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postal address:
Max-Wien-Platz 1
D-07743 Jena
Germany

location of institute:
Beutenberg Campus
Albert-Einstein-Straße 15
D-07745 Jena

Authors
Prof. Dr. Andreas Tünnermann
Dr. Ernst-Bernhard Kley
Dr. Stefan Nolte
Dr. Georgy Onishchukov
Dr. Jens-Peter Ruske
Prof. Dr. Frank Wyrowski
Dr. Holger Zellmer

Content

Foreword

■ Tailored Light – Licht nach Maß

Recent market surveys clearly show that optical technologies will be an enabler and a catalyst for future developments in communication and information, automotive and transport, production and life science. The use of optical technologies will lead to new products, methods and processes of outstandingly higher quality and productivity together with better safety and environmental sustainability. The Institute of Applied Physics (IAP) with its competence in optics is established in these growing markets and ready for future challenges.

The research at the IAP was focused on the design and manufacture of opto-mechanical systems and had been performed in close collaboration with the Fraunhofer Institute of Applied Optics and Precision Engineering (IOF), of which I am also the director. An area of research common to both the IAP and the IOF is the field of micro- and nano-structured optics. This collaboration on micro- and nano-optics was the base of an application in a competition to establish centers of excellence for the fostering of new scientific talent, organized by the German Federal Ministry of Education and Research. The application was positively evaluated by an international group of referees in the spring of 2004. The center of excellence ultra optics® in Jena is one of six centers in Germany and will be supported with 10 M€ over the next 5 years. This support will be used for basic research in the field of nano-optics to allow for the creation of novel optical systems with highly complex functions.

Current research projects are related to the development of multi-functional optical systems for application in information technology. The structures providing the required optical functions very often have their origin in nature. The eye of the fly, for example, was the model for a newly developed ultra-thin camera objective at the IOF with an overall height of less than 0.3 mm. The bristles of the sea mouse helped in the development of novel fiber lasers and amplifiers. The latter work was honored with the Berthold Leibinger Innovation Award 2004.

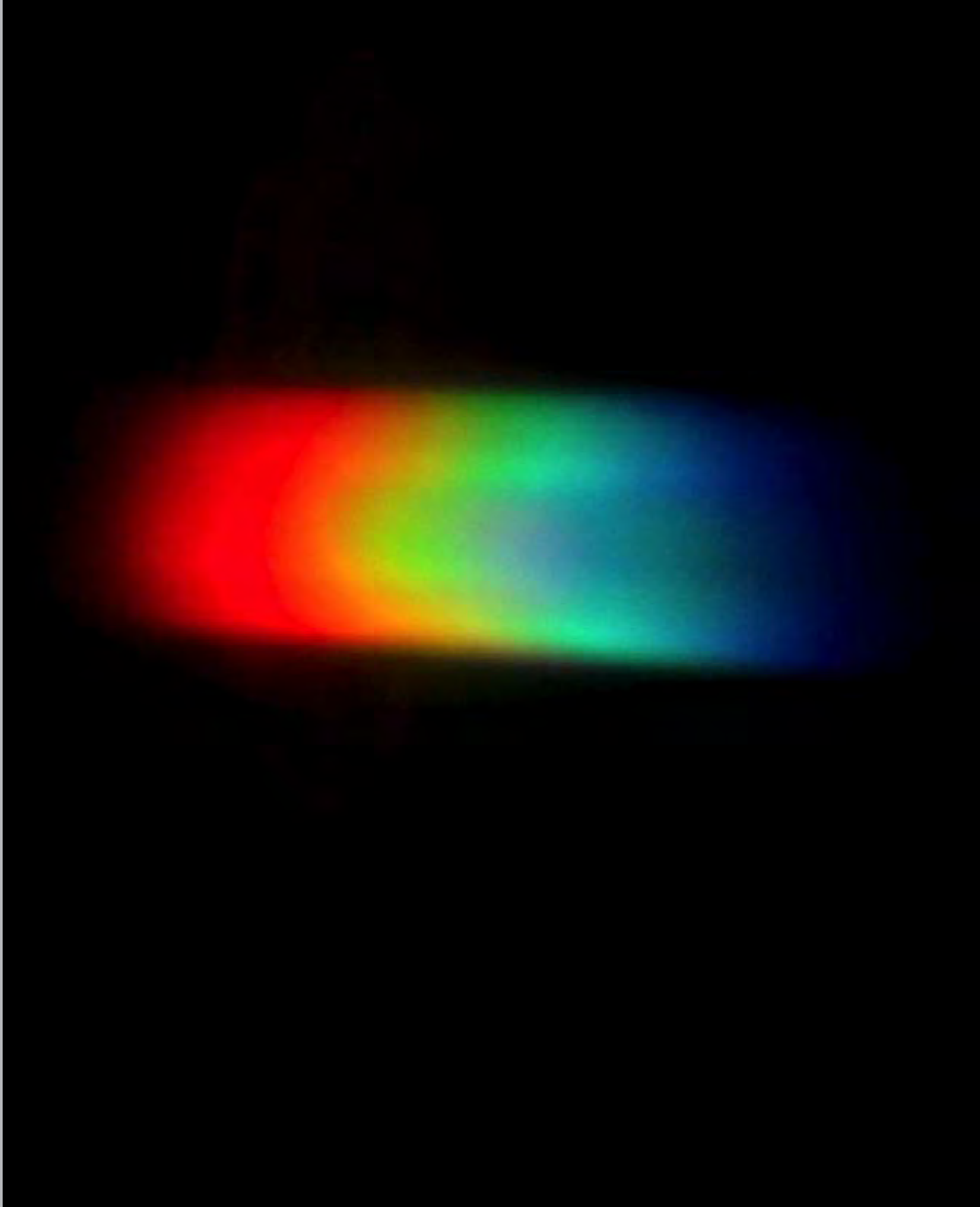
I would like to thank our partners in industry and science for their excellent collaborative work and also: the German Federal Ministry of Education and Research, Thuringia's ministry for science, research and the arts and the Deutsche Forschungsgemeinschaft for their ongoing support.

I hold my colleagues at the IAP in high esteem for their outstanding results and commitment.

Jena, February 2005

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

The Institute



Research Profile

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 30 scientists and engineers are working presently in education and R&D. In addition, about 15 diploma and PhD students and visiting scientists are researching at the IAP.
The institute has a floorspace of 1,200 m² 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) and optic / optoelectronic testing and measuring instrumentation.

Research Fields

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

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

for optical information and communication technology, medicine and biology, process technology including material processing and optical measurement techniques.

Staff Members

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Secretary

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Will, Matthias
Wittig, Lars-Christian
Wyrowski, Frank Prof. Dr.
Head of Optical Engineering
Zellmer, Holger Dr.
Head of Fiber & Waveguide Lasers

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University of Toronto, Canada
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Robert Bosch GmbH
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University of Joensuu, Finland
Hanna Lajunen
University of Joensuu, Finland
Jani Tervo Dr.
University of Joensuu, Finland
Suhas Poyyil Veetil
Indian Institute of Technology, Madras, India

Lectures

Lectures – Summer Semester 2004

Prof. Dr. Andreas Tünnermann:
V: Atom- und Molekülphysik
P: Physikalisches Grundpraktikum

Prof. Dr. Frank Wyrowski:
V: Technische Thermodynamik
S: Technische Thermodynamik
WV: Wellenoptisches Design II

Prof. Wolfgang Karthe,
Prof. Falk Lederer,
Prof. Andreas Tünnermann:
WS: Angewandte Photonik

Dr. Jens-Peter Ruske,
Dr. Holger Zellmer:
S: Experimentalphysik

Friederike Ewald, Kai-Uwe Amthor,
Christian Thierfelder,
Dr. Stefan Nolte, Thomas Schreiber,
Sabine Volkmer
S: Atom- und Molekülphysik

Lectures – Winter Semester 2004/05

Prof. Dr. Andreas Tünnermann:
P: Physikalisches Grundpraktikum
WV: Grundlagen d. Laserphysik
WV: Experimentelle Methoden der Atom- und Molekülphysik

Prof. Dr. Frank Wyrowski:
WV: Wellenoptische Methoden im Optikdesign
WP: Wellenoptisches Design in der Praxis

Prof. Wolfgang Karthe,
Prof. Falk Lederer,
Prof. Andreas Tünnermann:
WS: Angewandte Photonik

Dr. Jens-Peter Ruske,
Dr. Holger Zellmer:
S: Experimentalphysik

Diploma Theses · Doctoral Theses · Habilitation

Diploma Theses

Ulrike Fuchs
Theoretische und experimentelle Untersuchungen zur Propagation ultrakurzer Laserpulse durch Fokussierungsoptiken

Tobias Gnausch
Formung von LED-Strahlung mittels deterministischer Diffuser

Jens Jahn
Design und Analyse diffraktiver optischer Systeme in der Beleuchtungstechnik

Thomas Kämpfe
Strahlformung für die Holographie

Thomas Käsebier
Entwicklung eines Verfahrens zur Herstellung kontinuierlicher Höhenprofile für die Integrierte Optik und Mikrooptik

Gabor Matthäus
Verstärkung und thermische Effekte in neodymdotierten aktiven Wellenleitern

Thomas Paul
Untersuchungen zur Genauigkeit der Modellierung linearer optischer Systeme

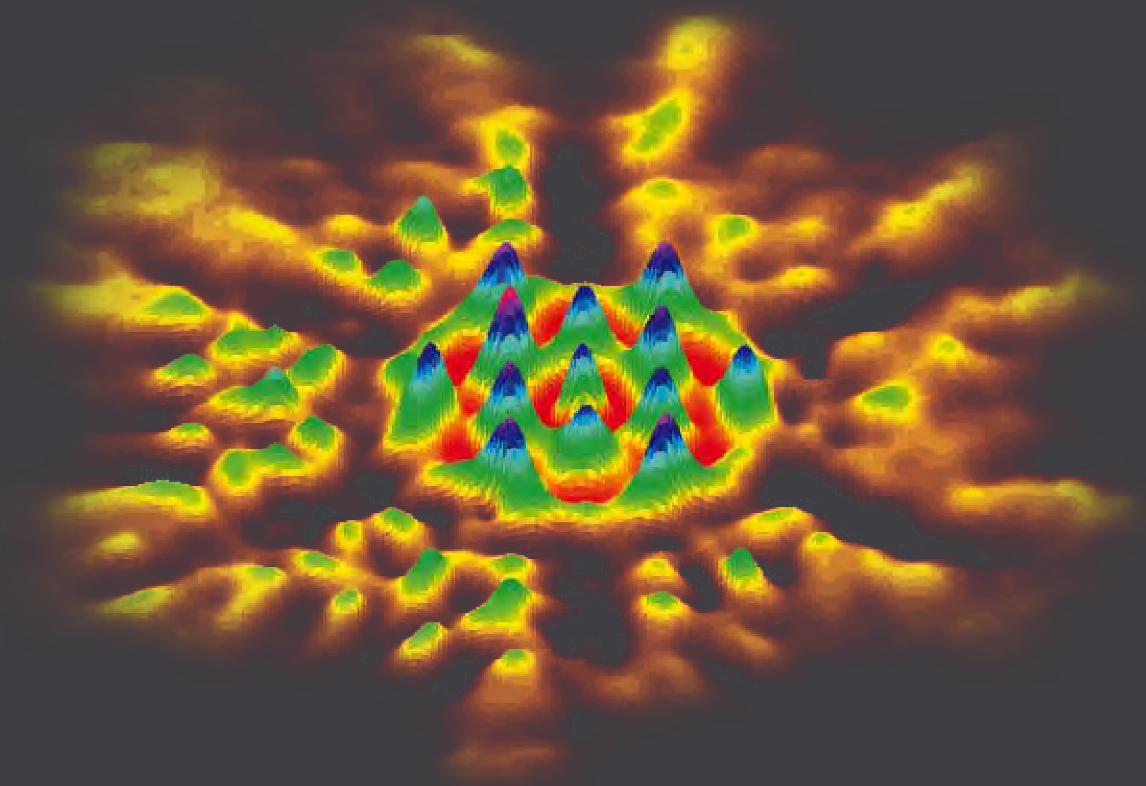
Doctoral Theses

Matthias Will
Ultrakurzpulsinduzierte Brechzahlmodifikationen in transparenten Festkörpern

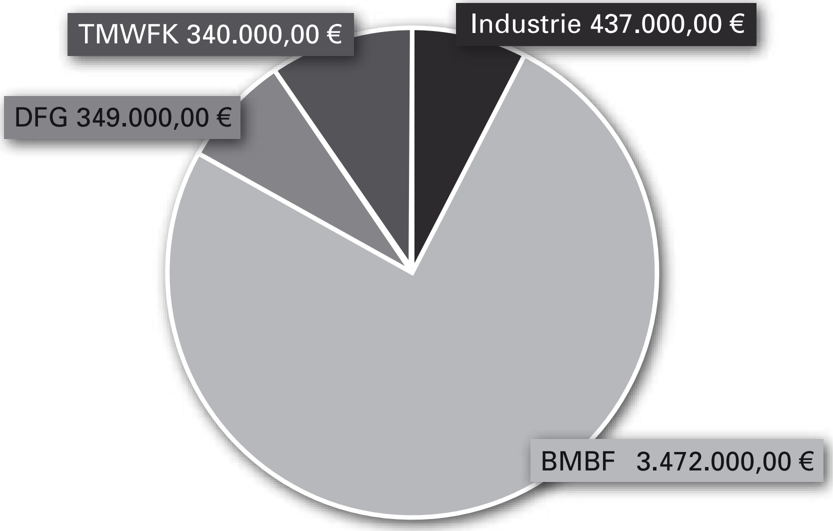
Habilitation

Jens-Peter Ruske
Integriert-optische Bauelementkonzepte zur Führung und Beeinflussung von Licht hoher Leistung und Photonenenergie

Projects



Statistics



Externally Funded Projects

DFG-Vorhaben:

Teilchenstrahl-stimulierte Ultrapräzisions-Oberflächenbearbeitung;
TP Ionenätzen
(Project term: 1/2000 – 12/2004), Forschergruppe

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

SFB Transregio: Gravitationswellenastronomie
(Project term: 1/2003 – 12/2006)

Projects

Photonische Kristalle, TV: 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)

Monolithische Integration photonischer Bauelemente auf Basis der Flüssigphasenepitaxie (SPP: Integrierte elektrokeramische Funktionsstrukturen)
(Project term: 11/2003 – 10/2005)

10th Microoptics Conference 1. – 3.9.04
(Project term: 9/2004)

Nichtlineare-raumzeitliche Dynamik in dissipativen und
diskreten optischen Systemen (Zentralprojekt)
(Project term: 3/2004 – 6/2007)

Dimensionseffekte in diskreten Systemen (Teilprojekt)
(Project term: 3/2004 – 6/2007)

Neue Strategien der Mess- und Prüftechnik für die Produktion von
Mikrosystemen und Nanostrukturen – NanoStreu
(Project term: 10/2004 – 9/2006)

TMWFK-Vorhaben:

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

OPTOMATRONIK: Integriert-optische Systemtechnik: Konzeption, Darstellung und Charakterisierung mikro- und nanostrukturierter optischer Elemente - Strukturtransfer
(Project term: 10/2004 – 6/2005)

BMBF-Vorhaben:

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

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

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

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

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

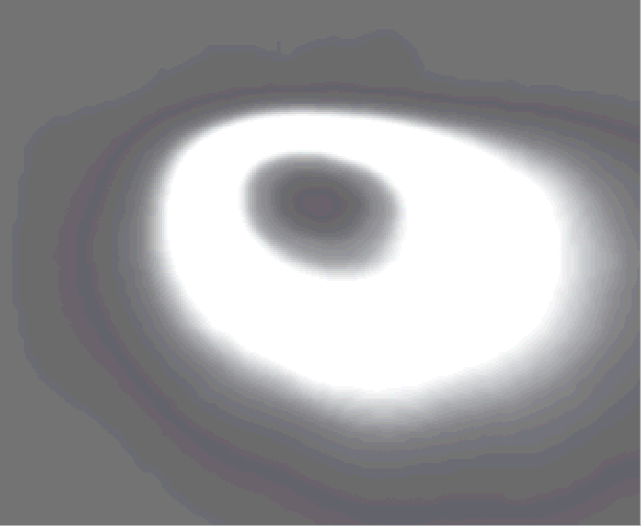
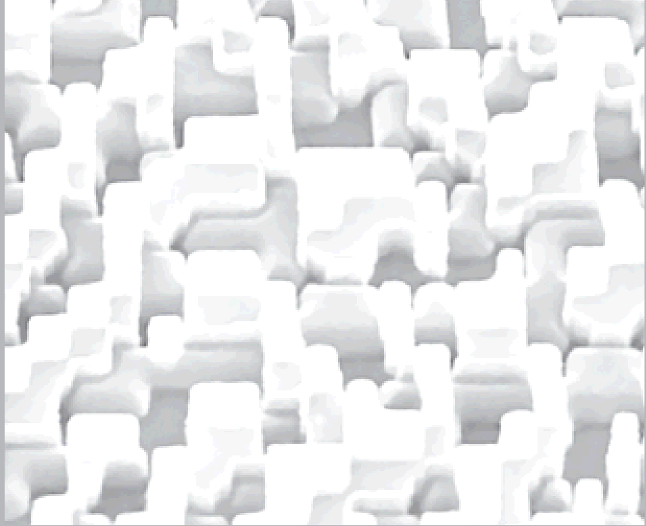
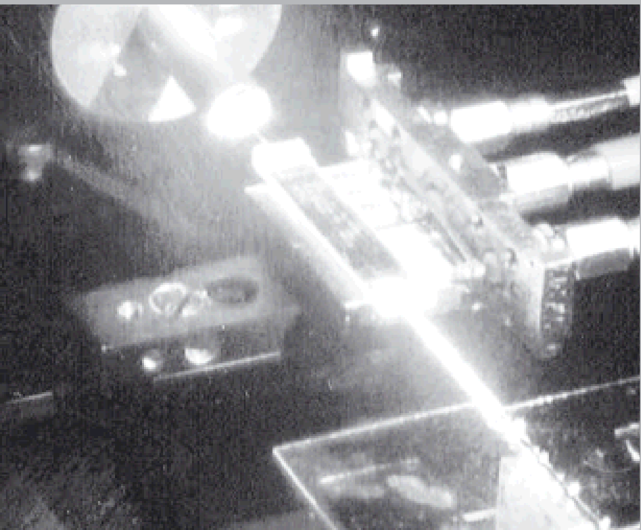
Photonische Kristallfasern für neuartige Lichtquellen mit steuerbarer Funktionalität – TV: Nanostrukturierte Wellenleiter zur Erzeugung und Führung hoher Leistungsdichten (PHOFAS)
(Project term: 6/2002 – 5/2005)

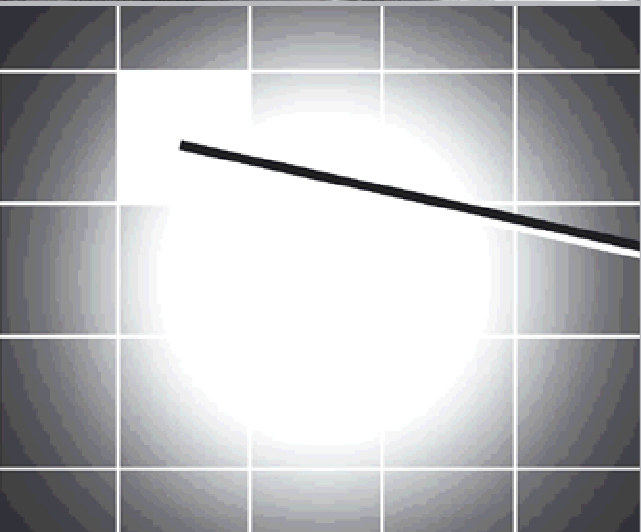
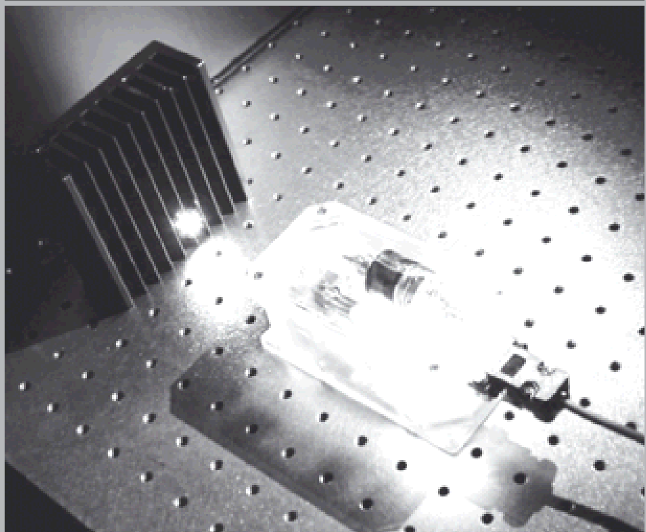
CoOp: Verbundprojekt Hybride Integrationstechnologie für kompakte, funktionale und fertigungstaugliche optische Module, TV: 3D-Lithografie
(Project term: 5/2004 – 6/2006)

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

Zentrum für Innovationskompetenz ULTRAOPTICS, strategische Investitionen
(Project term: 6/2004 – 12/2004)

Thermo-optisches Design von Hochleistungsfaserverstärkern
(UA: Thermo-optische Analyse von Faserverstärkersystemen)
(Project term: 7/2004 – 3/2005)

Achievements & Results

- Microstructure Technology & Microoptics
- Ultrafast Optics
- Optical Communication Systems
- Integrated Optics
- Fiber & Waveguide Lasers
- Optical Engineering

Achievements & Results

Microstructure Technology & Microoptics

Dielectric pinhole for high power and high divergencies

Dr. Ernst-Bernhard Kley

Introduction and principle

To remove disturbances of the lateral intensity distribution of laser beams, which can for instance be caused by impurities of optical components, spatial frequency filtering can be applied. This method is based on the assumption, that the spatial frequencies of unwanted disturbances (in the following called "noise") are significantly higher compared to the ones of the intensity distribution itself (called "signal"). Thus, in any spatial frequency plane, for example in the back-focus-plane of a lens, a pinhole separates high and low spatial frequencies and thus cleans the beam (Fig. 1).

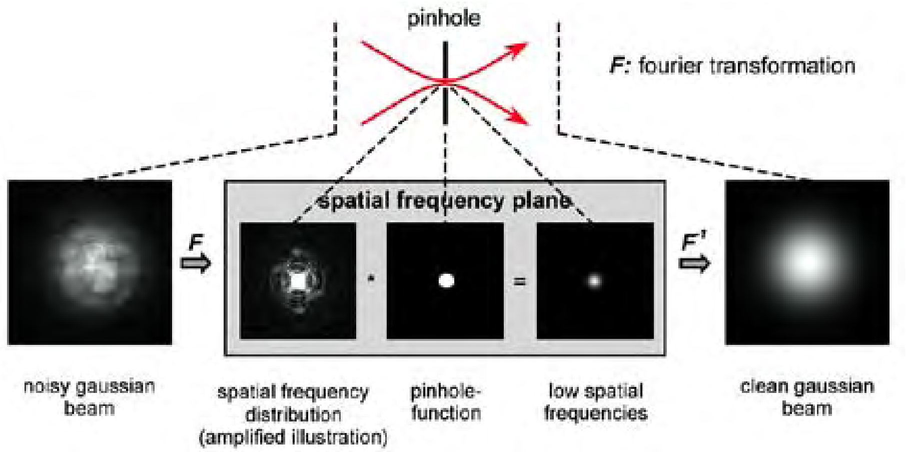


Figure 1: Principle of spatial frequency filtering

When the outgoing beam has a high divergence, the beam-waist becomes both narrow and thin (Fig. 2). Conventional pinholes, based on absorption or reflection have to have a minimum thickness, depending on the optical power they are designed to withstand. Otherwise they can be destroyed, either slowly over time or very rapidly, if fluctuations of the lateral focus-position occur. However, a large thickness means, that the hole of the pinhole gets the characteristic of a tunnel, if a very small hole diameter is chosen, which can lead to an undesired cutting of the beam and to a degradation of the edges of the hole over time (Fig. 2). On the other hand, if a hole diameter much larger than the dimensions of the beam-waist is chosen, the filtering effect will be reduced. Thus, the filtering of very intense laser-beams with a high divergence is problematic. To avoid these problems we presented a new concept of non-absorbing, dielectric pinholes. The basic idea is to deflect the noise instead of absorbing or reflecting it. This allows the optical energy to be safely absorbed later on (Fig. 3). The damage threshold of the pinhole itself is determined by the properties of the structures, deflecting the light. For binary phase gratings it is comparable with the bulk material (e.g. fused silica: approx. 4000 J/cm^2,). The height of the structures is in the range of the wavelength of the used light, so a tunnel shape is avoided even for very high divergencies. These characteristics suggest the use of dielectric pinholes for filtering high power, high divergence laser beams.

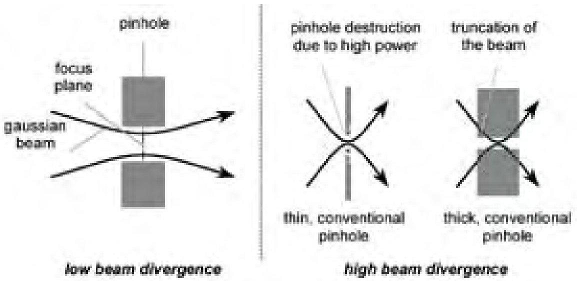


Figure 2: Problems while filtering high divergencies

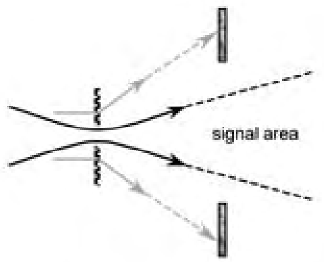
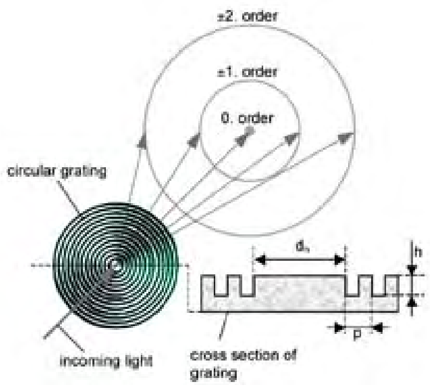


Figure 3: New idea for dielectric pinhole

Design of the pinhole device

The dielectric pinhole is a circular grating with an unstructured region in the middle, representing the“hole”. The grating deflects the noise into circular diffraction orders, while the signal passes through the hole. For the design of the dielectric pinhole it is important, that firstly the gaussian beam itself remains undisturbed and secondly the noise is separated and does not interfere with the signal later on. These demands must be considered for the design of the pinhole parameters (Fig. 4), which are the hole-diameter d_h, the deflection angle Θ_d, and the grating parameters period *p*, height *h* and fill-factor *f*.



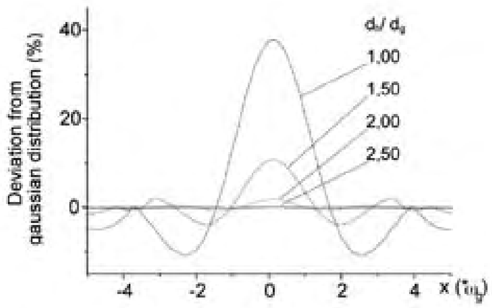


Figure 4: Circular grating as dielectric pinhole Figure 5: Intensity deviations caused by beam cutting

The Fourier transformation of a gaussian distribution has itself a gaussian shape, which reaches zero not until infinity. Therefore a perfect separation of noise and signal is never possible. The pinhole diameter should thus be chosen as small as possible in a way, that the intensity fluctuations, caused by the cutting of the beam at the pinhole, are at least as small as the fluctuations, caused by the unfiltered part of the noise. Fig. 5 shows the deviation of the intensity of a gaussian beam for different ratios d_h/d_g, where d_g is the beam waist diameter.

The spatial intensity distribution of the noise is often unknown or fluctuating, so the optimal pinhole diameter can only be determined experimentally. For practical applications, d_h/d_g=2.5 is a good approximation, since it introduces errors of less than ±0.3% while maintaining a good filtering effect for typical noise distributions.

The circular grating diffracts the light into deflection orders. The deflection-angle β_d, which is responsible for the separation of signal and noise, has to be determined. Its exact value depends on the spatial distribution of the noise, but an estimation can be done in the following way (Fig. 6). Typically, only the gaussian beam itself is modulated by the noise with no significant noise amplitudes outside of the beam. Thus, if the complete beam was deflected (Fig. 6a), also in the deflected beam the noise would only fill the area of the gaussian beam, measured by Θ_G. When signal and noise are separated by a hole in the middle of the deflecting structures, the spatial area filled by the deflected noise stays the same (Fig. 6b). Hence β_d can be estimated to

$$\beta_d \ge 2\Theta_G \,. \qquad (1)$$

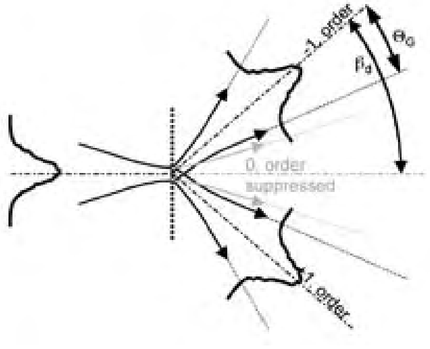


Fig. 6a

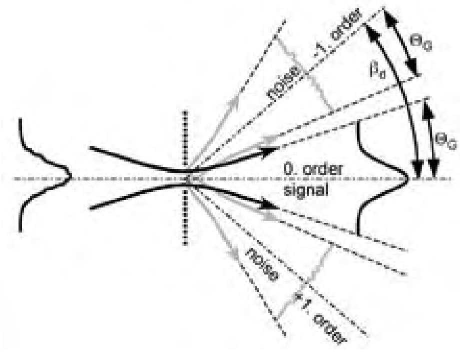


Fig. 6b

The period of the grating *p* determines the diffraction angles φ_m according to the diffraction equation

$$\sin(\varphi_m) = \sin(\varphi_{in}) + \frac{m\lambda}{p} \tag{2}$$

where φ_{in} is the incident angle, λ is the wavelength and *m* an integer number. Since the pinhole is placed into the focus of the beam, φ_{in} can assumed to be zero. The angle of the first orders must fulfill equation (1). The zeroth order remains in the signal area. It has to be suppressed by optimizing the grating parameters *h* and *f*. This grating profile design has to be done with respect to the polarization of the beam also.

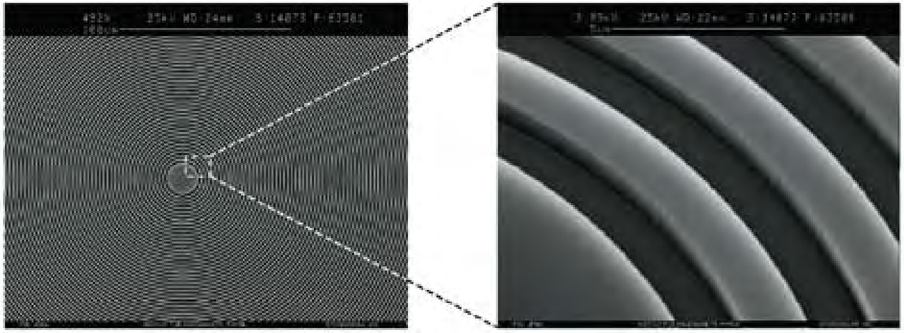


Figure 10: SEM pictures of fabricated grating

Figure 10 shows a fabricated grating. A simple demonstration of the optical effect of the pinhole device can be seen in figure 11.

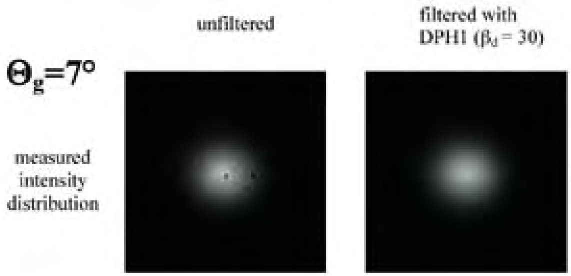


Figure 11: Gaussian beam, left side unfiltered, right filtered

Application

Some advantages of such pinhole devices are of importance. Firstly, it can be used for high intense laser beams with high divergencies. Secondly, the handling is very comfortable, which means the adjustment of the pinhole turned out to be easy. This is because the transmitting diffraction orders can always be seen and can be used to determine the pinhole position. A further advantage is the lithographic fabrication that defines the hole quality perfectly and enables the integration with other optical elements fabricated by lithography. An example is the combination of a pinhole with a beam shaping element for holographic recording applications sketched in figure 12.

The beam shaping element was fabricated by gray tone lithography and proportional etching into fused silica on the front side of a substrate. Additionally it is structured with a statistical nanopattern (moth eye pattern) for antireflection purpose (figure 13). The pinhole is located on the backside of the substrate and contains statistical nanopattern also.

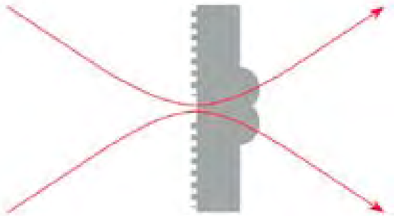
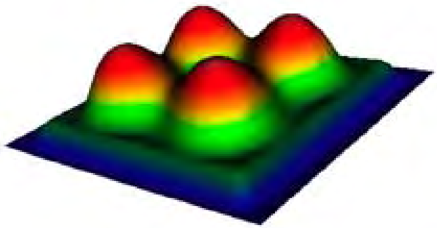


Figure 12: Sketch of the monolithic integration of a dielectric pinhole and a beam shaping element



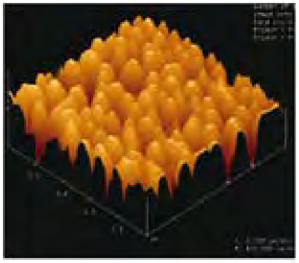
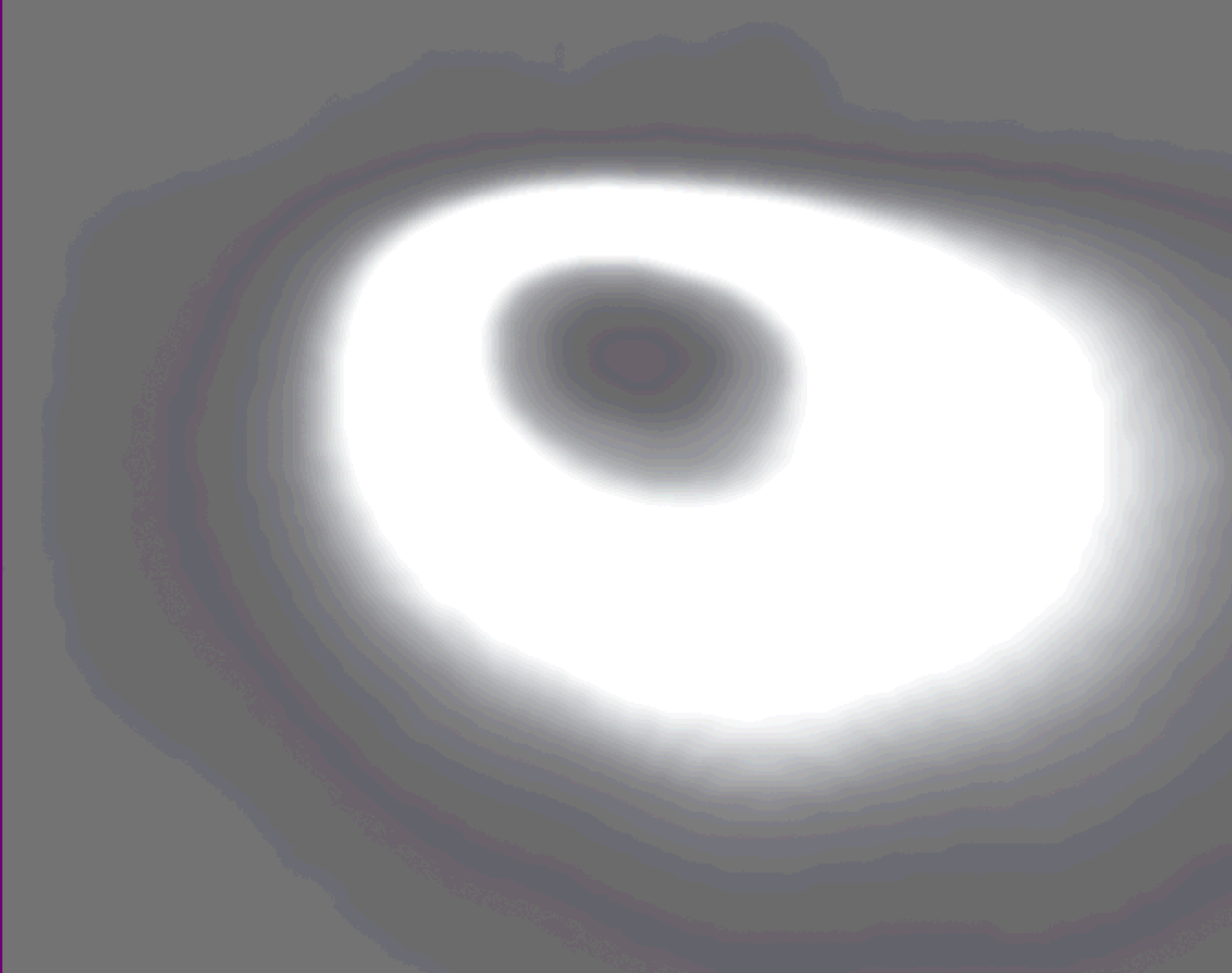


Figure 13: Left, surface profile of the beam shaping element, measured with a white light profilometer Right, statistical nanopattern for antireflection, measured with AFM

Achievements & Results



■ Ultrafast Optics

Optical waveguides in crystalline silicon by mid-infrared femtosecond laser pulses

Dr. Stefan Nolte

Silicon, the standard material for microelectronics, is relatively unexplored for micro-optical applications. Although it offers high transmission throughout the whole optical telecommunications band – wavelengths ranging from 1.3 to 1.6 µm – the limited modulation rate in silicon based integrated optical devices hindered its use. However, recent developments of silicon-based optical circuits made it possible to surpass the 1-GHz modulation rate threshold for optical networking applications. Here, we describe our investigations on generating buried refractive-index structures in silicon by ultrashort laser pulses as a new means for shaping passive microoptical components for near-infrared applications. The use of bulk silicon – unexploited in today's microelectronic applications – offers the possibility to combine optical guided-wave structures with photodetectors and electronic processing onto the same silicon chip. This promises highly functional system-on-a-chip devices that will accelerate application directions in fiber-to-the-home, optically interconnected computers, sensor systems, and display technologies.
The fabrication of guided-wave optics in bulk glasses by means of femtosecond laser irradiation was studied within the past ten years. Focusing the intense femtosecond laser pulses inside the material allows to create three-dimensionally localized structural and refractive index changes within the focal volume, where the laser intensity overcomes some threshold. In this way, low-loss as well as true three-dimensional integrated optical devices have been realized. However, crystalline media have only been used for modification in a few investigations. Here, we extend these investigations to bulk crystalline silicon. Due to the 1.1-eV bandgap the material is opaque to the 800-nm Ti:Sapphire laser radiation (or its upconverted harmonics), which have typically been applied so far to form optical waveguides inside glasses.

Thus, we downconverted the femtosecond laser pulses to a mid-infrared wave-length of 2.4 µm in order to drive nonlinear three-photon absorption in the laser focal volume without inducing bulk absorption in the surrounding medium.
For our experiments we used a commercial chirped-pulse-amplified Ti:sapphire laser (Spectra-Physics, Spitfire) providing 70-fs pulses of 600-µJ energy at 1-kHz repetition rate. Using an optical parametric amplifier (OPA; Spectra-Physics OPA-800C) the photon energy was split, resulting in a 2.4-µm wavelength idler beam, to which silicon is transparent. The photon energy associated with the 2.4-µm light is slightly less than half of the silicon band-gap, ensuring that laser interactions are initiated by a nonlinear three-photon process. This is in accordance with third- or higher-order processes most frequently applied in demonstrations of ultrafast laser waveguide writing in transparent glasses. Figure 1 shows the beam profile of the idler radiation as well as an autocorrelation providing a pulse duration of < 100 fs.

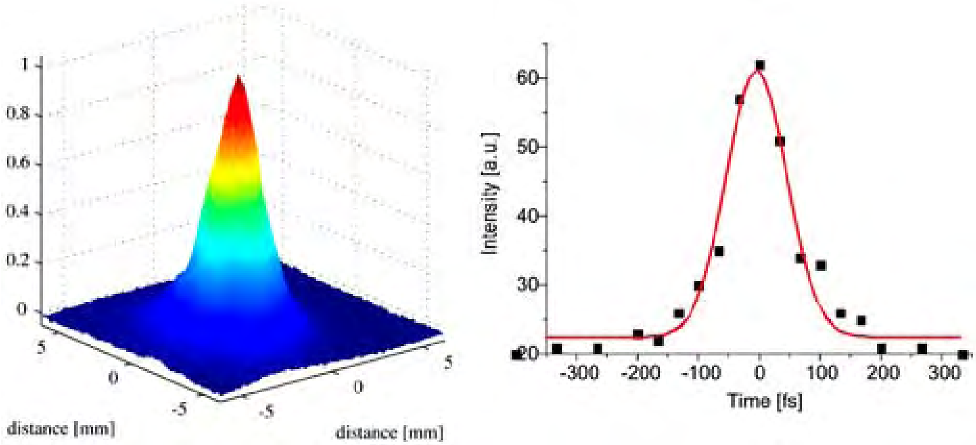


Figure 1: Characterization of the writing femtosecond laser beam. Beam profile (left) and autocorrelation of the idler radiation yielding a pulse duration < 100 fs (right).

The idler beam of the OPA was focused by an aluminum-coated Schwarzschild reflective objective with a numerical aperture of 0.5 into a c:Si wafer overcoated with a 20-µm-thick oxide layer in order to provide some impedance matching owing to the high refractive index of silicon (n ~ 3.5). However, as further investigations showed, this oxide layer is not necessary and does not provide significant benefits. The on-target energy was 1.7 µJ/pulse. The beam was focused to various depths in the silicon bulk, and the sample was translated transversely at 2 mm/min. The polarization of the beam was perpendicular to the trajectory.
After fabrication, the end facets of the silicon wafer were polished to yield 6.7-mm-long waveguides. For characterization of the induced modifications laser sources at 1320 and 1550 nm were launched by butt coupling a single-mode glass fiber or by free-space lens firing into the front facet of the polished sample. The near-field mode profiles of the waveguides were captured at the output facet with a standard 40x microscope objective on a high-resolution infrared camera.
Low-loss waveguides could be observed only in a narrow focusing depth range of 90–130 µm from the silica–silicon interface. Focusing closer to the interface (0–75 µm) or very deep into the bulk (>150 µm) produced waveguiding structures that were overly lossy or exhibited complex transverse intensity profiles. Whereas the waveguide's properties depend largely on the focusing depth, its position was highly invariant to this parameter. Waveguides appeared at only very small distances of approximately 5–20 µm below the silica–silicon interface, irrespective of the laser focusing depths. This behavior is still under investigation.

Figure 2 shows the single-mode beam profile of a low-loss waveguide at 1550 nm and its position relative to the wafer structure. This sample was fabricated by an ultrafast laser beam focused at 130 μm below the interface, and lens end firing was then applied to excite the guided mode. The extension of guided light patterns both laterally and vertically downward indicates the creation of a complex refractive-index profile between the laser focus position and the glass-silicon interface.

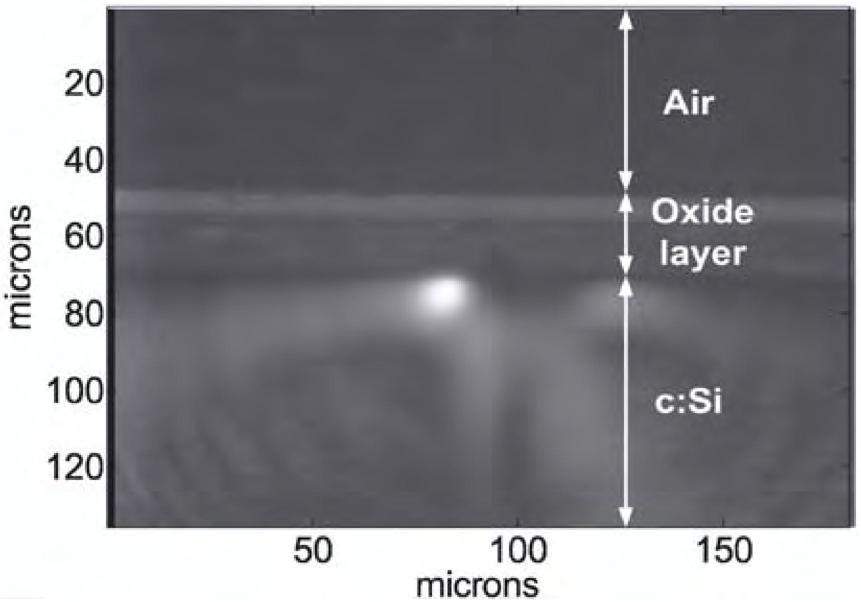


Figure 2: Image of the silicon wafer end facet, showing the waveguide beam profile (at 1550 nm) and its position with respect to the wafer structure. The waveguide was written with an ultrafast laser beam focused ~130 μm below the silica-silicon interface.

The strongly guiding structures showed large birefringent properties. Waveguides exhibited significant loss for the state of polarization parallel to the wafer surface, such that mode profiles as shown in Fig. 2 were not observable. The orthogonal polarization counterpart (perpendicular to the wafer surface) was strongly guided and exhibited moderately low loss.
Although the reasons behind this strong induced anisotropy are not fully understood, we expect the physics of the waveguide formation to be similar to what we previously observed in crystalline quartz. There, strong and rapid heating inside the focal volume of the laser beam leads to local amorphization of the crystal, henceforth exerting nonuniform stress on the surrounding medium, which remains crystalline. As a result, an anisotropic increase in refractive index arises outside the focal volume.

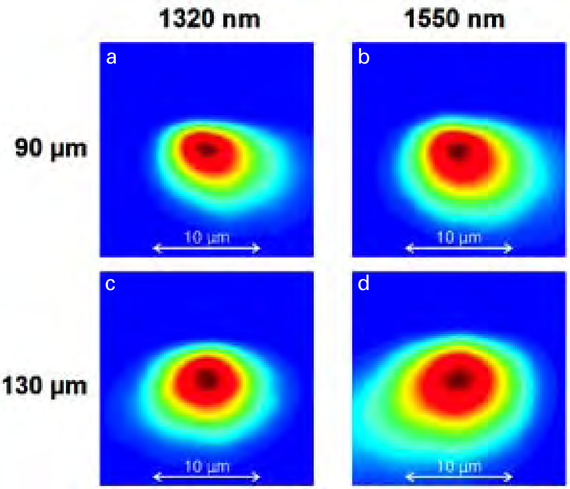


Figure 3: Near-field intensity distributions for silicon waveguides written with the ultrafast laser focused (a), (b) 90 µm and (c), (d) 130 µm below the silica–silicon interface. Probe wavelengths are (a), (c) 1320 nm and (b), (d) 1550 nm.

Fiber butt coupling provided better efficiency than lens firing, yielding the near-field intensity distributions for 1320- and 1550-nm guided light shown in Fig. 3. The leakage of background light noted outside the mode profile in Fig. 2 is no longer apparent here. The mode profiles shown in Figs. 3(c) and (d) belong to the same waveguide depicted in Fig. 2.

A polarization controller was used to launch linearly polarized light perpendicular to the wafer surface. The mode profiles indicate single-mode guiding at both 1320 and 1550 nm. The close proximity of the low-index oxide layer (n ~ 1.47), only ~ 5 µm above the silicon (n ~3.46) waveguide, distorts the vertical symmetry of the beam profile, increasing the intensity gradient along the direction perpendicular to the wafer surface. We estimated a refractive-index increase of ~0.002 for the fabricated waveguides by solving the Helmholtz equation for the observed waveguide mode profiles in Fig. 3. The resulting refractive index distribution of the waveguide is given in Fig. 4.

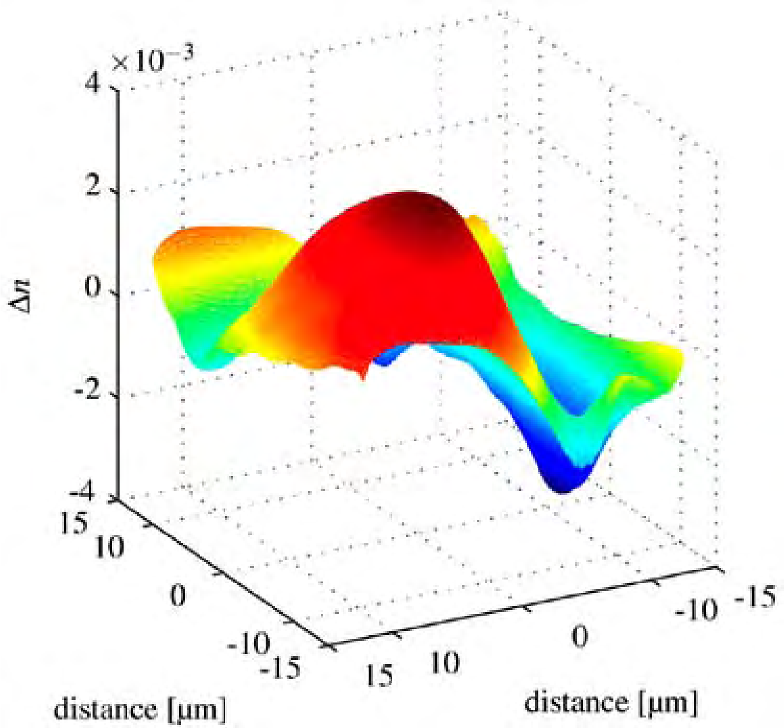


Figure 4: Refractive index distribution of the waveguide shown in Figs. 2 and 3(c), 3(d), respectively. The maximum refractive index change obtained is Δn ~ 0.002.

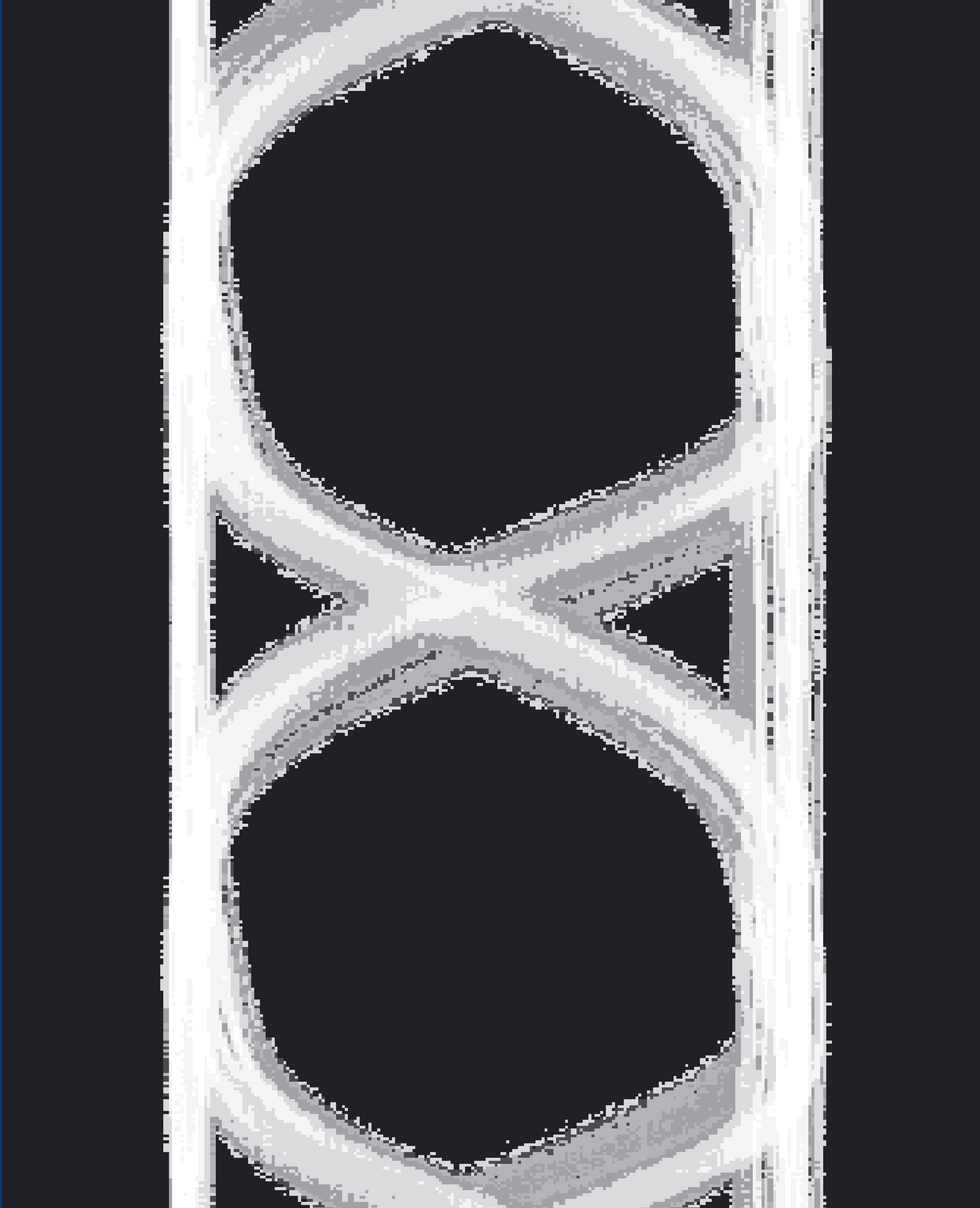
To assess insertion loss we measured the transmitted power by an infrared photodetector. The lowest losses were found for laser scans focused 90 – 130 µm below the silica–silicon interface. The total transmittance for the best waveguides was approximately $T=39\%$ at both 1320 and 1550 nm. After accounting for 30% Fresnel reflection at each silicon–air interface, the insertion losses (excluding Fresnel reflection) reduce to 1 dB (79% transmission) for the 6.7-mm-long waveguides at both wavelengths. The coupling loss that is due to modal mismatch between these guided modes and those that belong to the singlemode fiber was numerically estimated by the overlap integral method. Modestly high coupling efficiencies of η = 90–94% were found.

On this basis, we infer an upper limit of α = 1.2 dB/cm for silicon waveguide propagation loss in the optical telecom spectral band. Losses of this magnitude exceed the standard attenuation figures of merit in today's integrated optics industry of 0.1 dB/cm but are highly attractive for less demanding applications such as metro-optical networks.

In conclusion, low-loss optical waveguides were directly inscribed in bulk c:Si by femtosecond laser pulses for the first time. Key to this demonstration was the extension of the standard ultrafast laser processing into the midinfrared spectrum using an OPA for access to the infrared transmission window of silicon for nonlinear laser interactions. This midinfrared femtosecond laser writing method promises a flexible new means for creating three-dimensional optical circuits in silicon. Such technique is fully compatible with CMOS fabrication technology, facilitating inexpensive integration of high-speed electronics with passive optics, and is therefore well suited to a broad range of applications.

This research was supported by the Thuringian Ministry of Science and Art (TMWFK, B507-02006), the Natural Sciences and Engineering Research Council of Canada, the Canadian Institute for Photonics Innovation, and exchange offices at the universities of Toronto and Jena.

Achievements & Results



Optical Communication Systems

High bit-rate optical fiber communication systems

Dr. Georgy Onishchukov

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). The group of Prof. F. Lederer at the Institute of Solid State Theory and Theoretical Optics, Friedrich Schiller University of Jena provides the theoretical support. Since noise accumulation and signal distortions are the main effects limiting the transmission distance in such systems the emphasis is placed on the signal regeneration using in-line saturable absorbers (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 SOA saturation energy and 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 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.

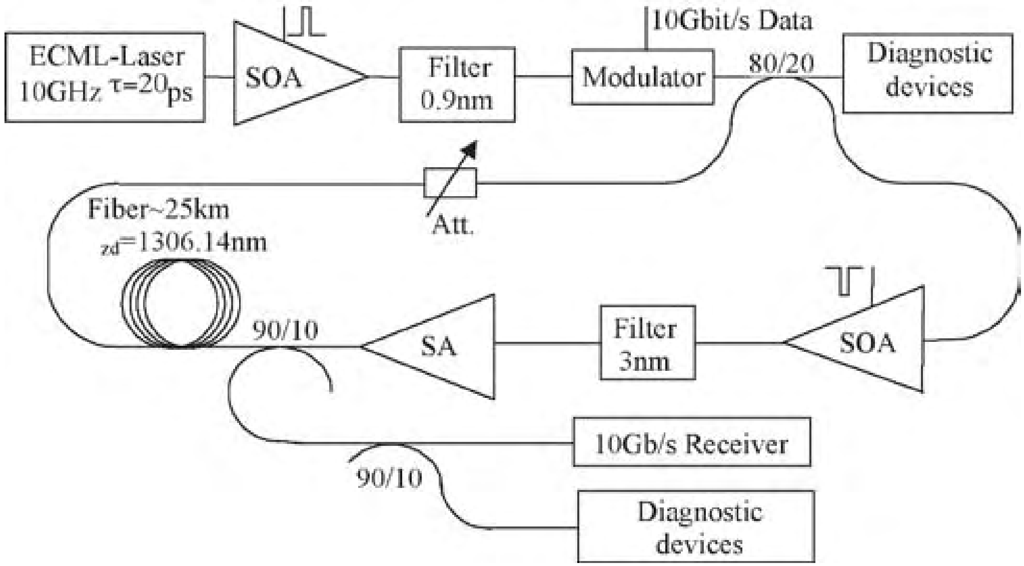


Figure 1: Re-circulating fiber loop set-up for simulation of systems with in-line Semiconductor Optical Amplifier (SOA) and Saturable Absorber (SA).

In the system with in-line SOA and SA a kind of "auto"-2R-Regeneration is realized in a very simple way that is different from common regenerators with an additional laser and an optical gate controlled by the data signal to be regenerated. 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 most signal distortions critical in high bit-rate systems, like PMD, dispersive waves, FWM, etc. Our investigations of bifurcation behavior of 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 low power 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 has also been 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.

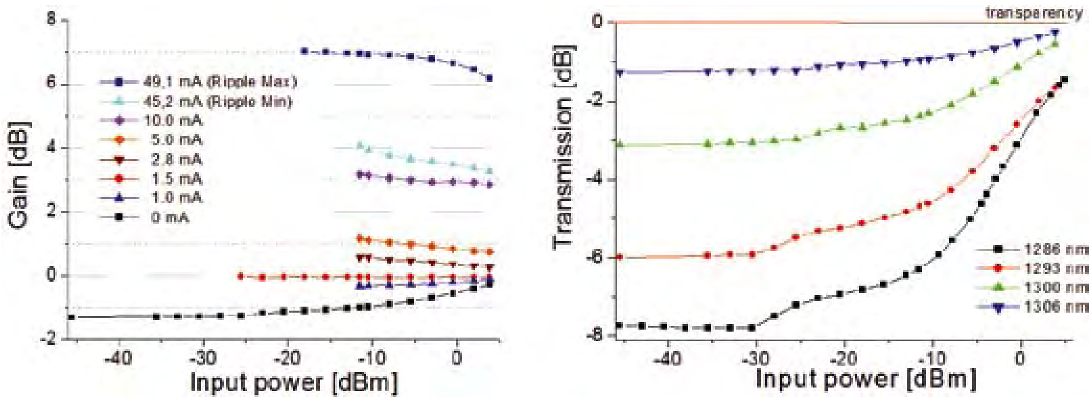
If the ASE and pulse distortions are suppressed using SA, timing jitter becomes the main effect, which limits the transmission system performance. Our investigations have shown that a very low (2 ps at 30 000 km) timing jitter could be obtained in the system with SOA and SA. The main source of the timing jitter 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: low fiber dispersion, high soliton energy, and strong in-line spectral filtering could be easy satisfied.

Recent progress in self-assembled quantum dot (QD) technology has led to the development of unique QD semiconductor optical amplifiers (QD-SOA) with very promising features that could provide a breakthrough improvement of SOA performance in optical networks - more than an order of magnitude decrease of the gain recovery time and a smaller Henry factor, resulting in reduction of signal distortions caused by cross-gain and cross-phase modulation.

The first one would allow to reduce the intersymbol interference effect and to increase the bit rate and the second – to decrease signal spectral width and to increase signal power as numerical simulations showed.

Our investigations of performance of the QD-SOA sample from the group of Prof. L. F. Lester at the Center for High Technology Materials, University of New Mexico, USA showed that it is a really challenging solution but an optimization of QD-SOA structures and of chip mounting is necessary in order to make it possible to use high pump currents, which are necessary for optimum QD-SOA performance. The pump current limitations come primarily from the onset of lasing. Improvement of the structure cooling in the case of flip-chip mounting would be also desirable. Nevertheless as expected the QD-SOA indeed showed weaker intersymbol interference and smaller spectral signal distortions compared with common SOA when a distributed Raman fiber amplifier was used to compensate for high fiber-to-chip coupling losses in the unoptimized QD-SOA device.

The main subject of our research in 2004 was investigations of Quantum Dot Saturable Absorber (QD-SA) parameters and of its performance in the system. The group of Prof. J. P. Reithmaier at the University of Würzburg provided the QD-SA structures with necessary for this application short chip length. When operated as SOA they have parameters quite similar to that of the sample from New Mexico. In the SA mode of operation the small signal absorption on the red side of the band is dependent on the applied reverse bias voltage and it is smaller than the gain at the same wavelength (fig.2) due to quantum-confined Stark effect.



a b

Figure 2: Quantum Dot Saturable Absorber (QD-SA) sample: gain and absorption saturation by 10-ps pulses at 1306 nm for different pump current (a) and absorption saturation at pump current 0 mA for different wavelengths (b). The gain is practically wavelength independent in this spectral region.

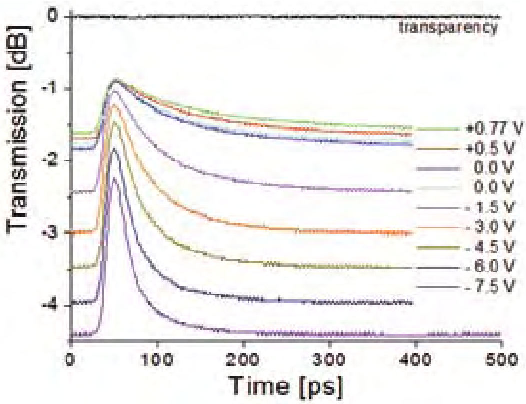


Figure 3: QD-SA absorption relaxation dynamics at 1306-nm for different reverse bias voltage.

The pump-probe measurements of the SA absorption dynamics (fig.3) showed that the relaxation time is rather slow (~100 ps) at low reverse bias voltage but quickly drops down to 20-30 ps at voltage ~5 V. At higher voltage its effect on the SA relaxation time is small and other means are to be used to decrease the relaxation time down to ~5 ps. The dynamics is similar in the whole spectral region studied and the bleached transmission for a given input signal power is practically voltage independent.

The effects of the QD-SA relaxation time and of the small signal absorption have been studied in the system with two MQW-SOA. Stable pulse transmission could be obtained practically in the whole range of applied reverse bias voltage from –1.7 V to –8 V with an optimum at –4 V. Optimum spectral filter bandwidth was again ~3 nm because of the MQW-SOA used.

Numerical simulations show that Hopf instabilities (self-stating undamped oscillations) could be observed in certain conditions. Although such behavior has not been experimentally observed till now – very weakly damped oscillation have been obtained for optimum adjustment of the spectral filter wavelength and of the net gain in the system (fig.4) confirming the theoretical results.

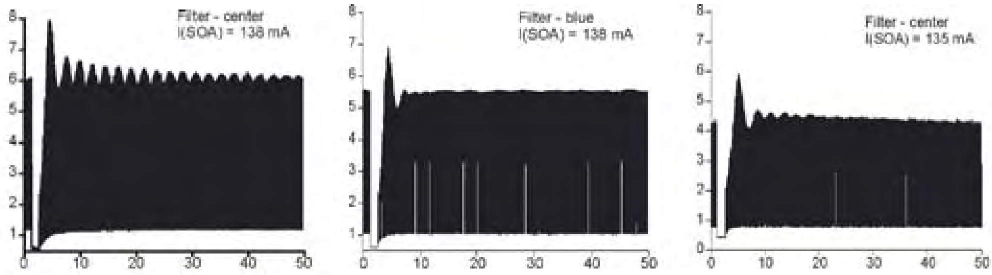


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Figure 4: Signal relaxation dynamics in the system with QD-SA and MQW-SOA: adjustment optimum for undamped oscillations (a), very strong damping for blue shifted spectral filter (b), strong damping for lower net small signal gain (c).

Self-organization of the pulses due to electrostrictive effect in the fiber has been found in the system when it runs as a ring laser without input signal (fig.5). In the region where the dissipative solitons are stable the pulse repetition frequency is ~400 MHz with typical stabilization time of few seconds. Noise statistic has also been studied in these system operation modes.

The investigations had been partially funded by the DFG.

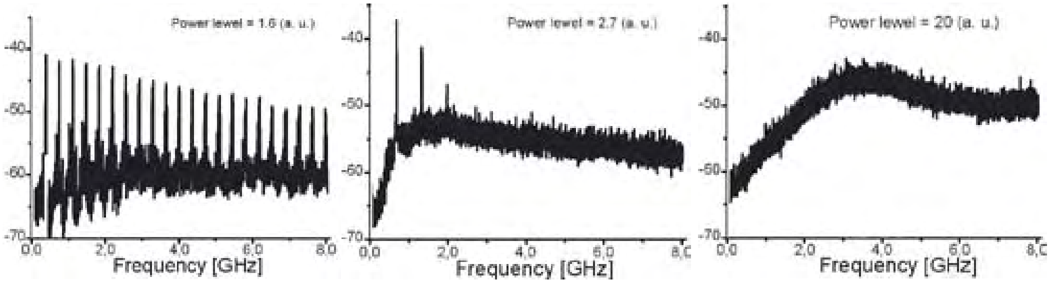

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Figure 5: High frequency signal spectra in the system with QD-SA and MQW-SOA without input signal: optimum conditions (a), near the upper boundary of dissipative soliton stability range (b) and above it (c).

Achievements & Results

Integrated Optics

Integrated optical ultrashort-pulse picker with high extinction ratio

Jens-Peter Ruske, Ekkehard A. Werner, Brit Zeitner and Andreas Tünnermann

An integrated optical Mach-Zehnder modulator in lithium niobate was used for pulse picking of a 140 fs laser oscillator at 1064 nm with 76 MHz repetition rate. Maximum extinction ratio of about 1000:1 was demonstrated at a peak power of about 120 Watt.

Introduction

The advantages in laser material processing applying high power ultrashort light pulses with a duration of some hundred femtoseconds due to a minimum thermal deterioration have been demonstrated [1-5]. However, for real world applications, high repetition rate laser systems are needed, which are not available today. To overcome this limitation, a novel ultrashort pulse laser design based on fibre amplifiers has been developed recently. To avoid damage of the fibre amplifier a chirped pulse amplification system can be used. The oscillator pulses are stretched to some hundred picoseconds first using a fibre stretcher, than amplified in one or more steps and compressed with a grating compressor finally. Most experiments are carried out using Nd:glass oscillators at 1064 nm with pulse lengths in the range of 150 fs, an average power of more than 10 mW and a repetition rate of about 100 MHz.
Average output powers of more than 20 Watt have been demonstrated [6].
For higher amplification by increasing the laser population inversion it is necessary to reduce the repetition rate using a pulse picker with rise times less than 5 ns. An extinction ratio of at least 1000:1 is required because of the high amplification characteristics of the fibres.
Integrated-optical phase modulators in lithium niobate are able to operate at modulation frequencies up to the gigahertz range with a high extinction ratio in cw operation [7] and at high optical cw power [8]. However, there are no experiences about the modulator characteristics if ultrashort pulses are transmitted, which have a bandwidth of at least 10 nm.

In this paper we report on to our knowledge first investigations of the use of an integrated-optical modulator for picking Nd:glass oscillator laser pulses. Since their lower photorefractive sensitivity, annealed proton exchanged waveguides in magnesium doped lithium niobate have been used instead of well known titanium indiffused waveguides.

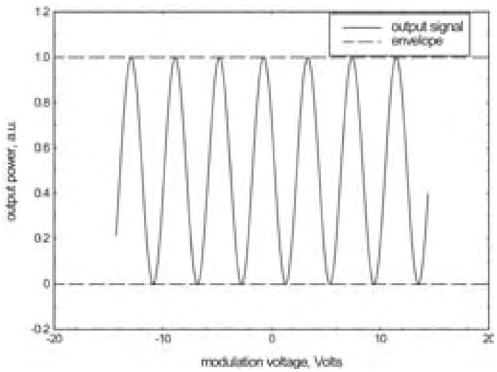

Figure 1: Modulation curve (cw operation)

Experiments

The experiments were carried out with electrooptically controlled Mach-Zehnder interferometer modulators in congruent Mg-doped x-cut lithium niobate made by Yamaju Ceramics Co., Ltd., Japan. 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 modulator was about 4 dB, measured with the fibrecoupling method. The half wave voltage measured with a cw Nd:YAG laser was 2.1 V, the extinction ratio was determined to be 4800:1 (Fig. 1). The modulators were pigtailed with 1.5 metres polarisation maintaining fibres at each end.

Figure 2 shows the experimental setup. The light of a passively mode locked Nd:glass oscillator with a pulse length of 140 fs (FWHM), a spectral pulse width of 8,4 nm (FWHM) around the central wavelength 1064 nm and a repetition rate of 76 MHz was coupled into the modulator input fibre, so that the average power in the input fibre was 30 mW. Due to the modulator attenuation the output power was 12 mW. The input fibre acts as fibre stretcher, therefore the pulse length at the modulator input face is 3,2 ps (FWHM) with a spectral width of 30 nm (FWHM). That implies that the peak power at the modulator input face was about 120 W. A photodiode in the laser provided an electrical synchronisation signal at every pulse, which was used for pulse counting and pulse selection. For compensation of different electrical and optical pulse propagation times a variable delay was integrated. A pulse generator triggered by the counter switched the modulator. The optical output was measured with a GHz-photodiode and an oscilloscope.

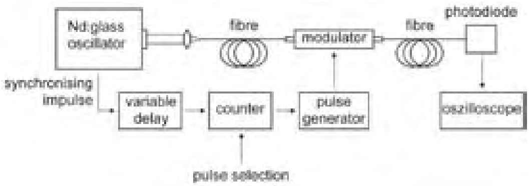

Figure 2: Experimental setup

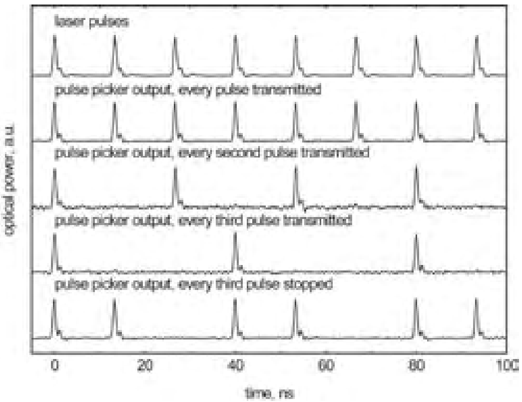

Figure 3: Demonstration of pulse picking

In figure 3 various states of pulse picker operation are depicted. For better demonstration only a small number of laser pulses is picked out of the pulse chain. The unsymmetrical pulse shape is due to some interference in the electronic part of the experimental setup. It was expected, that the extinction ratio in pulsed operation is less than in cw operation because of the higher spectral width.

Furthermore, it should be depend on the order of Mach-Zehnder-interference because of the changing optical path length difference between both interferometer arms.

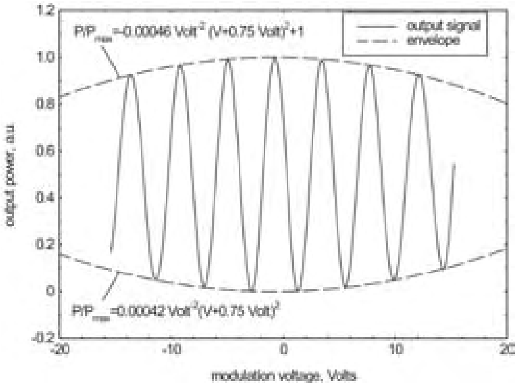

Figure 4: Modulation curve (pulsed operation)

The experiments showed, that an extinction ratio of 1000:1 is reached in low interference orders in pulsed operation. To higher orders the minimum transmitted power increases, the maximum transmitted power decreases, so that the extinction ratio is reduced strongly (Fig. 4). It can be calculated by the envelopes of the standardised output power P/P_{max} drawn in the figure.

Conclusion

We have shown the successful use of an integrated-optical amplitude modulator made of magnesium doped lithium niobate as pulse picker in an ultrashort pulse laser system at an average output power of 12 mW.

The extinction ratio is 1000:1 in low modulation orders and decreases with increasing order. The technical parameters allow the modulator use in fibre chirped pulse amplification systems.

Acknowledgment

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Achievements & Results

■ Otical Engineering

Wave-optical design and its relation to diffractive optics

Frank Wyrowski

Abstract

Actually optical engineering experiences a generalization. Physical optics modelling and design methods enrich geometric optics based techniques which still dominate the design of optical systems. The role of diffractive optics in this process is discussed. © 2004 Optical Society of America

OCIS codes: (220.0220) Optical design and fabrication;
(260.1960) Diffraction theory

1 Wave-optical modelling in optical engineering

Innovation through photonics demands optical systems which provide tailored electromagnetic radiation. To this end an electromagnetic field, which is generated by a suitable photon source, is transformed by the system.
The transformation serves to deliver an output field which enables the application of concern. Dependent on the relation between the input and the output field the transformation performs for instance an imaging, replication, shaping or diffusion of the input field. The transformation of electromagnetic fields for obtaining tailored radiation is referred to as *photon management* [1].

In general an application sets specific requirements to the output field.
For instance the image of an input field needs to possess a minimum resolution and some magnification. In another application the system should transform an incident laser beam into a beam of prescribed maximum beam parameter M^2. The constraints on the output field must be formulated in mathematical form and result in a set of merit functions which define the demanded optical function of the system. In modelling and design merit functions are utilized to evaluate the quality of the output field with respect to the application.

Dependent on the application merit functions need access to different field parameters for its evaluation. For instance calculation of M^2 requires access to the amplitude of the output beam. The coupling effciency of a beam into a fiber requires access to the complex amplitude for its determination. State of polarization, energy density, intensity, phase, or degree of coherence can be required to allow the evaluation of merit functions too. Therefore, optical engineering that is based on an electromagnetic field model offers maximum flexibility to define and evaluate merit functions. This flexibility is needed in optical engineering for photon management.

The output field as specified by merit functions is to be obtained by propagating the input field through an appropriate system. Often this requires a physical-optics propagation model, though, dependent on the field and the system, also geometrical optics can be suitable.

One realizes that innovation through photonics is often based on photon management and photon management naturally requires a wave-optical field model throughout the system and typically wave-optical field propagation at least in parts of the system. The systematic inclusion of wave optics in optical engineering is referred to as *wave-optical engineering* [2].
It turns out, that techniques which have been developed in diffractive optics and grating theory can often be applied directly or in a generalized form in wave-optical engineering.

2 Representation and propagation of electromagnetic fields
Let us consider the propagation of an electromagnetic field through a system. In front and behind the system we assume a homogeneous dielectric like air. Then, the input as well as the output field is completely described by two independent components, for instance the *x*- and *y*-components of the electric field vector. Moreover it is very convenient to restrict to harmonic fields and

to use the complex-amplitude description for the field components (partially coherent light can often be modelled by using a suitable superposition of harmonic fields). Therefore, in wave-optical engineering, we need to consider two complex amplitudes in order to represent and to propagate the entire harmonic electromagnetic field. A ray optical representation typically causes a loss of field information and is not suitable in wave-optical engineering in general.

The propagation of harmonic fields through a system requires in particular tools for propagating electromagnetic fields in homogenous dielectrics and through interfaces of general shape. The angular spectrum of plane waves methods and its paraxial approximation are well-known techniques to solve the propagation problem for homogenous dielectrics. It should be mentioned that also in wave-optical engineering geometrical optics is sometimes an appropriate technique for propagation in uniform media. This depends on the type of fields to be propagated, but it is essential to use geometrical optics in combination with a full electromagnetic field representation by complex amplitudes. While in case of a ray optical representation the use of geometrical optics leads to ray tracing, geometrical optics maintains the wave-optical field representation if the input field is represented by complex amplitudes.
This means that the wave-optical representation of radiation is more fundamental for wave-optical engineering than the use of wave-optical propagation techniques. On the base of a wave-optical light model the propagation model must be chosen as accurately as necessary for a specific application.

Let us now turn to the propagation of harmonic fields through interfaces.
The propagation of plane waves through planar and stratified interfaces, as well as gratings is well-understood and rigorously solved problems.
The propagation through general interfaces has no rigorous solution but requires heavy numerical approaches typically not suitable for optical engineering. But they can be used to model the response of local structure details in interfaces during propagation. Thus, approximate methods must be

developed for wave-optical engineering. It is logical to develop methods using the known elementary solutions for plane and periodic interfaces. This leads to the class of Local Elementary Interface Approximations (LEIA), which includes as special cases ray tracing and the well-known thin element approximation often used in diffractive optics. On the other hand, the class of Locally Independent Response Approximations (LIRA) applies the knowledge of the response of local structure details to approximately model the propagation through general interfaces. LEIA is well suited for interfaces with a moderate modulation, whereas LIRA allows for instance the modelling of propagation through profiles with abrupt transitions. These techniques have started to form the backbone of modelling propagation in current wave-optical engineering.

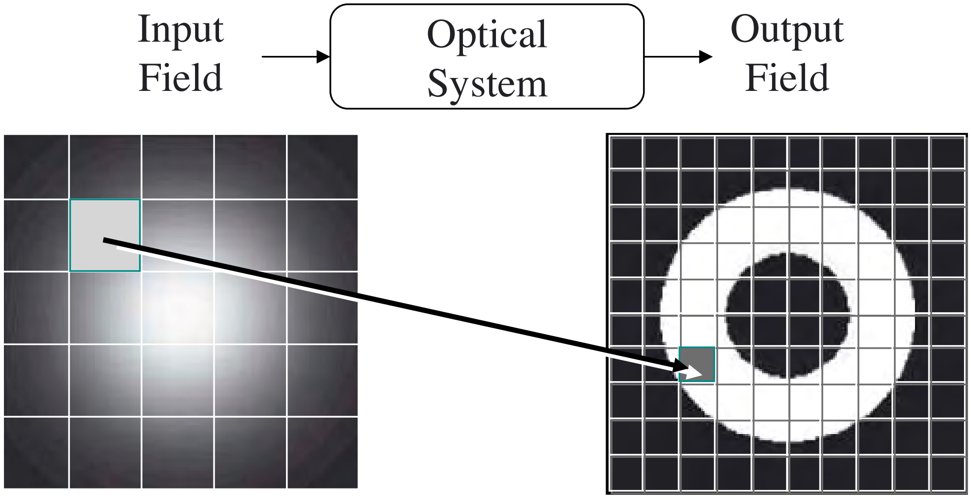

Figure 1: In a gedankenexperiment the light distributions in the input and the output plane of a light transforming system may be divided by the meshes of a net. Here a Gaussian input and a ringshaped output field are chosen and the meshes are assumed to be squares. The type of connection between the meshes are a powerful way to classify approaches to realize light transformations. In particular it gives a better understanding of the importance of diffractive optics.

3 Wave-optical system design techniques

In optical design of imaging systems, parametric optimization of an initial system guess is well established. This technique is usually not suitable in wave-optical engineering because of the significantly larger number of parameters involved. Therefore generalized techniques and novel approaches for the wave-optical design of systems for photon management are to be developed. We are still in the beginning of that development. Basic concepts and ideas are based on the generalization of the ideal lens concept and a thorough understanding of the nature of light transforming systems. Established design strategies are included in those general approaches. Naturally it turns out that design techniques of diffractive optics are of great value in wave-optical engineering.

In the presentation special emphasis is given on the characteristics of the light transformation to be obtained by a system and the possible need to apply diffractive optics for the realization of the system. It is shown to be of fundamental importance, how the light distribution in the input plane of the system is related to the distribution in the output plane. To this end a net concept is introduced which is illustrated in Fig. 1. It connects meshes in the input plane with meshes in the output plane. This model is used to characterize light transformation approaches and not to state a design technique. Dependent on the number of meshes in both planes and its connection various types of light transformations can be identified. All of them possess different characteristics and dependent on the applications pros and cons. For instance the known diffractive optics approaches for beam shaping and beam splitting constitute special cases of this classification. It will be shown how the net concept helps to understand when diffractive optics offers an alternative way to realize light transformations and when it is mandatory to apply diffractive elements.

The concepts are used to discuss application examples, for instance the pattern generation technique shown in Fig. 2.

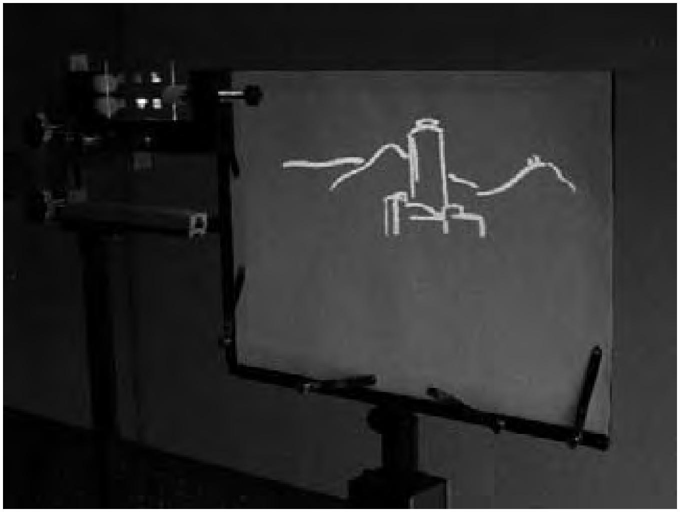

Figure 2: Optical demonstration of the use of a diffuser which transforms a laser diode beam into an intensity displaying the “skyline” of Jena. No additional optical element is needed. Stray light appears but is laterally separated from the desired signal and thus it is easy to be filtered. The element has been designed and fabricated in cooperation with LightTrans GmbH (Jena, Germany).

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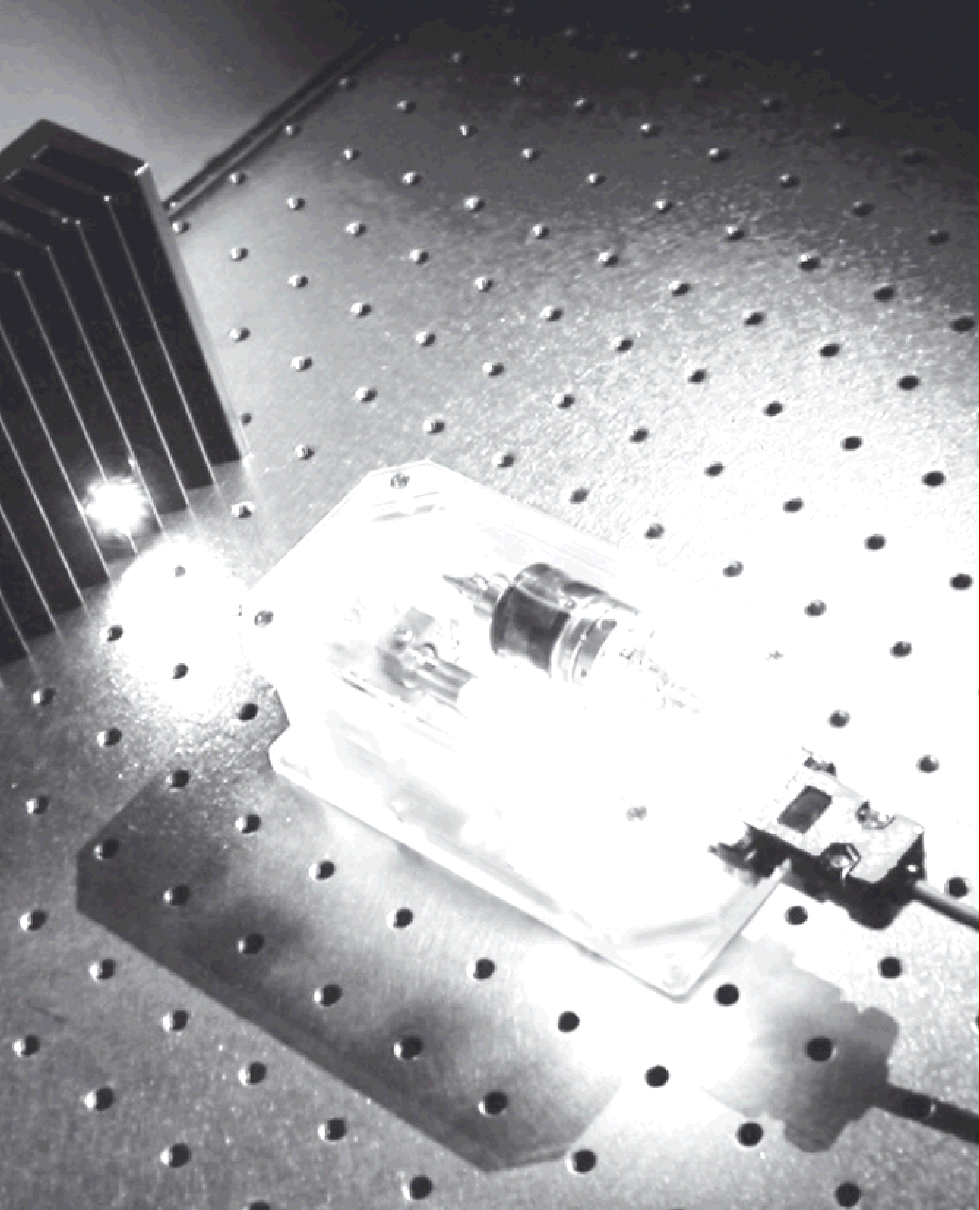


Achievements & Results

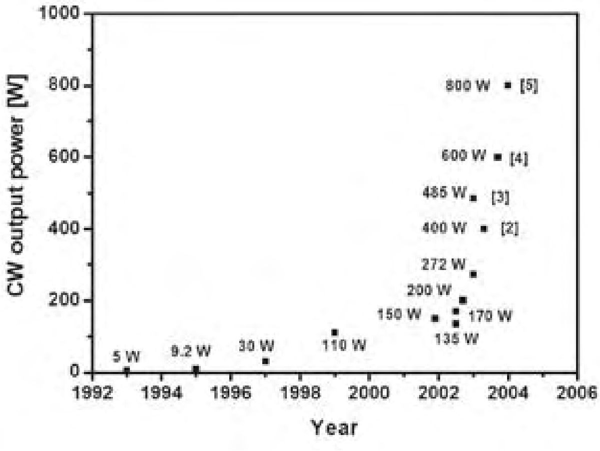
■ Fiber & Waveguide Lasers

Scaling Photonic Crystal Fibers to Kilowatts

J. Limpert, A. Liem, T. Schreiber, F. Röser, H. Zellmer, A. Tünnermann

The first fiber lasers were operated in the beginning of the sixties at wavelengths around one micron with output powers in the order of a few milliwatts. Owing to recent developments of reliable high brightness all solid state pump sources and the use of cladding pumping these devices are no longer restricted to low-power operation. The main performance advantages of rare-earth-doped fibers are the outstanding heat dissipation capabilities, which are due to the large ratio of surface to active volume of such a long and thin gain medium (the fiber). Furthermore, the beam quality is given by the refractive index profile of the active doped core and is therefore independent of the pump power. Fiber lasers and amplifiers offer a very high single-pass gain and therefore low laser thresholds and efficient diode-pumped operation. Moreover, the broad gain bandwidth, the compactness, robustness and simplicity of operation are preferable features of fiber lasers making them superior over their bulk solid-state counterparts.
However, the large product of intensity and interaction length inside the fiber core enforces nonlinear effects, such as stimulated Raman scattering (SRS), which restrict power scaling even in the continuous-wave regime. Based on novel fibers with reduced nonlinearity a tremendous power increase has been achieved recently. Figure 1 shows the cw output power evolution over the last decade of conventional fiber lasers with single transverse mode operation.

In general, nonlinear processes scale with the intensity in the fiber core and the interaction length. Consequently, the restrictions due to nonlinearity can be overcome by applying fibers with large-core-area and short absorption lengths. The scope of this paper is to discuss the novel properties which are gained by micro-structuring the fiber and how they can allow for a significant power scaling of continuous-wave and pulsed fiber laser systems.

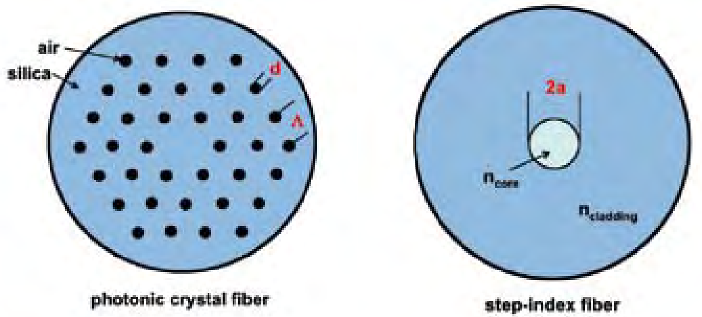


Figue 1: Power evolution of cw double-clad fiber lasers with diffraction-limited beam quality over the last decade.

Most applications rely on diffraction-limited beam quality, but the scalability of the core size of a conventional step-index single-mode fiber is limited. While single-mode operation is maintained the core size can be increased only when reducing the numerical aperture relative to the standard telecommunication value of about 0.16. But the smallest index step which can be precisely obtained applying MCVD fiber perform fabrication technology and ensures low propagation losses is in the range of 0.06. Therefore, single-mode cores with a diameter of ~15 µm are possible in the 1 µm wavelength range. As a consequence of the limited numerical aperture a further increase of the core size leads to the propagation of higher order transverse modes. However, several techniques have been demonstrated to ensure single-mode operation in slightly multi-mode fibers, such as the application of bending losses, which are significantly higher for higher-order transverse modes compared to the LP_{01} mode. Therefore, a properly coiled fiber can prefer single-mode operation in a slightly multi-mode fiber. Other approaches base on a preferential gain to the fundamental mode, created by an optimally overlapping rare-earth dopant distribution.
Alternatively, one can optimize the design of a multi-mode fiber to avoid mode scattering of the fundamental mode to higher order modes combined with a careful excitation of the fundamental mode at the beginning of the fiber (e.g. by inserting tapered sections). Applying these techniques diffraction limited output is extracted from a step-index multi-mode fiber with a fundamental mode-field-diameter of 30 µm.

However, robust and environmentally stable fundamental mode operation is just possible in a true single-mode fiber. Therefore, a single-mode large-mode-area fiber would be a significant achievement. Microstructuring the fiber adds several attractive properties to conventional fibers, that is why photonic crystal fibers (PCFs), also called air-silica microstructure or holey fibers, are currently subject of intense research. Besides other interesting novel features a photonic crystal fiber can be strictly single-mode over a large wavelength range or in other words the mode area of a photonic crystal fiber can be scaled to infinity at a fixed operation wavelength. This property offers significant power scaling capabilities and constitutes the main focus of the presented paper.

The cladding of a photonic crystal fiber consists of a triangular array of air holes with diameter d and pitch Λ, as shown in figure 2. A high index defect is created by one missing air hole, allowing for light guidance by modified total internal reflection. In analogy to conventional step-index fibers a normalized frequency parameter (V-parameter) for a photonic crystal fiber can be defined. For a photonic crystal fiber having a core formed from a single missing hole, the V-parameter is shown on the left hand side of figure 2.



$$V_{PCF} = \frac{2\pi}{\lambda} \cdot \Lambda \cdot \sqrt{n_{core}^2(\lambda) - n_{cladding}^2(\lambda)}$$

single-mode condition: $V_{PCF} < \pi$

$$V_{SI} = \frac{2\pi}{\lambda} \cdot a \cdot \sqrt{n_{core}^2 - n_{cladding}^2}$$

single-mode condition: $V_{SI} < 2.405$

Figure 2: Schematic illustration of a photonic crystal and step-index fiber and comparison of higher-order mode cut-off condition.

The condition for higher order mode cut-off can be formulated as $V_{PCF} = \pi$. In contrast to step-index fibers the effective index of the core and in particular the index of the cladding region are strongly wavelength dependent, as shown in figure 3. If the ratio of wavelength of the guided mode to hole-to-hole distance λ/Λ approaches zero, then the effective cladding index approaches the effective core index.

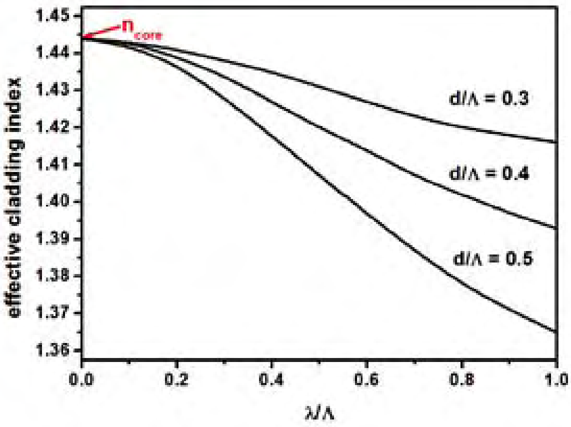


Figure 3: Effective index of a photonic crystal cladding.

These unusual dispersion properties of the cladding facilitate the design of endlessly single-mode optical fibers or (in principle) unlimited large effective mode-areas.
The endlessly single-mode condition is a relative hole size, d/Λ, below a value of approximately 0.45 (see figure 4).

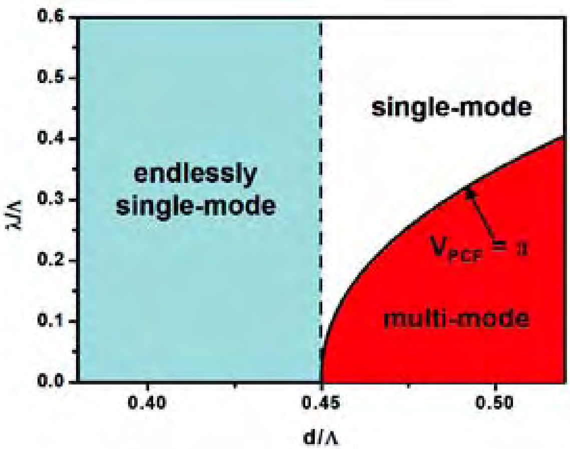


Figure 4: Single-mode and multi-mode parameter space.

A more descriptive explanation of these unusual guiding properties is to consider the air holes (diameter d, spacing Λ) as a modal filter or modal sieve. Due to the evanescence of light in air the holes are strong barriers and can be considered as the wire mesh of the sieve. The fundamental transverse mode with a lobe dimension of $\sim 2\Lambda$ fits into the core and can not escape through the too narrow silica gaps between the air holes. In contrast the higher order modes have significantly smaller lobe dimensions and can therefore slip between the gaps. It becomes clear that, if the relative hole size d/Λ is made larger then more and more higher order modes become trapped. Thus, just the geometry determines the number of guided modes and as already discussed above no higher order transverse modes are guided at all wavelengths or all core sizes if $d/\Lambda < 0.45$.

Of course, the scaling of the core size is limited by increasing propagation losses. If the V-parameter value of the photonic crystal fiber is smaller than one, the confinement of the mode is too weak causing leakage loss in a finite cladding structure PCF. On the other hand, if the value λ/Λ becomes too small (<0.1) scattering losses due to longitudinal non-uniformities increase, e.g. losses due to micro-bending, macro-bending and dielectric imperfections play an important role. Taking all these design considerations into account the realization of "one missing-hole" photonic crystal fibers with a mode-field-diameter of about 26 µm in the 1.5 micron wavelength region with low bending loss has been demonstrated.

The gain medium of a fiber laser can be fabricated by replacing the pure silica core by a rare-earth-doped rod. In general, the core is furthermore co-doped with fluorine to compensate for the refractive index increase due to the rare-earth-ion and necessary co-doping. This provides a refractive index of the rods that is closely matched to silica. Thus, the refractive index step can be reduced to $\sim 10^{-5}$ even at relatively high ytterbium doping levels, therefore the guiding properties are determined by the photonic crystal structure surrounding the core and not by the index step due to the dopants.

However, if further scaling of the mode area of single-mode fibers is intended then improved large-mode-area PCF designs which are based on cores formed by more than one missing air hole might be considered. Numerical simulations and experiments have shown that a three missing hole design (shown in figure 5) can realize 30% larger mode-field-diameters compared to an one missing air hole fiber with unchanged propagation losses. Applying even a seven missing hole design mode-field-diameters of >35 µm are achievable with low bending losses and even mode-field-diameters >45 µm are possible if bending losses do not play an important role, i.e. if the absorption length is sufficiently short so that the device no longer requires bending of the fiber (typically for fiber lengths of around 1 meter or shorter).
Such single-mode large-mode-area designs significantly reduce nonlinear effects, which constitutes in general the performance limitation of fiber laser and amplifier systems.

Figure 5: Microscope images of a one, three and seven missing-hole photonic crystal fiber (core region).

A further advantage of microstructuring a fiber is the possibility to form an air-cladding region to introduce the double-clad concept with the promising feature of a high numerical aperture of the inner cladding. This is achieved by surrounding the inner cladding with a web of silica bridges which are substantially narrower than the wavelength of the guided radiation.
Numerical apertures of up to 0.8 are reported.

Conventional polymer claddings just facilitate a numerical aperture of about 0.4. The benefit of such an air-clad fiber with a high NA is that the diameter of the inner cladding (pump core) can be significantly reduced with remaining brightness acceptation of pump radiation, leading to a reduced absorption length. Or considered from a different point of view: the high numerical aperture together with realizable larger inner-cladding diameters offer the avoidance of sophisticated coupling optics of high power diode laser stacks into the active fiber. Furthermore, no radiation has direct contact to the coating material, what makes these fibers predestinated for high power operation.

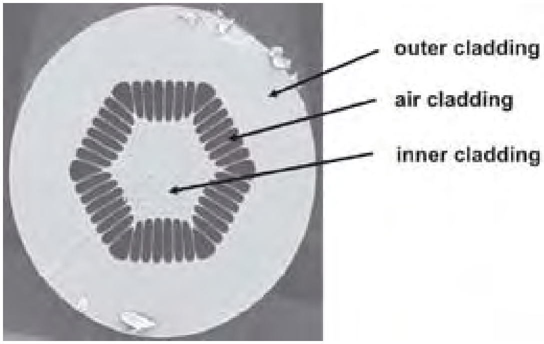


Figure 6: Air-clad photonic crystal fiber.

Figure 6 shows the cross section of the first ytterbium-doped large-mode-area photonic crystal fiber pushed to high power levels.
The fiber has a 28-µm single-mode core (3 missing holes) and a 150-µm diameter inner cladding with a numerical aperture of >0.55 surrounded by an air-cladding region.

Up to 80 W of output power are extracted out of a just 2.3 m long fiber. This result could even be scaled up to 260 W out of a 4 m long photonic crystal fiber with a similar core design but slightly modified inner cladding dimensions. The output characteristic of this laser is shown in figure 7.

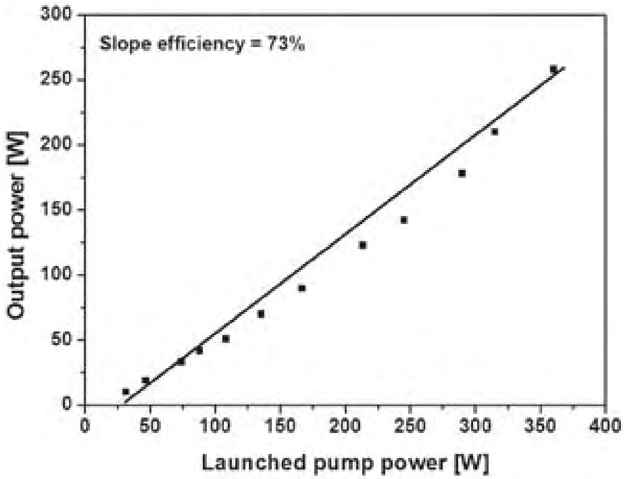


Figure 7: Laser characteristic of the high power air-clad microstructure ytterbium-doped large-mode-area fiber.

To estimate the scalability of diffraction-limited output power of an air-cooled single-mode fiber limitations due to damage, thermal load and nonlinearity have to be considered. The presented calculations base on a microstructured single-mode core with a mode-field diameter of 35 µm as discussed above. Figure 8 summarizes the restrictions of the output power as a function of fiber length.

The surface damage of fused silica is approximately 2 GW/cm², typically this value is significantly reduced in doped glasses. Experimentally demonstrated are >500 MW/cm², this value leads to a damage threshold of about 4.6 kW (black line) in a core with a MFD of 35 µm. Detailed investigations of the thermo-optical behaviour of air-clad rare-earth-doped microstructured fibers have shown that these fibers have basically the same heat dissipation capabilities as conventional double-clad fibers if the air-cladding region is properly designed. An extracted power of 100 W/m is experimentally demonstrated without any thermal problems out of air-cooled fibers with outer diameter larger than 400 µm. This value is assumed as the limit in figure 8 (solid blue line). The calculated threshold of nonlinearity (stimulated Raman scattering) as a function of the fiber length bases on several experimental results which are supported by numerical simulations (red line). This analysis leads to the conclusion that it is possible to extract a power in the range of ~3 kW from an air-cooled photonic crystal single-mode fiber laser. If more sophisticated cooling techniques are applied (e.g. forced air-cooling or passive water cooling) the extracted power can be easily enhanced to 200 W/m without thermo-optical issues (dashed blue lines). According to figure 8 this leads to a possible output power of 4 kW. Due to the recent developments of reliable high brightness all solid state pump sources and the advances in fiber manufacturing technology these power levels will be demonstrated soon.

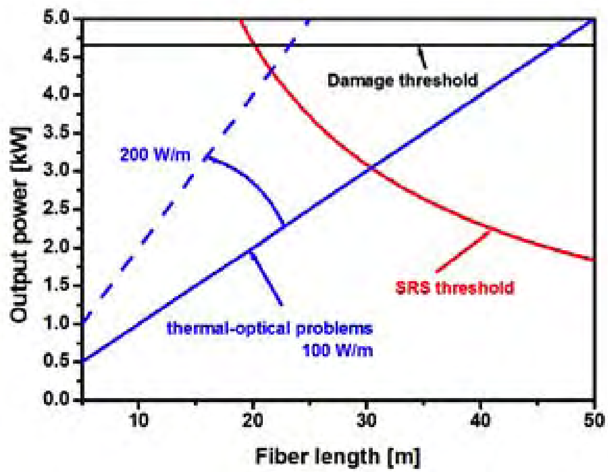


Figure 8: Summary of thermal, damage and nonlinearity limits of a continuous-wave fiber laser with a 35-µm MFD core.

In conclusion, photonic crystal fibers offer several new properties that allow for a power scaling of rare-earth-doped fiber laser systems. The most remarkable are significantly increased single-mode core sizes, what constitutes a reduction of nonlinearity by one order of magnitude compared to conventional step-index single-mode fibers and the air-cladding region which facilitates significantly enhanced numerical apertures of the inner cladding and easy handling of high power fiber lasers. Photonic crystal fibers have the potential to revolutionize rare-earth-doped fiber in high power operation.

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A. Tünnermann, S. Nolte, H. Zellmer
Fiber lasers and amplifiers – Novel avenues to real world applications of ultrashort lasers
The 5th International Symposium on Laser Precision Microfabrication (LPM), Nara, Japan (2004)

S. Nolte, M. Will, J. Burghoff, A. Tünnermann
Ultrafast Laser Processing – New Possibilities for Photonic Device Production
The 5th International Symposium on Laser Precision Microfabrication (LPM), Nara, Japan (2004)

S. Nolte, M. Will, J. Burghoff, A. Tünnermann
Ultrafast laser processing: New options for 3D photonic structures
34th Winter Colloquium on The Physics of Quantum Electronics (PQE), Snowbird, Utah, USA (2004)

F. Lederer, T. Pertsch, U. Peschel, J. Kobelke, K. Schuster, H. Bartelt, S. Nolte, A. Tünnermann
Localization and delocalization in disordered nonlinear fiber arrays
CLEO 2004, San Francisco, USA

E.-B. Kley
Micro- and Nano-Machined Optics
CLEO/IQEC 2004, OSA, May 16-21. 2004, Baltimore, San Francisco USA, Short Course SC199

E.-B. Kley
Basics and Visions of Micro- and Nano-Optics
The First German – Vietnam Summer School on Modern Optics and New-Materials, Hanoi, September 6-10, 2004

E.-B. Kley
Fabrication and Application of Micro- and Nano-Optical Elements
The First German – Vietnam Summer School on Modern Optics and New-Materials, Hanoi, September 6-10, 2004

E.-B. Kley
Optical Gratings, unique elements for many different optical functions and applications
The First German – Vietnam Summer School on Modern Optics and New-Materials, Hanoi, September 6-10, 2004

E.-B. Kley
Micro- and Nano-optics: Visions, Technologies and Applications
Workshop on Semiconductor Processing for Photonic Devices, September 30 – October 2, 2004, Warsaw, Poland

Frank Wyrowski
Photon Management - The Art of Harnessing Light
SPIE's Photonics Europe, Strasbourg, France

Frank Wyrowski
Enabling Innovation through Optics and Photonics
ICO 2004, Tokio, Japan

Frank Wyrowski
Wave-optical modeling and design and its relation to diffractive optics
OSA's DOMO 2004, Rochester, USA

Frank Wyrowski
Innovation Through Photonics by Wave-Optical Engineering
Photonics 2004, Kochi, India

Conference Contributions

J. Limpert, A. Liem, M. Reich, T. Schreiber, H. Zellmer, A. Tünnermann, J. Broeng, G. Vienne, A. Peterson, C. Jakobsen
High power picosecond amplification in a low-nonlinearity single-mode photonic crystal fiber
Advanced Solid State Photonics, Santa Fe, February 1-4, 2004, Paper

T. Schreiber, J. Limpert, A. Liem, S. Nolte, H. Zellmer, T. Peschel, V. Guyenot, A. Tünnermann
Thermo-optical analysis of air-clad photonic crystal fiber lasers
Advanced Solid State Photonics, Santa Fe, February 1-4, 2004, Paper TuA2

J. Limpert, T. Schreiber, A. Liem, S. Nolte, H. Zellmer, A. Tünnermann
Megawatt peak power level fiber laser system based on compression in air-guiding photonic bandgap fiber
Advanced Solid State Photonics, Santa Fe, February 1-4, 2004, Paper MD1

A. Liem, J. Limpert, T. Schreiber, S. Nolte, H. Zellmer, A. Tünnermann, J. Broeng, G. Vienne, A. Peterson, C. Jakobsen, T. Peschel, V. Guyenot, A. Tünnermann, V. Reichel, S. Unger
Air-clad large-mode-area photonic crystal fibers: power scaling concepts up to the multi kW-range
Photonics West, San Jose, January 24-29, 2004

A. Liem, J. Limpert, H. Zellmer, A. Tünnermann, V. Reichel, K. Mörl, S. Jetschke, S. Unger, H.-R. Müller, J. Kirchhof, T. Sandrock, A. Harschak
1.3 kW Yb-doped fiber laser with excellent beam quality
CLEO 2004, San Francisco, May 16-21, 2004, Postdeadline paper CPDD2

F. Röser, J. Limpert, T. Schreiber, H. Zellmer, A. Tünnermann
High energy ultrashort pulse fiber amplifier without CPA
EPS-QEOD Europhoton Conference Lausanne, Switzerland, August, 29 – September 3, 2004, Paper TuE3

M. Reich, J. Limpert, A. Liem, T. Clausnitzer, E.-B. Kley, H. Zellmer, A. Tünnermann
Spectral beam combining of Ytterbium-doped fiber lasers with a total output power of 100 W
EPS-QEOD Europhoton Conference Lausanne, Switzerland, August, 29 – September 3, 2004, Paper FrA4

E. Wikszak, J. Burghoff, M. Will, S. Nolte, A. Tünnermann, T. Gabler
Recording of fiber Bragg gratings with femtosecond pulses using a "point by point" technique
CLEO 2004, San Francisco, USA

J. Limpert, T. Schreiber, S. Nolte, H. Zellmer, A. Tünnermann, A. Liem
All fiber CPA system based on air-guiding photonic bandgap fiber compressor
CLEO 2004, San Francisco, USA

M. Augustin, H.-J. Fuchs, D. Schelle, E.-B. Kley, S. Nolte, A. Tünnermann, R. Iliew, C. Etrich, U. Peschel, F. Lederer
Investigation of mini-stop bands in wide photonic crystal waveguides with a low in-plane index contrast
CLEO 2004, San Francisco, USA

J. Burghoff, T. Pertsch, M. Will, S. Nolte, A. Tünnermann, U. Peschel, F. Lederer
Two-dimensional discrete diffraction in silica waveguide arrays
CLEO 2004, San Francisco, USA

J. Limpert, A. Liem, T. Schreiber, S. Nolte, H. Zellmer, A. Tünnermann, J. Broeng, A. Petersson, C. Jacobsen, H. Simonsen, N. A. Mortensen
Extended large-mode-area single-mode microstructured fiber laser
CLEO 2004, San Francisco, USA

P. Triebel, P. Weissbrodt, S. Nolte, A. Tünnermann, U. Peschel, F. Lederer
Propagation effects of surface waves on periodic Chromium structures
Photonics Europe 2004, Strasbourg, Frankreich

J. Limpert, T. Schreiber, A. Liem, S. Nolte, H. Zellmer, T. Peschel, V. Guyenot, A. Tünnermann
Thermo-optical analysis of air-clad photonic crystal fiber lasers
ASSP 2004, Santa Fe, USA

S. Nolte, J. Burghoff, M. Will, A. Tünnermann
Femtosecond writing of high quality waveguides inside phosphate glasses and crystalline media using a bifocal approach
Photonics West/LASE 2004, San Jose, USA

M. Will, J. Burghoff, J. Limpert, T. Schreiber, S. Nolte, A. Tünnermann
High speed fabrication of optical waveguides inside glasses using a high rep.-rate fiber CPA system
Photonics West/LASE 2004, San Jose, USA

M. Augustin, H.-J. Fuchs, E.-B. Kley, S. Nolte, A. Tünnermann, R. Iliew, C. Etrich, U. Peschel, F. Lederer
Highly efficient waveguide bands in low in-plane index contrast photonic crystals
Photonics West 2004, San Jose, USA

Activities

Awards

Dr. Stefan Nolte, Prof. Dr. Andreas Tünnermann, Dr. Holger Zellmer
Berthold Leibinger Innovationspreis 2004

Markus Augustin
Poster Award Photonics West 2004

Thomas Schreiber
Best Student Paper Advanced Solid-State Photonics 2004 (ASSP)
Poster Award Photonics West 2004

Organizing Activities

Prof. A. Tünnermann

- Scientific Advisory Board VDI-Kompetenzfeld: Optische Technologien
- Supervisory Board BioCentiv Jena
- Board Member European Physical Society; Quantum Electronics and Optics Division
- Member of Scientific Advisory Board Optics Communication
- DFG-Forschergruppe: Nichtlineare Dynamik in dissipativen und diskreten optischen Systemen (Speaker)
- Programme Committee Member Advanced Solid–State Photonics ´04
- Programme Committee Member Photonics West: Micromaching for micro- and nano-optics conference 2004
- Programme Committee Member Photonics West: Fiber lasers: Technology, systems and applications 2004
- Programme Committee Member 17th Annual IEEE/LEOS Annual Meeting; Topic: High Power & Short Wavelength Lasers (HPSW) 2004
- Programme Committee Member MOC '04
- Founder and Shareholder Guided Color Technologies Jena GmbH
- Photonics West: Fiber lasers: Technology, systems and applications 2004
- Personal Member: DPG, EPS, OSA, IEEE, WLT, VWT (Ausschuss f. Fo & Innov.)
- Reviewer for: Appl. Opt., Appl. Phys. B, Opt. Express, Opt. Commun., Opt. Lett., IEEE J. Quantum

Prof. F. Wyrowski

- Member of Board of Directors of SPIE - The International Society for Optical Engineering (und weiterer Gremien der SPIE)
- Member of Board of Editors of Journal of Modern Optics
- Reviewer for diverse optic journals

Dr. J.-P. Ruske

- Arbeitskreis “Integrierte Optik”

Dr. H. Zellmer

- Programme Committee Member: CLEO/IQEC 2004, EPW-QEOD Europhoton Conference 2004
- Reviews for: Optics Letters, Optics Communications, Electronic Letters, Photonics Technology Letters, Applied Physics B, IEEE Photonics Technology Letters, JOSA B

Dr. S. Nolte

- Programme Committee Member: CLEO (Laser Applications and Optical Instrumentation Systems)
- Programme Committee Member: Photonics West/LASE (Commercial and Biomedical Applications of Ultrafast Lasers)
- Reviewer for: Opt. Lett., Opt. Commun., Appl. Phys. A, Appl. Phys. B, Appl. Opt., Reviewer for: JOSA B, Opt. Express

Dr. G. Onishchukov

- Reviewer for: Opt. Commun., IEEE Photonics Technol. Lett., Electron Lett.

Dr. E.-B. Kley

- Programme Committee Member: CLEO (Micro-Optics and Photonics Nanostructures)
- Programme Committee Member: Photonics West/LASE (Micromachining Technology for Microoptics and Nanooptics)
- Reviewer for: Appl. Opt., Journal of Microlithography, Microfabrication, and Microsystems, Opt. Express

IAP

Friedrich-Schiller-University Jena
Institute of Applied Physics
Beutenberg Campus
Albert-Einstein-Straße 15
D-07745 Jena

www.iap.uni-jena.de