'17 Annual Report

Institute of Applied Physics
Friedrich-Schiller-Universität Jena

Imprint

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EDITORIAL
Ira Winkler, Dr. Frank Schrempel

LAYOUT
Ira Winkler

PHOTOS/GRAFICS
Institute of Applied Physics (IAP), Fraunhofer IOF [W. Oppel],
Friedrich Schiller University Jena [J.-P. Kasper], PAF-FSU
p.68: aboutpixel.de/Lektüre©marshi

Cover: ALD-coated lens.

Content

PREFACE / VORWORT

Dear colleagues,

we dared to accomplish the step into a new field of technology - quantum technology - and successfully started it in 2017. We have recognized that particularly imaging and spectroscopic quantum methods already captivate through revolutionary research results with a high degree of practical relevance. Quantum imaging allows light sources, imaging and sample interaction to operate at tailored wavelengths. Applications in hardly accessible spectral ranges benefit from the technical precision of the visible and near-infrared optics. Specialists therefore speak about the "second quantum revolution", which will bring disruptive changes in science, business and society. Technologies such as photonics and sensors, which enable quantum systems to be controlled, thus become the "key technology of the key technology" of the 21st century and multiply their value-added potential.

Founded in 2017 as a Thuringian initiative, the Innovation Center for Quantum Optics and Sensor Technology (InQuoSens), will give answers about questions of basic research and applied research in combination with our expertise. It summarizes the expertise of key partners in the region and creates an important laboratory infrastructure. This research focus is now also reflected in the extension of the IAP group name from "Nano Optics" to "Nano & Quantum Optics".

Accompanying this, the "Leistungszentrum Photonik", with its partners Friedrich Schiller University Jena and Fraunhofer IOF in close cooperation with partners of the TU Ilmenau, will lay the scientific and technological foundations for developing this application potential along the entire optical spectrum. To implement these goals, this year's commissioning of the fiber technology center was an important step in completing the process chain of fiber lasers. This means that shortest innovation cycles can be achieved. Our researchers already hold various world records, such as with 4.5 KW the highest performance of a fiber mode with low bandwidth! It is therefore not surprising that our lasers mold the core of the most brilliant attosecond laser system on the European Extreme Light Infrastructure (ELI). It will help researchers from all over the world to better understand the dynamics of atoms.

This allowed our scientists to confirm their excellent reputation in the professional world and international experts followed the invitation to our workshop "Next generation fiber technology - perspectives and roadmap" of the ERC-MIMAS project. Over 40 scientists and stakeholders from business and society have developed perspectives for the laser development of the coming decades. They laid the basis for the progressing of this dynamic industry and point the way to scientific breakthrough experiments and visionary applications of laser light.

I am particularly proud that we have succeeded in being selected as a pilot project with the "Max Planck School of Photonics". The program of the Max Planck Schools aims to bring together special academic focuses in Germany across all locations and to take on a global pioneering role in the academic promotion of young researchers. A network has been formed with partners from six other locations as well as from institutes of all four non-university research institutions in Germany, which in the future will provide about 60 of the best Master's students and more than 100 excellent PhD students an academic "home".

Also successful was the continuation of the Verbund-ZIK "HiteCom" by "OptiCon" for the investigation of high-temperature conversion processes as well as the installation of the BMBF junior research group "NanoScopeFutur-2D", under which Falk Eilenberger returns to the IAP and investigates applications of 2D materials, especially for microscopy.

I am also very pleased about the local perception of our institute: at the "Lange Nacht der Wissenschaften" enthusiastic visitors listened to our colleagues and marveled at great demonstrators. I would like to take this opportunity to once again thank all the colleagues and emphasize that the number of more than 1000 guests who found their way to the suburban IAP in pouring rain expresses a high recognition of our work. In addition, many pupils are interested in our research and would like to complete their school-internship at the IAP. It is amazing that the requests come not only from high schools in Jena, but now also from Weimar and Gera! With the newly established “Lichtwerkstatt” at the ACP, all those interested laymen got a meeting place where they can fiddled with new ideas and expert advice can be obtained. In this context, the visit of students of the Bashkir University in Ufa worth mentioning, as we are obviously known till there. The delegation was impressed by our work and labs - which reminds us of the outstanding conditions we have for our work.

Finally, I'd like remind of the retirement of Ernst-Bernhard Kley for age reasons. He has shaped the research profile of the IAP like no other and has made a significant contribution to the fact that nanostructured optical systems today have a broad field of application and often exceed classic solutions. Among other things, it was able to contribute to the GAIA mission of the ESA: nanostructured gratings from his group measure our galaxy with unrivalled precision and generate a wealth of data that will benefit researcher for many years to come. He leaves a big gap from a scientific and human point of view. Dr. Kley handed over the leadership of his group to Dr. Uwe Zeitner. I am pleased to be able to further intensify the cooperation with this cherished colleague.

I thank all of you for your commitment, openness, creativity and confidence, without the optics world class research would be unthinkable and look forward to the next success stories in the 2018.

Prof. Dr. Andreas Tünnermann

Liebe Kolleginnen & Kollegen,

wir haben den Sprung in ein neues Technologiefeld – der Quantentechnologie – gewagt und 2017 erfolgreich damit begonnen. Wir haben erkannt, dass insbesondere abbildende und spektroskopische Quanten-Verfahren schon heute durch revolutionäre Forschungsergebnisse mit hohem Anwendungsbezug bestechen. Durch Quantenimaging können Lichtquellen, Abbildung und Probeninteraktion auf maßgeschneiderten Wellenlängen operieren. Anwendungen in kaum erschlossenen Spektralbereichen profitieren von der technischen Präzision der sichtbaren und nahinfraroten Optik. Spezialisten sprechen von der „zweiten Quantenrevolution“, die disruptive Veränderungen in Wissenschaft, Wirtschaft und Gesellschaft nach sich ziehen wird. Technologien, wie Photonik und Sensorik, die es ermöglichen Quantensysteme zu kontrollieren, werden so zu „Schlüsseltechnologie der Schlüsseltechnologie“ des 21. Jahrhunderts und multiplizieren ihr Wertschöpfungspotential.

Im 2017 als Landesinitiative gegründeten Innovationszentrum für Quantenoptik und Sensorik (InQuoSens) werden nun Fragestellungen der Grundlagenforschung und angewandten Forschung mit unserer Kompetenz beantwortet und zusammengeführt. Darüber hinaus fasst es die Expertise wichtiger Partner in der Region zusammen und schafft eine wichtige Laborinfrastruktur. Dieser Forschungsschwerpunkt schlägt sich nun auch nieder in der Erweiterung des IAP Gruppennamens von „Nano Optics“ zu „Nano & Quantum Optics“.

Flankierend dazu wird das Leistungszentrum Photonik mit seinen Partnern Friedrich-Schiller-Universität Jena und Fraunhofer IOF in enger Kooperation mit Partnern der TU Ilmenau wissenschaftlich-technologische Grundlagen legen, dieses Anwendungspotential entlang des gesamten optischen Spektrums neu zu erschließen. Zur Umsetzung dieser Ziele war die diesjährige Inbetriebnahme des Fasertechnologiezentrums eine wichtige Stufe zur Vervollständigung der Prozesskette von Faserlasern. Damit sind kürzeste Innovationszyklen umsetzbar. Bereits jetzt halten unsere Forscher diverse Weltrekorde, wie z.B. mit 4,5 Kilowatt die höchste Leistung aus einer Fasermode mit geringer Bandbreite! Daher wundert es nicht, dass unsere Laser das Herzstück des brillantesten Attosekundenlasersystems überhaupt am europäischen „Extreme Light Infrastructure (ELI)“ bilden. Es wird Forschern aus aller Welt helfen, die Dynamik der Atome noch besser zu verstehen.

So konnten unsere Wissenschaftler ihren ausgezeichneten Ruf in der Fachwelt untermauern und international wurde der Einladung zum Workshop „Next generation fiber technology - perspectives and roadmap“ des ERC-MIMAS Projekts gefolgt. Über 40 Wissenschaftler sowie Stakeholder aus Wirtschaft und Gesellschaft haben Perspektiven für die Laserentwicklung der kommenden Jahrzehnte entwickelt. Sie legten damit einen Grundstein zur Entwicklung eines dynamischen Wirtschaftszweigs und weisen den Weg zu wissenschaftlichen Durchbruchsexperimenten und visionären Anwendungen von Laserlicht.

Ich bin besonders stolz darauf, dass es uns gelungen ist, mit der „Max Planck School of Photonics“ als Pilotprojekt zur Förderung ausgewählt worden zu sein. Das Programm der Max Planck Schools zielt darauf ab, besondere akademische Schwerpunkte Deutschlands standortübergreifend zu bündeln und eine globale Vorreiterstellung in der akademischen Nachwuchsförderung zu übernehmen. Mit Partnern sechs weiterer Standorte sowie aus Instituten aller vier außeruniversitären Forschungseinrichtungen Deutschlands wurde ein Netzwerk geformt, welches zukünftig ca. 60 der besten Masterstudenten sowie mehr als 100 exzellenten Doktoranden ein akademisches „Zuhause“ bietet.

Erfolgreich waren auch die Weiterführung des Verbund-ZIKs „HiteCom“ durch „OptiCon" zur Untersuchung von Hochtemperaturkonversionsprozessen sowie die Installation der BMBF-Nachwuchsgruppe „NanoScopeFutur-2D“, unter welcher Falk Eilenberger wieder ans IAP zurückkehrt und sich mit der Untersuchung von bzw. mit Anwendungen von 2D-Materialien, insbesondere in der Mikroskopie, beschäftigt.

Besonders freut mich auch die lokale Wahrnehmung unseres Instituts: zur „Langen Nacht der Wissenschaften“ lauschten Scharen begeisterter Besucher unseren Kollegen und bestaunten tolle Demonstratoren. Ich möchte mich an dieser Stelle nochmals bei allen Kollegen bedanken und herausheben, dass die Zahl von mehr als 1000 Gästen, die bei strömendem Regen ihren Weg ins suburbane IAP gefunden haben, eine hohe Anerkennung unserer geleisteten Arbeit ausdrückt. Zudem interessieren sich viele Schüler für unsere Forschungsarbeiten und möchten ihr Schülerpraktikum am IAP absolvieren. Erstaunlich ist, dass die Anfragen nicht nur aus Jenenser Gymnasien kommen, sondern mittlerweile auch aus Weimar und Gera! All diesen interessierten Laien und darüber hinaus, soll mit der neu am ACP etablierten Lichtwerkstatt ein Treffpunkt gegeben werden, an dem über neuen Ideen getüftelt und Expertenrat eingeholt werden kann.
In diesem Zusammenhang ist auch der Besuch von Studenten der Baschkirischen Universität aus Ufa erwähnenswert, da wir offensichtlich bis dorthin bekannt sind. Die Delegation war beeindruckt von unseren Arbeiten und Laboren – was uns in Erinnerung bringt, welche herausragenden Voraussetzungen wir für unsere Arbeit haben.

Schließlich möchte ich noch das Ausscheiden aus Altersgründen von Dr. Ernst-Bernhard Kley als AG-Leiter in den Ruhestand erinnern. Er hat wie kein anderer das Forschungsprofil des IAP geprägt und wesentlich dazu beigetragen, dass nanostrukturierte optische Systeme heute ein breites Anwendungsfeld haben und klassische Lösungen oft übertreffen. Unter anderem konnte damit zur GAIA-Mission der ESA beigetragen werden: nanostrukturierte Gitter aus seiner Arbeitsgruppe vermessen unsere Galaxie mit unerreichter Präzision und erzeugen einen Datenschatz von dem Forscher noch viele Jahre profitieren werden. Er hinterlässt somit eine große Lücke aus wissenschaftlicher und menschlicher Sicht. Dr. Kley übergab die Leitung seiner Gruppe an Dr. Uwe Zeitner. Ich freue mich, die Zusammenarbeit mit diesem geschätzten Kollegen noch weiter vertiefen zu können.

Ich danke allen für Ihr Engagement, Offenheit, Kreativität und Vertrauen, ohne die Optikforschung auf Weltniveau kaum denkbar wäre und wünsche uns allen neue Erfolgsgeschichten in 2018.

Prof. Dr. Andreas Tünnermann

The Institute of Applied Physics (IAP) at the Friedrich Schiller University Jena (FSU Jena) has a long-standing tradition and competence in design, fabrication and application of active and passive optical and photonic elements. It also very well-known for its developments in the area of high power laser technology. Collaborative projects with companies ensure practical relevance and feasibility.

Research Profile

The institute conducts fundamental and applied research in the fields of micro-, nano- and quantum optics, fiber and waveguide optics, ultrafast optics as well as optical engineering.

Our researcher develop novel optical materials, elements and concepts for information and communication technology, life science and medicine, environment and energy as well as process technology including material processing and optical measurement techniques.

Current research topics - investigated by over 140 scientists - concern function, design, fabrication and applications of micro- and nano-optical elements. Those are e.g. plasmonic resonant nanometric structures, polarizers from IR to DUV range, 3D nano-structuring of crystals with ion beam and Atomic Layer Deposition of optical coatings.

Also light propagation and non-linear light-matter interaction in e.g. photonic nanomaterials, including metamaterials, photonic crystals, as well as effective media, quantum phenomena and integrated quantum optics, application of photonic nanomaterials and advanced photonic concepts for astronomical instruments are investigated.

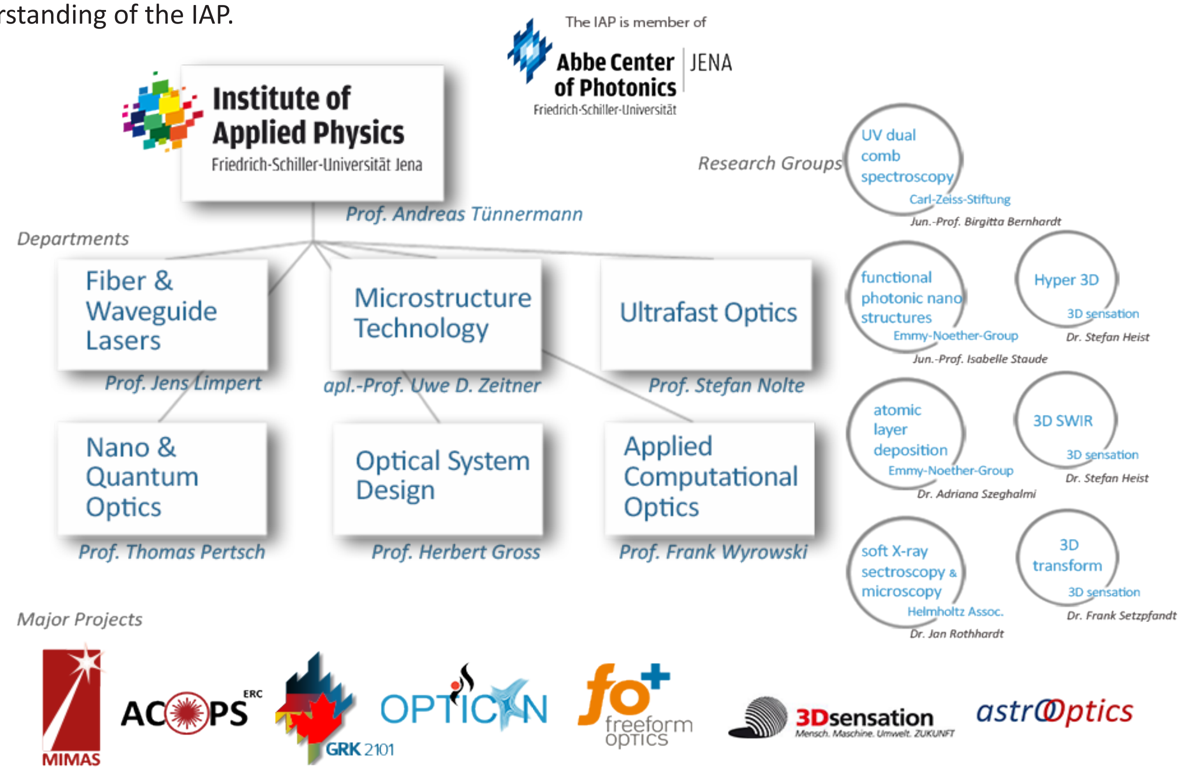
Further research fields are the applications of femtosecond laser pulses, such as material processing and spectroscopic analyses, as well as micro- and nano-structuring, medical laser application and for additive manufac-turing usage of ultrashort laser pulses. For further aims, new concepts for solid-state lasers with focus on fiber laser technology are to be developed, such as novel large core diameter fibers, fiber optical amplification of ultra short laser pulses and Mid-IR up to soft x-ray laser sources. With those, absorption spectroscopy with ultrahigh spectral resolution, especially in the (extreme) ultraviolet (XUV) region can be realized.

The endowed professorship of Herbert Gross addresses classical optical design as well as design of modern optical systems, like freeform optics, illumination systems, laser and delivery systems. Furthermore, aberration theory, quality, performance and tolerancing evaluation of optical systems are on behalf of that research group.

By investigating these fields of research, particularly in close cooperation with the Fraunhofer Institute of Applied Physics and Precision Engineering (IOF) as well as many partner companies, the IAP covers numerous parts of the innovation chain - from interdisciplinary fundamental research to the demonstration of prototypes. This expertise offers remarkable contributions to solve issues in the above mentioned emerging fields.

Excellence in research is confirmed by the structural anchoring of the Competence Centre (ZIK) ultra optics into one of three key research areas of the Abbe Center of Photonics (ACP), two awarded ERC Grants "Multi-dimensional interferometric amplification of ultrashort laser pulses - MIMAS" (2015) and "Advanced Coherent Ultrafast Laser Pulse Stacking - ACOPS" (2014) as well as the pilot project "Max Planck School of Photonics" (2017).

But not only excellent research makes the Institute splendid, also outstanding laboratory equipment, an excellent staff and a high commitment to the training of students and scientists in cooperation with the Abbe School of Photonics (www.asp.uni-jena.de) belongs to the self-understanding of the IAP.



Structure of our Institute.

Research Facilities / Resources

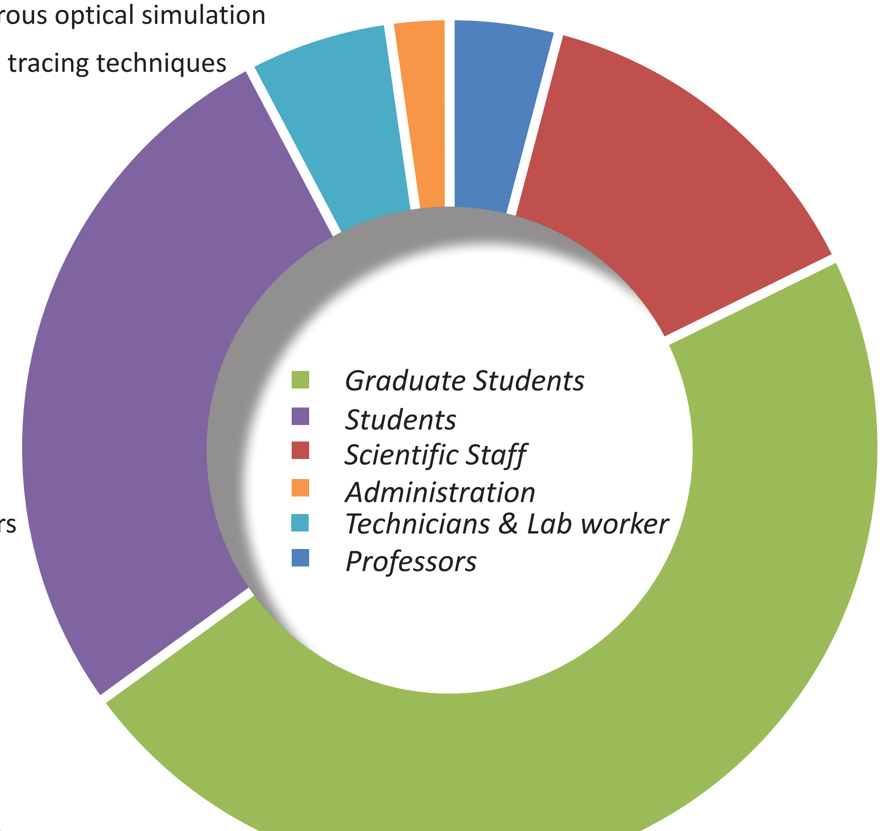
Excellence in research requires high quality equipment for experimental questions and analysis. The state-of-the-art technical infrastructure is driven constantly forward by acquired adaptions for scientific questions.

860 m² class 10,000 to 10 clean room area for:

- Electron beam lithography equipped with variable shaped beam and cell projection
- Laser lithography & Photolitography
- Coating technologies (sputtering, electron beam evaporation, ALD)
- Dry etching (RIE, RIBE, ICP)
- Cross beam, scanning electron microscopy, equipped with EDX and EBSD
- Helium ion microscopy
- Scanning nearfield optical microscopy
- Interference optical surface profilometry
- UV-VIS spectrometry & FTIR spectrometry
- Ellipsometry
- Nonlinear optical waveguide characterization
- High repetition rate ultrashort pulse laser systems (25fs to 20ps) including wavelength conversion covering the range from 4nm to 10µm
- High-precision positioning and laser scanning systems
- Laser micro-structuring and additive technology
- Rigorous optical simulation
- Field tracing techniques

Staff (status 12/2017)

9	professors
30	scientists
17	technical & administrative staff members
104	PhD-students
60	students & trainees (over the year)



ABBASIRAD Najmeh
ABBE Sylvia
ABEL Johann Jakob
ABELE Pierre-Anton
ACKERMANN Roland
ALBERUCCI Alessandro
AMUAH Emmannuel Baffu
ARSLAN Dennis
BALADRON ZORITA Olga
BECKER Nils
BEER Sebastian
BEIER Franz
BEIER Matthias
BELADIYA Vivek
BERGNER Klaus
BERLICH René
BLUMRÖDER Ulrike
BOCK Victor
BOHN Justus
BÖSEL Christoph
BREITKOPF Sven
BRÖMEL Anika
BRÜCKNER Xun
BUCHER Tobias
BULDT Joachim
CAI Danyun
DIENER Romina
DIETRICH Kay
DIETRICH Patrick
EICHELKRAUT Toni
ESCHEN Wilhelm
FALKNER Matthias
FASOLD Stefan
FEDERTOVA Anna
FELDE Nadja
FRANKE Christian
FRÖBEL Friedrich Georg
FUCHS Hans-Jörg
FÜßEL Daniel
GAIDA Christian
GEBHARDT Martin
GEIß Reinhard
GHAZARYAN Lilit
GIERSCHKE Philipp
GOEBEL Thorsten
GOTTSCHALL Thomas
GOY Matthias
GRÄF Waltraud
GRÄFE Markus
GRIGOROVA Teodora
GROSS Herbert
GUZMAN-SILVA Diego
HECK Maximilian
HEILMANN René
HEINRICH Matthias
HEIST Stefan
HELLER Lukas
HEUERMANN Tobias
HEUSINGER Martin
HILBERT Vinzenz
HILPERT Enrico
JAUREGUI MISAS Cesar
JAVADZADEH Atefeh
JUNGHANNS Marcus
KADEN Lisa
KAISER Thomas
KAMMEL Robert
KÄMMER Helena
KÄSEBIER Thomas
KEMPER Falk
KERSTAN Marita
KESSLER Victor
KIENEL Marco
KIRSCHE Alexander
KLAS Robert
KLEY Ernst-Bernhard
KLUGE Anja
KNOPFHeiko
KOESTER Jan-Philipp
KRÄMER Ria
KÜFFNER Erik
KÜHN Dominik
KUMAR Pawan
KUND Stefan
KUNDU Rohan
LIAKHOV Evgenii
LAMMERS Kim
LANDMANN Martin
LIMPERT Jens
LIU Chang
LÖCHNER Franz
LU XIANG
MAC CIARNAÍN Rossá
MACZEWSKY Lucas
MÁNKOWSKI Vojtech
MARTIN Bodo
MATTHÄUS Gabor
MATZDORF Christian
MERX Sebastian
MIDDENTS Wilko
MINARDI Stefano
MOHAMAD HEDER Siti Harvati
MÜLLER Michael
MÜLLER Lauren
MÜLLER Robert
MUNIZ Andre Luiz Marques
MUNSER Anne-Sophie
MUPPARAPU Rajeshkumar
NARANTSATSRALT Bayarjargal
NATHANAEL Anne
NAUJOK Philipp
NIEDLICH Stefan
NOLTE Stefan
OLESZKO Mateusz
OTTO Christiane
PAKHOMOV Anton
PEREZ LEIJA Armando
PERTSCH Thomas
PFEIFER Kristin
PLEGUEZUELO Pol Ribes
PUSAPATI Varun Varma
RAN Yang
RICHTER Daniel
RICHTER Hannes
ROCKSTROH Sabine
ROCKSTROH Werner
ROTHHARDT Carolin
ROTHHARDT Jan
SAHRAEI Negin
SARAVI Sina
SAUTTER Jürgen
SCHAARSCHMIDT Kay
SCHELLE Detlef
SCHENK Paul
SCHMELZ David
SCHMIDT Holger
SCHMIDT Sören
SCHOEPPNER Tyler
SCHREMPEL Frank
SCHULTZE-BERNHARDT Birgitta
SCHUSTER Vittoria
SCHWARTZ Georg
SCHWINDE Stefan
SEKMAN Jusuf
SERGEEV Natali
SETZPFANDT Frank
SEYFARTH Brian
SHESTAEV Evgeny
SHI Rui
SHU Zhe
SIEFKE Thomas
SIEMS Malte
SINGH Vikram
SIRMACI Yunus Denizhan
SOLLAPUR Rudrakant
SPÄTHE Anna
SPERRHAKE Jan
SPIRA Susanne
STANICKI Jakob Badru
STARK Lars Henning
STAUDE Isabelle
STEGLICH Martin
STEINBERG Carola
STEINERT Michael
STEINKOPFF Albrecht
STEMPFHUBER Sven
STIHLER Christoph
STOCK Carsten
STOCK Johannes
STÜTZER Simon
STUTZKI Fabian
SZEGHALMI Adriana
TADESSE Getnet Kassa
TISCHNER Katrin
THAKUR Hitesh
TSCHERNAJEW Maxim
TÜNNERMANN Andreas
ULLSPERGER Tobias
VASKIN Aleksandr
VETTER Christian
VETTER Julia
VOIGT Daniel
VON LUKOWICZ Henrik
WALTHER Markus
WANG Ziyao
WEBER Anne
WEICHELT Tina
WIDHOLZ Georg
WINKLER Ira
WORKU Norman Girma
WOHLFEIL Shulin
WYROWSKI Frank
YANG Liangxin
YOUNESI Mohammadreza
ZEITNER Uwe
ZEUNER Julia
ZHANG Yueqian
ZHONG Huiying
ZHONG Yi
ZHOU Wenjia
ZILK Matthias
ZIMMERMANN Felix
ZOU Chengjun

Guests

Guests indicate the national and international visibility of research results and enrich the structures of the Institute of Applied Physics with new thinking and perspectives - not only in research and teaching, but also open eyes to other cultures and strengthen the network by personal relations.

BENSON Oliver	Humboldt University, Berlin, Germany
CAMACHO MORALES Maria del Rocio	Australian National University, Canberra, Australia
del ROCIO Maria	Australian National University, Canberra, Australia
CHUNG Hung-Pin	National Central University, Jhongli, Taiwan
FICK Jochen	Institut Néel, Grenoble, France
HARDT Steffen	Technische Universität Darmstadt, Germany
JIN Chunqi	Changchun Institute of Optics, Fine Mechanics and Physics, Changchun, China
KAPITANOVA Polina	ITMO University, St. Petersburg, Russia
KOMARS Andrei	Australian National University, Canberra, Australia
MURAUSKI Anatoly	National Academy of Science of Belarus, Minsk, Belarus
MURAVSKY Alexander	National Academy of Science of Belarus, Minsk, Belarus
RUTCKAIA Viktoriia	Martin-Luther-University Halle- Wittenberg, Halle, Germany
SUKHORUKOV Andrey	Australian National University, Canberra, Australia
TEICHERT Christian	Montanuniversität Leoben, Austria
WANG Lei	Australian National University, Canberra, Australia
WERDEHAUSEN Daniel	Carl Zeiss AG, Jena, Germany

Research Stays

Going abroad is an important experience for everyone - but in work and research contexts this is a particular challenge. Personal contacts are intensified and immersion in another (working) culture is only possible in this way. This extends the horizon of thinking also for research work at home.

DIENER Romina	Ècole Polytechnique, Palaiseau, France
DIETRICH Kay	National Synchrotron Radiation Laboratory, University of Science and Technology of China, Hefei, China
FALKNER Matthias	Institute of Physics, University of Belgrade, Serbia
GEIß Reinhard	Institute of Physics, University of Belgrade, Serbia
	National Central University, Jhongli, Taiwan
	Australian University of Sydney, Australia
	Royal Melbourne Institute of Technology, Australia
GOEBEL Thorsten	Macquarie University, Sydney, Australia
GROSS Herbert	Universität Innsbruck, Austria
HECK Maximilian	Université Laval, Québec, Canada
SETZPFANDT Frank	Institute of Physics, University of Belgrade, Serbia
WYROWSKI Frank	Jiangsu Industrial Technology Research Institute, Nanjing, China
	Suzhou Institute of Biomedical Engineering and Technology, Suzhou, China
	Han´s Laser, Shenzen, China
	Spectra Physics, Santa Clara, USA
	IGuzzini, Alcona, Italy

Cooperations

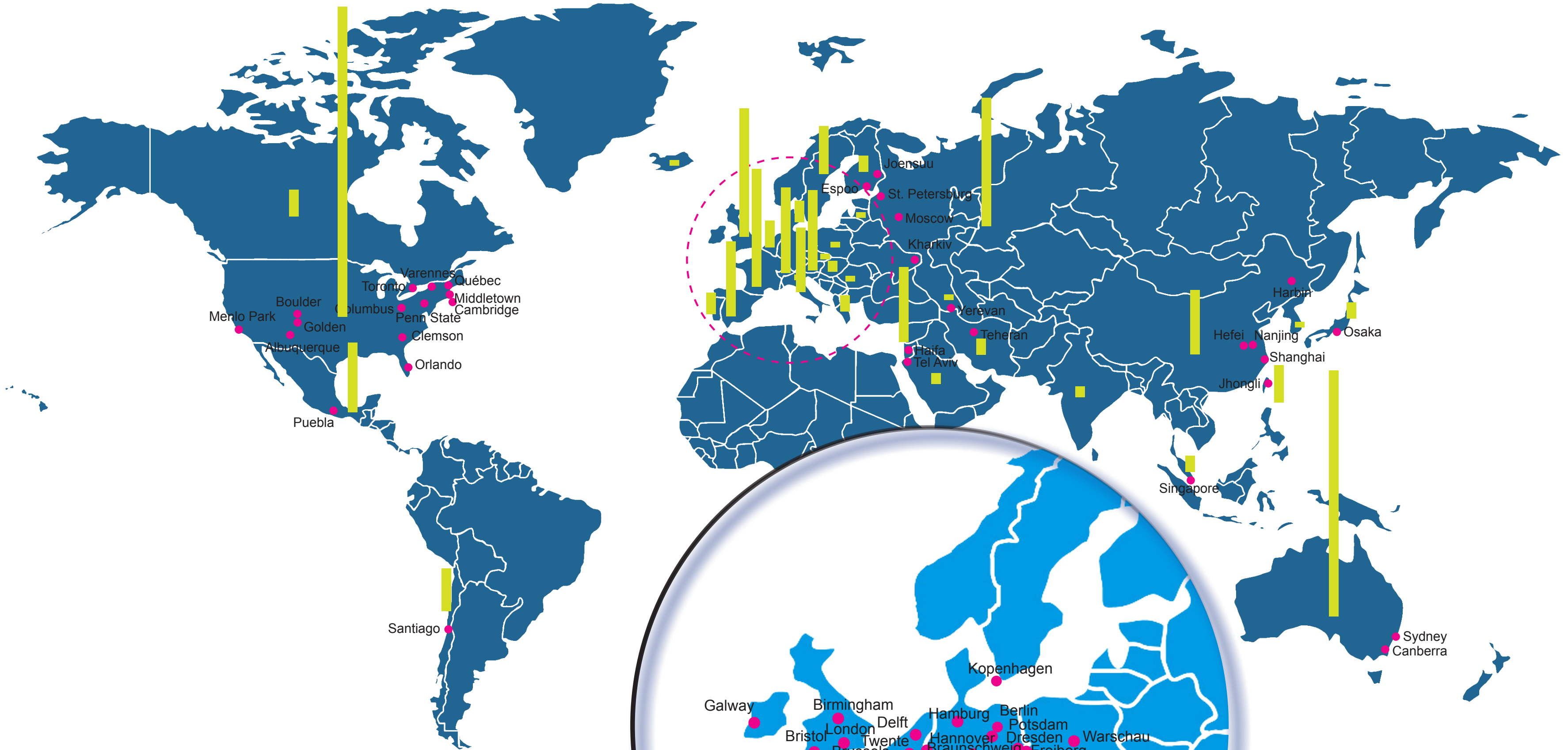
The IAP is cooperating with most of the departments of the Faculty of Physics and Astronomy at Friedrich Schiller University, 2017 in particular with the Institute of Optics and Quantum Electronics and the Otto Schott Institute of Materials Research. Furthermore, cooperations with instituts of other faculties exist, like the Institute of Geosciences. Over the years, the collaboration with the University of Applied Sciences (EAH) Jena is grown steadily.

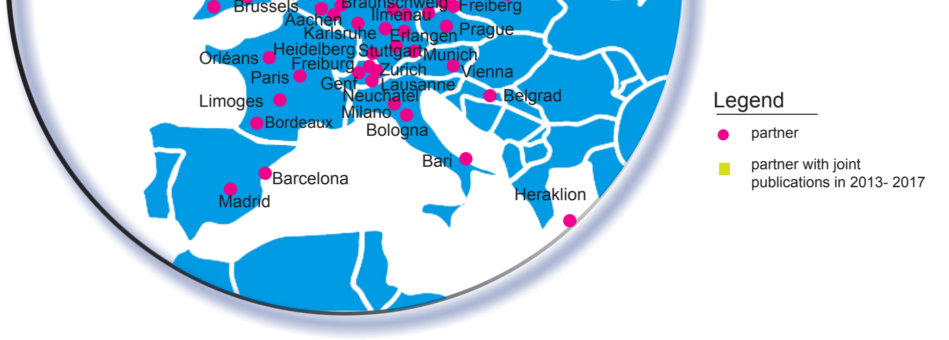
In our work we are connected to many important research centers of Germany, like the Max-Planck-Institute of Quantum Optics (MPQ) as well as the Karlsruhe Institute of Technology and Institutes of the Leibniz Association - such as the Institute for Astrophysics Potsdam (AIP) and the Institute of Photonic Technology Jena (IPHT).

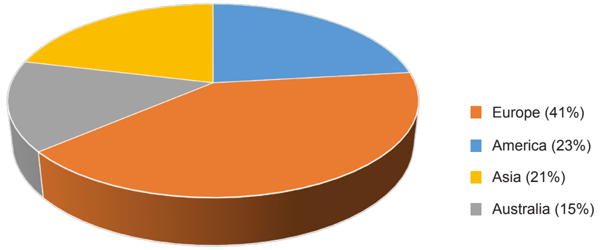
Traditionally, the IAP is linked closely to the Fraunhofer Institute for Applied Optics and Precision Engineering (IOF). Based on this networking between the two Institutes, one major goal is to develop an outstanding international center of excellence for micro- and nano-structured optics, optical systems and laser development and application. Therefore, the "Leistungszentrum Photonics" was associated together with the Abbe School of Photonics. Another huge step into the direction of producing worldleading laser is the joint operation of the "Faserzentrum" together with Fraunhofer IOF, Helmholtz Institute Jena and IPHT.

In addition, the IAP maintains close contacts to universities and research facilities nearly all over the world for years: major international collaborations exist with the Centre of Ultrahigh bandwidth Devices for Optical Systems (CUDOS) and the Australian National University, as well as the University of Toronto, the Vrije Universiteit Brussel and Universities in China, Russia, Serbia, Israel, Great Britain and USA.

At the German-Canadian International Research Training Group GRK 2101 “Guided light, tightly packed” we are cooperating with the University of Toronto, Université Laval and the Institut National de la Recherche Scientifique (INRS) – the coordination lies in the hands of our partner Abbe School of Photonics here in Jena.







Partners of the IAP and a quantitative figure of common publications in 2013-17.

Cooperations with Joint Research Topics (Selection)

ARC Centre of Ultra-Bandwidth Devices
University of Sydney, Australia
Benjamin Eggleton

Aston University
Birmingham, UK
Sergei Turitsyn

AT Technologies
Veldhoven, The Netherlands
Mikhail Loktev

Brussels Photonics Team
Vrije Universiteit Brussel, Belgium
Hugo Thienpont, Fabian Duerr

Carl Zeiss AG, Oberkochen, Germany
Daniel Krähmer

Centre d'optique, photonique et laser
Université Laval, Québec, Canada
Réal Vallée, Martin Bernier

CNRS - Centre national de la recherche scientifique, France
François Goudail, Olivier Uteza

Centre of Ultrahigh bandwidth Devices for Optical Systems (CUDOS), MQ Photonics Research Centre, Department of Physics and Astronomy, Macquarie University, Sydney, Australia
Michael Withford, Alex Fuerbach

College of Optics and Photonics, CREOL & FPCE
University of Central Florida, Orlando, USA
Kathleen Richardson, Martin Richardson, Rodrigo Amezcua

Datalogic
Bolognia, Italy
Federico Canini

Department of Electrical and Computer Engineering, University of Toronto, Canada
Peter Herman

Department of Physics,
Colorado School of Mines, Golden, USA
Jeff Squier

Department of Physics and Mathematics
University of Eastern Finland, Joensuu, Finland
Jari Turunen

Department of Physics, ETH Zürich
Switzerland
Ursula Keller

Engineering Center OPTICA
State University of Information, Mechanics, and Optics (ITMO), St. Petersburg, Russia
Irina Livshits

Centre for Innovation Competence
ZIK innoFSPEC
Leibniz-Institut für Astrophysik Potsdam
Potsdam, Germany
Martin Roth

DESY, Helmholtz-Gesellschaft
Hamburg, Germany
Guoqing Chang

ELI-ALPS, Extreme Light Infrastructure
Szeged, Hungary
Karoly Osvay

Institut für Physik der Kondensierten Materie, Universität Erlangen, Germany
Peter Hommelhoff

Institut für Geophysik und Extraterrestrische Physik, TU Braunschweig, Deutschland
Jürgen Blum

Institut für Theoretische Festköperphysik
Karlruher Institut für Technologie (KIT)
Karlsruhe, Germany
Carsten Rockstuhl

Institute of Physics, University of Belgrade
Belgrade, Serbia
Goran Isic

JENOPTIK Optical Systems GmbH
Jena, Germany
Helmut Bernitzki

Laboratory of Nanophotonics & Metamaterials
Lomonosov Moscow State University
Moscow, Russia
Andrey Fedyanin

Max-Planck Institut für Quantenoptik
Garching, Germany
Ioachim Pupeza

Physikalisch-Technische Bundesanstalt
Braunschweig, Germany
Stefanie Kroker

National Accelerator Laboratory SLAC
Menlo Park, USA
Christian Roedel, Frank Seiboth

National Synchrotron Radiation Laboratory
University of Science and Technology, Hefei, China
Ying Liu

Nonlinear Physics Center
Australian National University
Canberra, Australia
Dragomir Neshev

Optical Sciences Center
National Central University, Jhongli, Taiwan
Wei-Kun Chang

Optics Research Group
Delft University of Technology
The Netherlands
Paul Urbach

Sandia National Laboratories
Albuquerque, New Mexico, USA
Igal Brener

Sandia National Laboratories, Albuquerque, USA
Igal Brener

School of Electronic and Optical Engineering
Nanjing University of Science & Technology
Nanjing, China
Jun Ma

Technical University of Denmark
Lyngby, Denmark
Asger Mortensen

VTT Technical Research Centre of Finland
Espoo, Finland
Matti Putkonen

EDUCATION

An essential part of the IAP is the training of young scientists on fundamental knowlegde and at the interface of physics, chemistry and material science. Together with our partner in education - the Abbe School of Photonics (ASP) - we offer an education in interdisciplinary international Master´s degree and graduation programs, and running the International Research Training Group (GRK 2101) "Guided light, tightly packed: novel concepts, components and applications".

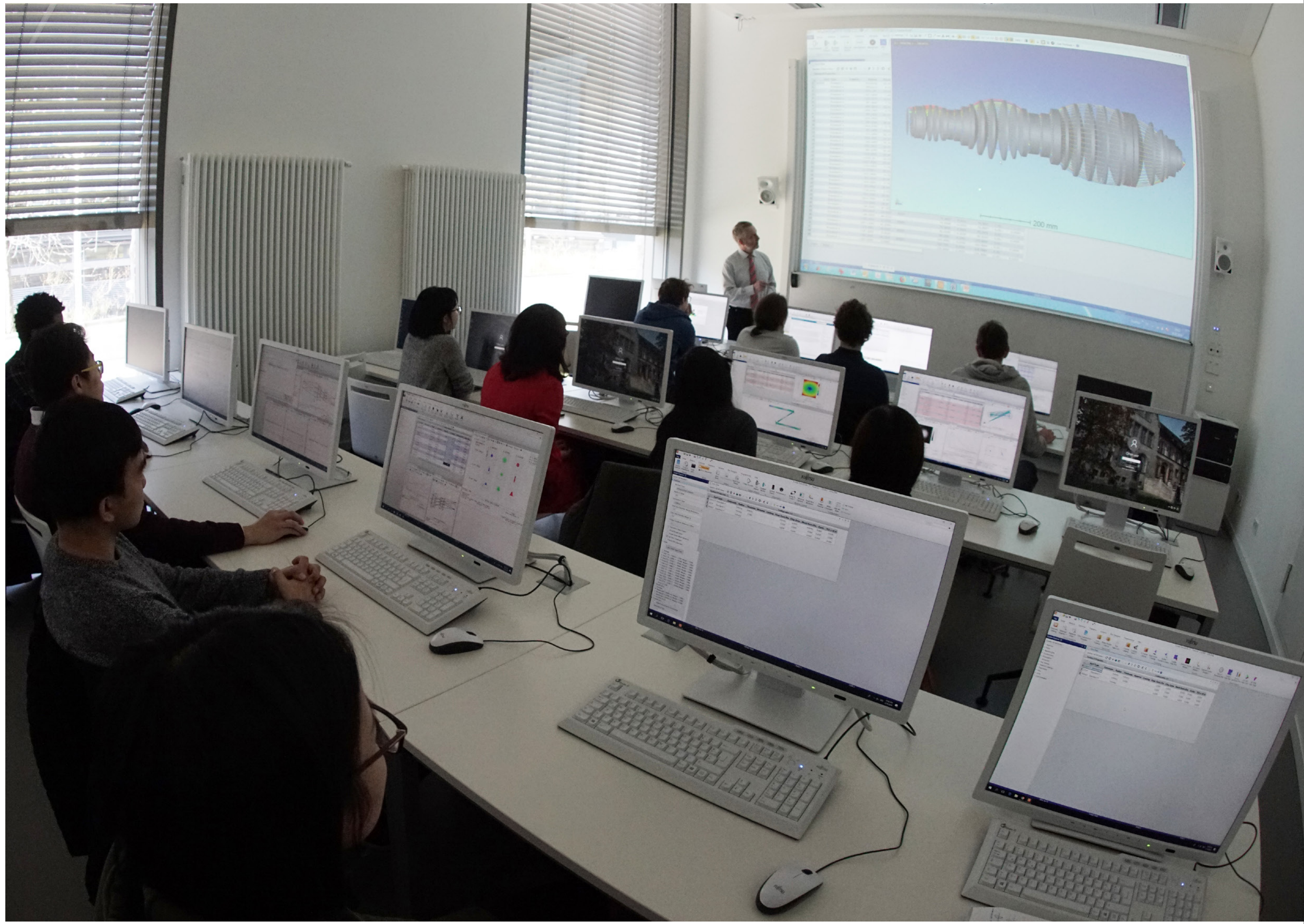
Lectures

Elective & Special Courses (Lectures & Seminars)

- Analytical instrumentation
- Computational photonics
- Design & correction of optical systems
- Diffractive optics
- Fundamentals of modern optics
- Grundlagen der Laserphysik
- Imaging and aberration theory
- Introduction to applications of modern optics and photonics in astronomy
- Introduction to nanooptics
- Introduction to optical modeling
- Lasers in medicine
- Lens design I
- Lens design II
- Light source modeling
- Micro/nanotechnology
- Microscopy
- Optical engineering
- Optical metrology and sensing
- Physical optics
- Physical optics design
- Physical optics modeling
- Quantum optics
- Thin film optics
- Ultrafast optics

Seminars of the Institute & Devisions

- Advanced Fabrication Technologies
- Applied Computational Optics
- Applied Physics
- Atomic Layer Deposition
- Design of Optical Systems
- Fiber Lasers
- Functional Photonic Nanostructures
- Graduate Seminar
- Microstructure Technologies - Microoptics
- Nano Optics
- Ultrafast Optics



Prof. Herbert Gross explains lens design via ZEMAX in the new ACP computer pool.

TEACHING

Habilitations

César Jáuregui Misas
Mode instabilities in high-power fiber laser systems

Marco Ornigotti
Nondiffracting Optical Waves with Angular Momentum

Bachelor Theses

Colin Froidevaux
Entwicklung eines Single-Shot-M²-Messgeräts

Alexandra Maria Hufnagel
Charakterisierung der Erwärmung von Faser-Bragg-Gittern für monolithische Hochleistungsfaserlaser

Johanna Kölbel
Measurement of laser-induced damage and degradation of optical components

Master Theses

Pooya Aminjavaheri
Physical and Chemical Characterisation of Printable Functional Materials for Semiconductor Applications

Vivek Beladiya
Effect of substrate biasing on Al_2O_3 and SiO_2 thin films deposited by PEALD

Justus Bohn
Coupling of quantum dot emission to dielectric metasurfaces integrated in to a liquid crystal cell

Xun Brückner
Development and Characterization of a Burst-Mode Ultrafast Fiber Laser

Adrian Bubholz
Untersuchung analytischer Methoden zur Vorhersage von Streulicht in optischen Systemen

Tobias Bucher
Integration of MoS_2 monolayers with dielectric nanoantennas

Danyun Cai
Investigations on high-NA objective lenses with narrow bandwidth including a diffractive element

Wilhelm Eschen
High Resolution Coherent Imaging by Laserdriven XUV-Sources

Philipp Gierschke
Aufbau und Untersuchung des Amplitudenrauschens einer Ytterbium-dotierten Faserverstärkerkette

Paul Harrison
Nanoparticle enhanced second harmonic generation in molybdenum disulfide

Martin Hubold
Charaterization and optimization of stray light in a aminiaturized multi-aperture imaging system

Alexander Kirsche
Erzeugung hoher Harmonischer mit einem ringförmigen Strahl und Trennung der verschiedenen Strahlkomponenten

Pawan Kumar
Temporal manipulation of single photon wavepackets generated by spontaneous parametric down-conversion

Vojtěch Mańkowski
Time-resolved polarization microscopy of plasma-generated birefringent modifications

Sebastian Merx
Phase retrieval of micro-optical gradient-index components by intensity measurements

Younesi Mohammadreza
Scattering properties of scanning near-field optical microscopy tips

Tobias Pelgen
Beschreibung und technologiebedingte Optimierung von Freiformlinsen für Projektionsscheinwerfer im Automotivbereich

Tom Pertermann
Analyse der Ortsfrequenzen verschiedener Oberflächenfehler auf Metallspiegeln

Olga Rusyakina
Fabrication and characterization of fiver-optical micro probes

David Schmelz
Konzeptionierung und Realisierung einer diffusen Lichteinkoppelstruktur für Ge-on-Si-Bildsensoren

Yusuf Sekman
Freeform system tolerance evaluation

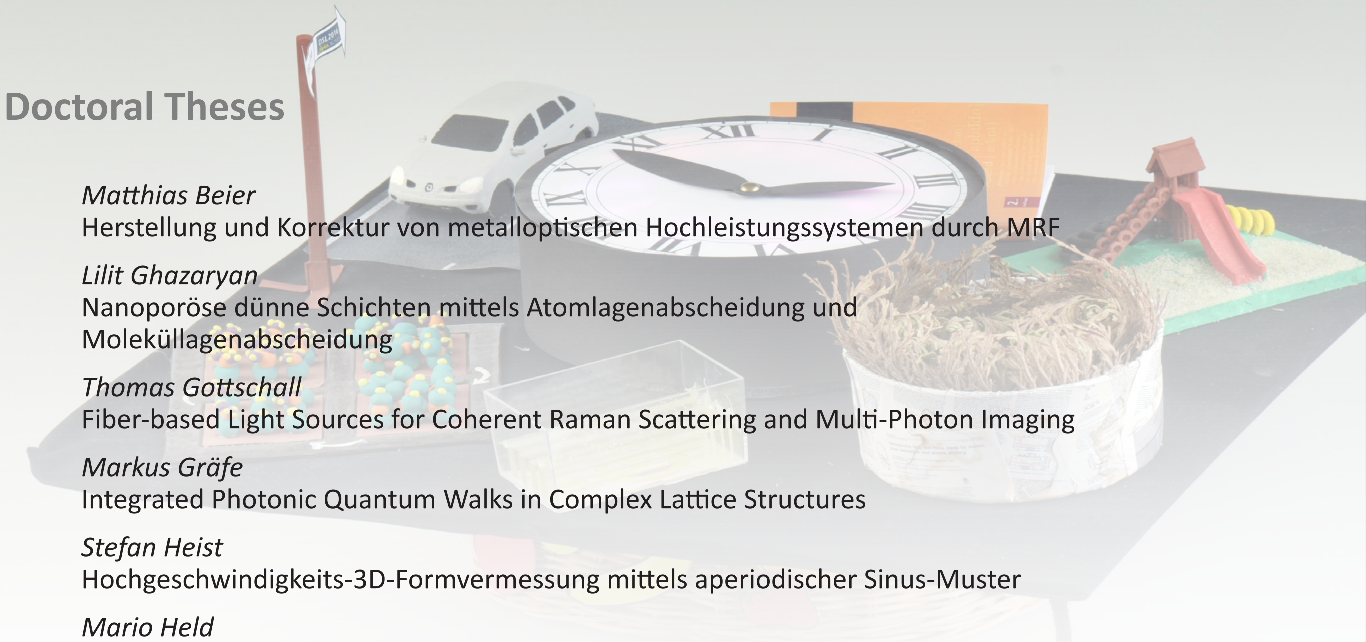
Brian Seyfahrt
Spatial beam shaping of ultrashort laser pulses for glass processing applications

Malte Per Siems
Untersuchung und Anpassung der Eigenschaften ultrakurzpulsgeschriebener Volumen-Bragg-Gitter in Kieselglas

Carsten Stock
Design und Herstellung von nanooptischen Verzögerungsplatten

Johannes Wilde
Theoretical Investigation of the Optical Properties of Coupled Nano-Waveguides

Doctoral Theses



Matthias Beier
Herstellung und Korrektur von metalloptischen Hochleistungssystemen durch MRF

Lilit Ghazaryan
Nanoporöse dünne Schichten mittels Atomlagenabscheidung und Molekülagenabscheidung

Thomas Gottschall
Fiber-based Light Sources for Coherent Raman Scattering and Multi-Photon Imaging

Markus Gräfe
Integrated Photonic Quantum Walks in Complex Lattice Structures

Stefan Heist
Hochgeschwindigkeits-3D-Formvermessung mittels aperiodischer Sinus-Muster

Mario Held
Präparation und Eigenschaften elektronenstrahlgedampfter Mischschichten für die Optik

Marco Kienel
Power Scaling of Ultrashort Pulses by Spatial and Temporal Coherent Combining

Jan Kinast
Entwicklung und Analyse einer athermalen Werkstoffkombination für formstabile Metalloptiken auf Basis von amorphen chemisch abgeschiedenen Nickel-Phosphor-Schichten im Temperaturbereich von +/- 180 Grad Celsius

Rossá Mac Ciarnaín
Emission Properties of Small Molecule Phosphor Emitters in Organic Light Emitting Diodes

Zhe Shu
Solution-processed organic light sources for microfluidic Lab-on-a-Chip systems

Christian Vetter
Radially self-accelerating optical beams

Julia Zeuner
Complex edge states in tailored photonic graphene

Minyi Zhong
Propagation of partially coherent light in optical systems

Felix Zimmermann
Ultrashort pulse induced nanostructures in transparent materials

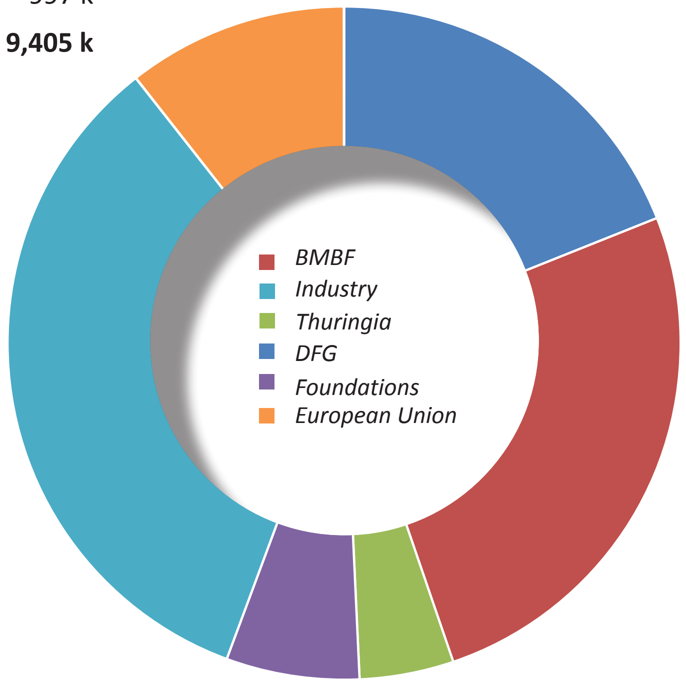
International scientists visted well equipped laboratories of the ERC Grant project"Multi-dimensional interferometric amplification of ultrasound laser pulses - MIMAS" in November in Jena.

PROJECTS

"Applied Physics“ is implemented in numerous projects in different application fields that contain fundamental research as well as application aspects. Accordingly, strong partners were explored and cooperations expanded. Thus, the IAP can continuously link the results at the value chain and transfer these results from basic research into innovative and novel demonstrators.

External funding

DFG (German Research Society)	€	1,782 k
BMBF (Federal Ministriy)	€	2,427 k
State of Thuringia	€	424 k
Foundations	€	603 k
Contract Research	€	3,172 k
European Union	€	997 k
Total:	**€**	**9,405 k**



PROJECTS Selection

European Union

ERC Advanced Grant MIMAS "Multi-dimensional interferometric amplification of ultrashort laser pulses"

ERC Consolidator Grant ACOPS "Advanced coherent ultrafast laser pulse stacking"

Marie Skłodowska-Curie Innovative Training Networks (ITN-EID) “Lossless management - Optical design for manufacture at different length scales”

FP7-PEOPLE-2013-ITN “Luminous fluid flow in 2nd structures: experiment and theory”

BMBF

Federal Ministry of Education and Research

Verbund-ZIK Hitecom II - Spektroskopische Untersuchungen zur Vergasung von Kokspartikeln unter Hochdruck- und Hochtemperaturbedingungen

Verbund-ZIK OPTICON - Entwicklung spektroskopischer Methoden für Konversionsprozesse unter Hochdruck-/Hochtemperaturbedingungen

Verbund-ZIK astrOOptics - Astrooptic components TP 2: „astrooptic components“

Verbund APPA R&D - Licht-Materie-Wechselwirkung mit hochgeladenen Ionen

Program "Zwangzig20" - Project "3Dsensation":

- Dreidimensionale Visualisierungssysteme auf der Basis photonischer Nanomaterialien
- Methoden zur ultraschnellen Detektion und Manipulation von ultrakurzen Lichtpulsen
- Methoden zur ultraschnellen dreidimensionalen Detektion zeitveränderlicher Lichtfelder
- Hyperspektrale Sensorik auf Basis photonischer Nanomaterialien
- Eigenhaptische Manipulation ausgedehnter 3D-Strukturen im Raum; TP1: Erzeugung ausgedehnter 3D-Strukturen im Raum mittels Laser

Forschergruppen:

- Augensichere 3D-Bildgebung im SWIR
- Transformationsoptik für multidimensionale Detektion
- Hochdynamische 3D-Sensorik in erweiterten Spektralbereichen

DFG - German Research Foundation

Research Training Groups

- International Research Training Group GRK 2101 "Guided light, tightly packed: novel concepts, components and applications"

Priority Programs (Schwerpunktprogramme SPP)

- SPP 1839 „Kontrolle der Streufeldwechselwirkung in ungeordneten zweidimensionalen Anordnungen von Silizium-Nanopartikeln“
- SPP 1839 „Photonische Topologische Materialien mit Unordnung“
- SPP 1839 „Kontrolle der Streufeldwechselwirkung in ungeordneten zweidimensionalen Anordnungen von Silizium-Nanopartikeln“

Research Groups

- FOR 2285 "Laserbasierte Simulation von Hochgeschwindigkeits-kollissionen und strukturelle Zustände des Staubs in Trümmerscheiben“

State of Thuringia

Thuringian Ministry of Economy, Science and Digital Society

Thüringer Innovationszentrum „Thüringer Innovationszentrum für Quantenoptik und Sensorik“

TAB-Research Groups

- Mikrostrukturtechnologie zur Überwindung von Leistungsgrenzen faserbasierter Lasersysteme (FaserForLaser)
- 3D-Bildaufnahme und -Verarbeitung mit höchstem kontinuierlichem Datendurchsatz für die Mensch-Maschine Interaktion und adaptive Fertigung
- Achromatische Diffraktive Optiken auf Nichtplanaren Substratoberflächen

ProExz-ACP2020 “Table-top XUV interferometry”

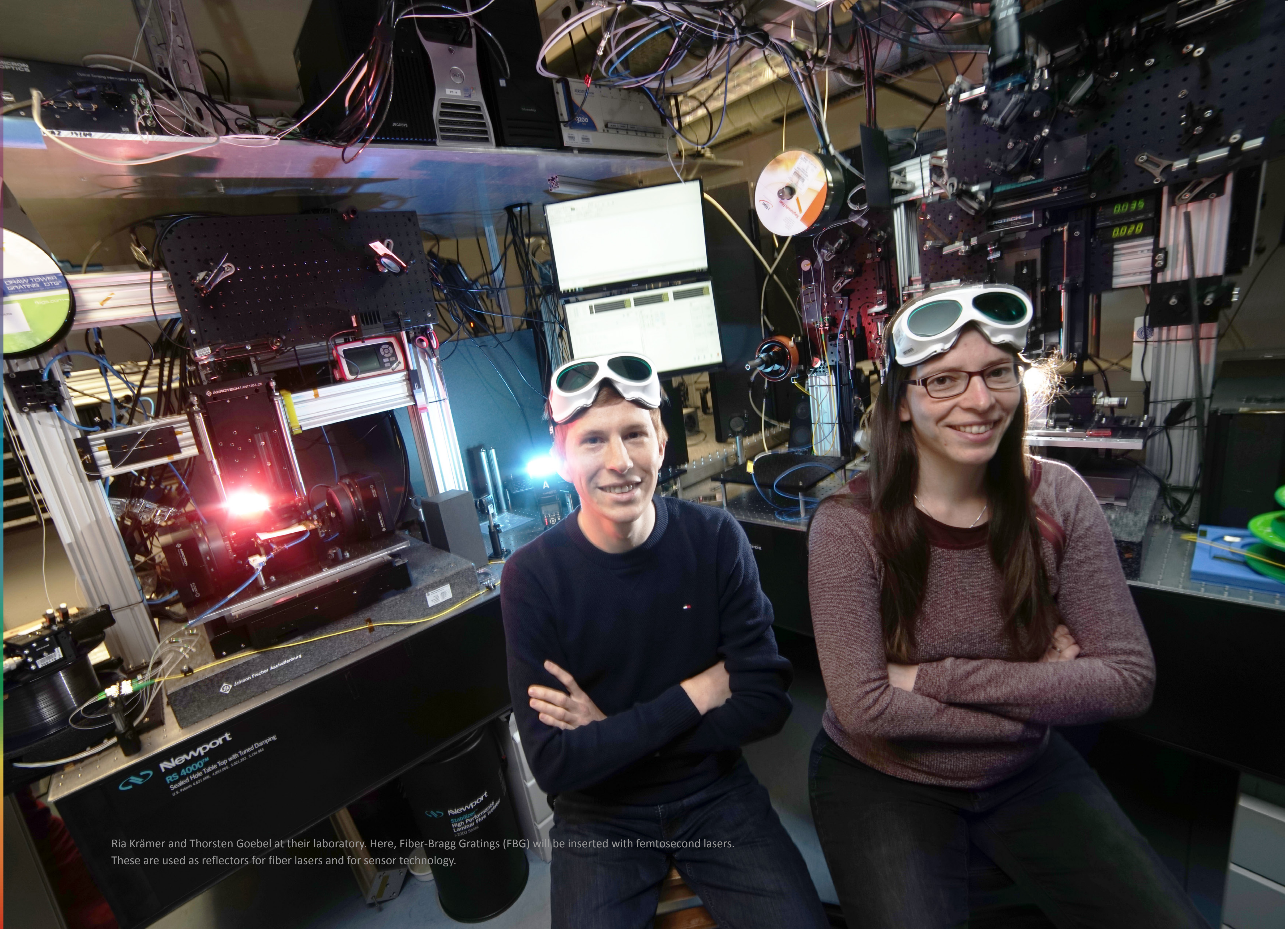
ProExz-ACP2020 “Nachwuchsgruppe: Functional Photonic Nanostructures”

KoMIMAS - Koordinierung ERC-"Advanced Grant"

Contract Research

The IAP runs a very dense network of industry partners. Contract research have been made - very often in common with the Fraunhofer IOF - both with medium size regional and large size international companies, such as ORAFOL Fresnel Optics GmbH, Layertec GmbH, Carl Zeiss AG, TRUMPF GmbH + Co. KG or the European Space Agency (ESA).

RESEARCH



Ria Krämer and Thorsten Goebel at their laboratory. Here, Fiber-Bragg Gratings (FBG) will be inserted with femtosecond lasers. These are used as reflectors for fiber lasers and for sensor technology.

RESEARCH - Achievements & Results

An intense engagement with all the research topics of the institute ultimately leads to the specialization of separate research groups on key challenges. In turn, each group contributes with their results to the solution of partial tasks of the other work groups. This constantly self-fertilising approach itself leads to remarkable results. Measurably honored are such results by success in granting research contracts, the strong interest in cooperation with the IAP and the number of scientists and students who would like to work at IAP scientifically.

Prof. Dr. Jens Limpert
(+49) 3641 | 9 47811 phone
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Michael Müller is tuning the laser main amplifier stage.

Fiber & Waveguide Lasers

This research group is working on the development of new concepts for solid-state lasers with focus on fiber laser technology.

Scientific focus lies on:

- Fiber optical amplification of ultra-short laser pulses
- Ultra-short pulse oscillators, few-cycle pulse generation and amplification
- Conception of novel large core diameter fibers
- Simulation of non-linear effects and amplification dynamics in active fibers
- Fiber optical frequency conversion
- Mid-IR laser sources
- High Harmonic Generation and applications in imaging and spectroscopy

Authors:
Michael Müller, Arno Klenke, Henning Stark, Joachim Buldt, Thomas Gottschall, Andreas Tünnermann and Jens Limpert

1.9 kW average power 16-channel ultrafast fiber laser system

Ytterbium-doped ultrafast fiber lasers are versatile tools in scientific applications. An example is the generation of high-harmonics for experiments with attosecond pulses or diffraction imaging. The demands of these applications pushed the development of very-large-mode-area fibers and chirped-pulse amplification systems to handle non-linear effects associated with the amplification of ultra-short pulses. Both technologies have matured and are con-strained by manufacturing cost and tolerances. Now, the next generation power scaling technique is coherent beam combination (CBC, /1/).

In this contribution, an ultrafast fiber laser based on CBC of 16 amplifier channels is presented, demonstrating the huge power scaling potential this tech-nique.

The setup is depicted in Fig. 1. The centerpiece of this system is a 16-channel interferometer with one ytterbium-doped large-pitch fiber amplifier (LPF) in each channel. The system is are arranged in two layers.

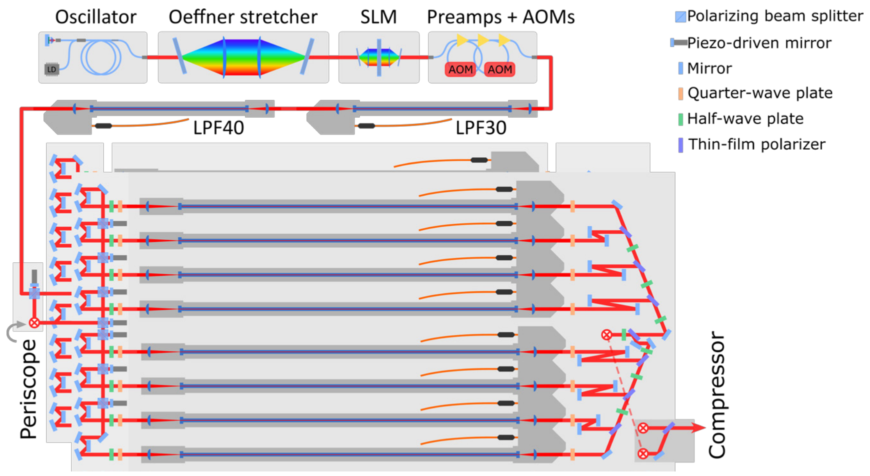


Figure 1:
Schematic of the setup of the 16-channel laser.

A seed beam provided by preamplifiers is split into these channels using polarization beam splitters and half-wave plates (HWP). Each interferometer channel is equipped with a piezo-driven mirror for phase stabilization against environmental perturbations. After the amplifiers, the beams are superposed via polarization beam combining using thin-film polarizers (TFP). After each combination step, the superposed beam features linear polarization. Using a HWP after each step, the polarization is rotated back to p-state to allow full transmission through the following TFP. The output beam is enlarged in a lens telescope and is sent into a Treacy-type compressor. A more detailed description of the conceptually identical precursor to this system can be found in/2/.

The system frontend was set to generate a seed pulses with 481 kHz repetition rate and an average power of 41 W. The individual amplifiers delivered between 130 W to 150 W of average power at maximum pump power of 250W (976nm pumping). All beams combined yield 1925 W average power at 92% efficiency. The output spectrum features a FHWM of 10.2 nm supporting a transform limited pulse duration of 200 fs. The pulse du-ration was measured with an auto-correlator to be 220 fs FWHM. The most remarkable result is that the output beam quality is close to diffraction limited with M^2= 1.1 on both beam axis, which is as good as the beam quality from a single emitter. Hence, coherent beam combination allows for power scaling far beyond the performance of a single amplifier channel without deterioration of laser parameters.

In summary, a 16-channel ultrafast fiber laser system is presented, delivering the highest average power ever reported from an ultrafast fiber laser system. Output characteristics of individual amplifiers are maintained, allowing the development of ultra-high peak power laser sources far beyond the state of the art. One day, CBC will enable lasers even for particle acceleration that are technically impossible today /3/.

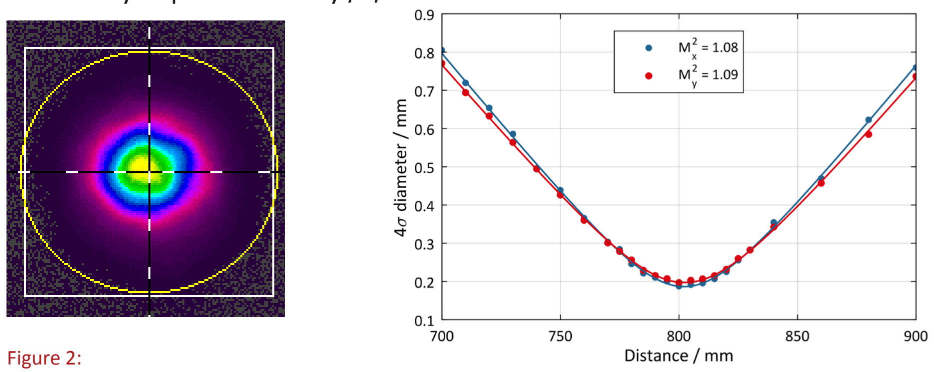


Figure 2:
Beam caustic and output beam profile at 1.9kW average power proving a diffraction limited beam quality.

/1/ T.Y. Fan, et al., Beam combining of ytterbium fiber amplifiers, J. Opt. Soc. Am. B 24, 8 (2007).

/2/ M. Müller, et al., 1 kW 1 mJ eight-channel ultrafast fiber laser, Opt. Lett. 41, 15 (2016).

/3/ W. Leemans, White paper of the ICFA-ICUIL joint task force: High power laser technology for accelerators, ICFA Beam Dyn.Newslett. 56 (2011).

Authors:
Getnet K. Tadesse, I. Wahyutama, R. Klas, S. Demmler, M. Tschernajew, J. Limpert and J. Rothhardt

Soft X-ray Spectroscopy and Microscopy Group

The research group, led by Dr. Rothhardt, investigates matter on smallest spatial and temporal scales by using modern laser-based XUV and soft x-ray sources. There are strong cooperations between the Helmholtz-Institute Jena and our Institute, depended on the common research interests, like:

- laser-based short wavelength sources
- nanometer scale imaging techniques
- ultrafast spectroscopy
- XUV spectroscopy of highly-charged ions

Research methods

The group utilizes a variety of modern imaging and spectroscopy techniques including:

- coherent diffraction imaging and holographic techniques
- XUV Laser spectroscopy
- pump-probe spectroscopy

The group utilizes modern experimental equipment including:

- high average power femtosecond lasers
- high photon flux table-top XUV and soft x-ray sources
- XUV and soft x-ray spectrometers and detectors

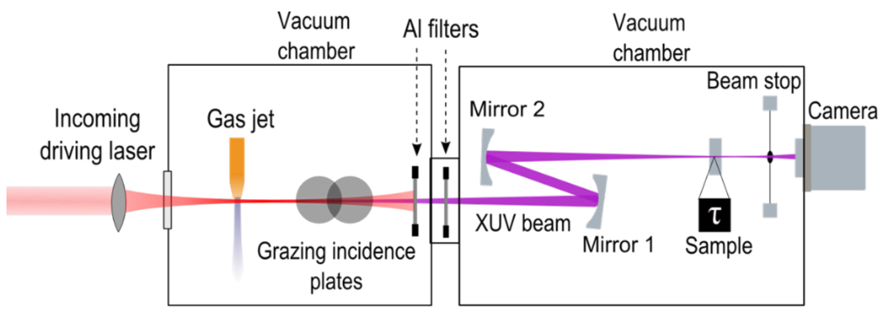


Figure 1:
Experimental setup of the table-top XUV Nanoscope. XUV light is generated by focusing femtosecond pulses from an infrared fiber laser into an argon gas jet. It is then refocused onto the sample and a CCD-Camera records the diffraction pattern behind the sample.

HI Jena
Helmholtz Institute Jena

Table-top Nanoscale imaging with XUV light

Coherent diffractive imaging is nowadays a well-established technique at synchrotron light sources and allows nano-scale imaging with only a few-nanometers resolution. Since only the diffraction pattern is detected and the object exit wave is reconstructed by iterative computer algorithms, no imaging optics are required. Hence, the resolution is solely determined by the wavelength and the maximum scattering angle which can be detected with sufficient signal-to-noise ratio.

We developed a table-top implementation of this technique by utilizing high harmonics generated by focusing an infrared femtosecond fiber laser into an argon gas jet (Figure 1). The generated XUV radiation (18 nm wavelength) is separated from the fundamental infrared light and refocused onto the sample by using two concave multilayer mirrors. A typical diffraction pattern of a test structure, recorded by an XUV-CCD, is shown in Figure 2(a).

Due to the record high photon flux of our table-top XUV source /1/, as well as the excellent beam quality and spatial coherence, the diffraction pattern (Figure 2(a)) has been detected with a numerical aperture as high as 0.7. Figure 2(b) and (c) display the reconstructed amplitude and phase of the light wave exiting the employed sample. The achieved spatial resolution is better than 15 nm (Abbe-limit: 12 nm) and represents a new record for table-top XUV and X-ray microscopes. Moreover, a single 3 s acquisition is sufficient to achieve ~25 nm resolution, which will allow scanning on extended samples and 3D tomography on the nanoscale in the near future. Further advances in femtosecond fiber laser technology and high harmonic generation will ultimately enable few-nanometer resolution imaging of 3D nanostructures e.g. modern nano-optical and nano-electronic devices.

/1/ J. Rothhardt,et al., High-repetition-rate and high-photon-flux 70 eV high-harmonic source for coincidence ion imaging of gas-phase molecules, Opt. Express 24, 18133–18147 (2016).

/2/ G. Tadesse, et al., High Speed and High Resolution Table-Top Nanoscale Imaging, Opt. Lett. 41, 5170-5173 (2016).

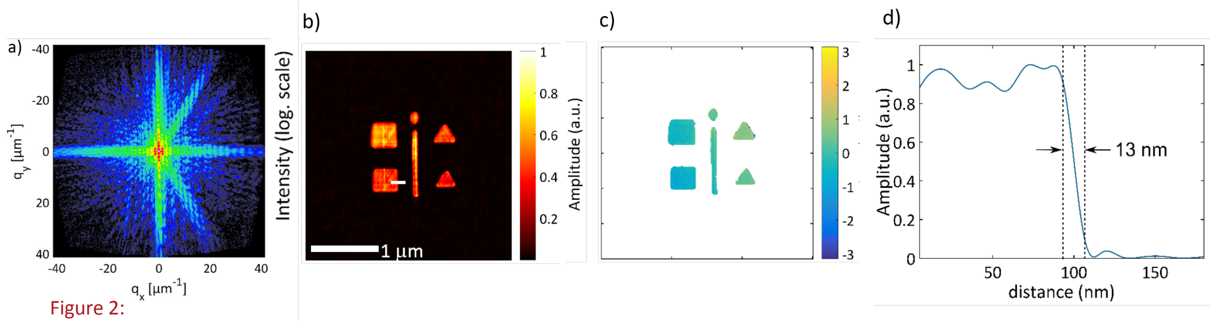
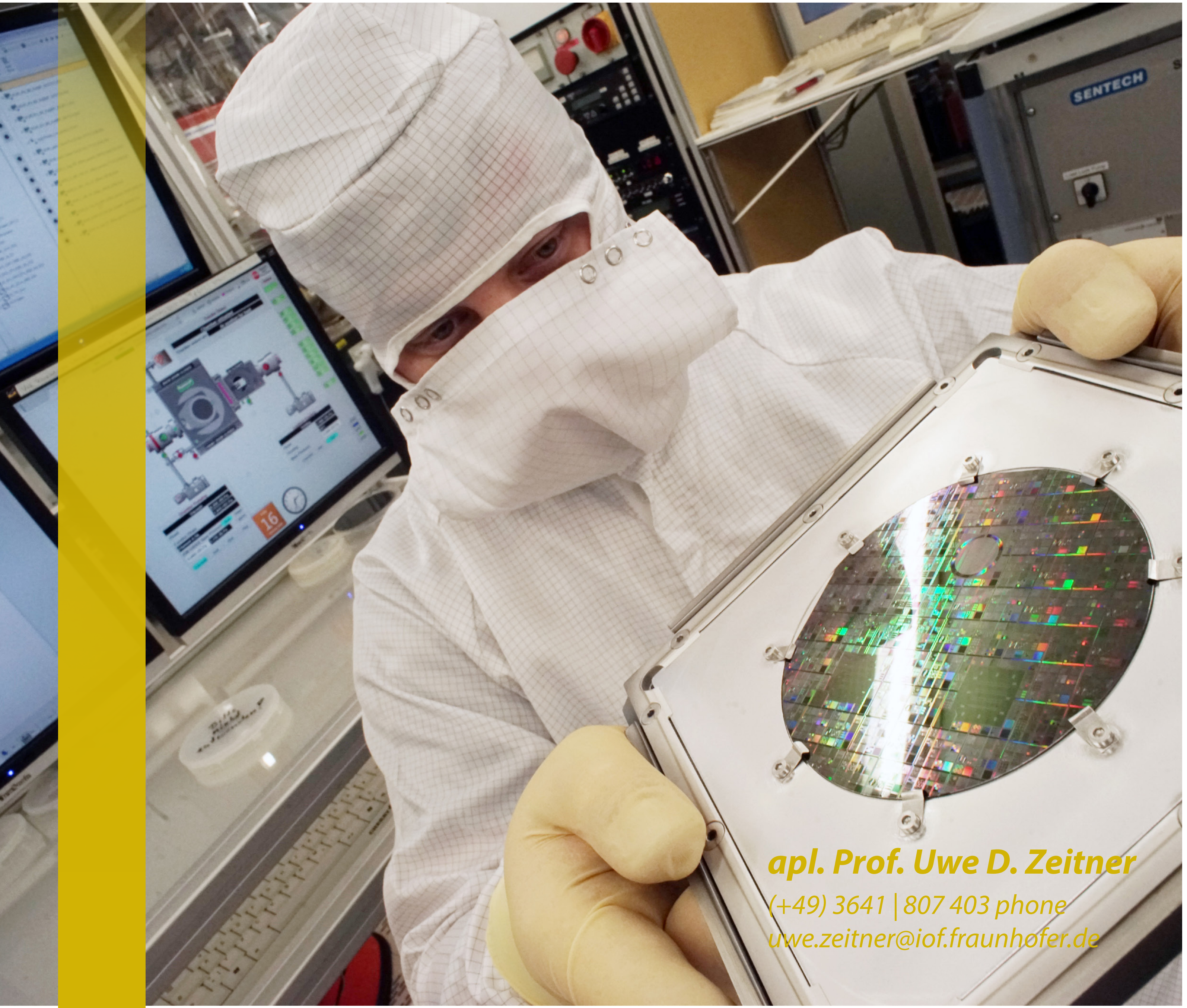


Figure 2:
(a) Measured diffraction pattern, (b) Reconstructed amplitude, (c) reconstructed phase. The achieved resolution is ~13 nm, (d) cross-section at an edge of the sample.



apl. Prof. Uwe D. Zeitner
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100 mm wafer on a sample carrier, background: Oxford Ionfab 300 LC.

Microstructure Technology & Microoptics

This research group concentrates fundamentally on function and design of micro- and nano-optical elements as well as applications and technology developments for micro structuring.

The following research priorities have been treated:

- Plasmonic resonant nanometric structures
- Resonant reflective monolithic gratings
- Transmissive, reflective and diffractive elements based on effective media
- Metallic and dielectric polarizers from IR to DUV range
- 3D nano-structuring of crystals with ion beam
- Optical and opto-electronic applications of antireflective fused silica and silicon surfaces
- Microoptical light-trapping in optoelectronic devices
- Material-scientific aspects

In September 2017, apl.-Prof. Uwe D. Zeitner succeeds Dr. Ernst-Bernhard Kley and is now leading this research group.

Authors:
Uwe D. Zeitner, Frank Burmeister, Thomas Flügel-Paul, Philipp Schleicher and Tino Benkenstein

Asphere-Test-CGHs based on effective-index structures

Testing of spherical optics is typically performed using interferometric methods. During such a measurement, the surface being tested is illuminated with a spherical wave and deviations of the surface shape from this wave can be characterized by superposition of the reflected light with a reference wave. In recent years, aspherical and freeform optical surfaces have gained increasing importance for the realization of optical systems. For their characterization, the above-mentioned method is no longer suitable as the surface shape inherently deviates from a sphere and no useful information can be extracted from the interferometric measurement. In such cases, the use of computer generated holograms (CGH) for adapting the interferometric illumination wave specifically to the optics being tested has been an established method for some time. Thus, these CGHs represent a ruler for the aspherical surface.

The light deflecting structure of CGHs typically consist of a binary grating with locally varying period. Such patterns achieve a diffraction efficiency in the range of 40%, resulting in an overall light portion of only 16%, usable for the measurement as the light passes the element twice. The unused light remains in the beam path of the interferometer and can thus interfere with the measurement, or even make it impossible. Higher diffraction efficiencies are achievable e.g. by microstructures comprising a larger number of height levels (e.g. 4-level elements). Their lithographic realization, however, requires a significantly higher effort and the typical fabrication tol-erances are reducing the wavefront accuracy of the CGH.

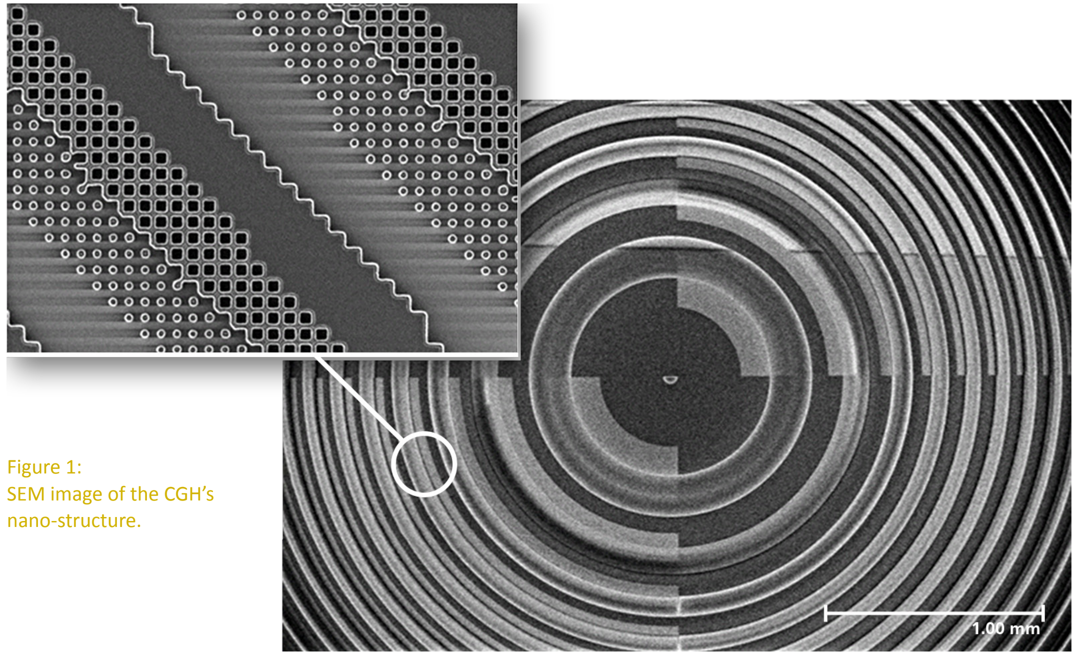


Figure 1:
SEM image of the CGH's nano-structure.

Figure 2:
Effective-index asphere test-CGH.

For the first time, the efficiency improving multi-level function of such an asphere test-CGH has been realized by sub-wavelength structures at the Fraunhofer Institute of Applied Optics and Precision Engineering. Because of their small lateral dimensions, the interferometric light does not resolve these structures. Nevertheless, by locally varying the duty-cycle of the structures, a lateral variation of the phase-delay can be implemented. Their optical function is therefore similar to that of a material with locally varying effective refractive index. A great advantage of this realization method for a multi-level structure is the fact that only a binary surface profile is required which is fabricated in a single lithographic patterning step. Consequently, the achievable wavefront accuracy is identical to that of a simple 2-level CGH and the accuracy reduction due to subsequent lithography layers can be completely avoided. The realized test CGH was characterized to show a diffraction efficiency of 76% in single pass transmission, which corresponds exactly to the theoretically ex-pected value.

Authors:
Martin Steglich, Tyler J. Schoeppner and Thomas Käsebier

Black Germanium Antireflection Structures

Owing to its low dispersion, good chemical stability and excellent mechanical properties, Germanium is one of the most utilized materials for optics operating in the infrared spectral range from 2 µm to 15 µm of wavelength. As a result of its high refractive index of about 4 it however suffers from intrinsically high reflection losses, thus making the employment of anti-reflection (AR) coatings inevitable for practical applications of Germanium optics.

A cost-efficient alternative to AR coatings is given by monolithic "Black Germanium" antireflection structures. Instead of extensively depositing several µm thick optical layer systems, here a stochastic surface structure (Fig. 1) is produced in Germanium by a self-organized, mask-free plasma etch process which is accompanied by a drastical reduction of reflectivity (Fig. 2). In this way the reflection of Germanium can be reduced to less than 1% over wide spectral and angular ranges (Fig. 3).

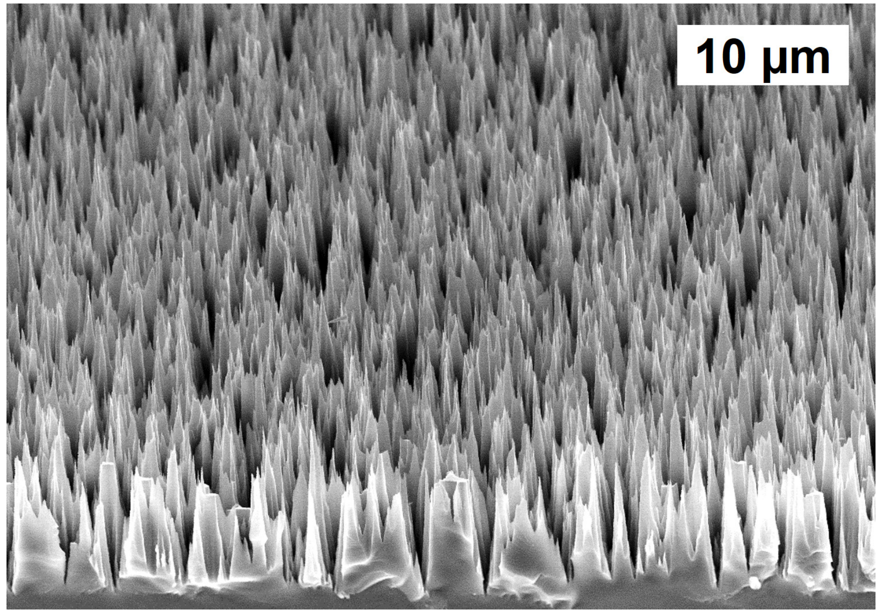


Figure 1:
SEM image of a Black Germanium antireflection structure under an angle of 30°.

Due to its monolithic nature Black Germanium does not suffer from thermal stress or film stress. The rather simple structure fabrication allows for high cost reductions compared to AR layer systems. In addition the manufacturing is patternable, i.e. in regions that have been lithographically defined before.

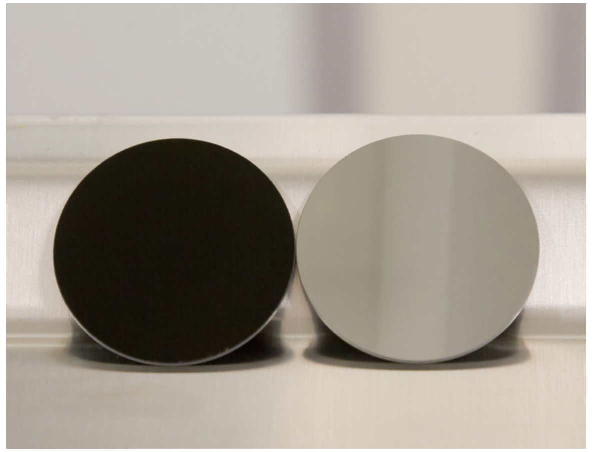


Figure 2:
Photo of a Germanium window of 30 mm diameter with and without Black Germanium antireflection structure.

Potential application areas of Black Germanium comprise the utilization as AR structure both in imaging and non-imaging Ge-optics, as well as in Ge-based opto-sensors. Furthermore the structures can be used for the suppression of optical ghosts in IR optics.

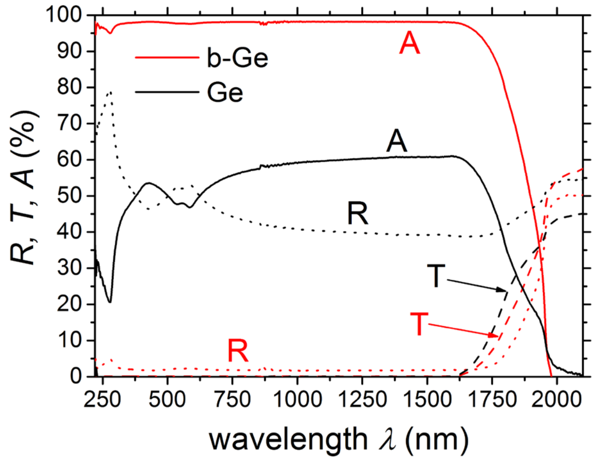


Figure 3:
Optical spectra (reflection R, transmission T and absorption A) of Black Germanium (b-Ge) in the UV-NIR. For comparison the corresponding spectra of unstructured Germanium is shown, too (Ge).

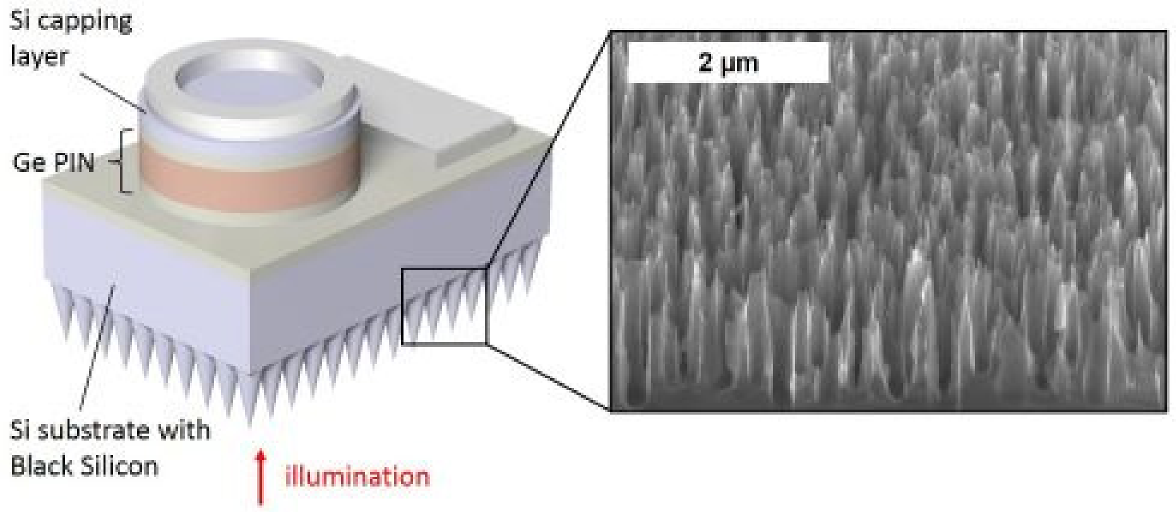
This project is cofinanced by the joint research project "Nachtsichtkamera für automotive Anwendungen (NASIKA)"
German Ministry of Education and Research (BMBF), contract no.: 03VP00413.

Authors:
Martin Steglich

Junior Research Group: Eye-safe 3D metrology in the SWIR - 3Dsensation

Conventional 3D metrology systems usually operate at wavelengths around 800 nm due to the human eye's blindness in this spectral region. However, hazard potential is rather high at these wavelengths as the eye is highly transparent up to about 1400 nm of wavelength, thus impeding tightly linked human-machine interactions relying on the three-dimensional recognition of human beings, e.g. their mimics and gestures, by empathic machine systems.

To solve this problem, the research group Eye-safe 3D metrology in the SWIR seeks to establish a both high-performant and cost-efficient 3D metrology working in the Short-Wavelength Infrared (SWIR), particularly at around 1450 nm. At these wavelengths, the optical absorption of water (for example by the tear film on the human's eye) represents a natural protection mechanism for hazardous, high intensity optical irradiation, therefore allowing for around 2 orders of magnitude higher maximum admissible optical intensities according to DIN EN 60825-1.



A major requirement for eye-safe metrology systems is the availability of cost-efficient SWIR sensors. For that, one major focus of our work is the development of CMOS capable Germanium-on-Silicon (Ge-on-Si) sensors for normal incidence and maximization of their optical responsivity by means of diffractive light-trapping structures.

Further efforts, undertaken in close cooperation with external partners from research and industry, comprise the design and demonstration of novel 3D metrology systems operating in the SWIR.

Figure 1:
Schematic illustration of a Ge-on-Si photodiode with diffractive "Black Silicon" light-trapping structure. The sensor is illuminated via the sensor rear side where the Black Silicon is located, yielding a strong light-trapping effect and, thus, a drastically increased light absorption in the device.

3Dsensation
Mensch. Maschine. Umwelt. ZUKUNFT

This Junior Research Group "Augensichere 3D-Messtechnik im SWIR (3D-SWIR)", funded by the German Federal Ministry of Education and Research (BMBF), contract no. 03ZZ0435, is part of the innovation alliance "3Dsensation". "3Dsensation" is a consortium consisting of industry partners and research institutions from different branches of science. This consortium fosters interdisciplinary research and development work with the aim to tackle central technical, sociological and ethical challenges of man-machine interaction.

Junior Research Group: Atomic Layer Deposition - Emmy Noether Group

Atomic layer deposition (ALD) is a thin film coating technology based on self-limiting sur-face reactions. The thickness of ALD films is controlled with sub-nanometer precision by the number of ALD cycles. The films manifest high uniformity and low roughness. The decisive advantage of ALD over other established coating techniques is its ability of con-formal coating on curved and high aspect ratio substrates. A wide range of materials, including oxides, nitrides, fluorides, sulfides, metals and hybrid organic-inorganic composites, can be deposited via the ALD and molecular layer deposition (MLD) techniques. Additionally, composite materials with tailored composition and material properties are possible. The above-mentioned materials find numerous applications in the fields of photovoltaics, electronics, catalysis, biotechnology, display technology, and photonics.

Currently the focus lies on coatings for:

- low and high refractive index materials
- porous materials
- advanced nanostructuring technologies
- interference coatings
- functional coatings for diffractive optical elements
- space & laser technology, spectrometry, UV-VIS, DUV, EUV, BEUV, x-ray optics
- understanding chemical reactions during nucleation and film growth.

Research methods

The ALD facility has two plasma-enhanced atomic layer deposition reactors at hand and are equipped with in situ monitoring techniques for experimental characterization by means of spectro-scopic ellipsometry in the 245…1700 nm spectral range. The equipment comprises:

- OpAL PEALD, Oxford Plasma Technologies
- Sunale R200, Picosun Oy
- J. A. Woollam spectroscopic ellipsometer.

Authors:
Kristin Pfeiffer, Lilit Ghazaryan, Ulrike Schulz and Adriana Szeghalmi

3D conformal antireflective coatings by ALD

Antireflective (AR) coatings based on the interference of the reflections at the interface of alternating thin films with low and high refractive indices require precise thickness control. Conventional physical vapor deposition techniques usually produce a non-uniform thickness distribution on strongly curved substrates which severely affects the optical function. We demonstrate the suitability of atomic layer deposition (ALD) to achieve high AR performance even on steeply curved substrates. ALD is based on cyclic self-limiting surface reactions. The thickness of each layer is determined by the number of ALD cycles regardless of the substrate's shape.

An ALD Al_2O_3 / TiO_2 / SiO_2 – multilayer system has been applied to a fused silica half-ball lens to reduce the reflectance to Rav < 0.3 % in the wavelength range of 390 nm to 750 nm (Fig. 1). Excel-lent agreement of all measured spectra along the lens surface and the design is demonstrated.

Furthermore, single layer AR coatings consisting of nanoporous SiO_2 have been applied. These layers have been realized by the deposition of Al_2O_3:SiO_2 composite materials, where the alumina component was removed by subsequent wet chemical etching. We achieved a conformal AR with Rav < 0.1% in the wavelength range of 600 nm to 700 nm on an aspheric B270 lens (see Fig. 2).

Atomic layer deposition is a promising technology for coating thin optical films on complexly shaped components, such as convex and concave lenses, cylinders, ball lenses, in tubes or other substrates which are difficult to functionalize precisely with conventional coating technologies.

/1/ K. Pfeiffer, U. Schulz, A. Tünnermann, A. Szeghalmi, Coatings, 7, 118 (2017).

/2/ L. Ghazaryan, E. B. Kley, A. Tünnermann, A. Szeghalmi, Nanotechnology, 27, 255603 (2016).

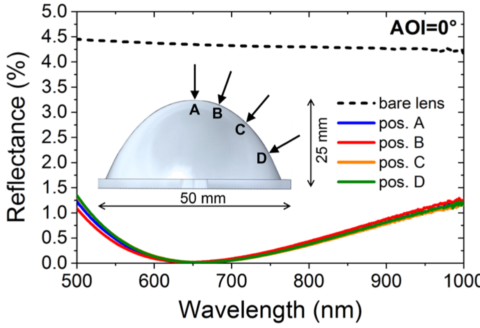


Figure 1:
Reflectance of an ALD - multilayer AR coated half-ball lens.

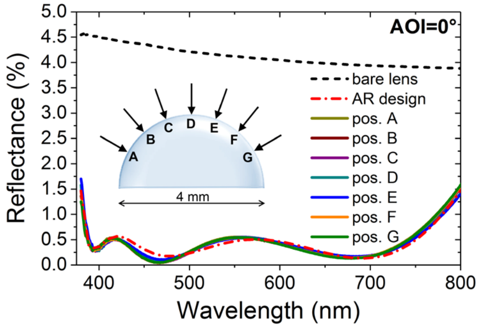
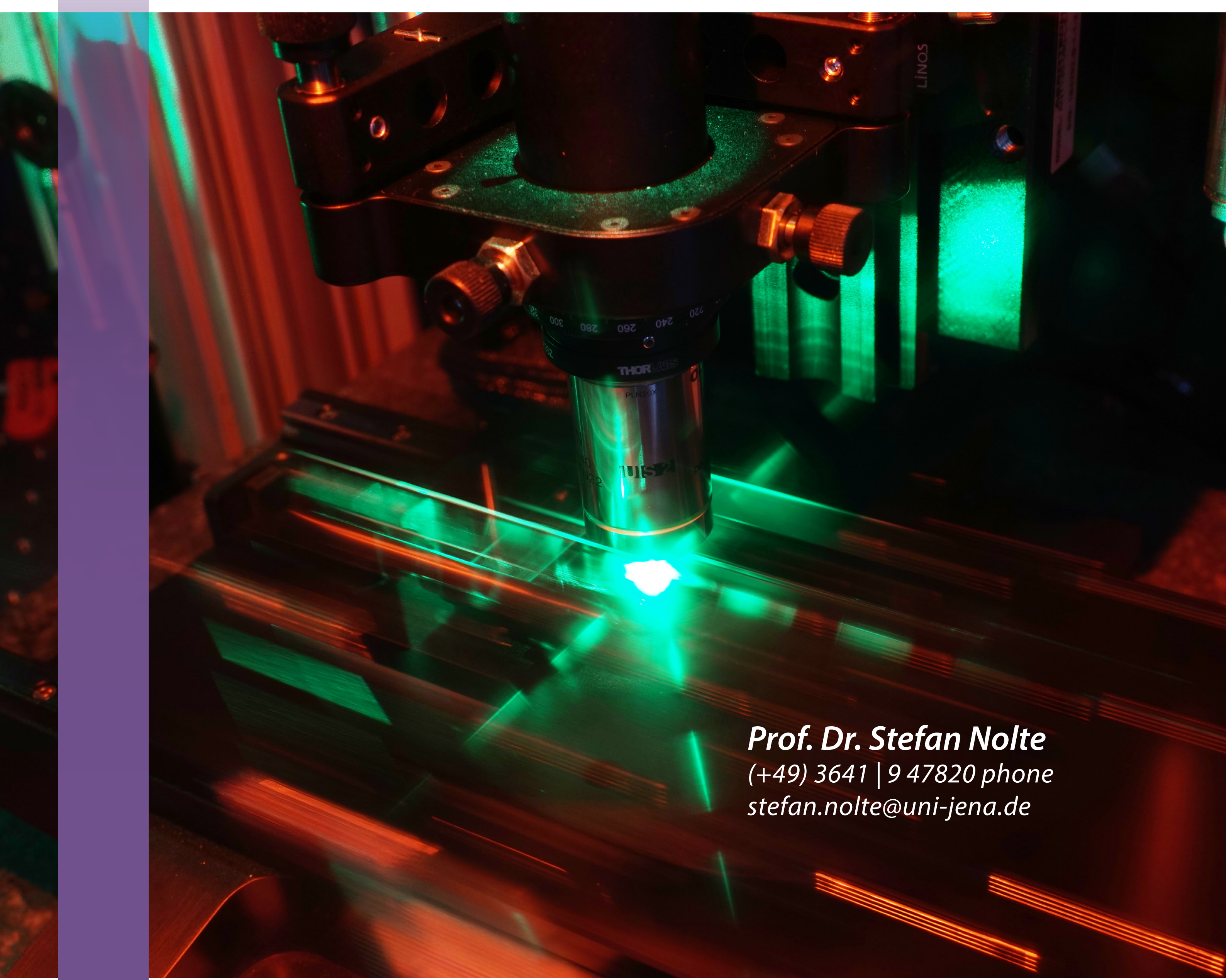


Figure 2:
Reflectance of a nanoporous SiO_2 single-layer AR coated aspheric lens.



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Plasma of a laser writer for generating waveguides.

Ultrafast Optics

The group Ultrafast Optics works on applications of femtosecond laser pulses, such as materials processing and micro/nano structuring of optical materials.

The scientific topics are:

- Linear and nonlinear laser-matter interaction:
  A fundamental understanding of the interaction between ultra-short laser pulse solids forms the basis for the work of our group. For this purpose, propagation and absorption effects as well as subsequent relaxation processes are analyzed in detail.
- Micro-and nanostructuring with ultrashort laser pulses: Ultra-short laser pulses allow high-precision structuring on the micro- to nanometer scale. Our investigations range from ablation to the defined manipulation of material properties.
- Volume modifications in glasses: The nonlinear absorption inside transparent materials allows the modification of the propagation properties of light. Application examples include fiber and volume bragg gratings, waveguide systems, and artificially birefringent structures.
- Spectroscopic methods for gas analysis: Non-linear spectroscopy methods are developed for the analysis of gases under extreme conditions.

Authors:
Gabor Matthäus and Stefan Nolte

Additive manufacturing using ultrashort laser pulses

Laser assisted additive manufacturing (AM) allows the layer-wise build-up of elements with highly complex geometries. In particular, for the processing of metals, the powder bed method is well-established. However, the application of conventional continuous wave lasers significantly limits the range of applicable materials. In particular, materials with high thermal conductivity, as well as elements with increased melting temperature, are problematic. Furthermore, non-eutectic materials often show segregation during laser melting, yielding strong degradation of the microstructure stability.

The application of ultrashort pulse (USP) laser radiation for local melting of the powder significantly increases the range of applicable materials. USP laser systems typically deliver laser radiation with pulse durations below 100 ps (10^{-10} s). Here, the available peak power extends from MW to GW. Within this range, the melting temperature of any material

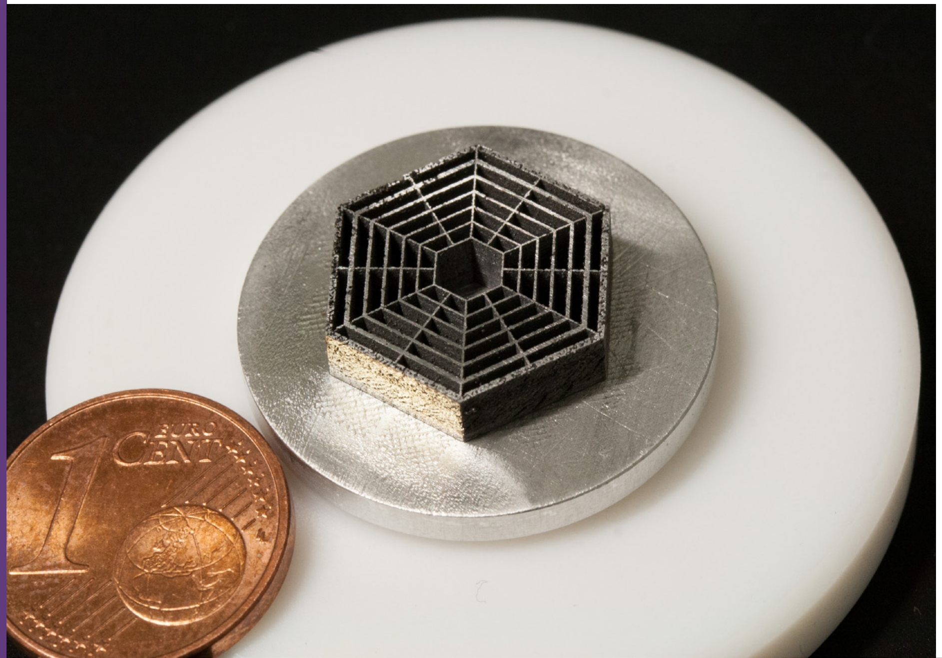


Figure 1:
Additively manufactured 3D structure fromAl$Si_4$0. The minimally achieved wall thickness is below 50 µm.

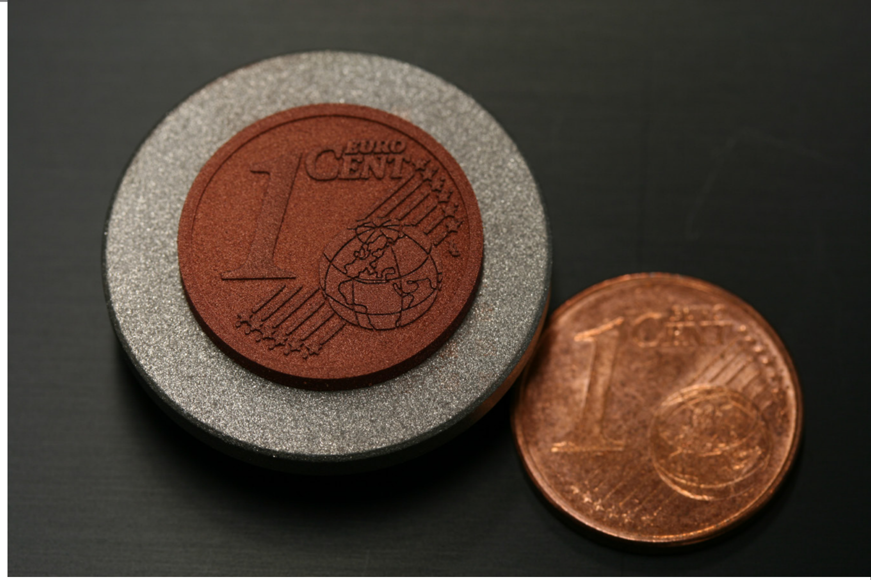


Figure 2:
Additively manufactured 3D structure from pure copper. The minimally achieved wall thickness is below 100 µm.

can be reached. The high intensities within the focal region yield nonlinear absorption which allow for the melting of transparent materials. Moreover, the extremely short interaction times between laser radiation and material support processing within the non-thermal equilibrium. Thus, segregation processes of composites within the melt bath can be suppressed and the local heat expansion can be further minimized. As a consequence, complex elements with optimized micro-structure can be fabricated.

For example, devices of hypereutectic aluminum alloy (Al$Si_4$0) could be produced by using USP-AM. The minimum wall thickness achieved was below 50 µm (Fig. 1 /1/). Al$Si_4$0 is well suited for the fabrication of optical elements due to the adapted thermal expansion coefficient /2/. Moreover, the application of optimized laser parameters improved the microstructure by reducing the appearance of segregation within the supersaturated alloy.

A further example is copper which exhibits high reflectivity values in the NIR (> 98 % @ 1030 nm) and an extremely high thermal conductivity. Until now, these properties prevented the manufacturing of pure copper parts using commercially available AM machines. By using USP-AM, complex 3D parts could be generated featuring wall thicknesses below 100 µm (Fig. 2 /3/).

/1/ T. Ullsperger et al., Selective laser melting of hypereutectic AL-$Si_4$0-Powder using ultra-short laser pulses, Appl.Phys. A, 123, 798 (2017).

/2/ Patent DE 10 2005 026 418 A1, (2006).

/3/ L. Kaden et al., Selective laser melting of copper using ultrashort laser pulses, Appl. Phys. A, 123, 596 (2017).

Author:
Roland Ackermann

Verbund-ZIK OptiCon
Optical in situ investigation and modeling of high-temperature conversion processes

The results of the joint project "HITECOM - High Temperature Converting Optical Measurement" between the both Centers of Innovation Competence (ZIK) "Virtuhcon" at TU Freiberg and "ultra optics" at our institute, gave rise to a follow-up project, founded by the Federal Ministry of Education and Research (BMBF) with a total of € 4.7 million for additional three years.

Background of the research in the new joint project "OptiCon - Optical in situ investigation and modeling of high-temperature conversion processes" is the development of resource-efficient technologies for energy and material conversion, which defines new demands on technology development. The experience at the fields of Laser physics and modelling of high-temperature conversion processes in Jena and Freiberg will be used, to establish a new experimental and theoretical method based on an experimental material data investigation. The high-temperature reactions during the fabrication of synthesis gas will be gauged in detail and used for the development of high-resolution numerical models. The application of these numerical models ends in a time- and cost-optimized new development of resource-efficient high-temperature conversion processes in industrial scale.

In the OptiCon network, the HITECOM approach is to be applied to other fields of technology with high utilization potential. Particularly energy- and resource-intensive high-temperature processes in metallurgy (e.g. ore smelting, metal recycling, development of renewable raw materials) have a high savings potential in terms of their resource requirements. According to the OptiCon strategy, the key reactions should be scientifically penetrated, modeling tools for process optimization and redevelopment created, and new spectroscopy techniques developed for direct process analysis.

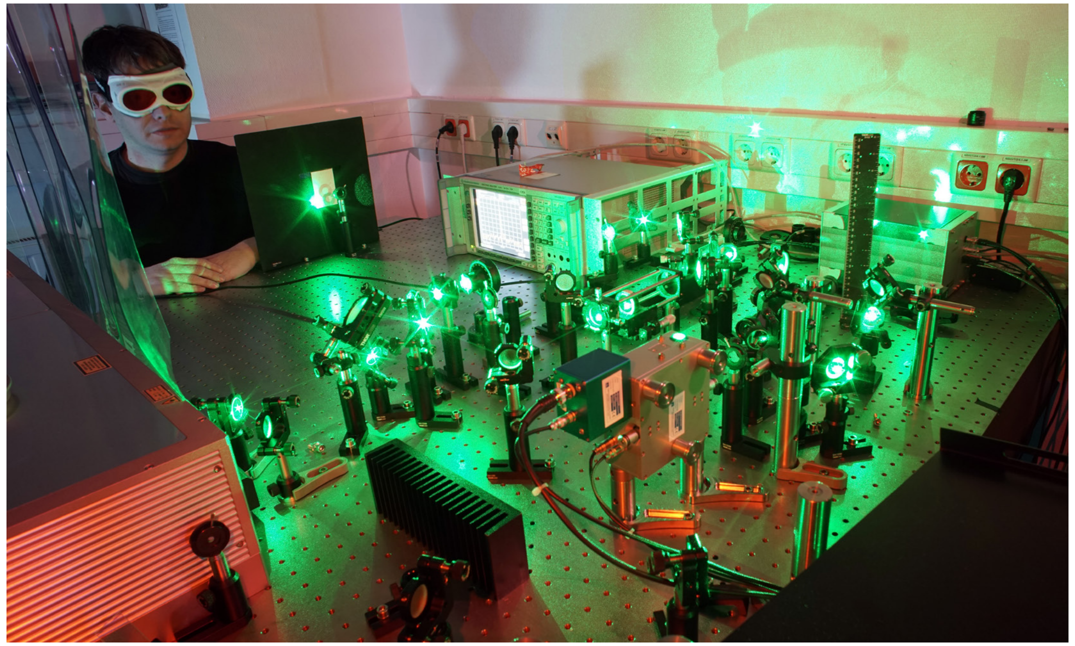
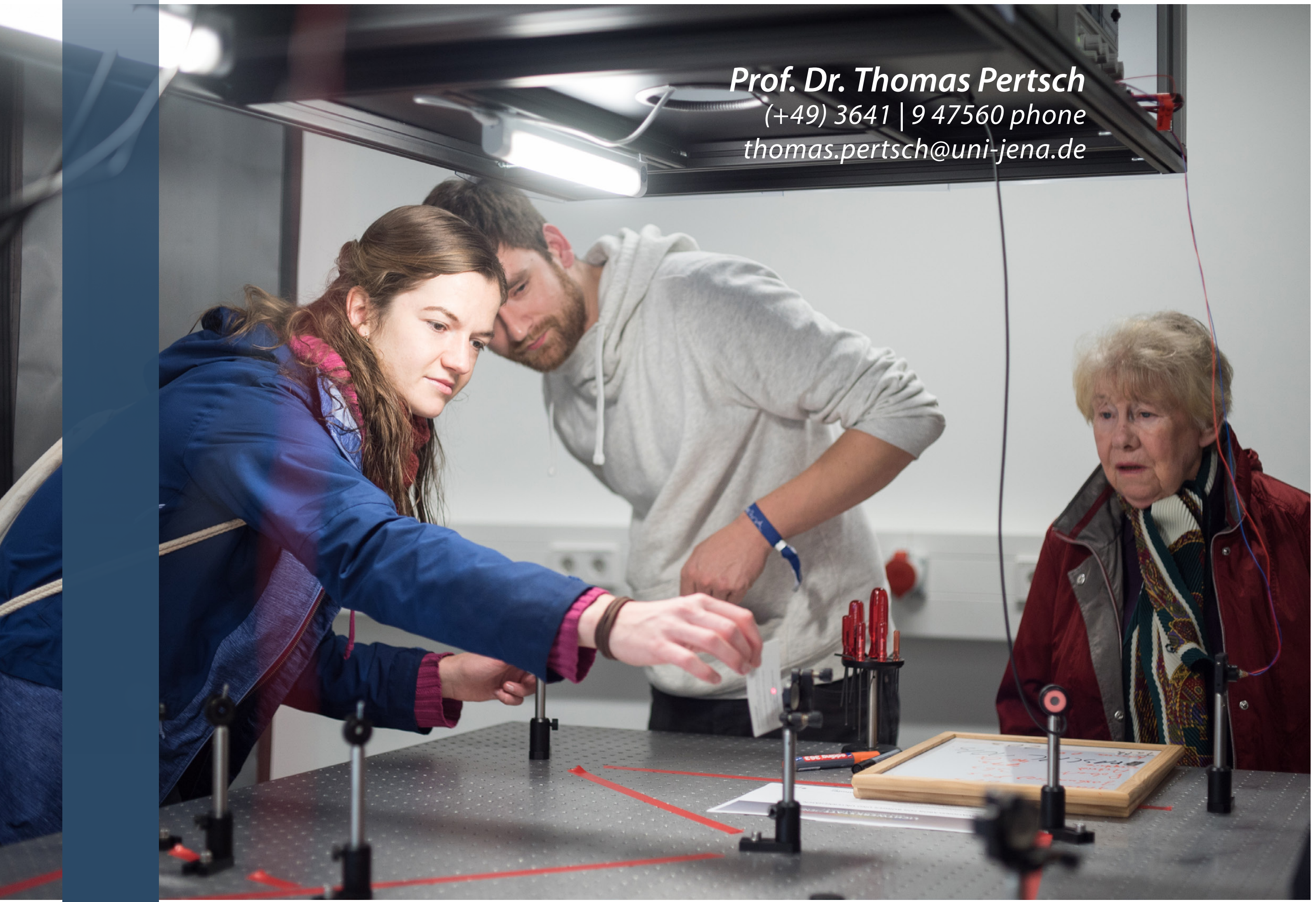


Figure 1:
R. Ackermann at his experimental setup for the follow-up project of Verbund-ZIK HiteCom.

The expected results and their application in an industrial scale increase the innovation potential of regional plant manufacturers and technology providers and thus contribute to securing and strengthening Germany as a research and technology location. Partners have already been found: Outotec GmbH & Co. KG and Air Liquide Research & Development GmbH are adressing the metallurgy and gasification technology sectors as leading technology providers and plant builders. The field of laser spectroscopic analysis methods is prominently represented by Active Fiber Systems GmbH and TRUMPF Scientific Lasers GmbH + Co. KG.



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The "Lichtwerkstatt" was installed at the ACP in 2017 as an initiative of the working group "Nano & Quantum Optics" to give laypersons, semi-professionals and experts the opportunity to try out their ideas all around the theme "Light".
At the "Lange Nacht der Wissenschaften" the audience met this concept with great enthusiasm.

Nano & Quantum Optics

The research group Nano & Quantum Optics deals with ultrafast light-matter interactions and optical quantum phenomena in microstructured and nanostructured matter, as e.g. photonic nanomaterials, metamaterials, photonic crystals, and effective media.

The scientific emphasis lies on:

- nonlinear spatio-temporal dynamics, integrated quantum optics, plasmonics, near field optics, high-Q nonlinear optical microresonators, opto-optical processes in integrated optics, all-optical signal processing
- Multi-tip scanning optical nearfield microscopy (SNOM), photoemission electron microscopy (PEEM)
- Application of photonic nanomaterials for multi-functional diffractive optical elements
- Application of optical nanostructures for efficiency enhancement of photovoltaic elements
- Application of advanced photonic concepts for astronomical instruments

Authors:
Frank Setzpfandt, Sina Saravi, Pawan Kumar and Thomas Pertsch

Integrated sources for entangled photon pairs

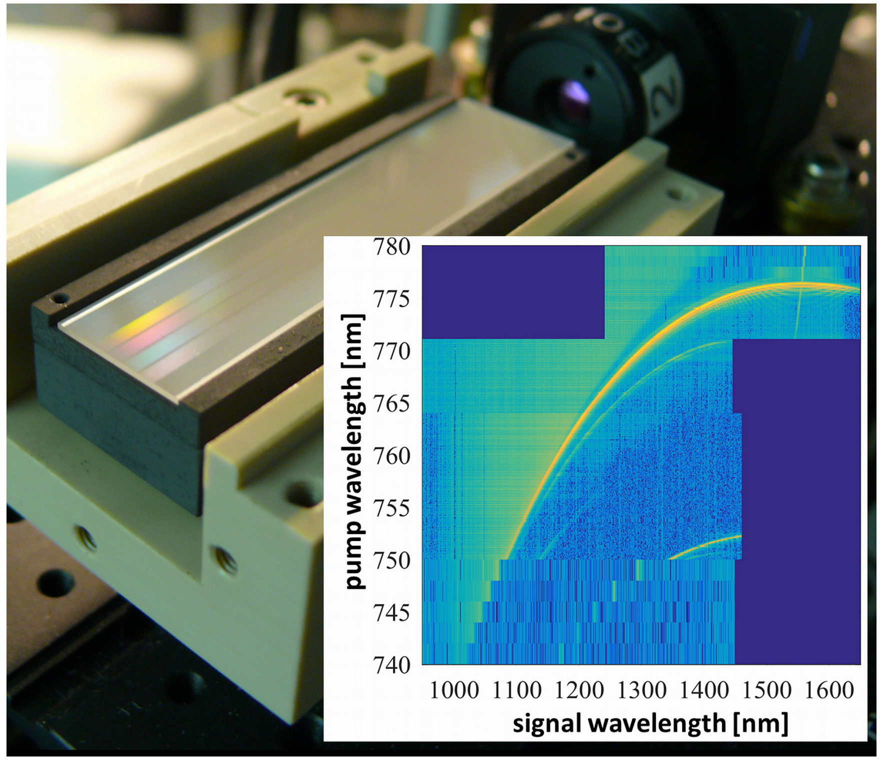

Figure 1:
Waveguide for photon-pair generation. Inset: Spectra of generated signal photons in dependence on the pump wavelength, the idler photons in the MIR spectral range were not detected.

Photon pairs with tailored properties are the basis for many applications in quantum optics. Usually, these special quantum states of light are generated by spontaneous parametric down-conversion in materials with 2nd order nonlinearity, where pump photons decay into pairs of signal and idler photons. Integrated optical systems enable a far-reaching control of such conversion processes and hence allow to generate photon pairs with properties optimized for specific application.

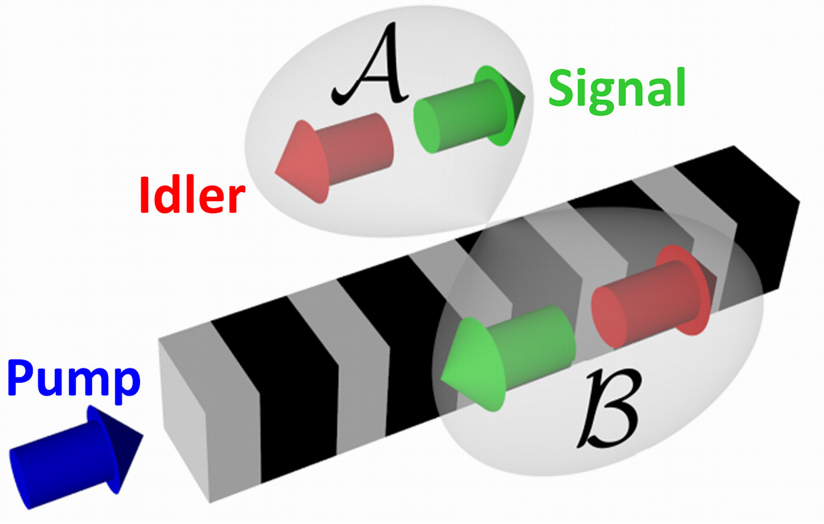

Figure 2:
Schematic visualization of a periodic waveguide for the generation of entangled photons using two simultaneous conversion processes A and B, which emit signal and idler photons in opposite directions.

/1/ A. S. Solntsev, P. Kumar, T. Pertsch, A. A. Sukhorukov, F. Setzpfandt, $LiNbO_3$ Waveguides for Integrated Quantum Spectroscopy, submitted to APL Photonics

/2/ S. Saravi, T. Pertsch, F. Setzpfandt, Generation of Counterpropagating Path-Entangled Photon Pairs in a Single Periodic Waveguide, Phys. Rev. Lett. 18, 183603 (2017).

Quantum spectroscopy uses quantum interference effects to enable spectroscopic measurements in hardly accessible spectral ranges, e.g. in the mid-infrared (MIR), by detecting only photons in a different spectral range. To this end, photon pairs with photons in both addressed spectral ranges are needed. An integrated source for such photon pairs was realized using a lithium niobate waveguide as shown in Fig. 1 /1/. It generated photon pairs with signal photons at 1 µm wavelength and idler photons at 2.7 µm wavelength, which could be controlled by changing the pump wavelength. This source can become the basis for realizing quantum spectroscopy on optical chips.

Additionally we developed new concepts to control also the spatial properties of the generated photon pairs using more complex waveguide geometries. For example, a periodically structured waveguide allows for the simultaneous generation of photon pairs where the signal is propagating either forward or backward and the idler in the corresponding opposite direction as schematically shown in Fig. 2. For specific waveguide geometries, this enables the generation of photon pairs maximally entangled in their propagation direction /2/. The generation of such quantum states in waveguide is an important step towards integration of complex photonic quantum systems.

Author:
Isabelle Staude

Junior Research Group: Functional Photonic Nanostructures
Emmy Noether Group

The research focuses lies on the use of designed photonic nanostructures which are to control the emission, absorption, and propagation of light at the nanoscale level. The research topics include:

- nanophotonics, -plasmonics, and –antennas
- high-index dielectric nanoparticles
- hybrid quantum systems and quantum emitters
- nanofabrication technology
- subwavelength optics
- metamaterials and photonic crystals

Research methods

For the experimental realization and study of functional photonic nanostructures, the junior research group Functional Photonic Nanostructures employs a range of state-of-the-art nanotechnology and optical characterization techniques, including:

- electron-beam lithography based nanofabrication
- linear and nonlinear optical spectroscopy
- time-resolved photoluminescence spectroscopy
- back focal plane imaging
- assembly of hybrid nanostructures via dry transfer
- assembly of hybrid quantum systems by selective surface functionalization

Recent Research Results

Resonant nanoparticles and their assemblies can show complex and often surprising interactions with light, giving rise to phenomena such as „magnetic light", directional scattering, Fano resonances, and strong near-field enhancements. Using the capabilities of modern nanotechnology, these interactions can be tailored by the size, shape, material composition, and arrangement of the nanoparticles. Resonant nanoparticle structures are a versatile research platform for investigating fundamental light-matter interactions and nanoscale coupling phenomena /1/. Furthermore, they provide unique optical functionalities, opening new opportunities for applications like next-generation (quantum) light sources, optical communications, and truly flat optical components. In our research, we combine top-down and bottom-up nanofabrication approaches to realize composite photonic systems. These systems are able to control the emission, propagation, and absorption of light at the nanoscale.

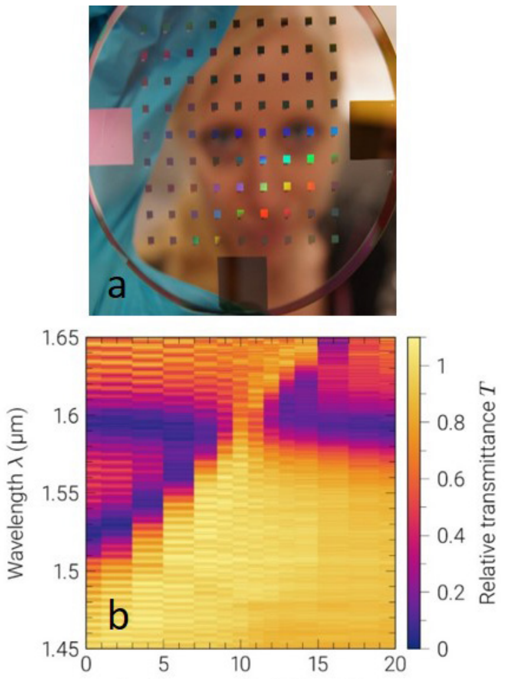

Fig. 1: (a) Example of fabricated silicon metasurfaces. Image: M. Decker.
(b) Transmission spectra of a silicon metasurface in dependence on the incidence angle of a TM-polarized plane wave. Image taken from /2/.

Recently we have focused on dielectric metasurfaces, which can provide local control of the phase of a light wave. Thereby, they enable functionalities like focussing, beam shaping and holographic imaging while having nanoscale thickness. Such metasurfaces consist of a carefully designed, two-dimensional arrangement of high-refractive-index dielectric nanoparticles, which exhibit electric and magnetic dipole resonances known from Mie scattering. When these resonances are designed to overlap spectrally, the nanoparticles scatter almost all light in the forward-direction only, and the metasurface becomes highly transparent.

In the last year, we have investigated this effect in dependence on the incidence angle and polarization of incident plane waves for a metasurface composed of silicon nanocylinders /2/. We showed that the resonance overlap can be designed to appear at an arbitrary incidence angle. Furthermore, since the metasurface blocks all light incident at angles other than the design angle, angle-selective functionalities may be implemented as well. These findings open interesting opportunities for the design of advanced wavefront-shaping devices and computer-generated holograms.

/1/ I. Staude, J. Schilling, Metamaterial-inspired silicon nanophotonics, Nature Photon. 11, 274-284 (2017).

/2/ D. Arslan, K. E. Chong, A. Miroshnichenko, D.-Y. Choi, D. Neshev, T. Pertsch, Y. S. Kivshar, I. Staude, Angle-selective all-dielectric Huygens' metasurfaces, J. Phys. D: Appl. Phys. 50, 434002 (2017).

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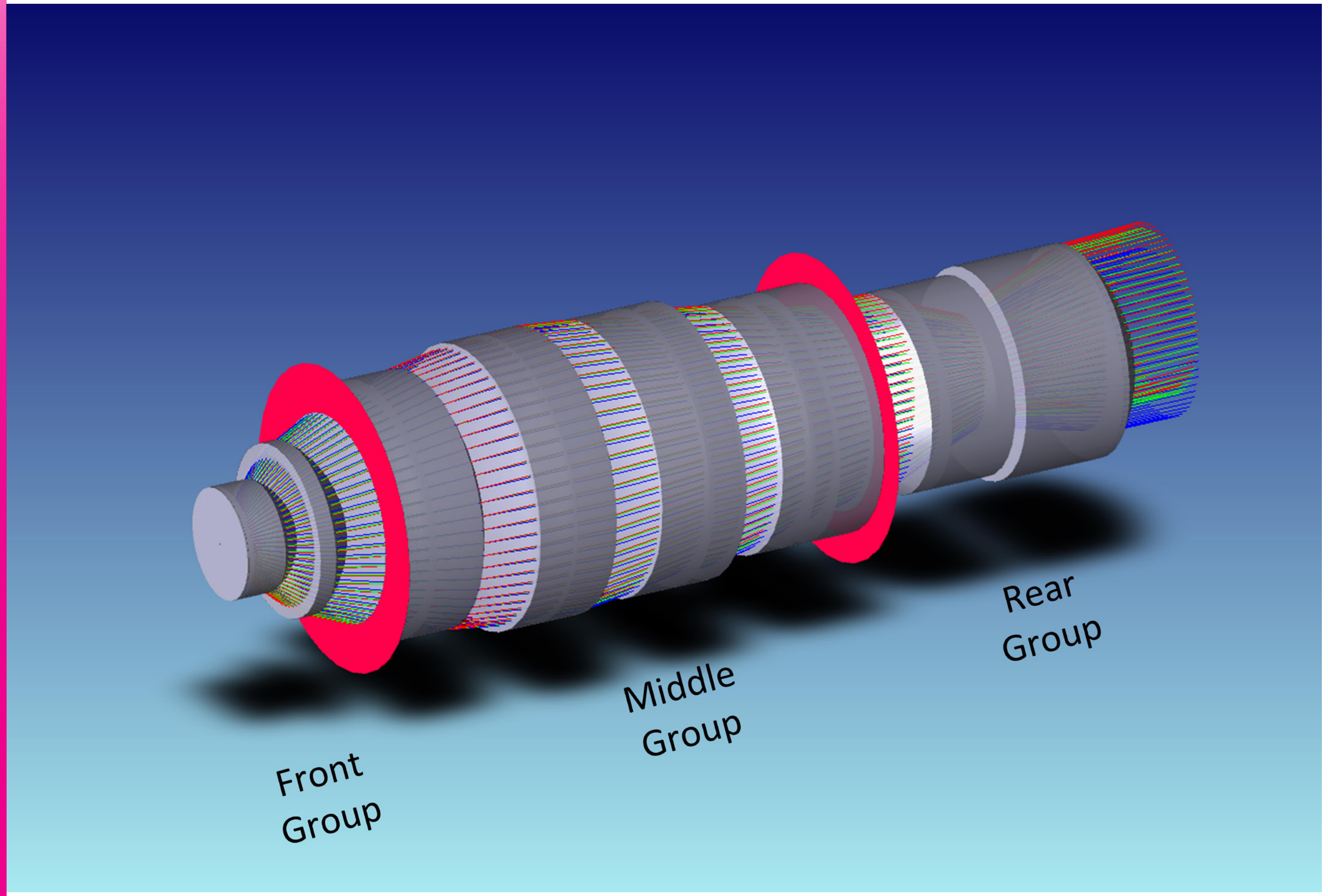

Classification of the optical system into three zones.

Optical System Design

In classical optics design, especially the following topics will be addressed:

- Design of modern optical system
- Aberration theory
- Quality evaluation of optical systems
- Measurement of the performance of optical systems
- Design of laser and delivery systems
- Design and evaluation of freeform optical systems for imaging and illumination
- Optimization methods in optical design
- Tolerancing of optical systems

In somewhat more general physical issues relating to optical systems, in particular the following topics of interest are:

- Simulation of diffraction effects
- Microscopic image formation
- Calculation algorithms of wave propagation
- Straylight and scattering in optical systems
- Modelling of illuminations systems
- Partial coherent imaging and beam propagation
- Point spread function engineering and Fourier optics.

The endowed professorship Theory of Optical Systems aims to support optical companies in their development and training. Amongst others, this could be reached in the project “Freeform Optics Plus (fo+)”, which combines research on the brand new technology field of freeforms in optics but also in education and training.

Authors:
Yuequian Zhang and Herbert Gross

Investigation of Microscopic Lenses

The modern microscopic objective is the most sophisticated optical component in microscopes, providing high contrast images with diffraction-limited resolution. The design of microscopic objectives has been developed for over a hundred of years, however, a systematic synthesis approach is rarely reported /1/. To understand the systematic behavior, we implemented a database with hundreds of patented objective examples /2/.

Sorted by magnification versus numerical aperture (NA), systems could be classified into five zones with linear boundaries on semi-log coordinates, shown as Fig. 1. The classification also implies the trend of the objective evolution from the 1830s to recent years.

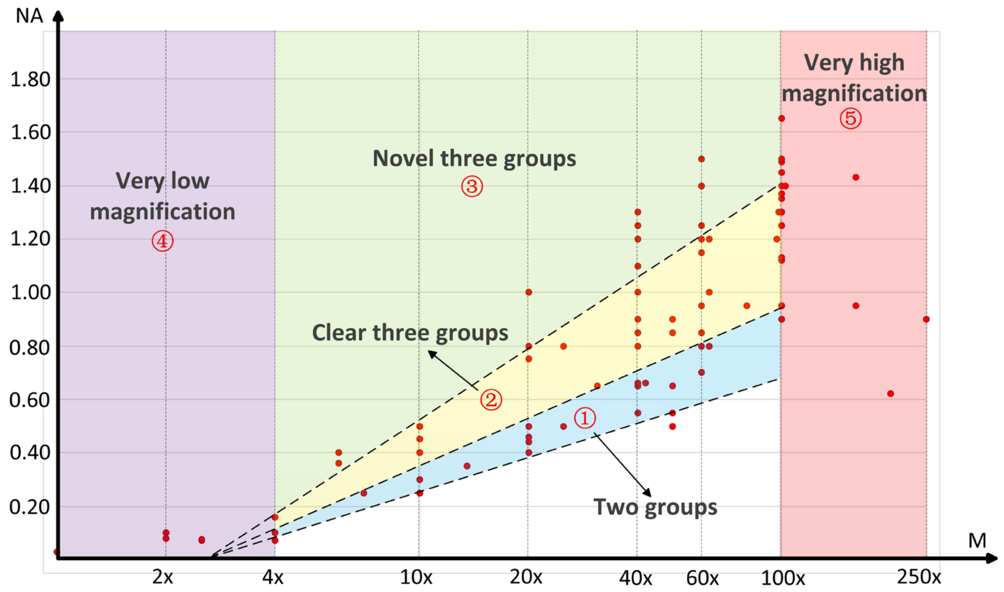

Figure 1:
Overview of microscopic objective database with five zones classification.

According to the structural characteristic and functionality for aberration correction, the most significant zone 2 and zone 3 objectives could be clearly divided into three groups, illustrated in front figure of the chapter at page 58. The spherical aberration and coma, which are introduced in the front group, are mostly corrected by the middle group. Astigmatism, which is slightly added by the front group, is compensated by a symmetric rear group. The positive Petzval curvature in the front group has to be compensated by meniscus thick lenses in the rear group. Axial chromatic aberration is corrected in the middle group, while the lateral chromatic aberration is corrected or controlled by the rear group.

The design principles are further investigated and summarized as lens module behavior. As a reversed process, a systematic approach for system modification and synthesis was achieved, which process is briefly demonstrated as Fig. 2.

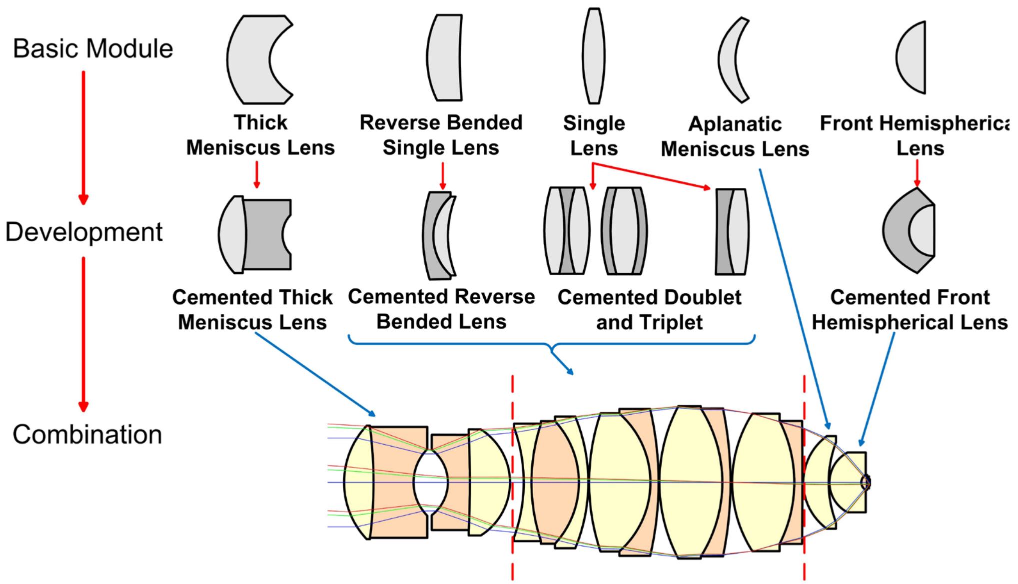

Figure 2:
Lens module classification and system synthesis process.

/1/ D.N. Frolov, Synthesis of the optical systems of lens objectives for microscopes, J. Opt. Technol. 69, 614 (2002).

/2/ Y. Zhang, H. Gross, Systematic design of microscopic lenses, Proc. SPIE ODC17 (2017).

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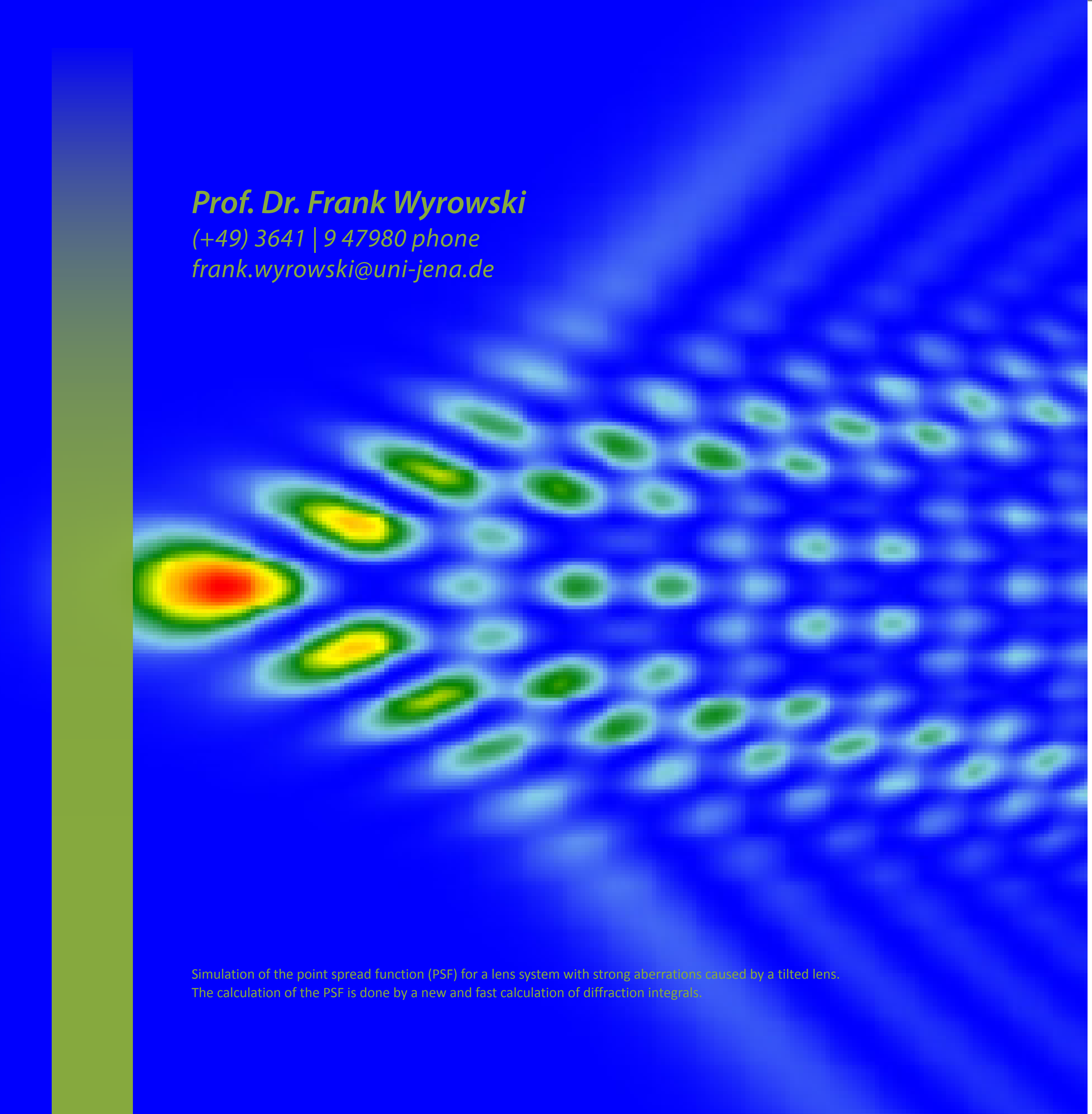

Simulation of the point spread function (PSF) for a lens system with strong aberrations caused by a tilted lens. The calculation of the PSF is done by a new and fast calculation of diffraction integrals.

Applied Computational Optics

The Applied Computational Optics Group works consistently on developing a physical optics concept which includes a geometric theory of electromagnetic fields. From a practical point of view, this enables the development of fast solvers of Maxwell's equations.

In 2017 we investigated the following research and development (R&D) topics, among others:

- Maxwell solver in the k-domain
- Fast Fourier transform algorithms with minimized sampling effort
- Spline interpolation of smooth functions in physical optics modeling
- Parametrization of electromagnetic fields
- Gouy phase shift
- Multiple aperture diffraction
- Geometric bidirectional operators
- Bidirectional scattering distribution function (BSDF)
- Use of ray data from LED measurements in physical optics modeling
- Partial coherence and partial polarization modeling
- Spatio-temporal simulation of ultrashort pulses
- Fast electromagnetic modeling of light propagation through crystals and graded-index media
- Modeling and design of freeform surfaces
- Design of light-shaping elements by mesh concepts
- Non-sequential physical optics modeling for virtual and mixed reality devices

Several topics have been developed in cooperation with LightTrans GmbH and Wyrowski Photonics UG using the optics software VirtualLab Fusion.

Author:
Frank Wyrowski

Geometric Fourier Transform

Physical optics includes ray optics as a special subset. In practice, however, physical optics and ray optics are treated separately, especially because rays traditionally do not include the field values. However, Born and Wolf postulated and partially developed an extension of geometrical optics for electromagnetic fields in "Principles of Optics". We asked ourselves which mathematical principle underlies the transition between the geometrical and diffractive subfields of physical optics. For this we formulate Maxwell`s equations in the Fourier domain and discuss mathematical approximations of the Fourier transformation. By means of the saddle-point method an asymptotic approximation can be obtained, which we have called geometric Fourier transform. It allows for a purely mathematical argument-based transition between geometric and diffractive methods of physical optics. It also shows that the geometrical methods of physical optics are numerically only as complex as ray tracing, but besides the diffractioncan account for all other physical optics effects such as interference, polarization and coherence (front figure of the chapter, see p.62).

/1/ F. Wyrowski, C. Hellmann, Combining geometrical and physical optics in smart ray tracing, SPIE Newsroom (2016).

/2/ F. Wyrowski, C. Hellmann, The geometric Fourier transform, Proc. DGaO (2017).

/3/ O. Baladron-Zorita, The role of the Gouy phase anomaly in the unification of the geometric and physical models for the propagation of field, Proc. DGaO (2017).

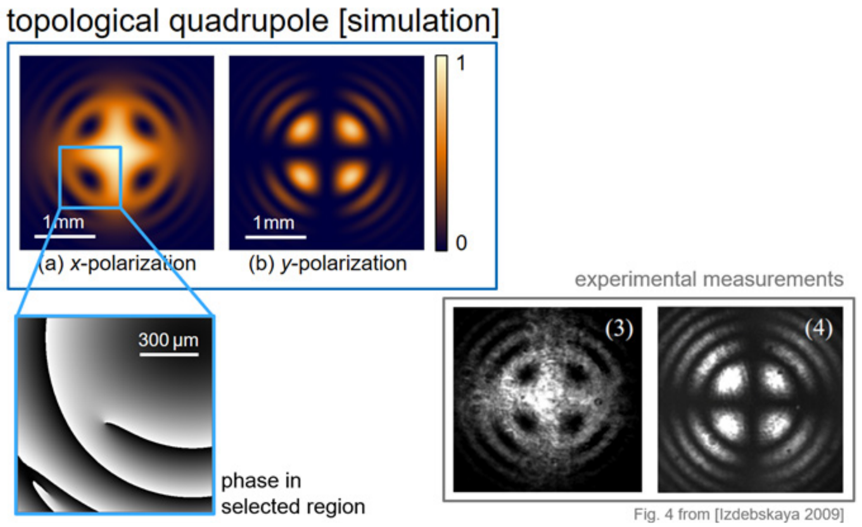

Figure1:
Simulation of the conversion of linearly polarized light in crystals (top) and comparison with experimental findings from Izdebskaya et al., "Dynamics of linear polarization conversion in uniaxial crystals," Opt. Express 17, 18196-18208 (2009).

Mixed und Augmented Reality Glasses

The combination of waveguide wafers, in which the light is guided by total reflection, with gratings at the frontal faces, currently represents a hot candidate for the implementation of glasses for mixed and augmented reality. There, the light of an imaging unit is coupled into in the waveguide and then guided to a virtual exit pupil. In this case, the largest possible exit pupil must be achieved. By including the gratings, the polarization of the light must be taken into account and the lattice effects incorporated by a rigorous grating simulation. As a result, this leads to a non-sequential coupling of different physical optics simulation methods. Our Field Tracing approach has proven to be particularly powerful for this application and has been implemented in LightTrans' VirtualLab Fusion software.

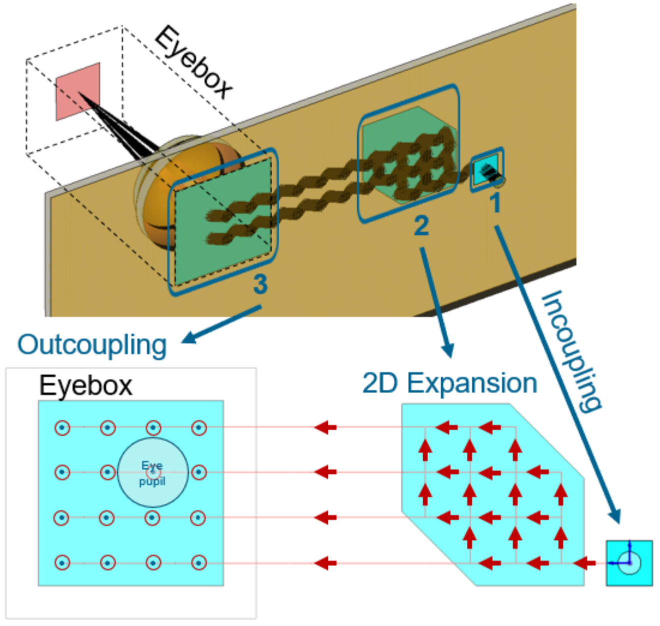

Figure2:
Typical light path in a waveguide for use in VR and AR: The light is coupled via a grating into a waveguide and then guided to the eye via total reflection and other gratings, where it is then decoupled via a grating.

Software Wyrowski VirtualLab Fusion „VR and AR Software Package", www.lighttrans.com

Crystal Optics

Anisotropic media can occur in crystals but also as stress-induced birefringence. We have developed rigorous methods to propagate electromagnetic fields through crystals. To do so, no assumptions about the crystal axes are necessary. In addition, we analyzed anisotropic layer systems, for example in the context of laser crystals. The modeling techniques can be used as methods in field tracing, enabling the physico-optical modeling of systems containing crystals and other anisotropic components. We have used these methods for a variety of applications, such as the modeling of polarization conversion, the generation of optical phase dislocations and locally polarized light, and magneto-optics (Fig. 1).

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Author:
Stefan Heist

Junior Research Group: High-Speed 3D Shape Measurement in Extended Spectral Ranges - 3Dsensation

This Junior Research Group "Hochdynamische 3D-Sensorik in erweiterten Spektralbereichen", funded by the German Federal Ministry of Education and Research (BMBF), is part of the innovation alliance "3Dsensation". "3Dsensation" is a consortium consisting of industry partners and research institutions from different branches of science. This consortium fosters interdisciplinary research and development work with the aim to tackle central technical, sociological and ethical challenges of man-machine interaction.

Hyper3D

The fast, accurate, and contactless three-dimensional detection of moving objects and scenes is an elementary task in countless areas of application. A typical representative of optical 3D measurement methods is the pattern projection. Conventionally, the patterns are projected in the visible spectral range. A stereo camera system detects the diffusely reflected light from the object surface. However, there exist classes of uncooperative materials like specularly reflecting or deep black surfaces and transparent or translucent materials, which are currently a big challenge for pattern projection technology. This junior research group aims to find a solution for the problem of the detectability of uncooperative objects by extending the spectral ranges into IR and UV for the projectors and cameras.

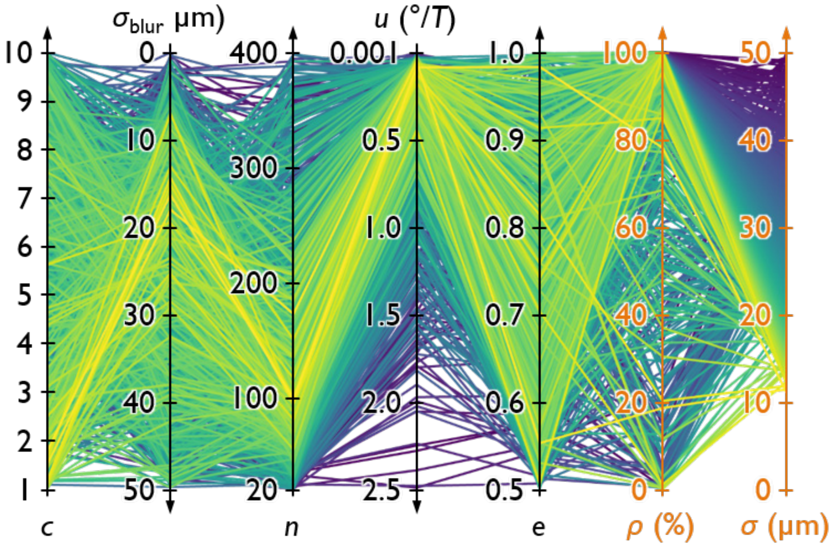

Figure 1:
Typical simulation result graph for GOBO optimization.

3Dsensation
Mensch. Maschine. Umwelt. ZUKUNFT

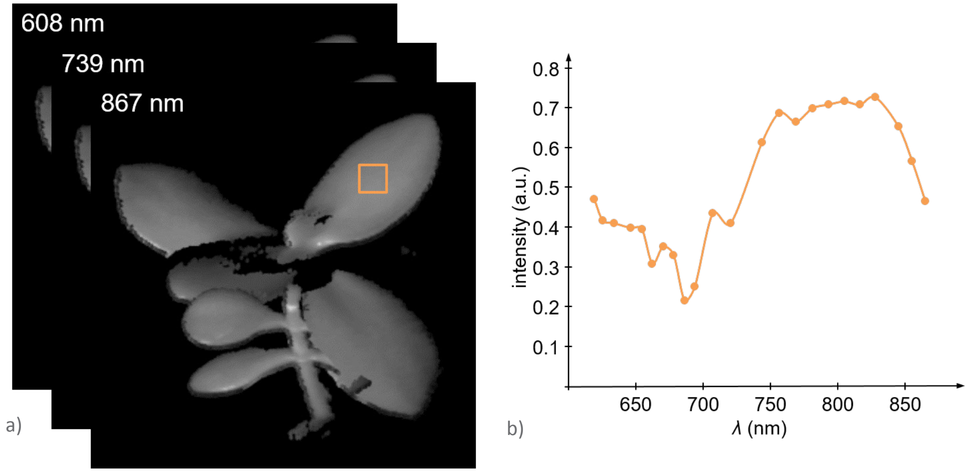

Figure 2:
(a) exemplary measurement images from a hyperspectral 3D sensor, (b) wavelength-dependent intensity response.

Recent Research Results

In 2016, we introduced a GOBO slide-based pattern projector, which allows for pattern projection at several 10,000 fps. The first experimental setups have been mainly developed based on empirical studies. This year, we have investigated the influence of GOBO parameters like number of illuminated strips and slits, rotational speed, or degree of defocusing of the GOBO wheel in order to optimize the completeness and accuracy of the 3D result (see Fig. 1). We have verified the theoretical results from a simulation experimentally by means of a GOBO projection-based 3D sensor.

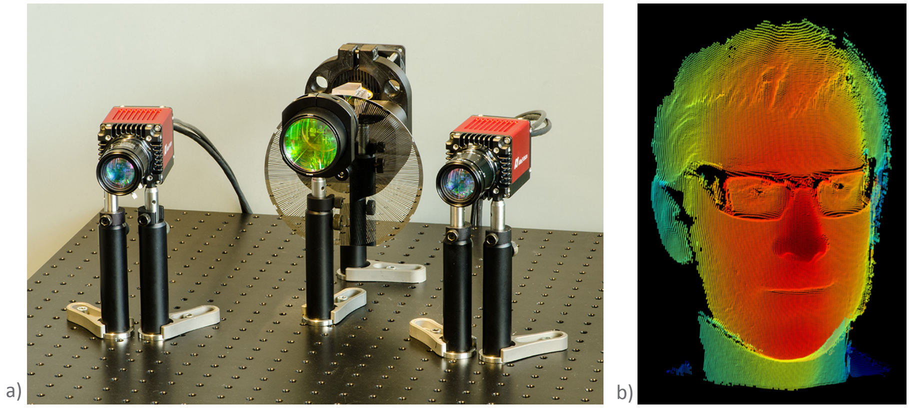

Figure 3:
(a) laboratory setup of a 3D SWIR sensor, (b) measurement example.

PUBLICATIONS

Aim of applied research is the implementation of the results and thus to make contributions to overcome certain problems of the future. For this reason, the research actually not only ends in itself, but their results must be discussed and adjusted with further findings. In the end again, new ideas and scientific approaches can be developed.

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R. Klas, S. Demmler, M. Tschernajew, S. Hädrich, Y. Shamir, A. Tünnermann, J. Rothhardt, J. Limpert, Milliwatt-Class High Harmonic Generation with an High Average Power Short Wavelength Fiber Laser, CLEO/Europe-EQEC , Munich, Germany, 2017.

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S. Schmidt, T. Tiess, S. Schroeter, H. Gross, Inverse scattering approach to characterize capillary optical fibers, OSA Meeting, San Diego, USA, 2017.

S. Zhang, C. Hellmann, F. Wyrowski, Fast simulation of electromagnetic field propagation through multiple non-parallel planar surfaces, 118. DGaO Jahrestagung, Dresden, Germany, 2017.

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T. Eidam, S. Hädrich, A. Hoffmann, J. Limpert, Efficient and compact nonlinear compression for medium energy high repetition rate and average power lasers, SPIE Photonics West, San Francisco, USA, 2017.

T. Gottschall, T. Meyer, C. Jáuregui-Misas, F. Just, T. Eidam, M. Schmitt, J. Popp, J. Limpert, A. Tünnermann, Widely tunable, fully automated, all-fiber dual-color laser system for stimulated Raman imaging, Advanced Solid State Lasers, Nagoya, Japan, 2017.

T. Gottschall, T. Meyer, C. Jauregui-Misas, M. Schmitt, J. Limpert, A. Tünnermann, All-fiber widely tunable optical parametric oscillator laser system, SPIE Photonics West, San Francisco, USA, 2017.

PUBLICATIONS

T. Gottschall, T. Meyer, C. Jaurequi, F. Just, T. Eidam, M. Schmitt, J. Limpert, J. Popp, A. Tünnermann, Fully automated all-fiber widely tunable optical parametric oscillator laser system, CLEO/Europe-EQEC, Munich, Germany, 2017.

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T.A. Goebel, C. Voigtländer, R.G. Krämer, C. Matzdorf, M. Heck, D. Richter, A. Tünnermann, S. Nolte, Wavelength tuning of through-coating-written fiber Bragg gratings, CLEO/Europe-EQEC, Munich, Germany, 2017.

Y. Zhong, H. Gross, Imaging system design of extended Yolo telescope with improved numerical aperture, Workshop on Freeforms, Changchun, China, 2017.

Z. Wang, S. Zhang, F. Wyrowski, The semi-analytical Fast Fourier Transform, 118. DGaO Jahrestagung, Dresden, Germany, 2017.

Colloquia

A. Szeghalmi: ALD Based Antireflection Coatings and Diffractive Optical Elements, JENOPTIK AG, Jena, Germany, 2017.

A. Szeghalmi: Atomlagenabscheidung in der Optik, LAYERTEC GmbH, Mellingen, Germany, 2017.

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A. Tünnermann: Center of Excellence Photonics: Enabling research – Empowering Innovations, Rochester University, Rochester Science Museum, Rochester, USA, 2017.

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C. Stock, T. Siefke, U. Zeitner, et al.: Nano-optical quarter-wave plates for applications in the visible wavelength regime: fabrication, tolerances and in-situ process control, Technische Universität Ilmenau, Germany, 2017).

H. Gross: Optische Systeme mit Freiformflächen, PTB Braunschweig, Germany, 2017.

I. Staude: Mie-resonant semiconductor metasurfaces beyond wavefront control, Heriot-Watt-University, Edinburgh, UK, 2017.

I. Staude: Mie-resonant semiconductor nanostructures as a platform for functional nanophotonics, Leibniz Institute for Analytical Sciences (ISAS), Berlin, Germany, 2017.

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J. Rothhardt: Nanoscale Imaging and Spectroscopy with High-Photon-Flux Table-top XUV sources, Friedrich-Schiller-Universität Jena, Germany, 2017.

J. Rothhardt: Nanoscale Imaging with High-Photon-Flux Table-top XUV sources, Julius-Maximilians-Universität, Würzburg, Germany, 2017.

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K. Dietrich: Optical research on metallic and dielectric nanostructures (at the IAP), University of Science and Technology of China (USTC), Hefei, China, 2017.

R. Ackermann: Gasspektroskopie unter Hochdruck-/Hochtemperaturbedingungen, Friedrich-Schiller-Universität Jena, Germany, 2017.

Granted Patents

C. Reinlein, E. Beckert, T. Peschel

Adaptiver Spiegel und Verfahren zu dessen Herstellung

EP 2257844B1

C. Rothhardt, G. Kalkowski, M. Rohde, R. Eberhardt

Method for joining substrates

US 9,815,262 B2

J. Limpert, F. Röser, T. Eidam, C. Jauregui, A. Tünnermann

Einzelmodenpropagation in mikrostrukturierten optischen Fasern

EP 2406674B1

M. Beier, J. Hartung, C. Damm, S. Risse, B. Satzer

Verfahren und Vorrichtung zur Herstellung eines optischen Bauteils mit mindestens drei monolithisch angeordneten optischen Funktionsflächen und optisches Bauteil

DE 10 2015 120 853 B3

S. Nolte, G. Matthäus, K. Bergner

Verfahren und System zum Bearbeiten eines Objekts mit einem Laserstrahl

DE 10 2013 204 222 B4

Wolfgang Tiefensee, Jürgen Popp and Bodo Ramelow celebrate the inauguration of the laser technology center at the 25th anniversary of the Fraunhofer IOF.

ACTIVITIES

A key feature of the IAP is the active and engaged exchange of its employees within the scientific community. This commitment can be measured in both the participation at conferences and at cooperation in projects with other institutions. Such community projects are the fruits of compulsory networking and strengthen the reputation of the institute within the research society and industrial associations. Appreciation of these efforts are also the call-ups of particular scientists in committees and editorial positions of academically approved journals.

Beside this, more and more it is a concern to involve the public in the work we do. We want to attract people for our topics to show them the significance of research for daily life but also win interest of young persons and so to encourage young scientific talents.

Cherished traditions

With a royal visit, we started the new year: the Dutch royal couple, King Willem-Alexander and Queen Maximá, have been informed about the research in the fields of optics and microelectronics in Jena at 08th February – this is not an every day experience!

In 2017, we again organized a lot for the young generation: in February, we informed pupils from Erfurt about our research areas as part of their career orientation; in March we got into conversation with pupils from Jena during the faculty‘s "Tag der Physik". A special highlight was, of course, the children's lecture in May, in which over 400 elementary school kids from Hermsdorf cold feel the magic of physics, too.

In 2017, five high school students from Jena, Weimar and Gera tested scientific work at the laser marker as part of their student internship. Eggs, glass and aluminum were successfully structured. In September, the IAP traditionally informed the newly enrolled students about our offers - from teaching and supervision up to the career prospects. Shortly thereafter, a group of young Bashkirs visited us as part of the DAAD exchange program and were enthusiastic about our technical and structural equipment.

As part of the "Lange Nacht der Wissenschaften (LNdW)" on 24.11.17 about 1000 people catched up on our work. Just as exciting are our alumni, whom are traditionally presented with lectures and lab-tours about the latest research trends of our institutes IAP and IOF before the summer festival (16.06.). To inspire laypeople even more for photonics, the „Lichtwerkstatt“n opened the doors at the ACP.

At the end of August we had to farewell Dr. Ernst-Bernhard Kley as group leader, but fortunately he still stays with us part-time with his expertise at the IAP.

Events in 2017 (right): 1) The royal visit of the Duch. 2 - 3) Frank Schrempel and Silvana Fischer aka Harry Potter and Hermine Granger with help from Mr. Finch (Thomas Schott) and Dementor (Petra Richter) abduct the children into the world of physics with a lot of magical phenomena and fun! 4) Falk Eilenberger tries to take over the world with help of physics at LNdW. 5) Many visitors of the LNdW also were excited by our competition in laser beam guidance. 6) E.-B. Kley gives a lecture at the joint Alumni Day for IAP and FhG-IOF fellows 7) Prime Minister Bodo Ramelow is expounded the technique of the new fiber technology center. 8) Many pupils again at the "Tag der Physik" at our both with the Fraunhofer-IOF. 9) U. Zeitner and E.-B. Kley at their ceremonial handover of the working group leadership. 10) New students listen to the information and tips of our colleagues. 11) A. Tünnermann congratulates Holger Schmidt to his 25th service anniversary. 12) Bashkir students are fascinated by our research.


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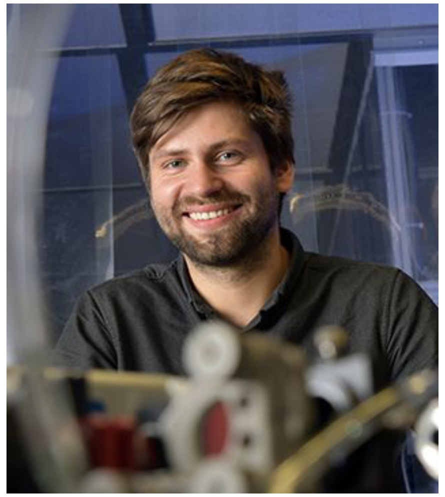
Awards



Martin Gebhardt at his work in the laboratory.

David Schmelz and a jury member during the awarding ceremony.

Justus Bohn
2nd Place Poster Award, Cumberland Lodge, UK
Complex Nanophotonics Science Camp
„Active spontaneous emission modulation by coupling to all-dielectric-metasurfaces embedded in a liquid crystal cell"

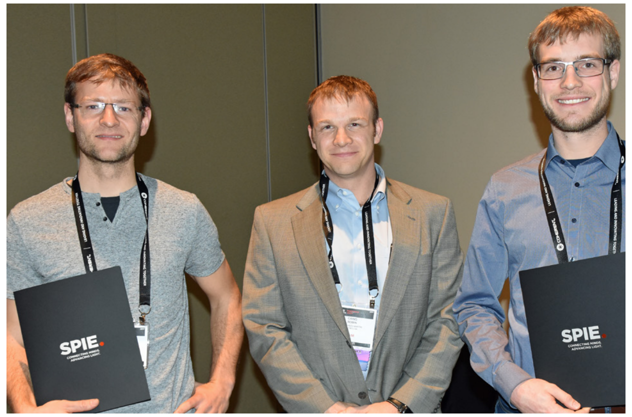
Martin Gebhardt
Best Overall Presentation,
OSA Laser Congress, Nagoya, Japan
Optical Society of America (OSA)
„Pulse refinement of a high-performance fiber laser system"

Thomas Gottschall
3rd Place Best Student Paper, San Francisco, USA
Photonics West „Fiber Lasers: Technology and Systems"
SPIE - The International Society for Optics and Photonics
„All-fiber widely tunable optical parametric oscillator laser system"

Arno Klenke
Dr.-Ing. Siegfried-Werth-Prize
Dr.-Ing. Siegfried Werth Stiftung
„Performance Scaling of laser amplifiers via coherent combination of ultrashort pulses"

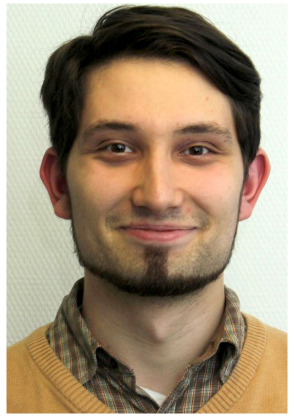
Michael Müller
2nd Place Best Student Oral Paper Competition, San Francisco, USA
Photonics West „Fiber Lasers: Technology and Systems"
SPIE - The International Society for Optics and Photonics
„2 mJ pulse energy 8-channel divided-pulse ultrafast fiber laser system"

David Schmelz
1st Place Best Master Thesis, Munich
LASER World of Photonics
Fraunhofer-Gesellschaft
& Special Award
Foundation for Technology, Innovation and Research Thuringia (STIFT)
„Conceptual design and realization of a diffuse light-coupling structure for Ge-on-Si image sensors"



Left to rigt: Thomas Gottschall, Stuart Jackson (Macquarie Univ.) and Michael Müller while the awarding ceremony at the Photonics West in San Francisco, 2017.

Justus Bohn



Jan Sperrhake

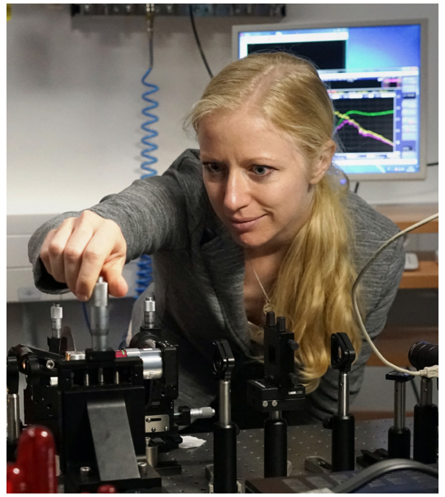
Arno Klenke received the Dr.-Ing. Siegfried-Werth-Prize at the Alumni-Day of the faculty, 9th of June 2017.

Johannes Stock is now working at the IAP research group "Optical System Design".

ACTIVITIES

Awards

Martin Steglich proudly presents his award in Munich.



Isabelle Staude at the ACP-lab.

Jan Sperrhake
Best Student Poster Award, Belgrade, Serbia
Photonica 2017
Optical Society of America (OSA)
„Analysis of layer interactions between stacked metasurfaces"

Isabelle Staude
Hertha Sponer Preis
Deutsche Physikalische Gesellschaft (DPG)
„Future-oriented contribution to basic research in nanophotonics“

Martin Steglich
2nd Place Best Dissertation, Munich
LASER World of Photonics
Fraunhofer-Gesellschaft
„Black Silicon with ICP-RIE and its applications in optics and opto-electronics“

Johannes Stock
Examination award for best master thesis of the Faculty of Physics and Astronomy (PAF)
Friedrich Schiller University Jena
"Investigations on freeform surfaces under real conditions“

Green Photonics award ceremony at the LASER World of Photonics in Münich.

Organizing Activities

Birgitta Schultze-Bernhardt

Member of Deutsche Physikalische Gesellschaft (DPG)

Alumna of the Alexander-von-Humboldt Foundation

Referee for the scientific journals: Nature Photonics, Optics Letters, Optics Express, Journal of Chemical Physics, Laser and Photonics Reviews

Herbert Gross

Referee of several scientific journals

Member of the program committe conference „European Optical Society Annual Meeting“

Member in the expert committee of the Baden-Würtemberg foundation of Optical Technologies

E.-Bernhard Kley

Referee for several scientific journals

Stefan Heist

Referee for several scientific journals

Jens Limpert

Member of the Program Committee SPIE Photonics West Conference "LASE 2017"

Referee for several scientific journals

Stefan Nolte

Vice Dean, Department of Physics and Astronomy

Member of the executive board of the Abbe School of Photonics

Chair of the Faculty´s Budget Commission and member of the Budget Board of the Senate

Scientific Coordinator for International Graduate Research School GRK 2101 (DFG)

Member of jury “Jugend forscht”

Member of several scientific committees (e.g. CLEO Europe, Phot. West, LiM)

Fellow of the Optical Society of America (OSA)

Member of SPIE, LIA

Member of Deutsche Physikalische Gesellschaft (DPG)

Referee for several scientific journals

Thomas Pertsch

Member of the board of directors of the Abbe Center of Photonics at the Friedrich Schiller University Jena

Spokesman of the Abbe School of Photonics at the Friedrich Schiller University Jena

Member of the board of trustees of the High Performance Center for Photonics of the Fraunhofer Society

Member of the board of directors of the Thuringian Innovation Center for Quantum Optics and Sensing

Spokesman of the research initiative "Photonic Nanomaterials PhoNa"

Member of the committee for the Esther Hoffman Beller Medal of the Optical Society of America

Coordinator of the study program "Master of Science in Photonics"

Local coordinator of Erasmus Mundus Program – NANOPHI – Nonlinear Nanophotonics

Fellow of the Optical Society of America (OSA)

Referee for several international journals

Jan Rothhardt

Member of the extended directory board of the Helmholtz Institute Jena

Member of the Program committee for CLEO Europe conference

Member of the Program committee for IEEE photonics conference

Member Optical Society of America (OSA)

Referee for Nature Photonics, Nature Communications, Optics Letters, Optics Express, J Phys B, Appl. Phys B, Applied Optics, European Physical Journal D

Lecturer on “LASERS” for high school students at the Gymnasium Leinefelde

Frank Schrempel

Coordinaton of the IAP at the Beutenberg Campus e.V

Referee for several scientific journals

Frank Setzpfandt

Referee for Physical Reviews A, Physical Review Letters, Nature Communications

organization of Spring School "Methods in modern photonics", Jena

BIrgitta Schultze-Bernhardt

- Referee for several scientific journals

Isabelle Staude

- Session Chair at SPIE Optics + Photonics 2017 (San Diego), ICCES Conference 2017 (Funchal), SPIE Photonics West 2017 (San Francisco)
- Reviewer for several scientific journals including Nature Materials, Nature Photonics, ACS Nano, Advanced Materials and Optica
- Member of Deutsche Physikalische Gesellschaft (DPG)
- Member of AcademiaNet
- Coordinator of the research association “Nano-Film” within the funding program “Photonik Plus” of the German Federal Ministry for Education and Research (BMBF)
- Hertha-Sponer Prize 2017 of the German Physical Society (DPG)

Adriana Szeghalmi

- Member of Deutsche Physikalische Gesellschaft (DPG)
- Member of the Optical Society of America (OSA)
- Reviewer for several scientific journals

Andreas Tünnermann

- Council member of the Faculty
- Council member of the TU Bergakademie Freiberg
- Member of program committee "Photonik", BMBF
- Chairman of the Technical Council Fraunhofer-Gesellschaft
- Member of the steering committee Fraunhofer-Gesellschaft
- Member of the VDI / VDE-GMA Advisory Board FB 8 "Optical Technologies of the Society for Measurement and Automation"
- Board of Trustees Leibinger Stiftung
- Board of Trustees MPA, Heidelberg
- Board of Trustees MPQ, Garching
- Board of Directors Helmholtz Institute, Jena
- Chairman "AG Naturwissenschaften", Wissenschaftliche Gesellschaft Lasertechnik e.V.
- Member of acatech "Deutsche Akademie der Technikwissenschaften"
- Fellow of SPIE International Society of Optics and Photonics
- Supervisory board member Jenoptik AG
- Stakeholder Photonics 21-Platform
- Director of the Abbe Center of Photonics at the Friedrich Schiller University Jena
- Spokesman of the DFG International Research Training Group GRK2101 "Guided light, tightly packed: novel concepts, components and applications"
- Spokesman of the Abbe School of Photonics at the Friedrich Schiller University Jena
- Spokesman of the Fraunhofer Innovation Cluster
- Spokesman of the BMBF Center for Innovation Competence ZIK “ultra optics”
- Spokesman of the BMBF Wachstumskern “Freeform optics plus fo+”
- Spokesman of the BMBF program Zwanzig20 “3Dsensation”
- Member of the Executive Board OptoNet e.V.
- Referee for several scientific journals
- Co-Editor Applied Physics B
- Editorial Advisory Board Lasers&Photonics Review
- Fellow of OSA – Optical Society of America
- Member of Technical Council committee Docter Optics

Frank Wyrowski

- Visiting Professor at the Chinese Academy of Science, China
- Visiting Professor at the Institute of Technology (HIT), China
- Conference Co-Chair: SPIE Workshop on Light Shaping
- Conference Co-Chair: SPIE Meeting on Computational Optics
- Conference Co-Chair: EOS Topical Meeting on Diffractive Optics
- Member of the Technical Program Committee SPIE Conference on Optics and Photonics for Information Processing
- Member of the Technical Program Committee SPIE Conference on Digital Optics for Immersive Displays
- Member of the Technical Program Committee OSA Conference on Digital Holography and 3D Imaging
- Referee for several scientific journals
- President of the LightTrans GmbH
- President of Wyrowski Photonics UG

Uwe D. Zeitner

- Referee for several scientific journals

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