive format (deinterlacing). In this case, only the missing lines of a field have to be generated, which is the more simple case, because interpolation has spatial support from the same time instant.
- Generation of unknown frames or fields to produce a sequence with changed repetition rate (intermediate image interpolation). In this case, unknown data have to

be generated at time instants where no spatial support (no really-acquired image information) is available.

In many cases, a format-converted sequence consists of frames or fields of both types, and a periodicity can be observed where some of the frames or fields are deinterlaced ones, and others are interpolated ones. This is shown in Fig. 8 for the cases of motion-compensated 75 Hz and 100 Hz upconversion from a 50 Hz input signal. Motion can only be estimated at the temporal positions of the original 50 Hz sequence; in order to interpolate intermediate images, it is necessary to scale the motion shift according to the respective temporal position. In the 75 Hz case, each third frame can be generated by deinterlacing, while the remaining ones must be produced by intermediate image interpolation. With 100 Hz, the method of output frame generation alternates between deinterlacing and intermediate interpolation. With respect to motion compensated filtering, the intermediate interpolation is the more critical case, because wrong motion estimation effects irreversibly wrong placement of certain parts in the intermediate image. Hence, an analysis of the reliability of motion estimation is of extreme importance.

It is possible to apply motion-compensated interpolation concepts in combination with different filter types. The most

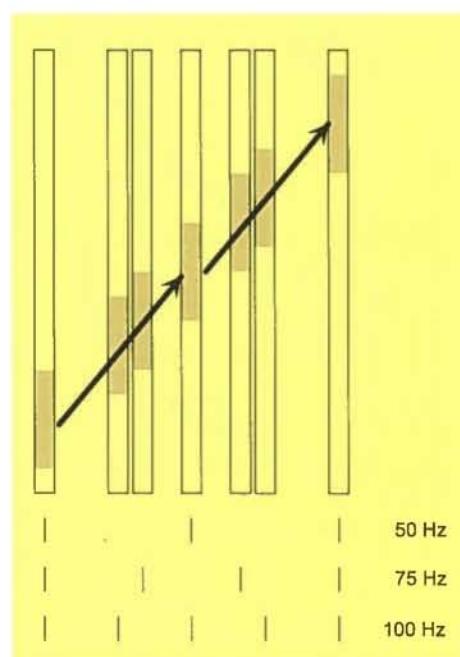


Fig. 8.

Time positions of frames in 50, 75 and 100 Hz sequences.

popular concepts are linear filters and non-linear filters, especially median filters among the latter class. Median filters have the desirable property, that the sharpness of the interpolated frames or fields is only gradually affected, because the value obtained is always an original value selected among different input values. The concepts that were investigated here for intermediate image interpolation are mostly based on median filters, but in addition some linear filter elements have been incorporated.

Our interpolation concept can be used to interpolate fields or frames, virtually at

the deinterlaced image from the original nearest to  $t'$  (either  $t-2$  or  $t-1$ ) is output;  
 • In all other cases, the motion-compensated interpolation image is output, unless the motion estimation within a specific area was classified as unreliable by the local fallback decision; in the latter case, again the deinterlaced version from the original nearest to  $t'$  is output in that area;  
 • To avoid artifacts at the transitions between local fallback- and non-fallback areas, a blending filter is applied perpendicular to the transition positions, which coincide with block borders of the motion estimation.

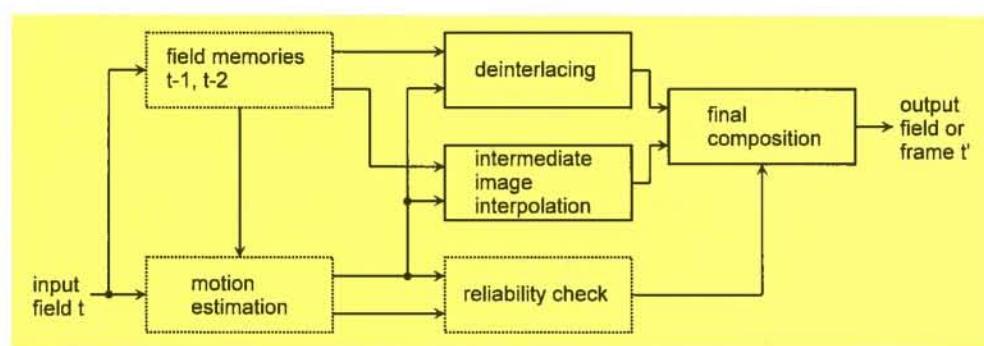


Fig. 9.  
Structure of the  
error-tolerant system  
for upconversion.

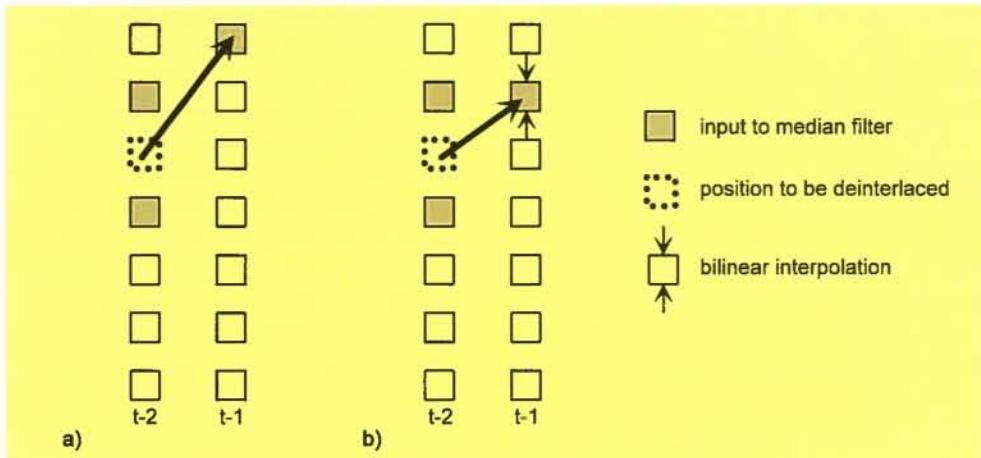
any frame rate, with the upper limit depending on the processing capability of the available hardware. The block diagram of the whole format conversion system is shown in Fig. 9. Herein, the dotted blocks indicate those elements that were already described in section 2. Interpolation is performed with one field delay after motion estimation. While motion estimation is performed between fields  $t$ ,  $t-1$  and  $t-2$ , the conversion filter performs generation of an intermediate image  $t'$  anywhere between fields  $t-2$  and  $t-1$ , or deinterlaces one of these fields, using the motion vector estimated one time period earlier. For this purpose, it is necessary to scale the motion vectors, depending on the relative position of  $t'$  between both original fields. The vector memory necessary anyway for recursive block matching also can be used to realize the one-field delay between estimation and up-conversion. The last block of the figure, which performs final composition of the format-converted output, has the following functions:

- If  $t'$  coincides with one of  $t-2$  or  $t-1$ , or if it is very near to one of these, it is output as deinterlaced image;
- If the global fallback mode is switched,

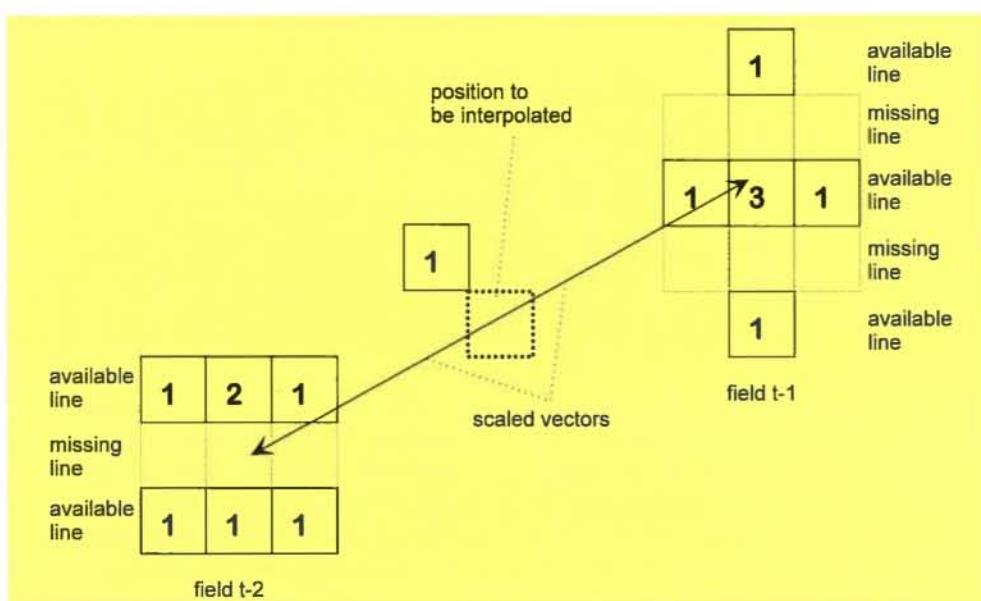
Deinterlacing is based on a 3-tap median filter. Two of the values are from the same field, the pixels above and below the one which should be generated, while the third is taken either from the subsequent field (if deinterlacing is performed in field  $t-2$ , as shown in Fig. 10) or from the preceding field (if deinterlacing is performed in field  $t-1$ ). The origin of this third value takes into account the motion shift. It is either an existing value, if the motion shift between the two fields is by an even number of pixels (Fig. 10a), or a value linearly-interpolated from the two values above and below, if the motion shift is by an odd number of pixels (Fig. 10b).

For intermediate image interpolation, a weighted median filter is applied, which is fed by values from fields  $t-2$  and  $t-1$ . However, the geometry of this filter highly depends on the configuration, whether the scaled vectors point to available or missing lines within the fields  $t-2$  and  $t-1$ . One possible case is shown in Fig. 11, which contains both filter geometries with the appropriate weight factors. Since the median calculation requires an odd number of input values, one already-calculated value from the image  $t'$ , which is posi-

**Fig. 10.**  
Deinterlacing a with  
motion shift by even  
number b with  
motion shift by odd  
number of pixels.



**Fig. 11.**  
Median filter for  
intermediate image  
interpolation configura-  
tion, where the vec-  
tor points to an avail-  
able line in field t-1,  
and to a not-available  
line in field t-2.



tioned top-left from the pixel to be interpolated, is used additionally.

In movie mode, pairs of subsequent fields that are input to the interpolator either do not have a temporal shift (if they are from the same frame), or exhibit the full frame-motion shift. The original input was a progressive sequence with 24 Hz frame rate, but the even and odd lines of the frames are separated into two fields. This fact has to be taken into regard during motion estimation, because fields from the same time frame will show no difference caused by motion. Motion is then estimated by the hybrid recursive estimator only from an even field towards the next even field, or from an odd field towards the next odd field, such that always the frame motion is estimated. Deinterlacing is performed as simple combination of two fields originating from the same time

frame, and intermediate image interpolation is always applied between two fields deriving from different time frames.

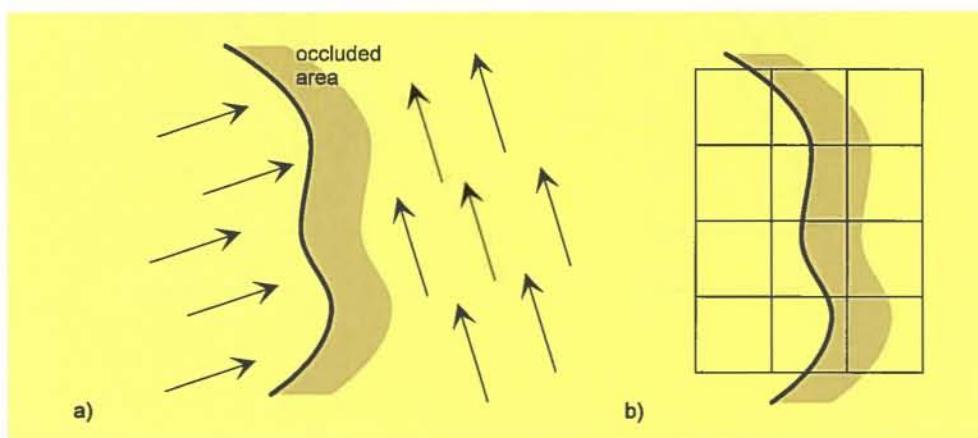
#### 4. Object-based format conversion

Algorithms for motion-compensated format conversion described so far are based on block motion vector estimation, even though the motion vector field is made "dense" by median erosion. The disadvantage is an inaccuracy of motion estimation near object boundaries. At these positions, we can expect discontinuities in the motion vector field, and an occluded area (Fig. 12a), which will only coincide with block boundaries (Fig. 12b). Furthermore, the block-recursive matching algorithm, though its convergence is speeded up by the pixel recursion in the

hybrid estimator, is not guaranteed to find the correct vector in only one step at an object boundary. One of the greatest problems occurring with moving objects is the occlusion of background parts, which has as a consequence that certain areas will not exist in one of the two images that are compared during motion estimation. Within these areas (indicated as shaded regions in Fig. 12), motion estimation is extremely unreliable with both block-matching and optical-flow approaches.

such that object-based conversion to the display format can be performed separately for each object, optionally each with different input format. Finally, all objects are composed together, taking into account the mutual occlusion.

- If object-based conversion shall be applied to full-screen images, which are not separated into objects, a real time segmentation of the scene is necessary. With today technology, only low-complexity segmentation [6] or edge-detection algorithms



**Fig. 12.**  
a) Discontinuity of the motion vector field at an object border.  
b) Missing coincidence between block and object borders.

One of the consequences of inaccurate motion estimation are possible artifacts during interpolation. Though these artifacts are somewhat compensated by introduction of the local fallback mode, this leads to less sharpness in the generated images, and in some cases parts of the uncovered background move with the foreground object. It is not straightforward to define the correct motion within covered or uncovered background areas, as it is shown in Fig. 13a. In the ideal case, the motion of adjacent background areas can be extended into the covered/uncovered area, and instead of interpolation from both images, only extrapolation either from the preceding (for the covered case) or from the subsequent frame (for the uncovered case) has to be performed (see Fig. 13b).

The knowledge about object borders can be acquired by different ways, depending on the target application of object-based format conversion:

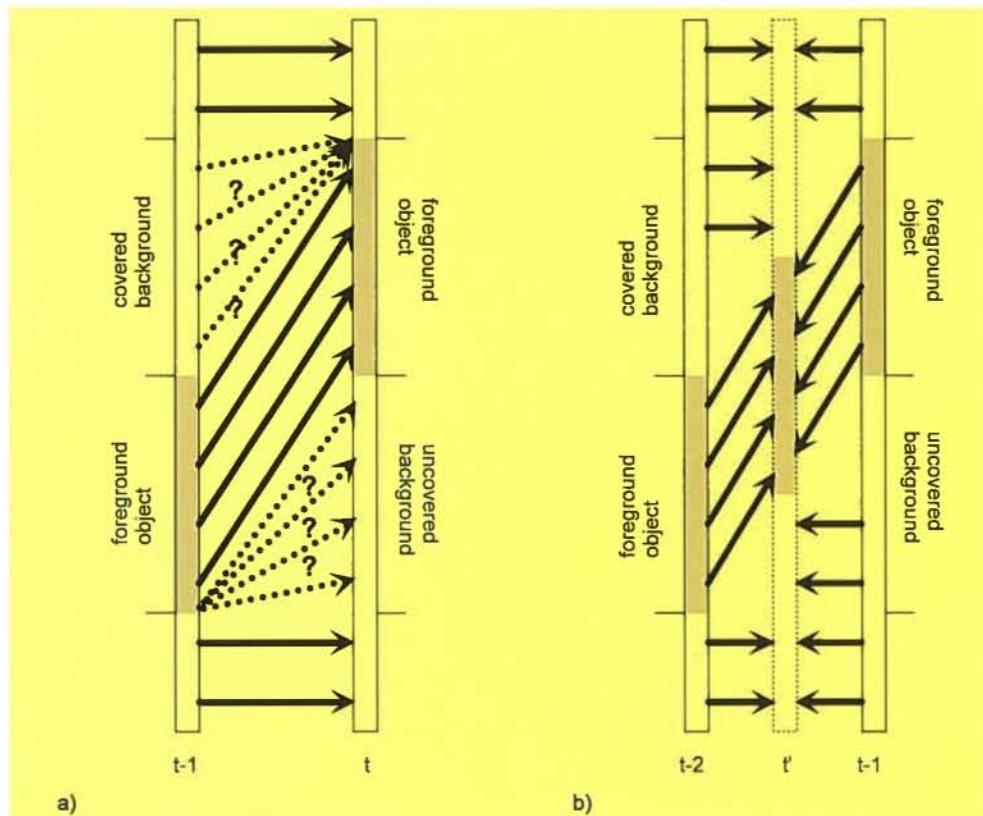
- Multimedia screen presentations are often composed from different visual components, like full-screen or partial-screen video, single video objects, graphics, text. In this case, positions and motion of the single components are exactly known,

can be used for this purpose. Of course, if object border detection fails, or wrong vectors are used in the occluded areas, new artifacts may appear. Results given in the next section show, that additional quality can be gained by application of such techniques. Herein, it is necessary again to define a fallback mode which switches back to the conventional interpolation in the cases of unreliable segmentation or unreliable motion estimation.

Object-based format conversion techniques have potential applications for multimedia applications with arbitrarily-shaped visual objects, and in additional options demanding for high quality, like on-line slow-motion generation from a video signal.

## 5. Results and examples

The format conversion system based on hybrid recursive motion estimation and motion-compensated frame interpolation results in a noticeable increase in quality, when compared to static format converters for typical video scenes. Fig. 14 shows



**Fig. 13.**  
Motion vectors that  
cannot be estimated,  
and correct extrapola-  
tion of covered/un-  
covered areas in an  
intermediate image  
interpolation.

an example, where simple field merging and frame repetition (so-called "frame grabber" technique) is compared to motion-compensated frame generation. The example of Fig. 14b shows the case of deinterlacing, which means that the original temporal position of the image is not changed. In the case where the temporal position has to be shifted, the error-tolerant intermediate image interpolation scheme is applied, which usually results in similar high quality. However, in rare cases, where the motion estimation has significantly failed, some isolated frames may still bear artifacts, as shown in Fig. 15a. This is

indeed barely visible, if the frames are dis-  
played in original high speed (e.g. 75 Hz),  
because human vision is insensible to these  
fast detail changes. If, however, up-con-  
verted frames have to be displayed with  
lower speed, as it would be necessary in a  
slow-motion application, artifacts in isolat-  
ed frames become highly visible. Fig. 15b shows,  
how the object-based interpolation scheme  
can overcome this problem at the  
expense of higher complexity.



**Fig. 14.**  
Up-conversion of  
interlaced video fields  
to progressive frames  
(deinterlacing).  
a) Frame grabber  
technique  
b) Motion-compen-  
sated technique.



**Fig. 15.**  
Comparison of conventional (block-based) and object-based intermediate image interpolation.  
a) isolated frame where conventional error-tolerant interpolation has failed  
b) enhancement by object-based scheme.

## 6. Conclusions

As the results show, it is possible to realize format conversion systems with low complexity, which produce sufficiently high quality for multimedia terminals with arbitrary display refresh rates and progressive or interlaced display scans. For this purpose, it is highly necessary to use motion-compensated up-conversion techniques. Expenditures of computational power for the motion estimation procedure, which is the most demanding task in such systems, can be highly reduced by use of appropriate algorithms like hybrid recursive motion estimation, without substantial loss in quality of estimation results. An error-tolerant intermediate-image interpolation scheme can cope with false motion estimates, as they may occasionally occur, if a full-frame video sequence is displayed with original speed. For advanced multimedia applications, which require composition of arbitrarily-shaped video objects or slow-motion display from video sequences, it will be necessary to use more sophisticated up-conversion techniques, like the object-based methods also introduced in this report.

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**D. Razic, Aufbau und Test eines optischen Phasenkonjugators in einer Polarisations-Diversitäts-Anordnung (Development of an optical phase conjugator in a polatrisation diversity arrangement),** TU Berlin, Fachbereich 12 (Elektrotechnik). Supervisor at HHI: H.G. Weber.

**C. Warmuth, Polarisationsabhängigkeit von Wellenleiterkomponenten in Silica-Technik (Polarisation dependence of waveguide components in silica technique)** TU Berlin, Fachbereich 4 (Physik). Supervisor at HHI: B. Kuhlow.

**Ch. Weißig, Entwicklung, Aufbau und Test eines PCMCIA Interfaces für ein MC68332 Microcontroller-Modul unter Berücksichtigung des PC Card Standards (Design, implementation and test of a PCMCIA interface for a micro controller module under consideration of the PC card standard),** TU Berlin, Fachbereich 12 (Elektrotechnik). Supervisor at HHI: U. Höfker.

## LECTURES

H.-G. Bach, Meßverfahren für Halbleiterbauelemente, TU Berlin

G. Boerger, Elektrobiologie, Neurophysiologische Grundlagen, TU Berlin

G. Boerger, Elektrobiologie, Meßtechnik, TU Berlin

B. Kuhlow, Einführung in die optische Signalverarbeitung, TU Berlin

T. Meiers, Programmieren in PASCAL, TFH Berlin

T. Meiers, Programmieren in C, TFH Berlin

J.-R. Ohm, Digitale Übertragung I

J.-R. Ohm, Digitale Übertragung II

J.-R. Ohm, Bilddatenverarbeitung

A. Paraskevopoulos, Halbleitertechnologie für die Integration in der Optoelektronik, TU Berlin

B. Strelbel, Optical Waveguides, TU Berlin

H.G. Weber, Grundlagen und Anwendungen der linearen und nichtlinearen Faseroptik, TU Berlin

## WORKSHOPS ORGANISED

MINT Status Seminar, January

IPhotonik-Arbeitsgruppe 2, WDM-Netze: Stand der Technik und Perspektiven, April

7th European Workshop on Metal-Organic Vapour Phase Epitaxy and Related Growth Techniques, EW MOVPE, jointly organised with TU Berlin and FBH Berlin, June

Picture Coding Symposium (PCS '97), jointly organised with IEEE and VDE/ITG, September

Status Seminar of BMBF project "Autostereoskopische Einpersonen-Monitore mit Trackingsystem", October

## CONTRIBUTIONS TO EXHIBITIONS

**LOB '97**, Laser & Optik Berlin, February: Photonic components and systems; Optical packaging devices (jointly with APhS)

**OFC '97**, Dallas, USA, February: Photonic components and systems (jointly with APhS, Berlin); Simulation tool for optical network design (start up company BNeD)

**CeBIT '97**, Hannover, March: MPEG-2 Video compression, MPEG-2 Surround-Sound-Decoder, MPEG-4 Video Compression, MPEG-4 Objects on Demand

**Hannover-Messe '97**, Hannover, April: Optoelectronic device technologies, display technologies, image and sound signal processing for applications in telecommunication, measurement and characterization, sensors and biomedicine etc. (joint exhibition with Berlin Universities and Research Institutes); optical packaging devices

**Laser '97**, München, June: 10 Gbit/s optical transmission system with monolithic integrated optoelectronic components, optical packaging devices up to 40 Gbit/s (jointly with APhS); Optical signal regeneration at high bit rates (3R) (jointly with TU Berlin and University of Potsdam)

**Forschungspolitische Dialoge in Berlin**, Optoelektronik – Motor des Wirtschaftswachstums im 21. Jahrhundert, WZB Berlin, June: Photonic components and systems

**Internationale Funkausstellung (IFA '97)**, Berlin, September: Exhibit of MINT project: MPEG-4 Coding, Objects on Demand, 3D Video from CD-ROM, Digital Multimedia Broadcasting, Formats conversion, RISO-Demonstrator (exhibit of Deutsche Telekom Berkom – developed by HHI); Interactive 3-D Visualization for Autostereoscopic Multimedia Displays

**ICSPAT '97**, San Diego, USA, September: Highly-Optimized Real Time Single-DSP

MPEG-2 Surround Sound Decoder	ACTS, Photonics Area: Auditor
<b>ECOC '97</b> , Edinburgh, UK, September: Transponder, BroadNed – simulation tool for optical communication systems, high speed tunable femtosecond laser (jointly with the start up companies BNED and LKF)	ACTS, Photonics Area: Evaluator
<b>Forschungsforum '97</b> , Leipzig, September: Presentation at BMBF- Forschungsforum 1997: Objects on Demand, MPEG-2 Image Compression, 3D Video from CD-ROM	ACTS, Steering Committee: Member
Exhibition during 1997 Picture Coding Symposium ( <b>PCS '97</b> ), Berlin, September MPEG-2 Video compression, Objects on Demand, RISO-Demonstrator (exhibit of Deutsche Telekom Berkom – developed by HHI)	ACTS Technical Audit, Photonics Area: Auditor
First Annual Multimedia Technical Expo ( <b>MTX '97</b> ), Fribourg, CH, November: MPEG-2 Multichannel DSP-based Audiodecoder, MPEG-2 Compression Software, HDTV Videodecoder	COST 211ter, Simulation Group: Chairman
	COST 239, Management Committee: Member
	COST 240, Management Committee: Vice Chairman and Liason Officer COST 239/240
	DFG-Schwerpunktprogramm "Optische Signalverarbeitung": Evaluator
	MINT: Chairman of the Steering Committee
	Nationaler ACTS-Lenkungsausschuß
	Photonik II Joint Research Program: Overall control jointly with IAF
	POLIKOM: Member of the Advisory Council

## COMMITTEE ACTIVITIES

### Standardisation Committees

DIN Arbeitskreis Integrierte Optik: Member  
 DIN Normenausschuß Feinmechanik und  
 Optik: Member  
 ETSI, Human Factors Group: Member  
 ISO/MPEG, Video Group: Chairman  
 ISO/MPEG: Head of the German  
 Delegation  
 ISO/MPEG: Member (2x)  
 ITU-T, Human Factors Group: Member (2x)  
 VDI/VDE, Arbeitskreis Integrierte Optik:  
 Member

### Conference and Workshop Program Committees

Analysis for Multimedia Interactive  
 Services, 1997, Louvain-la-Neuve, COST  
 211ter  
 European Conference on Multimedia  
 Applications, Services and Techniques,  
 1997, Milano, ACTS, COST 237  
 European Workshop on Metal-Organic  
 Vapour Phase Epitaxy (EWMOPVE VII),  
 1997, Berlin, Vice-Chairman and Program  
 Committee Member  
 8th European Conference on Integrated  
 Optics (ECIO '97), 1997, Stockholm:  
 Program Committee

### Research Program Committees

ACTS 3rd Call, Photonics Area: Evaluator

IEEE Lasers and Electro-Optics Society  
 Annual Meeting, LEOS '97, San Francisco,  
 Program Committee Member

International Picture Coding Symposium  
(PCS '97), 1997, Berlin

International Workshop on Audio-Visual  
Services over Packet Networks, 1997,  
Aberdeen

Optical Amplifiers and their Application,  
Program Committee

SID International Symposium, 1997,  
Boston

#### **Editorial Boards**

Fernseh- und Kinotechnik: Guest Editor

IEE-Electronic Letters: Referee

IEEE Signal Processing Magazine: Associate  
Editor

IEEE Transactions on Circuits and Systems  
for Video Technology: Associate Editor

Image Communication: Associate Editor

Image Communication: Guest Editor

#### **Other Committees**

Deutsche Gesellschaft für Angewandte  
Optik, Microoptics Group: Member

DVB/DTV-SA: Chairman

DVB/TM: Member

Eduard-Rhein-Preis: Curatorship

FKTG, Urteil-Preis-Komitee: Curatorship

Intersdisciplinary Optoelectronics Joint  
Research, IFV, Berlin, Advisory Council:  
Member

ITG, FA Fernsehtechnik und elektronische  
Medien: Member

ITG, FG Digitale Bildcodierung: Member

ITG, FG Integrierte Optik: Member

ITG, FG Optische Polymerfasern: Member  
(2x)

ITG-FG Optische Teilnehmerzugangsnetze:  
Member

Münchener Kreis, Research Committee:  
Member

## **EXCHANGE PROGRAM**

#### **Scientists Visiting HHI**

H. Imaizumi, NHK Labs., Tokyo, Japan,  
financed by NHK, for 6 months

H. Kizuki, Mitsubishi Electric Corp., Hyogo,  
Japan, financed by Mitsubishi Electric  
Corp., for one year

G. Lin, University of Xiamen, Xiamen, PR  
China, financed by HHI, for 6 months

S. Owu, Kings College, London, UK,  
financed by Kings College London, for 3  
months

P. McKeever, University of Glasgow, UK,  
financed by HHI, for 6 months

J. R. Salgueiro, Universidad de Compostela,  
Spain, financed by DAAD, for 2 months

Y. Sugaya, Fujitsu Laboratories LTD.,  
Kawasaki, Japan, financed by Fujitsu, for  
one year

#### **HHI Scientists Visiting Foreign Institutes**

H. Boche, ETH Zürich, Inst. f.  
Kommunikationstechnik, financed by HHI,  
for 6 months

H. Boche, Robert Bosch GmbH Hildesheim,  
financed by HHI, for 2 months

## **COOPERATIONS**

#### **Industry**

Advanced Photonic Systems, Berlin

Aixtron, Aachen

Alcatel Alsthom Recherche, Paris

Alcatel Telecom, Stuttgart

Berliner Institut für Optik, Berlin	Sentech Instruments, Berlin
Bosch Telecom, Backnang	SHF Design, Berlin
British Telecom, Martelsham Heath, UK	Siemens Nixdorf AG, Augsburg
Carl Zeiss, Jena, Oberkochen	Siemens AG, Berlin, München, Regensburg
Deutsche Telekom, Berlin, Darmstadt	Video Authoring System Group Inc., LA, USA
Deutsche Telekom - Berkom, Berlin, Darmstadt	<b>Universities and Institutes</b>
Deutsche Thomson Brandt, Hannover, Villingen	ATR, Kyoto, J
DSPecialist, Berlin	Bundesanstalt für Materialforschung und - prüfung (BAM), Berlin
France Telecom, CNET, F	DLR - Institut für Nachrichtentechnik, Oberpfaffenhofen
France Telecom, Marcoussis, F	ETH Zürich, CH
Fujitsu Mikroelektronik GmbH, Dreieich- Buchschlag	Ferdinand-Braun-Institut, Berlin
Grundig AG, Fürth	FhG Institut für Angewandte Festkörperphysik, Freiburg
Hewlett Packard, Böblingen	FhG Institut für Angewandte Materialforschung, Teltow
IOT Entwicklungsgesellschaft für Integrierte Optik-Technologie mbH	FhG Institut für Angewandte Optik und Feinmechanik, Jena
ISE Interactive Systems Entwicklungsgesellschaft, Villingen- Schwenningen	FhG Institut für Integrierte Schaltungen, Erlangen
LKF Advanced Optics GmbH, Berlin	Forschungszentrum Informatik, Karlsruhe
Lucent Technologies, Holmdel, USA	Gesellschaft für angewandte Optik und Spektroskopie e.V., Berlin
Mikroelektronik-Anwendungszentrum GmbH im Land Brandenburg	Hahn-Meitner-Institut, Berlin
Mikroelektronik-Anwendungszentrum Hamburg GmbH	Humboldt-Universität, Berlin
Motorola GmbH, München	Institut für Polymerforschung, Dresden
NTT, Kyoto, J	Institut für Rundfunktechnik, München
Planar Systems, Oregon, USA	Max-Born-Institut, Berlin
Raytek GmbH, Berlin	NHK Research Labs., Tokyo, J.
Robert Bosch GmbH, Hildesheim, Stuttgart	RWTH Aachen
2SK Media Technologies, Berlin	



Tohoku University, Sendai, Japan

## START UP COMPANIES

TU Berlin

LKF Advanced Optics GmbH, Berlin  
(Tunable femto second laser)

TU Braunschweig

DSPecialists GmbH, Berlin (Components  
for audio signal processing)

TU Chemnitz/Zwickau

BNeD GmbH, Berlin (Optical network  
design tools)

TU Darmstadt

2SK Media Technologies GbR, Berlin  
(MPEG compression software)

TU Eindhoven, NL

u2t Innovative Optoelectronic  
Components GmbH, Berlin (Ultrafast pho-  
toreceivers on InP)

TU Hannover

Usability Lab am HHI, Berlin (Human fac-  
tors support for the development of infor-  
mation technology)

TU Ilmenau

TU München

Universität Dortmund

Universität - GH Duisburg

Universität Erlangen

University of Glasgow

Universität Karlsruhe

Universität Kaiserslautern

Universität Konstanz

Universität Linz, A

Universität Marburg

Universität Potsdam

Universität Stuttgart

Universität Tübingen

Universität Ulm

University of Glasgow, UK

Walter-Schottky-Institut, München

Weierstraß-Institut für Angewandte  
Stochastik, Berlin

Weizmann Institute of Science, Rehovot, IL

Wuhan Research Institute for Posts &  
Telecommunications, PR China

## **HHI AT A GLANCE**

Government research institute (Federal Republic of Germany and State of Berlin)  
Total staff at end of 1997: 254 employees

## **Areas of Research and Development**

### **Photonic Networks**

- Design, development and demonstration of optical communication networks and subsystems (access and customer networks, core networks)
- Investigation and development of WDM and high-speed OTDM techniques for high capacity transmission and routing
- Exploration of high speed transmission performance of photonic networks
- Development of techniques for network operation and maintenance
- Development and fabrication of photonic devices and integrated circuits (transmitters, modulators, switches, optical amplifiers, filters, multiplexers and demultiplexers, signal regenerators, transceivers, receiver frontends) based on InP, SiO<sub>2</sub>/Si and polymers

### **Mobile Broadband Systems**

- Development of optical microwave generation and transmission systems for cellular mobile communication systems
- Development of RF and IR mobile systems for broadband in-house communication
- Investigations on time varying transmission channels for mobile communication systems
- Design of problemspecific algorithms for signal processing
- Development of methods to increase the transmission capacity in cellular mobile communication systems

### **Electronic Imaging Technology for Multimedia**

- Development of algorithms and hardware architectures for video and audio compression
- Development of algorithms and hardware architectures for image analysis and synthesis
- Design of integrated circuits for image processing
- Development of user interfaces for multimedia applications
- Analysis and optimization of communication services
- Development of 3D display technologies
- Development of electroluminescent flat-panel displays
- Development of an optical pickup for DVD-systems

## **HEINRICH-HERTZ-INSTITUT FÜR NACHRICHTENTECHNIK BERLIN GMBH**

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Scientific Managing Director:  
Prof. Dr. Clemens Baack  
Administrative Managing Director:  
Dr. Wolfgang Grunow

## **INFORMATION CONTACT**

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