Institute of Applied Physics

Annual Report

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This Annual Report details the activities of the Institute of Applied Physics (IAP) of the Friedrich Schiller University Jena. It provides information on the people working at the IAP and gives a summary of current research projects.

Two of the research highlights are the demonstration of fiber optical amplification of ultrashort pulses up to energies of more than 100 µJ using the chirped pulse amplification technique, and the demonstration of information transmission in optical fiber communication over distances up to 28 000 km at high bit rates using soliton pulses (τ_p = 6 ps).

The past year was essentially characterized, on the one hand, by expansion due to the start of new research projects, e. g. on the development of photonic crystals. The overall number of scientists, technical personnel and students working at the IAP increased significantly, novel equipment was installed. On the other hand, the year 2000 was characterized by limitations in the daily work due to the reconstruction of the institute.

The institute during reconstruction.

The research activities had been partially supported by the European Commission Directorate-General XII: Science Research and Development, German Ministry of Education and Research, German Research Foundation, Thuringian Ministry of Science, Research and Art and industrial clients with a volume of almost 3 million €.

In the name of the entire staff of the IAP, I thank all of those who took interest in our work and supported our institute in the past year.

Though adequate funding is a necessity, it does not suffice. The results and success of 2000, described on the following pages, would not been achieved without the skills of our staff. I thank all my colleagues for their hard and dedicated work in the past year, being confident that the IAP is well prepared for the future. ■

Jena, April 2001

Prof. Dr. Andreas Tünnermann
(Head 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 lithogarphy, reactive ion and reactive ion beam etching, diffusion and ion exchange ovens, coating facilities, scanning electron and atomic force microscopy), optic/optoelectronic 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

Application fields are optical information and communication technology, medicine and biology, process technology including material processing as well as optical measurement techniques. These activities are partially supported by the European Commission Directorate-General XII: Science, Research and Development, German Ministry of Education and Research, German Research Foundation, and Thuringian Ministry of Science, Research and Art.

Staff Members

Abbe, Sylvia	
Augustin, Markus	
Bakonyi, Zoltan	
Beeker, Christian	
Bernhardt, Jens	
Brüntjen, Thorsten	
Chichkov, Boris N.	Dr.
Clausnitzer, Tina	
Cumme, Matthias	
Drauschke, Andreas	
Dubs, Carsten	Dr.
Dürselen, Andrea	
Erdmann, Tobias	
Erler, Marco	
Fuchs, Hans-Jörg	Dr.
Gräf, Waltraud	
Gründer, Hans-Georg	
Grusemann, Ulrich	
Häußler, Sieglinde	
Hartung, Holger	
Hartwig, Michael	

Harzendorf, Torsten		
Hermann, Andreas		
Höfer, Sven		
Hübner, Heike		
Hübner, Uwe	Dr.	
Kästner, Tobias		
Kley, Ernst-Bernhard	Dr.	Microstructure technology
Kölling, Kevin		
Liem, Andreas		
Limpert, Jens		
Lührs, Hendrik		Coordination office Optomatronik
Martin, Bodo		
Matsushima, Kyoji	Dr.	
Nolte, Stefan	Dr.	Ultrafast optics
Okhrimchuk, Andrej	Dr.	
Onishchukov, George	Dr.	
Osipov, Vladimir	Dr.	
Otto, Christiane		
Podorov, Sergej	Dr.	
Raubach, Sebastian		
Riedel, Peter	Dr.	
Rockstroh, Sabine		Secretary
Rockstroh, Werner		
Rottschalk, Matthias	Dr.	
Ruske, Jens-Peter	Dr.	Integrated optics
Schelle, Detlef		
Schimmel, Hagen		

Schmeißer, Volkmar		
Schmidt, Holger		
Schnabel, Bernd		
Steinberg, Carola		
Steppa, Denny		
Thieme, Mike		
Thomas, Jens		
Tünnermann, Andreas	Prof. Dr.	**Head of the institute**
Werner, Ekkehard		
Will, Matthias		
Wittig, Lars		
Wyrowski, Frank	Prof. Dr.	Optical design
Zeitner, Brit		
Zellmer, Holger	Dr.	Fiber and waveguide lasers
Zöllner, Karsten		

Lectures

I. Summer Semester 2000

Prof. Dr. Frank Wyrowski

Optikdesign	(Lecture)
Experimente im virtuellen Optiklabor	(Seminar/practical course)
Ausgewählte Themen der Mikrooptik	(Lecture)
Wellenoptisches Systemdesign	(Seminar)

Prof. Dr. Andreas Tünnermann

Integrierte Optik	(Lecture)
Experimentalphysik für Chemiker, Geowissen-schaftler und Werkstoffwissenschaftler II	(Lecture and seminars)
Institutsseminar	(Seminar)

II. Winter Semester 2000/2001

Prof. Dr. Andreas Tünnermann

Festkörperlasertechnologie – Grundlagen und Anwendung	(Lecture)
Institutsseminar	(Seminar)

Prof. Dr. Andreas Tünnermann, PD Dr. Boris Chichkov

Ausgewählte nichtlinear-optische Effekte bei der Wechselwirkung von Laserstrahlung mit Materie	(Seminar)

Prof. Dr. Andreas Tünnermann, PD Dr. Boris Chichkov,
Dr. Jens-Peter Ruske, Dr. Holger Zellmer

Nichtlinear-optische Effekte bei der Wechselwirkung von Laserstrahlung mit Materie	(Practical course)

Prof. Dr. Andreas Tünnermann, Dr. George Onishchukov

Faseroptische Datenübertragungssysteme (Lecture)

Prof. Dr. Frank Wyrowski

Experimente im virtuellen Labor (Practical course)

Wellenoptisches Systemdesign (Seminar)

Dr. Ernst-Bernhard Kley, Dr. Jens-Peter Ruske

Miniaturisierte Optik (Lecture)

Diploma Theses

Marco Erler: Untersuchung der physikalischen Eigenschaften integrierter Polarisatoren zur Verbesserung des Kontrastverhältnisses von Intensitätsmodulatoren auf Basis von KTP

Torsten Harzendorf: Untersuchungen zu den Herstellungsmöglichkeiten glatter Höhenprofile für mikrooptische Bauelemente

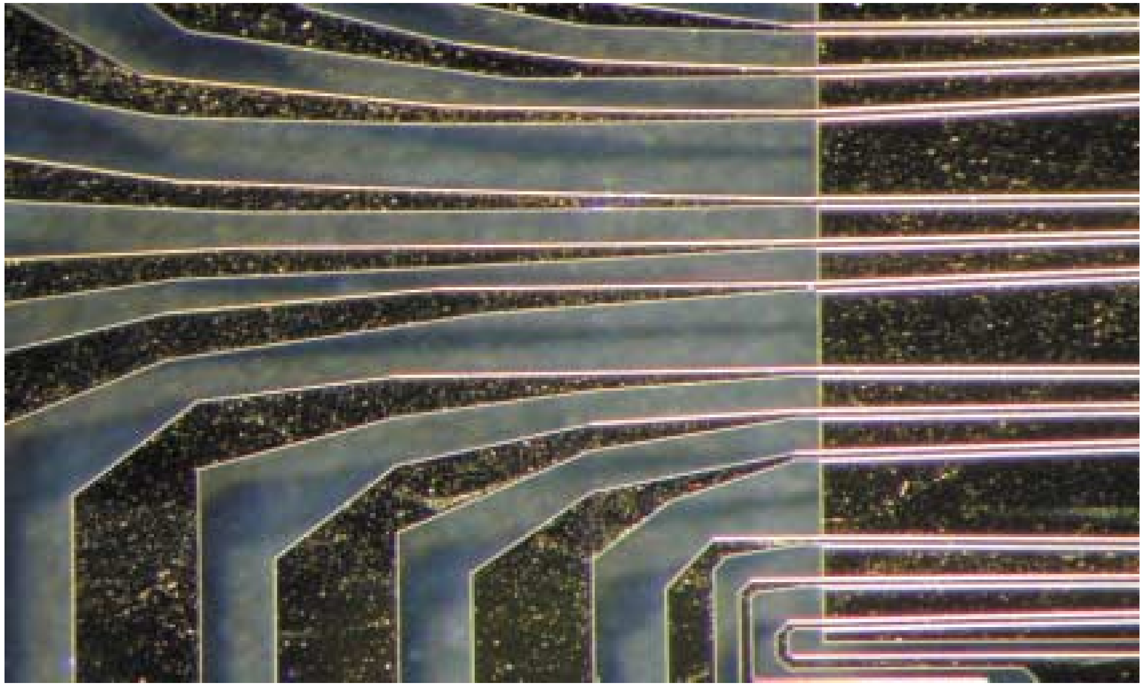
Ralph Kecke: Entwicklung und Realisierung eines aktiv modengekoppelten Faserlasers im sichtbaren Spektralbereich

Doctoral Theses

Bernd Schnabel: Theorie und Fabrikation von Subwellenlängenstrukturen am Beispiel polarisierender Metallstreifengitter

Statistics

The research activities of the IAP are partially supported by the European Commission Directorate-General XII: Science, Research and Development, 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 2.7 million € (5.2 million DM).



Detail of an integrated-optical modulator –
development funded by the TMWFK project „Integriert-optische Systemtechnik".

Externally Funded Projects

I. DFG Projects

(a) Nanostrukturierte photonische Komponenten und deren Wechselwirkung mit Licht
Runtime: April 2000 – March 2002

(b) Teilchenstrahl-stimulierte Ultrapräszisions-Oberflächenbearbeitung; TP Ionenätzen
Runtime: January 2000 – December 2001

(c) Brechzahlmodifikation in optisch transparenten Materialien durch Strukturänderungen bei der Bestrahlung mit ultrakurzen Lichtpulsen; SFB TP B12
Runtime: January 1999 – December 2001

(d) Wellenoptisches Design monofunktionaler optischer Systeme
Runtime: August 2000 – July 2002

(e) Mikrooptische Funktionselemente – Innovationskolleg Optische Informationstechnik, TP 3
Runtime: December 1994 – March 2000

(f) 3D- Wellenleiteroptik – Innovationskolleg Optische Informationstechnik, TP 4
Runtime: December 1994 – March 2000

(g) Nachrichtenübertragung mit Solitonen – Innovationskolleg Optische Informationstechnik, TP 1
Runtime: December 1994 – April 2000

(h) Optische Übermittlungsverfahren in der Informationstechnik (DFG Schwerpunktprogramm), Projekt: Sättigbare Absorber zur Rauschunterdrückung in hochbitratigen optischen Übertragungsstrecken mit Halbleiterverstärkern
(in cooperation with Prof. Lederer, IFTO, Friedrich Schiller University Jena)

II. TMWFK Projects

(a) Härtung und Strukturierung von Polymerschichten mit blauemittierenden Lasern
Runtime: October 1999 – September 2001

(b) Faserlaser im sichtbaren Spektralbereich für die medizinische Diagnostik – FASIMED
Runtime: September 1998 – February 2000

(c) Intra-Netz Optomatronik
Runtime: January 2000 – December 2001

(d) Integriert-optische Systemtechnik: Herstellung und hybride Integration von aktiven und passiven miniaturisierten optischen Elementen
Runtime: April 1999 – March 2002

(e) Integriert-optische Systemtechnik: Herstellung und hybride Integration von aktiven und passiven miniaturisierten optischen Elementen – Investitionen
Runtime: March 1999 – December 2001

(f) Leistungsskalierung von Faserlasern im sichtbaren Spektralbereich für die medizinische Therapie – LEFAMET
Runtime: October 1999 – December 2000

(g) Zentrum für Optomatronik – Realisierung von Optiklaboren
Runtime: May 2000 – December 2000

(h) Aufbau eines Technologielabors zur Untersuchung des Verstärkungsprozesses ultrakurzer Pulse in dotierten Wellenleitern
Runtime: November 2000 – December 2000

III. BMBF Projects

(a) Elekrooptischer Lasermikromodulator (MIKROMOD), TP: Integriert-optische Modulatoren vom Mach-Zehnder-Interferometer
Runtime: October 1996 – March 2000

(b) Technologisch orientierte Untersuchungen zur Einführung geeigneter Schichtsysteme zur Erzeugung minimaler Strukturabmessungen sowie Belichtungen von SET-Bauelementen und Bauelementenarrays – Teil II (UA BMBF),
Runtime: July 1997 – June 2000

(c) Entwicklung und Musterfertigung von passiven mikrooptischen Komponenten für ein DVD-Pick-up-System mit elektrooptischen Aktuatoren – NEOPICK (UA BMBF),
Runtime: October 1996 – June 2000

(d) Herstellung strukturierter Beleuchtungskomponenten für die EUV-Lithographie (UA BMBF),
Runtime: May 2000 – April 2001

(e) Herstellung und Anwendung von Polarisationsgittern – SENTEX (UA BMBF),
Runtime: January 2000 – December 2001

(f) Diffraktive Kombinationsoptiken für Hochleistungsdiodenlaser (UA BMBF),
Runtime: October 1999 – December 2002

(g) Herstellung und Charakterisierung von Nano-Prägewerkzeugen und meßtechnische Bewertung ihrer Replikate; Schwerpunkt: Hohe Aspektverhältnisse – FOKEN,
Runtime: July 2000 – June 2002

(h) MICROPHOT – Laserdirect: Faseroptische Hochleistungslaser für die Druckvorstufe; Teilvorhaben: Neuartige Skalierungskonzepte für Faserlaser und

-verstärker in kontinuierlichem und gepulstem Betrieb
Runtime: July 2000 – June 2003

(i) MICROPHOT – OMP: Integriert-optische Modulationskonzepte im sichtbaren Spektralbereich
Runtime: July 2000 – June 2003

(j) Verbundprojekt Kompetenznetze Optische Technologien (Phase 2) im TV Kompetenznetz OptoNet
Runtime: November 2000 – January 2001

(k) Grundlegende Untersuchungen zur Materialbearbeitung sowie die Berechnung und Erprobung optischer Elemente zur Strahlformung ultrakurzer Laserpulse
Runtime: May 2000 – September 2002

(l) Laserstrahlformung mit Hilfe spezieller optischer Elemente
Runtime: May 2000 – September 2002

IV. EU Projects

(a) Nano-Fabrication of DFB-Lasers and SAW-Devices by Off-Axis Holographic Lithography – SAWLASE, BriteEuram,
Runtime: October 1998 – September 2000

(b) Development of New Dielectric and Optical Materials and Process Technologies for Low Cost Electrical and/or Optical Packaging and Testing of Precompetitive Demonstrators – DONDODEM, BriteEuram,
Runtime: September 1998 – August 2001

(c) Semiconductor devices for optical signal processing – COST 267
(in cooperation with Prof. Lederer, IFTO, Friedrich-Schiller University Jena)

Achievements and Results

I. Optical fiber communication systems **Dr. George Onishchukov**

The research in the field of optical fiber communication systems at the IAP is focused on the investigation of performance of high bit-rate optical fiber communication systems based on soliton transmission. The emphasis is placed on the study of physical processes limiting the transmission distance in a re-circulating fiber loop setup. During the period of the report, the research has concentrated on the specific features of two system types: one with in-line semiconductor optical amplifiers and saturable absorbers, the other one with distributed Raman fiber amplifiers.

Saturable absorbers in systems with semiconductor optical amplifiers

Semiconductor optical amplifiers (SOA) are very promising elements of integrated lightwave circuits for optical fiber communication systems. It has been previously shown by the group that Return-to-Zero (RZ) transmission systems with in-line SOA suffer from the fast signal decay and growth of amplified spontaneous emission (ASE) because of the low saturation energy and short recovery time of the SOA. It has been proposed and demonstrated that when using in-line saturable absorbers (SA), it is possible to completely suppress ASE growth and increase the maximum transmission distance many times – up to 30 000 km for 5 Gbit/s. The limiting feature in that system is the SOA gain recovery causing bit rate dependent amplitude pattern and temporal walk off effects and setting the limit on the maximum bit rate in the system. One possibility to speed up the gain recovery and to reduce harmful effects is to use the gain-clamped SOA design. Such a SOA prototype was purchased from JDS-Uniphase (Netherlands). The dynamics of the gain recovery in the SOA has been studied in a pump-probe setup. Characteristic features of strongly dumped relaxation oscillations have been found. The dependence of the gain recovery on the operating parameters like pump current and temperature has been investigated. Finally using the gain-clamped SOA after appropriate adjustment of its operation conditions it was possible to compensate for the dynamics of gain recovery in the common SOA part of the SOA-SA module in the setup scheme shown in fig.1.

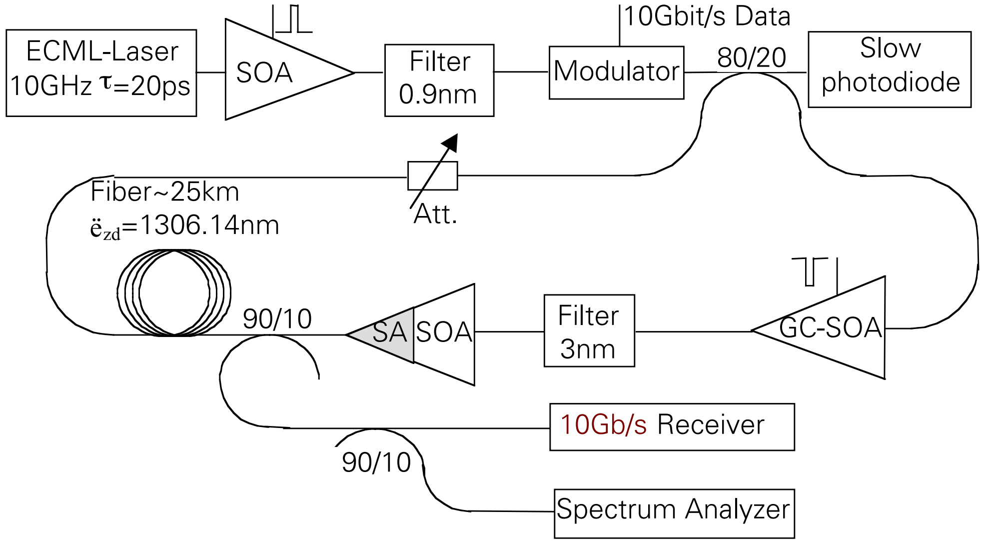


Fig.1 System with in-line gain-clamped SOA and SA.

The 10 Gbit/s transmission over 5 000 km was demonstrated (fig.2). The results together with previously obtained ones are the world longest transmission distances realized in the system with in-line SOA.

Fig.2 Eye-diagram at 5 000 km.

From fundamental point of view, the optical fiber transmission line with in-line SOA and SA represents an essentially nonlinear, strongly dissipative system, where the parameters of the pulses (autosolitons) are completely determined by the system parameters. In contrast to common soliton systems, the autosoliton parameters are independent of the initial pulse duration, wavelength, and energy, and this feature has been proved in our experiments. It has been also shown that such a system with two competing noninstantaneous nonlinearities (SOA and SA) could have a new type of bifurcation behavior for a certain set of element parameters as shown in fig.3. Its specific is that for supercritical bifurcation of CW radiation the bifurcation of the solitons is subcritical. In the region of negative linear net gain, there are only two stable solutions – trivial zero background and autosolitons. It is in contrast to the other well known nonlinear systems where the bifurcation behavior of the CW radiation and of solitons have the same features – either both supercritical or both subcritical. Dynamics of the system have been also studied: switching of autosolitons and their relaxation. The effect of slowing down of the relaxation, which is typical for nonlinear systems, has been demonstrated (fig.4).

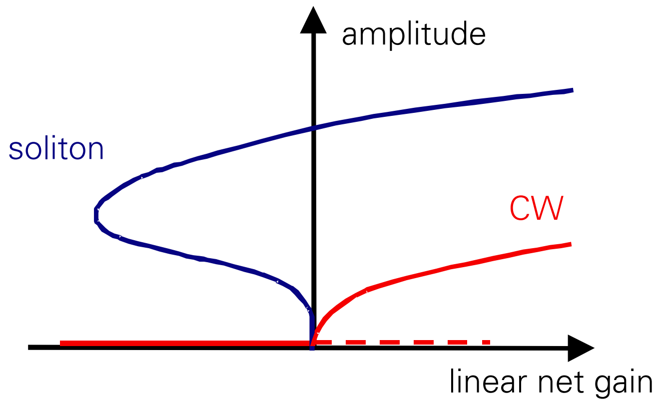


Fig.3 Bifurcation diagram of dissipative solitons in system with competing noninstantaneous nonlinearities.

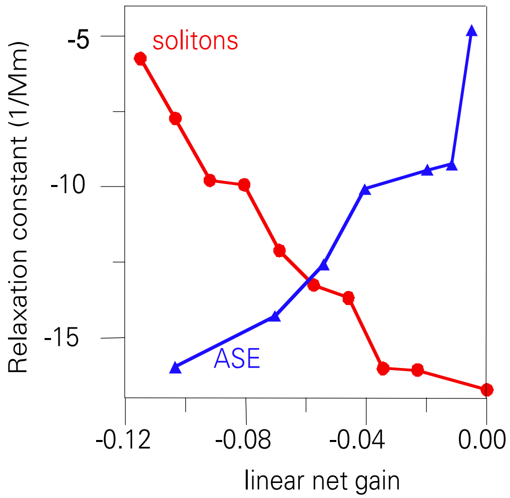


Fig.4 Dependence of relaxation constant for dissipative solitons and amplified spontaneous emission on net gain.

Timing jitter is another performance limiting parameter of a transmission system and important for applications. The investigation of the effect has been started and it has been shown that very low (2 ps at 30 000 km) timing jitter could be obtained in the system. The unique features of the system with in-line SOA-SA which are responsible for it are the following: On the one hand, the system can operate at zero fiber dispersion with non-vanishing pulse energy as in popular up-to-date systems with dispersion management. On the other hand, the effect of in-line SA is that a strong in-line spectral filtering can be used without transmission deterioration. These two features provide a very strong suppression of the timing jitter, due to the Gordon-Haus effect, which is the main source of timing jitter in soliton systems.

Distributed Raman amplification

Raman fiber amplifiers are also among the most promising candidates for 1.3 – 1.6 µm amplification because of their flexibility regarding the operation wavelength. Another attractive feature of Raman amplification for high bite-rate soliton transmission is that it provides a distributed amplification, which significantly decreases the signal power swing in comparison with lumped amplification. However up to now, long-haul transmission experiments with Raman amplification have been restricted to the 1.5 µm communication window. We have investigated 10 Gb/s soliton transmission using distributed Raman amplification in the 1.3 µm region and using the setup shown in fig.5.

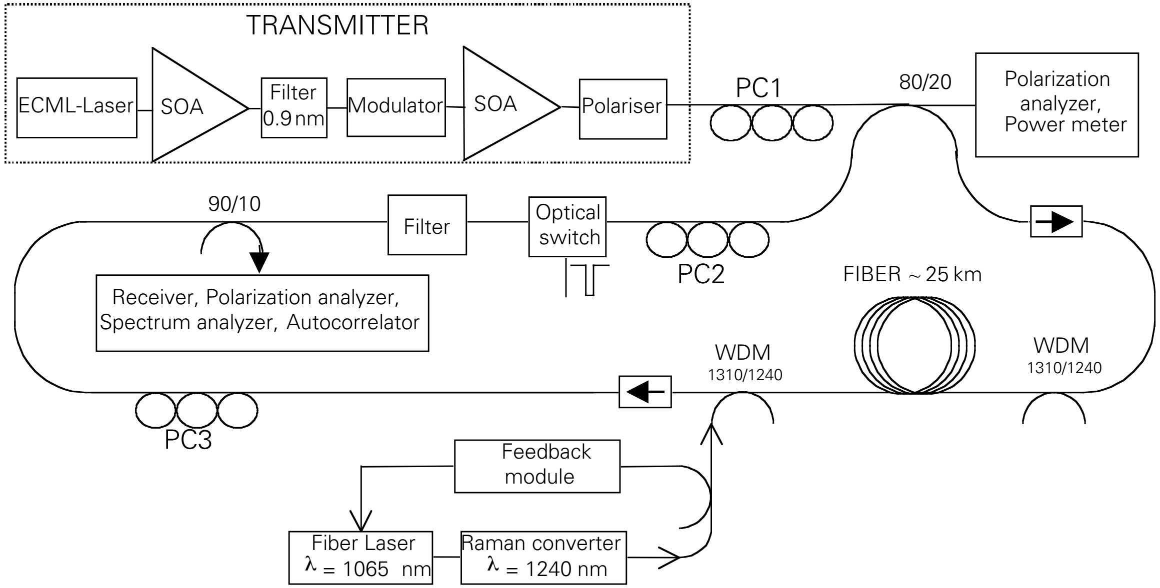


Fig.5 System with distributed fiber Raman amplification.

Error-free (estimated from Q-factor and timing jitter) 10 Gb/s pulse transmission up to 10 000 km has been obtained in a standard communication fiber in the 1307 – 1311 nm wavelength (D = 0.14 – 0.47 ps/nm/km) region. Solitons have been proved to be the optimal signal for such a system. It has been established that the most critical system requirements for fiber loop experiments are high pump power stability (0.02 %) and high uniformity of the signal polarization state. We verified that dispersive waves generated by PMD are detrimental for soliton transmission, but they can be minimized by implementation of an element with polarization dependent transmittance and a proper adjustment of the signal polarization state. It has been found that the polarization hole burning could be a detrimental effect for distributed Raman amplification in fibers with low PMD. The fundamental limiting factor for long-haul transmission, provided that the PMD effect is reduced, is the timing jitter due to spontaneous emission (Gordon-Haus effect). The soliton pulse duration of about 6 ps shows the potential for obtaining similar transmission results at higher bit rates, too. It has also been demonstrated that transmission distances up to 28 000 km can be reached by reducing the timing jitter using a narrow in-line filter (see fig.6). ■

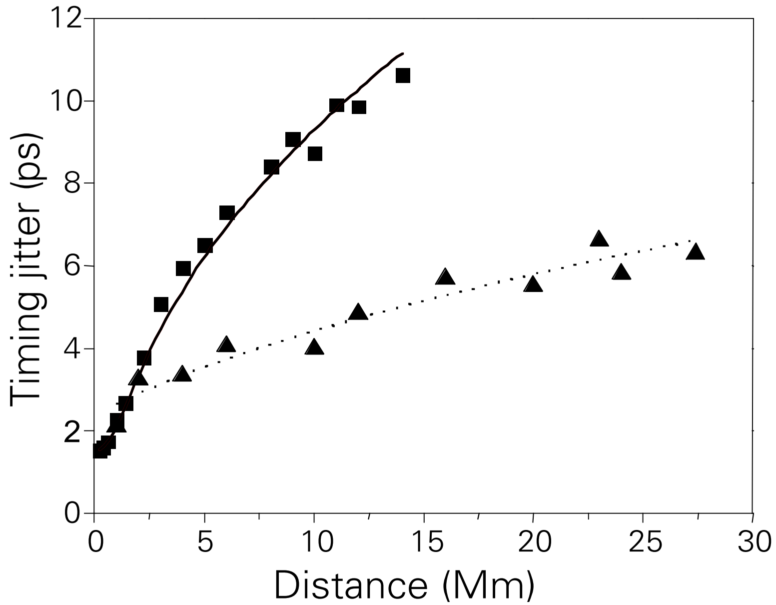


Fig.6 Timing jitter distance dependence for 3 nm (solid) and 3 nm (dashed) filters.

II. High average power ultrafast fiber CPA system **Dr. Holger Zellmer**

The field of fiber lasers and amplifiers is one of the main research areas of the IAP. Subjects are up-conversion lasers with emission wavelengths in the visible spectral range and near infrared double clad fiber lasers. The demonstration of a fiber CPA laser system for applications in medicine and micro machining is the most promising result in this field.

Fiber laser CPA system

Today, regenerative amplifiers using chirped pulse amplification technique (CPA) are generally applied to realize these parameters with repetition rates of up to 10 kHz. Higher repetition rates can be achieved by applying the CPA technique to fiber amplifiers. Neodymium and ytterbium-doped fibers can provide broad gain bandwidths (> 50 nm), optical pumping efficiencies as high as 80% and high optical gain and power. Using double-clad fiber designs, cw powers in a nearly single spatial mode beam of several 10 W have been reported for diode pumped systems.

The experimental setup of our high-energy fiber CPA system is shown in fig. 1. The system consists of a passively mode-locked, diode-pumped solid-state laser system, a fiber stretcher, two single-mode neodymium-doped fiber preamplifiers, two ytterbium-doped fiber power amplifiers and a diffraction-grating compressor. As a femtosecond seed source, a Nd:glass laser system is applied which is based on a semiconductor saturable absorber mirror (SESAM). The laser is running at 82 MHz repetition rate producing pulses as short as 150 fs at ~1060 nm and an average power of 100 mW. After adjusting the repetition rate of the seed pulses in a first acousto-optic modulator (AOM I) to 2 MHz, about 25 pJ pulse energy was coupled into a dispersive delay line consisting of a 2000 m long step-index single-mode fiber which stretched the pulses to a width of about 800 ps. The broadened spectrum ($\Delta\lambda$ = 9.9 nm), compared with the transform limited spectrum of the Nd:glass oscillator ($\Delta\lambda$ = 6.9 nm), is due to inherent self phase modulation in the 2 km long stretcher fiber.

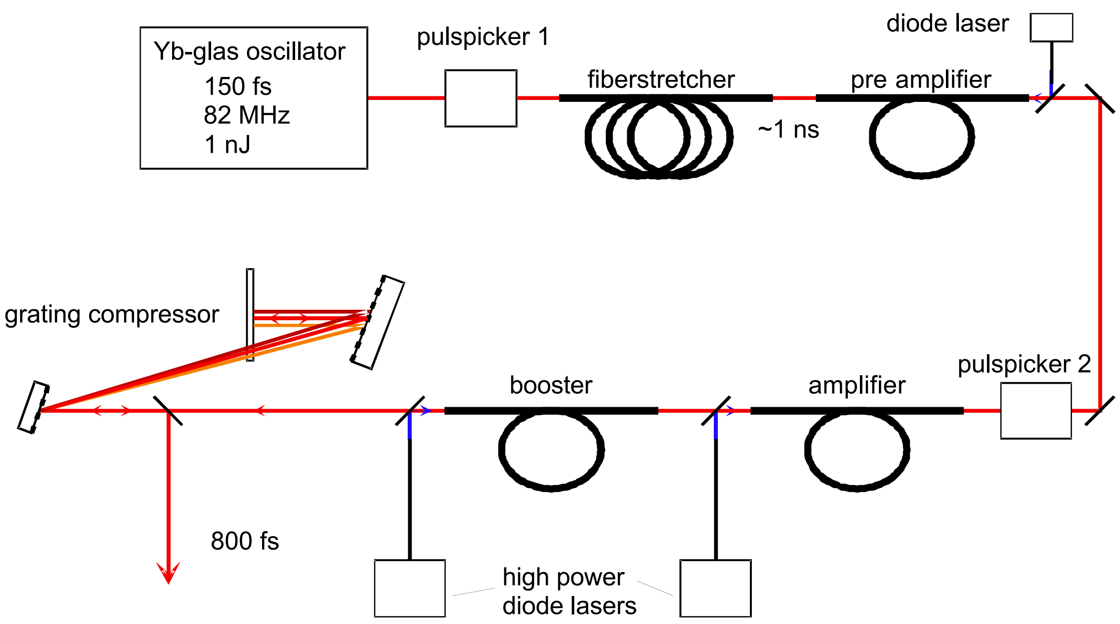


Fig.1 Setup of the fiber CPA system.

The preamplifiers consisted of two diode pumped double clad fibers doped with 8000 ppm (mol) neodymium. The diameter of the active core is 6 µm at a numerical aperture of 0.16 (λ_{cutoff} < 1 µm), the pump core diameter is 100 µm at a NA of 0.38. The length of the preamplifiers is 1 and 3 m, respectively. After the second preamplifier, the pulse energy has increased to 5 nJ, corresponding to a net gain of 23 dB. The spectral width is narrowed to about 6 nm and the pulses are shortened due to the amplification process to about 500 ps. In order to suppress amplified spontaneous emission one has to run this preamplifier stage at repetition rates higher than 1 MHz. To vary the repetition rate of the power amplifier stage, we employed a second acousto-optic modulator.

The first power amplifier is using a 10 m long ytterbium-doped double clad fiber, fabricated by IPHT Jena. A fiber coupled diode laser delivering 45 W at 940 nm is employed as pump source. The diameters of the active core and the D-shaped pump core are 11 µm (NA = 0.16) and 400 µm (NA = 0.38), respectively. The ytterbium doping concentration is 6500 ppm (mol). When seeded with 1.5 nJ at a repetition rate of 2 MHz, we were able to generate average powers up to 4.6 W of amplified pulses with a launched pump power of 20 W. In this case, the slope efficiency yields to 32%. Reducing the repetition rate of AOM II to 32 kHz, an average power as high as 3.2 W could be reached, resulting in pulse energies of 100 µJ without any significant changes in intensity spectrum. The amplified pulse spectrum at 32 kHz is shown in fig. 3. The beam profile of the amplified pulses is nearly diffraction limited with a M^2 ~ 1.7.

The stretched and amplified pulses were compressed using a conventional diffraction-grating compressor. In order to demonstrate the possibility of compression of the generated 100 µJ pulses, we picked up a fraction of the amplifier output with a single-mode fiber and sent it through a pair of 1200 l/mm gratings. Even though we used no polarization maintaining fibers, the efficiency of the compressor in a double pass is 25%. Best compression was found at a grating separation of ~ 530 cm. The autocorrelation trace of 850 fs compressed pulses which were picked up just after the 11 µm power amplifier is shown in fig. 4. The pulse duration is limited, due to third order dispersion effects of the fiber stretcher, which cannot be compensated by a grating compressor.

The second power amplifier consisted of 3 m of fiber with a 50 µm diameter, 0.16-NA ytterbium-doped core, a 400 µm D-shaped inner cladding with NA = 0.38, and a polymer outer cladding. When seeded with 1.7 µJ at a repetition rate of 2 MHz, we were able to produce average powers up to 22 W of amplified pulses with a launched pump power of 50 W. The slope efficiency of the last amplifier stage is as high as 52%. Reducing the repetition rate of AOM II to 128 kHz, the pulse energies could be increased up to 130 µJ, i.e. an average power of 16.5 W. A smooth beam profile was observed, emerging the last power amplifier with a M^2

~ 7. The compression of the emitted pulses to few ps is possible, but we observed a strongly modulated autocorrelation trace with broad wings due to interference between guided modes.

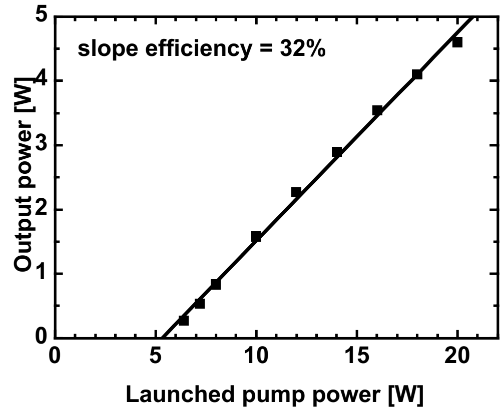


Fig.2 Slope of the first power amplifier operating at 2 MHz repetition rate.

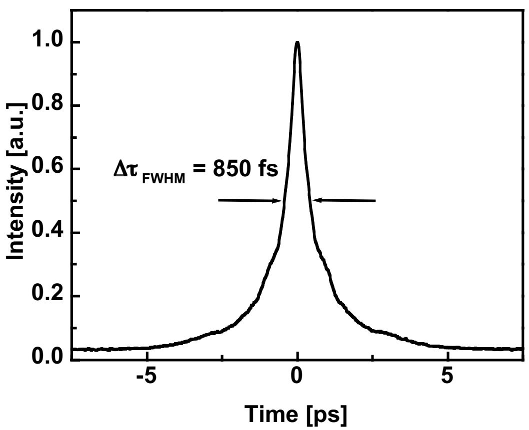


Fig.3 Autocorrelation trace of recompressed pulses after first power amplifier.

In conclusion, we have demonstrated the potential of high-gain Yb-doped fiber amplifier systems to provide ultrashort pulses with average powers in excess of 20 W and energies of more than 100 µJ. Investigations to further increase the pulse energy to more than 1 mJ are presently under progress in collaboration with the Max Born Institute Berlin and the Institute for Physical High Technology Jena. ■

III. Wave-Optical Engineering **Prof. Dr. Frank Wyrowski**

The investigation of the wave nature of light in the analysis and the design of optical systems constitutes one basic subject of the research and development of the institute.

Subject of wave-optical engineering

In contemporary optical systems design, ray tracing, which has its basis in geometrical optics, is the employed standard tool. Through the use of modern computer technology, ray tracing has become an extremely powerful technique in the design of both imaging and lighting systems. Indeed, the success of ray-tracing methods has led many optical systems designers to rely fully on ray tracing. Yet there are several reasons in modern optical engineering, which require access to a wave-optical field representation of light. One exemplary situation is the propagation through miniaturized or micro-structured optical systems and components. The development of optical systems with novel functionalities often rely on merit functions which are defined via the field representation of light. The light coupling efficiency into a fiber is an example of such a merit function. In addition, modern optical design concepts, like amplitude matching, require a field representation of light.

Optical system's design that takes to some extent the wave nature of light into consideration is appropriately called wave-optical engineering or physical-optics system design. This modern field in optical design actually gains momentum to obtain innovative optical solutions.

Wave-optical engineering deals with the modeling of sources, the analysis and modeling of linear interaction of light with inhomogeneous media, and the development of strategies, which allow the design of systems that perform a desired optical function. One example of our research activities is briefly described in the following.

Example: High-resolution proximity printing by wave-optically designed masks

Proximity printing is a high throughput and cost effective lithographic technique for production of e.g. large area flat panel displays. The resolution of this technique, however, is limited due to diffraction effects that occur at mask pattern edges. We can improve the resolution drastically by replacing the conventional photomask with a mask, which compensates these diffraction effects. The resulting mask modulates phase and amplitude of the exposure beam in such a way that the required image is formed at a predetermined distance behind the mask. This research project was based on a cooperation between the Institute of Applied Physics, the LightTrans GmbH in Jena, and Philips CFT in The Netherlands. The masks that have been examined are designed to form an image at a distance of 50 micron behind the mask. The mask contains 2 amplitude and 4 phase levels, and the pixel size is 1 micron. Under these conditions, a 3-micron line/space pattern is clearly resolved, whereas under conventional conditions the image is completely distorted.

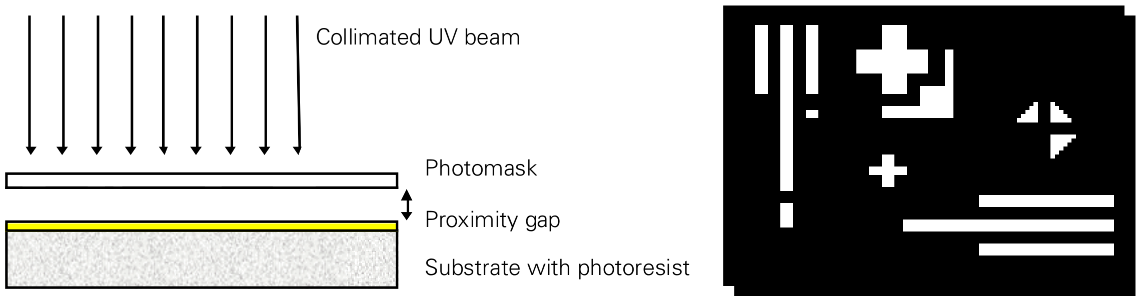
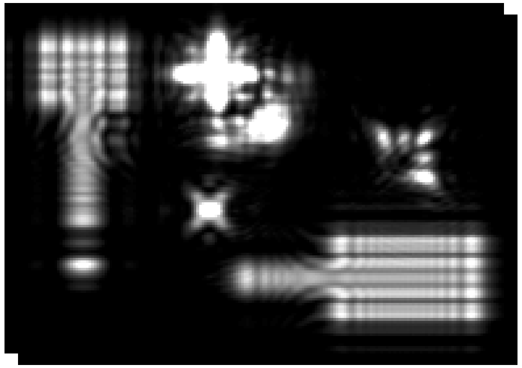


Fig.1 Schematic representation of proximity printing and layout of the photomask and target pattern used in this study. The line width in the target pattern is 3 microns.

Fig. 1 illustrates the basic subject of consideration. In the conventional technology, a mask is applied in which the transmission is proportional to the goal light distribution, that is for instance the target pattern in fig. 1. Then, the intensity and resist transmission shown in fig. 2 results. Obviously, the details of the target pattern are not resolved but destroyed by diffraction effects.



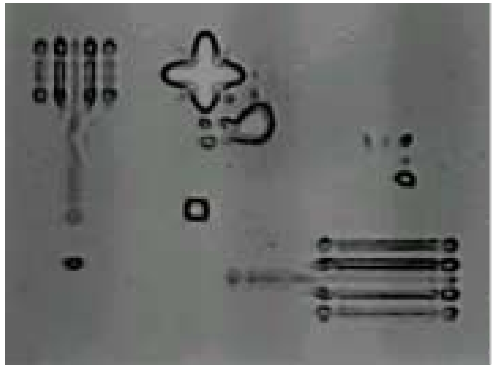


Fig.2 Calculated intensity distribution (left) 50 micron behind the photomask as defined in figure 1 (right) and (right) the practically obtained corresponding photoresist profile.

On the basis of wave-optical design methods, we calculated a mask with 2 amplitude transmission values (0 and 1) and 4 phase transmission values (0, 90, 180, and 270 degrees). This mask was fabricated by using the Leica e-beam writer ZBA 23 H and etching technique by structuring a chromium layer, which realizes the binary amplitude transmission and a four level surface profile in fused silica, which generates the desired phase transmission. A SEM photograph of the resulting mask is depicted in fig. 3.

This mask was used in an optical experiment and the result is shown in fig. 4. Obviously, the 3-micron line/space pattern is now clearly resolved.

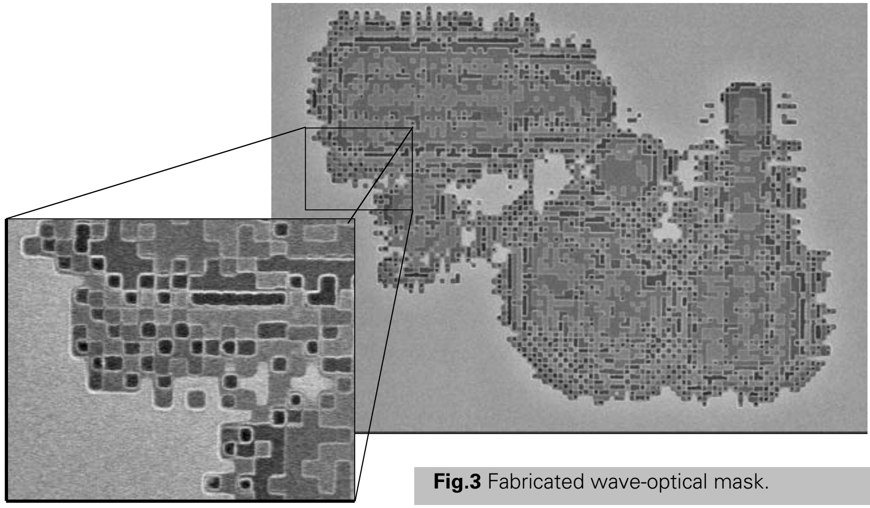


Fig.3 Fabricated wave-optical mask.

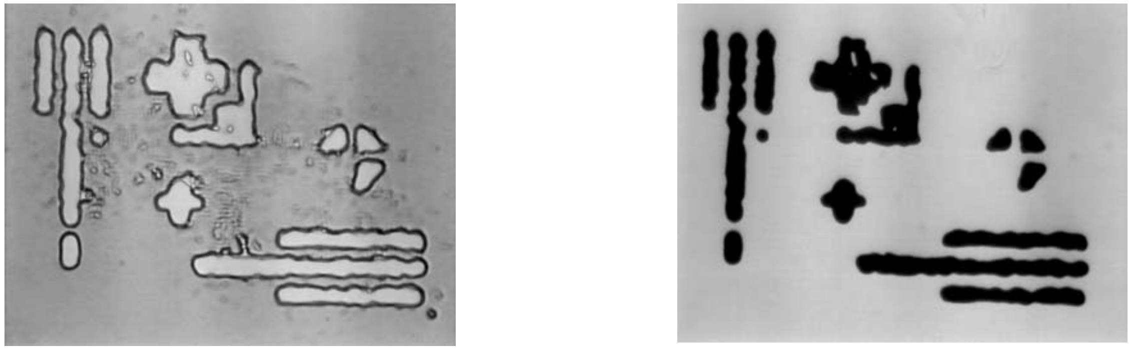


Fig.4 Practically obtained photoresist pattern for a proximity gap of 50 micron and resulting ultimate pattern etched in chromium layer.

This example demonstrates the importance of the consideration of the wave nature of light in modern optical engineering. ■

IV. Micro- and nano-optical devices

Dr. Ernst-Bernhard Kley

At the Institute of Applied Physics, investigations are performed in order to realize micro- and nano-structured surfaces with complex optical functions. This includes design, manufacturing, and characterization. One activity is related to the development of micro-optics for holography. Here, a main problem is the unsatisfying low productivity because of the low exploitation of the laser power that is used for the recording. This is caused by the expanding of the beam that is necessary for getting a uniform intensity distribution in the central beam area in the recording plane. To overcome this problem all the intensity of the beam should be converted into a top-hat intensity distribution that is well adapted to the recording area. It is well known that beam shaping elements can do this conversion [1–3], but such elements usually generate a wave front aberration which can not be accepted for holography. In addition, such elements show unacceptable wavelength aberrations if they are realized as diffractive ones. Therefore, basic considerations as well as test experiments are necessary to realize a high efficient full color holography.

Basic Considerations

The holographic recording of a lens function that can be realized with a typical well-known setup is one aim of the present work. As the lens aperture is rectangular (quadratic) and all the laser power should be used for the recording of the hologram, we need to concentrate the recording beams into a uniform illuminated field adapted to this aperture. Different kinds of beam shaping elements can make the conversion into such a top-hat or super Gaussian distribution, but for its application in holography we meet the following demands:

· Low wave front distortion for getting a satisfying interference pattern,
· high conversion efficiency for an effective use of the laser power,
· low wavelength aberration, this could offer the use of the elements in the whole visible range,
· large depth of sharpness for getting a large alignment tolerance.

All the demands can only be fulfilled by a refractive beam shaping element which is designed for a very small beam diameter. If, additionally, the designed element does not change the numerical aperture of the beam, its phase profile is most shallow. This leads to a minimal wave front distortion and the technological feasibility of the element is guaranteed, too. Fig. 1 shows the calculated surface profile of a beam shaping element designed for the conversion of a Gaussian intensity distribution (fiber output) into a rectangular top-hat intensity distribution. The conversion efficiency is greater than 99,5% [4]. Note that due to the small absolute sizes the far field intensity distribution has established in a distance of some millimeters behind the element.

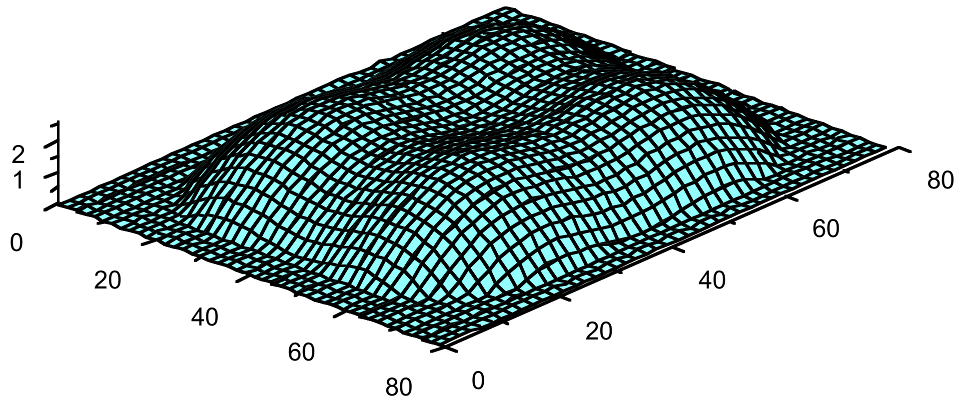


Fig.1 Designed surface profile of a beam shaping element for the conversion of a Gaussian beam (∅ 20µm) into a rectangular top-hat distribution (all dimensions in µm).

Experiments

The beam shaping elements were fabricated by using gray tone lithography based on HEBS-glass and proportional transfer by reactive ion beam etching. Detailed reports of the technologies are given in [4, 5]. There has also been shown that the transformed top-hat distributions have a very good homogeneity.

Verification of the wave front consideration was realized by the setup shown in fig. 2. The light of a He-Ne-Laser @ 633nm was coupled into two fibers and the beam shaping elements were placed 100µm behind the fiber end-faces. A beam splitter superposed the shaped beams and the interference pattern was imaged by a CCD-camera from a rotating screen.

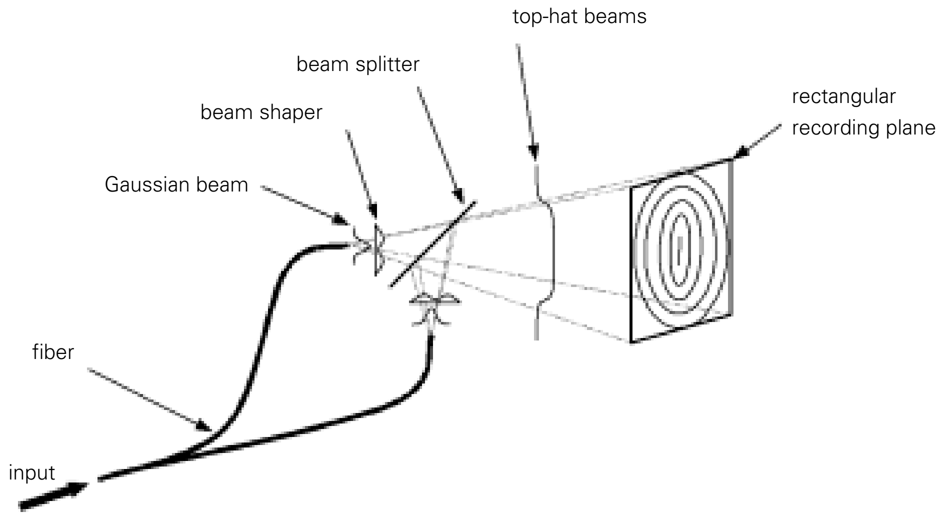


Fig.2 Setup for the interferometric wave front testing.

One problem of this setup is the variable phase relation between the interfering beams due to different changes in length of the fibers in case of thermal instability. To overcome this problem, we successfully tested a feedback controlling system that stabilizes the optical path difference by a piezoelectric actuator.

In the next step, the interference experiment with the setup of fig. 2 was simulated. The superposition of two shaped beams as well as the superposition of one shaped and one unshaped beam is of interest for the holographic application. Results of the calculations are the interference patterns shown in fig. 3 a) and b).

Superposition of two quadratic top-hat distributions leads to the interference pattern of fig. 3 c). The fringes are circular because the difference in phase is only a spherical term. Superposition of the top-hat distribution with the unshaped Gaussian beam result in interference patterns as shown in fig. 3 d). Measured and calculated distributions show good correspondence (distortions are caused by non perpendicular recording with the camera).

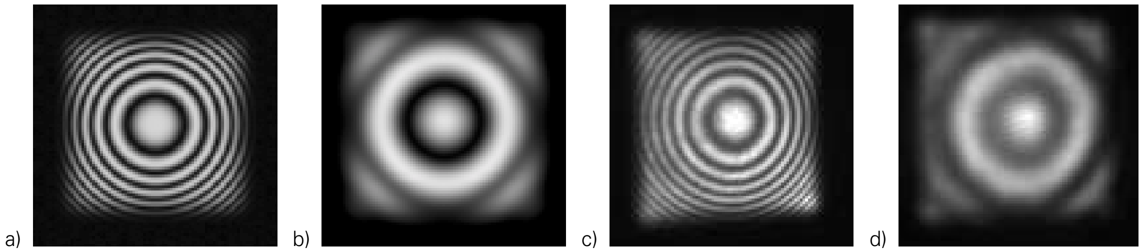


Fig.3 Simulated and measured interference patterns of the superposition of two quadratic top-hat distributions a) and c) and one shaped and one unshaped beam b) and d).

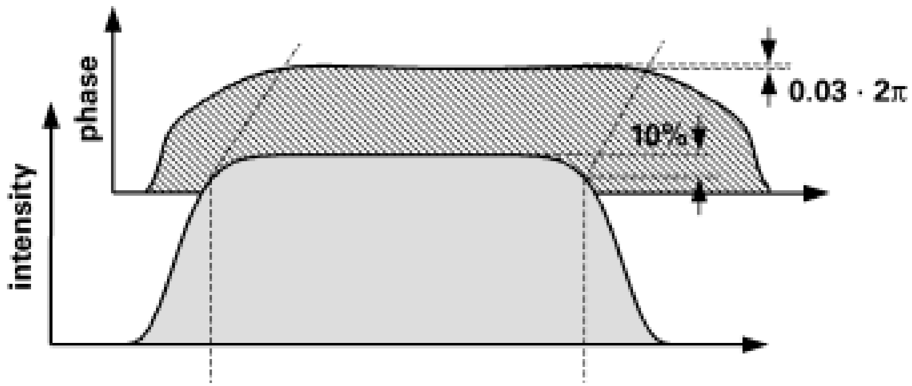


Fig.4 Calculated deviation between the transformed wave front and spherical phase (background), corresponding top hat intensity distribution (foreground).

A small deviation of the transformed to the desired wave front is important for the holographic recording. Here, we need a spherical phase in the region of constant intensity. Therefore we calculated the wave front deviation between the shaped beam and the unshaped spherical phase (fig. 4). The area with a maximum intensity decrease of 10% contains 76% of the whole intensity. Within this region, the wave front deviation amounts only 3% of the wavelength.

In Conclusion, we have tested the possibility to use beam shaping elements which perform the conversion of a Gaussian intensity distribution into a top-hat distribution for a more efficient holographic recording. Basic considerations have shown (computer simulations as well as experiments) that refractive micro optical beam shaping elements have this potential with a wave front aberration of only 0.03 λ and an efficiency of 76 % (intensity modulation < 10 %). Compared with the efficiency of conventional holographic recording, we found a gain of 11.7. This can be increased even more if an optimized beam shaping element is used which generates a higher order of super Gaussian. This leads to an increased wave front aberration on the other side.

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V. Integrated-optical high power amplitude modulator for the visible wavelength range in KTP **Dr. Jens-Peter Ruske**

The Institute of Applied Physics is developing novel integrated optical devices. One topic is the realization of amplitude modulators working in the visible spectral range for color image generation.

A suitable candidate is the integrated-optical Mach-Zehnder-interferometer (MZI) in KTP [Ruske et al. 1998]. However, due to the very small cross section of its singlemode waveguides, it can only be used for low power applications. If the guided power is higher than some 100 mW, the resulting power density inside the waveguide and at the coupling faces will destroy the material. One way to overcome this limitation is to increase the cross section of the waveguide. The refractive index increase (Δn) of large mode area waveguides has to be very low, because singlemode waveguides are needed for MZI. With these waveguides, bends, needed in MZI's, are not possible because of their weak guidance. Therefore a new modulation principle has to be applied, called the Asymmetric Diffraction Amplitude Modulator (ADAM) [Pertsch and Wächter 1999].

This device is based on a diffraction zone embedded asymmetrically between an input and an output waveguide (fig. 1). In off-state, the light is asymmetrically diffracted because of the one-sided reflecting boundary of the diffraction zone. At the end of the diffraction zone, only a negligible fraction of light couples into the output waveguide. To switch the device to on-state, the refractive index of a barrier region is reduced by applying a voltage to an appropriate pair of electrodes, due to the electro-optical effect. This barrier creates a waveguide connecting the input and output. In contrast to the Mach-Zehnder-interferometer, the ADAM has high transmission in the active state (voltage switched on) and low transmission in the inactive state (voltage switched off)

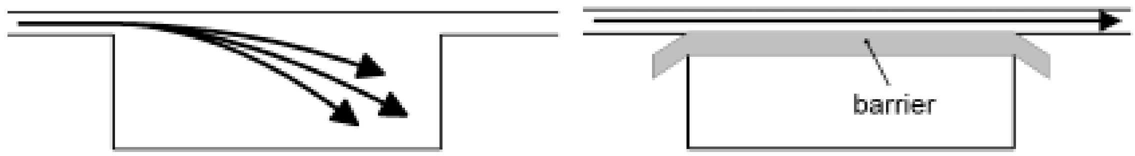

Fig.1 Function of the Asymmetric Diffraction Amplitude Modulator off-state (left) and on-state (right).

Theoretical simulations

A pair of electrodes on the surface of the chip creates the barrier in the ADAM. The electro-optical coefficient r_{33} of KTP has the largest value. Using this coefficient and z-cut material, the barrier is created directly below the electrode. Two different configurations are possible:

With an electrode pair above the diffraction zone, the refractive index is lowered directly beside the waveguide (fig. 2, left). Another possible configuration is a triple electrode to raise the refractive index within the waveguide and lower the index in both the diffraction zone and outside the waveguide (fig. 2, right).

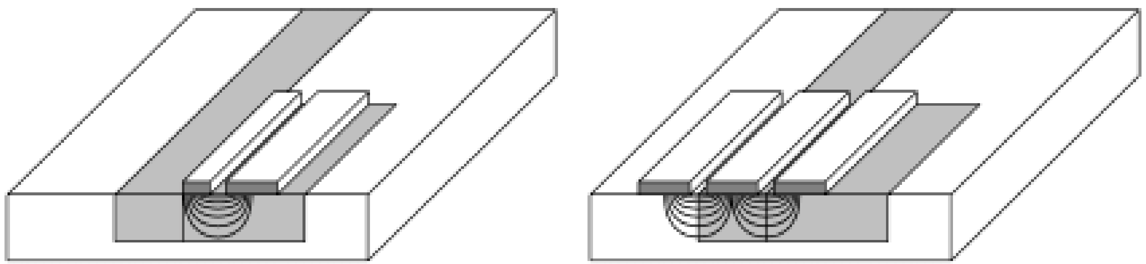

Fig.2 Possible configurations of electrodes for the ADAM.

We used beam propagation method (BPM) to find the optimal configuration and position of the electrodes. The BPM calculations were made using waveguides with a Gaussian profile, a length of 3 mm, and a modulation voltage of 30 volts.

The BPM showed that the transmission in the active state for the triple electrode is between 33% and 59%. The efficiency of the double electrode configuration is much higher and the transmission reaches 97% (fig. 3). We chose this configuration for the experimental realization.

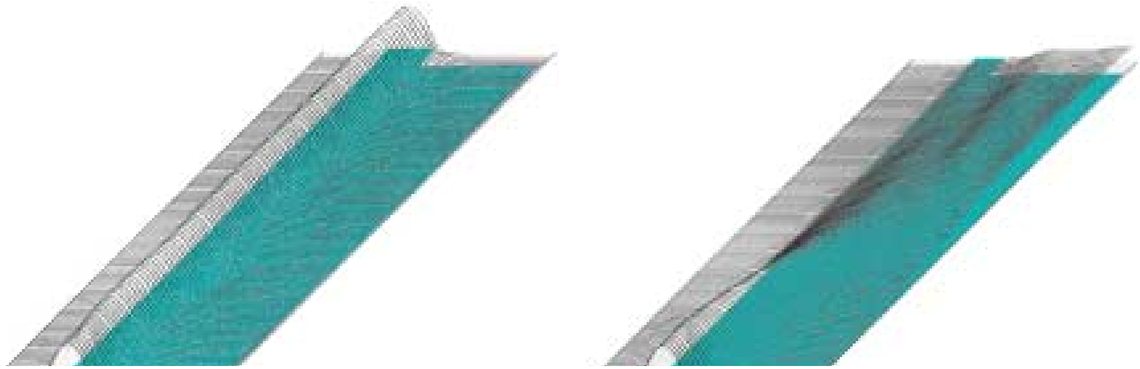

Fig.3 BPM calculation for the ADAM with electrode pair; on-state (left) and off-state (right).

Fabrication and Experiments

The Δn of the waveguide needs to be sufficiently low to minimize the modulation voltage required for creation of a barrier. In order to guide high powers (> 1 W), the waveguide needs to have a large cross section. The field distribution should be symmetrical.

Conventional singlemode waveguides for the visible spectral range are approx. 3-5 µm wide and approx. 4 µm deep with a Δn of about $4 \cdot 10^{-3}$. Their width can easily be increased by broadening the ion exchange mask. The depth of the waveguide cannot be increased by extending the duration of the ionic exchange process because of simultaneous increase of Δn. Thus, the waveguide would get lost of its singlemode behavior. So only a short ionic exchange of the crystal in a $RbNO_3/KNO_3/Ba(NO_3)_2$-melt is performed. This results in a smooth waveguide with erfc-profile and a relatively high Δn [Roelofs et al. 1991]. During the following annealing, the Rb-ions diffuse into the crystal, forming a deeper Gaussian profile with low Δn (fig. 4). The width and the depth of the waveguide can be controlled independently because of the diffusion anisotropy of Rb-ions in KTP [Bierlein and Vanderzeele 1989].

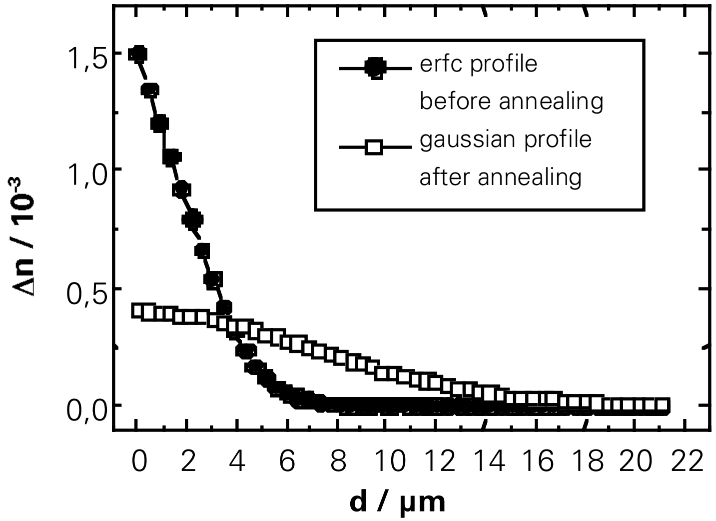

Fig.4 Profiles of the waveguide before and after annealing.

The ADAM was fabricated in z-cut KTP, propagation in y-direction. An ion exchange mask was made by photolithography and lift-off technique. The ionic exchange in a 75% $RbNO_3$/22% KNO_3/ 3% $Ba(NO_3)_2$ – melt at 310°C for 3–7 min was followed by annealing at 350°C for 10 – 30 min. After the polishing of the endfaces the gold electrodes were sputtered.

The attenuation of the waveguides is relatively high, values between 2 and 4 dB/cm were measured. The waveguides are able to guide a power up to 4 W @ 532nm.

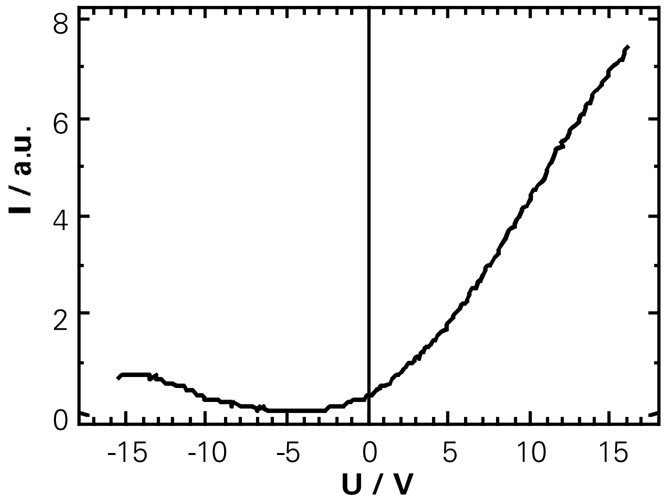

Fig.5 Output intensity of ADAM versus applied voltage.

The output intensity of the ADAM versus the applied voltage is shown in fig. 5. At U=0 V the transmission is low, the modulator is switched off. The increase of the transmission corresponds to a positive voltage. But if a negative voltage is applied, the transmission shows a weak increase, too. In this case, the refractive index below the electrode next to the waveguide is increased and the barrier is formed under the second electrode. So a broader waveguide with a lower transmission is formed. The modulation voltage does not have an offset compared to MZI modulators. We measured a maximum extinction ratio of 1:300. The modulation frequency of the ADAM reaches the hundred megahertz range because of the similar electrode structure compared to conventional MZI modulators.

In order to measure the intensity distribution in the diffraction zone, a modulator chip was cut at the end of the diffraction zone and this face was polished. By coupling light into the other end, the changes of the optical field distribution within the diffraction zone can be measured by means of a CCD-camera when a modulation voltage is applied (fig. 6).

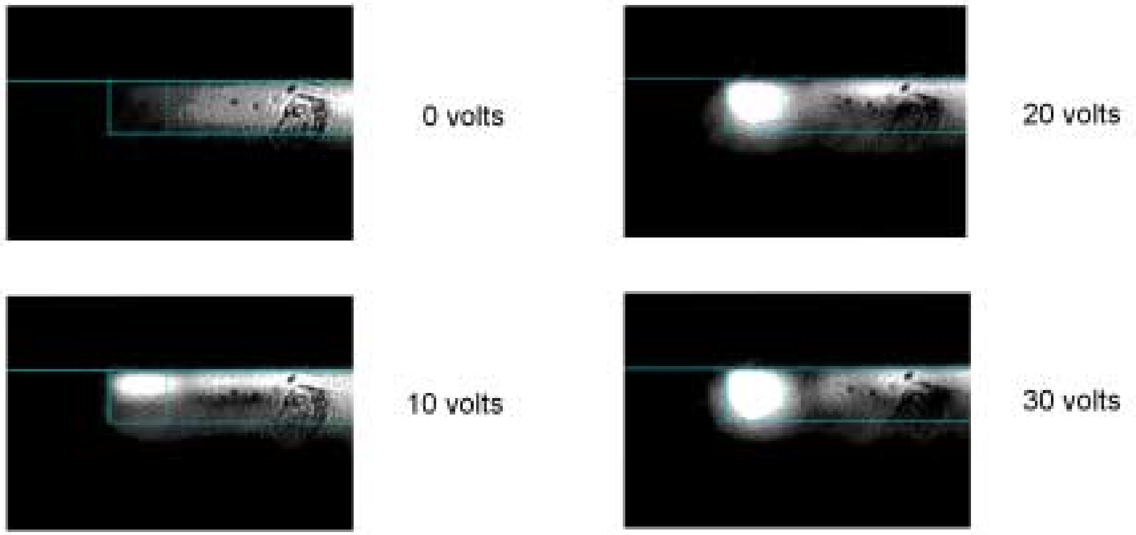

Fig.6 Intensity distribution at the end of the diffraction zone of ADAM at different voltages.

The performed measurements indicate that in contrast to MZI modulators the new type of integrated electro-optical modulators has the potential to handle high optical powers in the visible wavelength range. New applications in printing and display technology can be supported.

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VI. Microfabrication of optical waveguides in transparent materials

Dr. Stefan Nolte

At the Institute of Applied Physics, the investigation of the interaction between ultrashort laser pulses and matter is one topic of research. Besides the study of the basic interaction process, novel concepts for production technology based on laser machining are developed.

The fabrication of optical waveguides and waveguide arrays in different glasses and crystals is required for many applications in integrated optics. At present, the waveguiding structures are fabricated by ionic diffusion or exchange into a transparent substrate, by laser irradiation of special photorefractive materials, or by lithographic methods. Although these technologies are well established and successful, a quest for new, more flexible techniques allowing to fabricate three-dimensional photonic structures continues.

Recently, a novel direct laser-writing technique, based on femtosecond laser pulses, has been demonstrated. When tightly focused into the bulk of a transparent material, these pulses can produce a permanent refractive index modification inside a small focal volume. In this volume, the laser intensity is high enough for multiphoton absorption, optical breakdown, and microplasma formation. The evolution of this microplasma, which is driven by free electrons, induces structural (and refractive index) changes in the focal region by leaving a nonelastic thermo-mechanical stress and/or by the formation of color centers. These mechanisms are universal and allow to perform three-dimensional refractive index patterning and to fabricate complicated photonic structures in practically every transparent material.

In the following, we report on investigations of the fabrication of waveguiding structures in fused silica and crystalline quartz. For the microfabrication of the optical waveguides, 800 nm laser pulses (Ti:Sapphire laser system) with a pulse duration of 120 fs and a pulse energy of a few µJ are focused tightly into the bulk of the transparent sample by a microscope objective or a lens with short focal length (see fig. 1). When the sample is moved with respect to the laser beam axis, an optical waveguide can be produced, i.e. directly written into the material.

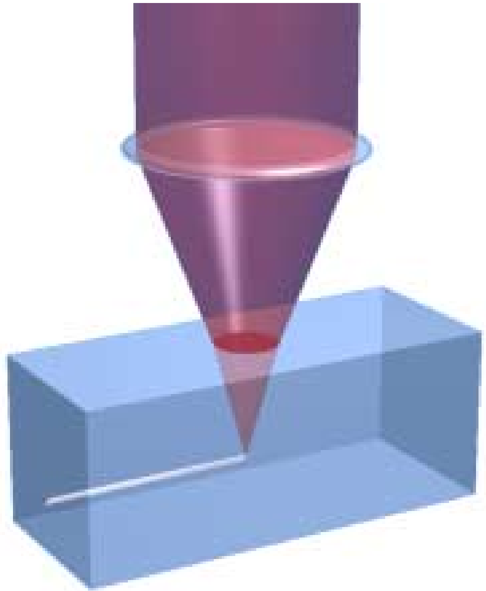

Fig.1 Schematic setup used for the microfabricaton of optical waveguides in transparent media.

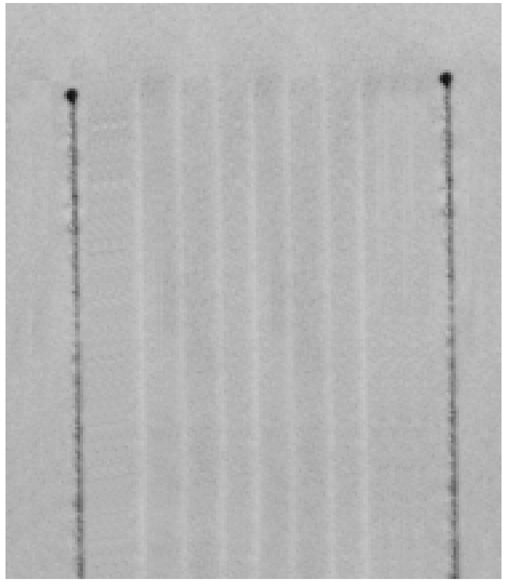

Fig.2 Polarization contrast optical microscope image of several waveguides in fused silica (top view). The modified area is marked left and right (micro-structured traces).

Waveguides in fused silica

In fused silica, we could produce waveguides using ultrashort laser pulses with a damping of <1 dB/cm and a maximum refractive index increase of $5x10^{-3}$, which is fairly comparable to conventional integrated optics devices. These waveguiding structures are temperature stable up to 700 K. Fig. 2 shows a polarization contrast microscope image of several waveguides. To mark the modified area, destroyed traces are produced at the borders (left and right).

It is interesting to note that only by changing the writing speed, waveguides with a controllable mode number can be produced. Fig. 3 shows the near-field distribution of 514 nm laser radiation that is guided by the waveguides (only the highest guided mode is shown). Each near-field image corresponds to a waveguide written with a different velocity but otherwise constant parameters. While the wavguides are single-mode down to a writing speed of 0.5 mm/s, they become multi-mode with slower writing speed. This is mainly due to a higher increase of the refractive index in the modified area. The profile of the refractive index remains almost constant.

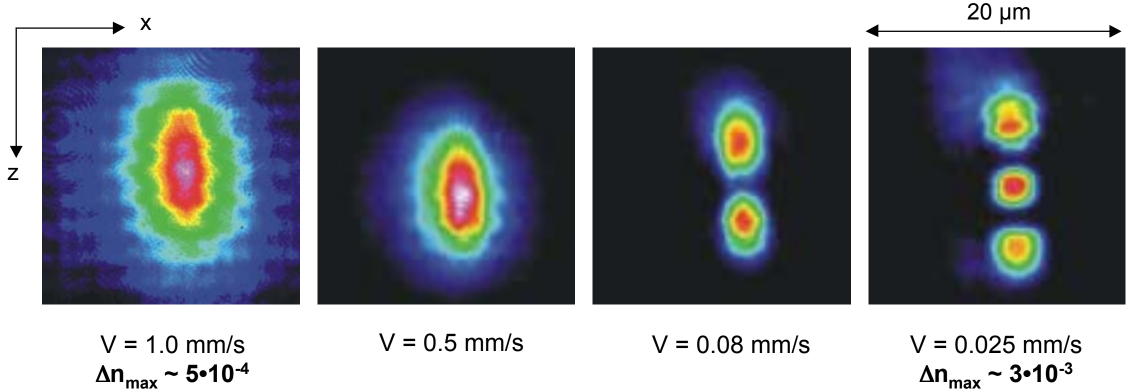

Fig.3 Near-field distributions of 514 nm laser radiation at the end-surface of waveguides in fused silica. For all waveguides, the highest order mode that is guided is shown. For the production of these waveguides, only the writing velocity is varied from v = 1.0 mm/s (left) to 0.025 mm/s (right). This mainly results in an increase of the refractive index change from $\Delta n = 5x10^{-4}$ to $3x10^{-3}$.

Based on measurements of the refractive index profile with a refracted near-field profilometer, the near-field distribution was calculated by solving the Helmholtz equation in the paraxial approximation (BeamPROP 4.0, RSoft, Inc.). The calculated and measured near-field distributions are in very good agreement, as shown in fig. 4.

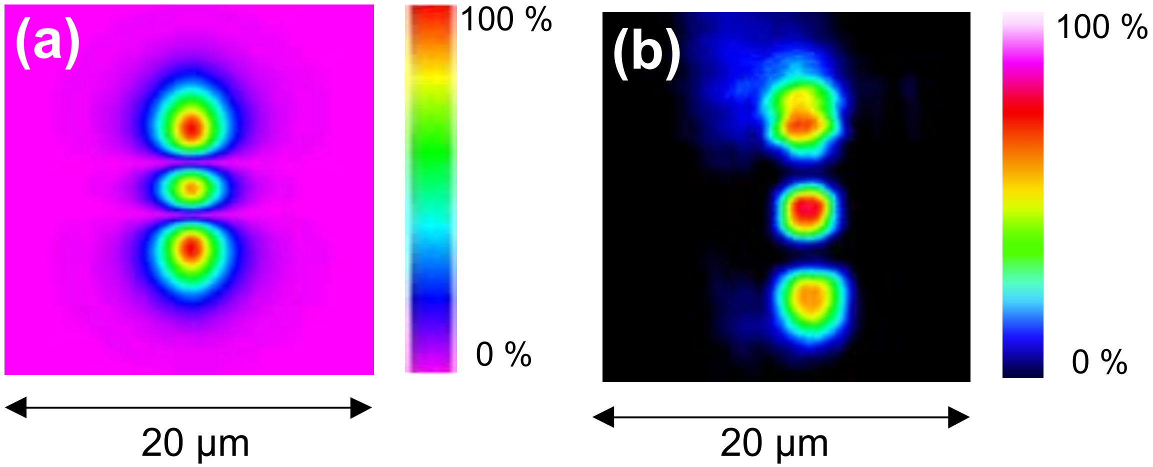

Fig.4 Comparison of the calculated (a) and measured (b) near-field distribution for the highest order mode of the right waveguide of fig. 3.

Waveguides in crystalline quartz

In crystalline materials, using ultrashort laser pulses can also produce waveguiding structures. The observed refractive index increase of up to $\Delta n \approx 10^{-2}$, which is deduced from interferometric analysis, is even higher than in glasses. These waveguide structures are stable up to temperatures as high as 1500 K (for more than one hour).

Fig. 5 shows two polarization contrast optical microscope images of waveguides produced in crystalline quartz. The left image shows a top view of several parallel waveguides written in different depths, and in the right image, the magnified cross section (end view) of one of these waveguides is displayed.

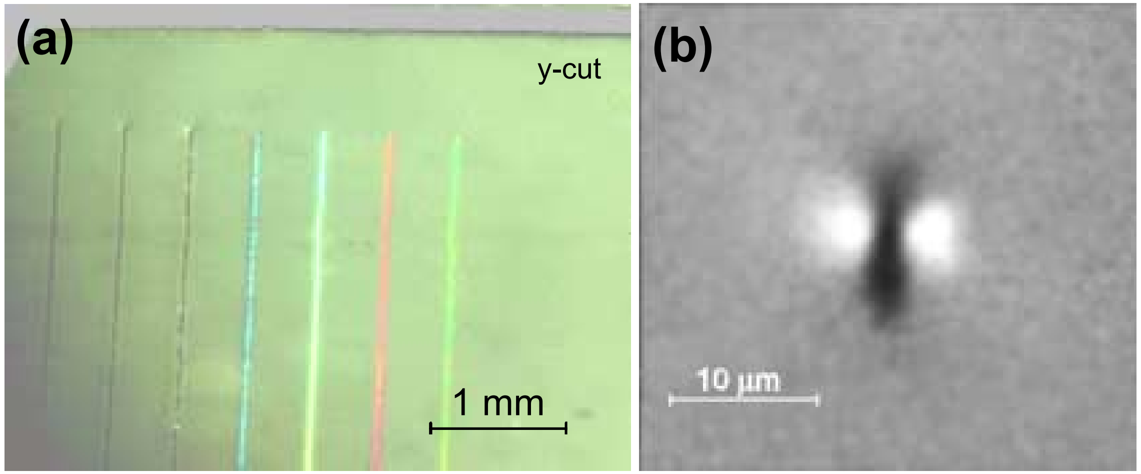

Fig.5 Top view polarization contrast microscope image (left) of waveguides produced in crystalline quartz (spacing between the waveguides is 0.5 mm). In the right image a cross section of one of the waveguides (polarization contrast microscope) is shown.

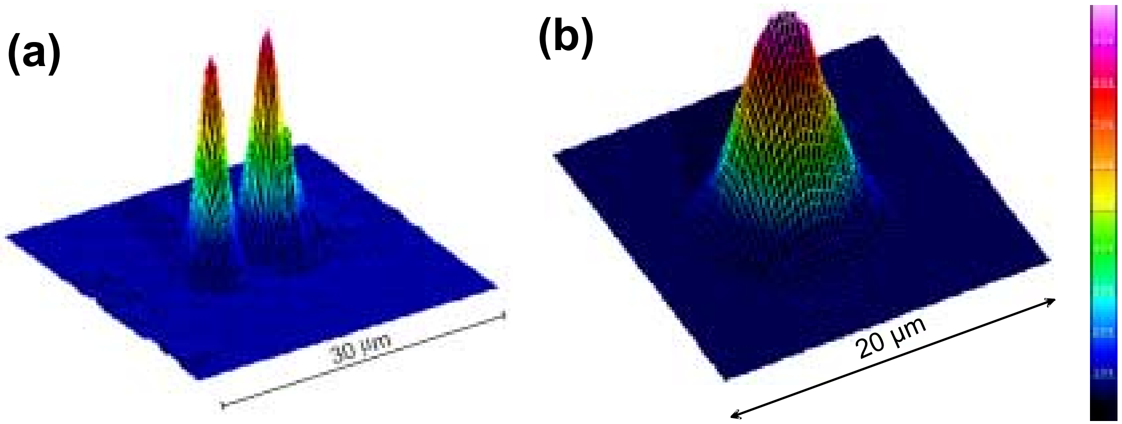

Fig.6 Near-field distributions of guided radiation at 514 nm. Different modes are guided.

The image of the end view (fig. 5, right) shows details of the generated modifications inside the material. The dark area corresponds to the laser beam focus; the bright areas correspond to the induced stress. X-ray topography and transmission electron microscope (TEM) analysis of these structures reveal that the crystalline structure in the central part is strongly disturbed. This core is surrounded by an area with a deformed lattice, which is probably responsible for the refractive index increase. Fig. 6 shows two different near-field distributions of 514 nm laser radiation guided in these structures.

In conclusion

The use of ultrashort laser pulses allows producing waveguides in the bulk of transparent materials. By carefully choosing the processing parameters, waveguides with different properties can be designed in glasses as well as in crystalline materials. This could open up new applications in integrated optics (e.g. the fabrication of 3-dimensional optical elements). ■

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Conference Contributions

I. **A. Tünnermann, H. Zellmer**: Hochleistungs-Faserlasersysteme im Sichtbaren und Infraroten; L.O.B. 2000, Laser+Optik Berlin, March 8–9, 2000 (invited)

II. **A. Tünnermann**: Faserlaser und -verstärker – Neuartige Konzepte für kohärente Strahlungsquellen im sichtbaren und nahinfraroten Spektralbereich; Atomphysikalisches Kolloquium der Universität Bonn, 2000 (invited)

III. **J. Limpert, H. Zellmer, P. Riedel, A. Tünnermann**: Upconversion-Prozesse in Dysprosium, Europium, Samarium und Terbium; Fachvortrag (invited), Frühjahrstagung der DPG, Bonn, 2000

IV. **A. Tünnermann, S. Nolte**: Neue Trends in der Mikro- und Nanobearbeitung durch den Einsatz von Ultrakurzpulslasern; Thüringer Lasersymposium, Jena, 2000 (invited)

V. **S. Nolte, J.-P. Ruske, M. Will, A. Tünnermann**: Mikrostrukturierung im Volumen transparenter Materialien mit ultrakurzen Laserpulsen, Thüringer Lasersymposium, Jena, 2000

VI. R. Schiek, W. Elflein, T. Pertsch, **A. Tünnermann**, K. R. Parameswaran, M. M. Fejer: Femtosecond all-optical switching in a lithium niobate directional coupler with cascaded nonlinearity; Nonlinear Optics: Materials, Fundamentals and Applications, Kaua'i-Lihue, Hawaii/USA, 2000 (invited)

VII. **L. Wittig, E.-B. Kley, A. Tünnermann**: Refraktive Strahlformer hergestellt durch Elektronenstrahl- und Grautonlithographie; Mikrooptik-Workshop, Hagen, 2000 (invited)

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XII. **L. Wittig, M. Cumme, T. Harzendorf, E.-B. Kley**: Intermittence effect in electron beam writing; Micro- and Nano-Engineering 2000, September 18–21, 2000 (Poster)

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XIV. M. Barge, S. Bruynooghe, F. Clube, A. Nobari, J.-L. Saussol, E. Grass, H. Mayer, **B. Schnabel, E.-B. Kley**: 120 nm lithography at 364 nm wavelength using off-axis TIR holography; Micro- and Nano-Engineering 2000

XV. **U. Hübner**, R. Plontke, M. Blume, A. Reinhardt, H. W. P. Koops: On-line nanolithography using electron beam induced deposition technique; Micro- and Nano-Engineering 2000, September 18–21, 2000

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XXVII. **S. Nolte**, F. Korte, G. Kamlage, **M. Will, B. Chichkov, A. Tünnermann**: Microstructuring of Solid Targets with Femtosecond Laser Pulses; RGLS, Vladimir/Suzdal (Rußland), 2000

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Patent Applications

I. **J.-P. Ruske, H. Zellmer, A. Tünnermann**: Direkt modulierbarer Laser; Patent Nr. 100 06 050, Applicant: LDT Gera

II. **H. Zellmer, A. Tünnermann**: Faseroptischer Verstärker; Patent Nr. 100 09 379, Applicant: LDT Gera

III. Kränert, T. Gabler, **H. Zellmer, A. Tünnermann**: Faserverstärker; Patent Nr. 100 09 380, Applicant: LDT Gera

IV. Kränert, T. Gabler, **H. Zellmer, A. Tünnermann**: Anordnung zur Erzeugung roter, grüner und blauer Laserstrahlung; Patent Nr. 100 09 381, Applicant: LDT Gera

Fairs

MTT 2000 (Mikrotechnik Thüringen, Erfurt)	Fiber laser, integrated-optical modulator with scanner, beam-shaping elements
Optatech 2000 (Frankfurt/Main)	Fiber laser, integrated-optical modulator, beam-shaping elements

Convention

Annual Meeting of German Society of Applied Optics
(June 13–17, 2000, Jena)
Conference Chair: **Prof. Dr. Frank Wyrowski**

Organizing Activities

Prof. Dr. Andreas Tünnermann

CLEO/Europe 2000 (Nice/France)	General Program Chair
CLEO2000 (Baltimore, Maryland/USA)	Program Committee Member „Solid state lasers“
MTT 2000 (Mikrotechnik Thüringen, Erfurt)	Program Committee Counselor
BMBF-Leitprojekt (07/00) „MICROPHOT“	Network Coordinator
OptoNet e. V.	Founder and member of the board
Forschungsschwerpunkt Optomatronik/ Zentrum für Optomatronik	Member

Dr. Stefan Nolte

CLEO2001 (Baltimore, Maryland/USA)	Program Committee Member „Laser Applications and Optical Instrumentation Systems“

Dr. Holger Zellmer

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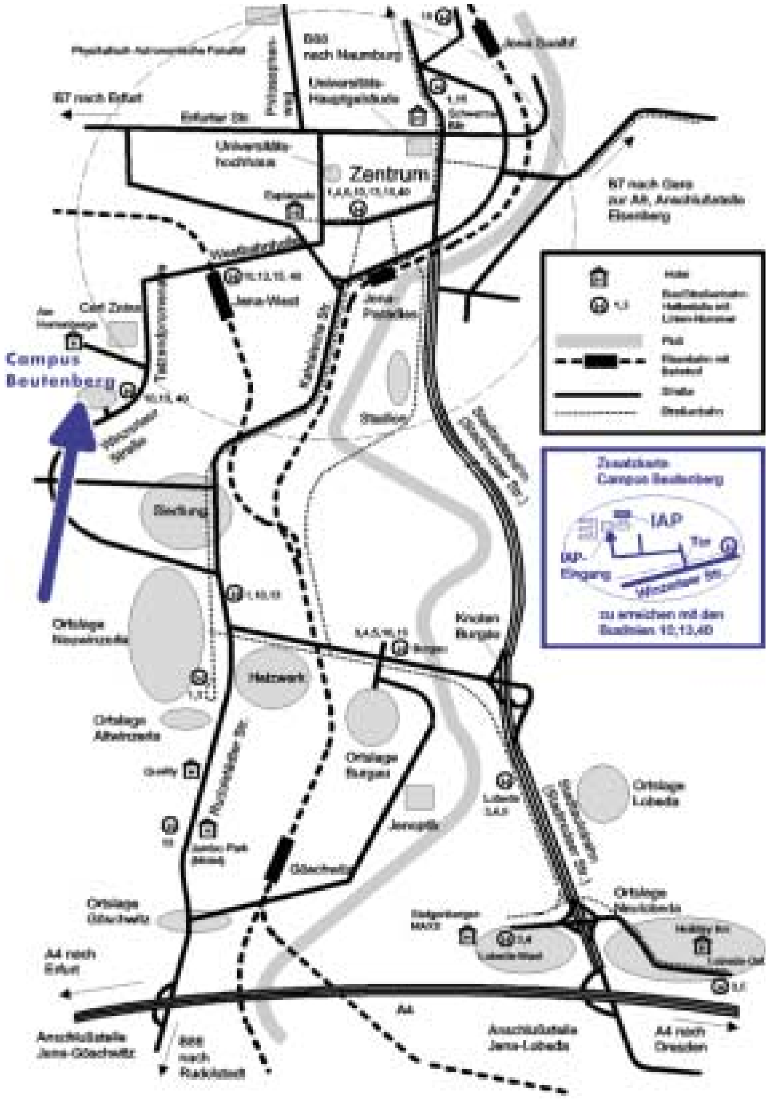
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