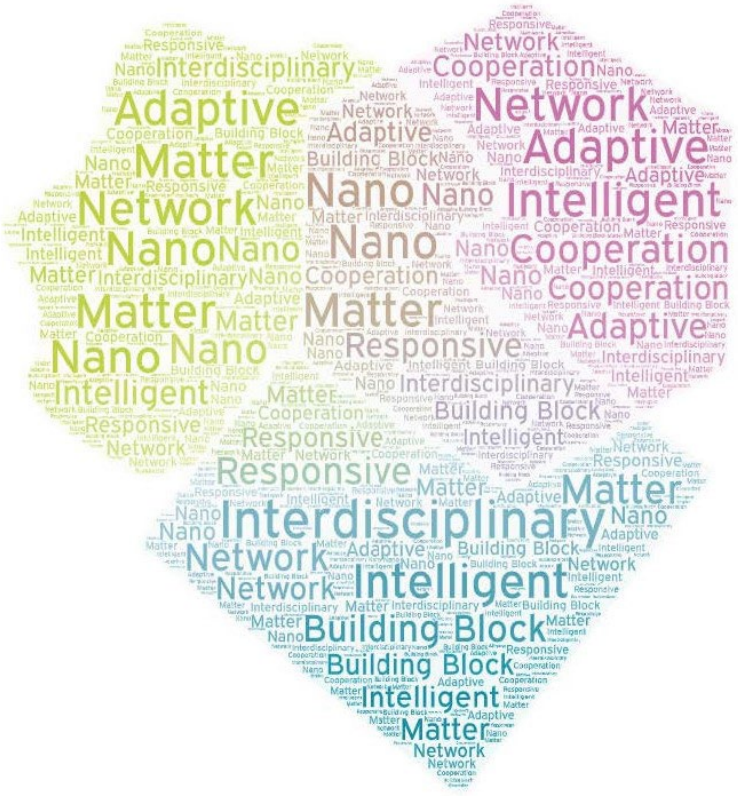
Universität Münster

Center for Soft Nanoscience

CRC 1459 INTELLIGENT MATTER

3rd Münster Symposium on Intelligent Matter

September 25th, 2024
Münster, Germany



Book of Abstracts

3rd Münster Symposium on Intelligent Matter
September 25th, 2024

PROGRAM

9:50 am	*Welcome to MüSIM 2024!*	*Bart Jan Ravoo, CRC 1459 Spokesperson*
10:00 am	**Stephen Mann** University of Bristol, United Kingdom ***Programmable Agency in Synthetic Protocells and Prototissues***	*Chair: Johanna Bergmann*
11:00 am	**Shiki Yagai** Chiba University, Japan ***The Discovery and Evolution of Curved Supramolecular Polymers***	*Chair: Sebastian Baumert*
12:00 pm	Business Lunch	
1:00 pm	*Poster Sessions*	
2:40 pm	**MüSIM 2024 Young Researcher Award** **Pengrong Lyu** Eindhoven University of Technology, The Netherlands	*Chair: Christina Kriegel, CRC 1459 Managing Director*
3:00pm	**Heike Riel** IBM Research Europe, Switzerland ***What's Next in Computing – From Bits to Quantum Bits***	*Chair: Akhil Varri*
4:00 pm	**Metin Sitti** Koç University, Turkey & MPI Intelligent Systems, Germany ***Physical Intelligence of Small-Scale Machines***	*Chair: Ivonne Bente*
5:00 pm	*Poster Prizes* Closing Remarks	*Nikos Doltsinis, CRC 1459 Co-Spokesperson*
5:30 pm	MüSIM 2024 Networking Event	

MüSIM2024 Speakers

Prof. Dr. Stephen Mann

University of Bristol
Max Planck Bristol Centre for Minimal Biology,
Centre for Protolife Research and Centre for Organized Matter Chemistry, School of Chemistry,
Bristol, United Kingdom

Stephen Mann is Professor of Chemistry, co-Director of the Max Planck Bristol Centre for Minimal Biology, and Director of the Centres for Organized Matter Chemistry and Protolife Research at the University of Bristol, UK. Professor Mann is distinguished for contributions to biomineralization, bioinspired materials chemistry and protocell research. He is a Fellow of the Royal Society UK, Fellow of the Royal Society of Chemistry, and a Member of Academia Europaea and the European Academy of Sciences and Arts. He has received awards from the Royal Society of Chemistry (de Gennes Prize; SCF French-British Prize; Nyholm Medal) and has been a visiting professor at the College de France and Harvard University. He was awarded the Royal Society Davy Medal in 2016. Professor Mann has published over 570 scientific papers with an h-index of 140. His current research focuses on the development of synthetic protobiology and the transition from non-living to living matter.

Programmable Agency in Synthetic Protocells and Prototissues

Stephen Mann, University of Bristol, United Kingdom

Recent progress in the chemical construction of compartmentalized semipermeable microscale objects comprising embodied cytomimetic functions is paving the way towards rudimentary forms of artificial cell-like materials (protocells/prototissues) as a step towards future proto-living technologies.

In this talk, I will demonstrate simple forms of individuated and collective behaviour in synthetic protocells and protocell communities. I will discuss: (i) enzyme-powered sensing, motility and oscillation in DNA-based protocells,1,2 (ii) coordinated assembly of beating or extendable prototissues,3,4 (iii) oligonucleotide-based signal processing in protocell networks,5,6 and (iv) living cell/synthetic cell hybrids.7 These studies offer new pathways towards intelligent matter based on artificial life materials capable of autonomic behaviour and programmable agency.

References:

[1] Kumar et al., Enzyme-powered motility in buoyant organoclay/DNA protocells. Nature Chemistry 10, 1154-1163 (2018).
[2] Peschke P et al., Autonomous Oscillatory Movement of Sensory Protocells in Stratified Chemical Media. CHEM. 10, 1-15 (2024).
[3] Gobbo P et al., Programmed assembly of synthetic protocells into contractile prototissues. Nature Materials, 17, 1145-1153 (2018).
[4] Gao N et al., Chemical-mediated translocation in protocell-based micro-actuators. Nature Chemistry 13, 868–879 (2021).
[5] Joesaar A, et al; DNA-based communication in populations of synthetic protocells. Nature Nanotechnology 14, 369-378 (2019).
[6] Yang et al., Protocellular CRISPR/Cas-based diffusive communication using transcriptional RNA signaling. ACIE. 61, e20222436 (2022).
[7] Xu et al. Living material assembly of bacteriogenic protocells. Nature 609, 1029-1037 (2022).

MüSIM2024 Speakers

Dr. Heike Riel

IBM Research Europe
Zurich, Switzerland

Heike Riel is IBM Fellow, Head of Science & Technology and Lead of IBM Research Quantum Europe & Africa. She leads the Science of Quantum & InformationTechnology department aiming to create scientific and technological breakthroughs in Quantum Computing and Technologies, Physics of Artificial Intelligence, Nanoscience and Nanotechnology and to explore new directions to computing.
She received the master's in physics from the Friedrich-Alexander University of Erlangen-Nürnberg and the PhD in physics from University of Bayreuth and an MBA from Henley Business College.
She has received several prestigious honors, e.g., elected member of the Leopoldina – German National Academy of Sciences and the Swiss Academy of Engineering Sciences; she was awarded the APS David Adler Lectureship Award in the Field of Materials Physics, the Applied Physics Award of the Swiss Physical Society, and the 2022 IEEE Andrew S. Grove Award. She was honored as Fellow of the American Physical Society, and with an honorary doctorate by Lund University. In February 2022 she was elected to the National Academy of Engineering

What's Next in Computing – From Bits to Quantum Bits

Heike Riel, IBM Research Europe, Switzerland

Digital computers, which represent information in the form of bits, have evolved in unprecedented ways over many years and have become ubiquitous in our lives. Today, these classic miniaturization-based technologies are reaching their limits, and new computing paradigms are being sought to reduce power consumption and increase computing power. Two new approaches have made tremendous progress in recent years. First, analog processors as accelerators for artificial intelligence problems, and second, quantum computers for complex computational problems that are intractable for classical computers, even high-performance computers. Quantum computers, as a fundamentally new computing paradigm, are based on the laws of quantum mechanics and are designed and built from scratch. Recently, significant progress has been made and quantum processors with more than 1000 qubits are already available.
In this talk, an overview of the state of research of the new computing paradigms in artificial intelligence computing and especially quantum computing will be given.

MüSIM2024 Speakers

Prof. Dr. Metin Sitti

Koç University
Istanbul, Turkey &
MPI for Intelligent Systems
Stuttgart, Germany

Metin Sitti is the President and Professor of Koç University in Istanbul, Turkey since fall 2023. Formerly, he was a Director of the Physical Intelligence Department at Max Planck Institute for Intelligent Systems in Stuttgart, Germany (2014-2023), Professor at ETH Zurich, Switzerland (2020-2024), and Professor at Carnegie Mellon University (2002-2014) and a research scientist at UC Berkeley (1999-2002) in USA. He received his BSc (1992) and MSc (1994) degrees from Boğaziçi University, Turkey, and PhD degree from University of Tokyo, Japan (1999). His research interests include small-scale mobile robotics, bio-inspiration, wireless medical devices, and physical intelligence. He is a National Academy of Engineering (NAE) Member in USA and an IEEE Fellow. He received the Highly Cited Researcher recognition (2021, 2022, 2023), Breakthrough of the Year Award in the Falling Walls World Science Summit (2020), ERC Advanced Grant (2019), Rahmi Koç Science Medal (2018), SPIE Nanoengineering Pioneer Award (2011), and NSF CAREER Award (2005). He is the editor-in-chief of Progress in Biomedical Engineering and Journal of Micro-Bio Robotics journals and associate editor in Science Advances journal.

Physical Intelligence of Small-Scale Machines

Metin Sitti, Koç University, Istanbul, Turkey &
MPI Intelligent Systems, Stuttgart, Germany

Intelligence of physical agents is not only enabled by their computational intelligence in their brain, but also by their physical intelligence encoded in their body. This presentation reports bioinspired and abstract physical intelligence methods designed and implemented in small-scale robots from insect scale down to cell-size scale. Light-powered phototactic and bacteria-driven chemo/magnetotactic microswimmers are presented at the cell-size scale. At the milliscale, bioinspired soft-bodied robots with shape and stiffness programming capability, physical adaptation in confined spaces, and multifunctionality are presented. Liquid crystal elastomer types of stimuli-responsive materials are integrated with magneto-elastic composites towards self-sensing and self-adapting millirobots. Finally, mechanical computing systems using bistable metastructures are proposed to encode physical computing in millimachines.

MüSIM2024 Speakers

Prof. Dr. Shiki Yagai

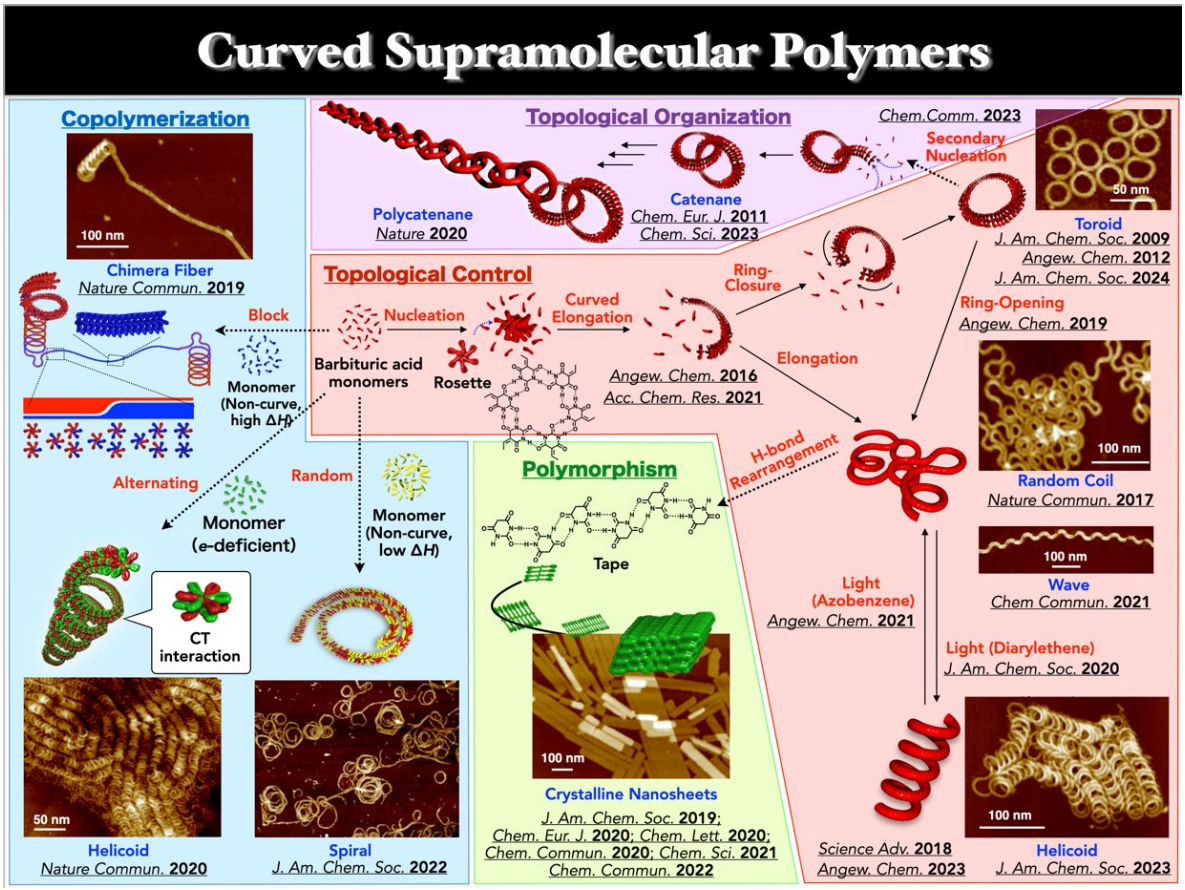
Chiba University
Institute for Advanced Academic Research
Department of Applied Chemistry and Biotechnology
Chiba, Japan

Shiki Yagai has had a distinguished career in the field of engineering, marked by significant contributions to academia and research, beginning his career as an Assistant Professor at the Faculty of Engineering, Chiba University (2002 – 2007). He then served as a PRESTO researcher at the Japan Science and Technology Agency (2006 – 2010), before his promotion to Associate Professor at the Graduate School of Engineering, Chiba University (2010), where he mentored students and advanced his research. His promotion to Professor in July 2017 at the Institute for Global Prominent Research (IGPR) and later at the Institute for Advanced Academic Research (IAAR) in 2022 highlighted his leadership and contributions. Since 2023, he has also served as Head Investigator for the Grant-in-Aid for Transformative Research Areas in "Materials Science of Meso-Hierarchy."
Shiki Yagai's research excellence has been recognized with numerous awards, including the the Swiss Chemical Society Lectureships Award (2017), the Nagase Science and Technology Foundation Award (2018), the JSPS Prize for developing Topological Supramolecular Polymers (2020), the Chemical Society of Japan Award for Creative Work (2022), and the Inoue Prize for Science (2023).
Shiki Yagai continues to advance the field of materials science and engineering, inspiring and influencing both his peers and the next generation of scientists.

The Discovery and Evolution of Curved Supramolecular Polymers

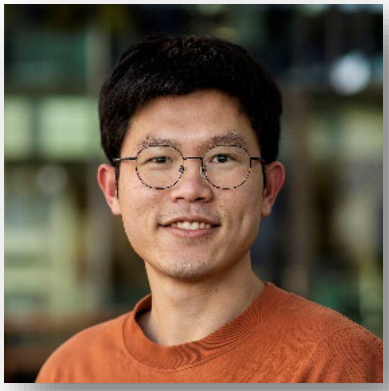
Shiki Yagai, Chiba University, Japan

One-dimensional molecular aggregates, known as supramolecular polymers, are emerging polymeric materials owing to their reversible bonding. However, to compete over covalent counterparts, development of supramolecular polymers with well-defined higher-order structures are desired. We have addressed this issue based on our unexpected discovery in 2009 and 2012 on the formation of nanorings from hydrogen-bonded rosettes (hexameric oligomers) of a p-conjugated compounds bearing barbituric acid and long alkyl tails. Uniform diameters of nanorings about 20 nm allowed us to establish the concept of "intrinsic curvature" as a result of a high degree of internal order upon the continuous stacking of rosettes. Based on this concept, we synthesized various p-conjugated compounds based on the above molecular design. By studying the self-assembly behaviors of these molecules, now we are able to prepare a variety of curved supramolecular polymers which can be dictated based on distinct topic: topological control and properties (red area), dynamic copolymerization (blue area), polymorphism (green area), topological organization (purple area). Some recent examples of these will be presented in my presentation.



For references, please visit the website of Yagai Group (http://chem.tf.chiba-u.jp/yagai/).

MüSIM2024 Young Researcher Awardee



Pengrong Lyu, MS

Chemical Engineering and Chemistry
Human Interactive Materials
Eindhoven University of Technology
Eindhoven, The Netherlands

For his contribution:

Advancing Interactive Systems with Liquid Crystal Network-Based Adaptive Electronics

Pengrong Lyu, Dirk J. Broer, and Danqing Liu
Nature Communications | (2024) 15: 4191

Achieving adaptive behavior in artificial systems, analogous to living organisms, has been a long-standing goal in electronics and materials science. Efforts to integrate adaptive capabilities into synthetic electronics traditionally involved a typical architecture comprising of sensors, an external controller, and actuators constructed from multiple materials. However, challenges arise when attempting to unite these three components into a single entity capable of independently coping with dynamic environments. Here, we unveil an adaptive electronic unit based on a liquid crystal polymer that seamlessly incorporates sensing, signal processing, and actuating functionalities. The polymer forms a film that undergoes anisotropic deformations when exposed to a minor heat pulse generated by human touch. We integrate this property into an electric circuit to facilitate switching. We showcase the concept by creating an interactive system that features distributed information processing including feedback loops and enabling cascading signal transmission across multiple adaptive units. This system responds progressively, in a multi-layered cascade to a dynamic change in its environment. The incorporation of adaptive capabilities into a single piece of responsive material holds immense potential for expediting progress in next-generation flexible electronics, soft robotics, and swarm intelligence.

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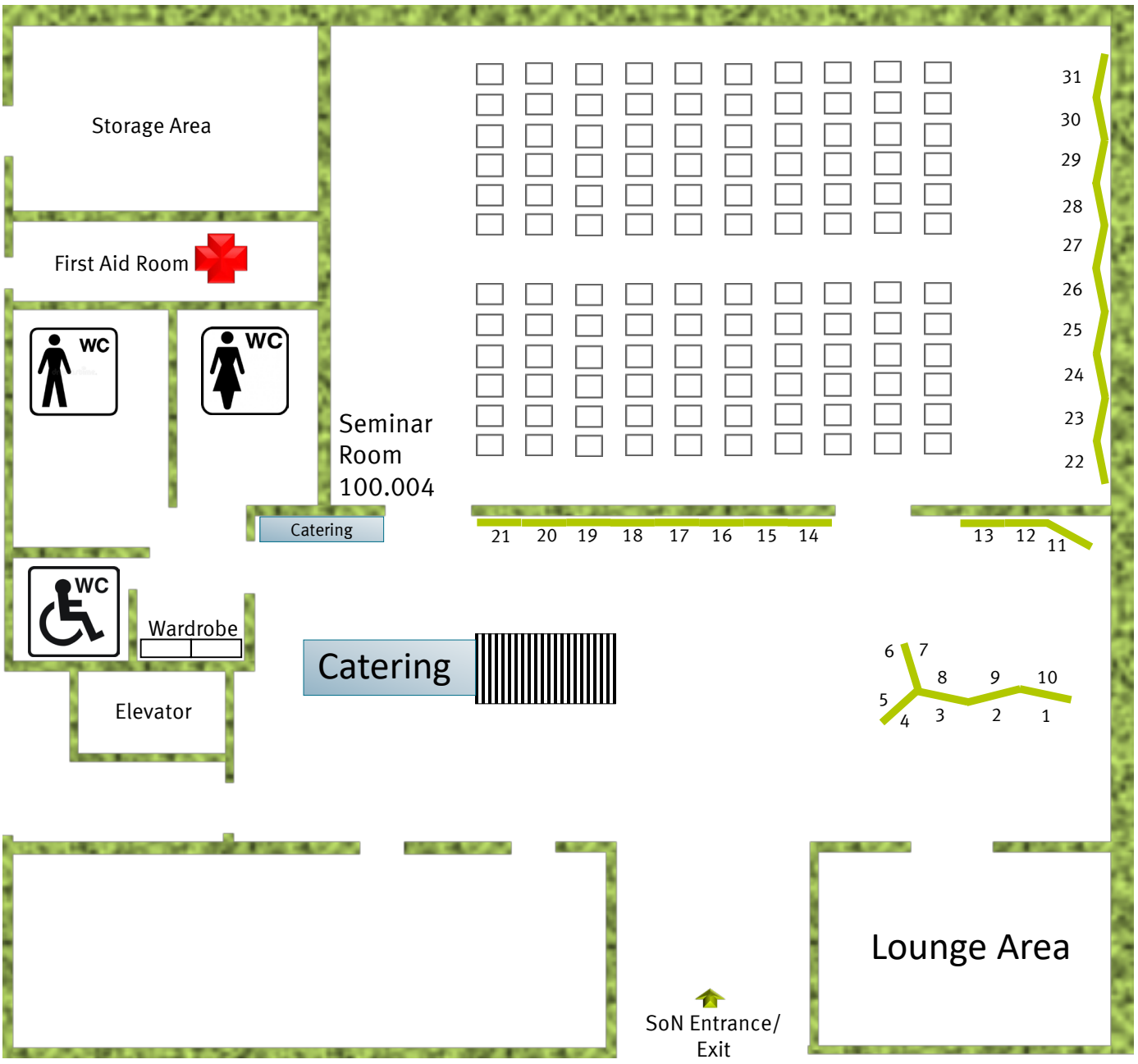
Poster Sessions Setup

Center for Soft Nanoscience Foyer, Seminar Room



Poster Session I (odd numbers): 1:00pm – 1:50pm

Poster Session II (even numbers): 1:50pm – 2:40pm

MüSIM2024 Poster Contributions

(alphabetical order, first author´s surname)

01. Unidirectional Molecular Adaptation by Coupled Stimuli
Sebastian Baumert, Torsten Dünnebacke, Sebastian Hochstädt, Sabine Käfer, Michael Ryan Hansen, Johannes Neugebauer, and Gustavo Fernández
University of Münster, Germany

02. Integrating Memory into Hybrid Opto-Electronic Circuits
Ivonne Bente[1], Reinier J.C. Cool[1,2], Donato F. Falcone[3], Laura Bégon-Lours[3], Valeria Bragaglia[3], Bert Jan Offrein[2,3], Wilfred G. van der Wiel[1,2] and Wolfram H. P. Pernice[1,4]
[1]University of Münster, Germany [2]University of Twente, The Netherlands [3]IBM Research Europe – Zurich Research Laboratory, Switzerland [4]Heidelberg University, Germany

03. Self-Assembly of Hybrid Nanostructures for Brain-Inspired Electronics
Marc Beuel[1,2], Jonas Mensing[1], Lisa Schlichter[1], Andreas Heuer[1], Bart Jan Ravoo[1], and Wilfred van der Wiel[1,2]
[1]University of Münster, Germany [2]University of Twente, The Netherlands

04. Tuning Electronic Behaviour of Carbene Molecular Tunneling Junction by Monolayer Structure
Alessandro Borrini[1], Ankita Das[2], Saurabh Soni[1], Frank Glorius[2], and Christian A. Nijhuis[1,2]
[1]University of Twente, The Netherlands [2]University of Münster, Germany

05. Mechanophores as Kick-Starters for Reaction Cascades
P. Jarne de Jong and Michael M. Lerch
University of Groningen, The Netherlands

06. Adaptive Air-Water Interfaces with Spiro-Pyran and Arylazopyrazole Photoswitches
Michael Hardt, H. Gökberk Özcelik, Andreas Heuer, and Björn Braunschweig
University of Münster, Germany

07. Towards a Scalable Fabrication of Biobased Photonic Pigments
Maria Karsakova and Michael M. Lerch
University of Groningen, The Netherlands

08. Bio-Inspired Active Plasmonic Nanofilters for Computer Vision
Gyurin Kim, Doeun Kim, Jang-hwan Han, Juhwan Kim, Joo Hwan Ko, Young Min Song and Hyeon-Ho Jeong
Gwangju Institute of Science & Technology, Rep. of Korea

09. Coherent Nanophotonic Neural Networks with Adaptive Molecular Systems
Peter Lazarowicz, Marco Butz, Marlon Becker, Carsten Schuck, and Benjamin Risse
University of Münster, Germany

MüSIM2024 Poster Contributions

(alphabetical order, first author´s surname)

10. **Conducting Droplet as a Neuron-Like Oscillator for Computing**
    Yi Li, Saurabh Soni, Arjan Vellema, Qianqi Lin, Mathieu Odijk, and Christian A. Nijhuis
    University of Twente, The Netherlands

11. **Advancing Interactive Systems with Liquid Crystal Network-Based Adaptive Electronics**
    Pengrong Lyu, Dirk J. Broer and Danqing Liu
    Eindhoven University of Technology, The Netherlands

12. **Probing the Roles of Temperature and Cooperative Effects in CISS**
    Paul V. Möllers[1], Adrian J. Urban[2,3], Steven De Feyter[3], Hiroshi M. Yamamoto[2], and Helmut Zacharias[1]
    [1]University of Münster, Germany [2]Research Center of Integrative Molecular Systems, Japan, [3]KU Leuven, Belgium

13. **Adaptive Cell-Matrix Nanosystems**
    Theresa Mößer[1], Tobias Rex[1], Inka Schröter[2], Carsten Grashoff[1], Cristian A. Strassert[1], and Britta Trappmann[2]
    [1]University of Münster, Germany [2]Technical University Dortmund, Germany

14. **Developing Tunable Triplet Emitters towards Adaptive Electroluminescent Materials**
    Thaison Nguyen, Alex Oster, Dominik Schwab, Maria Victoria Cappellari, Nikos Doltsinis, and Cristian A. Strassert
    University of Münster, Germany

15. **Spin Wave Device as a Basis for Neuromorphic Computing**
    Kirill O. Nikolaev[1], Dmitrii Raskhodchikov[1], Jannis Bensmann[1], Emma Lomonte[1], Lin Jin[1], Robert Schmidt[1], Johannes Kern[1], Steffen Michaelis de Vasconcellos[1], Rudolf Bratschitsch[1], Sergej O. Demokritov[1], Wolfram H. P. Pernice[1,2], and Vladislav E. Demidov[1]
    [1]University of Münster, Germany [2]Heidelberg University, Germany

16. **Photo-Induced Drug Release at Interfaces with Arylazopyrazoles**
    Ipsita Pani, Michael Hardt, Dana Glikman and Björn Braunschweig
    University of Münster, Germany

17. **Control of the Primary and Secondary Structure in Synthetic Polymers to Access Adaptive Soft Materials**
    Christophe Pauly, Kirill Markelov, and Armido Studer
    University of Münster, Germany

MüSIM2024 Poster Contributions

(alphabetical order, first author´s surname)

18. **GRACYASK: GRAphs CYcles And SKyrmions**
    Sinuhe Perea
    London Centre of Nanotechnology, UK

19. **Adaptive Polymer Morphologies through Reversible Block Fragmentation**
    Yorick Post[1], Katharina Ziegler[1], Bart Jan Ravoo[1], and André H. Gröschel[2]
    [1]University of Münster, Germany [2]University of Bayreuth, Germany

20. **Electrochromic Dye-Doped Liquid Crystal PMMA Microcapsules**
    Yinggi Ren and Michael Lerch
    University of Groningen, The Netherlands

21. **SmartMatters4You: Students Gain Insights into Research at the CRC 1459 "Intelligent Matter"**
    Julian Repke
    University of Münster, Germany

22. **Adaptive Matter Systems Based on Light-Driven Refractive Microparticles**
    Matthias Rüschenbaum[1], Julian Jeggle[1], Elena Vinnemeier[1], Jörg Imbrock[1], Cornelia Denz[2], and Raphael Wittkowski[1]
    [1]University of Münster, Germany [2]Physikalisch-Technische Bundesanstalt (PTB), Germany

23. **Supramolecular Polymer Coatings Based on Peptide Self-Assembly**
    Mahdi Samapour[1], Sebastian Beil[2], Tobias Schnitzer[3], and Michael Lerch[1]
    [1]University of Groningen, The Netherlands [2]MPI for Chemical Energy Conversion, Germany
    [3]Albert-Ludwigs University Freiburg, Germany

24. **New Photoswitches for Integration in Adaptive Nanosystems**
    Bastian Stövesand, Arne Nalop, Bart Jan Ravoo, and Frank Glorius
    University of Münster, Germany

25. **A Semi-Synthetic Nanosystem for Programmable Control of Output Based on Rational Design and Directed Evolution**
    Aileen Tekath[1], Raminta Mineikaitė[1], Nicolas Cornelissen[1], and Andrea Rentmeister[2]
    [1]University of Münster, Germany [2]Ludwigs-Maximilians-University, Germany

26. **Rational Design of Liquid Crystalline Elastomers with Programmable Multi-Step Deformability**
    Foteini Trigka and Michael M. Lerch
    University of Groningen, The Netherlands

MüSIM2024 Poster Contributions

(alphabetical order, first author´s surname)

27. **Mixed-Mode in-Memory Computing using Adaptive Phase Change Materials**
Niklas Vollmar[1], Daniel Wendland[1], Akhil Varri[1], Anna Ovvyan[1], Nishant Saxena[1], Zhongyu Tang[2], Wolfram Pernice[2], and Martin Salinga[1]
[1]University of Münster, [2]Heidelberg University

28. **Light Driven Metamachines**
Gan Wang[1], Marcel Rey[1,2], Antonio Ciarlo[1], Mohanmmad Mahdi Shanei[3], Kunli Xiong[1,4], Giuseppe Pesce[5], Mikael Käll[3], and Giovanni Volpe[1]
[1]University of Gothenburg, [2]University of Münster, [3]Chalmers University of Technology, Sweden
[4]Uppsala University, Sweden [5]University of Naples Federico II, Italy

29. **Supramolecular Light-Switchable Triazole-Hosts for Photoadaptive Anion Binding**
Leonard Wyszynski, Leon Hoppmann, Marcus Böckmann, Nikos Doltsinis, Monika Schönhoff and Olga García Mancheño
University of Münster, Germany

30. **Autonomous Cargo Delivery Empowered by Self-Regulating Bacteriabots**
Xiaoran Zheng, Yanjun Zheng and Seraphine Wegner
University of Münster, Germany

31. **Oscillatory Light Emission in Plasmonic Molecular Junctions**
Riccardo Zinelli, Zijia Wu, Saurabh Soni, Christian A. Nijhuis, Qianqi Lin
University of Twente, The Netherlands

MüSIM2024 Poster Abstracts

1

Unidirectional Molecular Adaptation by Coupled Stimuli

Sebastian Baumert, Torsten Dünnebacke, Sebastian Hochstädt, Sabine Käfer, Michael Ryan Hansen, Johannes Neugebauer, and Gustavo Fernández

University of Münster, Organisch-Chemisches Institut, Corrensstraße 36, 48149 Münster Germany
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Adaptation transcends scale in both natural and artificial systems, but delineating the causative factors of this phenomenon requires urgent clarification. Herein, we unravel the molecular requirements for adaptation and establish a link to rationalize adaptive behavior by electronic communication. These concepts were established by analyzing a model compound exhibiting π-conjugated light- and pH-responsive units, which enable the combined or independent application of different stimuli. Hereby we demonstrate that adaptation arises from coupled stimuli, as the final outcome of the system depends on their sequence of application. Our findings go beyond state-of-the art (multi)stimuli-responsive systems and allow us to draw up design guidelines for adaptive behavior at the molecular level.

2

Integrating Memory into Hybrid Opto-Electronic Circuits

I. Bente[1,2,3], R.I.C. Cool[1,4,5], D. Falcone[6], L. Bégon-Lours[6], V. Bragaglia[6], B. Offrein[5,6], W.G. van der Wiel[1,4,5] and W.H.P. Pernice[1,2,3,7]

[1] *University of Münster, Center for Soft Nanoscience (SoN), Busso-Peus-Str. 10, 48149, Münster, Germany*

[2] *University of Münster, Institute of Physics, University of Münster, Wilhelm-Klemm-Str. 10, 48149 Münster, Germany*

[3] *CeNTech – Center for Nanotechnology, Heisenbergstr. 11, 48149 Münster, Germany,*

[4] *University of Twente, Faculty of Electrical Engineering, Mathematics and Computer Science, Hallenweg 23, 7522NH, Enschede, The Netherlands*

[5] *University of Twente, MESA+ Institute, Hallenweg 15, 7522NH, Enschede, The Netherlands*

[6] *IBM Research Europe - Zurich Research Laboratory, CH-8803, Rüschlikon, Switzerland*

[7] *University of Heidelberg, Kirchhoff-Institut für Physik, Im Neuenheimer Feld 227, 69120 Heidelberg, Germany*

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Combining technologies meant for edge AI applications could enhance the individual technologies strengths and suppress their weaknesses. Low energy and ultra-low latency preprocessing of Photonic Convolution Processors (PCP) combined with the rich processing capabilities of Dopant Network Processing Units (DNPU) is a very promising combination. A first layer of a software neural network is directly built in hardware. The PCP represents the inputs and multiplication by the weight matrix, achter which the DNPUs directly perform a tunable non-linear operation. To enhance this system, PCPs and DNPUS are being upgraded to the next generation. The PCPs are enhanced by optimizing its multiplexing capabilities and electronic control. Memory is introduced to DNPUs by means of a ferroelectric layer, greatly improving its energy efficiency and scalability. PCPs with DNPUs could prove to be a promising system for the next generation of AI edge applications.

3

Self-Assembly of Hybrid Nanostructures for Brain-Inspired Electronics

Marc Beuel[1,2,4], Jonas Mensing[3], Lisa Schlichter[2], Andreas Heuer[3], Bart Jan Ravoo[2], and Wilfred G. van der Wiel[1,4]

[1] University of Twente, BRAINS Center for Brain-Inspired Nano Systems and MESA+ Institute for Nanotechnology, Drienerlolaan 5, 7522 NB Enschede, The Netherlands
[2] University of Münster Center for Soft Nanoscience / Organisch-Chemisches Institut, Busso-Peuss-Straße 10, 48149 Münster, Germany
[3] University of Münster, Institut für Physikalische Chemie, Correnstraße 28-30, 48149 Münster, Germany
[4] University of Münster, Physikalisches Institut, Wilhelm-Klemm-Straße 10, 48149 Münster, Germany
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Disordered hybrid nanomaterial networks exhibit complex energy landscapes [1] that can be tuned towards reconfigurable computational functionality, such as logic operations, feature extraction or other non-linear information processing. In this project, hybrid organic-inorganic nanostructures based on the assembly of nanoparticle networks connected by junctions composed of tailor-made organic ligands are constructed. Magnetite (MNP) [3] or gold nanoparticles (AuNP) act as single electron transistors while organic ligands act as tunable tunnel barriers introducing synaptic, tunable memory. Host-guest complexes with cyclodextrin and various guest molecules (e.g. semi-conductors and molecular switches like AAP) are explored as supramolecular junctions. By using dip pen nanolithography [2], the supramolecular are deposited on surfaces between nanoelectrodes. A genetic algorithm is used to find suitable configurations of control voltages to mimic the desired computations (for example by Evolution-in-materia). The theoretical underpinning of NP networks is investigated by developing a highly optimized physical model to simulate charge transport processes within the network stochastically [4] or by a meanfield approximation [6]. Besides, statistical and data-driven tools investigate requirements for computing and memory functionalities [4,5,6,7].

References:

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[2] L. Schlichter, F. Bosse, B.J. Tyler, H. F. Arlinghaus, B.J. Ravoo, Small 2023, 19, 2208069.
[3] L. Schlichter, J. Jersch, S.O. Demokritov, B. J. Ravoo, Langmuir 2024, 40, 13669-13675.
[4] J. Mensing, W. G. van der Wiel, A. Heuer, Frontiers in Nanotechnology, 2024, 6, fnano.2024.1364985.
[5] H. Tertilt, J. Mensing, M. Becker, W. G. van der Wiel, P. A. Bobbert, A. Heuer, Physical Review Applied, 2023, accepted.
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[7] H. Tertilit, J. Bakker, M. Becker, B. de Wilde, I. Klanberg, B. J. Geurts, W. G. van der Wiel, A. Heuer, P. A. Bobbert, Physical Review Applied 2022, 7, PhysRevApplied.17.064025.

4

Tuning Electronic Behaviour of Carbene Molecular Tunneling Junction by Monolayer Structure

Alessandro Borrini[1], Ankita Das[2], Saurabh Soni[1], Frank Glorius[2], and Christian A. Nijhuis[1,2]

[1]University of Twente, Hybrid Materials for Opto-Electronics Group, Department of Molecules and Materials, MESA+ Institute for Nanotechnology, Molecules Center and Center for Brain-Inspired Nano Systems, Faculty of Science and Technology, P.O. Box 2017, 7500 AE Enschede, The Netherlands

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N-heterocyclic carbenes (NHCs) show great potential to be used as a robust alternative to thiols to form self-assembled monolayers (SAMs)[1–4]. NHCs have been proved to form high crystalline SAMs and to be thermally stable.[5] Few molecular electronic devices have been proposed so far, based on single-molecule scanning tunneling microscope-based break junction (STM-BJ)[6], and molecular tunnelling junction by eutectic Ga–In (EGaIn) technique[5]. However, devices based on NHCs SAMs have not been explored much as memristor electronics for computing applications. Here, we functionalize dimethylimidazolylidene (IMe) with a redox active anthraquinone (AQ) moiety to enable multi-state memory. We characterized the surface of these thin (~ 1.4 nm) SAMs, and measured the molecular tunnelling junction using EGaIn technique. Hysteresis is observed proving that it can function as a memory device. Furthermore, we showed that depending on the bias window applied these junctions can be reconfigured as normal or variable resistor. Devices to enable multi-function at one spot for computing applications is thus developed.

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5

Mechanophores as Kick-Starters for Reaction Cascades

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From cells and bacteria to the Venus fly trap, mechano-responsiveness is widespread in nature.[1, 2] Commonly, such mechanical input is converted into chemical signals via signal transduction and amplification. We envisioned synthetic system mimicking this behavior, in which a mechanophore is used to start a reaction cascade. Up to date, there are several examples where mechanical force was applied to a sample to release molecular cargo,[3-5] which then may change the material environment and trigger functional responses. At the same time, mechanophores have been used for cascade reactions by means of a mechanoresponsive catalys[6, 7]. Next to that, mechanophores have been used to initiate self-healing and strengthening (with the use of bis-maleimide)[8, 9]. Our work utilizes a different strategy and couples a mechanophore to an autocatalytic reaction cascade. In this way, a small amount of mechanophore is sufficient to initiate and amplify a chemical signal. Amplification by autocatalysis coupled to mechanical triggers may paves the way for mechanoresponsive smart materials with amplifying responses for chemical communication and artificial signal transduction.

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6

Adaptive Air-Water Interfaces with Spiro-Pyran and Arylazopyrazole Photoswitches

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Interfaces that respond to stimuli like light or temperature are of significant interest in the field of dynamic materials.1,2 Using molecular switches that react to different triggers enables the precondition of the properties of fluid interfaces and introducing a basic level of adaptivity, thereby extending the possibilities of soft matter interfaces beyond responsive functions. We explore the adaptive behaviour of air-water interfaces decorated by spiropyran (SP) and arylazopyrazole (AAP) photo-responsive surfac-tants. When exposed to UV light, the SP surfactants become more surface active, while the AAP surfactants undergo E/Z photoisomerization, significantly reducing their surface activity.

By adjusting the intensity and duration of the UV exposure, the interfacial properties can be shifted from a simple responsive state to a more complex, conditioned response, accompanied by a dramatic alteration in interfacial chemistry. Vibrational sum-frequency generation (SFG) and neutron reflectometry suggest that prolonged UV exposure induces SP and AAP surfactant aggregation at the air-water interface, driving the conditioned response where thick SP layers form in the presence of Z-AAP. These experiments are complemented with classical molecular dynamics simulations of the AAP and SP surfactants that visualize the occurrences at the air-water interface depending on the surface coverage.

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7

Towards a Scalable Fabrication of Biobased Photonic Pigments

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Photonic pigments, as compared to traditional chemical dyes may provide better resistance to fading and can be made with renewable materials. The bottom-up assembly of photonic pigments comprises the controlled self-assembly of nanoparticles within confining emulsion droplets.

While microfluidics and small scale emulsification procedures have proven effective in creating optically high-quality structurally colored pigments, this approach to fabrication suffers from long assembly times and a lack of scalability. In this project, we explore ways to speed and scale-up colloidal assembly of naturally sourced building blocks in emulsion droplets and characterize their optical properties. Shortening the self-assembly process and increasing scale will be vital steps towards a cost-effective, sustainable, and ultimately appealing paint product.

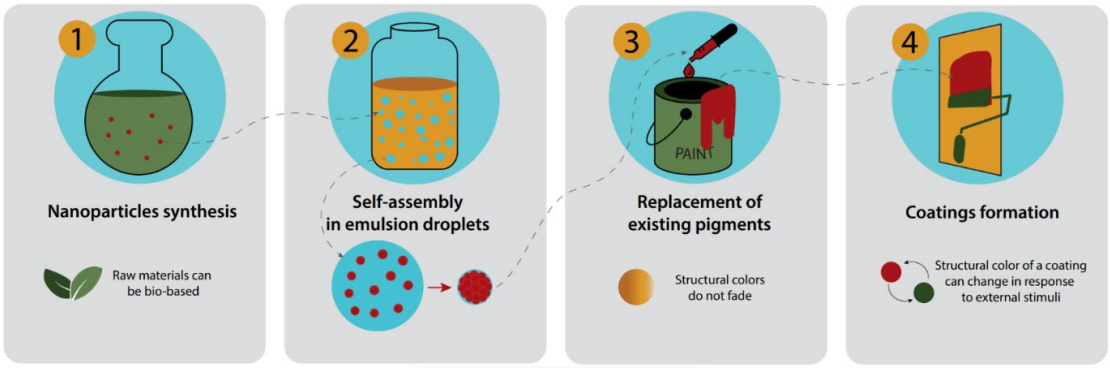

Fig. 1. – General steps of photonic pigments formation and their application

8

Bio-Inspired Active Plasmonic Nanofilters for Computer Vision

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Adaptive multicolor filters are vital for achieving accurate color representation in outdoor visual devices. Inspired by the structure of a deer's eye [1], we present a multicolor nanofilter made from multilayered plasmonic nanocomposites, where metallic nanoparticles are embedded in a conductive polymer nanofilm. These nanocomposites, less than 100 nm thick, are fabricated using a lithography-free method and feature distinct optical modes that produce dichroic colors. Notably, the filter can electrically adjust these colors across the visible spectrum with less than 1 V and a switching speed of 3.5 seconds. This programmable function enables dynamic modulation of white light's color temperature from warm to cool (3250 K–6250 K), enhancing outdoor optical device performance.

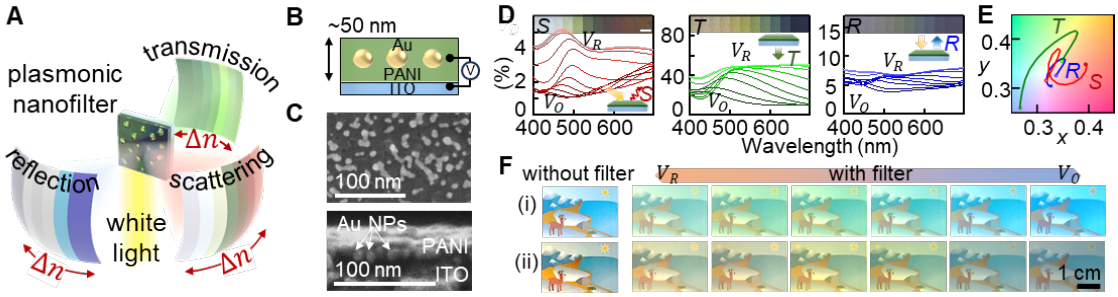

Fig. 1. (A) Electrically switchable plasmonic nano-filter with (B) the plasmonic nanocomposite and (C) its electron microscopic images at the top (top) and side (bottom). (D) Color dynamics and optical dynamic images (scale bar: 500 μm) of scattering (top), transmission (middle), and reflection (bottom) of the fabricated plasmonic nano-filter when the voltage is applied from -0.2 V (V_R) to 0.8 V (V_O). (E) Associated color gamut plots (CIE 1931 chromaticity). (F) Color temperatures modulated by the nanofilter under (i) cool and (ii) warm white LEDs.

Acknowledgement

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9

Coherent Nanophotonic Neural Networks with Adaptive Molecular Systems

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Optical Neural Networks (ONNs) have become increasingly important as candidates to overcome the limitations of Van Neumann-based Artificial Neural Networks (ANNs). While linear operations within ONNs have been successfully demonstrated, nonlinear ONN building blocks required to implement ANN activation functions pose a significant challenge. Therefore, this work is dedicated to the implementation of optical nonlinear activation functions and other fundamental ONN building blocks. Adaptive molecular systems and soft materials are used for this purpose.

One approach is to exploit the saturable absorption of soft materials as a basis for nonlinear activation behaviour. We employ sub-wavelength waveguides surrounded by doped semiconductors to produce this nonlinear response. Whereas for adaptive molecular systems, we developed a generally applicable platform that allows the integration of various molecular systems. As a first demonstration we integrated photoswitchable azobenzenes to introduce a concentration-dependent nonlinear activation behaviour in the form of a saturable absorption effect. We demonstrated the capability of this platform by solving the classification task of the MNIST data set. Simultaneously we develop an “inverse design” platform which generates unintuitive structures to reduce device footprint and improve scalability. In combination, these lay the groundwork for chip-scale nonlinear activation behaviour.

10

Conducting Droplet as a Neuron-Like Oscillator for Computing

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Biomimetic systems, emulating neuronal behavior and bio-inspired computing, are important based on understanding of neuronal functions. Wherein oscillatory system is promising by producing rhythmic patterns (e.g., mimicking brain waves). Specifically, high-order complexity is essential to reach rich dynamics in neural behavior (e.g., tonic, adapt and burst firing). Yet the system achieving such rich dynamics within one oscillator is rarely studied. The potential of soft materials and chemicals in mimicking natural oscillation is great but not fully appreciated. Here we report a self-driven oscillator based on liquid metal (alloy of Ga and In) droplet, driven by a continuous applied DC voltage, which are visually recorded in real time. The characteristics of this oscillator depends on the voltage, pH and viscosity of the medium in which the droplet oscillates. This oscillator exhibits high-order complexity, with its current output resembling the action potentials of various types of neurons. Furthermore, we demonstrate waveform classification using this oscillator.

11

Advancing Interactive Systems with Liquid Crystal Network-Based Adaptive Electronics

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Achieving adaptive behavior in artificial systems, analogous to living organisms, has been a long-standing goal in electronics and materials science. Efforts to integrate adaptive capabilities into synthetic electronics traditionally involved a typical architecture comprising of sensors, an external controller, and actuators constructed from multiple materials. However, challenges arise when attempting to unite these three components into a single entity capable of independently coping with dynamic environments. Here, we unveil an adaptive electronic unit based on a liquid crystal polymer that seamlessly incorporates sensing, signal processing, and actuating functionalities. The polymer forms a film that undergoes anisotropic deformations when exposed to a minor heat pulse generated by human touch. We integrate this property into an electric circuit to facilitate switching. We showcase the concept by creating an interactive system that features distributed information processing including feedback loops and enabling cascading signal transmission across multiple adaptive units. This system responds progressively, in a multi-layered cascade to a dynamic change in its environment. The incorporation of adaptive capabilities into a single piece of responsive material holds immense potential for expediting progress in next-generation flexible electronics, soft robotics, and swarm intelligence.

12

Probing the Roles of Temperature and Cooperative Effects in CISS

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Chirality-induced spin selectivity (CISS) has previously been evidenced in a variety of experimental configurations, ranging from photoemission in UHV to voltammetry in an electrochemical cell. CISS has been exploited to enhance the selectivity of chemical reactions, for enantiomer separation, and to fabricate spintronic devices. Nevertheless, a consensus on the fundamental understanding is still lacking. Theoretical studies suggest that mechanisms mediated by molecu-lar vibrations could underlie the effect, and account for its robustness. While CISS can occur in isolated molecules, both theoretical and experimental studies exist which suggest an enhancement in dense molecular layers.

We investigate the roles of molecular vibrations and intermolecular interactions in CISS in monolayers of helical tetrapyrrole molecules. The spin polarization of photoelectrons emitted from tetrapyrrole-functionalized surfaces was measured as a function of the temperature and the surface coverage.

In combination with the temperature-dependent population of those vibrational modes which vary the helical molecular geometry, the data demonstrate that molecular vibrations do not play a significant role for CISS in the TPBT layers. While the spin polarization scales nonlinearly with the surface coverage, this behavior can be rationalized through changes of the photoelectron yield upon surface functionalization, and therefore represents no evidence for cooperative effects in CISS.

13

Adaptive Cell-Matrix Nanosystems

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The overall goal of this project was to explore a novel cell-matrix nanosystem in which mammalian cells are used as processing elements that endow a nanomaterial with responsive, adaptive and, in the end, intelligent properties. To achieve this, we planned to connect protein-based fluorescence biosensors with cells that, by exerting forces onto the biosensors, modulate the fluorescent readout. Despite a range of technical challenges, our work demonstrates that this approach is indeed feasible. Ongoing experiments focus on the optimization of a 2D nanosystem in which the biosensor will be specifically immobilized on a glass surface, enabling direct interaction with cell adhesion sites. First steps to improve the dynamic range of the system by combining the biosensor with metal-organic compounds are promising and indicate that future readouts using phosphorescence-based imaging may be possible.

14

Developing Tunable Triplet Emitters towards Adaptive Electroluminescent Materials

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Innovative light-emitting materials based on photoluminescent metal-organic coordination compounds will be designed and synthesized. By attaching to metal nanoparticles or by being incorporated within soft polymeric matrices, these materials exhibit adaptiveness to various external stimuli including light, temperature, pressure, mechanical forces, and electrochemical potential. This adaptability positions them as powerful tools for detecting subtle environmental changes with high precision, makes them ideal candidates for applications as sensitives sensor. In the long term, the developed concepts will enable advanced optical information storage and processing by embedment in nanophotonic matrices and incorporation into neuromorphic computing architectures.

15

Spin Wave Device as a Basis for Neuromorphic Computing

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Signal processing and computation utilizing spin waves propagating through nanoscale magnetic structures and networks have gained significant recognition in recent years as a promising technology capable of overcoming the limitations inherent in conventional semiconductor microelectronics [1,2]. This technology leverages the ability to encode information in the phase, amplitude, and frequency of spin waves, enabling various data-processing operations by exploiting the dependency of spin-wave propagation characteristics on these parameters. Among the spin-wave devices, frequency demultiplexers hold a particularly pivotal role. They enable the separation of information channels within the frequency domain, similar to the function they serve in microwave and photonic communication systems. We use microfocus Brillouin-light-scattering spectroscopy to directly visualize the propagation and transformation of spin waves in a magnetic cross composed of two 750-nm-wide YIG waveguides, intersecting at an angle of 30° [3].

In addition, recent research shows that magnon structures can operate at zero bias field, which greatly facilitates the integration of spin wave devices into complex computing networks [4].

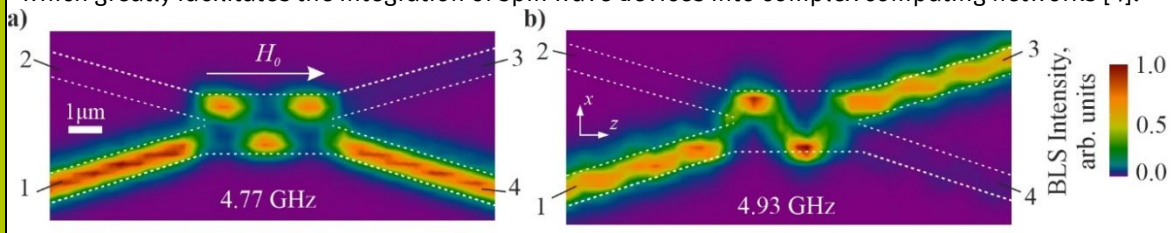

Figure 1. Representative spatial maps of spin-wave intensity recorded at different excitation frequencies.

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16

Photo-Induced Drug Release at Interfaces with Arylazopyrazoles

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Smart stimuli-responsive materials have significantly advanced the field of high-precision drug delivery. While much attention has been focused on characterizing drug release in bulk aqueous solutions, the aqueous-hydrophobic interfaces, crucial for biological systems remain less explored. These interfaces are pivotal for key biomolecular interactions. In this study, we investigate drug release at the air-water interface as a model to mimic the organic/aqueous interface of cells. Utilizing the advantages of light as an external stimulus and the superior properties of arylazopyrazoles (AAP) compared to conventional azobenzene photoswitches, we investigate a micellar nanocarrier system for the controlled capture and release of the chemotherapeutic drug Doxorubicin. Employing interface-sensitive techniques such as the Langmuir-Blodgett technique, surface tensiometry, and interface-specific vibrational sum frequency generation (SFG) spectroscopy, we demonstrate the photoresponsive release of Doxorubicin from AAP photosurfactant micelles at the air-water interface. Complementary fluorescence measurements further confirm additional drug release in bulk aqueous solutions.

17

Control of the Primary and Secondary Structure in Synthetic Polymers to Access Adaptive Soft Materials

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Controlled radical polymerization is crucial for synthesizing well-defined polymers with low polydispersity. In this context, nitroxide-mediated polymerization (NMP) has emerged as a valuable method, yielding narrow mass distributions essential for the development of next-generation materials. A notable limitation of traditional NMP is its requirement for elevated temperatures. However, mechanically induced stress on the C-ON bond could also promote bond cleavage, facilitating a sonochemical nitroxide-mediated polymerization. Building on our previous research, we aimed to combine NMP with mechanochemistry by developing nitroxide-based mechanophore macroinitiators that can be activated by mechanical force.
The control over the primary structure of the polymer is crucial for designing responsive and adaptive soft materials. Block-copolymers are generally known for featuring distinct responsive properties such as thermo-, photo- and pH-responsivity. In contrast, only few examples of alternating copolymers showing such distinct responsive behavior are known in literature. Postmodification of a polymer accomplishes the alteration of the respective polymers' properties by introducing new functionalities. In addition, postmodification methods such as thiol-ene-click, amidation/esterification and azide-alkyne-cyclocaddition approaches allow selective tuning of the properties of the polymer towards responsive and adaptive behavior.

18

GRACYASK: GRAphs, CYcles, And SKyrmions

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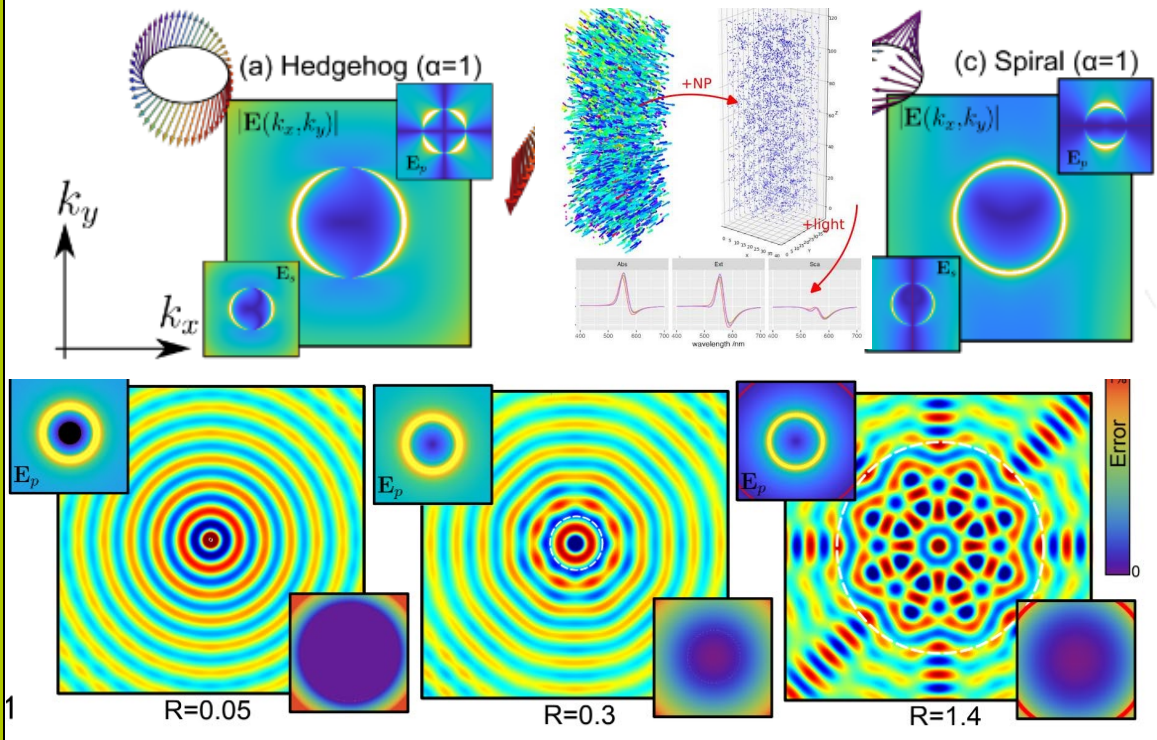
In recent years, the boundaries between mathematics and natural sciences have increasingly blurred out due to the parallel advances in fabrication techniques and lab characterisation of nanomaterials. By extending initial simple re-writing rules from Cayley diagrams, it is possible to construct hypergraph sets that elucidate topological features across a wide range of phenomena in soft-matter dynamics. These include fiber bundles, self-assembling cholesteric liquid crystal templates, near-field chiral nanomagnetism, or the formation of mother-of-pearl. Classifying these topological defects using Toulouse-Kleman parameters facilitates the definition of a generalised framework for encompassing skyrmion-like structures in discretised inelastic lattices, liquid crystals, chiral electromagnetism, and biomineralisation, respectively. This framework reveals important nuances regarding general principles of discontinuity cancellation in continuous media and stabilization mechanisms via topological protection, which are crucial for technological applications like toroidal metasurfaces characterisation, racetrack memory spintronics or bottom-up approaches to structural colour.



19

Adaptive Polymer Morphologies through Reversible Block Fragmentation

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Supramolecular structures, which can be operated out-of-equilibrium, are extremely interesting for the development of intelligent materials.[1] In this project, we aim to design a block copolymer that is able to dynamically alter its composition through energy-driven supramolecular fragmentation. Our polymer system consists of two different parts, which are connected through host-guest chemistry. The first part is a block copolymer including the hydrophobic, amorphous poly(methyl methacrylate-co-hexyl methacrylate) (PMH) with low Mn and tuneable glass transition temperature, as well as a short, hydrophilic poly(oligo(ethylene glycol) methacrylate (POEGMA) with a β cyclodextrin (β-CD) host molecule as end group. The second part is a longer hydrophilic POEGMA homopolymer with an arylazopyrazole (AAP) guest molecule as end group.
Connecting our two different polymers with this host-guest complex, it will be possible to create reversible micelle morphologies. Driven by a difference in binding affinity of the different photo-isomers of AAPs, irradiation by light allows a reversible dissociation. The E-isomer can form a host-guest complex with the β-CD, while the binding affinity of the Z-isomer is too low for that.[2]
With this polymer system we want to develop dissipative block copolymer nanostructures, which can potentially form out-of-equilibrium morphologies.

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20

Electrochromic Dye-Doped Liquid Crystal PMMA Microcapsules

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Electrical skin is a rapidly evolving field that aims to develop flexible, stretchable, and highly sensitive electronic devices capable of mimicking the functionalities of human skin. However, state-of-the-art wearable electronics face limitations regarding wearability and functionality due to the mechanical incompatibility between conventional rigid, planar electronics and soft, curvy human skin surfaces[1]. PMMA capsules, with their biocompatible and mechanically flexible properties, offer a versatile platform for incorporating various materials and functionalities[2]. Liquid crystals, known for their responsiveness to electric fields, provide a means to detect and transduce these stimuli into electrical signals[3]. The encapsulation of liquid crystals provides protection against environmental factors, ensuring the stability and durability of sensing and actuation functionalities. In addition, the flexibility of PMMA capsules allows for conformal contact with the skin, enabling comfortable and non- invasive usage of electrical skin devices[4].

In this project, we aim to fabricate dye-doped liquid crystal (LC) PMMA microcapsules with a core-shell structure by using emulsion polymerization. The reason for the core-shell structure is due to the protective effect of microcapsules and the LCs do not stain each other when different dichroic dyes are doped. PMMA can play a role in the fabrication of e-skin due to its transparency, flexibility, and biocompatibility[5]. These core-shell structures will then be implemented within electrical skin platforms. By combining dye-doped LCs, the PMMA microcapsules can confer electrical conductivity to the e-skin, thereby facilitating the detection of electrical signals or providing electrical stimulation for diverse functionalities.

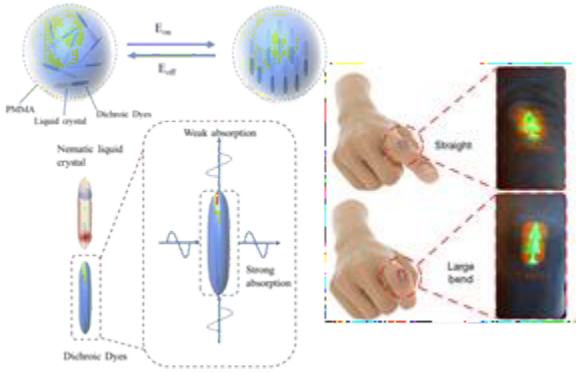

Fig. 1 The mechanism diagram of the dye-doped liquid crystals and conceptual design of application in e-skin[6].

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21

SmartMatters4You: Students Gain Insights into Research at the CRC 1459 “Intelligent Matter”

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Since 2019, the number of first-year students in STEM courses has been falling. Aside from the fact that a general recruitment of STEM students is very important for Germany as a technology location, it is particularly important to recruit women for STEM courses. In 2021 only 35% of STEM students in Germany were female[1].

SmartMatter4You empowers scientifically interested female upper school students to pursue a career in science. Through the cooperation from the research in the CRC 1459 “Intelligent Matter” and the know-how of the school laboratory MExLab Physik the students can experience unique access to highly topical research in interdisciplinary workshops and take part in hands-on excursions to science-related companies.

SmartMatters4You helps to bridge the gender gap by raising awareness of gender equality and using empirically proven strategies for success[2]. A major goal of the project is to arouse fascination and convey the importance of basic research in order to attract the female scientists of tomorrow. In a scientific accompanying study, the mechanisms of the career choice decisions of high school students and the role of social barriers are examined from an interdisciplinary perspective using methods of empirical social research. In 2024, the project will be carried out for the third time, so that the first results on its effectiveness will be available.

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22

Adaptive Matter Systems Based on Light-Driven Refractive Microparticles

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Active matter systems are known to exhibit a wide variety of collective phenomena aided by the inherent non-equilibrium nature of these systems. In recent years, there have been efforts to utilize this class of matter as a platform for intelligent materials. Here we present a novel approach to this end in the form of an active matter system consisting of symmetry-broken refractive microparticles that are capable of self-propulsion under illumination. These particles are fabricated via two-photon polymerization in configurable shapes and with configurable motion patterns. We start by characterizing the motion of individual particles both experimentally and theoretically. Next, we observe collective behavior in dilute suspensions of the particles, e.g., the formation of small rotating clusters as a result of particle interactions. Finally, we investigate denser suspensions and show that information encoded via a non-homogeneous illumination pattern can be propagated through networks of interacting particles. The feedback loop between particle propulsion and particle interaction enables systems of refractive microparticles to transcend purely responsive behavior and form an adaptive system. Finally, we give a brief outlook on possible improvements in particle design and the use in physical reservoir computing as the next step towards intelligent matter.

23

Supramolecular Polymer Coatings Based on Peptide Self-Assembly

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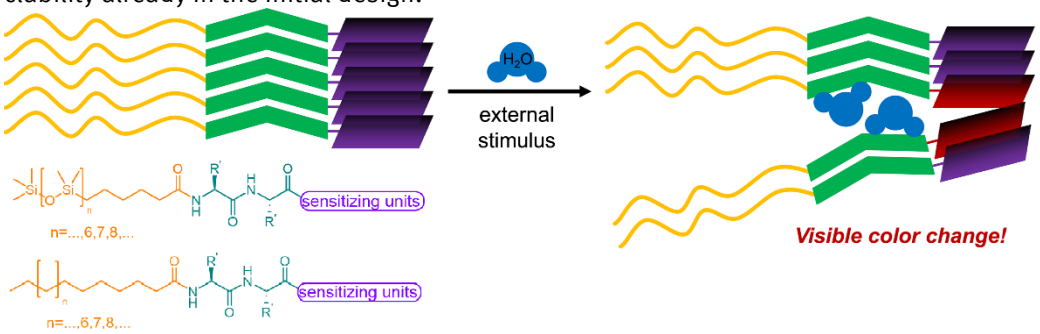
Numerous industrial coatings lack the responsiveness and recyclability necessary. Additionally, bio-based coatings are rare, and when available, they often lack degradation tracking or damage indication, moreover their potential impact on the food chain poses concerns. In our endeavor, we aimed to tackle these multifaceted challenges through the innovative modular design of our coatings.

Climate change is one of the main issues of today's world; circular economy is one way governments try to tackle this issue within the framework of the Paris Agreement [1]. Recycling of existing materials, including their coatings, is essential to achieve a circular economy, yet according to the American Coating Association many industrial coatings lack recyclability. In this project, we aim to develop responsive bio-based coatings as "recyclable" alternatives for traditional coatings. External stimuli (pH, ions, or mechanical stress) may cause structural changes to the coatings, indicate damage, and help with recycling. Moreover, these coatings can act as a selective permeable membrane for chemicals or gases like H_2O, O_2, etc. [2] The responsiveness of the supramolcular polymer coatings and final assembly structure can be tailored by modifying the assembly protocol (Solvent, etc.) and finetuning of the building block structures. [3] Taking advantage of the modularity of our coatings that contain a mono disperse hydrophobic polymer (yellow), a crystalline motif (green), and a sensitizing unit (purple), we can easily design various types of novel responsive coatings. The supramolecular nature of the assembled coating enables a higher degree of recyclability already in the initial design.



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New Photoswitches for Integration in Adaptive Nanosystems

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Molecular photoswitches are versatile sensors and actuators for the development of intelligent matter. In this project we develop new photoswitches as building blocks for the assembly of adaptive molecular nanosystems with inherent feedback by optical and chemical signals. The project will focus on the development of molecular photoswitches that enable out-of-equilibrium light-induced supramolecular materials based on the self-assembly diazocines which form supramolecular assemblies as well as adaptive supramolecular materials that can be stimulated with visible light using disequilibration by sensitization under confinement of arylazopyrazoles. Furthermore, we will advance photo-responsive N-heterocyclic carbenes as surface ligands towards the development of adaptive solid-state systems. We will prepare photoswitches conjugated to NHCs and investigate their self-assembly as ligands for nanoparticles and surfaces. Our photoswitches will be integrated in adaptive molecular systems and soft materials such as adaptive supramolecular polymers, active colloids, adaptive polymer complexes and micelles, self-regulating vesicles and hydrogel actuators.

25

A Semi-Synthetic Nanosystem for Programmable Control of Output Based on Rational Design and Directed Evolution

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In this project, we were aiming to engineer a biological system that responds to non-natural fuel (e.g. substrates) and changes of the environment (e.g. light). Integration of feedback loops should help to realize adaptive behavior and self- regulation. Specifically, this means that we aim to change gene expression at the level of transcription or translation in response to AdoMet analogs or their metabolic precursors (i.e. methionine analogs). To achieve this, we synthesized methionine analogs, which can be converted by engineered methionine adenosyltransferases (MATs) to the corresponding AdoMet analogs.[1] MATs are self-regulated by product inhibition through AdoMet (analogs). This can be circumvented when directly coupling methyltransferases (MTases) to the MAT reaction.[2] MTases use AdoMet as cofactor to methylate biomolecules. Usage of promiscuous MTases allows transferring non- natural groups to nucleic acids to regulate their functionalities.[3]

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Rational Design of Liquid Crystalline Elastomers with Programmable Multi-Step Deformability

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Robots have reshaped manufacturing, yet their usefulness for applications beyond industry, *e.g.* disaster relief, (health)care, and prostheses/exoskeletons requires novel approaches to program deformations in soft and hybrid bodies.[1] Programming motion in materials through stimuli other than electricity such as chemical and/or physical means remains challenging. So far, only single and/or material-specific deformations can be chemically programmed.[2]

To enhance the versatility of soft robotic materials, we present a new liquid-crystalline *end-on* architecture capable of exhibiting unanticipated deformations upon heating, rooted in multiple phase-transitions. Liquid crystalline elastomers (LCEs) provide a range of stimuli-driven deformations; the molecularly controllable self-assembly of mesogens generates ordered phases, enabling multiple predictable directions of macroscopic deformations within a single material.[3] We show that the molecular structure can program liquid crystalline phases, and consequently phase transitions. A systematic analysis of the mesogens' structure impact on self-assembled configurations, and the dynamic deformations of magnetically aligned, UV-polymerized elastomer microstructures is displayed, which allows us to extract general principles for the rational design of LCEs with user-defined deformability.

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Mixed-Mode in-Memory Computing using Adaptive Phase Change Materials

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The recent developments in generative AI have made the need for fast and efficient computing more evident than ever. As improvements of conventional electronic computer chips based on the von Neumann architecture are failing to keep up with the steep rise in computational demand, alternative and novel computing paradigms are heavily researched. One promising candidate is photonic in-memory computing.

Here, we show our studies of photonic integrated circuits using adaptive phase-change materials (PCMs) as non-volatile and scalable photonic memory elements. Switching these elements electrically enables us to implement opto-electronic feedback for so called mixed-mode computing.

However, mixed-mode circuits require the integration of algorithms and various hardware components into one system. On the algorithm level, we explore new paradigms for efficient neural network calculations in mixed-mode circuits. On the hardware level, we work on each of these components including mixed-mode PCM synapses, waveguide crossbar arrays with trimmed directional couplers and resonators, as well as efficient, large-bandwidth electrical and optical packaging.

28

Light Driven Metamachines

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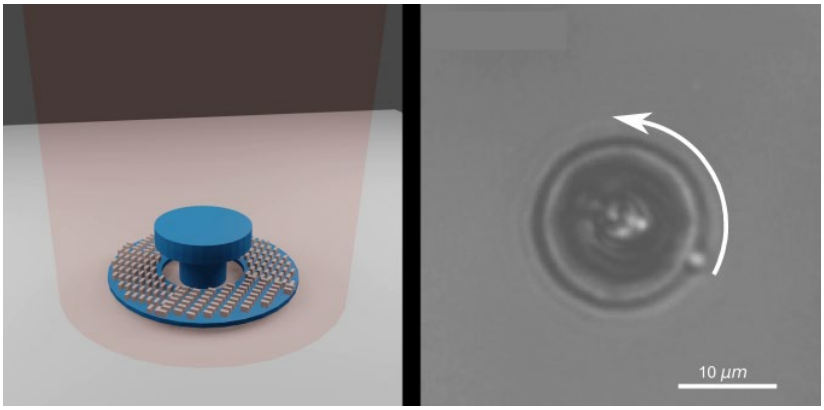
The incorporation of Moore's law into integrated circuits has spurred opportunities for downsizing traditional mechanical components. Despite advancements in single on-chip motors using electrical, optical, and magnetic drives under ~100 μm, creating complex machines with multiple units remains challenging. Here, we developed a ~10 μm on-chip micromotor using a method compatible with complementary metal oxide semiconductors (CMOS) process. The meta-surface is embedded with the motor to control the incident laser beam direction, enabling momentum exchange with light for movement[1,2,3]. The rotation direction and speed are adjustable through the meta-surface, along with the intensity and polarization of applied light. By combining these motors and controlling the configuration, we create complex machines with a size similar to traditional machines below 50um, such as the rotary motion mode of multiple gear coupled gear trains, and the linear motion mode combined with rack and pinion, and combine the micro metal The mirror is introduced into the machine to realize the self-controlled scanning function of the laser in a fixed area.



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Supramolecular Light-Switchable Triazole-Hosts for Photoadaptive Anion Binding

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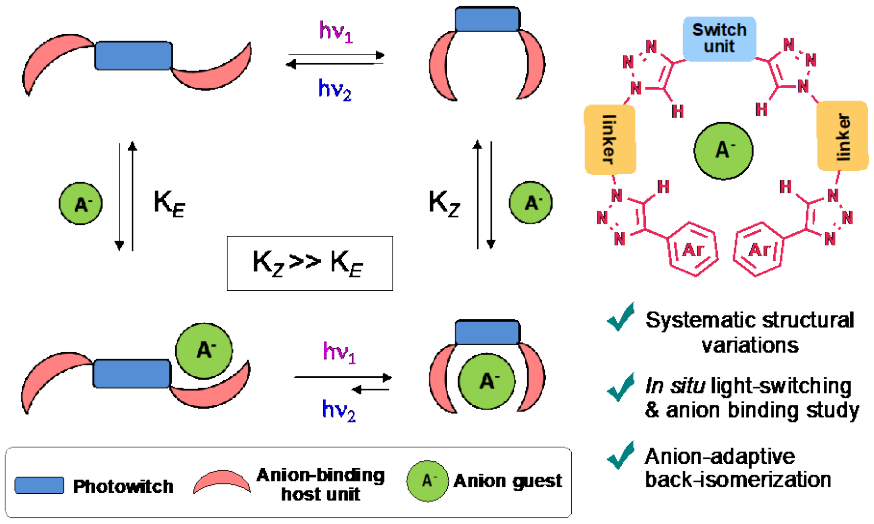
In order to develop adaptive materials with controllable anion binding, photo-responsive tetratriazole host structures containing azobenzene or arylazopyrazole as molecular switching unit are developed. These allow Z-selective anion binding based on a larger anion-binding constant as compared to the E form, and thus induce photo-reversible anion availability. Here we present a study on the role of different functional units of the hosts: On the one hand the structure (hexyl versus phenyl) of linkers, the positioning of triazole binding units and the addition of solubility tags is explored to identify optimal binding motifs. Host structures providing sufficient binding, as well as large contrast of the binding constant of each isomeric form are identified. Ab initio DFT calculations demonstrate the conformational arrangement of the host-anion complex, which aids the structural design.



Towards adaptive behaviour, the influence of the anion binding state on isomerization efficiency is investigated. For both, photoisomerization and thermal isomerization a stabilization of the Z form is found to be induced by anion binding. Thus, the Z isomer with a bound anion forms a trapped state with enhanced lifetime, which will be further exploited in developing adaptive materials.

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Autonomous Cargo Delivery Empowered by Self-Regulating Bacteriabots

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Recent progress in small-scale robotic technologies provides exciting opportunities to enhance quality of life. However, efforts to empower small-scale robots with autonomous decision making, enabling them to interact with their surroundings and execute desired tasks, remains challenging. To address this, we designed autonomous bacteriabots that are able to assemble by themselves, transport their cargo to a desired position and know where to drop it by sensing their environment. These bacteriabots are composed of a genetically engineered bacteria capable of producing bioluminescence in the presence of specific chemical signals and a photoswitchable membrane-binding small unilamellar vesicles (SUVs). By interfacing engineered living cells with synthetic cargos, we established the chemo-opto-cargo self-regulatory network within the bacteriabots, enabling them to translate dynamic environmental signals into cellular bioluminescence outputs, and further regulate cargo integration through light signaling. Furthermore, we demonstrate autonomous cargo transport to desired locations, driven by the synergy between the chemo-opto-cargo self-regulatory network and the inherent chemotaxis of bacteria. Due to its simplicity and reconfigurability, the self-regulating bacteriabots opens previously unexplored avenues in microrobotic design, offering broad applications in robotics, environmental remediation, and biomedical engineering.

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Oscillatory Light Emission in Plasmonic Molecular Junctions

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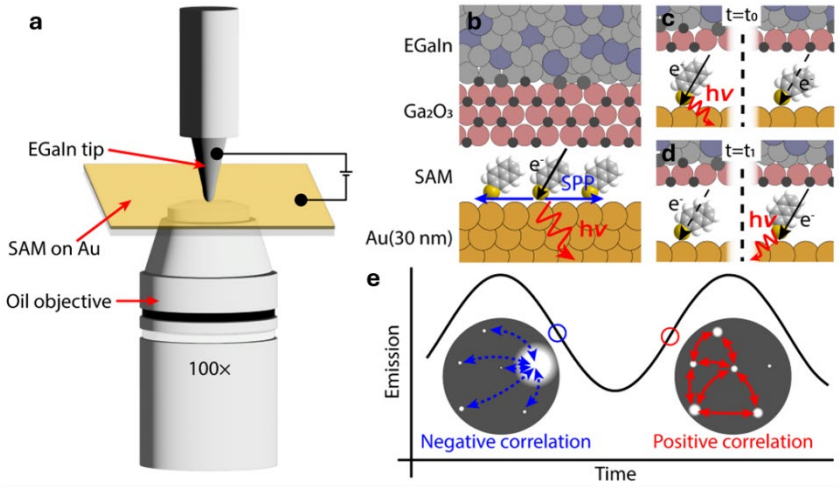
Oscillations are ubiquitous in nature and scientific world. Oscillators continue to captivate research interests in, for example, microfluidic networks to mimic microcirculation of blood flow,[1] photothermal heating of hydrogel to build feedback loop,[2] laser-driven Rabi oscillations to understand bond breakings.[3] However, oscillations at nanoscale remains scarce. Contemporary nano-oscillators based on spin-torque are limited to magnetic field application.[4] Bridging optics and electronics can potentially construct nano-oscillators, yet is not achieved. Here, we report a molecular-scale optoelectronic oscillatory system based on electrically driven plasmon excitation. This system generates light emission from inelastic electron tunnelling (IET), where electrons lose their energy to molecules and excite the surface plasmon polaritons (SPP) that subsequently decay radiatively.[5,6] By sandwiching naphthalene-2-thiol (NPT) in the plasmonic junctions, in-situ opto-electrical measurements show that ensemble emission is oscillatory at sub-100 mHz, with the highest continuous frequency tunable by applied voltage; and individual emissions from single-molecules correlate. Such nanoscale plasmonic junctions demonstrates oscillatory light emission, posing a great interest to the broad community, especially for surface-enhanced Raman spectroscopy based on similar plasmonic nanogaps.[7,8]



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