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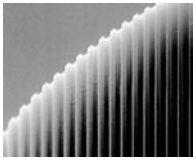
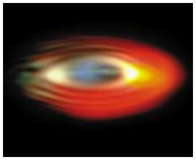
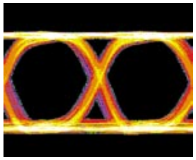
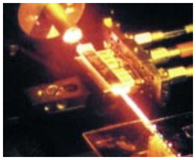
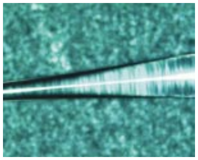




"Do today what others only think of doing tomorrow, for only change is constant."
We at the Institute of Applied Physics (IAP) are committed to this quotation from Heraklit (480 BC), because the advancement of science and engineering is our primary objective.

In the year 2003 the IAP has made significant and prominent contributions in the field of science and engineering, illustrations of which are: new optical elements based on nano-structures with specific characteristics and high power ultrafast fiber-laser systems. The novel system reported in the latter case boasts unique functional characteristics in pulsed operation, thereby opening up new fields of application for laser systems. The award of the 2003 Thuringian Prize for Basic Science and the Otto-Schott-Prize manifestly shows that this work is both outstanding and appreciated.

Changes hold chances. In autumn 2003, I have taken over the position of a director of the Fraunhofer Institute for Applied Optics and Precision Mechanics (IOF). This change in the institute's leadership of the IOF has led to a closer relationship between the Friedrich-Schiller-University and the Fraunhofer Institute. The resultant collaboration between these institutions has created a nationally and internationally outstanding level of competence in the field of micro- and nano-structured optics, which is a basic requirement for optical systems technology. It is the technological base for the production and hybrid integration of both active and passive, miniaturized optical elements. It allows for the transition of discrete optical elements into optical systems, similar to the technological and economical breakthrough of microelectronics in the mid 1960's. Over the next few years we will try to use this potential effectively to shape the development of modern optics.

I would like to thank our partners in industry and science for their excellent collaborative work and also the German Federal Ministry of Education and Research, Thuringia's Ministry for Science Research and the Arts and the Deutsche Forschungsgemeinschaft for their ongoing support.

I pay tribute to all my colleagues and thank them for their outstanding results and commitment. Their work forms the foundation for the continuous progress of the IAP.

Jena, May 2004

Prof. Dr. Andreas Tünnermann
(Director of the Institute of Applied Physics)

The Institute of Applied Physics at the Friedrich Schiller University Jena has a longstanding tradition and competence in design, fabrication and application of active and passive photonic elements for both, optic and optoelectronic devices. A total staff of more than 30 scientists and engineers is presently working in education and R&D. In addition, about 20 diploma and PhD students and visiting scientists are researching at the IAP. Focal point of research is the generation, control and amplification of spatially and/or temporally confined light.

The institute has a floor space of 1,200 m^2 with installed clean rooms and optical laboratories including microstructure technology (electron beam and photo lithography, reactive ion and reactive ion beam etching, diffusion and ion exchange ovens, coating facilities, scanning electron and atomic force microscopy), optic/optelectronic testing and measuring instrumentation.

Research Profile

The Institute of Applied Physics at the Friedrich Schiller University Jena is engaged in the development of:

· Advanced micro-and nano-processing technology
· All solid state lasers
· Amplitude and phase masks
· Calibration tools
· Electro-optical materials
· Fiber and waveguide lasers and amplifiers
· Integrated optical devices
· Microoptics (refractive/diffractive)
· Nonlinear optical devices
· Physical optical elements
· Ultrafast optics

Staff Members

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Rockstroh, Sabine		*Secretary*
Rockstroh, Werner		
Röser, Fabian		
Ruske, Jens-Peter	Dr.	*Integrated Optics*

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Schmidt, Oliver		
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Stumpf, Max		
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Wikszak, Elodie		
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Wittig, Lars-Christian		
Würfel, Eduard		
Wyrowski, Frank	Prof. Dr.	*Optical Engineering*
Zellmer, Holger	Dr.	*Fiber and Waveguide Lasers*

Guests

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Cohen, Alexander	Prof.	*Ben Gurion Univ. of the Negev, Beer Sheva, Israel*
König, Jens		*Robert Bosch GmbH*
Matsushima, Kyioji		*University of Osaka, Japan*
Nejadmalayeri, Amir Hossein		*University of Toronto, Canada*
Senthilkumaran, Paramasivam		*Indian Institute of Technology, New Delhi, India*
Willert, Markus		*Robert Bosch GmbH*
Zimmer, Hagen		*FH Münster*

Lectures – Summer Semester 2003

Prof. Dr. Andreas Tünnermann

V Atom- und Molekülphysik
P Physikalisches Grundpraktikum

Prof. Dr. Frank Wyrowski

V Technische Thermodynamik
S Technische Thermodynamik
WS Quellenmodellierung im Photon Management

Prof. Dr. Andreas Tünnermann, Prof. Dr. Hartmut Bartelt

WV Mikrooptik und Integrierte Optik

Prof. Dr. Andreas Tünnermann, Prof. Dr. Falk Lederer, Prof. Dr. Wolfgang Karthe

WS Angewandte Photonik

Dr. Jens-Peter Ruske, Dr. Holger Zellmer

S Experimentalphysik

Kay-Uwe Amthor, Friederike Ewald, Dr. Stefan Nolte, Thomas Schreiber

S Atom- und Molekülphysik

Lectures – Winter Semester 2003/04

Prof. Dr. Andreas Tünnermann

P	Physikalisches Grundpraktikum
WV	Experimentelle Methoden der optischen Spektroskopie

Prof. Dr. Frank Wyrowski

WV	Wellenoptische Methoden im Optikdesign
WS	Wellenoptische Methoden im Optikdesign

Prof. Dr. Andreas Tünnermann, Prof. Dr. Roland Sauerbrey

WV	Grundlagen der Laserphysik

Prof. Dr. Andreas Tünnermann, Prof. Dr. Falk Lederer, Prof. Dr. Wolfgang Karthe

WS	Angewandte Photonik

Dr. Jens-Peter Ruske, Dr. Holger Zellmer

S	Experimentalphysik

V	– Vorlesung
WV	– Wahlvorlesung
P	– Praktikum
S	– Seminar
WS	– Wahlseminar

Diploma Theses

Michael Banasch

Untersuchung zum Proximityeffekt bei der elektronen-lithographischen Herstellung computergenerierter Hologramme mit submikrometer Pixelgrößen

Fabian Röser

Gitterbasierte Meßstrategien zur Untersuchung photonischer Kristalle

Thomas Hübner

Schädigungsarmes Abtragen von Kniegelenkknorpel mit Laserpulsen

Elodie Wikszak

Generation of Bragg Gratings using Femtosecond Pulses

Oliver Günnel

Selektive Laserablation von Knieglenkknorpel mittels Plasmaanalyse

Doctoral Theses

Sven Bühling

Projektionsalgorithmen
im wellenoptischen Transmissionsdesign

Ekkehard Werner

Wellenleiterkonzepte zur Führung und Beeinflussung
von Licht hoher Leistung

Ulrich Grusemann

Untersuchungen zu einem temperaturkompensierten
Wellenlängensensor auf der Basis protonen-
ausgetauschter Wellenleiter in Lithium-Niobat

Jens Limpert

High power ultrafast fiber laser systems

Andreas Liem

Skalierungsverhalten von Faserlasern und -verstärkern

Markus Willert (guest)

Strukturierung von metallischen Werkstoffen
mit Laserstrahlung unter Vermeidung von Gefüge-
veränderungen

Habilitation

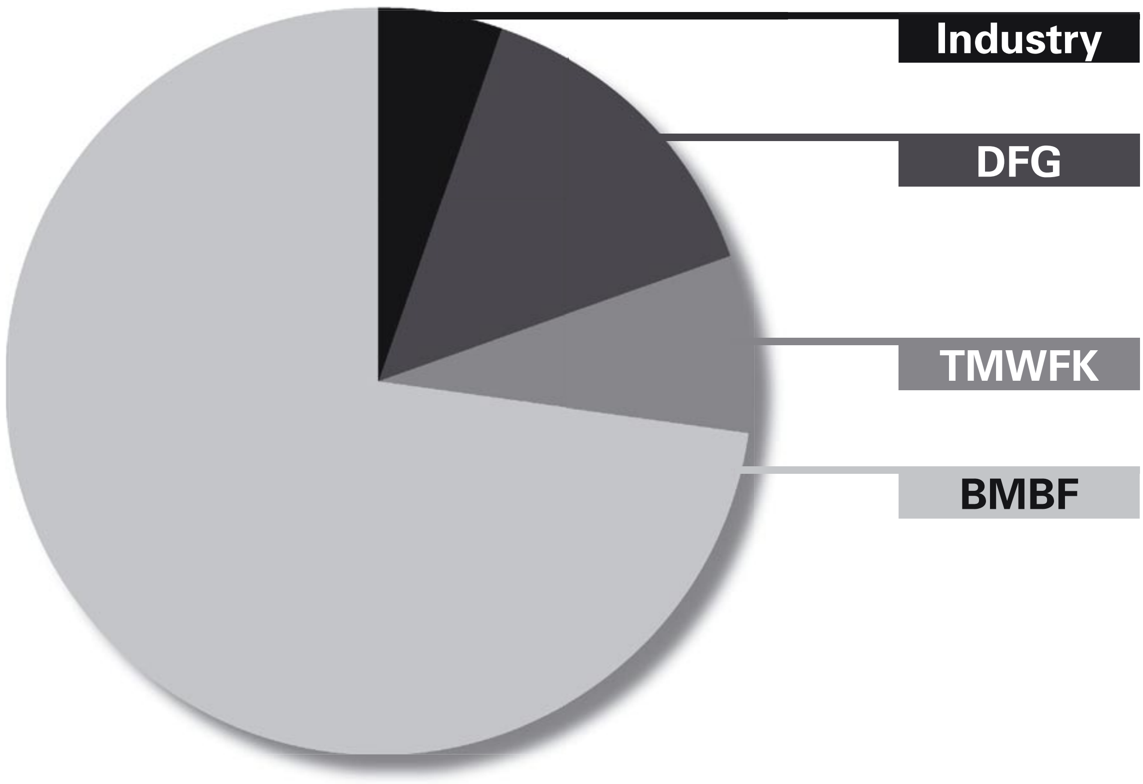
Holger Zellmer

High Power Fiber Lasers and Amplifiers

Statistics

The research activities of the IAP in 2003 were partially supported by the German Ministry of Education and Research (BMBF), German Research Foundation (DFG), Thuringian Ministry of Science, Research and Art (TMWFK) and industrial clients with a budget of about 2.1 million €.

Total number of public funded projects: > 20



Externally Funded Projects

DFG Projects

Forschergruppe: Teilchenstrahl-stimulierte Ultrapräzisions-Oberflächenbearbeitung
TP: Ionenätzen
(Project term: 1/2000 – 12/2003)

Wellenoptisches Design monofunktionaler optischer Systeme
(Project term: 8/2000-7/2004)

SFB Transregio: Gravitationswellenastronomie
TP: Hochauflösende Interferometerkonzepte auf der Basis
reflektierender optischer Komponenten
(Project term: 1/2003 – 12/2006)

SPP: Photonische Kristalle
TP: Low-index sandwich photonic crystals for linear and nonlinear applications
(Project term: 6/2003 -5/2005)

Hochbitratige optische Übertragungssysteme mit Halbleiterverstärkern und -absorbern
(Project term: 4/2002 – 5/2004)

SPP: Integrierte elektrokeramische Funktionsstrukturen
TP: Aktive und passive Bauelemente auf Basis
strukturierter elektrooptischer Schichtkeramiken
(Project term: 11/2003 – 10/2005)

TMWFK Projects

Digitale Modulationskonzepte für Fotoprintingsysteme
(Project term: 2/2001 – 2/2003)

OPTOMATRONIK: Integriert-optische Systemtechnik: Konzeption, Darstellung und Charakterisierung mikro- und nanostrukturierter optischer Elemente
(Project term: 4/2002 – 3/2005)

BMBF Projects

Diffraktive Kombinations-Optiken für Hochleistungsdiodenlaser (UA BMBF)
(Project term: 10/1999 – 1/2003)

Funktionale optische Komponententen mittels Nano-Replikationsverfahren (FOKEN)
TP: Prägewerkzeuge mit Schwerpunkt auf hohe Aspektverhältnisse
(Project term: 9/2001 – 7/2004)

MICROPHOT – Laserdirect: Faseroptische Hochleistungslaser für die Druckvorstufe
TP: Neuartige Skalierungskonzepte für Faserlaser und –verstärker in kontinuierlichen und gepulsten Betrieb
(Project term: 7/2000 – 6/2003)

MICROPHOT – OMP: Integriert-optische Modulationskonzepte im sichtbaren Spektralbereich
(Project term: 7/2000 – 3/2004)

Grundlegende Untersuchungen zur Materialbearbeitung sowie die Berechnung und Erprobung optischer Elemente zur Strahlformung ultrakurzer Laserpulse (PRIMUS)
(Project term: 5/2000 – 12/2003)

German-Israeli Cooperation in Ultrafast Laser Technologies (GILCULT)
TP: Ultrashort-pulse lasers and amplifiers based on diode pumped fiber laser crystals
(Project term: 3/2001 – 12/2004)

Präzise Materialbearbeitung mit Ultrakurzpuls-Strahlquellen
TP: Kurzpuls-Faserlaser CPA-System
(Project term: 7/2001 – 3/2004)

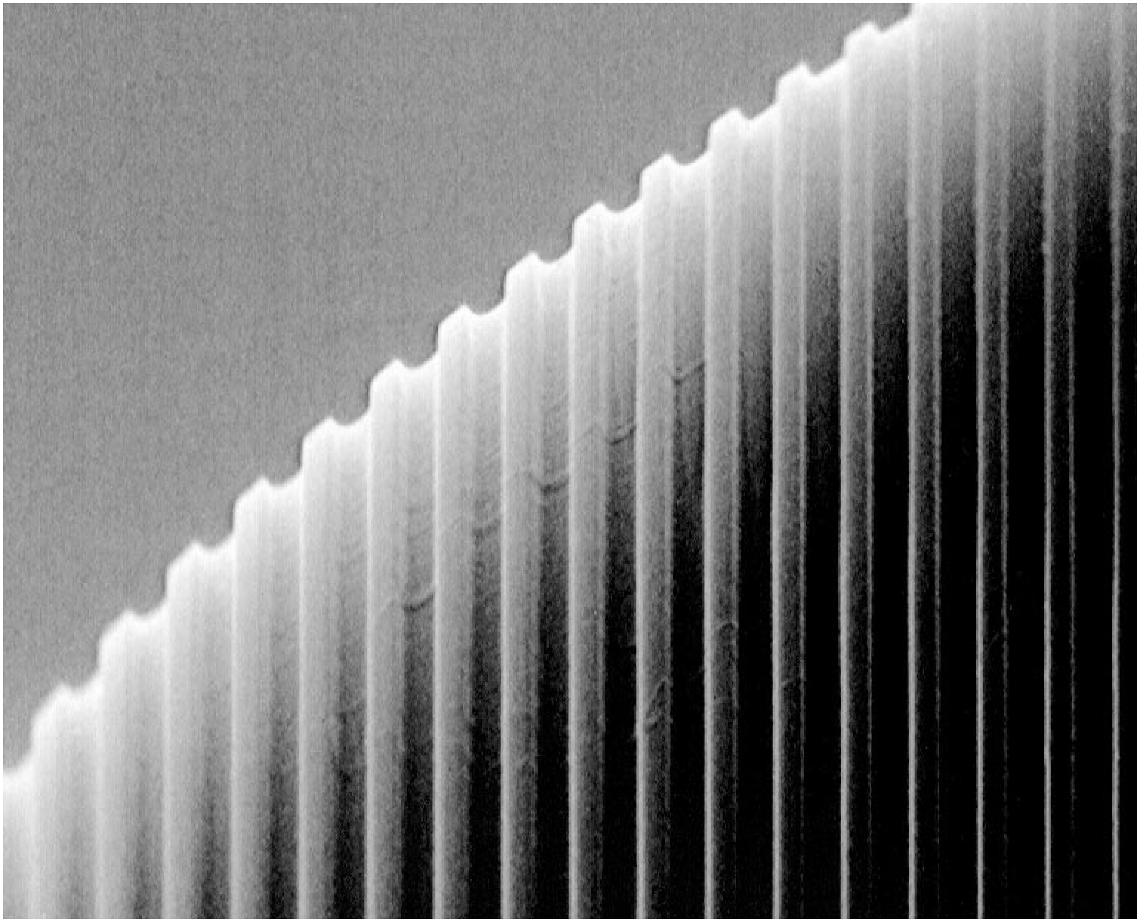
Förderschwerpunkt Photonische Kristalle – Photonic Crystal Optical Circuits (PCOC)
TP: Design, Herstellung und Charakterisierung von photonischen Kristallen
auf der Basis von oxidischen Gläsern
(Project term: 3/2002 – 9/2004)

Photonische Kristallfasern für neuartige Lichtquellen mit steuerbarer Funktionalität
TP: Nanostrukturierte Wellenleiter zur Erzeugung und Führung
hoher Leistungsdichten (PHOFAS)
(Project term: 6/2002 – 5/2005)

CoOp: Verbundprojekt Hybride Integrationstechnologie für kompakte, funktionale
und fertigungstaugliche optische Module
TP: 3D-Lithografie
(Project term: 1/2003 – 6/2006)

Entwicklung eines Strategiekonzeptes
für das Zentrum für Innovationskompetenz OPTOMATRONIK
(Project term: 1/2003 – 11/2003)

Neue Herstellungsverfahren für tageslichttaugliche Bildschirmhologramme (NHTB)
TP: Design und Technologieentwicklung für holografietaugliche
Strahlformungselemente (NHTB)
(Project term: 7/2003 – 6/2006)



MICROSTRUCTURE TECHNOLOGY · MICROOPTICS

Dr. Ernst-Bernhard Kley

Highly efficient transmission gratings for pulse compression

Caused by the rapid progress in fabrication techniques for diffraction gratings with periods in the micrometer range they became applicable in numerous scientific and industrial apllications. One example which is recently of great interest are high power ultrashort pulse laser systems. Gratings belong to the key components in the power amplifier system (CPA), where the pulses are firstly stretched in the time-domain, amplified and finally recompressed by a grating compressor (▸ fig.1).

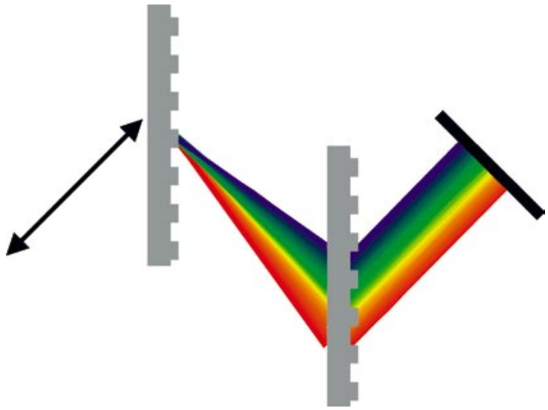


Fig.1 Setup of a pulse compressor based on transmission gratings

The demands on such gratings are besides a high dispersion a diffraction efficiency near 100% as well as a high damage threshold, because they have to resist extreme high pulse peak powers. The highest damage threshold can be expected by gratings in purely dielectric material, e.g. in fused silica. To form a grating compressor with these gratings they have to be illuminated under Littrow-mounting

$$\sin \varphi = \lambda / 2d$$

(λ...wavelength, d...grating period).

In this case the 0th and the –1st order propagate symmetrically. If the grating period fulfilles the condition

$$\lambda / 2 < d < 3\lambda / 2n$$

(n...refractive index of the substrate)

no higher orders can propagate in air as well as in the fused silica substrate. Thus, all incident light is distributed to these 4 orders (2 in reflection, 2 in transmission). We focused on gratings, which are optimized for a wavelength of 1060nm (Nd:glass-fiber laser). Numerical calculations show, that a binary grating with a period of 800nm can exhibit a diffraction efficiency up to 97% for linear polarized illumination. However, this high value can be provided only in a very small range of grating parameters. Moreover, the aspect ratio (groove depth to ridge width) is about 4:1.

These two issues make great demands on the accuracy of the employed fabrication technique. We used electron beam lithography for the pattern generation and reactive ion beam etching for the deep etching. The high diffraction efficiency was achieved iteratively: we etched the grating till the desired depth was nearly reached and removed the chromium etching mask. We measured the diffraction efficiency and calculated the real profile parameters. After that the etching mask was regenerated by oblique chromium coating and a further etching step was applied. With this method we achieved a diffraction efficiency of 95.5% for 1060nm. The damage resistance of these gratings was measured according to ISO 11254-2. The damage threshold was 1.25 J/cm^2 for 150fs pulses which is only a factor of 2 below the substrate material.

In some applications, e.g. fiber amplifyer systems, the light which is incident upon the gratings is not linearly polarized. In this case optimization for only one polarization would cause a great loss of energy. Therefore we investigated the possibility to design a grating which is highly efficient for both TE- (electric field vector parallel to the grooves) and TM- (electric field vector perpendicular to the grooves) polarization.

The diffraction on gratings whose periods are much larger than the wavelength can be described with a sufficient precision by the scalar diffraction theory. In the scalar approximation diffraction is independent of the polarization, but if the feature sizes of the grating become comparable with the wavelength the vectorial nature of light and thus the polarization dependence gains influence. The grating parameters have to be chosen properly to achieve a high diffraction efficiency for both polarizations. By rigorous numerical calculations on binary fused silica gratings we found, that a grating with a period equal to the wavelength, a groove depth of 2.55µm and a ridge width of 690nm exhibits a –1st order diffraction efficiency of 98% for both TE- and TM- polarized light. Similar to the fabrication of the gratings optimized for one polarization, we used the iterative etching-measuring method to approach the ideal grating parameters.

▸ Fig.2 shows an example for a fabricated grating. The diffraction efficiency was measured to be 93.7% for TE- resp. 94.1% for TM-polarized light. Compared to the polarization sensitive design, the entire efficiency of the compressor (4 pass) could be enhanced from 42% to 78%.

Gratings for the gravitational wave interferometry

Since 2003 the IAP is involved in the SFB "Gravitational wave astronomy". In collaboration with the Albert-Einstein Institute / University Hanover, which belong to the main supervisors of the gravitational wave detector GEO 600, new concepts for the interferometrical gravitational wave detection using reflective optics have to be investigated. Conventional detector systems are based on

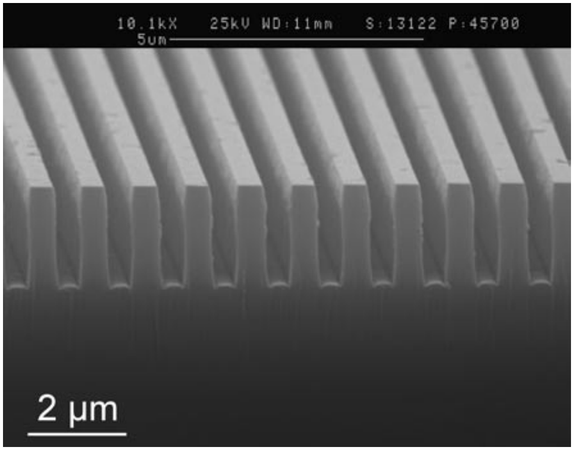
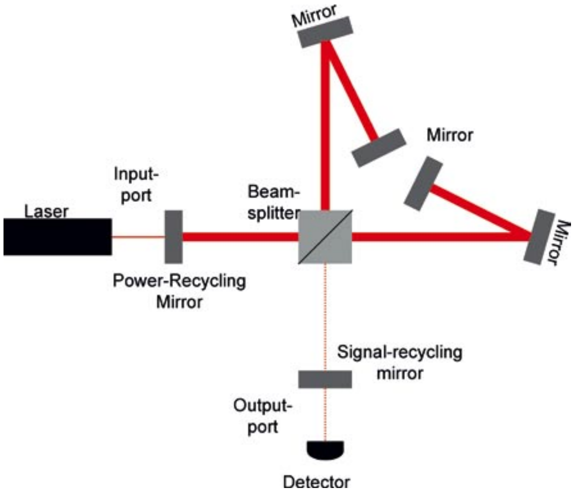


Fig.2 Scanning electron micrograph of a fabricated polarization independent high efficiency grating

Fig.3 Setup of the gravitional wave detector GEO 600 Power- and Signal recycling mirror effect an increased number of round trips of the light



self-contained Michelson interferometers like shown in ▸ fig.3 . In the case a gravitational wave approaches the earth the optical pathes in the interferometer arms are changed. The fluctuation of the space-time continuum can thus be measured as an intensity modulation at the output port of the interferometer. The sensitivity of the setup is determined by the length of the arms as well as the circulating power. To increase the power and the number of round-trips concepts like *Power recycling, Signal recycling* and arm cavities are integrated into the detectors. To date the circulating power at near infrared light (1064nm) is on the order of kWs. For future gravitational wave detectors it has to be increased up to MWs. However, in conventional systems the power is limited by thermally caused disturbances like thermal lensing or noise in the transmitted optics. To avoid these heating effects, they have to be replaced by reflecting (but still) dielectric components.

A main topic of this project is to investigate several interferometer concepts that are based on dielectric reflection gratings. Gratings are very well adapted for this problem since they can be used as beamsplitters and cavity-coupling components with defined beam intensities. To obtain a sensitivity large enough for the detection of gravitational waves, these gratings are aimed to possess losses less than 10^{-6}. That means on the one hand that the incomming light intensity has to be properly distributed to the desired diffraction orders, on the other hand losses like scattering and wave front deformation have to be eliminated.

▸ Fig.4 shows one example for a setup, where the low efficiency -1^{st} diffraction order of a grating (-2^{nd} order Littrow mounting) is used to couple light to a cavity. The cavity is

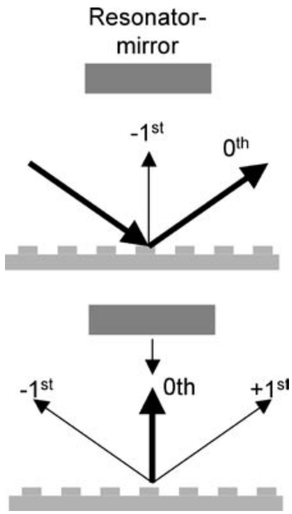


Fig.4 A dielectric grating as cavity coupler

a. incoupling by the lowly efficient -1^{st} order

b. cavity generation by the high 0^{th} order reflection built by an extreme low-loss mirror parallel to the grating and the grating itself. Therefore the reflectivity of the grating for normal incidence has to be nearly 100%. To avoid transmission and thus additional losses the grating is combined with a high reflecting dielectric stack made of alternating layers of tantalum and silica.

One challenge is here, to make the stack highly reflective for both normal and oblique incidence. By optimization of this stack we were able to find a design which provides a reflectivity higher than 99.95% for an incidence angle between 0° and 70°. In addition to the conventional way to fabricate highly reflective dielectric gratings, where a grating is etched in the top layer of the multilayer system, we investigated another approach, where a grating is etched into a dielectric substrate and afterwards overcoated by the multilayer system. ▸ Fig.5 shows the cross-section of one of the fabricated gratings. The diffraction efficiency in the -1^{st} order was measured to be 0.5%, the transmission for normal incidence was only 0.03%.

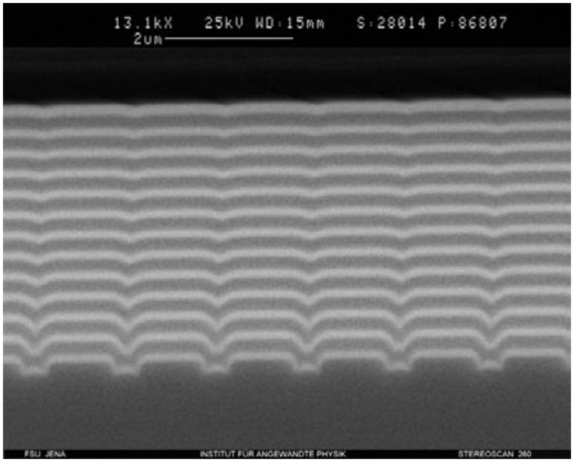


Fig.5 Cross-section of a shallow grating overcoated by a highly reflecting multilayer

For the investigation of scattering the IAP has purchased a ARS-measuring station that is able to measure straylight down to 10^{-6} of the incident light. Furthermore the wavefront accuracies will be measured by a new ZygoLOT wave front interferometer, which can detect wavefront distortions of $\lambda/40$ on substrate sizes up to 6inch.

Micro-optical polarimeter

Several applications in science and industry require precise measurement of the polarization of light. In previous times the polarization detection was commonly done using a rotatable analyzer in front of a detector. By acquiring the intensity in several analyzer positions the polarization of the incoming light can be calculated. However, this method results in a reduced temporal sampling rate depending on the number of spatial sampling points.

To overcome this problem we have developed an integrated micro-optical polarimeter which is able to detect 3 spatial orientations, 0°, 60° and 120°, in one step. It consists of a 1mm² transparent substrate, where 3 polarizing chromium grids are situated on (▸ fig.6). The requirements for a high polarization contrast are both a grating period much smaller than the wavelength and a high aspect ratio of the metal ridges. With electron beam lithography we are able to fabricate gratings with periods of 300nm or less, but the achievable aspect ratio is restricted by the technique that is used to transfer the e-beam written pattern in the chromium layer. Usually a groove depth of less than 100nm can be realized for this grating period. The theoretical contrast is less than 30:1 in this case. However, due to the skin effect only the surface of the chromium stripes can affect the optical properties.

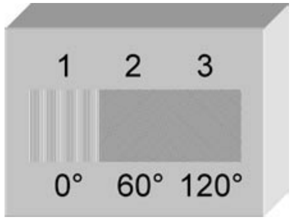
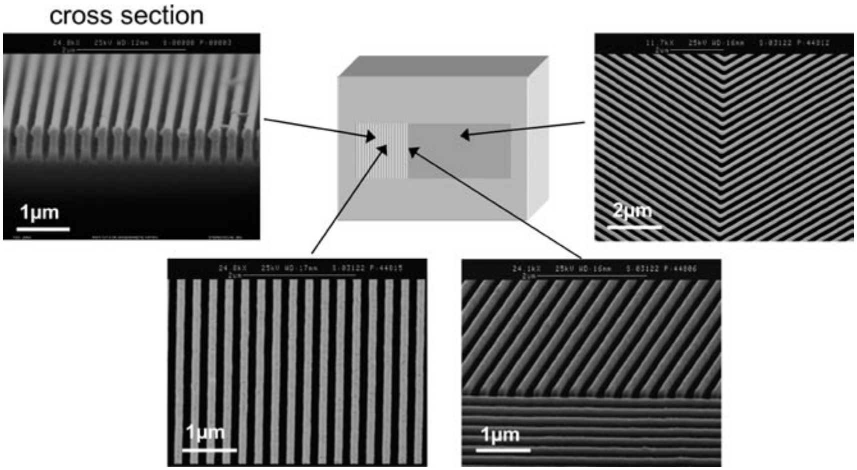


Fig.6 Layout of the micro-optical polarimeter

So it should be possible to use a deep dielectric carrier grating, which is overcoated by a metal layer (▸ fig.7). The carrier grating can be a fused silica grating, which we are able to etch with a groove depth in the order of 1µm by reactive ion beam etching. This grating is afterwards coated by chromium under oblique incidence.

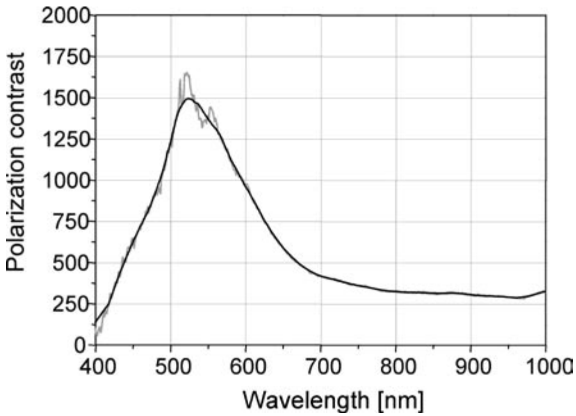
Fig.7 New approach to increase the aspect ratio of a polarizing metal grid: a deep fused silica grating is overcoated by chromium

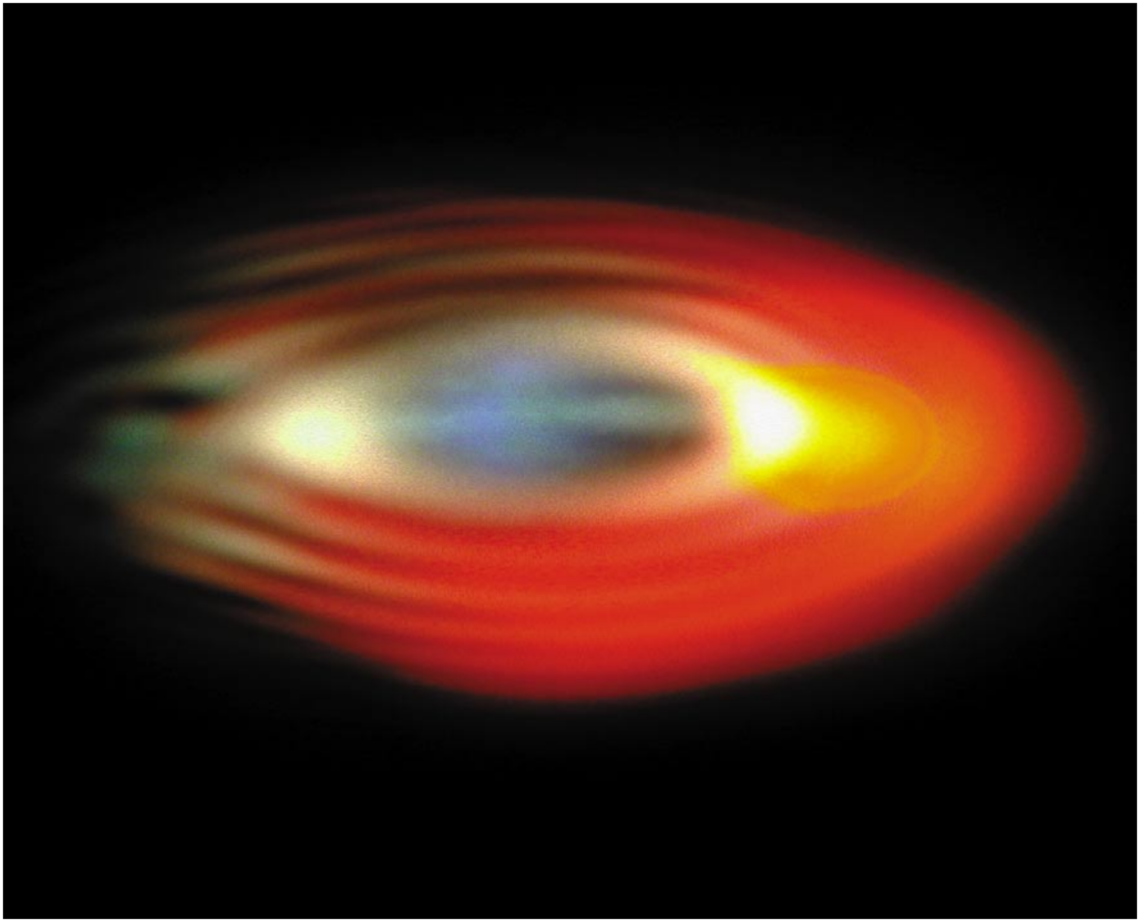


▸ Fig.8 shows some scanning electron microscope pictures of the fabricated sample. We finally measured the transmission spectrum of this device using TE- and TM-polarized light (▸ fig.9). The polarization contrast is higher than 300:1 over a spectral range from 450nm to 1000nm. It is even higher than 1000:1 between 490nm and 600nm. The device is already used for the detection of birefringence in the textile fiber racking in industrial spinning machines.

Fig.8 SEM pictures of the fabricated device

Fig.9 Measured polarization contrast as a function of the wavelength (grey line…measured values, black line…smoothed curve)





ULTRAFAST OPTICS

Dr. Stefan Nolte

High speed direct writing of optical waveguides inside glasses

The quest for highest integration in modern communication technology has spurred research to extend integrated optics to three dimensions. In addition, e.g. crossings can easily be avoided in a three-dimensional architecture. Since the presently used techniques for the production of integrated optical devices are in general limited to the generation of planar (2D) structures, the research within the Ultrafast Optics group was partially dedicated to the interaction of intense ultrashort laser pulses with transparent solids. By tightly focusing these laser pulses into the bulk localized refractive index changes can be induced which allow to guide light with damping losses below 0.4 dB/cm. In this way an alternative method for the direct writing of three-dimensional photonic structures within the bulk of glasses and crystals has been established.

As an example of a true three-dimensional device, the schematic of a 3D splitter is shown in ▸ Figure 1a together with the near-field intensity distribution at the end-surface of the realized device for a wavelength of 1.05 µm (▸ Figure 1b). The three exits are separated by 100 µm, and the total device length is 10 mm in this case.

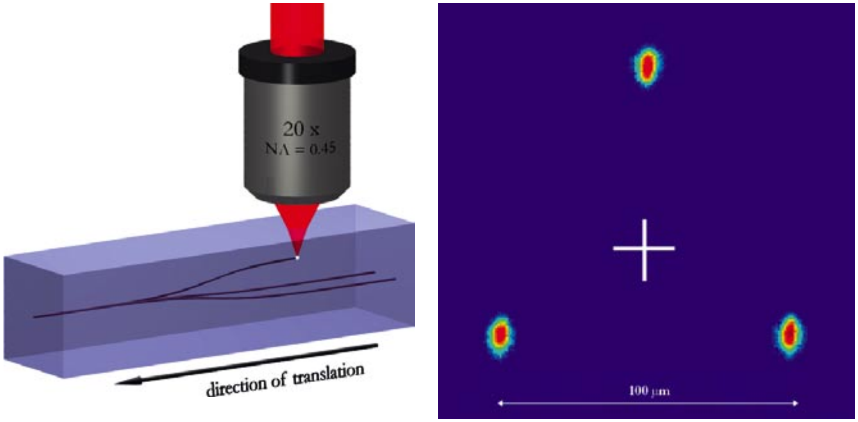


Fig.1

a Schematic of a true three-dimensional splitter.

b Measured near-field intensity distribution at the end-surface of the device for a wavelength of 1.05 µm. The cross marks the position of the incoupling fiber at the other end of the device.

In addition, this technique shows great potential since it is applicable to different materials. These include not only passive glasses and crystals but also doped glasses which allow for amplification. ▸ Figure 2 shows a waveguide written inside a bonded glass with a doped (Er/Yb) and an undoped region. Pump light at 800 nm is coupled into the device through the undoped region. The fluorescence from the doped region demonstrates that the waveguide was successfully written through the bond. The possibility to use solids consisting of different materials even increases the complexity of optical functions which can be implemented, like in this example a passive part and an active part where losses can be compensated.

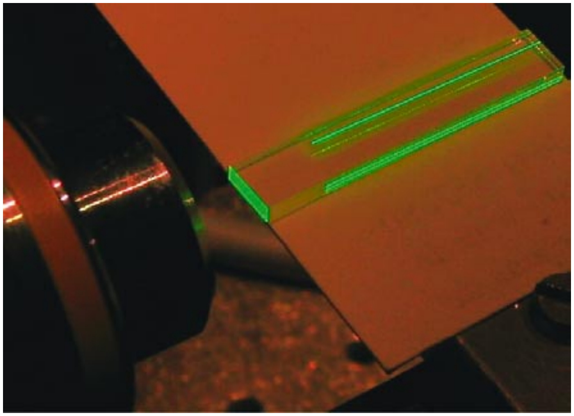


Fig.2 Femtosecond written waveguide in a bonded glass with a doped (Er/Yb) and an undoped region. Pump light at 800 nm is coupled into the device through the undoped region. The fluorescence from the doped region demonstrates that the waveguide was successfully written through the bond.

However, despite of all the advantages of this technology, one of the main drawbacks is the limited processing speed. In all examples discussed so far a regeneratively amplified Ti:sapphire laser system, which produces pulses at a wavelength of 800 nm and a repetition rate of 1 kHz has been used. The optical waveguides have been written by moving the samples at a speed of up to 1 mm/s. This is too slow when comparing with the presently used techniques.

In order to overcome this drawback a fiber laser has been set up in collaboration with the Fiber and Waveguide Lasers group. The principle setup of the system is shown in ▸ Figure 3. 150 fs-pulses of a passively mode locked Nd:Glass oscillator at a repetition rate of 75 MHz and a wavelength of 1060 nm are stretched in a grating stretcher to ~ 800 ps. The stretched pulses are amplified in two subsequent fiber amplifiers consisting of Yb-doped double-clad fibers, which are end-pumped by pigtailed diode lasers at 940 nm. After the preamplifier, the repetition rate is reduced to 2 MHz using an acousto-optical modulator (AOM). The pulses are amplified in the power amplifier to an average power of 2 W before they are compressed to a pulse duration of 300 fs using a grating compressor with an efficiency of 60 %. This results in a pulse energy of 0.6 µJ. Due to the single-mode fiber used for amplification the beam quality is diffraction limited ($M^2 < 1.1$).

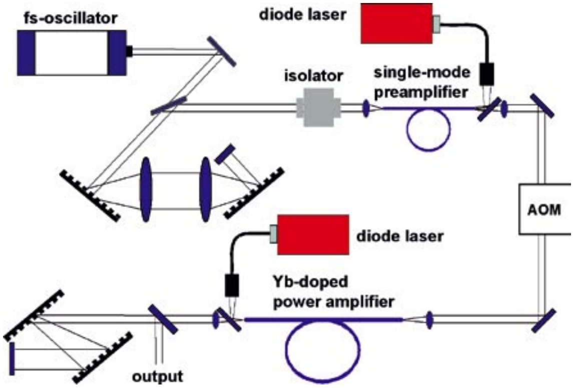


Fig.3 Schematic setup of the fiber based femtosecond CPA system for high speed writing.

In order to fabricate waveguides the pulses were focused with an aspherical lens (f = 8 mm, NA = 0.5) approximately 200 µm below the surface of a polished silicate glass sample (Schott AF45). The sample is moved perpendicular to the laser beam axis using a precise computer-controlled positioning system with a writing speed between 1 and 100 mm/s.

‣ Figure 4 shows transmission microscope images (cross section) of waveguides written with 400 nJ pulse energy and different writing speeds from 100 mm/s down to 1 mm/s (W1 = 100 mm/s, W2 = 50 mm/s, W3 = 20 mm/s, W4 = 10 mm/s, W5 = 5 mm/s, W6 = 2 mm/s, W7 = 1 mm/s). In all cases the laser was incident from the top.

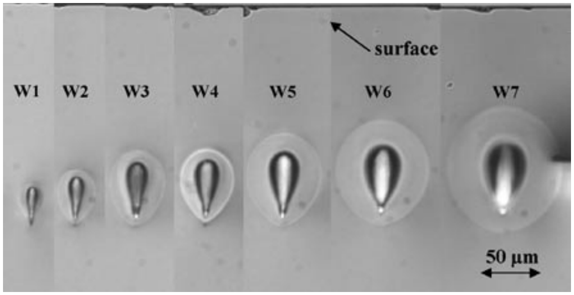


Fig.4 Microscope images (cross section) of waveguides written with 400 nJ pulses at writing speeds between 100 mm/s (left) and 1 mm/s (right)

In contrast to the waveguides produced with the low repetition rate laser system the structure sizes induced are no longer determined by the focusing conditions. They are much larger and increase with decreasing writing speed, i.e. with increasing number of pulses and, therefore, increasing total energy deposited on one spot. The interaction mechanism is completely different compared to the low repetition rate (1 kHz) machining. When such high repetition rates (2 MHz) are used the time between successive pulses is insufficient for the deposited heat to diffuse away. Consequently, heat accumulation takes place, and the glass starts to melt. Note that the molten material is enclosed deep inside the sample, which is different to the conventional melting of glass. Therefore, rapid cooling is taking place after the irradiation, starting from the outer boundaries. Since this resolidification process happens non-uniformly strong refractive index contrasts are generated. This can be seen in ▸ Figure 5, where the refractive index profile of a waveguide written with 10 mm/s (measured using a RNF profilometer) is shown. The central area shows a strong refractive index rise of $\Delta n \approx 8\times10^{-3}$ surrounded by a ring with decreased refractive index ($\Delta n \approx -4\times10^{-3}$). This is followed by a ring with slightly increased refractive index ($\Delta n \approx 2\times10^{-3}$).

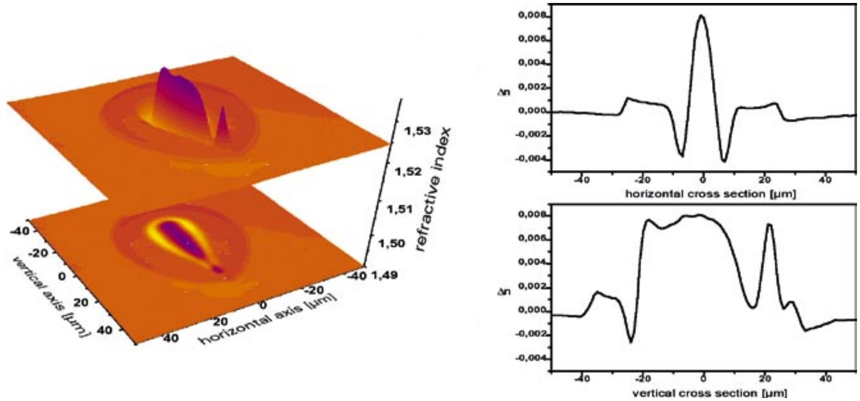


Fig.5 Refractive index profile for a waveguide written at 10 mm/s

According to the large refractive index difference of $>10^{-2}$ between the central region and the surrounding area with decreased refractive index light is guided very well in this structure. ▸ Figure 6 shows a comparison of the near-field intensity distribution of guided light at a wavelength of 514 nm (▸ Figure 6a) and of 1550 nm (▸ Figure 6b) when the light is launched into the central part of the structure. While the waveguide is highly multimode in case of the visible light, only a few modes are guided in the IR.

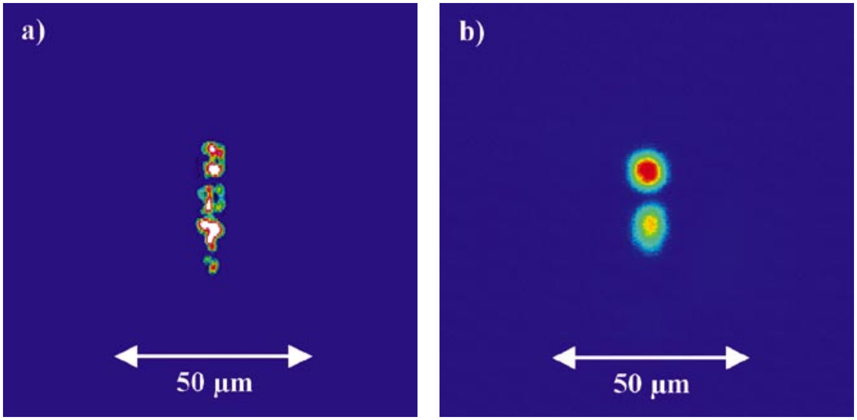
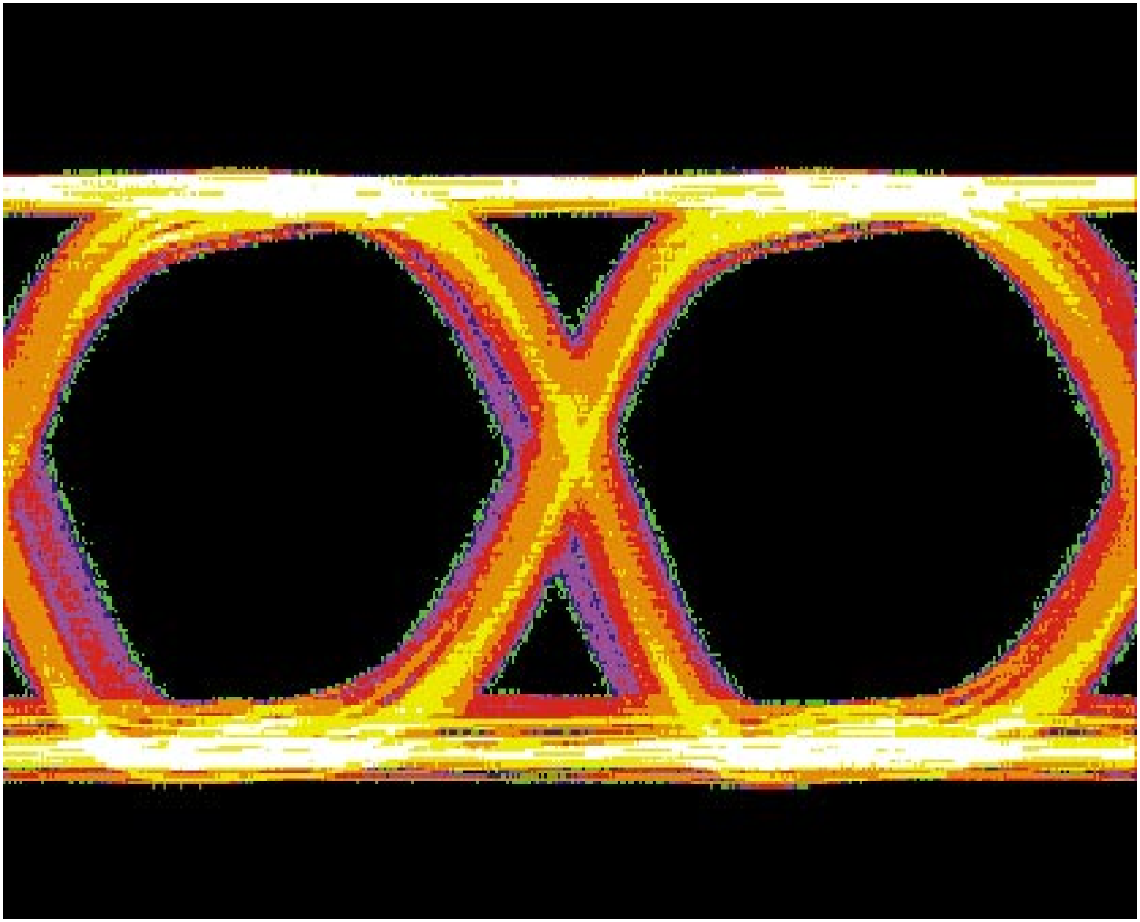


Fig.6 Near-field intensity distribution of the waveguide written at 10 mm/s
a for visible light (514 nm) and
b infrared light (1550 nm)
coupled into the central part of the structure.

The propagation losses of this waveguide have been determined (at 633 nm) by measuring the overall transmission through a 2 cm long waveguide sample. Therefore, light from a standard single mode fiber was launched into the central area of the waveguide. This yielded a total loss of 1 dB. Since the coupling losses are estimated to be small because of the high NA of the waveguide (due to the large refractive index difference), we neglect them and estimate the propagation losses to < 0.5 dB/cm. This is comparable to values achieved using low repetition rate amplifier systems (see above).

In conclusion, we have demonstrated high-speed direct writing of waveguides using a high repetition rate fiber based CPA system. Low loss waveguides (< 0.5 dB/cm) with a refractive index difference > 10^{-2} have been obtained at writing speeds of up to 100 mm/s for the first time. Such high fabrication speeds make an industrial use of this technique very attractive.

We like to acknowledge financial support from the Thuringian Ministry of Science, Research and Art (TMWFK, B507-02006) and the German Federal Ministry of Education and Research (BMBF, 13N8187) as well as support from SCHOTT Glas, Germany, and SCHOTT Glass Technologies, Inc., USA.



OPTICAL COMMUNICATION SYSTEMS

Dr. George Onishchukov

High bit-rate optical fiber communication systems

The research in the field of optical fiber communication systems at the IAP is focused on the performance of high bit-rate medium and long-haul systems with in-line semiconductor optical amplifiers (SOA) using a re-circulating fiber loop set up (▸ fig.1) with theoretical support being provided by the group of Prof. F. Lederer at the Institute of Solid State Theory and Theoretical Optics, Friedrich Schiller University of Jena. Since the main effect limiting the transmission distance in such systems is noise accumulation, the emphasis was placed on the study of signal regeneration using saturable absorbers (SA). Another main point of our research was new SOA types, particularly SOA based on self-assembled Quantum Dots (QD-SOA).

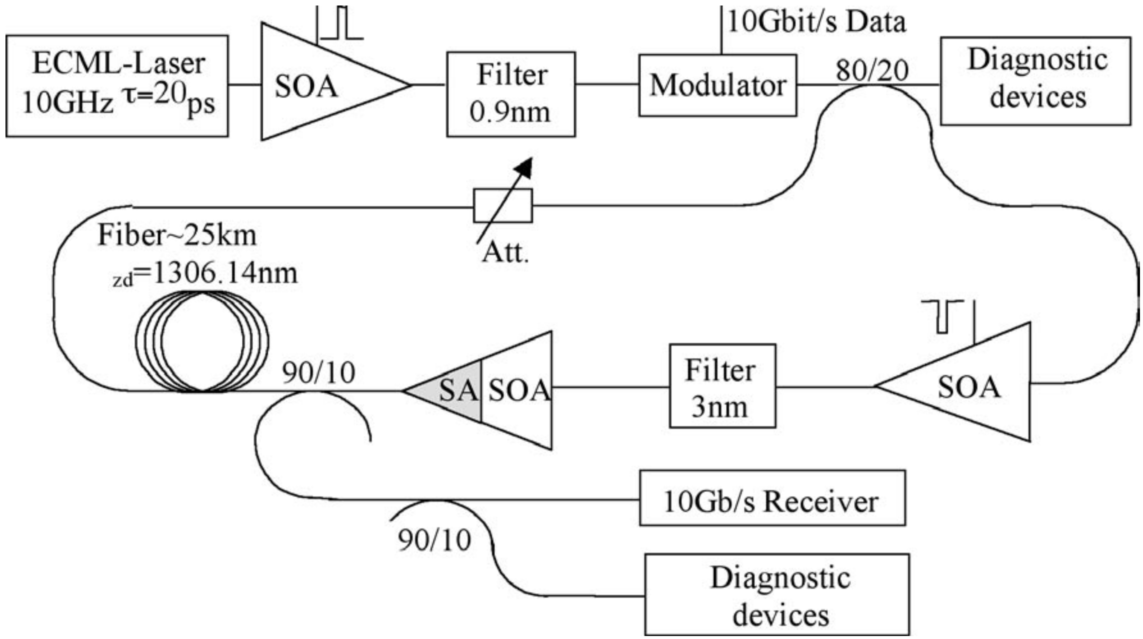


Fig.1 Re-circulating fiber loop set up for simulation of systems with in-line SOA and SA.

Semiconductor optical amplifiers (SOA) are very promising active elements of integrated lightwave circuits for optical fiber communication systems. It has been previously shown by our group that high bit-rate Return-to-Zero (RZ) transmission in systems with in-line SOA suffers from fast growth of amplified spontaneous emission (ASE) and signal decay because of the low saturation energy and SOA gain recovery time comparable with the signal bit rate. It has been proposed and demonstrated that when using in-line saturable absorbers (SA), it is possible to completely suppress ASE growth and to increase the maximum transmission distance many times – up to 30 000 km for 5 Gb/s using common commercially available devices. Transmission of 10 Gb/s over 5 000 km has been demonstrated using a gain-clamped SOA, which allows to control of the SOA gain recovery dynamics and to minimize other effects that limit transmission distance: data sequence dependent amplitude and spectral patterning and resulting temporal walk off effect. These results demonstrate the world's longest transmission distances realized in the system with in-line SOA.

Another important parameter, which limits the transmission system performance, is timing jitter. Our investigations have shown that a very low (2 ps at 30 000 km) timing jitter could be obtained in the system with SOA and SA. The main source of the timing jitter in the system is the Gordon-Haus effect suppressed by in-line spectral bandpass filter. The jitter suppression could be very effective because a system with in-line SOA and SA can operate at zero fiber dispersion with high pulse energy, outperforming systems with dispersion management. On the other hand, signal regeneration makes it possible to use narrow spectral bandpass filters without transmission deterioration caused by the growth of amplified spontaneous emission and dispersive waves. Thus all the conditions for low Gordon-Haus jitter could be easy satisfied: low fiber dispersion, high soliton energy, and strong in-line spectral filtering.

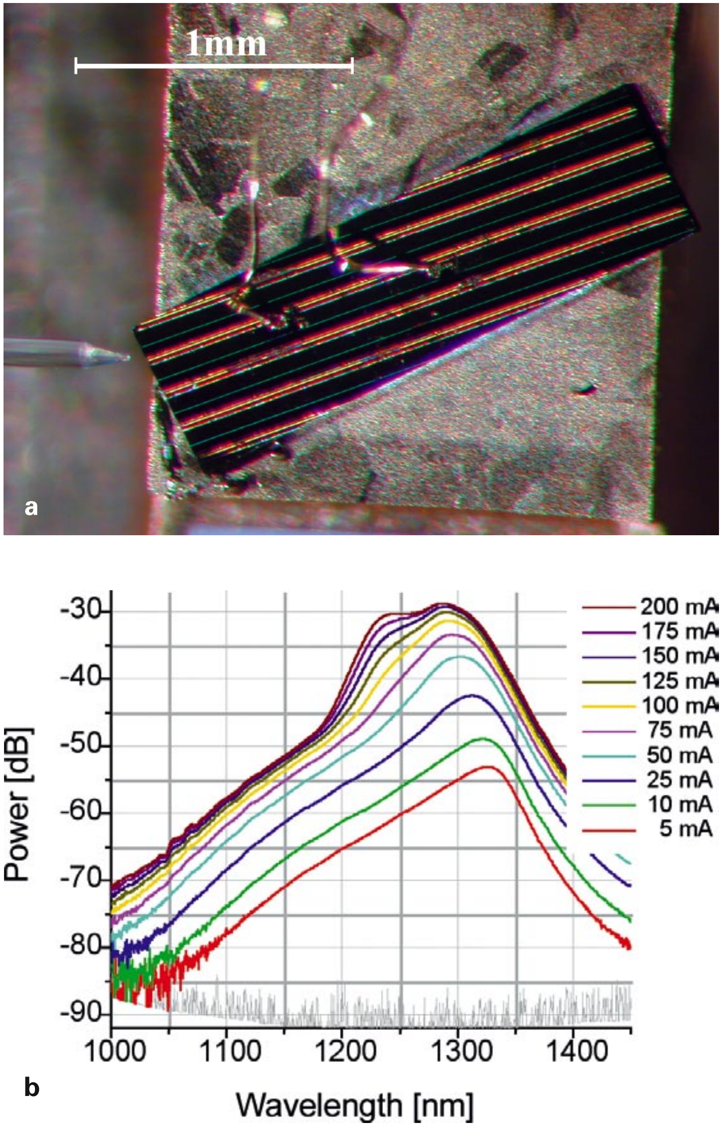
Different from common regenerators with an additional laser and optical gate controlled by the data to be regenerated, a kind of "auto"-2R-Regeneration is realized in our system with in-line SOA and SA. From a fundamental point of view, the system is essentially nonlinear and strongly dissipative. The parameters of the stationary pulses (autosolitons) are completely determined by the system parameters and in contrast to conservative soliton systems, they are independent of the initial pulse parameters like energy, duration, spectral width and to a certain extent even wavelength. It makes the system also very robust against other signal distortions critical in high bit-rate systems, like PMD, dispersive waves, FWM, etc. Our investigations of bifurcation behavior the system with two competing noninstantaneous nonlinearities (SOA and SA) have shown that in a certain system parameter range it is a truly digital optical system where only low-level trivial background solution (ASE or any quasi-CW radiation) and autosolitons (signal pulses) correspond to the two stable states. Its specific feature is that for supercritical bifurcation of CW radiation the bifurcation of the solitons is subcritical. It is in contrast to the other well known nonlinear systems with instantaneous nonlinearities where the bifurcation behavior of CW radiation and that of solitons are of the same type – either both supercritical or both subcritical. Dynamics of the system have been also studied: switching of autosolitons and their relaxation. The effect of critical slowing down of the relaxation, which is typical for nonlinear systems, has been demonstrated. Numerical simulations show that Hopf instabilities (self-stating, undamped oscillations) could be observed in the vicinity of the critical point, but such behavior has not been experimentally observed till now and the investigations of the effect are to be continued. Another interesting fundamental effect under study is the system instability if the period of lumped amplification, absorption, and spectral filtering reaches a resonance with soliton parameter oscillations in the system and the last could no more be described in the average soliton approximation.

Recent progress in quantum dot (QD) technology has led to the development of unique QD laser diodes with low threshold current, high output power, high temperature stability, high modulation bandwidth, and low chirp. Also, QD semiconductor optical amplifiers (QD-SOA) have very promising features that could provide breakthrough improvement of SOA performance in optical networks - more than an order of magnitude decrease of the gain recovery time and of the linewidth enhancement factor, resulting in reduction of signal distortions caused by cross-gain and cross-phase modulation. Moreover, similar to QD lasers, QD-SOA could have a lower power consumption and a higher temperature stability than common multiple-quantum-well

Fig.2

a Quantum dot semiconductor optical amplifier with InAs-InGaAs DWELL active region and

b its amplified spontaneous emission spectra at different currents



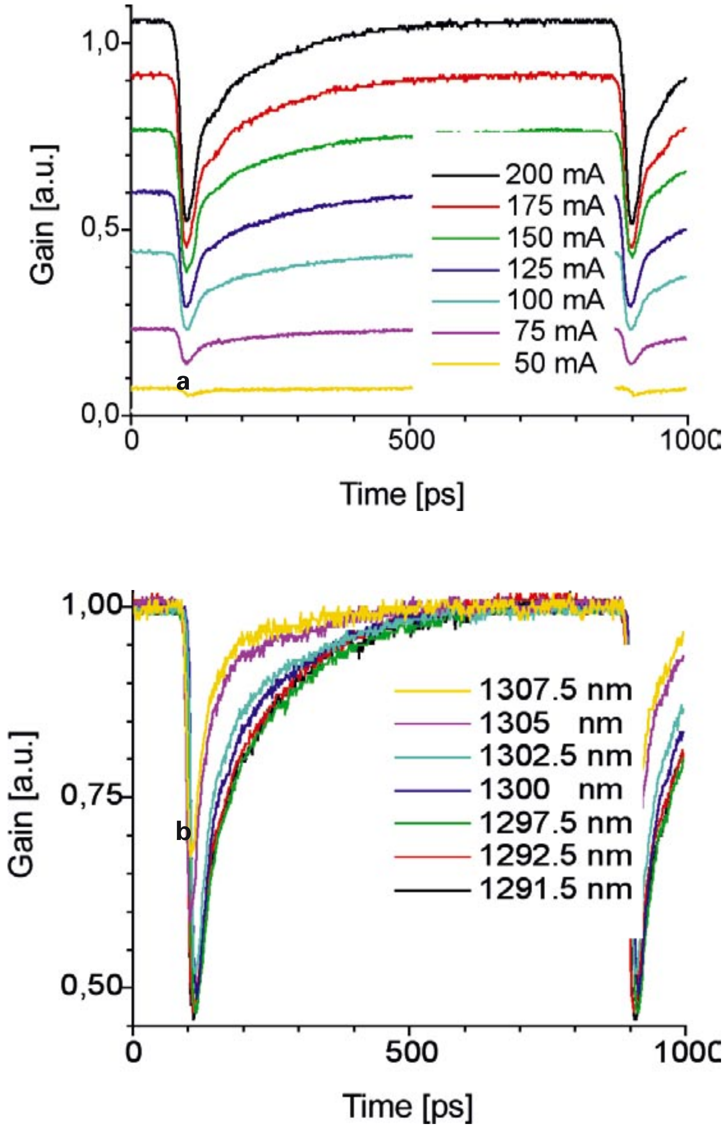
and bulk SOAs. Theoretical simulations of QD-SOAs have shown that the QD-SOA could achieve very good performance: saturation power of 20–25 dBm, gain above 45 dB, and noise figure of about 4 dB at the same time. Last but not least, the QD technology allows the mixing of different sizes of dots in one structure to realize extremely broadband amplifiers (~ 300 nm) with inhomogeneous broadening. This feature would be especially promising for use in broadband wavelength division multiplexing systems.

Fig.3

a QD-SOA gain recovery dynamics at different currents and

b its wavelength dependence.

The wavelength of 12-ps pump pulses is 1295 nm; shift of curves in (a) corresponds to the change of the small-signal gain. Probe pulse duration – 1.5 ps.

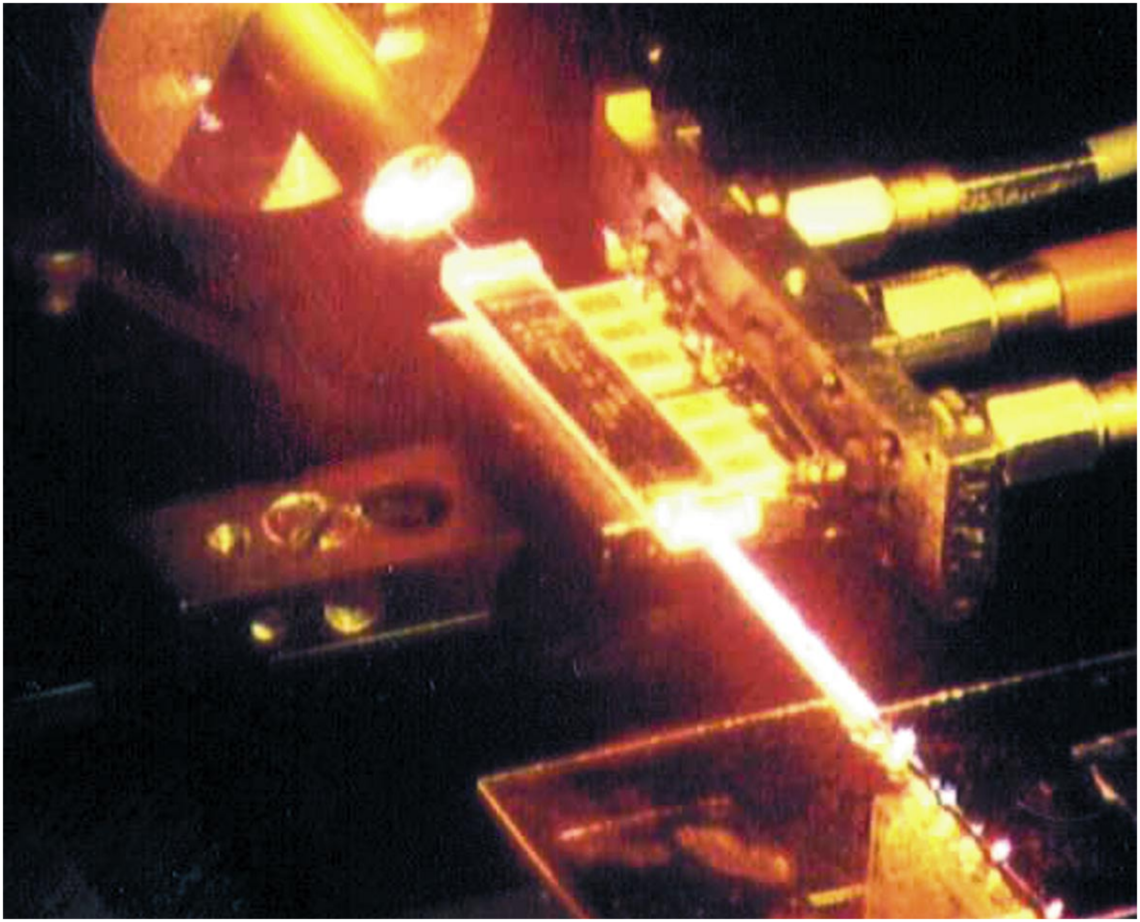


Parameters of a 1300-nm QD-SOA built using a 2.4-mm-long structure of six InAs–InGaAs DWELL layers with very high dot density (8 x 10^{11} cm^{-2}) have been studied. The device (▸ fig.2) was provided by the group of Prof. L. F. Lester at the Center for High Technology Materials, University of New Mexico, USA. A chip gain as high as 18 dB with 50-nm bandwidth has been reached at low pump current (100 mA). The output saturation power for a CW signal is 9 dBm. The static linewidth enhancement factor, measured using Hakki-Paoli method, is below 0.1.

The polarization dependence of the gain is more than 20 dB, and the noise figure is about 8 dB. Gain peak wavelength and bandwidth are practically temperature-independent. The obtained parameters are better than or comparable to that of a common SOA. The gain recovery dynamics of the QD-SOA sample was also studied. The pump-probe measurements were based on the beating of two pulse trains with close, about 1.25 GHz pulse repetition frequencies. The QD-SOA gain dynamics for different currents is shown in ▸ fig.3. We found that in that pump current range the recovery dynamics of the QD-SOA gain can be characterized by two time constants. The initial fast, incomplete gain recovery with a relaxation time of ~10 ps could not be attributed to intradot relaxation because usually the carrier relaxation time to the QD ground state and capture time are ~1 ps, but it could be an interdot ("tunneling") relaxation between the laterally coupled dots in a QD layer. The second, longer, ~150 ps relaxation time constant corresponds to the relaxation of the total carrier density in the semiconductor because of insufficient population of the quantum well carrier reservoir at these current levels. It is worth noting that the relaxation time constants were found to be practically independent of the driving current in the studied range as well as of the input pulse energy. In spite of the fact that the QD-SOA gain recovery is faster than that of common SOA, slow gain recovery component would remain an inhibiting factor for high-bit-rate transmission similar to the case of common bulk and MQW-SOA. The effect might be reduced by optimization of the structure design and especially by increasing the pump current, which in our case, was limited by the onset of lasing. Although the spectral broadening of the QD-SOA gain is generally speaking mainly inhomogeneous due to quantum dot size scattering, it has been found to be in fact quasi-homogeneous for both - CW-radiation and 10-ps pulses, with saturation being weaker and gain recovery being faster on the red side of the pump than on the blue one. More detailed investigations are necessary to completely clarify the physics of the gain recovery dynamics.

Recently the issue of efficient chip-to-fiber coupling for the QD-SOA chip with very strong, 1:3 beam ellipticity has been solved using special graded index lensed fiber tapers and the in-line performance of the QD-SOA has been studied in the fiber loop with additional Raman fiber amplification to compensate for excess loop losses. No essential improvement of the system performance has been found compared to that of the system with optimized MQW-SOA. It shows that also in the systems with QD-SOA it would be necessary to use SA for signal regeneration. Due to lower modal gain quantum dot structures could be easily used as saturable absorbers with reasonably long active waveguide length. The QD-SA structures with necessary for this application short chip length were provided by the group of Prof. J.P. Reithmaier at the University of Würzburg. When operated as SOA they have features similar to that of the samples from New Mexico. Preliminary results on their performance as SA shows that the absorption recovery time is quite short – ~10–50 ps and it is possible to control the small signal absorption and the recovery time by reversed bias voltage applied to the structure. The spectral broadening of the SA absorption has been found to be quasi-homogeneous similar to that of the SOA gain. Experiments on performance of the system with QD-SA are under run.

The investigations had been partially funded by the DFG.



INTEGRATED OPTICS

Dr. Jens-Peter Ruske, Brit Zeitner, Prof. Dr. Andreas Tünnermann,
Andreas Rasch (LITEF GmbH, Freiburg / Germany)

Photorefractive effect and high power transmission in $LiNbO_3$ channel waveguides

New developments in optical communication between geostationary and low earth orbit satellites base on Gigahertz phase modulation of light with a wavelength of 1064 nm [▸ 1]. An optical power of approximately 250 mW in continuous operation is required. Integrated-optical phase modulators in lithium niobate are able to operate at these high modulation frequencies. However, there are no experiences about the waveguide behaviour at guided power of more than approximately 10 mW. The photorefractive properties of pure and Fe-doped lithium niobate are well known for applications in holographic data storage [▸ 2,3]. Doping the crystal with Mg decreases the photorefractive sensitivity in bulk as well as waveguide applications [▸ 4]. In this paper we report on to our knowledge first investigations of the photorefractive waveguide behaviour at powers up to 120 mW and discuss scaling properties. Since their lower photorefractive sensitivity annealed proton exchanged waveguides have been preferred against titanium indiffused waveguides.

The experiments were carried out with straight waveguides in congruent undoped x-cut lithium niobate wafers made by NTT Electronics Corporation, Japan, because of its homogeneous and reproducible quality against doped material. The waveguides were prepared by proton exchange in a benzoic acid melt with 1 mol% lithium benzoate at a temperature of 180 °C, followed by an annealing procedure at a temperature of 340 °C, leading to polarising singlemode waveguides at 1064 nm (TE) with an elliptical nearfield distribution of 3 µm x 4 µm (FWHM). The insertion loss of a 3 cm long waveguide was about 2.5 dB, measured with the fibrecoupling method. The waveguide attenuation was about 0.4 dB/cm.

An interferometric set-up based on a two-beam interference of a low power probe beam at the wavelength 830 nm, which passed two simultaneously excited neighbouring channel waveguides was used for the investigation of the photorefractive changes of the effective refractive index N, which are induced by a second high power pump beam (1064 nm). The experimental arrangement was described earlier [▸ 5]. It allows the determination of light-induced phase shifts, the changes of the effective channel waveguide index and its sign, respectively, in dependence of time, wavelength and guided power. The measurement accuracy of the index changes is about 5×10^{-7} for typical sample lengths of about 3 cm due to the mechanical and thermal noise of the experimental set-up.

▸ Figure 1 shows the typical time dependence of the effective refractive index at the output power of 26 mW for an irradiation of 180 minutes. Irradiation leads to a decrease of the effective refractive index leading to a saturation at $-\Delta N_{,s}$. After switching off the pump beam the refractive index decrease relaxes. Both build up process and relaxation show the typical two-step behaviour which can be described as a sum of two exponential functions known also from [▸ 6]. The time constants for the build up process are in the range of 3 and 24 minutes and for the relaxation process 16 and 160 minutes, respectively. The build up time constants show a power dependence. The relaxation process is not complete. A complete relaxation can be reached by homogeneous irradiation with short wavelength light or heating the waveguide chip.

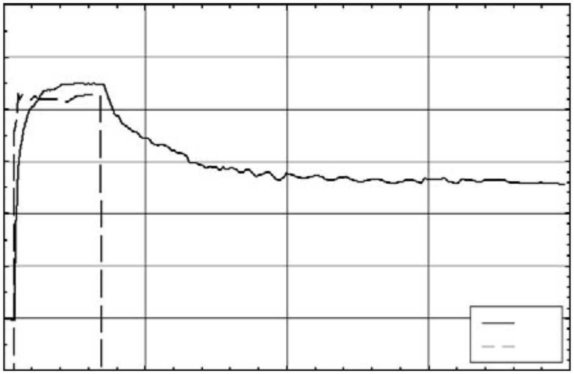


Fig.1 Time dependence of photorefractive index change

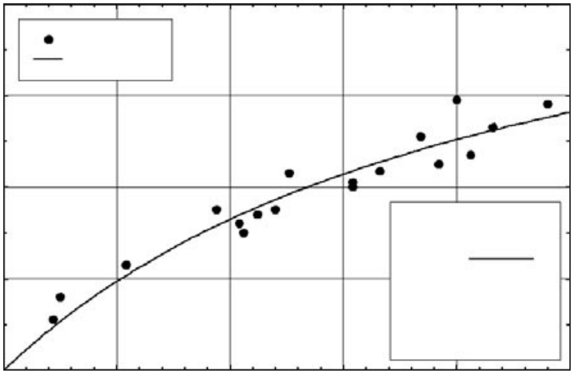


Fig.2 Power dependence of the photorefractive saturation value

These measurements were carried out at different powers and different waveguides with varying manufacturing data up to an output power of 120 mW using completely relaxed waveguides. The index changes in saturation are plotted against the output power in ▸ Figure 2. The index changes are lower than $-6x10^{-5}$ and are not disturbing the wave guidance. The use in a phase modulator is also not impaired because of the long photorefractive time constants against the modulation period of space communication.

According the theory [▸3] the amount of $\Delta N,s$ increases with the guided power and reaches a constant value at high powers, depending on the interaction between photocurrent, photo- and dark conductivity and follows the function $\Delta N,s = -aP / (b+cP)$ where P is the guided power, a, b and c are constants [▸7,8]. The saturation occurs at the value a/c and is estimated to be at $\Delta N,s \approx -1x10^{-4}$ from the curve fit in ▸ Figure 2.

The photorefractive index decrease may lead to higher waveguide attenuation during the irradiation. Especially the time interval which corresponds to the photorefractive time constants is of special interest. A highly stable measurement set up had to be chosen to measure the long term waveguide transmission. To avoid fibrecoupling instabilities the measurements were carried out at polarisation maintaining pigtailed waveguides. An Ytterbium-glass fibre laser with the wavelength 1060 nm and an adjustable output power up to 8 W was used because of its very stable beam profile and thus nearly no changes of the incoupling efficiency into the waveguide input fibre. To polarise the pump light a high power polarizer was inserted between laser and waveguide input fibre. To measure the input power P_{in} a calibrated fibre bend coupler was used, while the output power P_{out} could be measured directly.

The time dependences of P_{in} as well as P_{out} were measured at several constant laser power levels with durations between 8 hours and some days. ▸ Figure 3 shows this behaviour at an output power of 1.5 Watt. The ratio P_{out}/P_{in} gives information about the waveguide insertion loss and is plotted additionally. At output power levels less than 500 mW it did not change. At higher powers the ratio first decreases in very short time and increases in the following hour of irradiation leading to a saturation at approximately 90% of the initial value corresponding to an additional attenuation of 0.5 dB. It indicates a change of the insertion loss, possibly caused by changes of the fibre coupling efficiency due to photorefractive guided mode field distribution alterations. After each measurement the insertion loss was determined and no change was found at a measurement accuracy of 0.3 dB.

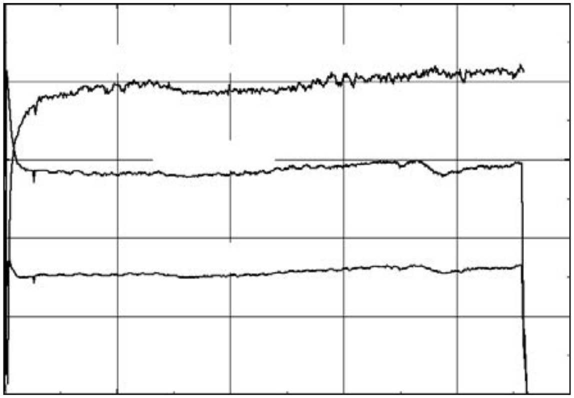


Fig.3 Long term irradiation at an output power of 1.5 W

To find possible long term degradation effects at space communication powers the irradiation time was extended up to 14 days at an output power of 300 mW. No noticeable changes of the ratio P_{out}/P_{in} could be determined.

The laser power was increased until the output power reached 2 Watt. It was held over 9 hours. After subsequent increase of the output power up to 2.7 W the input fibre core became destroyed, while the waveguide itself did not lost its transmission value.

We have shown the possibility of singlemode light guidance up to 2 W at 1064 nm in annealed proton exchanged waveguides for times much longer than the photorefractive time constants. Concerning the low amount of the index changes stable waveguidance should be possible for powers in the range of several 100 mW suitable for applications in space communication.

Acknowledgment

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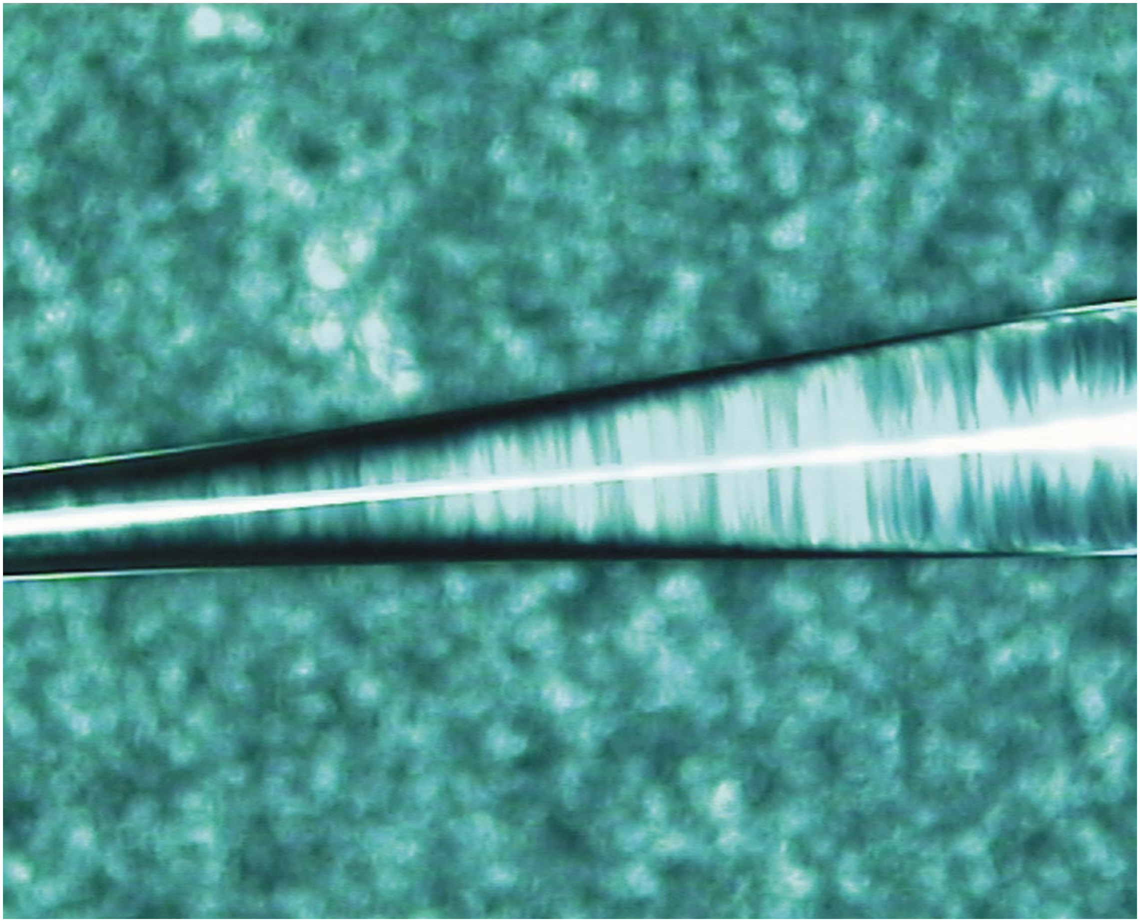


FIBER AND WAVEGUIDE LASERS

Dr. Holger Zellmer, Dr. Jens Limpert, Thomas Schreiber

All fiber chirped-pulse amplification system based on compression in air-guiding photonic bandgap fiber

Rare-earth-doped fibers have established themselves as a very attractive gain medium for ultrashort pulse amplification. This fact is due to their inherent properties such as high optical-to-optical efficiency, broad gain bandwidth and outstanding thermo-optical behavior, but also due to compactness, robustness and simplicity of operation. The main performance limitation of ultrafast fiber laser systems is nonlinearity in the fiber core, the most important being self phase modulation and stimulated Raman scattering. These restrictions can be overcome by applying so-called large-mode-area fibers and the well-known chirped-pulse amplification (CPA) technique. Fiber based chirped-pulse amplification has been demonstrated resulting in high energy and high average power femtosecond pulses.

In its simplest form such a CPA system consists of a diffraction grating stretcher and compressor unit with the doped fiber as gain medium in between. The use of bulk optics and gratings require free space propagation and therefore need alignment. This diminishes the advantage of a fiber based laser system. In order to build a complete fiber based system, the grating stretcher can be replaced by fiber integrated optical devices such as a standard singlemode fiber or a chirped fiber Bragg grating. Both approaches allow stretching to the nanosecond regime and in particular chirped fiber Bragg gratings provide an engineerability of higher order dispersion. In the case of the compressor the situation becomes more delicate due to the high peak power obtained in the amplifier. Of course, chirped fiber Bragg gratings also offer the possibility of fiber integrated pulse compression.

However, the pulse energy is typically restricted to the nanojoule range because of enhanced nonlinear pulse distortion with increasing pulse peak power during the compression. Alternatively, chirped-periodic quasi-phasematched gratings can be applied, offering scalability in peak power but are restricted in achievable time delay (~50 ps). In this contribution, we report for the first time to our knowledge on an all fiber CPA system based on pulse compression in an air-guiding photonic band gap fiber which possesses anomalous dispersion and a significantly reduced nonlinearity due to the guiding of the laser radiation in air. Using this approach we achieved 0.82 MW peak power pulses out of the fiber compressor without any nonlinear pulse distortion.

An air-guiding photonic band gap fiber usually consists of a stack of thin-walled capillaries with an extra large hole in the center, as shown in ▸Fig. 1. Light is guided in a well-defined wavelength range and trapped by a 2D photonic band gap (PBG) of the cladding. Due to the confinement of the radiation in the hollow core the nonlinearity is significantly reduced. Experiments have shown that the nonlinear coefficient of the hollow core fiber mode is very close to that of air. Therefore, these fibers can be very useful for the delivery of high energy ultrashort laser pulses. Furthermore, the risk of damage is reduced due to the airguiding.

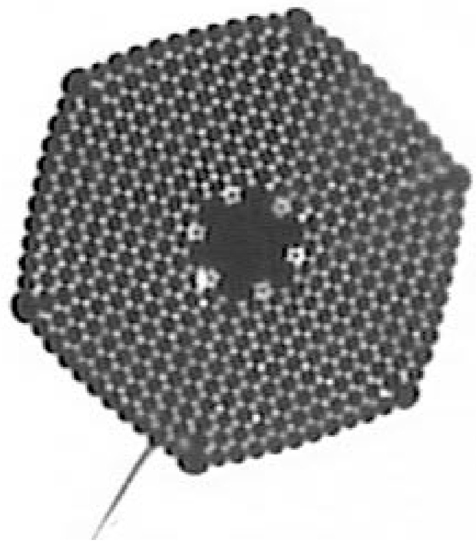


Fig.1 Microscope image of an air-guiding photonic bandgap fiber. Bright regions are fused silica and dark regions are air.

The dispersion characteristic of such a bandgap fiber with a well-defined transmission range is in first order determined by the Kramers-Kronig relation and waveguide dispersion. Therefore, the dispersion is anomalous over much of the transmission band. This implies that such fibers can support optical solitons, as recently demonstrated by the soliton-type propagation of 5 MW peak power pulses in the 1.5 µm wavelength region in a 1.7 m long bandgap fiber. In a conventional step-index singlemode fiber the propagation of such pulses over comparable fiber length would be impossible due to enhanced nonlinear pulse distortion.

In our experiment the anomalous dispersion over the bandgap is applied to compensate for the normal dispersion of an ultrashort fiber amplifier. The air-silica photonic bandgap fiber used (Crystal Fibre AIR-10-1060), shown in ▸ Fig. 1, has a core diameter of 10.5 µm and the bandgap ranges from 980 nm to 1080 nm with an attenuation of less than 0.1 dB/m. The spectral attenuation of this fiber is shown in ▸ Fig. 2. The group-velocity parameter at the operating wavelength, 1040nm, of the ultrafast fiber laser system is experimentally determined to –0.054 ps^2/m by measuring the temporal pulse broadening of an initially unchirped 250-fs pulse in the fiber. The propagation is assumed to be linear (only dispersion) since no changes in the spectrum are observable.

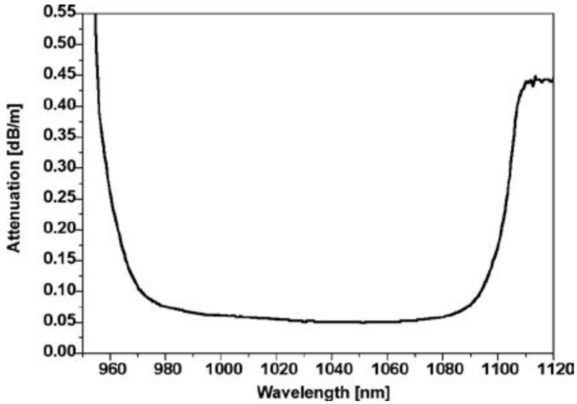
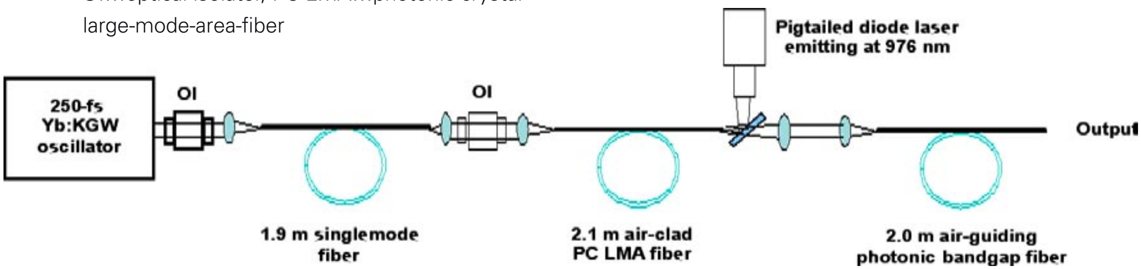


Fig.2 Measured spectral attenuation of the air-guiding photonic bandgap fiber.

The high peak power ultrafast fiber laser system consists of a mode-locked Yb:KGW oscillator, a standard single-mode stretcher fiber, a diode-pumped air-clad mircostructured large-mode-area ytterbium-doped fiber amplifier and the air-core photonic bandgap fiber for dispersion compensation, as shown in ▸ Fig. 3.

Fig.3 Experimental setup of the all fiber CPA system; OI…optical isolator, PC LMA…photonic crystal large-mode-area-fiber



The passively mode-locked Yb:KGW oscillator is running at 73 MHz repetition rate, producing pulses as short as 250 fs at 1040 nm center wavelength and 80 mW average power. A 1.9 m long step-index single-mode fiber is used for pulse pre-stretching to about 1.9 ps. In addition, a spectral broadening due to self-phase modulation is observed. At a transmitted output power of 40 mW the spectral width is as high as 20 nm. Launching the 250-fs pulses directly into the high gain amplifier fiber leads to an excessive spectral broadening due to selfphase modulation beyond the bandwidth limit of the ytterbium-doped fiber amplifier.

This results in a nonlinear chirp and therefore a reduction of re-compressibility of the pulses. The fiber amplifier is constructed using a 2.1m long air-clad microstructured ytterbiumdoped large-mode-area fiber. The single transverse mode core has a mode-field diameter of 21 µm and a 150 µm diameter inner cladding with a numerical aperture of 0.55. The fiber is pumped by a fiber-coupled diode laser emitting at 976 nm. The output characteristic of the amplifier is shown in ▸ Fig. 4. The 40 mW average seed power is amplified to a maximum of 8.2 W with a slope efficiency of 62% with respect to the launched pump power. At the highest output power the spectral width is increased to 28.5 nm (shown in ▸ Fig. 5) and the temporal width to 4.0 ps.

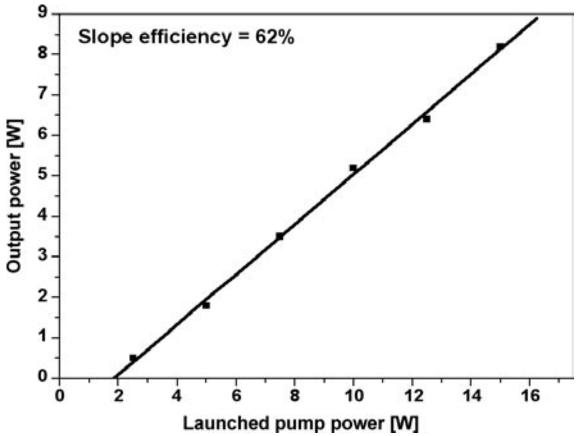


Fig.4 Output characteristics of the Ytterbium-doped fiber amplifier.

A length of 2 m of the air-guiding photonic bandgap fiber, described in Section 2, is used to recompress the amplified, positively chirped pulses. ▸ Figure 5 compares the spectrum of the amplifier output with the output of the photonic bandgap compressor fiber at the highest power level. No changes in spectrum are observed, this leads to the conclusion that neither the transmission characteristics of the bandgap nor nonlinear effects in the air-core fiber affect the pulses at this high peak power level.

The dispersion compensation is fine optimized by changing the length of the single-mode fiber in front of the fiber amplifier. The best compression is found at a stretcher fiber length of 1.9 m. ▸ Figure 6 shows the measured autocorrelation trace at the best achievable compression. The autocorrelation width is determined to be 156 fs, which corresponds to a pulse duration (FWHM) of 100 fs - assuming a $sech^2$ pulse shape. The wings in the autocorrelation trace can be attributed to nonlinearity (self-phase modulation) in the stretcher and amplifier fiber. They are not due to nonlinearity in the air-guiding compressor fiber which has been proven by the independence of the shape and width of the autocorrelation trace of the transmitted power through the bandgap fiber, what means that the propagation of the pulses in the compressor fiber is determined by dispersion. The maximum average output power of the fiber compressor is 6.0 W, therefore the throughput efficiency is as high as 73% (non-

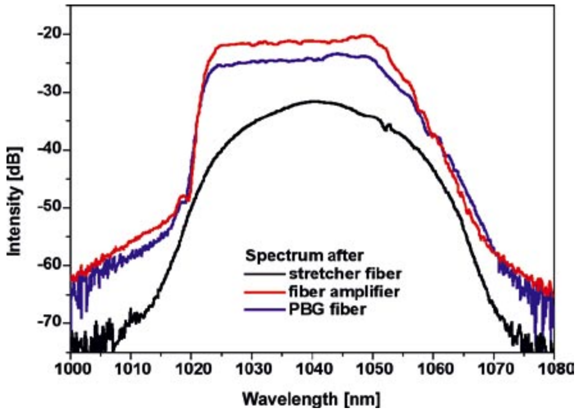


Fig.5 Measured spectra after the stretcher, amplifier and compressor fiber.

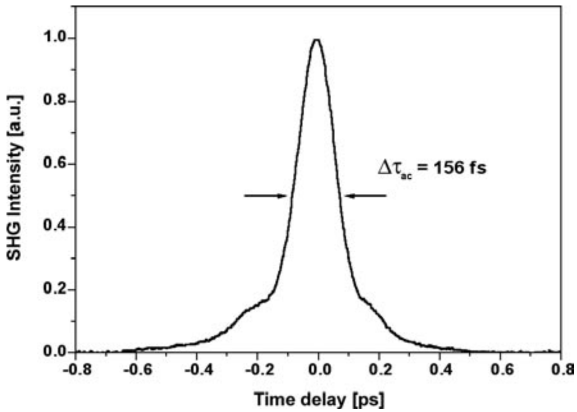


Fig.6 Measured autocorrelation trace of the fiber re-compressed 0.8 MW pulses

optimized). At a repetition rate of 73 MHz of the system this corresponds to a pulse energy of 82 nJ and a pulse peak power of 0.82 MW.

We have demonstrated for the first time, to our knowledge, a high peak power ultrafast fiber laser system based on compression in an air-guiding photonic bandgap fiber. The obtained 100-fs pulses with an average power as high as 6.0 W corresponds to a peak power of 0.82 MW. No nonlinear pulse distortions are observed in the compressor fiber at this peak power level. Since such air-guiding fibers have approximately three orders of magnitude lower nonlinearity compared to conventional single-mode fibers indicates that this approach can be scaled to the µJ pulse energy level with femtosecond pulse duration. Due to the air-guiding fiber, damage will not limit the scalability. Very high values of anomalous dispersion can be obtained especially on the long wavelength edge of the bandgap. Therefore significantly longer initially stretched pulses can be recompressed with a short length of photonic crystal fiber. The main advantage of this approach is the possibility to build up a very compact and completely fiber integrated high peak power and high energy fiber CPA system.

Acknowledgments

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LASER 2003, Munich	Presentation of fiber lasers and integrated-optical modulators

Organizing Activities

Prof. Dr. Andreas Tünnermann

Advanced Solid-State Photonics (ASSP) 2003, San Antonio	Programme Committee Member
Photonics West: "Micro Machining for Micro and Nano Optics"	Programme Committee Member
Photonics West: "Fiber Lasers: Technology, Systems and Applications"	Programme Committee Member
European Physical Society, Quantum Electronics and Optics Division	Member of the Board
CLEO/EUROPE 2003 (Munich)	General Chair
Beutenberg Campus e.V.	Founder and Member
BMBF-Leitprojekt "MICROPHOT"	Network Coordinator
Forschungsschwerpunkt Optomatronik / Zentrum für Optomatronik	Founder and Member of the Board
VDI-Kompetenzfeld: Optische Technologien	Advisory Board
Guided Color Technologies GmbH	Partner
Kompetenzzentrum UPOB	Member
Laser Zentrum Hannover e.V.	Member
OptoNet e.V.	Founder and Member of the Board
Wissenschaftliche Gesellschaft Lasertechnik e.V.	Member
BioCentiv Jena	Member of the Board

Applikationszentrum Mikrotechnik Thüringen	Scientific Advisory Board
Optics Communication	Member of Scientific Advisory Board

Prof. Dr. Frank Wyrowski

SPIE – The International Society for Optical Engineering	Member of the Board of Directors
Journal of Modern Optics	Member of the Board of Editors
SPIE Conferences on Wave-Optical Engineering, 2003, San Diego	Chairman
SPIE Conference on Wave-Optical Engineering II, 2003, San Diego	Chairman
EOS Topical Meeting on Diffractive Optics, 2003, Oxford / U.K.	Co-Chairman
Photonics Europe 2004	Member of the Steering Committee

Dr. Stefan Nolte

CLEO: “Laser Applications and Optical Instrumentation Systems”	Programme Committee Member
Photonics West / LASE: “Laser Applications in Microelectronics and Optoelectronic Manufacturing VIII”	Programme Committee Member
Photonics West / LASE: “Commercial and Biomedical Applications of Ultrafast Lasers”	Programme Committee Member

Dr. Jens-Peter Ruske

Working Group “Integrierte Optik”	Member

Dr. Holger Zellmer

CLEO 2003	Programme Committee Member
CLEO/EUROPE 2003	Programme Committee Member

Awards

Otto-Schott-Forschungspreis 2003, verliehen für Arbeiten auf dem Gebiet “Faserlaser und miniaturisierte Optik”	*Prof. Dr. Andreas Tünnermann*
Student Poster Award, Photonics West 2003	*Jonas Burghoff*

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