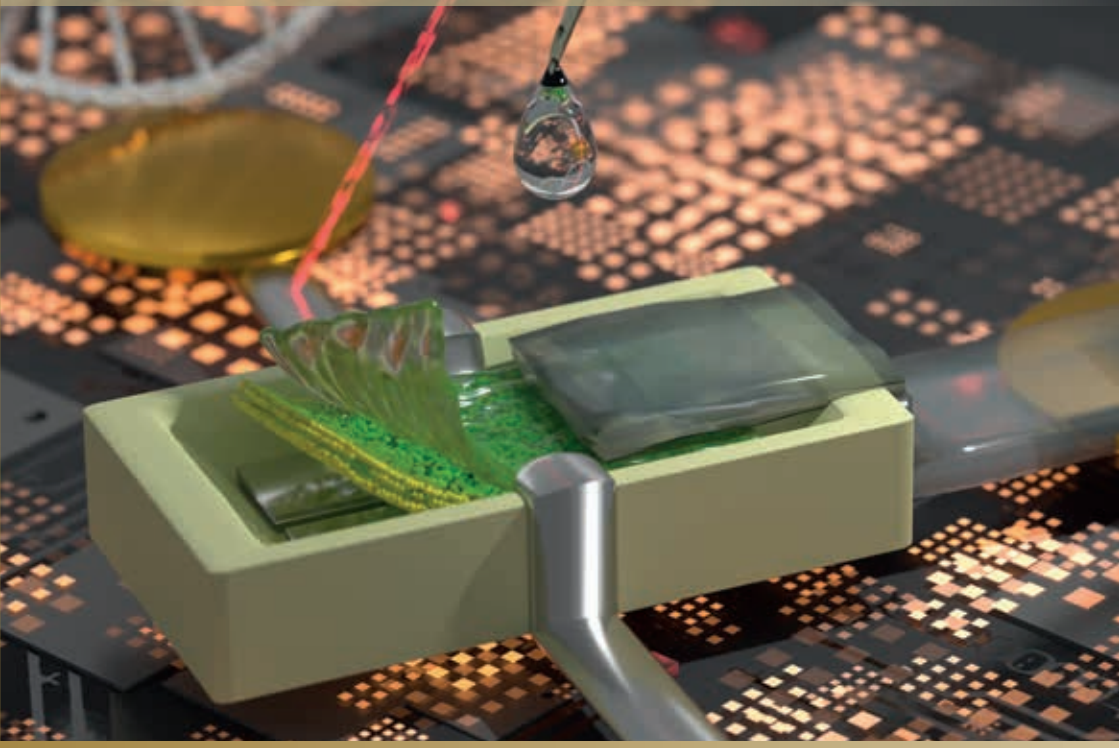
Additive Nano- and Micro-Fabrication in Optics, Electronics and Bioengineering



Abstract Booklet

March 23 – 27, 2025

Schöntal Monastery, Germany

Content

Welcome

Dear Colleagues and Friends,

We are delighted to welcome you to

The Future 3D Additive Manufacturing – The 3DMM2O Conference 2025: Additive Nano- and Micro-Fabrication in Optics, Electronics and Bioengineering.

The annual conference on topics surrounding 3D Additive Manufacturing is organized by the Cluster of Excellence "3D Matter Made to Order" (3DMM2O). 3DMM2O is a joint Research Cluster of Karlsruhe Institute of Technology (KIT) and Heidelberg University (Uni HD).

The conference shall be a platform for new approaches in the field of 3D Additive Manufacturing. It aims at bridging the gap between advanced additive manufacturing techniques and their application in fields such as optics, electronics, and bioengineering.

Lectures by international speakers, poster sessions and social networking events will give you an insight in alternating aspects of 3D Additive Manufacturing as well as the opportunity for inspiring and fruitful scientific discussions and exchange.

Enjoy the conference amidst the stunning and historic surroundings of Schöntal Monastery!

Jasmin Aghassi
Karlsruhe Institute of Technology (KIT)

Christian Koos
Karlsruhe Institute of Technology (KIT)

Wolfram Pernice
Heidelberg University (Uni HD)

Program

Sunday, March 23

4:00 PM	Check-In
6:00 PM–8:00 PM	**Dinner at Individual Time**
8:00 PM	Informal Get-Together

Monday, March 24

	Breakfast	
9:00 AM–9:05 AM	Opening & Welcome	
9:05 AM–9:45 AM	Integration of Scalable Photonic Neural Networks Using 3D Additive Fabrication	**Daniel Brunner**
9:45 AM–10:25 AM	Conductivity Switching in Molecular Ferroelectrics: A New Route to Neuromorphic Memory?	**Martijn Kemerink**
10:25 AM–10:40 AM	**Coffee Break**	
10:40 AM–10:55 AM	**Contributed Talk:** Light-Relay Materials for Spatiotemporal Remote Photoswitching and Hydrogel Actuation	**Diego Ciardi**
10:55 AM–11:10 AM	**Industry Talk:** BIO INX	**Jasper Van Hoorick**
11:10 AM–11:50 AM	Self-Healing, Stretchable and Recyclable Electronics	**Fabio Cicoira**
11:50 AM–12:00 PM	Group Picture	
12:00 PM–1:30 PM	**Lunch**	
1:30 PM–2:10 PM	Integrating 2D Materials in Silicon Microchips	**Mario Lanza**
2:10 PM–3:00 PM	Tailoring Carbon-Based Materials via Additive Nano- and Micro-Fabrication	**Ruth Schwaiger**
3:00 PM–3:20 PM	**Coffee Break**	
3:20 PM–4:00 PM	Polymeric Mixed Conductors for Bioelectronic Devices	**Sahika Inal**
4:00 PM–4:40 PM	Sorted and Functionalized Semiconducting Carbon Nanotubes for Optoelectronics	**Jana Zaumseil**
4:40 PM–5:00 PM	**Coffee Break**	
5:00 PM–5:10 PM	Flashtalks	
5:10 PM–7:00 PM	Poster Session I	
7:00 PM	**Dinner**	

Program

Tuesday, March 25

	Breakfast	
9:00 AM	Welcome	
9:00 AM–9:40 AM	Engineering iPSCs to Model Amyotrophic Lateral Sclerosis	**Akshay Bhinge**
9:40 AM–10:20 AM	Hybrid Synaptic Contacts Between Neurons and Functionalized Structured Surfaces	**Jürgen Klingauf**
10:20 AM–10:35 AM	**Coffee Break**	
10:35 AM–11:15 AM	Recapitulating Human Brain Development in a Dish to Understand Disease	**Simone Mayer**
11:15 AM–11:55 AM	Molecular Switches that Learn and Emulate Synaptic Behavior	**Christian Nijhuis**
11:55 AM–12:35 PM	Hydrogels in Microsystems: From Glucose Sensors to Neural Implants	**Simon Binder**
12:35 PM–2:00 PM	**Lunch**	
2:00 PM–2:40 PM	Volume Electron Microscopy for the Synaptic-Resolution Reconstruction of Neuronal Circuits	**Gaspar Jékely**
2:40 PM–3:20 PM	Model-based Thermoviscous Flow Robotics for High-Definition Microassembly	**Moritz Kreysing**
3:20 PM–3:35 PM	**Coffee Break**	
3:35 PM–4:15 PM	Biopolymers for Unconventional and Sustainable Electronics	**Luisa Petti**
4:15 PM–4:55 PM	Inverse Design of 3D-Printed Photonic Devices	**Carsten Rockstuhl**
4:55 PM–5:15 PM	**Coffee Break**	
5:15 PM–5:25 PM	Flashtalks	
5:25 PM–7:00 PM	Poster Session II	
7:00 PM	**Dinner**	

Wednesday, March 26

	Breakfast	
9:00 AM	Welcome	
9:00 AM–9:40 AM	3D Printed Complex Microoptics: Fundamentals and First Applications	**Harald Gießen**
9:40 AM–10:20 AM	Functional Nano-Imprint Lithography for Optics, Bio and Electronics	**Marc Verschuuren & Rob Voorkamp**
10:20 AM–10:35 AM	**Coffee Break**	
10:35 AM–11:15 AM	High-Quality Glass Micro- & Nanostructures by Two-Photon Grayscale Lithography (2GL®)	**Jens Bauer**
11:15 AM–11:30 AM	**Contributed Talk:** Soft and Stiff 3D Microstructures by Step-Growth Photopolymerization Using a Single Photoresin and Multi-Photon Laser Printing	**Florian Feist**
11:30 AM–11:45 AM	**Contributed Talk:** High-Efficiency Metagrating for Oblique Plance Microscopy	**Maryna Meretska**
11:45 AM–12:00 PM	**Contributed Talk:** 3D Multiphoton Nanolithography of Biomaterials	**Dmitry Sivun**
12:00 PM–1:30 PM	**Lunch**	
1:45 PM–2:00 PM	Meet for Social Program	
2:00 PM–6:00 PM	Social Program	
7:00 PM	**Conference Dinner & Poster Award**	

Thursday, March 27

	Check-Out, **Breakfast**
from 9:00 AM	Departure

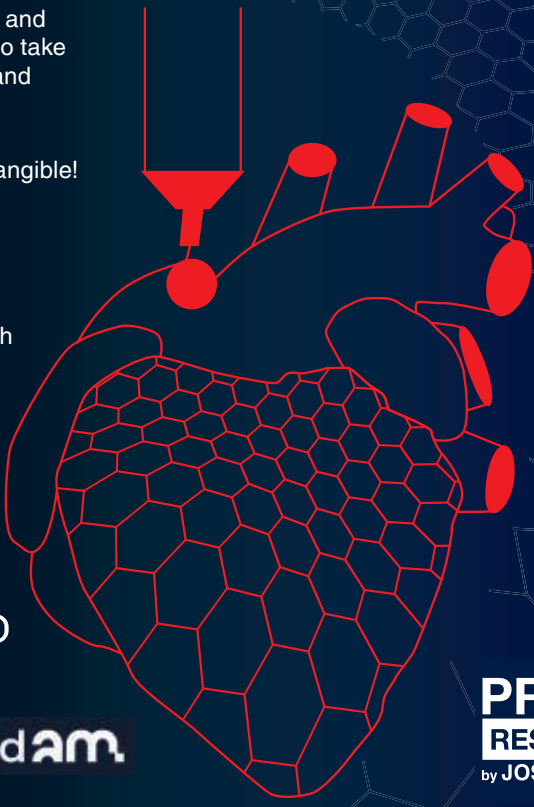
PROTHOTYPING
PRO3DUCTION

We offer a range of leading brands in 3D printing!

As a partner of science and industry, we are ready to take the next step with you and help shape the future of medicine.

We make innovations tangible!

- Highest precision
- Maximum reliability
- High-speed printing
- Complete solution with Carl Roth service



BIOINX

RAISE3D

forward am

Henkel

PRUSA RESEARCH by JOSEF PRUSA

► **You can find our entire 3D range in our webshop.**

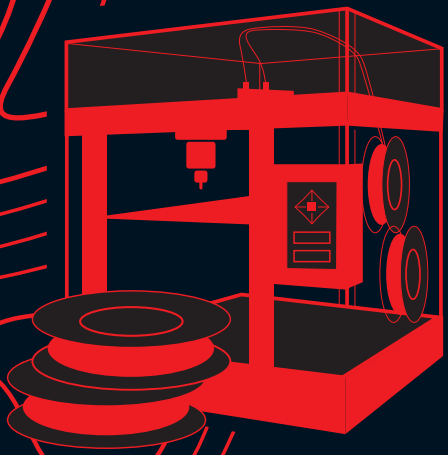
Carl Roth GmbH + Co. KG
Schoemperlenstraße 3-5 | 76185 Karlsruhe, Germany
P +49 721 5606-0 | **F** +49 721 5606-149
M info@carlroth.com | ***www.carlroth.com***

Your Partner for ***Labware, Life Science*** *and* ***Chemicals.***

ROTH

CONVENTIONAL 3D-PRINTING

by Carl ROTH



3D Printing – The Technology of the Future

- 3D Printers
- Filaments
- Resins
- Powders

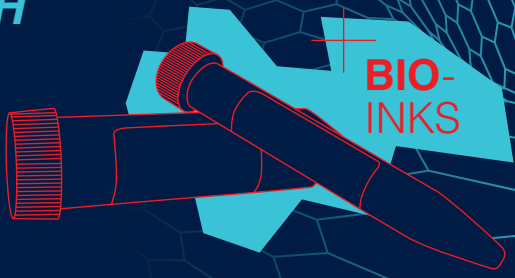
… and a range of Accessories!

3D-BIOPRINTING

by Carl ROTH

Bioinks for:

- Extrusion-based Bioprinting
- Volumetric Bioprinting
- Digital Light Projection
- Multiphoton Lithography



Labware, Life Science, Chemicals, Applications, 3D Printing.

CARL ROTH®

Speakers'

In Alphabetical Order

Wednesday, March 26
10:35 AM–11:15 AM

Jens Bauer

Karlsruhe Institute of Technology (KIT), Germany

HIGH-QUALITY GLASS MICRO- & NANOSTRUCTURES BY TWO-PHOTON GRAYSCALE LITHOGRAPHY (2GL®)

Two-photon grayscale lithography (2GL®), which is the two-photon polymerization (2PP) laser-printing with power modulated dynamic size control over the polymerized voxels, has demonstrated unprecedented combinations of pristine structure quality and high throughput.

However, the technique has so far only been demonstrated to manufacture polymer microstructures. Herein, we present a 2GL® fabrication route to print optical-grade silica glass micro- & nanostructures from our recently introduced pre-glass resin system, which is based on polyhedral oligomeric silsesquioxane (POSS) chemistry.

The POSS resin is shown to print pre-glass templates via 2GL® with sharply resolved features and minimal surface roughness at print speeds of hundreds of millimeters per second. Moderate thermal treatment at 650°C in air atmosphere drives-off the material's organic parts and converts the templates to high-quality silica glass structures.

We demonstrate a spectrum of glass benchmark structures with varying complexity and sizes and discuss adjusted chemical formulations for high-speed printing with minimal artefacts.

Abstracts

Tuesday, March 25
9:00 AM–9:40 AM

Akshay Bhinge

University of Exeter, UK

ENGINEERING IPSCS TO MODEL AMYOTROPHIC LATERAL SCLEROSIS

Amyotrophic lateral sclerosis (ALS) is a devastating neurodegenerative disease characterized by progressive motor neuron loss. Though animal models have provided key insights into disease pathogenesis, species-specific differences have hampered translation of these findings to humans.

Human induced pluripotent stem cells (iPSCs) have revolutionized our ability to study ALS by providing patient-derived models that capture disease-relevant cellular phenotypes. Using CRISPR-Cas9, we have engineered iPSCs to create physiologically relevant human models that recapitulate key cellular, molecular and biochemical features observed in ALS patient neurons.

Our models exhibit hallmark neurodegenerative phenotypes, offering a robust platform for mechanistic studies. We are now advancing these models into complex, multicellular 3D neural systems to better understand cell-cell interactions in disease, ultimately paving the way for therapeutic discovery.

Speakers'

Tuesday, March 25
11:55 AM–12:35 PM

Simon Binder

Karlsruhe Institute of Technology (KIT), Germany

HYDROGELS IN MICROSYSTEMS: FROM GLUCOSE SENSORS TO NEURAL IMPLANTS

Hydrogels are a group of soft materials which show excellent biocompatibility but can also be designed to respond with a volume change to parameters such as glucose, salinity or complex biomarkers. This makes them attractive for sensing applications, in particular for medical devices and implants.

The talk highlights how hydrogel-based sensors work and the various ways a hydrogel's volume response can be transduced into an electrical signal. The sensors presented are intended for applications in drug monitoring or blood glucose measurement, both as point-of-care device or subcutaneous implant. Moreover, hydrogels may also serve as scaffolds for guided cell growth. This is being utilised in neural implants for the brain-computer-interface. Starting from the "Utah Array" neural implant, an insight into a biohybrid version of such an implant will be given.

The biohybrid approach is expected to result in both improved implant acceptance as well as recording of neural activity with high spatial resolution.

Abstracts

Daniel Brunner

Institut FEMO-ST, France

INTEGRATION OF SCALABLE PHOTONIC NEURAL NETWORKS USING 3D ADDITIVE FABRICATION

Neural network (NN) concepts revolutionize computing by solving challenges previously thought to be reserved to the abstract intelligence of humans.

However, the astonishing and substantial conceptual breakthroughs are so far not mirrored by advances in integrated hardware specialized in physically implementing NNs. As always with computing, scalability is the key metric.

Integrated photonic architectures have the potential to revolutionize energy consumption and speed. However, conventional 2D lithography strongly limits the size of integrated NNs due to fundamental scaling laws.

We want to overcome this problem by using 3D printed photonic integration, where photonic waveguides realizing a NN's connections.

Speakers'

Monday, March 24
11:10 AM–11:50 AM

Fabio Cicoira

Polytechnique Montréal, Canada

SELF-HEALING, STRETCHABLE AND RECYCLABLE ELECTRONICS

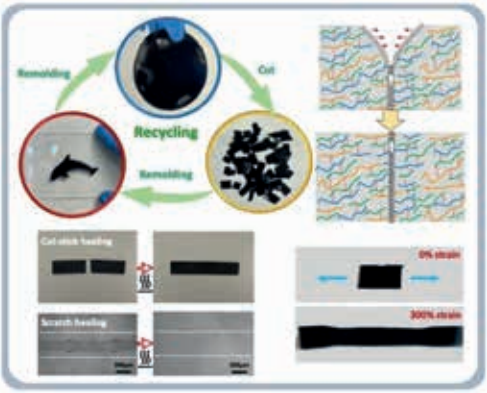
Materials able to regenerate after damage have attracted a great deal of attention since the ancient times. For instance, self-healing concretes, able to resist earthquakes, aging, weather, and seawater are known since the times of ancient Rome and are still the object of research.

While several mechanically healable materials have been reported, self-healing conductors are still relatively rare, and are attracting enormous interest for applications in electronic skin, wearable and stretchable sensors, actuators, transistors, energy harvesting, and storage devices, such as batteries and supercapacitors.[1] Self-healable and recyclable conducting materials have the potential to reduce electronic waste by enabling the repair and reuse of electronic components, which can extend the lifespan of electronic devices. Furthermore, they can be used for wearable electronic and biomedical devices, which are often subject to mechanical stress causing damage to their components.

Conducting polymers exhibit attractive properties that makes them ideal materials for bioelectronics and stretchable electronics, such as mixed ionic-electronic conductivity, leading to low interfacial impedance, tunability by chemical synthesis, ease of process via solution process and printing, and biomechanical compatibility with living tissues. However, they show typically poor mechanical properties and are therefore not suitable as self-healing materials.

Abstracts

In our group, we produced several self-healing and stretchable conductors by mixing aqueous suspensions of the conducting polymer poly(3,4-ethylenedioxythiophene) polystyrene sulfonate (PEDOT:PSS) with other materials providing the mechanical characteristics leading to self-healing, like for instance polyvinyl alcohol (PVA), polyethylene glycol, polyurethanes and tannic acid. [2-9] In this talk, various types of self-healing will be presented and correlated with the electrical and mechanical properties of the materials. The use of the self-healing gels and films as epidermal electrodes and other devices will be also discussed.



Conductive materials obtained from blends of polyurethane-PEDOT:PSS and PEG showcase exceptional stretchability, toughness, and self-healing properties. Moreover, these materials can be recycled several times and maintain their mechanical and electrical properties.

1 Y. Li, X. Zhou, B. Sarkar, F. Cicoira et al., Adv. Mater. 2108932, 2022.
2 Y. Li, X. Li, S. Zhang, F. Cicoira et al., Adv. Funct. Mater. 30, 2002853, 2020.
3 Y. Li, X. Li, R. N., S. Zhang, F. Cicoira, et al. Flexible and Printed Electronics 4, 044004, 2019.
4 S. Zhang, Y. Li, F. Cicoira et al. Adv. Electron. Mater 1900191, 2019.
5 S. Zhang, F. Cicoira, Adv. Mater. 29, 1703098, 2017.
6 X. Zhou, G. A. Lodygensky, F. Cicoira et al., Acta Biomaterialia 139, 296-306, 2022.
7 P. Kateb et al., Flexible and Printed Electronics, 8 (4), 045006, 2024.
8 X. Zhou, F. Cicoira et al., J. Mater. Chem. C, 12, 5708, 2024.
9 J. Kim., F. Cicoira et al. Mater. Horiz. 11, 348, 2024.

Speakers'

Wednesday, March 26
9:00 AM–9:40 AM

Harald Gießen

Stuttgart University, Germany

3D PRINTED COMPLEX MICROOPTICS: FUNDAMENTALS AND FIRST APPLICATIONS

We utilize femtosecond 3D printing to generate complex 3D microoptics, consisting of aspherical systems which include also doublet or multiplett lenses.

We demonstrate achromatic systems using hybrid refractive/diffractive optics as well as achromats using different materials with varying refractive index and dispersion.

Wavefront measurements of the 3D printed systems indicate aberrations over the entire image field of less than lambda/10.

These systems can be printed directly onto single mode or multicore optical fibers, to realize ultrasmall endoscopes and side-looking OCT systems for blood vessels.

We have demonstrated imaging of plaques in the coronary arteries of living pigs.

When printed onto single quantum emitters or single photon detectors, they allow for efficient in- and out-coupling to single mode fibers for quantum technologies.

Abstracts

Sahika Inal

King Abdullah University of Science and Technology (KAUST), Saudi Arabia

POLYMERIC MIXED CONDUCTORS FOR BIOELECTRONIC DEVICES

Organic mixed ionic and electronic charge conductors offer a unique toolbox for establishing electrical communication with biological systems.

In this talk, I will introduce this rising class of materials for bioelectronic interfacing and explain how their multifunctionality can be harnessed to develop next-generation optoelectronic devices operating at aqueous electrolyte interfaces.

I will specifically highlight one application where these devices are used to detect biochemical molecules. I will discuss two types of organic electronic sensors: one designed to detect Alzheimer's disease-associated proteins, surpassing the performance of current state-of-the-art methods, and another capable of detecting coronavirus spike proteins at the physical limit.

Drawing from our experience with patient samples, I will address potential shortcomings of proof-of-concept biosensor platforms and explore strategies for overcoming these challenges.

By tackling these problems, we improve device performance to a level that marks a considerable step toward biochemical sensing of infectious and noninfectious disease biomarkers.

Speakers'

Tuesday, March 25
2:00 PM–2:40 PM

Gaspar Jékely

Heidelberg University, Germany

VOLUME ELECTRON MICROSCOPY FOR THE SYNAPTIC-RESOLUTION RECONSTRUCTION OF NEURONAL CIRCUITS

Neuronal connectomics aims to map synaptic wiring diagrams in blocks of neural tissue or across entire organisms. Currently, only electron microscopy can provide synaptic resolution, but other modalities such as coherent X-ray and expansion microscopy are rapidly catching up.

I will talk about our volume EM pipeline and how we use it to map whole-body neural circuits in small aquatic animals. In the experimentally accessible and small larval stages of the marine annelid Platynereis, we can combine whole-body connectomics with neuronal activity imaging, behavioural experiments, transgenesis and CRISPR manipulations, to link genes to neurons and behaviours.

Similar approaches could be used to characterise structure-function relationships in neuronal organoids or hybrid neuron-on-chip systems.

Abstracts

Martijn Kemerink

Heidelberg University, Germany

CONDUCTIVITY SWITCHING IN MOLECULAR FERROELECTRICS: A NEW ROUTE TO NEUROMORPHIC MEMORY?

The sheer infinite freedom to design and synthesize organic molecules allows, amongst many other things, to fuse multiple functionalities in a single compound.

In this talk I will focus on a specific class of small molecular materials that combine dipolar and semiconducting functionalities. When brought into a (solid) state with sufficient long-range order, dipole-dipole interaction can give rise to a ferroelectric state. It turns out that the ferroelectric polarization couples to the charge transport, leading to a conductivity that is different for current flow parallel and anti-parallel to the polarization direction.

Since typical ferroelectric materials show (meta) stable intermediate polarization states, the resulting material has a continuously tunable conductivity, which might be relevant for neuromorphic applications. In this talk, I will present the current state of the art in terms of materials and formal understanding.

Speakers'

Tuesday, March 25
9:40 AM–10:20 AM

Jürgen Klingauf

University of Münster, Germany

HYBRID SYNAPTIC CONTACTS BETWEEN NEURONS AND FUNCTIONALIZED STRUCTURED SURFACES

In the central nervous system communication between neurons occurs at specialized junctions called synapses, whereby a single neuron may be in contact with many other neurons by hundreds of synapses.

At the chemical synapse, electrical signals trigger controlled secretion of neurotransmitter via exocytosis of synaptic vesicles at the presynaptic site. The neurotransmitters diffuse across the synaptic cleft and activate postsynaptic receptor channels, generating an electric signal in the postsynaptic cell. Progress in identifying the molecular mechanisms of synaptic vesicle fusion and recycling, however, has been hampered by the use of mass culturing systems which do not allow quantitative assessment at the individual synapse level and due to the small size of presynaptic boutons close to the diffraction limit of light.

We developed a purely presynaptic preparation, the xenapse, presynaptic boutons formed by cultured mouse hippocampal neurons or by induced human neurons on micropatterned host substrates (glass coverslips or chips) functionalized with synaptogenic cell adhesion proteins. Xenapses are formed en face directly onto the glass substrate enabling optical single vesicle recording by total internal reflection microscopy. Xenapses show all the hallmarks of a typical synapse both structurally and physiologically.

In summary, we established a more homogenous and scalable synaptic culture system with robust synapse formation, that can be used to interface living synapses with nanostructured biomimetic surfaces and communicate with single synaptic contacts in a biohybrid system.

Abstracts

Moritz Kreysing

Karlsruhe Institute of Technology (KIT), Germany

MODEL-BASED THERMOVISCOUS FLOW ROBOTICS FOR HIGH-DEFINITION MICROASSEMBLY

Optical traps have long been proposed for the precision assembly of microstructures, but their utility is limited by the material properties of both the medium and the particles.

Here, as an alternative, we employ laser-generated thermoviscous flows to achieve precise alignment of micro-objects regardless of their material characteristics. By creating complex laminar flow fields, we demonstrate micro-robotics with up to 30 degrees of freedom in viscous solutions.

Formulated as a global and fully differentiable optimization problem, our model-based approach nowyields (i) increased robustness and convergence and (ii) emergent collective behavior, and (iii) paves the way toward AI-controlled, objective-oriented micromanipulations.

Current research involves integrating 3D-printed channels to adavance thermoviscous flows manipulation within confined spaces, enhance imaging capabilities, and broaden the possibilities for manipulating biological cells.

Our results establish high-definition microfluidic manipulations with transformative potential for assembly, augmented micro-manufacturing, micro-robotics and optically actuated micro-factories, where the right things happen to be at the right place at the right time.

Speakers'

Monday, March 24
1:30 PM–2:10 PM

Mario Lanza

National University of Singapore

INTEGRATING 2D MATERIALS IN SILICON MICROCHIPS

Two-dimensional (2D) materials have outstanding physical, chemical and thermal properties that make them attractive for the fabrication of solid-state micro/nano-electronic devices and circuits. However, synthesizing high-quality 2D materials at the wafer scale is difficult, and integrating them in silicon microchips brings associated multiple challenges.

Nevertheless, in the past few years substantial progress has been achieved and leading companies like TSMC, Intel and Samsung have started to work in this direction too. In this talk I will discuss how to integrate 2D materials in micro/nano-electronic devices, circuits, and microchips, giving a general overview of the global progress achieved in the field and presenting our last developments in hybrid 2D/CMOS applications.

I will put special emphasis on devices and circuits for memristive technologies, including data storage, computation, encryption, and communication. I will also discuss the main technological challenges to face in the next years and provide some recommendations on how to solve them.

Abstracts

Simone Mayer

Karlsruhe Institute of Technology (KIT), Germany

RECAPITULATING HUMAN BRAIN DEVELOPMENT IN A DISH TO UNDERSTAND DISEASE

The human brain is characterized by unique features that are not present in other species including animal models.

The development of brain organoids derived from pluripotent stem cells over the last decade has revolutionized our understanding of human brain development at the molecular and cellular level. I am using brain organoids as a tool to model diverse neurodevelopmental and neurodegenerative disorders caused by genetic and environmental impacts.

Specifically for the rare pediatric disorder pontocerebellar hypoplasia, I have recently established brain region-specific organoid models that recapitulate the pathology in the neocortex and cerebellum. Using this unique tool, I am now investigating disease mechanisms as well as developing therapeutic approaches.

Additionally, my group is working on developing organoids as a model system further by enhancing analysis methods as well as through bioengineering approaches.

Speakers'

Tuesday, March 25
11:15 AM–11:55 AM

Christian Nijhuis

University of Twente, The Netherlands

MOLECULAR SWITCHES THAT LEARN AND EMULATE SYNAPTIC BEHAVIOR

Our brains constitute a molecular computer that is able to process enormous amounts of information with a tiny energy budget [1]. Inspired by the energy efficiency of brains and the ever-increasing demand for miniaturised electronics, there is a drive to develop devices that mimic the dynamic character of neurons and synapses. To achieve this goal, brain-like computing is emulated with energy inefficient and complex silicon-based circuits or with mesoscale memristors, but these approaches still require large amounts of energy.

For these reasons, it is important to develop new types of hardware that can mimic brain-like computation processes [1,2]. We have been developing molecular switches that behave like synapses with the aim to realize spiking neural networks.
I will introduce a new type of molecular switch that can remember its switching history [3]. By coupling fast electron transport to slow proton addition steps via dynamic covalent bonds, the switches display time-dependent switching probabilities which can be used for brains-inspired and reconfigurable electronics [4,5,6].

These artificial synapses are promising to develop alternative neural networks and open new ways to design electronic devices by exploiting their inherent dynamical properties.

1) Christensen et al. Neuromorph. Comput. Eng. 2022, 2, 022501.
2) Zhu, J., Zhang, T., Yang, Y.; Huang, R. A Appl. Phys. Rev. 2020, 7, 011312.
3) Thompson, D.; Barco, E. d.; Nijhuis, C. A. Appl. Phys. Lett. 117, 030502 (2020).
4) Wang, Y.; Zhang, Q.; Nickle, C.; Venkatakrishnarao, D.; Zhang, Z.; Leoncini A.; Qi, D.-C.; Han, Y.; del Barco, E.; Thompson, D.; Nijhuis, C. A. Nat. Mater. 2022, 21, 1403-14011.
5) Zhang, Q.; Wang, Y.; Nickle, C.; Zhang, Z.; Leonchini, A.; Qi, D.-C.; Sotthewes, k.; Borrini, A.; Zandvliet, H.J.W.; del Barco, E.; Thompson, D.; Nijhuis, C. A. Nat. Commun. 2024, 15, 8300.
6) Wang, Y.; Zhang, Q.; Nickle, C.; Zhang, Z.; Leonchini, A.; Qi, D.-C.; Borrini, A.; Han, Y,; del Barco, E.; Thompson, D.; Nijhuis, C. A. Nanoscale Horiz., 2025: DOI: 10.1039/D4NH00211C

Abstracts

Luisa Petti

Free University of Bozen-Bolzano, Italy

BIOPOLYMERS FOR UNCONVENTIONAL AND SUSTAINABLE ELECTRONICS

Recent advances in materials science and manufacturing have enhanced electronic devices by adding features like flexibility, stretchability, biocompatibility, and biodegradability. These capabilities are essential for smart devices that adapt to 3D surfaces, dissolve in specific environments, and interact with biological systems, benefiting fields such as environmental monitoring, wearable technology, medical implants, and sustainable agriculture. Biopolymers, as renewable and eco-friendly materials, provide a promising foundation for these technologies while addressing concerns about electronic waste.

Nanocellulose (CNC) and chitin nanocrystals (ChNC) are notable biopolymers due to their biodegradability and sustainable production. CNC offers high mechanical strength, optical transparency, and good dielectric properties, while chitosan, derived from chitin, is abundant, biocompatible, and possesses anti-bacterial and bio-adhesive properties. Demonstrated applications include flexible resistive temperature detectors (RTDs) and thermistors on chitosan substrates, which can be used to monitor body fluids, pollutants, and plant health, providing sustainable bio-interfacing options.

Biopolymer electrolytes also hold promise for solid-state organic electrochemical transistors (OECTs), which use electrolytes to conduct ions within an organic mixed ionic-electronic conductor. Unlike traditional electrolytes, biopolymer-based versions are biodegradable and derived from renewable resources, helping reduce environmental impact. Here we show printed chitosan- and agar-based electrolytes in OECTs enabling applications like biosensing, wearable technology, and neuromorphic circuits.

In addition to electronics, biopolymers act as scaffolds for cell growth and plant support in biohybrid systems. Hydrogels like polyethylene oxide (PEO) and alginate, used in 3D bioprinting, support cell growth and tissue regeneration. In agriculture, superabsorbent biopolymer scaffolds aid plant growth and water retention, with minimal environmental impact. This integration of biopolymers, electronics, and living systems can drive sustainable next-generation devices, aligning technology with nature.

Speakers'

Tuesday, March 25
4:15 PM–4:55 PM

Carsten Rockstuhl

Karlsruhe Institute of Technology (KIT), Germany

INVERSE DESIGN OF 3D-PRINTED PHOTONIC DEVICES

Nowadays, we can define the spatial distribution of materials over many centimeters with a typical voxel size well below one micrometer thanks to 3D nanoprinting technology.

The materials in reach with such a technology offer unprecedented degrees of freedom to control light propagation.

In this contribution, we outline various approaches to provide digital blueprints for structured photonic materials that are feasible for fabrication with additive manufacturing techniques and tailored to meet demands in various applications.

The structures we design comprise complex free-form surfaces and fully structured photonic materials in 3D. Multiple approaches for solving the inverse problem are exploited in this endeavor, e.g., the adjoint method, automatic differentiation, and machine learning-based methods.

Abstracts

Ruth Schwaiger

Forschungszentrum Jülich GmbH, Germany

TAILORING CARBON-BASED MATERIALS VIA ADDITIVE NANO- AND MICRO-FABRICATION

Carbon-based materials, ranging from amorphous carbon to nanostructured graphene and diamond-like carbon, exhibit exceptional mechanical properties such as high strength, elasticity, and wear resistance.

These properties, combined with their chemical stability and lightweight nature, make them ideal for diverse applications in optics, electronics, and bioengineering. The ability to fine-tune the microstructure through advanced additive fabrication techniques allows unprecedented control over their mechanical behavior and functional performance.

This presentation will explore the intersection of additive nano- and micro-fabrication and carbonbased materials, focusing on how microstructural engineering influences mechanical properties. We will discuss key fabrication techniques, which enable precise structural control at the nanoscale.

Furthermore, we will highlight how these innovations translate to real-world applications underscoring the extraordinary potential of carbon-based materials in pushing the boundaries of next-generation technologies.

Speakers'

Wednesday, March 26
9:40 AM–10:20 AM

Marc Verschuuren (photo)
and Rob Voorkamp

SCIL Nanoimprint Solutions, The Netherlands

FUNCTIONAL NANO-IMPRINT LITHOGRAPHY FOR OPTICS, BIO AND ELECTRONICS

Nanoimprint is a relatively new form of lithography where a patterned stamp is used to replicate the information. Substrate Conformal Imprint Lithography (SCIL) uses a soft-stamp based NIL technique and still achieves high resolution, low pattern deformation, and sub-micron overlay alignment.

Most NIL techniques use organic imprint resists that cure (transform from liquid to a solid after moulding into the inverse stamp shape) due to a crosslinking reaction initiated by UV radiation. Although being versatile, these organic materials do have disadvantages related to material stability under (blue) light and at elevated temperatures.

Inorganic materials made through a sol-gel route offer an inorganic based crosslinking route towards the direct replication of full inorganic patterns, offering additional functionality (chemical, physical). By optimizing the resist and imprint system together, a moderate shrinkage of ~ 8% has been achieved in combination with room temperature pattern formation within 1 minute. The resist systems cover a refractive index as low as 1.18 up to 2.1 in the visible and is UV and visible light stable and can retain 30nm patterns up to 1100°C. Faithful replication of patterns down to sub-10nm, aspect ratios >6 and pattern reproducibility with less than 1nm variation over 300mm wafers have been demonstrated. Additionally, the silicone rubber based stamps allow demoulding of negative release pattern, such as slanted gratings.

In the contribution, we will show examples of materials used for nano-photonics (meta-surfaces, DOEs), laser, bio-applications and possibilities for electronic components.

Abstracts

Jana Zaumseil

Heidelberg University, Germany

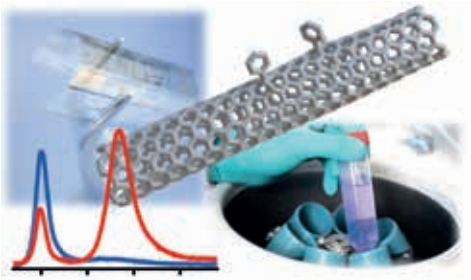
SORTED AND FUNCTIONALIZED SEMICONDUCTING CARBON NANOTUBES FOR OPTOELECTRONICS

Advanced dispersion and sorting methods have enabled the purification of large amounts of semiconducting single-walled carbon nanotubes (SWCNTs) with different diameters and bandgaps that can be integrated in various (opto-)electronic devices with outstanding properties. For example, field-effect and electrochemical transistors based on printed networks of sorted SWCNTs exhibit high charge carrier mobilities (>10 $cm^2/(Vs)$) and on/off current ratios (> 108) that are suitable for circuits or sensors.

Chemically doped SWCNT films show high electrical conductivities, high Seebeck coefficients as well as excellent power factors (up to 920 μW m-1 K-2) that make them a highly promising material for flexible thermoelectric generators. To further improve performance, it is important to understand the interplay of a multitude of parameters such as nanotube length, diameter distribution, alignment, n- and p-doping, dielectric environment, intentional and unintentional defects and their impact on macroscopic charge transport.

Moreover, the controlled introduction of luminescent defects through covalent functionalization leads to substantially enhanced near-infrared photo[1]luminescence for bio-imaging, optical sensors, light-emitting devices and even single[1]photon emitters, which opens up an even wider range of applications for these unique one-dimensional and printable semiconductors.

I will give an overview of our recent results and insights on covalent functionalization of SWCNTs, the impact of surface passivation on device performance and how to achieve stable p-doping via pH[1]dependent proton-coupled electron transfer.



Contributed

Sorted by Date

Monday, March 24

10:40 AM–10:55 AM	Light-Relay Materials for Spatiotemporal Remote Photoswitching and Hydrogel Actuation	**Diego Ciardi**

Talks

A **Contributed Talk** consists of a 10-minute talk and a 5-minute Q & A session.

Wednesday, March 26

11:15 AM–11:30 AM	Soft and Stiff 3D Microstructures by Step-Growth Photopolymerization Using a Single Photoresin and Multi-Photon Laser Printing	**Florian Feist**
11:30 AM–11:45 AM	High-Efficiency Metagrating for Oblique Plance Microscopy	**Maryna Meretska**
11:45 AM–12:00 PM	3D Multiphoton Nanolithography of Biomaterials	**Dmitry Sivun**

LIGHT-RELAY MATERIALS FOR SPATIOTEMPORAL REMOTE PHOTOSWITCHING AND HYDROGEL ACTUATION

Diego Ciardi

Franciela A. Soares; Brigitta Dzs*; Andreas Walther*

Light-responsive functional materials have been extensively explored, since light constitutes an extreme versatile tool that can be used to transmit energy and information. Within the soft matter domain, polymer gels, liquid crystals and/or biological materials endowed with photoresponsiveness have emerged as candidates for advanced optical materials.[1] As an example, photoswitchable hydrogels can undergo reversible structural or optical changes upon exposure to specific wavelengths of light, thus raising an increasing interest for soft robotics, biomedical engineering, and adaptive optics applications.

A fundamental challenge in the efficient activation of photoswitches is the necessity of an external light source to drive the forward and backward the isomerization process. Typically, light-emitting diodes (LEDs) are employed due to their tunability in intensity and wavelength. However, they illuminate a broad surface area, often requiring additional optical elements such as lenses or optical fibers to achieve localized irradiation. These conventional optical devices are usually composed of solid elements that are bulky, thus introducing experimental complexity and potential limitations in degrees-of-freedom.[2]

To address this limitation, we explore the use of a Digital Micromirror Device (DMD) as a versatile and high-resolution tool for spatially controlled light delivery. In this work, we demonstrate how a DMD can serve as the sole light source to precisely pattern, photoswitch, and actuate functionalized hydrogels, eliminating the need for complex optical setups. Furthermore, we introduce a strategy wherein functionalized hydrogels themselves act as wavelength converters, shifting the incident light to the desired spectral region for optimal photoswitching.

This methodology enables precise spatiotemporal control over the isomerization of azopyrazole-based photoswitches, leading to well-defined variations in color and lighttriggered actuation of the hydrogel[3]. By leveraging this approach, we establish a foundation for microscale communication through light-relay within hydrogel systems, opening avenues for programmable soft matter, optically controlled actuators, and photonicresponsive biomaterials.

1 Li, Quan; Schenning, A. P. H. J.; Bunning, T. J. Adv. Optical Mater. 2019, 7, 1901160
2 Zhang, Y.; Zheng, Z. J.; Li, Q. Responsive Materials, 2022, 2, e20230029
3 Ludwanowski et al., Angew. Chem. Int. Ed. 2021, 60, 4358 – 4367

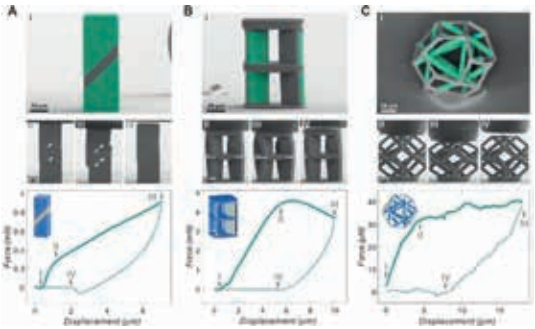
SOFT AND STIFF 3D MICROSTRUCTURES BY STEP-GROWTH PHOTOPOLYMERIZATION USING A SINGLE PHOTORESIN AND MULTI-PHOTON LASER PRINTING

Florian Feist

Tugce Nur Eren, Jiajie Liang, Jonathan Ludwig Günter Schneider,
Martin Wegener, Jens Bauer, Katharina Ehrmann, Christopher Barner-Kowollik

Manufacturing 3D microstructures with multi-material properties via two-photon 3D laser printing (2PLP) remains a significant challenge mainly due to restrictions inherent to conventional chain-growth photoresins. Herein, a crosslinker-, additive- and initiator-free resin formulation is introduced that allows for the printing of 3D microstructures with disparate mechanical properties via a gray-tone lithography approach.[1]

The step-growth photopolymerization-based self-dimerization of visible-light-active *ortho*-methylbenzaldehydes (*o*MBA) can be precisely controlled by simply altering the printing parameters (i.e., laser power, scan speed) on demand. It is established that the laser exposure dose (D_{exp}) directly influences the material properties. While stiff materials with a Young's modulus above 1300 MPa at the higher edge of the D_{exp} can be produced, soft materials with a Young's modulus of below 135 MPa at the lower edge of the Dexp can also be fabricated in a single step. Thus, the herein pioneered resin offers a very broad material property window for multi-material printing via 2PLP, which is not achievable with conventional resins. The introduced broad material property window are interesting for applications requiring diverse mechanical properties, such as in mechanobiology, microfluidics, or soft robotics. The capabilities of the advanced resin are demonstrated herein by printing structures with hard and soft segments in a single fabrication step and visualizing their unique mechanical response to compression via *in situ* measurements and imaging.



Multi-material demonstrator structures and their mechanical behavior under uniaxial compression.
A Multi-material micropillar.
B Chiral bi-material beam structure that transforms an applied compression into twisting.
C Truncated octahedron tensegrity metamaterial cell.
Force-displacement curves are provided, along with SEM images. The stiff blocks, bi-material beams and compression bars, respectively, are colorized in green.

[1] T. N. Eren,§ J. Liang,§ J. L. G. Schneider, M. Wegener, J. Bauer,* K. Ehrmann,* F. Feist,* C. Barner-Kowollik*, under revision.

HIGH-EFFICIENCY METAGRATING FOR OBLIQUE PLANE MICROSCOPY

Maryna Meretska

Akash Ibnun Nur[1], Martijn Moorlag[2,3], Reto Fiolka[4], Fabian Voigt[3], Maryna Leonidivna Meretska[1,3]

1 Karlsruhe Institute of Technology, Germany
2 Delft University of Technology. The Netherlands
3 Harvard University, USA; 4UT Southwestern, USA

Three-dimensional (3D) imaging systems are essential for studying and understanding the complex interactions among biological processes within an organism. These systems allow us to observe and analyze various characteristics, such as blood flow and neural activity. To achieve these objectives, it is crucial to develop high-performance, fast, and gentle 3D microscopy techniques.

Traditionally, researchers have utilized fluorescence-based microscopic systems, such as confocal and widefield microscopy, to create 3D images of biological samples. However, oblique plane microscopy (OPM) is gaining popularity because it employs a single objective for both illumination and fluorescence capture, thereby simplifying optical design and enhancing sample accessibility compared to traditional methods.

A key component of the OPM setup is the diffraction grating. Fluorescent light is directed onto the grating at an angle of 37 degrees, resulting in about 20% of the light being diffracted into the system. We have applied an inverse design technique to develop a metagrating that increases this efficiency, allowing the setup to capture 80% of the diffracted light.

3D MULTIPHOTON NANOLITHOGRAPHY OF BIOMATERIALS

Dmitry Sivun

Dmitry Sivun[1], Christoph Naderer[1], Stephan Haudum[2], Ian Teasdale[2] and Jaroslaw Jacak[1]

1 School of Medical Engineering and Applied Social Science, University of Applied Sciences Upper Austria, Linz, Austria
2 Institute of Polymer Chemistry, Johannes Kepler University, Linz, Austria

Over the past decade, additive manufacturing has gained increasing attention due to its wide range of applications, from biomedical engineering to aerospace. One rapidly growing field is tissue engineering, which relies on structuring biocompatible, biodegradable, and bioactive materials [1]. Structuring natural materials is typically limited to 2D with feature sizes in the tens of micrometers[2]. In contrast, synthetic polymers enable structuring with features below 100 nm, though most monomers have limited biocompatibility and too rigid for proper cell-scaffold interactions [3]. As a result, precise nano-structuring of functional biocompatible polymers remains a major challenge.

In this contribution, we present functional protein- and amino acid-based photoresists with tunable mechanical properties, enabling 3D multiphoton lithography (MPL). For protein-based resins, we employed methacrylated proteins (streptavidin, bovine serum albumin, collagen) as biofunctional monomers, with polyethylene glycol diacrylate or methacrylated hyaluronic acid as cross-linkers and riboflavin (vitamin B2) as a photoinitiator. For amino acid-based phosphorodiamidate monomers, we used vinyl-functionalized valine or alanine. We tested various resin combinations for their 2D/3D writing capabilities and quantitatively analyzed feature size, Young's modulus, and functionalization of the fabricated nanostructures using atomic force and single-molecule fluorescence microscopy. Our results demonstrate the fabrication of three-dimensional structures with Young's moduli ranging from 20 kPa to 100 MPa, depending on composition, and sub-diffraction-limited feature sizes.

Notably, amino acid-based polymers exhibited a unique property: their Young's modulus could change up to tenfold between dry and wet conditions without significant swelling. Additionally, we show that structured streptavidin retained its biological functionality after methacrylation and 3D MPL printing. Finally, we confirmed the applicability of our structures by fabricating supports for fluorescent absorbance immuno-assays and developing a delivery system for extracellular vesicles to HeLa cells.

[1] C. Liao, A. Wuethrich, M. Trau, Applied Materials Today 19 (2020) 100635.
[2] Z. Huang, G.C.-P. Tsui, Y. Deng, C.-Y. Tang, Nanotechnology Reviews 9 (2020) 1118–1136.
[3] B. Buchroithner, D. Hartmann, S. Mayr, Y. Jin Oh, D. Sivun, A. Karner, B. Buchegger, T. Griesser, P. Hinterdorfer, T. A. Klar, J. Jacak, Nanoscale Adv. 2 (2020) 2422–2428.

Flash Talks

Monday, March 24
5:00 – 5:10 PM

Auxetic Scaffolds via Multiphoton Lithography for Neuroregeneration	**Andreas Parlanis**
Bioinspired Multifunctional Hydrogel-based Scaffolds for Bone Tissue Regeneration via Multiphoton Lithography	**Myrto Charitaki**
POM@MOF Imprinted Electrochemical Sensor for Dopamine Detection	**Wenijing Wang**
Toward a T-Matrix-Based Multiple Scattering Framework for Acoustic Metastructures	**Nikita Ustimenko**
Multi-Scale Simulations for Predicting the Nonlinear Optical Properties of Metal-Organic Frameworks	**Mariia Poleva**
Optimizing the Performance of Printed Indium Oxide Thin-Film Transistors Through Gallium Incorporation	**Mahsa Saghafi**
Site-Selective Biofunctionalization of 3D Microstructures via Direct Ink Writing	**George Mathew**
3D Printing of Metallic Micro- and Nanostructures Using Localized Electrodeposition and Direct Electron Beam Writing	**Ekaterina Shabratova**
Singlet Fission of Pentacene Embedded in a Surface-Anchored Metal-Organic Framework	**Martin Richter**
Electron Probe Microanalysis to Determine Average Densities of Porous Thin Films	**Kristian Kraft**
Developing and Characterizing Conductive Hydrogels for 3D Printing	**Tamara Verena Unterreiner**

Tuesday, March 25
5:15 – 5:25 PM

3D Printing of PEDOT:PSS based Photoresin for Manufacturing Meta-structure Architected Pressure Sensors with High Sensitivity	**Ozan Karakaya**
Electrohydrodynamic Printing-based Microscale Organic Photodetectors	**Kai Xia**
Optically Induced Flows in Complex Laser-Printed Geometries	**Rayehe Rezaei**
THz System Packaging Facilitated by Tailored Metal-Coated 3D-Printed Freeform Structures	**Sina Foroutan-Barenji**
Inverse Design of Structurally Integral 3D Nanophotonic Devices using Auxiliary Thermal Solvers	**Oliver Kuster**
Linear and Nonlinear Optical Properties of Molecular Materials: A Scale-Bridging Computational Workflow	**Marjan Krstić**
Color and Fluorescence Switchable of 2D and 3D Printed Hybrid Materials	**Matthias Steurer**
Two Material Properties from One Wavelength-Orthogonal Photoresin Enabled by a Monochromatic Laser Integrated Stereolithographic Apparatus (Mono LISA)	**Xingyu Wu**
Unlocking the Flexibility of Multi-Material 3D Printing for Soft Iontronics	**Trevor Kalkus**

A **Flashtalk** consists of a 60-seconds talk.

Everyone who gives a **Flashtalk** also gives a **Poster Presentation on the same day**. The corresponding times of the **Poster Presentations** are as follows:

& Poster Presentation

Monday, March 24:
Poster Session I
5:10 – 7:00 PM

Tuesday, March 25:
Poster Session II
5:25 – 7:00 PM

Poster Presentation Only

Tuesday, March 25	Multiport High-Performance Plug-and-Play Optical Packaging for Photonic Integrated Circuits	**Erik Jung**
	Fast and Efficient Purification of DNA Origami	**Izar Schärf**
	Contraction-Enabled Super Resolution in 3D-Printed Glass Nanoarchitectures	**Jiajie Liang**
	Plateau Border-Type Truss-Lattice Metamaterials with Ultra-Lightweight Instability-Resistance	**Mirhan Özdemir**

AUXETIC SCAFFOLDS VIA MULTIPHOTON LITHOGRAPHY FOR NEUROREGENERATION

Andreas Parlanis[1,2],

Maria Farsari[1], Anthi Ranella[1]

1 Institute of Electronic Structure and Laser, Foundation for Research and Technology Hellas, Heraklion, Greece;
2 Department of Biology, University of Creter

Multiphoton lithography (MPL) is an additive manufacturing technology that can generate 3D structures. The beam's high intensity can cause the absorption of two or more photons within the focal volume of a photocurable material, leading the material to crosslink locally. Moving the beam in a 3D pattern permits the creation of 3D structures with great resolution.

Auxetic materials are materials with a negative Poisson's ratio that possess exceptional mechanical characteristics and have been highlighted as potential candidates for the fabrication of porous scaffolds.

This study aims to explore the influence of varying mechanical properties of scaffolds on the mechanotransduction pathways and neural regeneration of neural stem cells. Specifically, it involves a comparative analysis of three distinct porous scaffolds: auxetic elastic, non-auxetic elastic, and stiff fabricated through MPL.

Flash Talks

BIOINSPIRED MULTIFUNCTIONAL HYDROGEL-BASED SCAFFOLDS FOR BONE TISSUE REGENERATION VIA MULTIPHOTON LITHOGRAPHY

Myrto Charitaki[1,2],

Elmina Kambouraki[1], Anthi Ranella[1], Maria Farsari[1]

1 Foundation of Research and Technology, Greece;
2 Department of Materials Science and Engineering, University of Crete, Greece

The development of biomimetic scaffolds with precise architecture and multifunctionality is a pivotal challenge in regenerative medicine. In this study,2-photon polymerization (2PP),an advanced multiphoton lithography technique,enabled the fabrication of highly defined and complex scaffolds using gelatin methacrylate (GelMA).Although the fabrication of hydrogels using 2PP poses significant challenges,scaffolds with intricate architectures designed to mimic the hierarchical structure of bone successfully fabricated by overcoming these limitations.

GelMA,derived from hydrolyzed collagen,replicates the organic phase of bone,while inorganic components such as hydroxyapatite crystals and metal ions (zinc, magnesium, ferritin) were integrated to further enhance the biomimicry. Hydroxyapatite mineralization through hydrogel infusion,and incorporation of metal ions aimed to promote osteogenic properties.The mechanical characterization demonstrated significantly enhanced Young's modulus values in the MPa range,far surpassing traditional hydrogels reported in the literature,which typically exhibit kPa-scale moduli.

For biocompatibility and reduced cytotoxicity,we utilized curcumin,a natural compound with a favorable absorbance spectrum as a photoinitiator for 2PP. This innovation eliminated the need for synthetic photoinitiators and enabled the successful fabrication of complex scaffolds.Furthermore, curcumin's antimicrobial properties were leveraged,demonstrating promising results against common pathogens,and therefore adding a functional ability to the scaffold.

These scaffolds exhibit a unique combination of bioinspired composition,structural precision, mechanical strength,and antimicrobial functionality.Their ability to support cell differentiation and proliferation is under investigation,with preliminary results indicating their potential as a transformative platform for bone tissue regeneration. This work underscores the versatility of multiphoton lithography in creating next-generation biomaterials and highlights the significance of integrating biomimicry, multifunctionality, and advanced fabrication techniques for biomedical applications.

POM@MOF IMPRINTED ELECTROCHEMICAL SENSOR FOR DOPAMINE DETECTION

Wenjing Wang[1,2],

Srivatsan K. Vasantham1,2, Hongrong Hu3, George Mathew1,2, Yan Liu1, Jasmin Aghassi-Hagmann1, Annie K. Powell1,4,5, Michael Hirtz1,2

1 Institute of Nanotechnology (INT), Karlsruhe Institute of Technology, Karlsruhe, Germany;
2 Karlsruhe Nano Micro Facility (KNMFi), Karlsruhe Institute of Technology, Karlsruhe, Germany;
3 Institute of Computer Engineering, Heidelberg University, Heidelberg, Germany;
4 Institute of Inorganic Chemistry (AOC), Karlsruhe Institute of Technology, Karlsruhe, Germany;
5 Institute for Quantum Materials and Technologies (IQMT), Karlsruhe Institute of Technology, Karlsruhe, Germany;

Dopamine is one of the most abundant neurotransmitters in the neuronal system of humans and other mammalian species. It is involved in many biological processes, such as learning, cognition, regulating gastrointestinal motility and blood pressure etc. Abnormal concentration levels of dopamine in the human body are highly correlated with Parkinson's and Alzheimer's disease. Therefore, measuring dopamine concentration is crucial in understanding the physiological condition as well as in diagnosing related diseases. Various techniques have been developed for dopamine concentration detection, including high-performance liquid chromatography, mass spectroscopy, fluorescence spectroscopy, and other methods. However, these methods are time-consuming and require expensive equipment and skilled operators.

In this study, a polyoxometalate@MOF-based molecularly imprinted polymer electrochemical sensor was developed by utilizing capillary printing, providing a cost-effective way of fabricating an ease-of-use sensor for rapid dopamine detection in solution. Polyoxometalates, the key material of this design, are excellent electrocatalytic materials that can enhance and accelerate the electrochemical reaction on the electrodes. MOF serves as a framework where the nanometer polyoxometalates are anchored. The polyoxometalate@MOF composite works as the catalyst for the electro-redox reaction of dopamine. Then, the polyoxometalate@MOF composite was covered by a molecularly imprinted polymer, which mimics the antibody-antigen recognition strategy and increases the sensors' selectivity.

The designed material was applied to modify the working electrode of an electrochemical sensor, where its performance in quantitively detecting dopamine in solution was systematically tested.

TOWARD A T-MATRIX-BASED MULTIPLE SCATTERING FRAMEWORK FOR ACOUSTIC METASTRUCTURES

Nikita Ustimenko[1],

Carsten Rockstuhl1,2

1 Institute of Theoretical Solid State Physics, Karlsruhe Institute of Technology, Germany;
2 Institute of Nanotechnology, Karlsruhe Institute of Technology, Germany

Metamaterials, metasurfaces, and chains of a large number of periodically arranged scatterers have already demonstrated their ability to tailor optical and sound properties in many scenarios. Designing such metastructures requires efficient and fast simulation techniques.

One of them is the T-matrix method. Based on the T-matrix method and the multipolar expansion, various computational codes were developed for solving electromagnetic scattering problems. These codes have been essential to explore new physical phenomena in metamaterials and metasurfaces and are routinely used to design optimal structures. One of these codes is treams, a computational framework that offers quite fast and accurate scattering calculations, including 1D, 2D, or 3D lattices with different geometries, along with a user-friendly interface.

In this contribution, we report on extending this approach to linear pressure acoustics. We present a Python software package acoustotreams and its benchmark in various scattering scenarios of sound waves. The code allows us to study and design acoustic metasurfaces and metamaterials, selected examples thereof are demonstrated at the conference.

MULTI-SCALE SIMULATIONS FOR PREDICTING THE NONLINEAR OPTICAL PROPERTIES OF METAL-ORGANIC FRAMEWORKS

Mariia Poleva

Christof Holzer, Ivan Fernandez-Corbaton, Carsten Rockstuhl, Marjan Krstic

Karlsruher Institut für Technologie, Germany

Recently, a novel framework for describing nonlinear light-matter interactions from first principles was introduced [1]. This approach integrates quantum chemistry with high-speed optical simulations. The quantum chemistry simulations are performed using time-dependent density functional theory (TD-DFT) in the TURBOMOLE software package. From these simulations, we compute first-order hyperpolarizabilities, which are subsequently converted into hyper-T-matrices. These hyper-T-matrices along with T-matrices expressing the linear response of the molecule can be considered in optical simulations of functional photonic devices made from molecules. Hence, this approach can bridge the gap between TD-DFT and optical simulations, creating a multi-scale workflow. The optical simulations of the devices are then carried out using the in-house developed software treams [2], in which we incorporated the hyper-T-matrix formalism.

In this work, we study the optical properties of metal–organic frameworks (MOFs), crystalline porous materials known for their optical versatility. Utilizing the aforementioned framework, we investigate second harmonic (SH) generation from stacks of three distinct MOFs. Our study focuses on optimizing the stacking arrangement of layers composed of different MOFs to maximize the overall SH intensity. Additionally, we compare the total SH signals from these stacks, examining the impact of centrosymmetric versus non-centrosymmetric linkers characterizing each MOF. Layer-by-layer contributions to SH output were also evaluated, as well as the resonant conditions to enhance signals from such thin film stacks. Our results reveal that, surprisingly, alternating stacks where each layer differs from the previous one do not produce the highest SH intensity, despite the increased number of interfaces between materials.

[1] Zerulla, Benedikt, et al. "A Multi-Scale Approach to Simulate the Nonlinear Optical Response of Molecular Nanomaterials." Advanced Materials 36.8 (2024): 2311405.
[2] Beutel, Dominik, Ivan Fernandez-Corbaton, and Carsten Rockstuhl. "treams–a T-matrix-based scattering code for nanophotonics." Computer Physics Communications 297 (2024): 109076.

Flash Talks

OPTIMIZING THE PERFORMANCE OF PRINTED INDIUM OXIDE THIN-FILM TRANSISTORS THROUGH GALLIUM INCORPORATION

Mahsa Saghafi

Mohana Veerraju Kante, Ramin Shadkam, Evgeniy Boltynjuk, Simon Schweidler, Ben Breitung, Michael Hirtz, Jasmin Aghassi-Hagmann, Gabriel Cadilha Marques

Institute of Nanotechnology (INT), Karlsruhe Institute of Technology

Metal-oxide semiconductors, such as indium oxide (In2O3-x), are widely used in thin-film transistors (TFTs) due to their high carrier mobility and compatibility with printing techniques. However, the high carrier density caused by oxygen vacancies in In2O3-x leads to high leakage currents and negative threshold voltages, limiting their application in enhancement-mode devices. Introducing gallium as a dopant decreases oxygen vacancies due to gallium's stronger bonding with oxygen. This enables threshold voltage adjustment and improves device performance. Nevertheless, most solution-processed doped indium oxide thin films require calcination temperatures higher than 200 °C, which limits their application on flexible substrates.

In this study, indium oxide (In2O3-x) and indium gallium oxide (IGO) nanoparticles were synthesized using a precipitation process and formulated into water-based inks for low-temperature printing. This approach makes them compatible with flexible substrates such as paper due to low processing temperature (~100 °C), opening up possibilities for sustainable microelectronic systems. Gallium incorporation into the In2O3-x lattice reduced oxygen vacancies, increasing the threshold voltage (Vth) from 0.2 V to 0.5 V and lowering off-currents by up to three orders of magnitude, depending on gallium content. This optimization allows enhancement-mode electrolyte-gated transistors (EGTs) to operate with low leakage currents, making them ideal for low-power electronic applications.

Furthermore, inverter circuits developed with IGO-based EGTs outperformed In2O3-x-based EGTs, exhibiting higher gain and lower power consumption. These findings highlight the potential of gallium-doped indium oxide EGTs in advancing flexible, energy-efficient microelectronics.

SITE-SELECTIVE BIOFUNCTIONALIZATION OF 3D MICROSTRUCTURES VIA DIRECT INK WRITING

George Mathew[2]

Enrico Domenico Lemma[1,3], Dalila Fontana[3], Chunting Zhong[1,2], Alberto Rainer[3,4,5], Sylwia Sekula-Neuner[6], Jasmin Aghassi-Hagmann[1], Michael Hirtz[1,2], and Eider Berganza[7]

1 Institute of Nanotechnology (INT), Karlsruhe Institute of Technology , Karlsruhe, Germany
2 KarlsruheNanoMicro Facility (KNMFi), Karlsruhe Institute of Technology, Karlsruhe, Germany
3 Department of Engineering, Università Campus Bio-Medico of Rome, Italy
4 Fondazione Policlinico Universitario Campus Bio-Medico di Roma, Italy
5 Institute of Nanotechnology (NANOTEC), National Research Council, Italy
6 n.able GmbH, Eggenstein-Leopoldshafen, Germany
7 Instituto de Ciencia de Materiales de Madrid (CSIC), Madrid, Spain

Two-photon lithography has revolutionized multi-photon 3D laser printing, enabling precise fabrication of micro- and nanoscale structures. Despite many advancements, challenges still persist, particularly in biofunctionalization of 3D microstructures. This study introduces a novel approach combining twophoton lithography with scanning probe lithography for post-functionalization of 3D microstructures overcoming limitations in achieving spatially controlled biomolecule distribution.

The method utilizes a diverse range of biomolecule inks, including phospholipids, and two different proteins, introducing high spatial resolution and distinct functionalization on separate areas of the same microstructure. The surfaces of 3D microstructures are treated using bovine serum albumin and/or 3-(Glycidyloxypropyl)trimethoxysilane (GPTMS) to enhance ink retention. The study further demonstrates different strategies to create binding sites for cells by integrating different biomolecules, showcasing the potential for customized 3D cell microenvironments. Specific cell adhesion onto functionalized 3D microscaffolds is demonstrated, which paves the way for diverse applications in tissue engineering, biointerfacing with electronic devices and biomimetic modeling.

3D PRINTING OF METALLIC MICRO- AND NANOSTRUCTURES USING LOCALIZED ELECTRODEPOSITION AND DIRECT ELECTRON BEAM WRITING

Ekaterina Shabratova

Hady Yacoub, Viktor Krozer, Aleksei Tsarapkin, Patrick Scheele, Katja Höflich

Ferdinand-Braun-Institut (FBH), Berlin, Germany

Many advances in the fields of electronics, photonics, and medical engineering rely on the integration of micro- and nanostructures into modern technologies. However, fabricating certain free-standing structures, such as metallic helices, remains challenging for conventional lithographic methods. Additive fabrication techniques, based on localized electrodeposition and direct electron beam writing, offer an opportunity to expand the range of producible free-from three-dimensional designs.

Localized electrodeposition of metal ions onto a substrate that serves as a working electrode in a standard electrochemical cell can be employed for fabrication of structures in sub-millimeter scale. [1] The ions are dispersed using a hollow atomic force microscope cantilever, that allows for achieving a minimum voxel size of approximately 2 µm. While the process requires highly conductive substrates, many applications necessitate placing metallic objects onto semiconductor materials.

To address this issue, fabricated structures are transferred to various substrates inside a dual-beam instrument employing focused electron and ion beams for imaging and processing. Additionally, the same system can be used for direct writing of even smaller geometries. The electron beam locally dissociates precursor gas molecules, resulting in the fabrication of metal-organic structures with feature sizes below 50 nm. [2] Nonlinear growth processes are controlled by adjusting beam paths and printing strategies via Python programming.

The capabilities of these 3D manufacturing technologies, which cover scales from hundreds of micrometers to tens of nanometers, are currently being explored for applications in terahertz communication and light polarization control.

[1] Ercolano, G., van Nisselroy, C., Merle, T., Vörös, J., Momotenko, D., Koelmans, W., & Zambelli, T. (2019). Additive Manufacturing of Sub-Micron to Sub-mm Metal Structures with Hollow AFM Cantilevers. Micromachines, 11(1), 6. https://doi.org/10.3390/mi11010006
[2] Tsarapkin, A., Zurak, L., Maćkosz, K., Utke, I., Feichtner, T., & Höflich, K. (2024). Double helical plasmonic antennas.

SINGLET FISSION OF PENTACENE EMBEDDED IN A SURFACE-ANCHORED METAL-ORGANIC FRAMEWORK

Martin Richter[1]

Muhammad Jeneesh Kariyottukuniyil[2], Zhiyun Xu[3], Philipp Ludwig[4], Pavel Kolesnichenko[1], Christian Huck[1], Uwe Bunz[4], Christof Wöll[3], Wolfgang Wenzel[2], Petra Tegeder[1]

1 Physikalisch-Chemisches Institut, Ruprecht-Karls-Universität Heidelberg, Heidelberg, Germany
2 Institute of Nanotechnology, Karlsruher Institut für Technologie, Karlsruhe, Germany
3 Institut für Funktionelle Grenzflächen, Karlsruher Institut für Technologie, Karlsruhe, Germany
4 Organisch-Chemisches Institut, Ruprecht-Karls-Universität Heidelberg, Heidelberg, Germany

Singlet fission (SF) is a process where a singlet exciton is converted into two triplet excitons, significantly enhancing charge generation in organic solar cells. It has been shown that the rate of SF and the lifetime of the generated triplet excitons strongly depend on the molecular arrangement.

In thin films of small molecules the SF efficiency is determined by the crystal structure. Using a molecular engineering approach, we here exploit the design space accessible in metal-organic frameworks to enhance SF lifetimes. A cofacial orientation of pentacene molecules is achieved by embedding organic linkers containing pentacene in a surface-anchored metal-organic framework.

Transient absorption spectroscopy and a quantum mechanical analysis have been used to analyze the exciton dynamics in a broad spectral range from near-ultraviolet to near-infrared on time scales spanning nine orders of magnitude (femto- to microseconds). The observed time-resolved absorption spectra indicate that a singlet excited state generates a correlated triplet pair within a few picoseconds. Subsequent dynamics show the formation of long-lived excitons (39 µs) with triplet character. This exceeds by far the observed lifetime of triplet excitons generated in pentacene thin films and may enhance triplet exciton harvesting capabilities in photovoltaic cells.

Flash Talks

ELECTRON PROBE MICROANALYSIS TO DETERMINE AVERAGE DENSITIES OF POROUS THIN FILMS

Kristian Kraft

Erich Müller, Aina Quintilla, Lukas Grünewald, Hongrong Hu, Yan Liu,
Jasmin Aghassi-Hagmann, Yolita M. Eggeler

Printed microelectronics-based devices like memristors enable opportunities as new low energy data storage solution. They are printed in a vertical structure with the semiconductor sandwiched between two electrodes. Their performance correlates directly to the printed materials inner-structural details, which we analyze cross scales (µm→nm) using electron microscopy. To obtain the local thickness, density and composition of the individual layers involved we apply an advanced non-destructive method in the scanning electron microscopy (SEM) realm using energy dispersive X-ray spectroscopy (EDX). Based on recorded EDX spectra and thin film simulation a new workflow is presented to determine the density of inkjet printed porous ZnO in memristors, which are cross validated with transmission electron microscope (TEM).

Inkjet printed memristors are fabricated by thermal evaporation of a Au electrode. On top Zn nitrate precursor with a piezo inkjet-printer is deposited to form the active ZnO layer. After an annealing step a top Ag electrode is deposited.

For testing the proposed workflow, a model multi-layer system consisting of Al/Ti/Ag on Si with 20 nm Al, 50 nm Ti and 50 nm has been prepared by electron-beam physical vapor deposition. Using different primary electron energies EDX spectra of the individual layers of the multi-layer system are acquired and compared to spectra acquired from reference samples containing the same elements as in the multi-layer system. K-ratios are calculated from the spectra using NIST DTSA-2. The density is determined by the thin film simulation (BadgerFilm).

The layer thickness is found to be 20 nm for Al which is in good agreement with the nominal thickness. However, for the Ti and the Ag a thickness of 48 nm and 56 nm, respectively was determined which differs from 50 nm. To further verify these measurements, additional TEM analyses will be conducted.

As the next step, we will determine the layer thickness of the inkjet-printed memristors. Using this data, we will calculate the density of the ZnO layer. This will allow us to better understand the material properties and optimize the printing process for improved device performance.

DEVELOPING AND CHARACTERIZING CONDUCTIVE HYDROGELS FOR 3D PRINTING

Tamara Verena Unterreiner

Trevor Kalkus, Målin Schmidt, Mona Maria Hämmerle, Christine Selhuber-Unkel

Universität Heidelberg, Germany

Conductive hydrogels are promising materials for bioelectronic applications, particularly for interfacing with neuronal and muscle cells.

This work explores the formulation and characterization of PEDOT:PSS laden hydrogels optimized for extrusion 3D printing. Rheological and tensile testing confirm shear-thinning behavior, printability, and mechanical properties suitable for biomedical applications. Electrochemical impedance spectroscopy and equivalent circuit modeling provide insights into ionic and electronic transport, essential for optimizing conductivity and stimulation efficiency.

Beyond extrusion printing, we also explore 2PP DLW microscale printing of PEDOT:PSS functionalized hydrogels, a promising strategy for engineering the electronic interface with cells, organoids, and tissues.

3D PRINTING OF PEDOT:PSS BASED PHOTORESIN FOR MANUFACTURING META-STRUCTURE ARCHITECTED PRESSURE SENSORS WITH HIGH SENSITIVITY

Ozan Karakaya[1,2]

Naroa Lopez-Larrea[5], Ali Tunc[1,2], Mikel Rincon-Iglesias[1,2,4], David Mecerreyes5,6, Miryam Criado-Gonzalez[5], Gerardo Hernandez-Sosa[1,2,3]

1. Light Technology Institute, Karlsruhe Institute of Technology
2. InnovationLab, Heidelberg
3. Institute of Microstructure Technology, Karlsruhe Institute of Technology
4. BCMaterials, Basque Center Centre for Materials, Applications and Nanostructures, UPV/EHU
5. POLYMAT, University of the Basque Country UPV/EHU
6. Ikerbasque, Basque Foundation for Science

There is a growing demand for highly sensitive flexible pressure sensors that can serve a wide range of applications and meet diverse requirements.[1] Metastructured pressure sensors can offer high sensitivity, a wide sensing range, design flexibility, and adjustable performance.[2] However, manufacturing these multifunctional micro-detailed structures can be challenging, as it requires additional steps to cast the active material onto the printed structures.Here, we utilize a PEDOT:PSS based photoresin to 3D print body-centered cubic lattice-based pressure sensors.[3] Using this photoresin in a DLP printer enables the manufacturing of PEDOT:PSS based polymer composites with high resolution (27 µm planar and 50 µm thickness) in a single step, eliminating the need for additional processes. As for the sensor design, body-centered cubic lattices are chosen due to their adjustable mechanical properties, which can help in fine-tuning the device's sensitivity.

Electromechanical characterizations of lattices were conducted by applying compression onto samples while recording the corresponding electrical resistance. The sensor with a 30% relative density has Young's modulus of 0.21 MPa, while sensors with 40% and 20% relative densities exhibit Young's moduli of 0.61 MPa and 0.07 MPa, respectively, demonstrating the fine tunability of the lattices. The sensor with a 30% relative density exhibited sensitivity of 0.86 kPa^{-1} at 0–0.5 kPa, and 0.19 kPa^{-1} at 1–2 kPa range, showing its capability to operate across different pressure ranges. This process has been visualized by connecting the sensor in a circuit where the LED illuminates upon applying pressure to the sensor.

In the future, we plan to print various lattice designs with different mechanical properties to manufacture sensors with a high range of sensitivities at different detection rages. Manufactured sensors will be used in proof of concept applications in pressure mapping or directional pressure sensing.

[1] Li, et al. J. Mater. Chem. C, 2018, 6, 11878-11892.
[2] Zhao, et al. Adv. Eng. Mater. 2023, 25, 2301056.
[3] Lopez Larrea, et al. ACS Appl. Polym. Mater. 2022, 4, 6749−6759.

ELECTROHYDRODYNAMIC PRINTING-BASED MICROSCALE ORGANIC PHOTODETECTORS

Kai Xia[1,2]

Gerardo Hernandez-Sosa[1,2,3]

1 Light Technology Institute, Karlsruhe Institute of Technology,
2 InnovationLab, Heidelberg,
3 Institute of Microstructure Technology, Karlsruhe Institute of Technology

The rapid development of the Internet of Things (IoT) in recent years has dramatically increased the need for light sensing. Meanwhile, more novel organic semiconductor materials continuously spring up speeding up the research on solution-processed organic photodetectors (OPDs).[1, 2] This will fill the huge demand for light sensing. The pixel sizes of OPDs, defined by the overlapped electrodes, are typically in the millimeter range, which limits their utilization in high-end applications, especially for printed OPDs. Therefore, electrohydrodynamic (EHD) printing as a new printing technique has been used to reduce the electrode size further to a micrometer range.

Here we present fully printed microscale OPDs fabricated by combing EHD printing and inkjet printing. In our method, ultrafine Ag electrodes and poly(3,4-ethylenedioxythiophene) polystyrene sulfonate (PEDOT:PSS) electrodes are printed by an EHD printer. After optimizing the printing condition and annealing process of Ag ink we achieved ultrafine Ag electrodes with a width of < 5 µm and a resistance of ~ 500 Ω. Accordingly, relatively large-area layers such as the photoactive layer and charge transport layer are printed by conventional inkjet printers, which saves a lot of time compared to EHD printing.

Currently, we have achieved OPDs with a length and width < 5 µm (area is < 25 μm^2) that are much smaller than the size of many reported devices. The OPDs can respond quickly to pulsed light. We also obtained a very low dark current of ~ 7.5×10^{-11} A at a negative bias of -3 V. These microscale OPDs are very promising for use alone or for seamless integration with various organic electronics or even microscale 3D printed (electronic) systems in the IoT

[1] Strobel, et al. Adv. Mater. 2020, 32, 1908258
[2] Ruiz-Preciado, et al. npj. Flex. Electron. 2023, 7, 6

Flash Talks

OPTICALLY INDUCED FLOWS IN COMPLEX LASER-PRINTED GEOMETRIES

Rayehe Rezaei

Recent microfluidic studies have leveraged laser-induced thermo-viscous flow for precise particle positioning, with applications ranging from microscale robotics, biomedical engineering, and subcellular studies. These flows arise from the interaction between thermal expansion and heat induced viscosity changes in the fluid, where laser scanning along a designated path generates fluid movement and enables particle transport.

Such precise manipulation is particularly important for single-cell studies within lab-on-a-chip devices, where effective particle transport is critical in confined environments. The surrounding geometry in microfluidic systems plays a crucial role in shaping flow topology. Achieving precise particle manipulation within complex microfluidic environments requires a detailed understanding of thermo-viscous flows in the presence of obstacles, supported by robust theoretical models.

To investigate this, we employ additive nano- and micro-fabrication techniques, specifically the two-photon polymerization method, to create 3D microstructures that enable controlled experimental studies of flow behavior.

This research aims to enhance our understanding of how inhomogeneities influence flow dynamics and particle positioning. The findings will support accurate particle manipulation at the microscale within complex geometries, advancing lab-on-a-chip technologies and bioengineering applications, where analogous structural constraints and flow conditions critically influence performance and functionality.

THZ SYSTEM PACKAGING FACILITATED BY TAILORED METAL-COATED 3D-PRINTED FREEFORM STRUCTURES

Sina Foroutan-Barenji[1]

Pascal Maier[1,3], Weimu Xu[2], Alexander Kotz[1], Artem Kuzmin[3], Uli Lemmer[2], Wolfgang Freude[1], Christian Koos[1,3]

1 Institute of Photonics and Quantum Electronics (IPQ), KIT, Karlsruhe, Germany
2 Light Technology Institute (LTI), KIT, Karlsruhe, Germany
3 Institute of Microstructure Technology (IMT), KIT, Eggenstein-Leopoldshafen, Germany

3D printing of freeform millimeter-wave (mmW) interconnects presents a promising approach for THz packaging solutions operating above 100 GHz, offering unmatched design flexibility and high precision.

Previous studies have demonstrated the use of multi-photon laser lithography (MPL), a high-resolution direct-write fabrication method, to create metal-coated freeform structures (MCFS) for connecting coplanar waveguides (CPWs) on separate PCBs, achieving operational bandwidths of up to 300 GHz.

In this work, we applied MCFS in THz system packaging for the first time and successfully integrated a traveling wave amplifier (TWA) microchip. Electromagnetic simulations confirm the high performance of this approach, demonstrating excellent impedance matching across the D- and H-bands and low insertion with 3 dB-bandwidths exceeding 0.3 THz.

These results highlight the potential of 3D-printed interconnects as a transformative solution for THz system integration and advanced packaging.

INVERSE DESIGN OF STRUCTURALLY INTEGRAL 3D NANOPHOTONIC DEVICES USING AUXILIARY THERMAL SOLVERS

Oliver Kuster

Yannick Augenstein, Carsten Rockstuhl, Thomas Jebb Sturges

Karlsruhe Institute of Technology, Germany

3D additive manufacturing enables the fabrication of nanophotonic structures with subwavelength features that control light across macroscopic scales. Gradient-based optimization offers an efficient approach to designing these complex and non-intuitive structures. Still, expanding the methodology from 2D to 3D comes with challenges, such as structural integrity and connectivity. This work introduces a multi-objective optimization method to address these challenges in 3D nanophotonic designs.

Our method integrates electromagnetic simulation with a heat-diffusion solver to ensure continuous material and void connectivity. By modeling material regions as heat sources and boundaries as heat sinks, we strive to minimize the total temperature to penalize disconnected regions within the structure. Alongside the optical response, this temperature metric becomes part of our objective function. We demonstrate the utility of our algorithm by designing two 3D nanophotonic devices. The first is a focusing element. The second is a waveguide junction, which connects two incoming waveguides for two different wavelengths into two outgoing waveguides, which are rotated by 90° to the incoming waveguides. Our approach contributes a robust component to a design pipeline that generates digital blueprints for fabricable nanophotonic materials, paving the way for practical 3D nanoprinting applications.

LINEAR AND NONLINEAR OPTICAL PROPERTIES OF MOLECULAR MATERIALS: A SCALE-BRIDGING COMPUTATIONAL WORKFLOW

Marjan Krstić[1]

Mariia Poleva[1], Benedikt Zerulla[1], Ana Fingolo[2], Nadine von Coelln[3], Christian Huck[3], Petra Tegeder[3], ChristofWöll[2], Christof Holzer[1], Ivan Fernandez-Corbaton[4], Carsten Rockstuhl[1,4]

1. Institute of Theoretical Solid State Physics, Karlsruhe Institute of Technology, Karlsruhe, Germany
2. Institute of Functional Interfaces, Karlsruhe Institute of Technology, Karlsruhe, Germany
3. Institute for Physical Chemistry, Heidelberg University, Heidelberg, Germany
4. Institute of Nanotechnology, Karlsruhe Institute of Technology, Karlsruhe, Germany

Surface grown Metal-Organic Frameworks (SURMOFs) are an additively made porous crystalline class of materials with versatile applications chemistry, physics, engineering, etc. Especially interesting applications are in the field of optics. However, theoretical descriptions of light-matter interactions of such molecular materials were scarce. We present a general multiscale workflow to access linear and nonlinear optical properties of molecular materials and devices thereof by combining quantum chemistry calculations of molecular (hyper-)polarizabilities with Maxwell simulations. The connecting bridges between different levels of the description are the T-matrix[1,2] and its nonlinear counterpart, the hyper-T-matrix[3,4].

Multiple applications for this framework come in reach, and we present two of them at the conference. First, we looked into a linear optical response of chiral SURMOF as measured in Infrared (IR) spectroscopy. Our model predicts the orientation dependent IR absorbance and vibrational circular dichroism of up to 500 nm thick films.

These predictions were confirmed by subsequent measurements. Second, we focused into studying the effects of extended material surrounding on the emerging nonlinear second-harmonic response of ~60 nm thick Au-cysteine multi-sheet self-arranged nanoparticles. We demonstrate that only by proper consideration of polarization effects of the surrounding material, both in quantum calculations and in multiscale simulations, it is possible to achieve an agreement with experimental observations.

[1] B. Zerulla, M. Krstić, D. Beutel, C. Holzer, C. Wöll, C. Rockstuhl, I. Fernandez-Corbaton, Adv. Mater., 34, 2200350, (2022)
[2] B.Zerulla, C. Li, D. Beutel, S. Oßwald, C. Holzer, J. Bürck, S. Bräse, C. Wöll, I. Fernandez-Corbaton, L. Heinke, C. Rockstuhl, M. Krstić, Adv. Funct. Mater. 34, 20, 2301093, (2024)
[3] B. Zerulla, D. Beutel, C. Holzer, I. Fernandez-Corbaton, C. Rockstuhl, M. Krstić, Adv. Mater., 36, 2311405, (2024)
[4] B. Zerulla, A. L. Díaz, C. Holzer, C. Rockstuhl, I. Fernandez-Corbaton, M. Krstić, Adv. Optical Mater., 12, 2400150, (2024)

COLOR AND FLUORESCENCE SWITCHABLE 2D AND 3D PRINTED HYBRID MATERIALS

Matthias Steurer[1,2]

Xingyu Wu[1], Agnes C. Morrissey[2], Konstantin Faershteyn[2], Magdalena Fladung[1], Paul Somers[1], Florian Feist[1], Martin Bastmeyer[1], Martin Wegener[1], Claus Feldmann[1], Christopher Barner-Kowollik[1,2]

1 Karlsruhe Institute of Technology, Karlsruhe, Germany
2 Queensland University of Technology, Brisbane, Australia

Since the start of 3D printing with optics-based systems in 1970s,[1] additive manufacturing (AM) has become one of the most disruptive technologies of recent decades, enabling the fabrication of complex geometries using a wide range of materials for diverse applications, from architecture to medicine. Among various 3D printing techniques, light-based 3D printing techniques such as stereolithography (SLA) enable the fabrication of well defined, high-resolution 3D macro-objects by spatiotemporal control of chemical reactions.

To meet the demands from medicinal and electronics applications, hybrid materials combining organic and inorganic components are in critical demand.[2]

Herein, we introduce an ink system for light-driven 3D printing consisting of electrostatically stabilized inorganic-organic hybrid nanoparticles (IOH-NPs), a crosslinking monomer, and a photoinitiator that enables the printing of color- and fluorescence-switchable 3D objects. Nanoparticles (NPs) are often prone to aggregation in photoresins, causing significant light scattering that hinders the printing process. Furthermore, the particles may degrade upon exposure, resulting in the loss of their properties. These issues result in poor printing quality or a loss of functionality. By carefully selecting NPs and resin composition, we successfully incorporate IOH-NPs into a soft-matter 3D network enabling a fast pH-dependent color and fluorescence change over a wide pH range. In-depth characterization of the printed structures via imaging, spectroscopic, and spectrometric techniques reveals that the IOH-NPs remain intact after printing, enabling repeatable color and fluorescence switching of the 3D printed objects. We further demonstrate that multi-material objects can be fabricated entailing color-switchable and non-switchable structural elements. The hybrid materials for 3D printing introduced here enable tunable optical properties and hold promise for applications in sensors, optical devices, and more.

1 P. Somers, A. Münchinger, S. Maruo, C. Moser, X. Xu, M. Wegener, Nat. Rev. Phys. 2024, 6, 99–113.
2 I. Cooperstein, E. Sachyani-Keneth, E. Shukrun-Farrell, T. Rosental, X. Wang, A. Kamyshny, S. Magdassi, Adv. Mater. Interfaces 2018, 5, 1–15.

TWO MATERIAL PROPERTIES FROM ONE WAVELENGTH-ORTHOGONAL PHOTORESIN ENABLED BY A MONOCHROMATIC LASER INTEGRATED STEREOLITHOGRAPHIC APPARATUS (MONO LISA)

Xingyu Wu[1,2]

Katharina Ehrmann[2,3], Ching Thye Gan[2], Benjamin Leuschel[4], Fred Pashley-Johnson[2,5], Christopher Barner-Kowollik[1,2]

1: Karlsruhe Institute of Technology (KIT), Germany
2: Queensland University of Technology (QUT), Australia
3: Technische Universität Wien, Austria
4: CNRS, France
5: Ghent University, Belgium

Multi-material printing has experienced critical advances in recent years, yet material property differentiation capabilities remain limited both with regard to the accessible properties – typically hard vs. soft – and the achievable magnitude of differentiation. To enhance multi-material printing capabilities, precise photochemical control during 3D printing is essential. Wavelength-differentiation is a particularly intriguing concept yet challenging to implement.[1] Notably, dual-wavelength printing to fabricate hard and soft sections within one object has emerged, where one curing process is insensitive to visible light, while UV irradiation inevitably actives the entire resin, limiting true spatio-temporal control of the material properties.

Until now, pathway-independent wavelength-orthogonal printing has not been realized, where each wavelength exclusively triggers only one of two possible reactions, independent of the order in which the wavelengths are applied. Herein, we introduce a multi-wavelength printing technique employing a tunable laser to monochromatically deliver light to the printing platform loaded with a fully wavelength-orthogonal resin. Guided by photochemical action plots, two distinct wavelengths – each highly selective towards a specific photocycloaddtion reaction – are utilized to generate distinct networks within the photoresin.[2,3]

Ultimately, together with our printing technique, this orthogonally addressable photoresin allows fabricating multi-material objects with degradable and non-degradable properties, in a single fabrication step.

[1] K. Ehrmann, C. Barner-Kowollik, J. Am. Chem. Soc., 2023, 145, 24438.
[2] I. M. Irshadeen, S. L. Walden, M. Wegener, V. X. Truong, H. Frisch, J. P. Blinco, C. Barner-Kowollik, J. Am. Chem. Soc., 2021, 143, 21113.
[3] S. L. Walden, J. A. Carroll, A.-N. Unterreiner, C. Barner-Kowollik, Adv. Sci., 2024, 11, 2306014.

UNLOCKING THE FLEXIBILITY OF MULTI-MATERIAL 3D PRINTING FOR SOFT IONTRONICS

Trevor Kalkus

Heidelberg University, Germany

Wearable devices, soft robotics, and environmental sensors can benefit from the use of soft iontronic circuits to help match the viscoelastic properties of biological tissue. While circuit components like ionic diodes, transisters, power sources, and more have been developed, established fabrication methods prevent rapid prototyping, integration, and implementation.

3D printing has gained attention for disrupting many research fields, and we aim to prove this approach can also be implemented to revolutionize soft iontronics. We pioneer the fabrication of ionic diodes using multi-material 3D printing, and demonstrate the ability to rapidly prototype different designs with various sensitivity to strain. We are then able to incorporate these diodes into complex structures with advanced mechanical behavior. We highlight several freedoms offered by this fabrication method that promotes adaptability and personalization to demonstrate its suitability for a wide range of applications.

By adjusting the ink's composition, we can tune the ink's printing quality, the resulting hydrogel's stiffness, and the hydrogel's conductivity. Additionally, we can achieve different electrical and mechanical behavior based on the geometry of the printed device. Ultimately, we use the ionic diodes to make a logic circuit responsive to mechanical strain. Compared to previously established methods, multi-material printing reduces cost, wasted material, and time required to develop complex devices in a manner that can be personized and is highly reproducible.

The adaptability of both the ink and geometry afforded by extrusion printing make it an ideal candidate for enabling the next generation of iontronics with advanced computational and mechanical functionality.

MULTIPORT HIGH-PERFORMANCE PLUG-AND-PLAY OPTICAL PACKAGING FOR PHOTONIC INTEGRATED CIRCUITS

Erik Jung[1]

Helge Gehring[2], Frank Brückerhoff-Plückelmann[1], Linus Krämer[1], Clara Vazquez-Martel[3], Eva Blasco[3], Wolfram Pernice[1,2]

1. Heidelberg University, Kirchhoff Institute for Phyiscs, Heidelberg, Germany
2. University of Münster, CenTech, Münster, Germany
3. Heidelberg University, IMSEAM, Heidelberg, Germany

Integrated photonics is a key enabler for advancing classical and quantum technologies, driving progress in applications such as optical communication, sensing, quantum computing, and neuromorphic systems. Photonic integrated circuits (PICs) offer significant advantages, including high data throughput, low latency, and energy efficiency[1]. However, scalable and low-loss packaging solutions remain a major challenge, as efficient optical coupling is crucial for minimizing insertion losses and maximizing bandwidth[2]. Out-of-plane polymer couplers have emerged as a promising approach, providing low-loss, high-bandwidth operation while maintaining compatibility with scalable fabrication techniques[3].

This work introduces a self-aligning, multiport, low-loss, and high-bandwidth packaging solution for PICs. The design integrates a female Multi-fiber Termination Push-on (MTP) cable with micron-precise alignment features fabricated directly on the PIC using two-photon polymerization (TPP). Light coupling is achieved via 3D out-of-plane total reflection couplers (TRC couplers), demonstrating a maximum insertion loss of 0.55 dB over the 1500–1600 nm wavelength range. Additional packaging losses from the connector average +0.4 dB ± 0.13 dB across all wavelengths and ports.

The scalability of the packaging approach is demonstrated by interfacing a 17-port optical processor. The solution is compatible with various coupler types, including grating couplers, providing a versatile and cost-effective strategy to meet the growing demand for high-performance optical integration.

[1] L. Ranno et al., "Integrated Photonics Packaging: Challenges and Opportunities," ACS Photonics, vol. 9, no. 11, pp. 3467–3485, Nov. 2022, doi: 10.1021/acsphotonics.2c00891.
[2] H. Gehring, A. Eich, C. Schuck, and W. H. P. Pernice, "Broadband out-of-plane coupling at visible wavelengths," Opt. Lett., vol. 44, no. 20, p. 5089, Oct. 2019, doi: 10.1364/OL.44.005089.
[3] S. Yu et al., "Free-Form Micro-Optics Enabling Ultra-Broadband Low-Loss Off-Chip Coupling," Laser & Photonics Reviews, vol. 17, no. 6, p. 2200025, Jun. 2023, doi: 10.1002/lpor.202200025.

FAST AND EFFICIENT PURIFICATION OF DNA ORIGAMI

Izar Luas Schärf

Heidelberg University

DNA origami has long been of critical interest as a biophysical tool, especially when conjugated to functional elements such as proteins and peptides.

However, a simple “one size fits all” approach to purifying DNA origami and its protein conjugates has been lacking so far. We present a low-cost method for facile, scalable, benchtop gravity-driven size exclusion purification of DNA origami and its protein conjugates, with > 90% yield for pure origami within 5 minutes.

Protein-conjugated origami yields up to 40%. Additionally, we present a workflow that circumvents dilution problems of SEC and allows for arbitrary concentrations of origami-protein conjugates to be purified.

CONTRACTION-ENABLED SUPER RESOLUTION IN 3D-PRINTED GLASS NANOARCHITECTURES

Jiajie Liang[1]

Jens Bauer[1,2]

1 Institute of Nanotechnology, Karlsruhe Institute of Technology, Karlsruhe, Germany
2 Institute for Applied Materials, Karlsruhe Institute of Technology, Karlsruhe, Germany

The non-linear behavior in multi-photon-lithography enables the fabrication of polymer 3D structures with resolutions down to ~300 nm and feature size as small as ~80 nm[1]. By incorporating quenchers in the photoresists and using an inhibition laser beam[2,3], prior studies have demonstrated resolutions of 175 nm and feature size of 41 nm, respectively. However, ultimately the resolution remains above the diffraction limit due to the proximity effect[4]. Currently, higher resolution can only be achieved through focused electron beam induced deposition (FEBID)[5] and extreme ultraviolet (EUV) lithography[6].

Here, we exploit post-print thermolysis contraction of two-photon-polymerized preforms from a polyhedral oligomeric silsesquioxane (POSS) hybrid resist[7], to produce silica glass nanoarchitectures with sub-10 nm features and resolutions of free-standing structures down to ≤100 nm. Our material is composed of POSS nanocluster acting as the Si and O source and cross-linking acrylates, which undergoes fragmentation and degassing at elevated temperatures during the glass conversion. The thermal decomposition of the organic components results in structural shrinkage.

Here we leverage this thermal contraction to surpass the resolution limits of two-photon polymerization (2PP). With respect to our previous work, we modified the POSS-resin formulation and applied thermolysis procedure to deliberately maximize the achievable size contraction, while maintaining successful glass conversion of the printed templates. We utilize a high-efficiency photoinitiator (BDBuABnCHx, BBK)[8] to mitigate the proximity effect and enhance structural sharpness. We present a range of high-quality free-form glass nanostructures, including ≤100 nm-resolution woodpile photonic crystals, ~1.5 µm-size benchy boats and buckyballs, and nanotips with tip radii down to ~9 nm.

These examples demonstrate resolution and feature sizes approaching those achieved by FEBID and EUV lithography. Our results may open up new avenues for applications ranging from nano-photonics and sensing to bio-medicine, such as high-resolution scanning near-field optical microscope (SNOM)[9], tip-enhanced Raman spectroscopy (TERS) and virological nanopatterns[10].

1. Hahn, V. et al. Two-step absorption instead of two-photon absorption in 3D nanoprinting. Nat. Photonics 15, 932–938 (2021).
2. Guan, L. et al. Light and matter co-confined multi-photon lithography. Nat. Commun. 15, 1–11 (2024).
3. Fischer, J. Three-dimensional optical lithography beyond the diffraction limit. (Karlsruhe Institute of Technology, 2012).
4. Baldacchini, T. Three-Dimensional Microfabrication Using Two-Photon Polymerization. (Elsevier, 2019).
5. Keller, L. & Huth, M. Pattern generation for direct-write three-dimensional nanoscale structures via focused electron beam induced deposition. Beilstein J. Nanotechnol. 9, 2581–2598 (2018).
6. Solak, H. H. Nanolithography with coherent extreme ultraviolet light. J. Phys. D. Appl. Phys. 39, (2006).
7. Bauer, J., Crook, C. & Baldacchini, T. A sinterless, low-temperature route to 3D print nanoscale optical-grade glass. Science (80-.). 380, 960–966 (2023).
8. Kiefer, P. et al. Sensitive Photoresists for Rapid Multiphoton 3D Laser Micro- and Nanoprinting. Adv. Opt. Mater. 8, 2000895 (2020).
9. Long, L., Deng, Q., Huang, R., Li, J. & Li, Z. Y. 3D printing of plasmonic nanofocusing tip enabling high resolution, high throughput and high contrast optical near-field imaging. Light Sci. Appl. 12, (2023).
10. Mah, S. W. L. et al. Piercing of the Human Parainfluenza Virus by Nanostructured Surfaces. ACS Nano 18, 1404–1419 (2024).

PLATEAU BORDER-TYPE TRUSS-LATTICE METAMATERIALS WITH ULTRA-LIGHTWEIGHT INSTABILITY-RESISTANCE

Mirhan Özdemir[1]

Jens Bauer[1,2]

1 Institute of Nanotechnology, Karlsruhe Institute of Technology, Karlsruhe, Germany.
2 Institute for Applied Materials, Karlsruhe Institute of Technology, Karlsruhe, Germany.

Stretching-dominated truss-lattice metamaterials are well known to offer superior stiffness and strength over stochastic cellular solids [1]. However, at low densities buckling instability quickly negates these gains [2]. Nanolattice metamaterials leverage size effects to achieve near-theoretical strength [3], yet premature buckling remains a major challenge for lower relative densities. Existing approaches aiming to overcome this challenge, like fractal hierarchy [4, 5] and hollow lattices [6], improve stability but introduce severe trade-offs, such as geometrical knockdown factors, premature node buckling, and fabrication challenges from enclosed void spaces. Hence, ultralow-density metamaterials with significant load-bearing capability regime elusive today.

Inspired by the plateau border geometries in liquid foams, where neighboring gas bubbles meet at 120° angles to form curved triangular shapes, we propose a novel concept to designing truss-lattice members with concave three-fold rotation symmetric - plateau border-type - cross-sections. We demonstrate this approach to dramatically increase the buckling resistance of lightweight truss-lattice metamaterials without sacrificing elastic strength and stiffness or introducing significant anisotropy and fabrication complexity. We present a genetic algorithm (GA)-based stochastic optimization framework to generate several plateau border-type cross-sections. Under conservation of the cross-sectional area, the algorithm selects design parameters and conducts finite element buckling analyses with corresponding individual lattice members. Based on the obtained mechanical results, the algorithm iteratively refines the design through parameter mutation and selection until convergence to a maximum buckling performance which best suppresses both global and local modes. Our numerical results indicate that the plateau border-type designs may outperform conventional circular struts by up to ~5 times, at low relative densities. Preliminary experimental results with two-photon polymerization (TPP) 3D-printed, silica-glass octet lattices with and without the optimized designs are discussed. Our future work will expand the approach across a large range of relative densities and additional lattice topologies to evaluate the potential of plateau border-type cross-section design on buckling resistance in diverse configurations. Scalability by means of recently introduced high-throughput multi-focus TPP to explore the translation of microscale lattice properties to larger scales will be investigated [7].

Our work provides important groundwork for enhancing the mechanical efficiency of ultra-lightweight lattice materials in advanced engineering applications.

[1] Fleck, N. A., Deshpande, V. S., & Ashby, M. F. (2010). Micro-architectured materials: past, present and future. Proceedings of the Royal Society A: Mathematical, Physical and Engineering Sciences, 466(2121), 2495-2516.
[2] Bauer, J., Meza, L. R., Schaedler, T. A., Schwaiger, R., Zheng, X., & Valdevit, L. (2017). Nanolattices: an emerging class of mechanical metamaterials. Advanced Materials, 29(40), 1701850.
[3] Bauer, J., Schroer, A., Schwaiger, R., & Kraft, O. (2016). Approaching theoretical strength in glassy carbon nanolattices. Nature materials, 15(4), 438-443.
[4] Meza, L. R., Zelhofer, A. J., Clarke, N., Mateos, A. J., Kochmann, D. M., & Greer, J. R. (2015). Resilient 3D hierarchical architected metamaterials. Proceedings of the National Academy of Sciences, 112(37), 11502-11507
[5] Zheng, X., Smith, W., Jackson, J., Moran, B., Cui, H., Chen, D., ... & Spadaccini, C. M. (2016). Multiscale metallic metamaterials. Nature materials, 15(10), 1100-1106.
[6] Meza, L. R., Das, S., & Greer, J. R. (2014). Strong, lightweight, and recoverable three-dimensional ceramic nanolattices. Science, 345(6202), 1322-1326.
[7] Kiefer, P., Hahn, V., Kalt, S., Sun, Q., Eggeler, Y. M., & Wegener, M. (2025). A multi-photon (7× 7)-focus 3D laser printer based on a 3D-printed diffractive optical element and a 3D-printed multi-lens array. Light: Advanced Manufacturing, 4(1), 28-41.

We hope to see you again at

Future 3D Additive Manufacturing | The 3DMM2O Conference

March 23 – 26, 2026 | Schöntal Monastery

Frontiers for Theory, Computation and Design in 3D Materials

Save the Date

Carsten Rockstuhl
Karlsruhe Institute of Technology
(KIT)

Ulrich Schwarz
Heidelberg University
(Uni HD)

Wolfgang Wenzel
Karlsruhe Institute of Technology
(KIT)

Thank You

Dear Colleagues and Friends,

We want to take this opportunity to thank everyone involved in this conference: the invited speakers as well as the participants with or without oral and poster presentations, and our sponsoring partner Carl Roth GmbH.

Futhermore, the conference would not have been possible without the funding by the Deutsche Forschungsgemeinschaft (DFG) within the Excellence Strategy as well as the Carl Zeiss Foundation.

DFG Deutsche Forschungsgemeinschaft
Excellence Strategy
EXC 2082/1 – 390761711

Carl Zeiss Stiftung

HELMHOLTZ
RESEARCH FOR GRAND CHALLENGES

3D Matter Made to Order (3DMM2O)

Cluster of Excellence of the Karlsruhe Institute of Technology (KIT)
and Heidelberg University

3DMM2O Cluster Office

Schlossplatz 19, 76131 Karlsruhe, Germany
Phone: +49 721 608 47880
info@3dmm2o.de

WEB www.3dmm2o.de

www.linkedin.com/school/cluster-3dmm2o

www.instagram.com/cluster3dmm2o

www.facebook.com/Cluster3DMM2O

www.youtube.com/channel/UCufbI2dodiL46KZS9cYN9mw

Karlsruhe Institute of Technology

3D MATTER
MADE TO ORDER

UNIVERSITÄT
HEIDELBERG
ZUKUNFT
SEIT 1386