Fraunhofer

IPM

FRAUNHOFER INSTITUTE FOR PHYSICAL MEASUREMENT TECHNIQUES IPM

2017 2018

ANNUAL REPORT

MEASURING · MONITORING · OPTIMIZING

<< Cover *Cameras and laser scanners record large structures such as roads or buildings. The 3D data are automatically analyzed using smart algorithms. Fused data from the camera and laser scanner are shown on the left side, while the resulting classified data are shown on the right. Each color represents a specific object class (e.g. vehicle or road surface).*

PRODUCTION CONTROL

OBJECT AND SHAPE DETECTION

GAS AND PROCESS TECHNOLOGY

THERMAL ENERGY CONVERTERS

»Machine learning spurs innovations in measurement technology«

< Prof Dr Karsten Buse,
Executive Director

Dear customers and partners,

Machine learning has triggered a surge in innovation and is constantly entering new fields of application. These days, smart algorithms are also employed in areas where they were initially often seen in a critical light, or even dismissed as »voodoo«, given that decisions derived from artificial neural networks are not consistently traceable. This attitude has changed completely. Machine learning reaches a high level of confidence, is becoming ever more widespread and is spurring developments in measurement technology. Since 2017, we have utilized the technology, particularly »deep learning«, with great success to recognize and classify objects in 3D point clouds. The systems are trained by means of humans inputting interpreted data records. This allows them to achieve extremely high levels of reliability, and the speed with which data can now be automatically interpreted has risen dramatically. The potential applications have burgeoned.

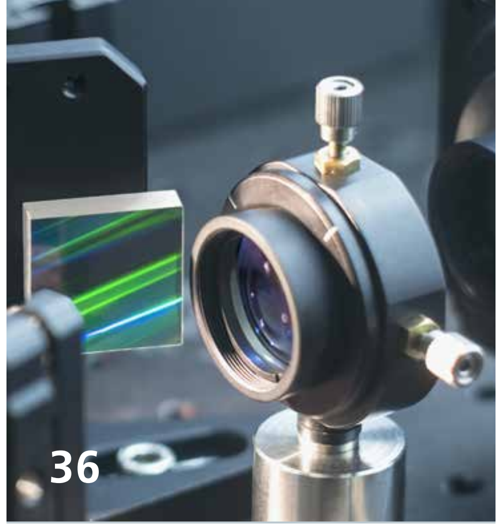
In addition to the fastest and most precise measurement systems, for which Fraunhofer IPM is globally renowned, we are now increasingly offering our clients automated data interpretation – right through to derived »yes« or »no« decisions for production control or safety technology. Alongside classic algorithms, machine learning has enormous potential in this field. In the coming years, this sub-section of artificial intelligence is set to cause many surprises and change the world. To give but two examples, learning cycles will likely allow machines to be trained for the quality control of new products simply and quickly in future; or it may become possible to connect multiple cheap gas sensors and train them to reliably »smell« a wide range of gases, something that is currently the preserve of expensive spectrometers and chromatographs. But even as data processing becomes increasingly important, it is of course the intrinsic quality of the measurements that remains the key factor in the vast majority of cases.

Our annual report gives details of new developments from the laboratories in our institute. We have selected a range of sample projects that invite you to reflect and question, less as a retrospective showcase and more as a basis for future ideas. Dive into the technical tricks and applications that made 2017 one of the best and most productive years, both professionally and financially speaking, in the history of Fraunhofer IPM. Amongst our achievements, we have succeeded in measuring surfaces with micrometer accuracy, even on steep edges – a prerequisite for high-precision optical gear measurement. We have also expanded our optical surface analytics to cover sheet metal lubrication inspection. With the aid of machine learning, our laser scanners help to survey large-scale construction sites, and by using two colors they are now able to »see« not only contours but also humidity, which is crucial when inspecting tunnels, for example. Semiconductor gas sensors are steadily becoming more reliable and have potential for use in monitoring food freshness, amongst other applications. Materials continue to play a major role, in terms of both the measuring of material properties and high-tech material applications. Examples include crystals for optical isolators in laser systems, thermoelectric materials used as energy harvesters to control small combustion plants, and caloric materials as a basis for novel, refrigerant-free, highly efficient heat pumps.

I very much hope you enjoy browsing these pages and discovering our innovations.

Yours,

Karsten Buse



CONTENTS

ORGANIZATION

MANAGEMENT

Executive Director
Prof Dr Karsten Buse
P +49 761 8857 - 111
karsten.buse@ipm.fraunhofer.de

Deputy Director
Dr Daniel Carl
P +49 761 8857 - 549
daniel.carl@ipm.fraunhofer.de

EXECUTIVE ASSISTANTS AND PUBLI C RELATIONS

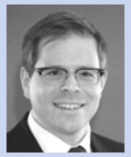
Science Management
Dr Rosita Sowade
P +49 761 8857 - 222
rosita.sowade@ipm.fraunhofer.de

Quality Management
Dr Arno Feißt
P +49 761 8857 - 288
arno.feisst@ipm.fraunhofer.de

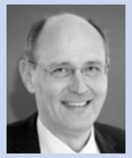
Communications and Media
Holger Kock
P +49 761 8857 - 129
holger.kock@ipm.fraunhofer.de

PRODUCTION CONTROL

Head of Department
Dr Daniel Carl
P +49 761 8857 - 549
daniel.carl@ipm.fraunhofer.de

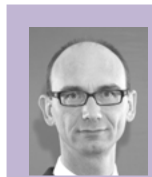


Inline Measurement Techniques
Dr Alexander Bertz
P +49 761 8857 - 362
alexander.bertz@ipm.fraunhofer.de



Optical Surface Analytics
Dr Albrecht Brandenburg
P +49 761 8857 - 306
albrecht.brandenburg@ipm.fraunhofer.de

OBJECT AND SHAPE DETECTION



Head of Department
Prof Dr Alexander Reiterer
P +49 761 8857 - 183
alexander.reiterer@ipm.fraunhofer.de

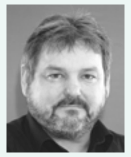
Laser Scanning
Prof Dr Alexander Reiterer
P +49 761 8857 - 183
alexander.reiterer@ipm.fraunhofer.de

GAS AND PROCESS TECHNOLOGY

Head of Department
Prof Dr Jürgen Wöllenstein
P +49 761 8857 - 134
juergen.woellenstein@ipm.fraunhofer.de

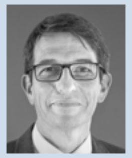
Integrated Sensor Systems
Dr Marie-Luise Bauersfeld
P +49 761 8857 - 290
marie-luise.bauersfeld@ipm.fraunhofer.de

Spectroscopy and Process Analytics
Dr Raimund Brunner
P +49 761 8857 - 310
raimund.brunner@ipm.fraunhofer.de

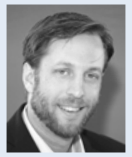


Thermal Measurement Techniques and Systems
Martin Jägle
P +49 761 8857 - 345
martin.jaegle@ipm.fraunhofer.de

THERMAL ENERGY CONVERTERS



Head of Department
Dr Olaf Schäfer-Welsen
P +49 761 8857 - 173
olaf.schaefer-welsen@ipm.fraunhofer.de

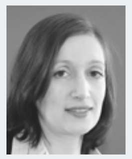


Calorics and Thermoelectrics
Dr Kilian Bartholomé
P +49 761 8857 - 238
kilian.bartholome@ipm.fraunhofer.de

TECHNICAL SERVICES

Head of Technical Services
Clemens Faller
P +49 761 8857 - 214
clemens.faller@ipm.fraunhofer.de

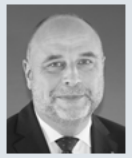
Mechanics und Construction
Thomas Hinrichs
P +49 761 8857 - 254
thomas.hinrichs@ipm.fraunhofer.de



Materials
Dr Karina Tarantik
P +49 761 8857 - 730
karina.tarantik@ipm.fraunhofer.de

Facility Management
Clemens Faller
P +49 761 8857 - 214
clemens.faller@ipm.fraunhofer.de

ADMINISTRATION AND IT



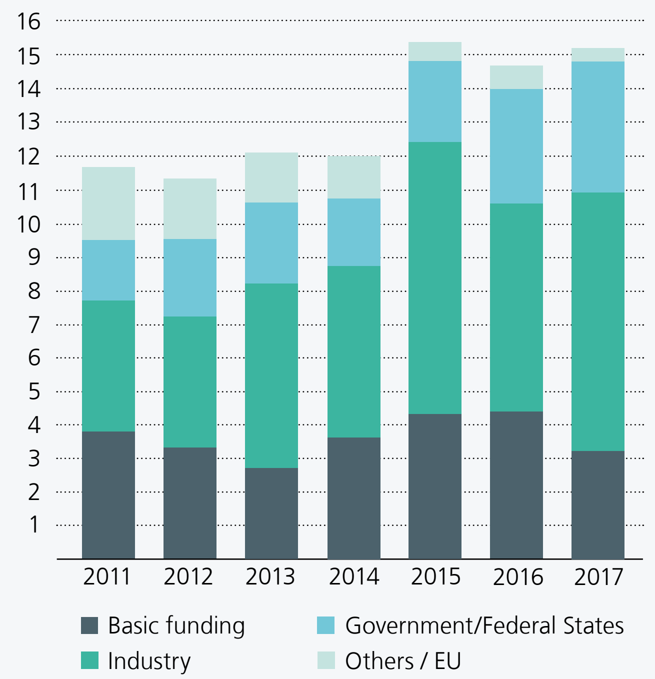
Head of Administration
Wolfgang Oesterling
P +49 761 8857 - 120
wolfgang.oesterling@ipm.fraunhofer.de

Administration
Sabine Gabele
P +49 761 8857 - 159
sabine.gabele@ipm.fraunhofer.de

Information and Communications Technology
Gerd Kühner
P +49 761 8857 - 226
gerd.kuehner@ipm.fraunhofer.de

Human Resources
Anneliese Macalister-Smith
P +49 761 8857 - 112
anneliese.macalister-smith@ipm.fraunhofer.de

Operating budget 2011 to 2017 in million euros*



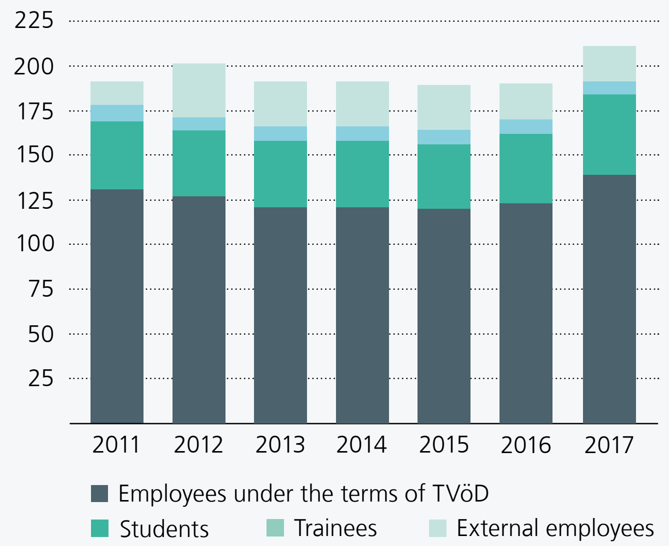
FIGURES

Operating budget

In 2017, the operating budget of Fraunhofer IPM was 15.2 million euros. The operating budget comprises industry revenues, revenues from publicly funded projects and basic funding. The proportion of external funds, consisting of external public funds and industry revenues, was 79 percent, or 12 million euros. Industry revenues made up 7.6 million euros or a 50.5 percent share of the operating budget.

** At the beginning of 2017, the »Materials Characterization and Testing« department at the Kaiserslautern site was assigned to another Fraunhofer institute. The values from the Kaiserslautern site have been retroactively removed from the diagrams for the years 2011 to 2016 for better comparability.*

Personnel development 2011 to 2017*



Personnel

In 2017, a total of 139 people were employed by Fraunhofer IPM under the terms of the Collective Agreement for the Public Service TVöD. In addition, approximately 55 students and young professionals work at the institute, of which 45 are undergraduate and graduate students and 7 are trainees. Fraunhofer IPM has around 20 external employees as well as a number of interns and assistants. Employees are spread across three basic areas: Approximately 50 percent of employees are scientific staff, 35 percent are engineers and technical staff and 15 percent are clerical staff in the fields of infrastructure and workshop.

> A time capsule containing two daily newspapers, euro coins, institute and building documents as well as parts of various measurement systems and other items were placed under the cornerstone.

CORNERSTONE LAID ON NEW CONSTRUCTION

After more than four years of planning, the cornerstone of the new main building was laid on July 4, 2017.
Participants at the ceremony included representatives of the state of Baden-Württemberg, the city of Freiburg, the University of Freiburg, the Fraunhofer-Gesellschaft and the lead architects as well as numerous employees of the institute. With usable floor space of 7500 m², the building offers employees considerably more room and better working conditions. The new location on the campus of the Faculty of Engineering strengthens the relationship with the University of Freiburg and creates an engaging environment for students, researchers and professionals. Costs for the new construction are estimated at 43.1 million euros. The German federal government and the state of Baden-Württemberg will each contribute 25 percent, and 50 percent will be funded by the European Regional Development Fund (ERDF). The state and federal governments will also each contribute an additional seven million euros in special funds for site preparation and basic equipment. The building is expected to be ready for occupancy in early 2020. The nearby Fraunhofer ISE will move into the institute's former main building.

OUR ADVISORY BOARD

In 2017 we welcomed six new members with expertise in research and industry to our advisory board, and four members resigned. The members of this expanded advisory board will bring new stimulus to the institute's strategic orientation and assist leadership.

Chairman
Dr Manfred Jagiella, Endress + Hauser Conducta GmbH & Co. KG

Members
Dr Lutz Aschke, TRUMPF Gruppe, Geschäftsbereich Lasertechnik

Prof Dr Frank Boochs, Hochschule Mainz, Fachbereich Geoinformatik & Vermessung

Dr Bernd Dallmann, Freiburg Wirtschaftsimmobilien GmbH & Co. KG

Dr Hans Eggers, Bundesministerium für Bildung und Forschung

Dr Jürgen Gieshoff, Umicore AG & Co. KG

Dr Ehrentraud Graw, Ministerium für Finanzen und Wirtschaft Baden-Württemberg

Dr Mathias Jonas, Internationale Hydrographische Organisation

Gerhard Kleinpeter, BMW AG

Prof Dr Gunther Neuhaus, Albert-Ludwigs-Universität Freiburg

Dr Volker Nussbaumer, Deutsche Telekom AG

Dr Stefan Raible, AMS Business Line Environmental Sensors

Prof Dr Michael Totzeck, Carl Zeiss AG

Prof Dr Ulrike Wallrabe, Institut für Mikrosystemtechnik IMTEK, Albert-Ludwigs-Universität Freiburg

> SOLAR is the longest running research mission on the international space station.

PROFESSORSHIPS AT THE UNIVERSITY OF FREIBURG

Fraunhofer IPM maintaines connections with the Albert-Ludwigs-Universität Freiburg in the form of two associated professorships in the Department of Microsystems Engineering (IMTEK). In April 2017, Dr Alexander Reiterer assumed the professorship for »Monitoring of large-scale structures« in the Department of Sustainable Systems Engineering (INATECH), which was newly established by Fraunhofer IPM and the University of Freiburg. Research carried out at the university is transferred to industrial application in cooperation with Fraunhofer IPM.

DEPARTMENT OF MICROSYSTEMS ENGINEERING – IMTEK

Professorship for Optical Systems
Prof Dr Karsten Buse

Research foci include nonlinear optical materials and optical resonators. Miniaturization of tunable laser light sources and frequency converters, which are tunable from the ultraviolet to mid infrared spectral range, is one objectives. The opportunity to specialize in »photonics«, which was initiated in collaboration with other optics professors, has been integrated into the curriculum of the master's program in microsystems engineering.

Professorship for Gas Sensors
Prof Dr Jürgen Wöllenstein

Gas-sensitive materials, sensors and sensor systems are being developed under the auspices of this professorship, with research centering on miniaturized, energy-saving gas measurement systems. One area of focus is the development of cost-efficient, energy-saving sensors based on microsystems technology.

DEPARTMENT OF SUBSTAINABLE SYSTEMS ENGINEERING – INATECH

Professorship for Monitoring Large-Scale Structures
Prof Dr Alexander Reiterer

Research foci include the inspection and monitoring of artificial and natural objects such as civil engineering structures, landslide-prone slopes or extensive areas of vegetation. In support of this work, innovative sensor concepts are being developed and implemented. Research activities include strategies for analyzing and interpreting data, including linkages to influence parameters, causative forces and changes measured, as well as the development and implementation of complete system chains – from data acquisition to data evaluation.

SOLACES: NINE YEARS ON THE ISS

Developed by Fraunhofer IPM, the solar spectrometer SolACES delivered solar activity data from the International Space Station for nine years.
A component of the research mission known as SOLAR, which concluded in 2017, the experiment was deactivated in a ceremony at B.USOC, the Belgian User Support and Operations Center in Brussels on Feb. 15, 2017. SolACES was deployed to measure extreme ultraviolet radiation (EUV), which is absorbed by the atmosphere and cannot be measured from the Earth's surface. Its high measuring accuracy was decisive in the decision by the European Space Agency (ESA) to extend the life of the experiment twice for a total of nine years' running time. Data collected by SolACES are used in calculations of advanced climate models. EUV radiation has a direct correlation with solar activity and enables scientists to draw conclusions about the effects of solar energy input on our climate.

SUCCESS IN ACQUIRING INDUSTRIAL CUSTOMERS ...

Fraunhofer IPM received Fraunhofer-Gesellschaft's internal »Customer Acquisition of the Month« award not just once, but three times in 2017.
The monthly award is presented for the highest value contract from the business community. In February a manufacturer of exhaust gas measurement systems awarded Dr Raimund Brunner's »Spectroscopy and Process Analytics« group a contract valued at over 526,000 euros. In October the Laser Scanning team, under the direction of Professor Alexander Reiterer, received the award for a nearly 1.3 million euro contract to develop railway measurement systems for Netherlands-based EURAILSCOUT Inspection and Analysis B.V. The following month a telecommunications firm commissioned the same group to develop analytic software for 3D measurement data in a contract valued at roughly 1.47 million euros. It was the institute's first pure software development contract. Contracts with industry make up a significant share of the Fraunhofer-Gesellschaft's funds. In 2017, Fraunhofer IPM received industry orders from private enterprises amounting to approximately 7.6 million euros.

... AND PUBLICLY SPONSORED PROJECTS

2017 saw the launch of five new projects funded by the German government and the Fraunhofer-Gesellschaft. Each is worth more than one million euros.
Within the TOXIG project funded by the Fraunhofer-Gesellschaft, Fraunhofer IPM is working with other Fraunhofer institutes to develop a toxic gas detection system based on the principle of color change. In a second project, the Fraunhofer-Gesellschaft is investing 1.3 million euros in the development of an optical measurement technique that will measure the geometry and surface structure of semi-finished products in free fall. The institute also submitted two successful applications for lighthouse projects, in which the Fraunhofer-Gesellschaft is funding cross-institute research on strategically important topics. The eHarsh project is creating a technology platform for particularly robust sensor systems, whilst QUILT is pooling the expertise of six institutes to allow new findings in quantum technology to be utilized for quantum imaging. Finally, in the MagMed project funded by the German Federal Ministry for Economic Affairs and Energy (BMWi), scientists are working together with Forschungszentrum Jülich to develop refrigerant-free cooling technology.

> Research for the future: Freiburg's five Fraunhofer institutes chose this android to illustrate their invitation for the Industry Week Baden-Württemberg 2017.

GAS SENSOR WORKSHOP: NEW APPLICATIONS FOR GAS SENSORS

Nearly one hundred experts convened at Fraunhofer IPM on March 16, 2017 to discuss future applications and trends in gas sensors technology.
Will the smartphones or clothing of tomorrow have gas sensors? What are the requirements for gas sensors under the new international exhaust gas testing standards? Questions like these were on the agenda at the institute's seventh Gas Sensor Workshop.
Expert talks covered a range of topics from complex spectroscopy systems designed for industrial process analytics to miniaturized gas sensors for everyday use in the home. The workshop has established itself as the gathering place of the gas sensor community. It takes places every two years, and the next one is scheduled for March 14th, 2019.

Companies demonstrate new sensors and systems at the exhibition.

GASSENSOR WORKSHOP

CALORIC SYSTEMS WORKSHOP: NEW TECHNOLOGIES FOR REFRIGERATION

Keen interest in alternative cooling technology: Tobias Hess demonstrates a caloric cooling circuit.

Fraunhofer IPM organized the first »Caloric Systems Workshop – Solid-State Cooling and Heating« on March 28, 2017 together with the German Society of Refrigeration and Air Conditioning (DKV).
Almost 80 participants from research and industry came to Freiburg to discuss the opportunities and technical challenges presented by heat pumps based on caloric materials. Solid-state cooling systems are seen as a promising alternative for future air conditioning and refrigeration technology. Advances in the development of magneto-, elasto- and electrocaloric materials are bringing the construction of such cooling systems within reach. They are efficient, quiet and operate without the use of refrigerants, which are harmful to health and the environment. Fraunhofer IPM presented an elastocaloric heat pump and a heat pipe concept for efficient heat dissipation in caloric cooling circuits at the workshop.

KALORIK WORKSHOP

LASER SPECTROSCOPY WORKSHOP

Trends in laser spectroscopy were the focus of an eponymous workshop organized by Fraunhofer IPM on November 28, 2017.
Over 50 participants discussed innovations in laser light sources and potential new applications for laser-based spectrometers. Scientific speakers presented advances in interband cascade lasers (ICL), optical parametric oscillators (OPO), quantum cascade lasers (QCL) and frequency combs. These lay the foundations for being able to determine the composition of gases and liquids with greater sensitivity and precision. Quantum sensor technology promises to facilitate another leap forward in the sensitivity of laser spectroscopy measuring techniques. New applications were also presented by industry representatives, for example in medical diagnostics.
At the workshop, Fraunhofer IPM also took the opportunity to bid farewell to a longstanding employee entering retirement: Dr Armin Lambrecht had worked for the institute in various roles for over 30 years. As head of today's »Gas and Process Technology« department, as well as its predecessor departments, he made a major contribution to driving forward work in the field of laser spectroscopy.

INDUSTRY MEETS RESEARCH

What can research do for local business? Scientists and company representatives reported on their joint projects.

INDUSTRIE WOCHE BW 2017 mitmachen, erleben

Freiburg's five Fraunhofer institutes were represented as research partners for industry at two events during Industry Week Baden-Württemberg.
As part of an industry forum for invited guests, the Fraunhofer representatives together with their respective industrial partners demonstrated what research can offer local business, using actual projects as case studies. The Sparkasse Freiburg provided the Meckelhalle in the city center for the evening event on June 21, 2017. One day later in the same space, an interactive installation open to the public demonstrated the role that applied research plays in our daily routine: On display were such things as a model of an automobile crash-test equipment, a system for monitoring drinking water, innovative cooling technology and liquid crystal lubricants. Roughly 120 students from local secondary schools participated in the various guided tours. Industry Week Baden-Württemberg was initiated by the Ministry of Economics, Employment and Housing. It took place throughout the state for the first time from June 19–25, 2017. Events and initiatives from the business world, public institutes and associations were on the program. Sparkasse Freiburg and IHK Südlicher Oberrhein (the Southern Upper Rhine Chamber of Commerce) were partners of the Fraunhofer event.

> Fraunhofer President Professor Reimund Neugebauer (2nd f. r.) congratulates prize winners Dr Markus Fratz (left), Dr Alexander Bertz (2nd f. l.) and Dr Tobias Beckmann (right) on the award.

SCHOOL MEETS RESEARCH

Fraunhofer IPM regularly offers secondary school students the opportunity to look behind the scenes of a research institute.
For the 17th time, the institute participated in the nationwide Girls' Day event. Employees from different departments dedicated an entire day to sparking the twelve girls' interest in technical subjects. Under the umbrella of two internship programs directed at secondary school students, a group of around 15 boys and girls spent one week each in the institute's labs and workshops in 2017. They were mentored by PhD candidates. »The internship gave me far more than just new and exciting knowledge,« wrote one of the participants in her final report. »It gave me a glimpse of a possible future career.«

Supporting the next generation: students experiment with clean room techniques.

CAN YOU BUILD LIGHT SABERS?

Hands-on: Sensor spheres for use in emergency scenarios. The children recorded their impressions in a hand-made book that was presented as a thank you to Executive Director Professor Karsten Buse.

Seventeen students at the Wittnau primary school visited the institute in October 2017 as part of a newspaper project – and posed many inquisitive questions.
The third and fourth grade students were investigating the institute as young journalists for the Badische Zeitung newspaper. There were plenty of things to see in the labs: The view through a scanning electron microscope showed a housefly's eye and a butterfly's wing in impressive magnification. In the workshop, the children were able to see how a milling machine uses a computer model to produce a component. In the gas lab, Dr Carolin Pannek demonstrated how introducing particular gases can make a liquid change color. The Laser Scanning team presented what is presumably Freiburg's longest aquarium, where underwater scanners are tested. Dr Markus Leidinger demonstrated how quickly and accurately 3D shapes can be surveyed by measuring a few of the visitors with a laser scanner. Thanks to Star Wars, the lasers held a particular appeal for the children: In the laser lab, the students marveled at laser light in different colors. Unfortunately, the request for the light saber had to be denied.

FRAUNHOFER PRIZE FOR INLINE DIGITAL HOLOGRAPHY

A Fraunhofer IPM team has been awarded the Joseph-von-Fraunhofer Prize for developing a digital holography measurement system for component inspection.
The measurement system developed by Dr Alexander Bertz, Dr Tobias Beckmann and Dr Markus Fratz maps component surfaces and microdefects during production. Here, the researchers employ an ultra-precise 3D measuring method: multiwavelength digital holography. Until now, this technique has been too slow and vibration-sensitive to be used in industrial production. The scientists have succeeded, however, in making digital holography suitable for industrial use. In contrast to conventional digital holography systems, which employ a single laser wavelength for interferometric measurements, the system developed by Fraunhofer IPM computes the results from a series images acquired at various wavelengths. Calculation steps are paralleled for the evaluation such that they utilize the full potential of a high-end graphics card. This makes the system so fast that objects can be accurately measured to the micrometer within a fraction of a second. As a result, full inline component inspection with micrometer precision is possible for the first time. The system is the fastest of its kind worldwide for performing ultra-precise instantaneous topography measurements. It was developed for a medium-sized automotive supplier.

»BLECHEXPO AWARD«

Fraunhofer IPM and Raziol Zibulla & Sohn GmbH have received the »Blechexpo 2017 Award« for an imaging inline measurement system for sheet metal lubrication.
For the first time, a fluorescence scanner developed at the institute is able to produce images showing lubrication across the entire surface area of metal sheets directly within the production process. To do this, a UV laser scans the sheet metal surface point-by-point, whereby the laser light is moved across the full sheet width, perpendicular to the feed direction, with the help of a polygon mirror. Most lubricants employed in sheet metal working exhibit strong fluorescence under UV light. A spectral evaluation of the fluorescence signals provides information on the thickness and homogeneity of oil films and generates high-contrast measurement images. Together with industrial partner Raziol, Fraunhofer IPM has integrated the measurement system into spray systems for sheet metal lubrication. The precise dosing and comprehensive application of thin oil films play an important role in forming and in protecting metal sheets again corrosion. This system enables 100% quality control and true process control in sheet lubrication.

The innovation prize was presented at the Blechexpo specialist trade show. Pictured here are Dr Albrecht Brandenburg (back row, right) and Dipl-Ing Philipp Holz (front row, left) who developed the system.

> Stephan Fetzner: »It quickly became clear to me that we were on to something special!«

>> »We're also seeing the market trend towards smaller devices in the area of stationary vehicle test benches,« says Fetzner. »Clients are looking for compact solutions here, too.«

»The devil is always in the detail«

Fraunhofer IPM is commissioned by AVL Emission Test Systems GmbH to design exhaust gas measurement systems for use during engine development. The work focuses specifically on the measurement of nitrous oxide. The two partners have been running development projects together for over eight years, and during this time have also branched out into the fields of trend analysis and technological forecasting. Stephan Fetzner leads the team in charge of developing device control and analytics systems at AVL Emission Test Systems GmbH in Gaggenau, Germany.

Mr. Fetzner, what does AVL ETS do exactly?
At our site in Gaggenau, we develop and produce exhaust gas measurement systems for use during engine development. Our SESAM measurement systems measure all important exhaust gas components in raw exhaust gas. One of our particular areas of focus here is the development of laughing gas measurement systems using quantum cascade lasers (QCL). These are relatively new systems, which we have launched on the market together with Fraunhofer IPM.

How did you come to work with Fraunhofer IPM?
Looking back, this marked the start of a successful journey for us. We had already worked with Fraunhofer IPM on a few smaller projects looking at hydrogen sensors. Then, in mid-2010, we were looking for a suitable partner to help us with the highly precise detection of laughing gas using laser spectroscopy. We were won over by Fraunhofer IPM's expertise in this new technology.

What expectations did you have at the start?
At the time, the technology we required was still very much in its infancy. We set ourselves the task of achieving a detection limit for laughing gas of less than 10 ppb with no cross sensitivity to other exhaust gas components. The first question we had to ask ourselves was whether this was even feasible. We wanted to find this out as quickly as possible, so the initial measurement system we developed was a simple, crudely designed tube with a laser and detector; each component was controlled separately and had its own display, power supply and lots of cables. Today's system looks very different, of course. It is not only fully integrated into its own industrial-grade housing, but also has its own integrated data interpretation and data interface. Nevertheless, on seeing how the very first design put together by Fraunhofer IPM immediately met our specifications, it quickly became clear to me that we were on to something special!

What have you come to appreciate the most about your working relationship with Fraunhofer IPM?
The specialist knowledge of Fraunhofer's staff. Their considerable expertise in laser spectroscopy has proved invaluable in helping us to develop a device that has never suffered from any serious teething problems. In fact, the measuring devices have lived up to our expectations from day one.

How important was Gaggenau's proximity to Freiburg?
The proximity proved very helpful whenever a prototype had to be delivered to us or we had to transport one of our systems to Freiburg. It also meant that we could try out ideas in the lab on the spur of the moment. It was extremely convenient that both sides were able to respond quickly and flexibly at all times. After all, when developing new products, the devil is always in the detail.

AVL EMISSION TEST SYSTEMS GMBH is a subsidiary of AVL List GmbH, the world's largest independent company for the development, simulation and testing of powertrain systems for passenger cars, commercial vehicles and large engines. AVL Emission Test Systems GmbH develops and manufactures gas analysis, measurement and automation systems for identifying engine and vehicle exhaust gases and evaporative emissions. The company has facilities in Neuss and Gaggenau in Germany, Graz in Austria and Plymouth in England. At the Gaggenau site, AVL Emission Test Systems GmbH employs around 110 people.

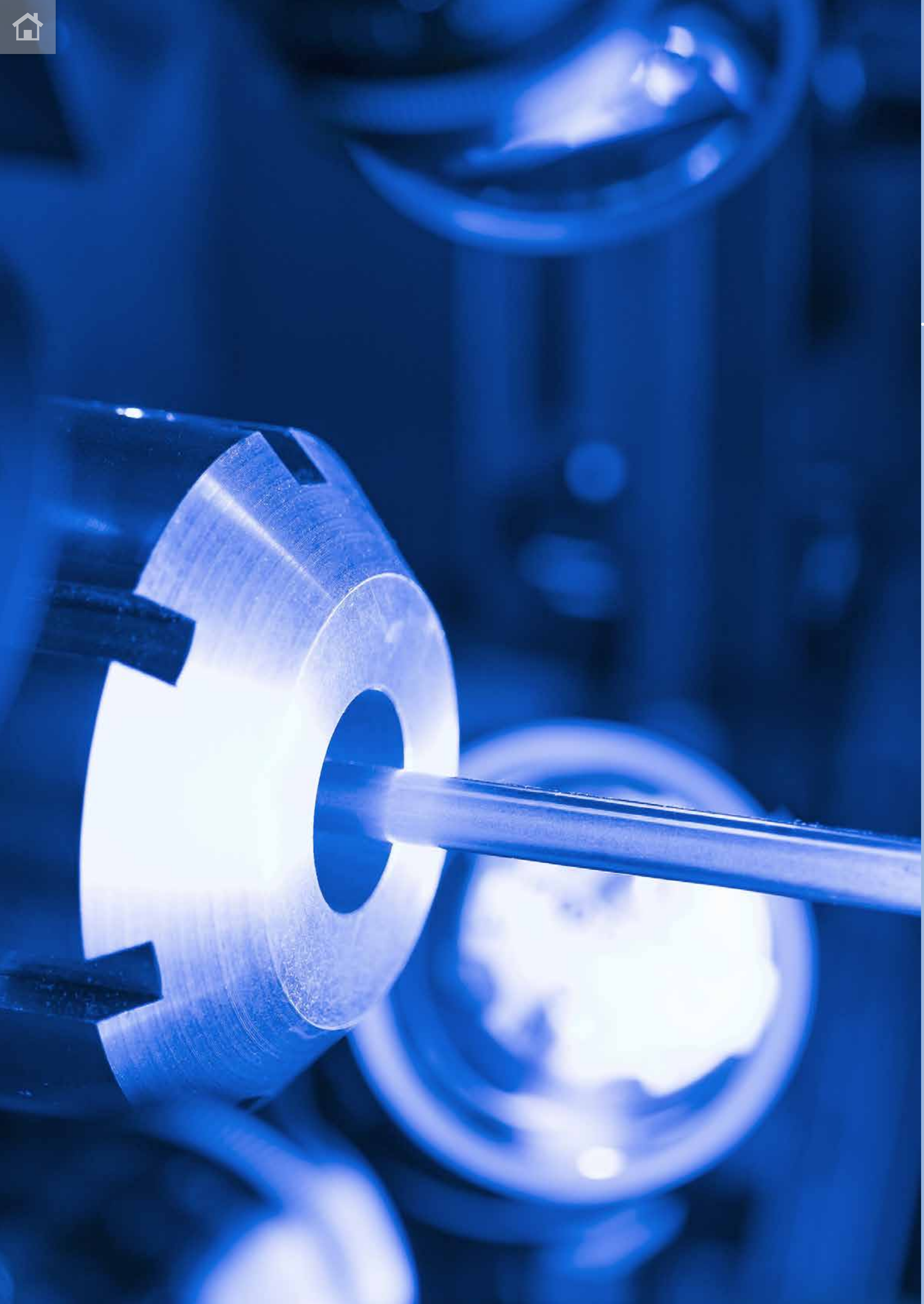
Has your work with Fraunhofer IPM helped AVL ETS to tap new markets?
It was actually lawmakers who created a new potential market for us by regulating laughing gas emissions. However, we hadn't developed any satisfactory solutions in this area and the competition was a step ahead of us. By joining forces with Fraunhofer IPM, we were quickly able to bridge this gap in our portfolio. It was important to us to stay up to date with all the necessary know-how ourselves, so that we could respond promptly to our clients' requests. And that is exactly what we have achieved.

What does the future hold for your industry?
There is a strong market trend towards mobile devices. Our clients are demanding smaller and smaller devices that minimize energy consumption and, wherever possible, operate without the need for calibration. The key concept here is »real drive emission«. We're also seeing this trend towards miniaturization in the area of stationary test benches. Clients are looking for compact solutions here too. This means we have to achieve the same levels of performance, e.g. in terms of response times, with less sample gas.

Test benches for use during engine development provide important insights that help make combustion engines even more efficient.

When does working with an external research partner prove worthwhile?
It's always worthwhile when you're looking to launch a new technology on to the market relatively quickly. If we'd worked alone, we would have needed to do a lot of preparation work to get up to speed with everything. This would have taken us years. Joining forces with a research partner allowed us to pool knowledge and resources. For example, our areas of expertise in measurement techniques, batch production, electronics and software development complement each other perfectly. Our cooperation also generated a number of patents for devices, which are now employed in measuring systems all over the world. We also always engage in very open discussions with each other. Even our managers meet annually to talk over new technologies and ideas as well as to consider future opportunities. Over the years this has resulted in a fruitful partnership based on a strong foundation of trust.

Thank you very much for talking to us!



BUSINESS UNIT **PRODUCTION CONTROL**

»We bring measurement techniques from the laboratory into production«

For production control, Fraunhofer IPM develops optical systems and imaging methods which can be used to analyze surfaces and 3D structures in production and to control processes. The systems measure fast and accurately so that small defects or impurities can be detected, even at high production speeds. This means that 100 percent production control in real-time is possible against the backdrop of the fourth industrial revolution.

A wide range of methods is used, including digital holography, infrared reflection spectroscopy and fluorescence methods, with fast, low-level image and data processing. The systems are used in applications such as forming technology in the automotive industry and for quality control in medical products.

Group Inline Measurement Techniques

- Surface inspection
- Shape measurements
- Marker-free component identification

Group Optical Surface Analytics

- Purity control and coating inspection
- Inline microscopy
- Laser-induced breakdown spectroscopy

CONTACT

Dr Daniel Carl
Head of Department
P +49 761 8857 - 549
daniel.carl@
ipm.fraunhofer.de

< An optical measurement system detects micron defects on wire surfaces during production.

GROUP **INLINE MEASUREMENT TECHNIQUES**

Dr Alexander Bertz, P +49 761 8857 - 362, alexander.bertz@ipm.fraunhofer.de

The main focus of this group is on 2D and 3D measuring systems for industry. These systems supply high precision measurements in real-time and under hardest production conditions, for example for controlling sensitive production processes. This is achieved by a combination of optical measuring techniques with extremely fast data processing.

EXPERTISE

Real-time inspection systems with customized image processing | Robust holographic 3D sensors for measurement with sub-micron precision | Algorithms for evaluating microscopic surface structures

APPLICATIONS

Customer-specific systems monitor and control the quality of components with complex geometries | Holographic systems measure gear geometries in line, precisely and non-contact | Optical readers identify single components without additional markers

SPECIFICATIONS

AUTOMATED VISUAL CONTROL

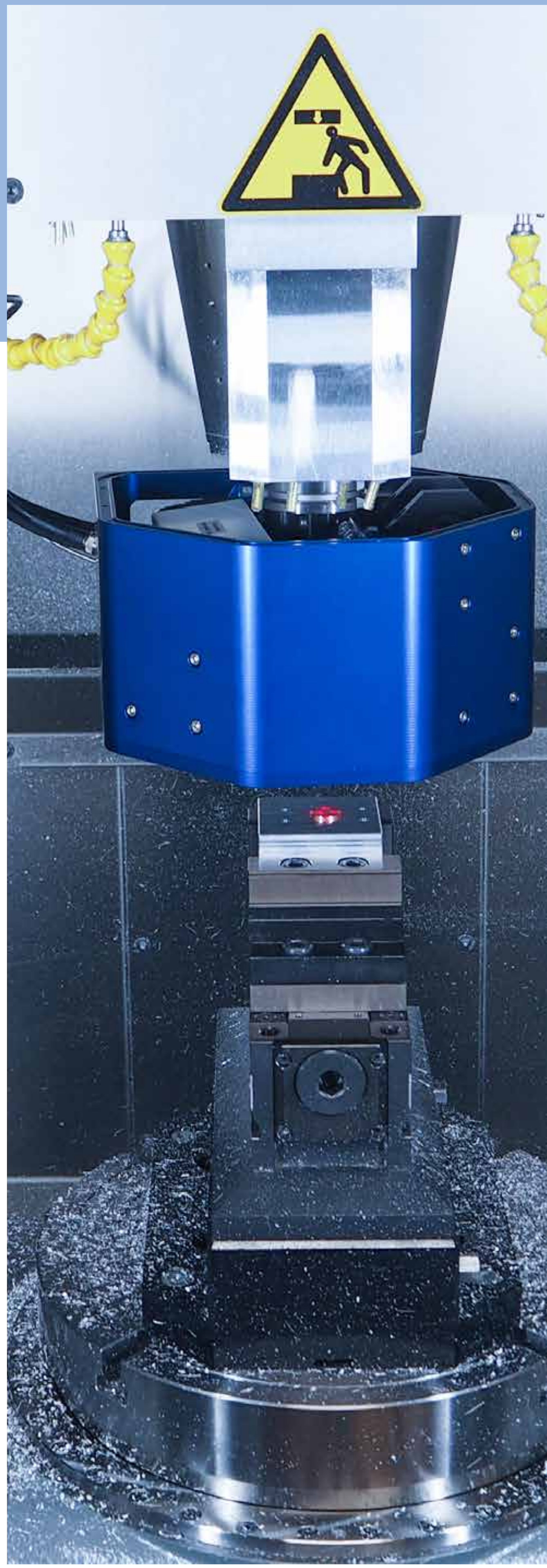
- 100 percent inline surface monitoring of wire at feeding rates of 30 m per second
- Complete quality check of die-cast parts and forged parts with complex geometries
- Customized systems for harsh production environments
- Inline geometry and surface detection

SHAPE MEASUREMENTS

- highly precise measurement of functional surfaces in the production line or in machine tools
- 100 million 3D measurement points per second
- Working distance of up to 300 mm feasible
- Measuring fields of 30 × 30 mm²
- Absolute height precision (< 1 µm)
- Lateral resolution (< 10 µm)

MARKER-FREE COMPONENT IDENTIFICATION

- No need for additional markers
- Robust against local damage and contamination
- Reliable identification of components in large batches
- Short read-out time (< 100 ms)
- Identification at production speed (< 500 ms)



>> HoloCut, a digital holographic sensor system, inspects component surfaces directly in the machine tool.

< A new linear holographic sensor can record the 3D surface information of a moving metal cylinder. It is already possible for displacements of up to one centimeter per second to occur without damaging the interferometric measurements.

SPONSORED BY THE FEDERAL MINISTRY OF EDUCATION AND RESEARCH
Funding Code: 13N14009
Joined project: Dynamic holographic measurement technique for measuring metallic free-formed surfaces (HoloMotion)

Federal Ministry of Education and Research

GROUP **INLINE MEASUREMENT TECHNIQUES**

Holography in motion: 3D data line by line

In recent years, Fraunhofer IPM has been successful in establishing an extremely fast, micrometer-accurate inline 3D measurement technique – namely, digital holography – in the industrial sector. To date, this technique has required test specimens to be stationary. Now, however, Fraunhofer IPM has demonstrated for the first time that holographic mapping can also be performed on moving surfaces – with the help of a linear sensor.

Fraunhofer IPM has made significant advances in extensive, micrometer-accurate surface measurement in recent years. The HoloTop and HoloCut system families are already used today to measure 3D test specimen surfaces in production lines or directly in machine tools. The measurement technique underpinning these systems is multiwavelength digital holography. Here, a computer utilizes several narrow-band lasers to generate a range of synthetic wavelengths for the measurements. This opens up a wide potential measurement spectrum which, depending on the roughness of the surface, can extend from the (sub)micrometer to the millimeter range. In order for measurements to be successful, however, the sensor and measured part must remain completely still for a tenth of a second. Even minuscule relative movements of ten nanometers during mapping would adversely affect the measurements.

Dynamic measuring – line by line

But what happens if production conditions prevent even these short stoppages? For example, if the test specimen is continuously in motion, and the handling required to capture still measurements would take up too much time? In theory, it should not be possible to use interferometric measurement techniques such as holography in these cases. But a new, patented approach developed by Fraunhofer IPM has recently proven that this is not so. Three factors are critical here: The choice of shutter, 3D reconstruction from a single hologram, and the object's direction of movement. On this basis, Fraunhofer IPM has been able to create the first holographic sensor that can reconstruct a moving object's surface line by line (Fig. above). 3D data for the entire surface structure are generated by using the computer to superimpose the individual lines (Fig. right). Displacements of a centimeter per second no longer pose a problem for the new sensor. This is revolutionary, and will soon open up many new applications for multiwavelength digital holography. Researchers at Fraunhofer IPM now want to increase the measuring speeds even further, which will allow equally precise 3D data to be recorded at even higher object speeds in the future.

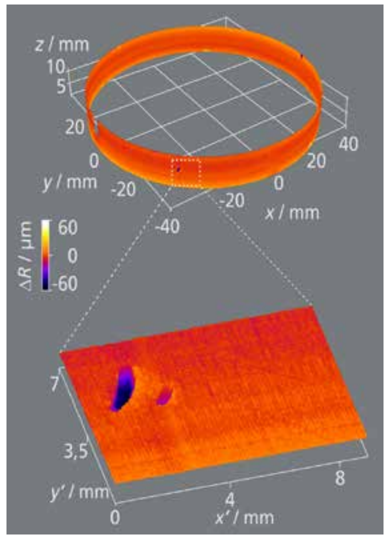
Multiwavelength holography

As indicated above, the new linear holographic sensors are also based on the principle of multiwavelength digital holography. In contrast to classic interferometry or holography with just a single laser wavelength, multiwavelength holography can also be used to map optically rough surfaces. The speckle noise generated on rough surfaces, which normally makes it impossible to use quantitative phase evaluation for determining topography, is eliminated thanks to numerical reconstruction at different wavelengths. This process creates a phase map at the beat frequency of the individual wavelengths, which contains the information on the topography of the illuminated object. The CPU-intensive digital holographic reconstruction of the complex-valued wave fields, in which the test specimen topography is stored, is performed on modern graphics cards and has been accelerated by several orders of magnitude in recent years. 3D sensors in the HoloTop product family developed by Fraunhofer IPM evaluate more than 100 million 3D measurement points per second, making them unrivalled in their precision and speed.

In **DIGITAL HOLOGRAPHY**, the phase information in the light is recorded in addition to the spatial intensity distribution of the light that is usually recorded photographically. A coherent light source – typically a laser – is required in order to do this. When the surface of a test specimen is illuminated using laser light, its shape is stored in the phase distribution of the backscattered light wave. Using interferometric recording and subsequent digital reconstruction, this information is made accessible and can be used to perform three-dimensional measurements of surfaces. The fundamental principle underlying holography dates back to an invention designed by Dennis Gabor in 1948, for which he was awarded the Nobel Prize in Physics in 1971.

New applications for holography

The combination of extreme accuracy, coaxial measuring ability and robustness against motion will open up many new applications for the new holographic sensor that are currently either impossible or very expensive. These include, for instance, 100 percent 3D micro-defect controls on continuous products, highly accurate inspection of die cast part geometry, and precise gear measurement. The latter is doubtless the most demanding task: Depending on the inclination angle and surface topography, even static optical measurements of metal gear teeth are extremely challenging. But if the new sensor makes it possible to comprehensively map gear wheel edges during rotation via holography, this would revolutionize gear measurement. This type of measurement system would have no competition on the market.



The 3D surface of the metal cylinder was mapped line by line whilst it was in motion (Figure p. 22). Deviation in height from the predetermined cylinder shape is measured with micrometer precision – even the smallest tool marks and defects are detected.

Dr Alexander Bertz, P +49 761 8857-362, alexander.bertz@ipm.fraunhofer.de

GROUP **OPTICAL SURFACE ANALYTICS**

Dr Albrecht Brandenburg, P +49 761 8857-306, albrecht.brandenburg@ipm.fraunhofer.de

The main focus of this group is the development of turnkey devices for surface analysis. These devices use fluorescence measurement techniques as well as infrared reflection spectroscopy and laser-induced breakdown spectroscopy. Fraunhofer IPM's long-standing experience in systems engineering encompasses optical units, image recording and image processing.

EXPERTISE

Fast, spatially resolved fluorescence measurement techniques with customer-specific lighting systems | Laser-induced breakdown spectroscopy | Inline microscopy systems with control units and data evaluation | Shortwave-infrared analysis: harnessing spectral dependence of absorption and scattering properties for materials analysis | Analysis of biochemical reactions with the help of fluorescence markers

APPLICATIONS

Inline purity control, revealing impurities on component surfaces | Detection of surface defects and surface coatings | Comprehensive oil film measurement of strip ware or complex 3D free-form components during production | Authenticity check by analyzing fluorescent pigments | Microscopy at production speed, e.g. 100 percent quality control of key components in medical devices | Substance-specific identification of materials on surfaces | In-vitro diagnostic systems

SPECIFICATIONS

PURITY CONTROL AND COATING INSPECTION

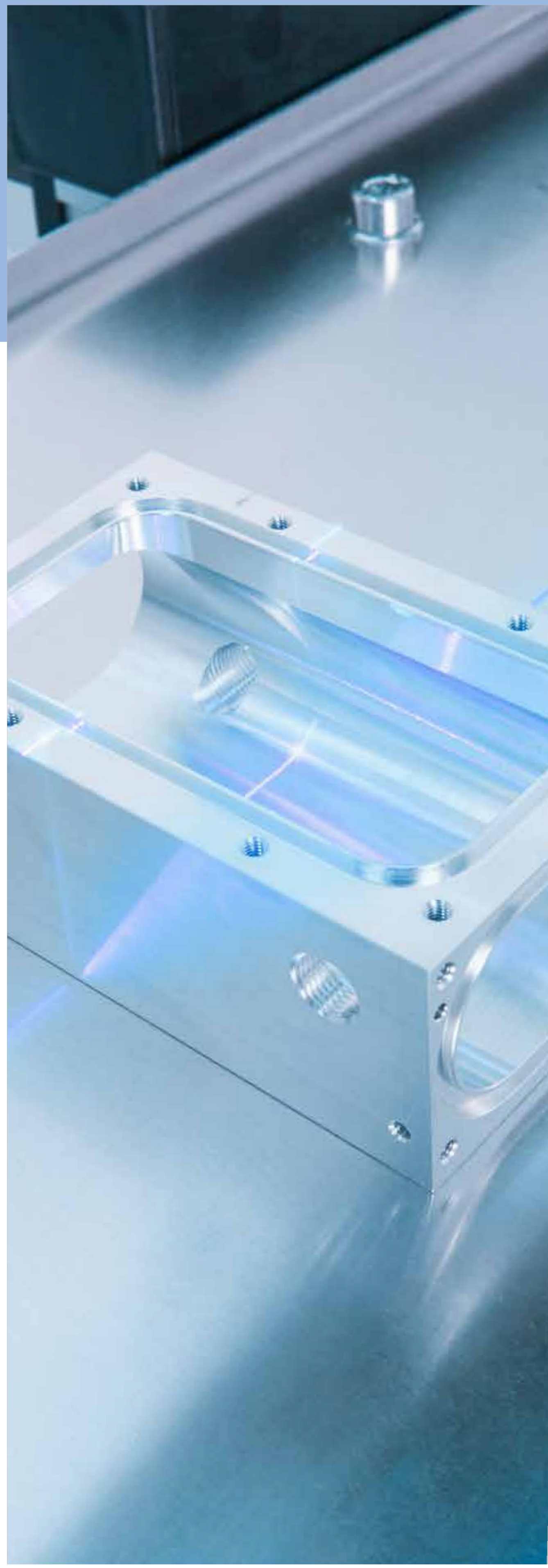
- Detecting position, form and quantity of film-like impurities at production speed
- Imaging detection of process auxiliaries such as lubricants, greases or cleaning agents (detection limit for standard lubricants: 0.01 g/m²)
- Camera system: detection area of some cm², optical resolution approx. 20 µm
- Scanner system: detection area of some m², optical resolution approx. 500 µm

INLINE MICROSCOPY

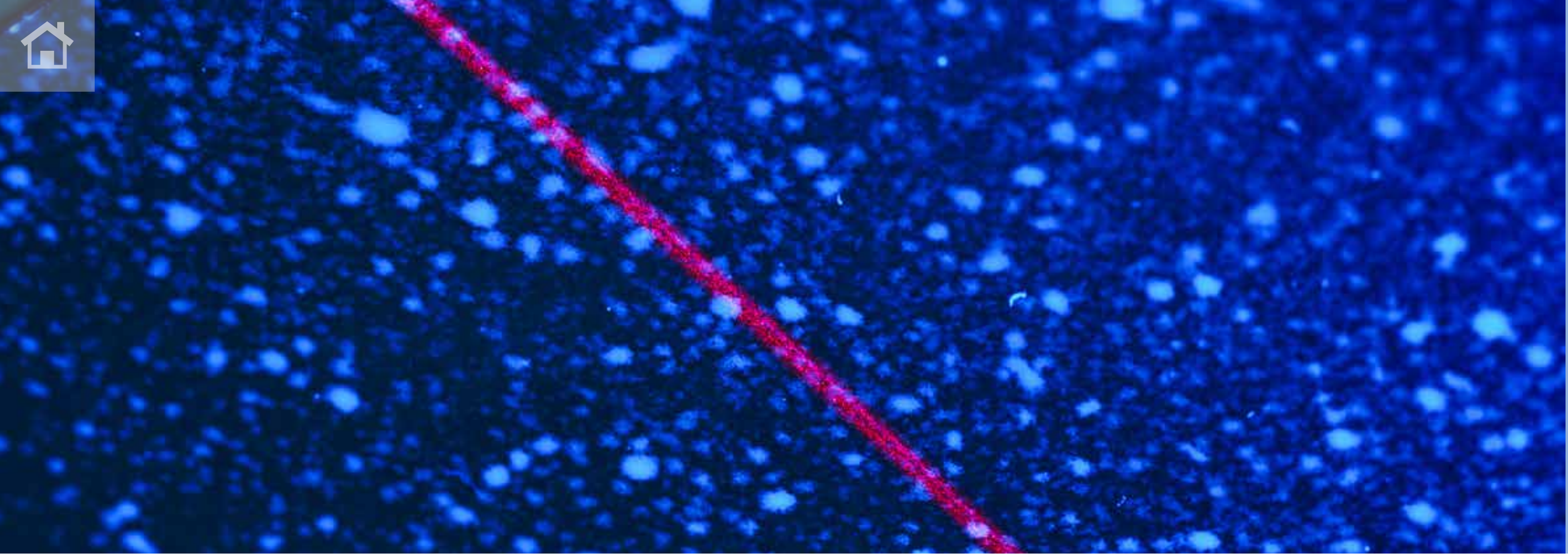
- Characterization of complex 3D microstructures
- Detecting structural defects, impurities, defective geometries or scratches
- Reproducibility of distance measurement in the sub-micron range
- Measuring device capability for determination of component geometries
- Frequencies of approx. 1 second

LASER-INDUCED BREAKDOWN SPECTROSCOPY

- Non-contact materials analysis on surfaces
- Layer thickness measurement of functional surfaces with thicknesses in the micrometer range
- Inline characterization of nanometer-thin anticorrosive coatings
- Detection of element concentrations in coatings in the order of ppm



>> Using fluorescence measurement, the F-Scanner reveals impurities on component surfaces during production.



< Thanks to measurements which cover the entire surface area, structures such as droplets can be detected in addition to changes in coating thickness.

GROUP **OPTICAL SURFACE ANALYTICS**

Quantitative coating control on assembly lines

Thin coatings and their compositions are key to the quality of many products. Paint, forming oil, surfacer and other functional coatings are usually applied at high speed, often across large areas. Fraunhofer IPM is developing measurement systems to perform both quantitative and qualitative checks on such coatings – quickly, across their entire surface area, and directly within the production line.

Today, many production steps must be inspected increasingly frequently and with ever greater precision. These include all surface coatings, which are a crucial factor in product quality. This is because only perfectly applied coatings – such as paints or anti-corrosion oils – fulfill their purpose. Fraunhofer IPM has therefore developed image-based measurement systems that enable quantitative checks to be carried out on coatings, directly on assembly lines during production.

Example: Oil film measurement

Conventional inline measurement systems for measuring oil film only measure surfaces point by point. The sensor is guided over the surface of the rollstock perpendicular to the feed direction. If the rate of feed is fast, this results in a zigzagging measurement line which only captures data for part of the surface. Interstices are generated which, together, amount to critical measurement gaps of as much as 100 square meters. In order to be absolutely sure of the coating quality throughout a product, the homogeneity and thickness of the coating need to be mapped across its entire surface. For this reason, high-speed laser scanners are used in the measurement systems developed by Fraunhofer IPM. Even with a throughput of several meters per second, 100 percent of the surface area can be analyzed as a direct part of the production process using these systems.

F-Scanner for full-face measurements

The high-speed laser scanner employed in the F-Scanner enables spatially resolved 100 percent monitoring of large surface areas on the assembly line. The measurement system records around 400 lines per second and, depending on the belt speed, achieves spatial resolution of some millimeters. This method enables high throughput rates with superior levels of sensitivity. Thanks to its collimated laser beam, the system also has great depth of field. In addition to its application in monitoring rollstock, it can also reliably detect problem areas in complex component geometries.

Fluorescence reveals the invisible

In the F-Scanner the laser scanner scans the surface point by point with UV light. Many organic materials, particularly fats, oils, polymers, release agents and transparent paints, exhibit strong fluorescence at these wavelengths. They convert part of the UV light into visible light. These fluorescence signals, as the measuring signal, are detected, interpreted and compiled to create a spatially resolved overall picture.

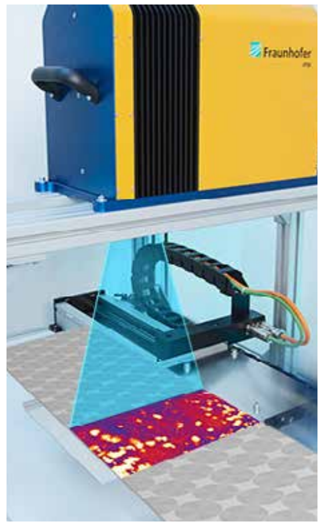
FLUORESCENCE is the emission of light seen in many, mainly organic, materials when they are excited by high-energy UV light. The spontaneously emitted fluorescent light has a longer wavelength than the previously absorbed UV light, and can be detected and evaluated separately from this using filtering. This enables quantitative statements to be made regarding coating coverage.

The fluorescence of the coating materials is analyzed in a way which allows clear, high-contrast measurement images of the thickness and homogeneity of coatings to be generated for the entire surface area. With appropriate calibration, surface coatings can be inspected with an accuracy of ±0.05 g/m²; the detection limit is in the region of 0.01 g/m². Fraunhofer IPM is already using this image-based fluorescence measurement technique in a range of applications, for example in detecting unwanted residue from lubricants, adhesives, degreasing agents and photoresists, in analyzing lubrication on metal strips, and in monitoring functional coatings such as adhesive agents.

Bespoke systems – with optimized image processing

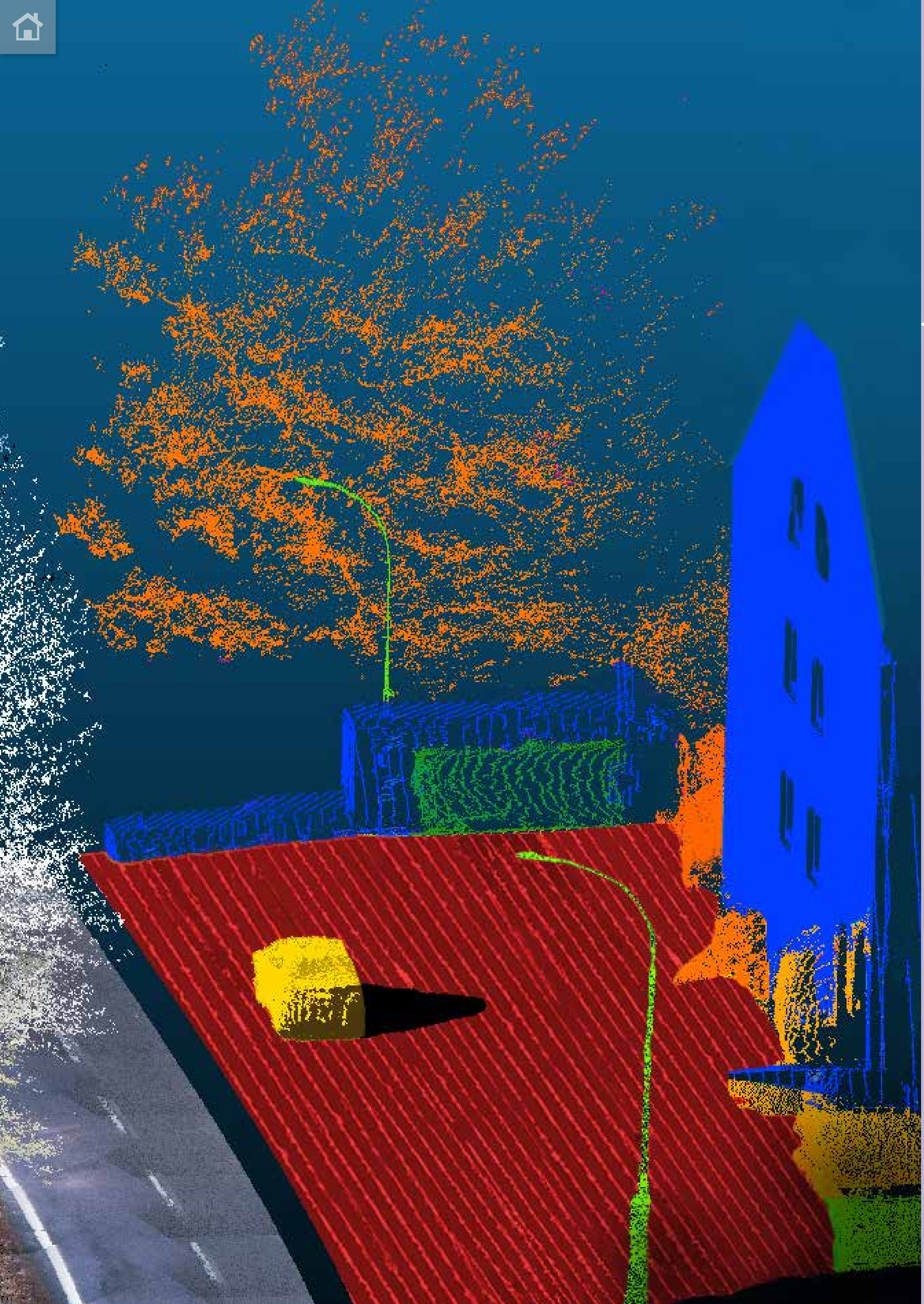
Fraunhofer IPM customizes scanner configurations according to the individual measuring task. The belt dimensions and speed, the mounting space available and the substances to be detected are all taken into account here. Metrological hardware forms just one part of the overall system, however. Automated image processing is at least equally important. The systems developed by Fraunhofer IPM interpret the fluorescence images using pattern recognition in real-time. Should the coating coverage exceed or fall short of predetermined thresholds, the next process step is adapted accordingly: The component is either rejected, cleaned or re-coated. Spatially resolved evaluation thus helps to achieve the best possible monitoring and documentation of production processes, and to optimize them on an ongoing basis as a result.

The fact that this works wonderfully well in practice is proven by the »Award for Blechexpo« which Fraunhofer IPM received in 2017 in the »Process Control and Quality Assurance« category (see page 15). The institute was awarded the prize jointly with the company Raziol Zibulla & Sohn GmbH for developing the first system which enables a controlled lubrication process with the help of the F-Scanner.



The F-Scanner measures coatings quantitatively using the fluorescence signal of the coating material applied. Evaluation is performed in real-time and thus allows processes to be optimized automatically.

Dr Albrecht Brandenburg, P +49 761 8857 - 306, albrecht.brandenburg@ipm.fraunhofer.de



BUSINESS UNIT **OBJECT AND SHAPE DETECTION**

»We accurately record and automatically analyze 3D data«

In the »Object and Shape Detection« business unit, we develop systems for detecting three-dimensional geometries and the location of objects. For this purpose, not only laser scanners but also custom-tailored lighting and camera systems are developed. These devices take measurements at high speed and with high precision, particularly from moving platforms.

We focus specifically on speed, robustness and long service life of the systems. The systems scan objects and shapes over a broad size range: from a few centimeters to into the 100-meter range. The measuring systems are in operation all over the world – for monitoring rail infrastructure and for measuring road surfaces. New applications include mobile data recording from the air and in water.

The efficient evaluation of measurement data is becoming increasingly important. In light of this, we are developing smart algorithms based on the concept of »Deep Learning«.

Group Laser Scanning

- Systems for railway measurement
- Systems for road measurement
- Autonomous systems
- Automated 3D data interpretation

CONTACT

Prof Dr
Alexander Reiterer
Head of Department
P +49 761 8857 - 183
alexander.reiterer@
ipm.fraunhofer.de

< Cameras and laser scanners monitor large structures such as streets or buildings. Learning algorithms are employed to automatically analyze the 3D data.

BUSINESS UNIT **OBJECT AND SHAPE DETECTION**

GROUP **LASER SCANNING**

Prof Dr Alexander Reiterer, P +49 761 8857 - 183, alexander.reiterer@ipm.fraunhofer.de

The main focus of this group is the development of optical measuring systems based on time-of-flight measurement, which enable the distance between objects to be measured at high speed and high precision. Combined with a scanning unit, these systems capture three-dimensional object geometries. Mobile laser scanning requires precise positioning and orientation of the measurement system. For this purpose, special camera-based methods, if necessary with conventional inertial sensor technology, are developed in order to enable the allocation of the measurement data to a fixed local coordinate system.

EXPERTISE

Time-of-flight measurement systems measure distances with sub-millimeter precision | Fast laser scanners scan of the surroundings | Small, light-weight laser scanners designed for mobile platforms

APPLICATIONS

Scanners and camera systems gauge and monitor railway infrastructure such as tracks, platforms, and catenary wires | Measurement systems on mobile platforms and autonomous vehicles inspect objects difficult to access, e.g. under water or from the air | »Deep-Learning« algorithms automatically interpret 3D point clouds, classifying objects, e.g. in road scenarios

SPECIFICATIONS

SYSTEMS FOR RAILWAY MEASUREMENT

- Detecting catenary wires at speeds of 250 km/h
- Monitoring clearance profile of railways with a precision of 3 mm
- Profiling speed of 800 profiles per second
- Measuring rail track profiles with a resolution of 0.3 mm

SYSTEMS FOR ROAD MEASUREMENT

- 2 million measurement points per second
- Measurement of transverse profiles with 0.3 mm precision
- Detection of 300 m wide road corridors with precisions of 3 mm
- Identifying cracks in road surfaces at speeds of 80 km/h with 1 mm resolution

AUTONOMOUS SYSTEMS

- Measuring distances under adverse environmental conditions (e.g. in turbid media, in fog)
- Interpretation of 3D measurement data by methods such as »Deep Learning«
- Miniaturizing complex measurement systems for use on autonomous vehicles with a total weight of less than 2 kg
- Determining the position of mobile measurement systems by using visual odometry, positioning and orientation systems

>> Installed on a drone, a laser scanner system measures the front of the city hall of Staufen, where cracks in buildings appeared in the aftermath of geothermal drillings.

< Monitoring large construction sites from the air with cameras and laser scanners supports optimal planning and documentation of construction projects.

GROUP **LASER SCANNING**

Construction progress: Aerial capture and automated analysis

Major construction sites have a lot going on, with large quantities of materials and objects moved around daily. A laser scanner developed by Fraunhofer IPM for STRABAG AG captures road construction sites from the air to document these changes. The 3D data obtained are automatically analyzed with specially designed software.

Monitoring and documenting project progress at major construction sites is important for providers of construction services such as STRABAG AG. Project managers in the construction industry are increasingly using digital data and special software for this purpose. These form the basis for what is known as Building Information Modeling (BIM), which helps with the optimal planning and implementation of construction projects.

Drones equipped with cameras have been in use for quite some time at major construction sites, such as traffic route construction, to document the status of the project. They fly over the area every few days and deliver a wealth of information including the position and size of asphalt and gravel surfaces, guardrails, curbs, manhole covers or trees as well as the stock and storage location of construction materials and equipment. At present, the 3D data computed from camera images is »manually« analyzed, that is, through visual inspection. A joint project of STRABAG and Fraunhofer IPM is aimed at making this process more efficient.

The challenge: Accurate recognition of objects in 3D point clouds

A measurement system developed by Fraunhofer IPM, which uses a laser scanner in addition to cameras, is installed on a UAV (unmanned aerial vehicle) platform and directly delivers a georeferenced 3D point cloud as well as camera data. The eye-safe measurement system weighs only two kilograms and can capture an area of several hundred square meters in less than ten minutes. The laser scanner generates up to 60 profiles per second with 1000 measuring points each perpendicular to the flight path. The precision of a single point measurement is approximately 1 cm.

The 3D data generated by the scanner offers two major advantages. Unlike camera images, the measuring beams penetrate vegetation, so that even ground points under trees or shrubs can be captured. In addition, this approach eliminates unwanted shadow effects, which are unavoidable with camera-only systems. Moreover, the 3D point clouds generated by the scanner with RGB information from the images provide the best basis for an automated analysis of the measured data. Until now, this process has been akin to that of »paint by numbers«: the 3D point cloud is analyzed by manually extracting objects. In the future, the process of data interpretation is expected to be taken over by specially designed learning algorithms that work on the principle of »deep learning« based on artificial neural networks (ANN). In its basic state, such an ANN resembles a crude network of artificial neural connections. The ANN is prepared for the eventual task of classification with a specially generated training dataset, as only known objects can be reliably identified.

TRAINING DATASET FOR ARTIFICIAL NEURAL NETWORKS (ANN): To create a training dataset, thousands of datasets containing the prototypical elements of a construction site scenario are manually annotated. All the border areas of a relevant object, a streetlight or a tree for instance, are marked down to the pixel. This creates prototypical polygon faces that are assigned to predefined object classes. These annotated faces serve as input patterns for the ANN and later recognize geometry, color and other descriptive parameters to create the associated output pattern, i.e. a specific object class. Fraunhofer IPM has developed a software tool for data annotation, which makes this process efficient.

Classified 3D model of the construction site

Apart from training the ANN, the other prerequisite for automated data analysis is the appropriate preparation of input data. The intelligent fusion of camera and scanner data forms the ideal data pool. The camera data plug any gaps in the 3D point cloud and provide additional color information, while depth information from the 3D point cloud enables, for example, better differentiation of overlapping objects than would have been possible with the help of camera data alone. A framework developed by Fraunhofer IPM projects the scanner data accurately and precisely onto the images of the color camera. This way each RGB image of the scene is assigned a corresponding depth channel. The RGB-D(epth) data prepared in this manner along with a trained network make the data analysis very robust to object variations and changes in view angles and light conditions. And that is critical, as no two construction sites are alike and no measurements are made in a controlled environment. Project partner STRABAG will get an executable software package that creates classified datasets in the industry-standard LAS format, which, if required, can be linked to other data such as BIM or CAD data. This creates the digital data that form the basis for the efficient management of large construction projects.

Ready for take-off: A STRABAG employee gets the drone ready to go. The data recorded are later automatically analyzed.

Prof Dr Alexander Reiterer, P +49 761 8857 - 183, alexander.reiterer@ipm.fraunhofer.de

< In the future, a novel measurement system will determine the geometry, surface structure and vegetation growth on tunnel constructions simultaneously and at high speed.

GROUP **LASER SCANNING**

Tunnel vision: Sensor determines condition of tunnel structures

In the future, a laser-based multispectral sensor will be able to simultaneously identify the geometry, surface structure, moisture level and vegetation growth of tunnel constructions. This system will determine all relevant parameters in a single measurement run at speeds of up to 80 km/h. As a result, it will be possible to perform inspection and maintenance of tunnels far more efficiently and economically.

Tunnels are critical transit connections for both passenger traffic and goods transportation, particularly in Central Europe. However, they also play an important role in drainage systems and as mine access shafts. In Germany alone, over four hundred road, rail and subway tunnels require regular inspections – and many of these are several decades old. In addition, there are some 250,000 kilometers of tunnel-like structures in the sewer network. Every year, the costs of maintaining and repairing tunnels amount to nearly one billion euros solely in Germany. As part of the IncaS (IntracavityScan) in-house Fraunhofer project, Fraunhofer IPM has developed a multispectral sensor that will significantly reduce the costs of tunnel inspection while improving the quality of measurement data at the same time.

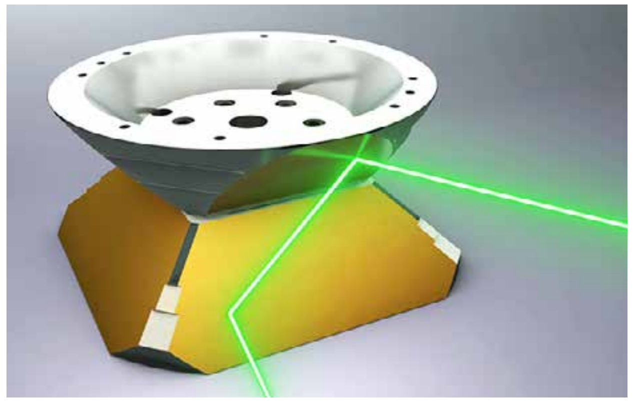
Multiwavelength measurement

The scientists use a novel laser scanner design for performing measurements with multiple wavelengths. The measured data of the different wavelength are then combined. This allows for a seamless and dense detection of 3D geometries, surface structures, moisture levels and vegetation growth on tunnels in a single measurement run. The measurement system operates at high travel speeds meaning that it will no longer be necessary to close routes during surveying. Propagation delays in laser light backscattering are used to survey the geometry of a given structure. Up to two million measuring points per second ensure high resolution. In order to measure surface moisture, two lasers with different wavelengths are used. The laser light is specifically absorbed by water, depending on the respective wavelength of 1.3 and 1.45 µm. An intensity analysis of the two signals gives the moisture value. These data on geometry and moisture allow the researchers to ascertain information on vegetation, such as moss and algae growth. Features of the surface structure are detected based on the intensity of the backscattered light: High spatial resolution is required here in order to generate realistic, photo-like images of cracks in the surface structure measuring just a few millimeters. The laser illuminates the object along a line parallel to the direction of travel. A specially adapted receiver lens forms a planar image of the signals and thus generates a continuous gray-scale picture of the surface. Resolutions of 1.5 mm x 1.5 mm are achieved at travel speeds of up to 80 km/h using this patented technology from Fraunhofer IPM.

CUTTING-EDGE TECHNOLOGY FOR TUNNEL INSPECTION: The geometry, wall surface structure, vegetation growth and wall moisture in tunnels are inspected every five years. Today, static laser scanners positioned at numerous points throughout a tunnel are predominantly used to measure geometries. A small number of systems perform these measurements from mobile platforms, usually on manually-driven inspection cars. Cracks and moisture are detected using cameras, while cavities are identified with a special hammer. All existing methods are time-consuming and labor-intensive, and require full closure of the structure – which has far-reaching economic consequences.

Innovative scanner design for true 360° scanning and multiwavelength measurements

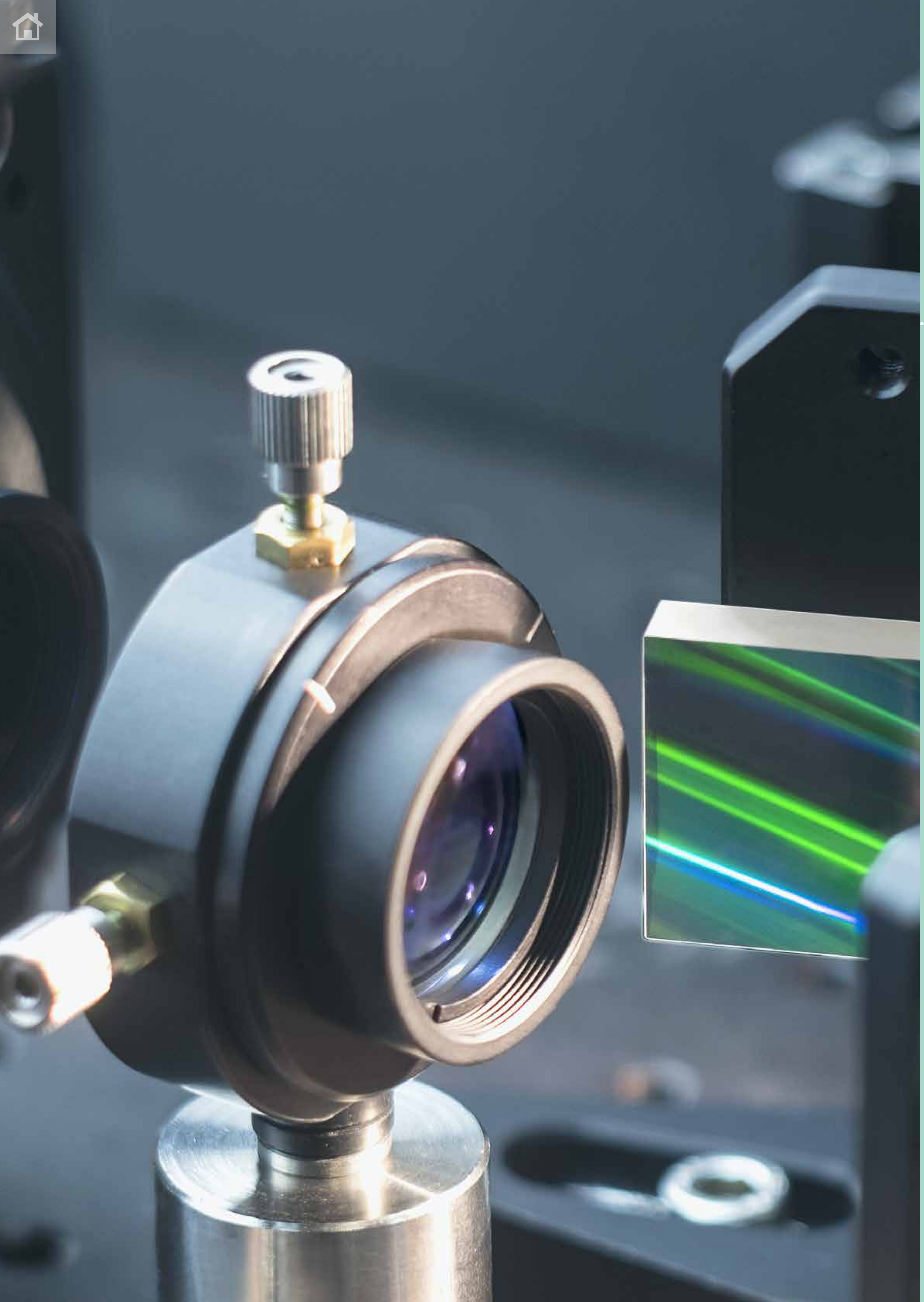
For the first time, a specially developed, square bifrustum-shaped scanning device has made it possible to use laser beams of several different wavelengths synchronously to produce undistorted images (see drawing). This was not possible with the laser scanners available to date, as the light paths could not be clearly isolated. The device also enables true 360° scanning for the first time. Previously, mechanical fixings created shading and made it necessary to perform multiple measurements. Data from several measurements had to be fused to create an unbroken 3D model – an error-prone process that has now been eliminated by the new system. The bifrustum has four facets that cover an angle range of just under 180° each so as to avoid artifacts in edge areas. Thanks to this geometry, the scanning speed is doubled in relation to the speed of rotation, enabling as yet unequalled scanning frequencies. Up to four identical laser systems per frustum and corresponding detection devices can be arranged around the deflection unit in a star shape to guarantee full coverage of all angles. The design ensures perfectly correlated data capture, both in terms of time and space, and enables the use of specially shaped laser beams. The beam propagates along a line to allow planar scanning and guarantee eye safety.



A specially configured deflection unit was designed to meet the requirements of 360° scanning and multiwavelength measurements. This also ensures that all eight laser beams are projected onto the tunnel wall without distortion. This image shows an example of one beam.

This will be the first cavity inspection system to measure all relevant parameters simultaneously, rapidly, and with high levels of resolution. Thanks to its perfect data synchronization, comparisons can be made with previous measurements allowing even small changes in a structure to be identified in good time.

Prof Dr Alexander Reiterer, P +49 761 8857 - 183, alexander.reiterer@ipm.fraunhofer.de



»Smart sensors will become a part of our everyday lives«

In its »Gas and Process Technology« business unit, Fraunhofer IPM develops and manufactures measuring and control systems to meet customer requirements. The main features of these systems are short measurement times, high precision and reliability, even in extreme conditions.

The expertise in the business unit includes laser spectroscopic methods for gas analysis, energy-efficient gas sensors, particle measuring technology and thermal sensors and systems. The scope of applications is massive – it extends from flue gas analysis and transport monitoring for food to sensors and systems for measuring very small temperature differentials.

Group Integrated Sensor Systems

- Gas sensitive materials
- Micro-optical components
- Miniaturized gas sensor systems

Group Spectroscopy and Process Analytics

- Spectroscopic analytics
- Optical systems
- Nonlinear optics

Group Thermal Measurement Techniques and Systems

- Custom-made microstructures
- Thermal measurement systems
- Simulation of physical processes

< Grating spectrometers rely on silicon detectors to quickly and efficiently detect light with wavelengths in the mid-infrared spectral range using nonlinear optical processes.

CONTACT

Prof Dr Jürgen Wöllenstein
Head of Department
P +49 761 8857 - 134
juergen.woellenstein@
ipm.fraunhofer.de

BUSINESS UNIT **GAS AND PROCESS TECHNOLOGY**

GROUP **INTEGRATED SENSOR SYSTEMS**

Dr Marie-Luise Bauersfeld, P +49 761 8857-290, marie-luise.bauersfeld@ipm.fraunhofer.de

The main focus of this group is the development of functional gas sensitive materials and surfaces, and miniaturized gas sensor systems. Gas sensor technology and electronics are combined in compact, low cost microsystems for this purpose.

EXPERTISE

Customer-specific synthesis and processing of gas sensitive materials for specific applications | Micro-structured IR emitters as light sources in micro-optical sensors (MOEMS) | Embedding energy efficient gas sensor systems into wireless sensor networks

APPLICATIONS

Efficient air conditioning technology through selective detection of gases such as CO_2 | Early detection of toxic gases like CO, NO_2 und NH_3 | Food quality monitoring in food warehouses or during transportation

SPECIFICATIONS

GAS SENSITIVE MATERIALS

- Materials synthesis and processing, layers of a few nm to some µm, coatings of micro-structured substrates (MEMS)
- Semiconductor gas sensors: metal oxide layers such as SnO_2, WO_3 or $Cr_{2-x}Ti_xO_{3+z}$ with catalytic additives
- Colorimetric gas sensors, e.g. color change materials for CO, NO_2 und NH_3

MICRO-OPTICAL COMPONENTS

- IR emitters for a wavelength range of 5 to 12 µm, can be modulated if desired
- IR detectors (e.g. made of PbSe) for a wavelength range of 3 to 5 µm
- Diffractive optics, e.g. Fresnel lenses made of silicon or components for IR emitters

MINIATURIZED GAS SENSOR SYSTEMS

- Detection of gas concentrations from ppb to percent according to measurement principle applied; modular systems by combining various sensor principles
- Sensor technology for energy self-sufficient systems with wireless communication
- Photoacoustic systems, filter photometers and miniaturized gas chromatography systems

>> In our gas laboratories, we test the measurement accuracy and reliability of gas sensors. Up to eight reference gases can be handled simultaneously.

< Losses of fresh fruit are high during storage. A measurement system monitors the concentration of ripening gases and thus establishes the conditions for optimized storage.

GROUP **INTEGRATED SENSOR SYSTEMS**

Sensor monitors ripening process in fruit warehouses

The aroma of fruit is determined by over a hundred components, and is an important quality criterion when consuming the product. A cocktail of scents provides food producers with valuable information, for instance on the ripening stage of fruits. In collaboration with industrial partners, Fraunhofer IPM is developing a miniaturized measurement system for detecting fruit ripening gases, which is intended for use in fruit warehouses and other applications.

According to a study conducted by the WWF, over ten percent of the fruit harvested in Germany spoils during transportation or storage. Optimized climate conditions during fruit storage can significantly reduce post-harvest spoilage and thus minimize both material and financial losses. To make this possible, precise knowledge is needed of the gas composition in warehouses. Increased concentrations of certain gases, for example, indicate premature ripening of fruit which may result in spoilage of the goods. Bacterial and fungal contamination can also be identified from gas concentrations in many cases.

It is the aim of the »FreshFruitLab« Eurostars project to develop sensors that continuously monitor relevant gases in fruit warehouses. Suitable measurement technology is needed to selectively control ripening processes and production steps, such as by feeding in ripening gases or regulating air change. Together with Scemtec Transponder Technology GmbH and Environmental Monitoring Systems EMS B.V. from the Netherlands, Fraunhofer IPM is developing a miniaturized gas sensor system for monitoring fruit ripening processes. The project is initially focused on the ripening gases typical for apples, pears and kiwi fruit. In principle, however, the measurement system is designed to cover a large range of food-related gases, and in the future could therefore be used on a broader scale for quality control in the food industry.

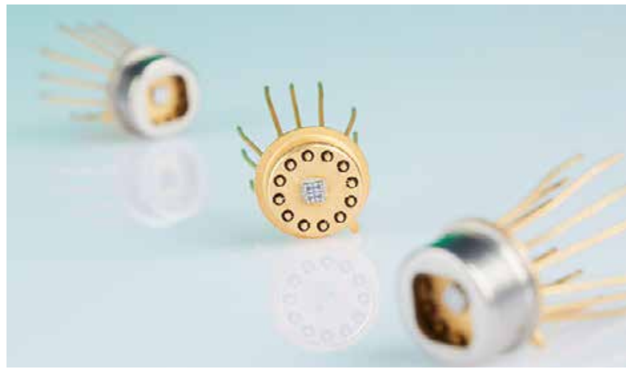
Gas chromatography with semiconductor gas sensors

To perform this highly-sensitive monitoring of fruit ripeness, the scientists use a combination of gas chromatography (GC) and semiconductor (SC) gas sensors as detectors. In order to record the large number of gases produced, commercial chromatographic separation columns are used that have very high separation efficiencies. Silicon-based, micromechanically-produced gas chromatographs are commercially available today. Heat conduction and surface acoustic wave sensors are generally used as detectors. Fraunhofer IPM uses SC gas sensors as detectors in its FreshFruitLab sensor to increase the detection sensitivity from ppm up to the ppb range. SC gas sensors react to almost all reducing and oxidizing gases, and thus not only enable the detection of trace gases, but also the analysis of complex aromas. Volatile organic compounds (VOC) are indicators of fruit ripeness. When monitoring the ripening of apples, pears and kiwi fruit, it is primarily short chain hydrocarbons from C2 to C4 that play a role. Components such as formaldehyde, methyl mercaptan, trimethylamine and sulfur compounds are also of interest for food monitoring. Tin oxide doped with platinum or palladium, lanthanum indium oxide, tungsten oxide and chromium titanium oxide have been identified as suitable, gas-sensitive metal oxides for sensitive detection of these VOCs. The sensor design includes four SC gas sensors based on these metal oxides to allow a wide range of relevant gases to be detected. Each sensing element can be heated separately and placed on a separate sensor platform in order to increase selectivity. The gas-sensitive surfaces measure 45 x 45 μm^2. The sensor array has a total area of 1.6 x 1.6 mm^2.

Low power – high sensitivity

To create a low power sensor, the SC gas sensors are deposited onto microstructured silicon substrates (called micro-hotplates) in the form of a specially developed, printable, metal oxide ink. There is no need for a photolithography process. These particularly porous, printed layers ensure a favorable ratio of surface to volume, and thus greater sensitivity. The sensor requires 15 milliwatts of power to generate an operating temperature of 400 °C meaning that, in principle, it can be battery operated. All this produces an economical, compact, sturdy device that can be configured for specific measuring tasks and employed as a portable or stationary unit in fruit warehouses. The sensitivity of the system is comparable to the precision of complex lab gas chromatographs, which have previously been tested separately for the monitoring of fruit ripening processes. As far as accuracy and objectivity are concerned, the sensor will always surpass the human nose.

GAS CHROMATOGRAPHY: The human nose is a highly sensitive sensor for volatile organic compounds (VOC). This human sensor is therefore still readily used today to identify the components in a mixture of volatile gases. Gas chromatography (GC) has become established as an analytical technique for characterizing VOCs. In this complex process, samples are evaporated and then broken down into their individual components in a separation column. Compact, reasonably-priced GC systems employing microsystems engineering processes have been produced since the early 1980s.



The semiconductor gas sensor detects volatile organic compounds down to the ppb range. Four gas sensitive surfaces (45 x 45 μm^2 each) are arranged on micro-hotplates with a size of 120 × 120 μm^2.

Dr Marie-Luise Bauersfeld, P +49 761 8857-290, marie-luise.bauersfeld@ipm.fraunhofer.de

GROUP **SPECTROSCOPY AND PROCESS ANALYTICS**

Dr Raimund Brunner, P +49 761 8857 - 310, raimund.brunner@ipm.fraunhofer.de

The main focus of this group is the development of spectroscopic systems for the detection and analysis of gases, liquids and solids. The group uses its long experience in exhaust gas, combustion gas and particle measuring technology for this purpose. Methods such as Raman, ATR or laser spectroscopy are employed. The group's services range from laboratory testing to prototype development and support in the implementation of batch production processes.

EXPERTISE

IR and laser spectrometers as a basis for measurement systems in gas and liquid analytics and materials testing | Methods for simulation and analysis of special optical assemblies and electronic components | Development and realization of tunable laser light sources for spectral ranges not yet covered

APPLICATIONS

Gas analyzers for monitoring the caloric value of natural gas in pipe systems | Fast process spectrometer for exhaust gas test bench in the context of motor development | Imaging IR measuring technology for safety and leakage surveillance of industry plants

SPECIFICATIONS

SPECTROSCOPIC ANALYTICS

- Optical trace gas analyzers based on quantum cascade lasers (QCL): sensitivity of 10 ppb for N_2O or NH_3 and 10 ppm for O_2
- Raman spectroscopy: analysis of liquids, biological cells or gases
- ATR spectroscopy: measuring gas concentrations in liquids down to the ppm range
- Laser absorption spectroscopy: determining residual absorption of down to 1 ppm in materials
- Chemometric data processing methods

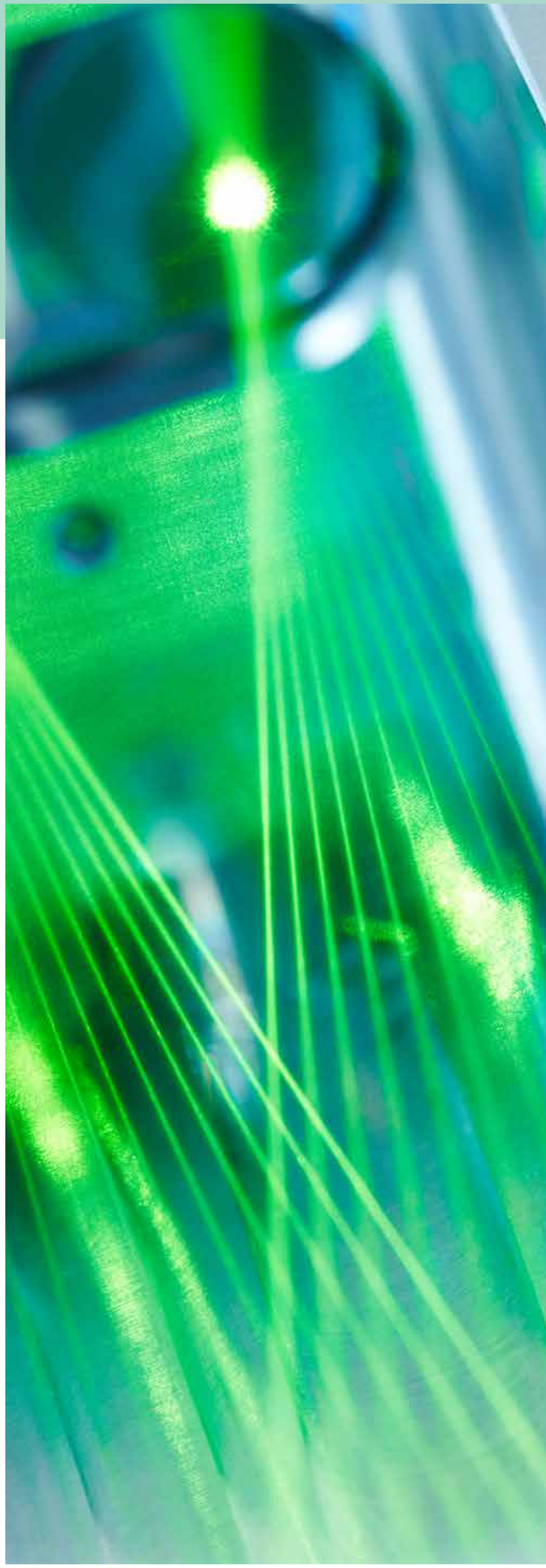
OPTICAL SYSTEMS

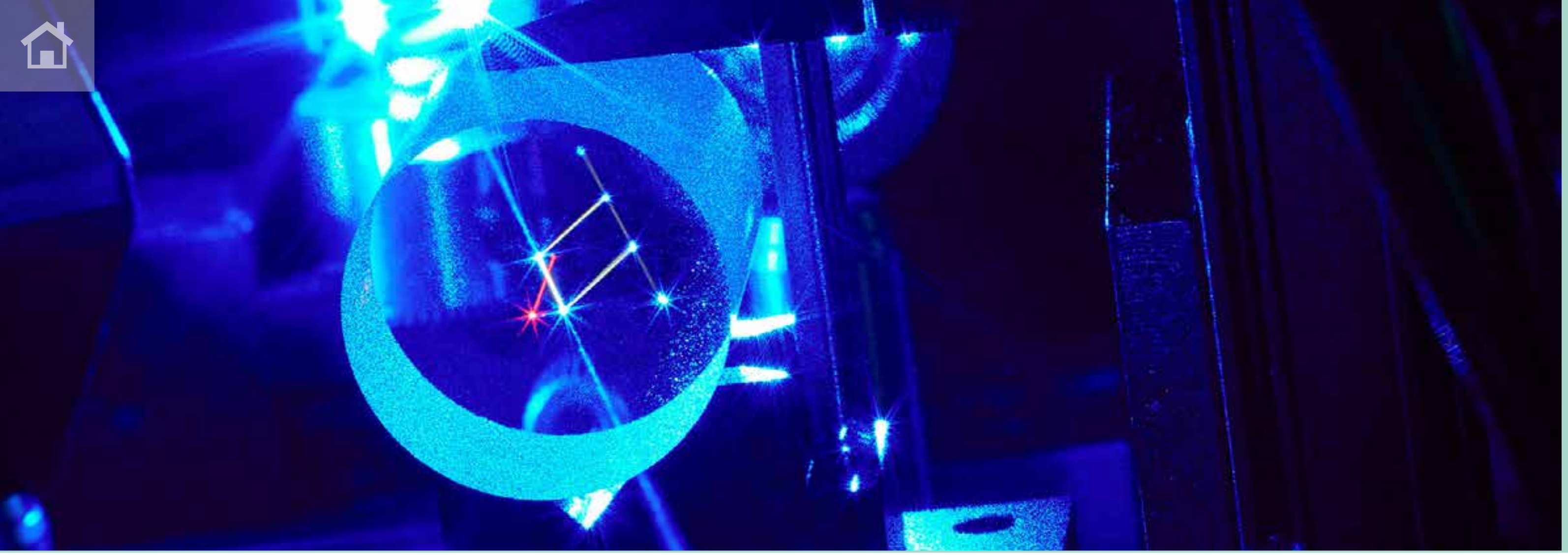
- Multi-reflection absorption cells: 0.1 to 15 m optical path, up to 200 °C
- Mirror optics: White, Herriott and single pass set-ups, UV optics
- Resonator systems: broadband optical ring resonators and linear resonators
- Simulation: optics, mechanics, current, electronics

NONLINEAR OPTICS

- Optical-parametric oscillators: tunable from 450 nm to 5 µm, 10 mW to 2 W output (depending on wavelength)
- 1 MHz line width
- Frequency doubling: over 50 percent conversion efficiency
- MIR-NIR conversion: recording of MIR process data with more than 5000 spectra per second

>> Multi-reflection measurement cells enable highly sensitive spectroscopic gas measurement.





< Faraday isolators made of innovative materials are key to the development of high-performance lasers. Novel measurement techniques allow very precise characterization of the materials' absorption properties.

GROUP **SPECTROSCOPY AND PROCESS ANALYTICS**

New Faraday isolators for improved laser sources

Customized Faraday isolators are playing an ever more important role in modern laser systems. Faraday isolators are optical components that act like optical diodes: They allow the transmission of light in one direction only. This protects the laser against harmful optical feedback. A measurement technique refined by Fraunhofer IPM is supporting materials development and quality inspection for Faraday isolators.

Faraday isolators are among the key components of many modern laser systems, where retroreflection can have a negative impact on how the lasers operate. This applies, for example, to high-performance ultrashort pulse disk lasers and fiber lasers, and likewise to miniaturized diode laser oscillator amplifier systems for quantum sensor applications. All of these laser systems are undergoing rapid development at present. The predominant Faraday isolator material – particularly where 1 µm high-power lasers are concerned – is currently terbium gallium garnet ($Tb_3Ga_5O_{12}$). However, this material is already reaching its limits within the performance parameters of today's laser systems.

New materials for new power ranges

Faraday isolators made from innovative materials such as potassium terbium fluoride (KTb_3F_{10}) may, in future, permit the development of high-power lasers and compact diode laser systems of an entirely new caliber. Materials of this kind are being developed and investigated as part of the IsoNova project funded by the German Federal Ministry of Education and Research (BMBF). In addition to Fraunhofer IPM, the project partners are the Leibniz Institute for Crystal Growth from Forschungsverbund Berlin e.V., Forschungsinstitut für mineralische und metallische Werkstoffe, Edelsteine/Edelmetalle (FEE) in Idar-Oberstein, Trumpf Laser GmbH in Schramberg and TOPTICA Photonics AG in Gräfelfing. The consortium covers the entire value chain – from developments in crystal growth to the evaluation of full Faraday isolators in laser fatigue tests. By selecting suitable materials and growing high-grade crystals for isolators, the aim is to reduce the limiting effects on operation to such a degree that an improvement of one order of magnitude is achieved for key usage parameters such as power handling capability and physical size.

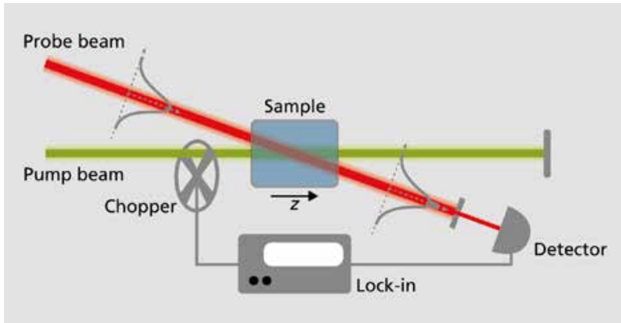
In the case of high-power lasers such as ultrashort pulse disk lasers, it is chiefly thermal effects that are hindering progression to the next power level. Even tiny absorption of just a fraction of the laser power in the rotator material leads to temperature increases and temperature gradients in the component. As a consequence, a thermal lens forms, beam quality degrades, and the isolating efficiency of the Faraday isolator decreases. Since these effects scale concurrently with the laser power, it becomes impossible to cover the entire power range with the same beam parameters.

FARADAY ISOLATORS are optical components that only permit the transmission of light in one direction. Light propagation in the opposite direction is blocked. This diode characteristic is obtained using a Faraday rotator positioned between two polarizers turned through 45° angles. The direction-dependent light transmission is caused by the rotation of the light wave's plane of polarization within the rotator in combination with two crossed polarizers. This is achieved by placing the rotator material in an axial magnetic field (Faraday effect).

The Faraday isolator thus becomes a bottleneck hampering the development and use of new laser systems. The isolator has a similar relevance for the miniaturization of laser systems, which is needed for applications in quantum optics, but is currently thwarted by the size of optical isolators. By developing new types of crystal, such as those based on cadmium manganese telluride (CdMnTe), it will be possible to make optical isolators, and thus laser systems, markedly smaller and therefore more robust, portable and cheaper, particularly for the visible spectrum.

Absorption spectroscopy on Faraday isolators

Fraunhofer IPM's task within the project consortium is to characterize the new materials with regard to their absorption properties. Key to this is a measurement technique refined at Fraunhofer IPM: Photothermal Common-Path Interferometry (PCI). Within the scope of the project, this method is being adapted to the specific requirements of the materials under investigation. It is well suited to determining residual absorption in optical materials down to the ppm range. By combining this technique with laser light sources that can be tuned to wide ranges, a technology made production-ready at Fraunhofer IPM, the absorption measurements can also be scaled to new materials without the need for reference samples. Furthermore, by recording absorption spectra not just during quality control but also in addition to this, the measurements can contribute valuable information to technological development work. The absorption measuring method therefore has a key analytical role in materials development: No other standard method meets all the necessary measurement requirements for spectral coverage and detection limits where low absorption is involved.



Photothermal Common-Path Interferometry (PCI) is a sensitive absorption measuring technique that utilize the unwanted thermal effects of absorption in materials to perform quantitative analyses of these materials. The beam from a powerful pump laser (green) is passed through the material. Part of the power is absorbed and leads to a localized increase in temperature, resulting in localized thermal expansion and changes in the refractive index. These effects are detected using a probe laser (red). Depending on the material absorbed power in the order of 10 µW can be detected.

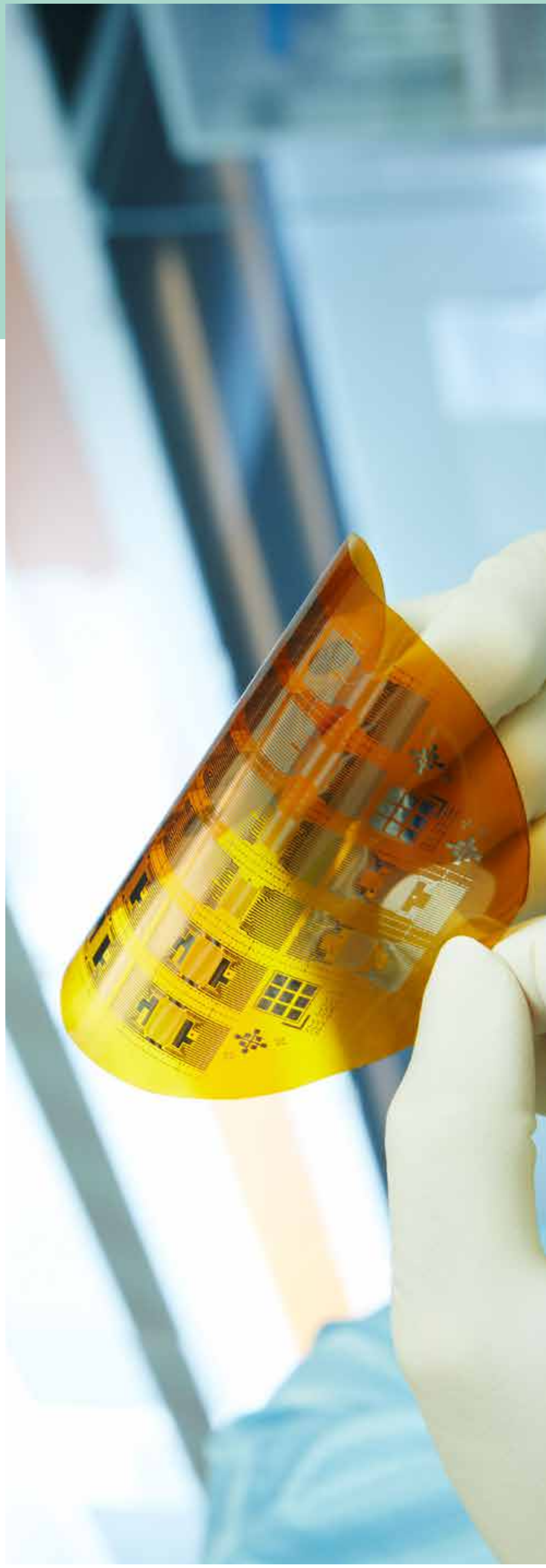
Dr Raimund Brunner, P +49 761 8857 - 310, raimund.brunner@ipm.fraunhofer.de

BUSINESS UNIT **GAS AND PROCESS TECHNOLOGY**

GROUP **THERMAL MEASUREMENT TECHNIQUES AND SYSTEMS**

Martin Jägle, P +49 761 8857-345, martin.jaegle@ipm.fraunhofer.de

This group develops thermal sensors and systems made of various materials. Flexible substrates allow very small temperature differentials to be measured using so-called calorimeter chips and a wide range of material parameters, such as thermal and electrical conductivity, to be determined using press-on measuring structures.



>> Micro calorimeters on flexible polyimide foils measure various physical material parameters such as temperature, thermal and electrical conductivity or thermal capacity.

EXPERTISE

Development and manufacture of custom-tailored microstructures and microsystems | Customer-specific measurement systems for temperature dependent determination of material parameters | Coupled thermal-electrical finite element models for thermal impedance analysis

APPLICATIONS

Low-cost fluid sensor technology on polymer substrates, e.g. for monitoring oil quality | Modelling and validation of energy storage systems for geothermal applications

SPECIFICATIONS

CUSTOM-MADE MICROSTRUCTURES

- Microstructures for organic electronics, heaters and microfluidics with structures of typically 1 µm
- Thermopile sensors, calorimetric sensors
- Thermal sensors for determining material parameters, especially thermal conductivity
- Electronic tongues

THERMAL MEASUREMENT SYSTEMS

- Systems for determining electrical conductivity, charge carrier concentration, Seebeck coefficient, majority charge carriers, e.g. by way of Hall measurements on semiconductors from –200 to 800 °C
- Systems for measurement of thermal properties of solids, liquids and gases by employing methods such as impedance and 3 omega

SIMULATION OF PHYSICAL PROCESSES

- Coupled finite element models (FEM)
- Computational fluid dynamics (CFD) with thermal analysis
- Simulation of geothermal processes and design of energy storage devices
- Thermal management for electronic systems

< The SRX-vdP system developed by Fraunhofer IPM measures the Seebeck coefficient and electrical conductivity of materials simultaneously. PTB uses the system to define reference materials.

GROUP **THERMAL MEASUREMENT TECHNIQUES AND SYSTEMS**

Reliable analysis of material properties

The validity and reproducibility of materials measurements are only as good as the methods and devices used in the measuring process. To ensure that these methods are verifiable and traceable, the Physikalisch-Technische Bundesanstalt (PTB), Germany's national metrology institute, is developing standard measurement techniques and calibration samples. Fraunhofer IPM has now completed development of the second generation of a test bench which PTB will use to characterize thermoelectric materials and semiconductors.

The SRX-vdP measuring device, which was developed by Fraunhofer IPM for PTB, simultaneously measures the Seebeck coefficient and the electrical conductivity of materials with very low measurement uncertainty. A key aim of the latest generation of this measuring device was to optimize measurements of electrical conductivity. To this end, the system draws on the advantages of three different measurement methods. The result is a unique measuring device which delivers comparable information on the material properties of semiconductors.

Flexibly adjust measurement conditions and procedures
A gas-tight measurement chambers enables precise control of the measurement atmosphere. The resulting defined measurement conditions ensure that the system delivers reproducible readings that can be traced to internationally standardized SI units and the International Temperature Scale of 1990 (ITS-90). PTB is using the system to define reference material samples for use in calibrating commercial measuring devices from various manufacturers. The SRX-vdP not only aids in the measurement of bulk materials, but also of thin layers, the characterization of which previously required alternative measuring setups or special adapters. In addition to round samples with a diameter of at least 10 mm, the device can measure square samples with an edge length of at least 10 mm. Such sample geometries offer a specific advantage: They allow additional measurements, such as determining thermal conductivity with laser flash analysis (LFA) or measuring the concentration of charge carriers using Hall measurement, to be conducted on the same sample. The measurements can be carried out in a temperature range from room temperature to 800 °C.

The right measurement method for the material
Electrical conductivity is measured using a four-point van der Pauw setup, which relies on four thermocouples on the underside of the sample. Micro heaters are placed beneath both ends of the sample, generating temperature gradients in both directions. The resulting voltage is measured by means of thermocouple wires and subsequently used to calculate the Seebeck coefficient. Additionally, the two additional thermocouples serve to verify the homogenity of the temperature gradient in the sample in order to identify any potential errors in measurement.

DIRECT MEASUREMENTS that can be traced to natural constants and deliver absolute values are more reliable than indirect measurements using reference values. Standard systems for characterizing thermoelectric materials rely on relative measurements to determine material quality. To facilitate this, validated measuring setups are used to measure various reference materials, which are then defined as the calibration standard. These calibration samples are broadly available, allowing anyone to validate their own measurement technology. As long as great care is taken, a diverse range of measurement equipment will produce the same, reproducible results; however, a broad range of calibration samples with varying geometries and material properties is needed.

Electrical conductivity is measured in up to three different ways at each temperature increment. As each of these measurement approaches offers particular advantages and disadvantages depending on the material, combining the three methods improves the overall quality of the measurements. The so-called delta method involves briefly and repeatedly applying different currents via the two contacts on the sample. The currents are applied in both directions, and the corresponding voltages across the sample are measured and used to calculate the resistance of the sample. The current-voltage sweep method involves applying an alternating voltage to the sample and measuring the current passing the sample. The resulting current-voltage curve is then used to calculate resistance. The third method, referred to as the AC method, uses a highly precise AC resistance bridge which relies on lock-in technology to measure sample resistance, enabling precise measurements even at very low currents. This yields a large number of measuring points and makes quality control possible before and during measurement at all temperature levels. As the position of the thermocouples is fixed, the intricate distance measurements typically required are no longer needed. Eliminating this source of error when determining electrical conductivity leads to a significant improvement in the precision and reproducibility of the measurement results. Individual measurement intervals and measurement repetitions as well as the selection of the appropriate measurement method can be flexibly programmed. From the simultaneous measurement of the Seebeck effect and electric conductivity, to flexibility with regards to measurement conditions, to the selection of the right measurement approach for the material in question, the advantages of the system are also valued by industry. Several of the techniques that feature in the PTB system are already in daily use in the laboratory devices of one of our industrial partners, and also future laboratory measuring devices will benefit from the technology.

The SRX-vdP measuring system combines the advantages of different measuring methods. The individual methods are already being employed in commercial laboratory devices for materials characterization.

Martin Jägle, P +49 761 8857 - 345, martin.jaegle@ipm.fraunhofer.de

BUSINESS UNIT **THERMAL ENERGY CONVERTERS**

»We offer innovative and efficient energy conversion«

Functional materials with special physical properties are a focus of the research performed by the »Thermal Energy Converters« business unit. We use caloric and thermoelectric materials to build innovative systems for cooling, temperature control and converting heat into electricity.

Using these materials in heat pumps, cooling systems and generators makes the systems we develop especially environmentally friendly, cost-efficient and durable. Beyond that, we devise, build and characterize new types of heat pipes.

Group Calorics and Thermoelectrics

- Cooling and heating
- Thermal management
- Waste heat recovery

CONTACT

Dr Olaf Schäfer-Welsen
Head of Department
P +49 761 8857 - 173
olaf.schaefer-welsen@ipm.fraunhofer.de

< Elastocaloric materials are suitable for efficient cooling systems.

GROUP **CALORICS AND THERMOELECTRICS**

Dr Kilian Bartholomé, P +49 761 8857-238, kilian.bartholome@ipm.fraunhofer.de

The group's primary focus is the development of functional materials with special physical properties. We use caloric and thermoelectric materials to build innovative systems for cooling, temperature control and converting heat into electricity. Using these materials in heat pumps, cooling systems and generators makes the systems we develop especially efficient and environmentally friendly. Our work draws on more than 20 years of experience in material synthesis and far-reaching expertise in special measurement techniques, simulation, module construction and system integration.

EXPERTISE

Magneto-, electro- and elastocaloric systems for efficient cooling and heating | Pulsed heat pipes for the efficient transfer of thermal energy from hotspots | Cost-efficient production of thermoelectric modules

APPLICATIONS

Caloric cooling systems for laboratory equipment | Optimized thermal management for reduced failure risk of electronic devices | Thermoelectric generators for enhancing electrical efficiency of combined heat and power plants (CHHP)

SPECIFICATIONS

COOLING AND HEATING

- Less need for energy thanks to efficient technology
- Cooling without harmful refrigerants
- Compact system design through high energy density of caloric materials
- Low-maintenance systems

THERMAL MANAGEMENT

- Fast and precise temperature regulation with Peltier elements
- Passive cooling of electronic parts by means of heat pipes
- Efficient thermal distribution by using pulsed heat pipes

WASTE HEAT RECOVERY

- Thermoelectric modules for high-temperature applications
- Enhancing electrical efficiency of CHPP with the help of thermoelectric modules
- Turning waste heat into electrical energy: in cars and in industrial processes

>> Heat pipes are passive cooling elements which dissipate heat extremely efficiently.

< Equipped with a thermoelectric generator, heating stoves could in future deliver not just warmth, but also electric power, which can be used for control engineering or smart home applications.

GROUP **CALORICS AND THERMOELECTRICS**

Nano-CHPP: Power from the stove

In the future, thermoelectric elements will help to convert waste heat from tiled stoves and other heating stoves into electric power. It will thus be possible to equip them with electrical control engineering and integrate them into smart home systems. Targeted combustion control would also bring about dramatic reductions in emissions from small furnaces.

In the future, fireplaces and stoves could deliver more than just comforting warmth: namely, electric power. This will become possible thanks to thermoelectric generators (TEGs) that convert heat into electricity. To date, TEGs have gained a market foothold in several niche applications, but are only suitable for use at maximum operating temperatures between 250 and 300 °C. However, temperatures of over 500 °C and direct integration within combustion chambers are possible with the TEGs developed at Fraunhofer IPM. This will make it possible to turn small furnaces into small-scale power plants generating both heat and electricity – nano-CHPPs.

The high-temperature TEGs are made from half-Heusler alloys. Individual thermoelectric modules are connected to form larger assemblies. These achieve surface power densities of up to 1.5 watts per square centimeter, and their efficiency is five percent. It is consequently possible to utilize these TEGs in stoves with even low outputs of just four kilowatts; i.e. even when only the embers are glowing. Electricity yields are particularly high in tiled stoves that are connected to a heating circuit as a heating system support. Here, the TEGs can be installed between the hot combustion chamber and the cool water pipe in the outer shell of the stove. This results in a large temperature difference, which increases efficiency.

Self-powered, smartly connected and low in emissions

Power generated in this way can be used for many different purposes: To supply small electric appliances, or the measurement and control technology that regulates operation and optimizes combustion, as well as to integrate the stove into a smart home system. Even slight drops in temperature are sufficient to cover the energy needs of approximately 10 to 50 watts. If more electricity is produced, it can also be used to charge smartphones, for example, or power LED lighting. Surplus electricity can be stored temporarily in batteries to ensure a continuous power supply.

In areas where there is no nationwide electricity supply but wood is generally abundant, for example in parts of Canada or Scandinavia, small furnaces could therefore be fitted with electric control units in the future. And pellet boilers could also regulate pellet feeding independently without connection to a power source, or control their heating output via room thermostats. It will also be possible to integrate tiled stoves, which previously generated heat in a completely unregulated way, into smart home systems alongside lighting, heating and ventilation technology. Equipped with a TEG and a small control module, fireplaces will be able to signal the ideal time to add more logs as the room temperature drops, or shut down the heating system as soon as the temperature exceeds a pre-determined threshold.

HEUSLER ALLOYS are named after the German chemist and engineer Friedrich Heusler, who in 1903 was the first to describe the effect whereby mixing the three non-magnetic metals copper, manganese and aluminum gives an alloy that has ferromagnetic properties. Half-Heusler compounds are alloys derived from this mixture which, although not ferromagnetic, have semiconducting properties. Fraunhofer IPM's research has proven that these half-Heusler alloys are sufficiently robust for high-temperature applications.

Fitting small furnaces with TEG technology will also contribute to reducing emissions in coming years. The power generated can be used to optimize the combustion process with the help of measurement and control technology. The control module comprises all the sensors (e.g. temperature sensor, Lambda probe) and actuators required for this. Employing simple sensor technology, it is capable of recognizing different operating states and, based on this information, of adapting the system's airflow to match requirements via a fan or an automated damper.

Promising tests: TEGs in micro-CHPPs

Finally, operation of a TEG has been tested in a small combined heat and power plant in Braunschweig. This pilot experiment using a commercial bismuth telluride TEG yielded promising results. The modules proved to be stable and delivered up to 500 watts of power – enough to supply an entire building with electricity. There are plans to conduct a further trial with half-Heusler modules in a local CHPP. Here, the aim is for the modules to convert waste heat at

Fitting small furnaces with a thermoelectric high-temperature generator will in future provide enough electric power for small regulators that signal the right time to add more logs or optimize air intake.

temperatures of up to around 500 °C into electricity. In the future, the modules could then be used in furnaces for single-family homes, where they would generate power from heat.

Dr Kilian Bartholomé, P +49 761 8857 - 238, kilian.bartholome@ipm.fraunhofer.de

< Specially structured copper plates are suitable for the manufacture of pulsating heat pipes needed to cool hotspots.

GROUP **CALORICS AND THERMOELECTRICS**

Efficient hotspot cooling

When electronic components fail, the cause is usually localized overheating: Over half of all defects in printed circuit boards can be attributed to poor thermal management. Efficient hotspot cooling is therefore becoming increasingly important, especially in power electronic systems. Fraunhofer IPM is developing an innovative new cooling technology specifically for this application – namely highly efficient heat spreaders based on pulsating heat pipes.

For decades, the processing power of electronic components has grown exponentially as predicted by Moore's law. Thermal power loss has also risen concomitantly with this. As a result of ever more powerful microelectronics with ever greater miniaturization, certain components such as MOSFET transistors can sustain thermal losses of up to 100 watts on surface areas of just one square centimeter. Highly effective cooling concepts are therefore required that will guarantee increasingly impressive thermal performance on ever smaller surface areas.

The ideal heat spreader: Passive and high performing

The passive solutions used to date for heat dissipation – such as copper plates and ceramic substrates – are now increasingly reaching their limits. And whilst active solutions that utilize ventilation or water cooling do achieve the high cooling performance required, they are usually too large, too expensive or too fault prone. What is lacking is a cost-effective, compact and highly efficient technology for dissipating excess heat away from hotspots on printed circuit boards in a targeted manner. An ideal heat spreader should distribute the patches of accumulated heat as evenly as possible across a large area to prevent temperature peaks at critical points.

Thanks to their low levels of heat resistance, heat spreaders with integrated heat pipes represent a promising technological approach. They have recently been employed as a passive solution for dissipating hotspots on printed circuit boards, where they effectively carry heat away to a heat sink on a parallel plane to the printed circuit board. When it comes to industrial-scale use, however, one problem remains unsolved: The hollow structure of standard heat pipes prevents them from being positively integrated into the PC board network. Heat pipes are often deformed, or even destroyed, as a result of the pressure involved in bonding printed circuit board stackups.

Pulsating heat pipes

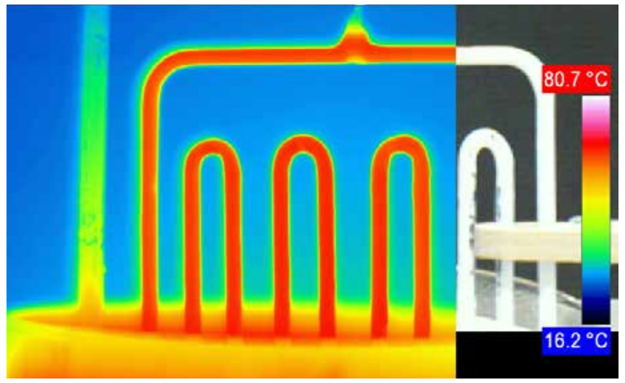
Whilst in a standard heat pipe the fluid returns to the heat source by means of either gravity or capillary action, a pulsating heat pipe consists of many thin, meander-line coils which are partially filled with liquid and subsequently evacuated. Such heat spreaders with integrated pulsating heat pipes have a thermal resistance that is up to ten times lower than for conventional, solid-material heat exchangers with the same dimensions – even with power losses of over 400 watts. Together with Fraunhofer IZM, Fraunhofer IPM is working on the problem of sensitivity to high compression forces: A new, planar design with radial heat transfer is designed to allow the pipes to be both bonded and integrated within the printed circuit board at the same time.

PULSATING HEAT PIPES can dissipate high rates of heat flux extremely efficiently. Just like conventional cooling fins, they belong to the class of passive cooling elements, though their heat transfer capabilities are far superior. Here, heat transfer takes place via a two-phase working medium: The surface tension causes contiguous segments of fluid and vapor to form. The vapor segments expand on the hot side and contract or condense again on the cold side. This means that there are always localized differences in temperature and pressure, which elicit a constant, pulsating motion of the segments. The motion of the segments allows fluid, and thus heat, to be transferred from the hot side to the cold side.

As part of its current research, Fraunhofer IPM is working to further optimize the design and production of pulsating heat pipes. For example, systems will in future be manufactured by means of 3D printing. The metrological characterization of heat spreaders also plays an important role here. Fraunhofer IPM is thus developing specialist measuring and inspection techniques for this purpose.

Compact, simple, cost effective

It is not only the outstanding cooling performance of the concept presented here which makes it ideal for industrial-scale use. This heat spreader is also a simple, compact and cost-effective solution for purely passive cooling and it requires neither moving parts nor a power supply. Thanks to their relatively small cavities compared to standard heat pipes, pulsating heat pipes are not sensitive to the high pressures exerted during the bonding of the printed circuit board stackup. At the same time, the entire system is lighter in weight than a customary heat spreader, and at a thickness of just one to three millimeters it is very flat and extremely compact, making it perfect for integration within printed circuit board structures. This enables excellent thermal coupling, particularly for embedded power components.



In a pulsating heat pipe the fluid returns to the heat source via thin, meander-line coils which are partially filled with liquid and subsequently evacuated.

Dr Kilian Bartholomé, P +49 761 8857 - 238, kilian.bartholome@ipm.fraunhofer.de

FRAUNHOFER-GESELLSCHAFT

Research of practical utility lies at the heart of all activities pursued by the Fraunhofer-Gesellschaft. Founded in 1949, the research organization undertakes applied research that drives economic development and serves the wider benefit of society. Its services are solicited by customers and contractual partners in industry, the service sector and public administration.

At present, the Fraunhofer-Gesellschaft maintains 72 institutes and research units. The majority of the more than 25 000 staff are qualified scientists and engineers, who work with an annual research budget of 2.3 billion euros. Of this sum, almost 2 billion euros is generated through contract research. Around 70 percent of the Fraunhofer-Gesellschaft's contract research revenue is derived from contracts with industry and from publicly financed research projects. Around 30 percent is contributed by the German federal and state governments in the form of base funding, enabling the institutes to work ahead on solutions to problems that will not become acutely relevant to industry and society until five or ten years from now.

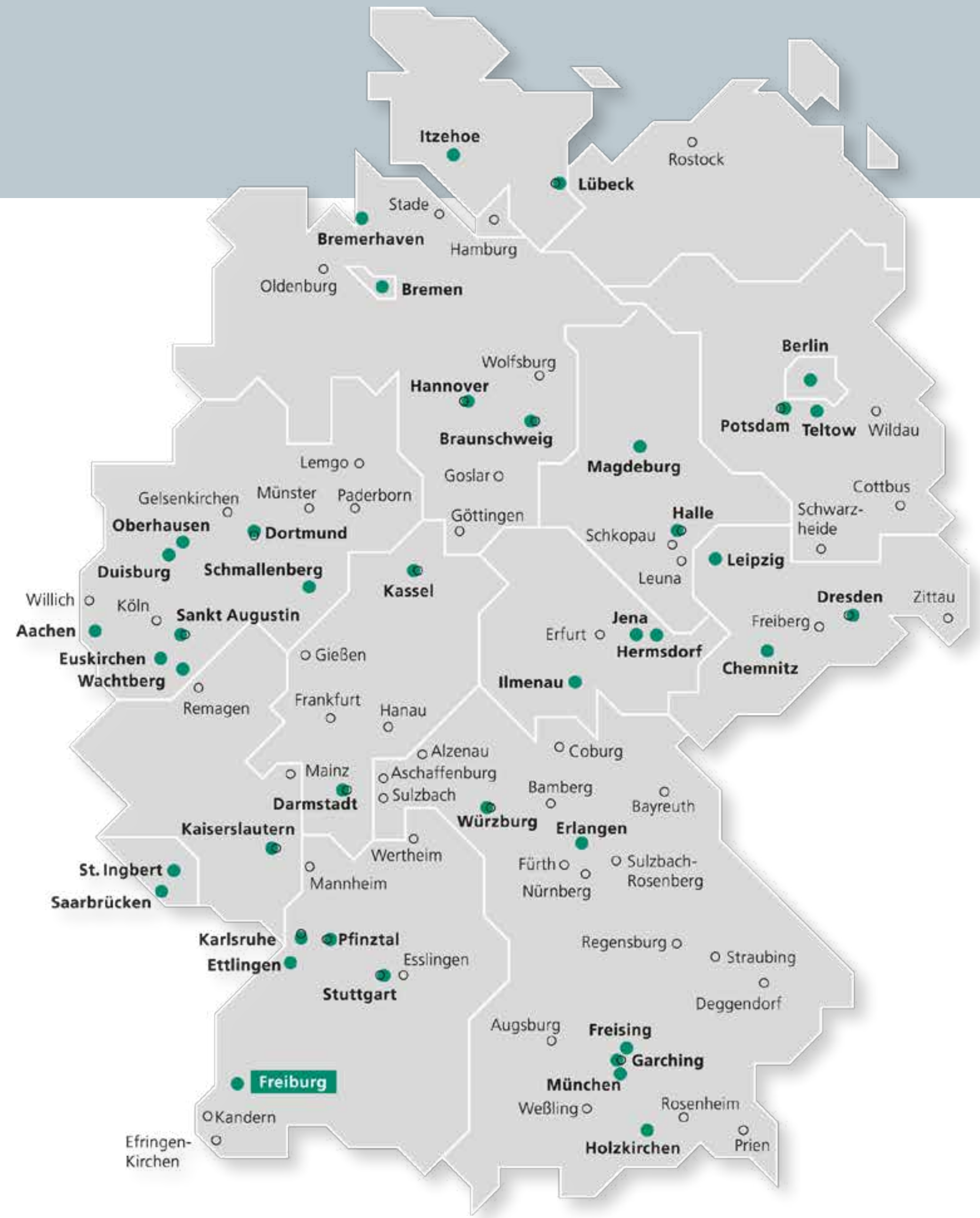
International collaborations with excellent research partners and innovative companies around the world ensure direct access to regions of the greatest importance to present and future scientific progress and economic development.

With its clearly defined mission of application-oriented research and its focus on key technologies of relevance to the future, the Fraunhofer-Gesellschaft plays a prominent role in the German and European innovation process. Applied research has a knock-on effect that extends beyond the direct benefits perceived by the customer: Through their research and development work, the Fraunhofer Institutes help to reinforce the competitive strength of the economy in their local region, and throughout Germany and Europe. They do so by promoting innovation, strengthening the technological base, improving the acceptance of new technologies, and helping to train the urgently needed future generation of scientists and engineers.

As an employer, the Fraunhofer-Gesellschaft offers its staff the opportunity to develop the professional and personal skills that will allow them to take up positions of responsibility within their institute, at universities, in industry and in society. Students who choose to work on projects at the Fraunhofer Institutes have excellent prospects of starting and developing a career in industry by virtue of the practical training and experience they have acquired.

The Fraunhofer-Gesellschaft is a recognized non-profit organization that takes its name from Joseph von Fraunhofer (1787–1826), the illustrious Munich researcher, inventor and entrepreneur.

www.fraunhofer.de/en



Main locations
Other locations

Fraunhofer Institute for Physical Measurement Techniques IPM
Heidenhofstrasse 8
D - 79110 Freiburg
P +49 761 8857 - 0
F +49 761 8857 - 224
info@ipm.fraunhofer.de

www.ipm.fraunhofer.de/en

OUR PARTNERS

We are actively involved in groups, specialist organizations and networks, within the Fraunhofer-Gesellschaft, nationwide – and worldwide.

Fraunhofer-Gesellschaft

- Fraunhofer Group Light & Surfaces
- Fraunhofer Cleaning Technology Alliance
- Fraunhofer Food Chain Management Alliance
- Fraunhofer Traffic and Transportation Alliance
- Fraunhofer Vision Alliance

International

- AAAS – American Association for the Advancement of Science
- ETS – European Thermoelectric Society
- ITS – International Thermoelectric Society
- IEEE – Institute of Electrical and Electronics Engineers
- MRS – Material Research Society
- OSA – Optical Society of America

Germany

- AMA Fachverband für Sensorik
- Arbeitskreis Prozessanalytik der GDCh und DECHEMA
- Biovalley Deutschland e.V.
- CAST e.V. – Competence Center for Applied Security
- CNA Cluster Bahntechnik e.V.
- DFO – Deutsche Forschungsgesellschaft für Oberflächenbehandlung
- DHyG – Deutsche Hydrographische Gesellschaft e.V.
- DKV – Deutscher Kälte- und Klimatechnischer Verein e.V.
- Draht-Welt Südwestfalen – netzwerkdraht e.V.
- DTG – Deutsche Thermoelektrik Gesellschaft e.V.
- FAIM – Forum Angewandte Informatik und Mikrosystemtechnik e.V.
- GDCh – Gesellschaft Deutscher Chemiker
- Green City Freiburg Regional Cluster
- innoEFF Innovations- und Effizienzcluster
- Klimaschutz am Oberrhein e.V. (Strategische Partner)
- microTEC Südwest e.V.
- Nano-Zentrum Euregio Bodensee e.V.
- Photonics BW Innovationsnetz für Optische Technologien
- SPECTARIS – Deutscher Industrieverband für optische, medizinische und mechatronische Technologien e.V.
- VDI/VDE – GMA Gesellschaft für Mess- und Automatisierungstechnik
- VDSI – Verband für Sicherheit, Gesundheit und Umweltschutz bei der Arbeit e.V.

PUBLICATIONS 2017

Fratz, M.; Beckmann, T.
3D-Oberflächenmessung mit digitaler Mehrwellenlängen-Holographie
Sackewitz, M.; Fraunhofer-Allianz Vision [Hrsg.]: Handbuch zur industriellen Bildverarbeitung. Stuttgart, 2017, 195-197

Bartholomé, K.; König, J. D.; Pernau, H.-F.; Balke, B.
Abwärme als Energiequelle: Thermoelektrische Module
Physik in unserer Zeit 48 (2), 89-95, 2017

Eberhardt, A.; Ulmer, U.; Schmitt, K.; Wöllenstein, J.
Advanced white cell design for investigation of ethylene using a nondispersive infrared photometer
AMA Conferences 2017. Proceedings: SENSOR 2017, 18th International Conference on Sensors and Measurement Technology, IRS² 2017, 15th International Conference on Infrared Sensors & Systems. Wunstorf, 2017, 779-782

Stemmler, S.; Weinacker, H.; Reiterer, A.; Koch, B.
Algorithmen für die automatische Erkennung von Blattstörungen - eine geometrische Merkmalsextraktion zur Bewertung der Zustände einzelner Blätter
Allgemeine Vermessungs-Nachrichten AVN 124 (11-12), 370-377, 2017

Cröll, A.; Tonn, J. C.; Post, E.; Böttner, H.; Danilewsky, A. N.
Anisotropic and temperature-dependent thermal conductivity of PbI_2
Journal of Crystal Growth 466, 16-21, 2017

Wolf, R.; Zappe, H.; Buse, K.; Breunig, I.
Batch-processed high-Q integrated lithium-niobate-on-insulator ridge waveguide whispering-gallery resonators
IEEE Conference on Lasers and Electro-Optics Europe & European Quantum Electronics Conference, CLEO/Europe-EQEC 2017. CD-ROM. Piscataway, NJ, 2017, 1 p.

Wolf, R.; Breunig, I.; Zappe, H.; Buse, K.
Cascaded second-order optical nonlinearities in on-chip micro rings
Optics Express 25 (24), 29927-29933, 2017

Schmitt, K.; Tarantik, K.; Pannek, C.; Benito-Altamirano, I.; Casals, O.; Fabrega, C.; Romano-Rodriguez, A.; Wöllenstein, J.; Prades, J. D.
Colorimetric sensor for bad odor detection using automated color correction
Fonseca, Luis [Hrsg.]: Smart Sensors, Actuators, and MEMS VIII. Proceedings of SPIE 10246, Art. 102461F, 2017

Thalmann, M.; Pernau, H.-F.; Strunk, C.; Scheer, E.; Pietsch, T.
Comparison of cryogenic low-pass filters
Review of Scientific Instruments 88 (11), 114703, 2017

Breunig, I.; Fürst, J. U.; Hanka, K.; Buse, K.
Continuous-wave optical parametric oscillation tunable up to 8 μm wavelength
Photorefractive Photonics 2017. Journal of Physics. Conference Series 867, 012010, 2017

Meisenheimer, S.-K.; Fürst, J. U.; Buse, K.; Breunig, I.
Continuous-wave optical parametric oscillation tunable up to an 8 μm wavelength
Optica 4 (2), 189-192, 2017

Veenhuizen, K.; Stone, G. A.; Knabe, B.; Buse, K.; Dierolf, V.
Dependence of stoichiometry of lithium niobate nanocrystals on initial lithium to niobium ratios in the synthesis step
International Conference on Defects in Insulating Materials, ICDIM 2016. IOP Conference Series. Materials Science and Engineering 169, 012022, 2017

Wittstock, V.; Scholz, L.; Bierer, B.; Ortiz Perez, A.; Wöllenstein, J.; Palzer, S.
Design of a LED-based sensor for monitoring the lower explosion limit of methane
Sensors and Actuators B 247, 930-939, 2017

Schiller, A.; Beckmann, T.; Fratz, M.; Belzer, D.; Bertz, A.; Carl, D.; Buse, K.
Digital holography on moving objects: Interference contrast as a function of velocity and aperture width
Applied Optics 56 (16), 4622-4628, 2017

PUBLICATIONS

Schiller, A.; Beckmann, T.; Fratz, M.; Belzer, D.; Bertz, A.; Carl, D.; Buse, K.
Digital holography on moving objects. Multiwavelength height measurements on inclined surfaces
Lehmann, P. H. [Hrsg.]: Optical Measurement Systems for Industrial Inspection X. Proceedings of SPIE 10329, Art. 103290D, 2017

Fratz, M.; Beckmann, T.; Schiller, A.; Seyler, T.; Bertz, A.; Carl, D.; Buse, K.
Digital holography: Evolution from a research topic to a versatile tool for the inline 100% 3D quality control in industry
AMA Conferences 2017. Proceedings: SENSOR 2017, 18th International Conference on Sensors and Measurement Technology, IRS² 2017, 15th International Conference on Infrared Sensors & Systems. Wunstorf, 2017, 286-289

Carl, D.
Digital-holographische 3D-Messtechnik
Sackewitz, M.; Fraunhofer-Allianz Vision [Hrsg.]: Handbuch zur industriellen Bildverarbeitung. Stuttgart, 2017, 134-137

Gobron, O.; Jung, K.; Galland, N.; Predehl, K.; Le Targat, R.; Ferrier, A.; Goldner, P.; Seidelin, S.; Coq, Y. le
Dispersive heterodyne probing method for laser frequency stabilization based on spectral hole burning in rare-earth doped crystals
Optics Express 25 (13), 15539-15548, 2017

Reiterer, A.; Predehl, K.; Leidinger, M.
Die Entwicklung von Laserscannern - Herausforderungen bei neuartigen Anwendungen
Terrestrisches Laserscanning, TLS 2017. DVW-Schriftenreihe 88, 9-21, 2017

Schäfer, R.; Schmidtke, G.; Strahl, T.; Pfeifer, M.; Brunner, R.
EUV data processing methods of the Solar Auto-Calibrating EUV Spectrometers (SolACES) aboard the International Space Station
Advances in Space Research 59 (9), 2207-2228, 2017

Lambrecht, A.; Maier, E.; Pernau, H.-F.; Strahl, T.; Herbst, J.
Gas leak detection by dilution of atmospheric oxygen
Sensors. Online Journal 17 (12), 2804, 2017

Werner, C. S.; Yoshiki, W.; Herr, S. J.; Breunig, I.; Buse, K.
Geometric tuning. Spectroscopy using whispering-gallery resonator frequency-synthesizers
Optica 4 (10), 1205-1208, 2017

Blug, A.; Saum, N.; Bertz, A.; Hofmann, A.
Inline-Oberflächenprüfung von Bahnware
Sackewitz, M.; Fraunhofer-Allianz Vision [Hrsg.]: Handbuch zur industriellen Bildverarbeitung. Stuttgart, 2017, 186-189

Palzer, S.; Wöllenstein, J.; Kneer, J.
Investigating the selective behaviour of CuO in gas sensing applications
7th Forum on New Materials 2016. Advances in Science and Technology 99, 33-39, 2017

Tarantik, K.; Schmitt, K.; Pannek, C.; Miensopust, L.; Wöllenstein, J.
Investigation of gasochromic rhodium complexes regarding their reactivity towards CO
Proceedings 1 (4), 454, 2017

Ersoez, B.; Bauersfeld, M.-L.; Wöllenstein, J.
Ionogel-based composite material for CO_2 sensing deposited on a chemiresistive transducer
Proceedings 1 (4), 314, 2017

Ziolkowski, P.; Boor, J. de; Stiewe, C.; Druschke, I.; Zabrocki, K.; Edler, F.; Haupt, S.; König, J. D.; Mueller, E. R.
Iron disilicide as high-temperature reference material for traceable measurements of Seebeck coefficient between 300 K and 800 K
Journal of Electronic Materials 46 (1), 51-63, 2017

Werner, C. S.; Herr, S.; Buse, K.; Sturman, B.; Soergel, E.; Razzaghi, C.; Breunig, I.
Large and accessible conductivity of charged domain walls in lithium niobate
Scientific Reports 7, 9862, 2017

Herr, S. J.; Buse, K.; Breunig, I.
Laser-active whispering-gallery resonators as versatile platform for optical three-wave mixing
IEEE Conference on Lasers and Electro-Optics Europe & European Quantum Electronics Conference, CLEO/Europe-EQEC 2017. CD-ROM. Piscataway, NJ, 2017, 1 p.

Gao, H.; Lyu, X.; Wöllenstein, J.; Palzer, S.
Layer by layer deposition of colloidal SnO_2 nano particles
Proceedings 1 (4), 318, 2017

Herr, S. J.; Buse, K.; Breunig, I.
LED-pumped whispering-gallery laser
Photonics Research 5 (6), B34-B38, 2017

Ortiz Perez, A.; Bierer, B.; Dinc, C.; Wöllenstein, J.; Palzer, S.
Low-power odor-sensing network based on wake-up nodes
Proceedings 1 (4), 570, 2017

Bierer, B.; Dinc, M. C.; Gao, H.; Wöllenstein, J.; Palzer, S.
MEMS-based array for hydrogen sulfide detection employing a phase transition
Fonseca, Luis [Hrsg.]: Smart Sensors, Actuators, and MEMS VIII. Proceedings of SPIE 10246, Art. 102460D, 2017

Scholz, L.; Ortiz Perez, A.; Bierer, B.; Eaksen, P.; Wöllenstein, J.; Palzer, S.
Miniature low-cost carbon dioxide sensor for mobile devices
IEEE Sensors Journal 17 (9), 2889-2895, 2017

Seyler, T.; Fratz, M.; Beckmann, T.; Bertz, A.; Carl, D.
Miniaturized multiwavelength digital holography sensor for extensive in-machine tool measurement
Lehmann, P. H. [Hrsg.]: Optical Measurement Systems for Industrial Inspection X. Proceedings of SPIE 10329, Art. 103290F, 2017

Opitz, F.; Treffinger, P.; Wöllenstein, J.
Modeling of radiative heat transfer in an electric arc furnace
Metallurgical and Materials Transactions B 48 (6), 3301-3315, 2017

Sandfort, V.; Trabold, B. M.; Abdolvand, A.; Bolwien, C.; Russell, P.; Wöllenstein, J.; Palzer, S.
Monitoring the Wobbe index of natural gas using fiber-enhanced Raman spectroscopy
Sensors. Online Journal 17 (12), 2714, 2017

Bartholomé, K.; Hess, T.; Winkler, M.; Mahlke, A.; König, J. D.
New concept for high-efficient cooling systems based on solid-state caloric materials as refrigerant
Junior, C. [Hrsg.]: Energy and Thermal Management, Air Conditioning, Waste Heat Recovery 2016. Cham, 2017, 178-186

Ortiz Perez, A.; Kallfaß-de Frenes, V.; Filbert, A.; Kneer, J.; Bierer, B.; Held, P.; Klein, P.; Wöllenstein, J.; Benyoucef, D.; Kallfaß, S.; Mescheder, U.; Palzer, S.
Odor-sensing system to support social participation of people suffering from incontinence
Sensors. Online Journal 17 (1), 58, 2017

Holz, P.; Lutz, C.; Brandenburg, A.
Optical scanner system for high resolution measurement of lubricant distributions on metal strips based on laser induced fluorescence
Lehmann, P. H. [Hrsg.]: Optical Measurement Systems for Industrial Inspection X. Proceedings of SPIE 10329, Art. 103292A, 2017

Werner, C. S.; Buse, K.; Breunig, I.
Piezo-tunable second-harmonic-generation in a whispering-gallery resonator
IEEE Conference on Lasers and Electro-Optics Europe & European Quantum Electronics Conference, CLEO/Europe-EQEC 2017. CD-ROM. Piscataway, NJ, 2017, 1 p.

Hoessbacher, C.; Josten, A.; Baeuerle, B.; Fedoryshyn, Y.; Hettrich, H.; Salamin, Y.; Heni, W.; Haffner, C.; Kaiser, C.; Schmid, R.; Elder, D. L.; Hillerkuss, D.; Möller, M.; Dalton, L. R.; Leuthold, J.
Plasmonic modulator with > 170 GHz bandwidth demonstrated at 100 GBd NRZ
Optics Express 25 (3), 1762-1768, 2017

Jia, Y.; Winkler, M.; Szabados, J.; Breunig, I.; Kirste, L.; Cimalla, V.; Zukauskaite, A.; Buse, K.
Potassium tantalate-niobate mixed crystal thin films for applications in nonlinear integrated optics
Photorefractive Photonics 2017. Journal of Physics. Conference Series 867, 012020, 2017

Jia, Y.; Szabados, J.; Winkler, M.; Breunig, I.; Cimalla, V.; Kirste, L.; Zukauskaite, A.; Buse, K.
Potassium-tantalate-niobate mixed crystal thin films for applications in nonlinear integrated optics
IEEE Conference on Lasers and Electro-Optics Europe & European Quantum Electronics Conference, CLEO/Europe-EQEC 2017. CD-ROM. Piscataway, NJ, 2017, 1 p.

Wolf, R.; Breunig, I.; Zappe, H.; Buse, K.
Q-factor enhancement of integrated lithium-niobate-on-insulator ridge waveguide whispering-gallery-mode resonators by surface polishing
Kudryashov, A.V. [Hrsg.]: Laser Resonators, Microresonators, and Beam Control XIX. Proceedings of SPIE 10090, Art. 1009002, 2017

Tarantik, K.; Kluge, M.; Bartholomé, K.; Geczi, E.; Vetter, U.; Vergez, M.; König, J. D.
Reproducibility and reliability in manufacturing new high-temperature thermoelectric modules
Junior, C. [Hrsg.]: Energy and Thermal Management, Air Conditioning, Waste Heat Recovery 2016. Cham, 2017, 109-115

Eberhardt, A.; Schmitt, K.; Wöllenstein, J.
Rotating interference filter spectrometer for the detection of ethylene in the ripening process of climacteric fruit
19th International Conference on Solid-State Sensors, Actuators and Microsystems, TRANSDUCERS 2017. Piscataway, NJ, 2017, 1445-1448

Gao, H. Jia, H.; Bierer, B.; Wöllenstein, J.; Lu, Y.; Palzer, S.
Scalable gas sensors fabrication to integrate metal oxide nanoparticles with well-defined shape and size
Sensors and Actuators B 249, 639-646, 2017

Herr, S.; Folwill, Y.; Buse, K.; Breunig, I.
Self-frequency doubling in a laser-active whispering-gallery resonator
Optics Letters 42 (13), 2627-2630, 2017

Wolf, S.; Trendle, T.; Kießling, J.; Herbst, J.; Buse, K.; Kühnemann, F.
Self-gated mid-infrared short pulse upconversion detection for gas sensing
Optics Express 25 (20), 24459-24468, 2017

Wolf, S.; Trendle, T.; Kießling, J.; Kühnemann, F.
Sensitive infrared detection through efficient pulsed upconversion for remote sensing applications
IEEE Conference on Lasers and Electro-Optics Europe & European Quantum Electronics Conference, CLEO/Europe-EQEC 2017. CD-ROM. Piscataway, NJ, 2017, 1 p.

Hansen, A.-L.; Dankwort, T.; Groß, H.; Etter, M.; König, J. D.; Düppel, V.; Kienle, L.; Bensch, W.
Structural properties of the thermoelectric material $CuCrS_2$ and of deintercalated $CuxCrS_2$ on different length scales: X-ray diffraction, pair distribution function and transmission electron microscopy studies
Journal of Materials Chemistry C 5 (36), 9331-9338, 2017

Pernau, H.-F.
Techniques for characterizing thermoelectric materials: Methods and the challenge of consistency
Pineda, D. D. [Hrsg.]: Thermoelectric Energy Conversion: Basic Concepts and Device Applications. Weinheim, 2017, 93-110

Jörg, C. I.; Letscher, F.; Fleischhauer, M.; Freymann, G. von
Temporal defects in photonic topological insulators
CLEO: QELS Fundamental Science, 2017, Art. FM2G.4

Jägle, M.; Pernau, H.-F.; Pfützner, M.; Benkendorf, M.; Li, X.; Bartel, M.; Herm, O.; Drost, S.; Rutsch, D.; Jacquot, A.; Wöllenstein, J.
Thermal-electrical impedance spectroscopy for fluid characterization
AMA Conferences 2017. Proceedings: SENSOR 2017, 18th International Conference on Sensors and Measurement Technology, IRS² 2017, 15th International Conference on Infrared Sensors & Systems. Wunstorf, 2017, 157-160

Moure, A.; Rull-Bravo, M.; Abad, B.; Campo, A. del; Munoz Rojo, M.; Aguirre, M. H.; Jacquot, A.; Fernandez, J. F.; Martin-Gonzalez, M.
Thermoelectric Skutterudite/oxide nanocomposites: Effective decoupling of electrical and thermal conductivity by functional interfaces
Nano Energy 31, 393-402, 2017

Hofmann, A.
Track & Trace ohne Markierung: Markierungsfreie Identifizierung und intrinsischer Fälschungsschutz in einem Schritt
Inspect 18 (1), 38-39, 2017

Reiterer, A.
Trends bei mobilen Laserscannern
Allgemeine Vermessungs-Nachrichten AVN 124 (11-12), 341, 2017

Wolf, S.; Kießling, J.; Kunz, M.; Popko, G.; Buse, K.; Kühnemann, F.
Upconversion-enabled array spectrometer for the mid-infrared, featuring kilohertz spectra acquisition rates
Optics Express 25 (13), 14504-14515, 2017

Breunig, I.
Whispering gallery optical parametric oscillators become mature
IEEE Conference on Lasers and Electro-Optics Europe & European Quantum Electronics Conference, CLEO/Europe-EQEC 2017. CD-ROM. Piscataway, NJ, 2017, 1 p.

DISSERTATIONS 2017

Schäfer, R.
Charakterisierung von gasbasierten Absolutdetektoren für den EUV-Bereich
[Freiburg/Brsg., Univ., Diss., 2017]

Wolf, S.
Infrarotspektroskopie mittels nichtlinear-optischer Hochkonversion
[Freiburg/Brsg., Univ., Diss., 2017]

Rademacher, S.
Verteiltes Gassensornetzwerk für die ortsaufgelöste Messung von Gasen im Katastrophenumfeld
Aachen, 2017 [Freiburg/Brsg., Univ., Diss., 2017]

GRANTED PATENTS 2017

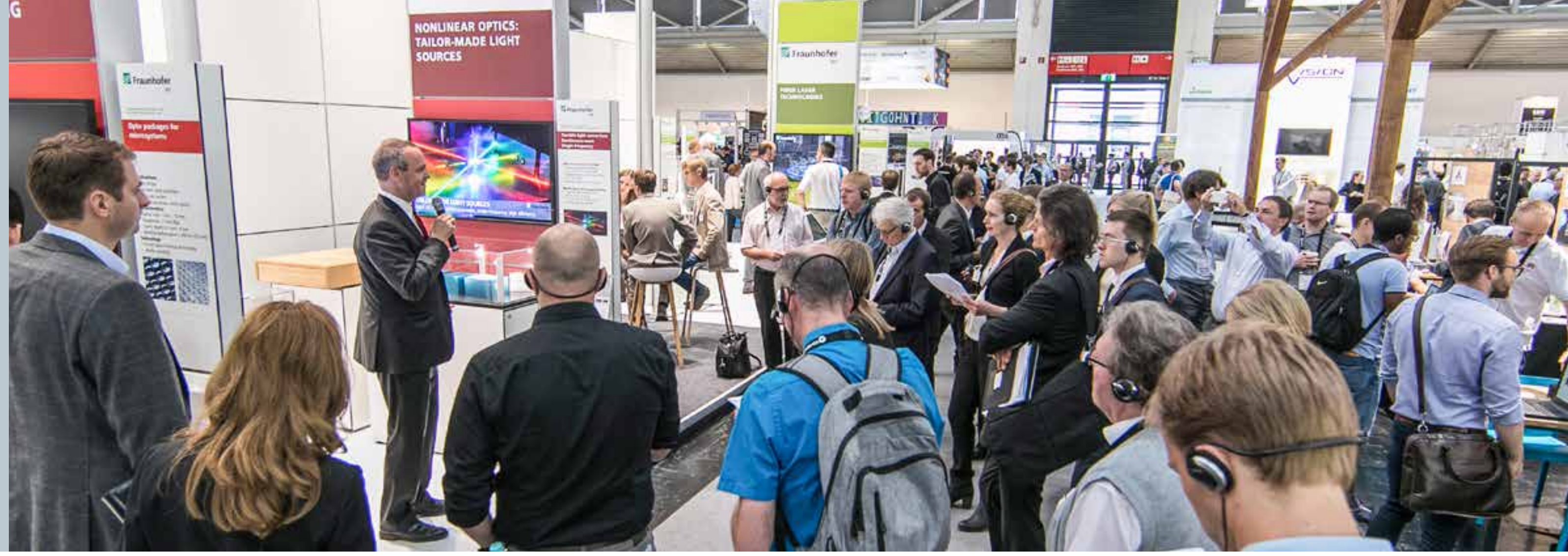
Fratz, M.; Hofmann, A.
Optische Linse und Herstellungsverfahren
DE 10 2009 011 838

Winkler, M.; König, J.
Verfahren zum Herstellen einer elektrischen Kontaktschicht an einem mehrschichtigen, elektrischen Bauelement
DE 10 2014 007 890

Blug, A.
Verfahren zur Zuordnung von Bildpunkten
DE 10 2009 006 089

Kießling, J.; Leidinger, M.; Kühnemann, F.
Vorrichtung und Verfahren zur nichtlinearen Frequenzkonversion elektromagnetischer Strahlung
DE 10 2016 112 343

Leidinger, M.; Kießling, J.; Kühnemann, F.
Wellenlängenmessvorrichtung und Verfahren zur Messung der Wellenlänge
DE 10 2016 107 501



> LASER World of PHOTONICS: Dr Frank Kühnemann is presenting a new generation of laser light sources developed by Fraunhofer IPM to the press.

FAIRS 2017

ISH
The world's leading trade fair for the topic of water and energy
Frankfurt, March 14–18, 2017
Own booth
Fraunhofer IPM presented thermoelectric generators for converting thermal energy into electricity, which can be used in a wide variety of systems.

Control
International Trade Fair for Quality Assurance
Stuttgart, May 9–12, 2017
Fraunhofer Vision Alliance booth
Fraunhofer IPM presented inline measurement systems for image-based surface inspection and marker-free tracing.

SENSOR+TEST
The Measurement Fair
Nuremberg, May 30 – June 1, 2017
Fraunhofer-Gesellschaft booth
Energy-efficient gas sensors as well as thermal sensors and systems for use in sensor networks were exhibited. In addition, the institute presented a system for marker-free tracing of semi-finished products.

LASER World of PHOTONICS
International Trade Fair and Congress for Photonics Components, Systems and Applications
Munich, June 26–29, 2017
Fraunhofer-Gesellschaft booth
The institute displayed laser sources and laser-based measurement and analysis systems for scientific, production-related, environmental and safety applications. Fraunhofer IPM also gave insights into the development status of inline holographic 3D measurement technology in the Open Innovation Area hosted by the University of Stuttgart.

INTERGEO
Global Hub of the Geospatial Community
Berlin, September 26–28, 2017
Own booth
Fraunhofer IPM debuted its Lightweight Airborne Profiler (LAP), a particularly lightweight laser scanner developed especially for use on aerial vehicles. A deep learning framework for automated analysis of 3D measurement data was also exhibited.

DeburringEXPO
Trade Fair for Deburring Technologies and Precision Surfaces
Karlsruhe, October 10–12, 2017
Fraunhofer-Gesellschaft booth
Fraunhofer IPM presented optical systems and imaging techniques that can be used to analyze surfaces and 3D structures during production, as well as to regulate processes. The systems enable 100 percent real-time monitoring. Furthermore, Tobias Seyler took part in an expert forum where he explained the advantages of multiwave digital holography for measuring precision surfaces and burr residue with micrometer accuracy.

parts2clean
Leading International Trade Fair for Industrial Parts and Surface Cleaning
Stuttgart, October 24–26, 2017
Fraunhofer-Gesellschaft booth
The institute showcased the F-Scanner, an image-based fluorescence measurement system for surface cleanliness inspection. The laser-based system measures impurities on component surfaces at the rate of production.

Blechexpo
International trade fair for sheet metal working
Stuttgart, November 7–10, 2017
Fraunhofer-Gesellschaft booth
Fraunhofer IPM exhibited two measurement systems. HoloTop illustrated the capabilities of digital holographic microscopy in inline 3D component measurement. In addition, Fraunhofer IPM and development partner Raziol Zibulla & Sohn GmbH were presented with the Award for Blechexpo in the Process Control and Quality Assurance category for their inline lubrication measurement system based on a fluorescence laser scanner.

<< At INTERGEO, Fraunhofer IPM debuted a »Deep Learning Framework« for automated analysis of 3D measurement data.

FAIRS 2018: PREVIEW

Control
Stuttgart, April 24–27, 2018

ACHEMA
Frankfurt, June 11–15, 2018

SENSOR+TEST
Nuremberg, June 26–28, 2018

InnoTrans
Berlin, September 18–21, 2018

Chillventa
Nuremberg, October 16–18, 2018

INTERGEO
Frankfurt, October 16.–18, 2018

parts2clean
Stuttgart, October 23–25, 2018

euroBLECH
Hannover, 23.10.2018–26.10.2018

EVENTS AT FREIBURG'S FRAUNHOFER INSTITUTES

Freiburg Science Market
Freiburg, July 14–15, 2017
Thousands of visitors were able to experience research at first hand at the Science Market. The event is organized by the University of Freiburg together with Freiburg Wirtschaft Touristik und Messe FWTM. The five Freiburg Fraunhofer institutes also attended, presenting research with a practical focus: What happens in a car crash? How can LED lighting improve quality of life? How can we optimize thermal processes? How can we build fridges without harmful refrigerants? And what do adhesion factors have to do with a Carrera track? The next Freiburg Science Market will take place on July 12 and 13, 2019.

Baden-Württemberg Industriewoche (Industry Week) Interactive exhibition / industry forum
Sparkassen-FinanzZentrum Freiburg, June 22, 2017
As part of the Industry Week 2017, scientists from Freiburg's five Fraunhofer institutes explained how new technology is developed at Fraunhofer – hand in hand with industry. Alongside an evening event for invited guests, guided tours were given to school classes, and a public exhibition was held at the premises of Sparkasse's Freiburg branch. Together, the five Freiburg Fraunhofer institutes highlighted the contribution that applied research makes to local companies.

EVENTS AND WORKSHOPS AT FRAUNHOFER IPM

7th Gas Sensor Workshop 2017
Fraunhofer IPM, March 16, 2017
This was the seventh workshop held by Fraunhofer IPM for the gas sensor community. Nine speakers presented applications and trends in gas sensor technology, and around one hundred experts in the field of gas sensors used the opportunity to share information and network with one another.

Caloric Systems Workshop 2017
Fraunhofer IPM, March 28, 2017
As a result of increased research and progress in caloric materials, the construction of especially energy-efficient caloric cooling systems and heat pumps is almost within reach. The Caloric Systems Workshop launched by Fraunhofer IPM in 2017 gave 60 participants an overview of the latest developments and trends in magnetocaloric, electrocaloric and elastocaloric systems.

Trends in laser spectroscopy – from source to application
Fraunhofer IPM, November 28, 2017
Today, lasers are among the most important optical tools – in both research and industry. Laser-based spectrometers are the system of choice for demanding measurement tasks, as they are fast, accurate and versatile. Around 50 participants came together to discuss new applications for classic laser spectroscopy as well as advances in the development of light sources for spectroscopy.

WORKSHOPS IN 2018: PREVIEW

Industry Workshop on Optical Gear Measurement
Fraunhofer IPM, June 14, 2018

MoLaS – Mobile Laser Scanning Technology Workshop
Fraunhofer IPM, November 14–15, 2018

EDITORIAL NOTES

Fraunhofer IPM
Fraunhofer Institute for
Physical Measurement Techniques IPM
Heidenhofstrasse 8
D - 79110 Freiburg
P + 49 761 8857 - 0
F + 49 761 8857 - 224
info@ipm.fraunhofer.de
www.ipm.fraunhofer.de/en

Editorial Address
Fraunhofer Institute for
Physical Measurement Techniques IPM
Communications and Media
Holger Kock
Heidenhofstrasse 8
D - 79110 Freiburg
P + 49 761 8857 - 129
holger.kock@ipm.fraunhofer.de

Editorial Team
Holger Kock, Anja Strobel, Tim Schröder (p. 54 - 55)

Design
Sonja Aust, Adam Lipinski

Translation
Übersetzungsbüro Peschel, Freiburg

Picture acknowledgements
Adam Lipinski / Fraunhofer IPM (35)
Allesandro Colle / Shutterstock (34)
Annelie Schiller / Fraunhofer IPM(23)
Artistdesign29 / Shutterstock (60)
AVL ETS GmbH (16; 17)
Caroline Schmidt / STRABAG SE (33)
Chlorophylle / Fotolia (40)
Delpixel / Shutterstock (54)
Dominik Störk / Fraunhofer IPM (Titel; 28)
Escherich / Fraunhofer (15)
Holger Kock / Fraunhofer IPM (3; 6; 7; 12; 14; 18; 19; 22; 29; 31; 36; 37; 50; 51; 56; 68)
Kai-Uwe Wudtke (9; 13; 25; 26; 27; 39; 41; 43; 44; 47; 48; 49; 53)
Klaus D. Wolf / Fraunhofer ILT (67)
Markus Leidinger / Fraunhofer IPM (66)
Markus Winkler, David Rapp / Fraunhofer IPM(57)
NASA (11)
Ociacia / Shutterstock (13)
Olivia Herm / Fraunhofer IPM(14)
Sonja Aust / Fraunhofer IPM (45; 55)
TimSiegert-batcam / Fotolia (32)
Tobias Seyler / Fraunhofer IPM (21)
VBM, Sebastian Hauenstein (15)

Print
Burger Druck GmbH, Waldkirch

MIX Paper from responsible sources FSC® C095332

www.ipm.fraunhofer.de/en