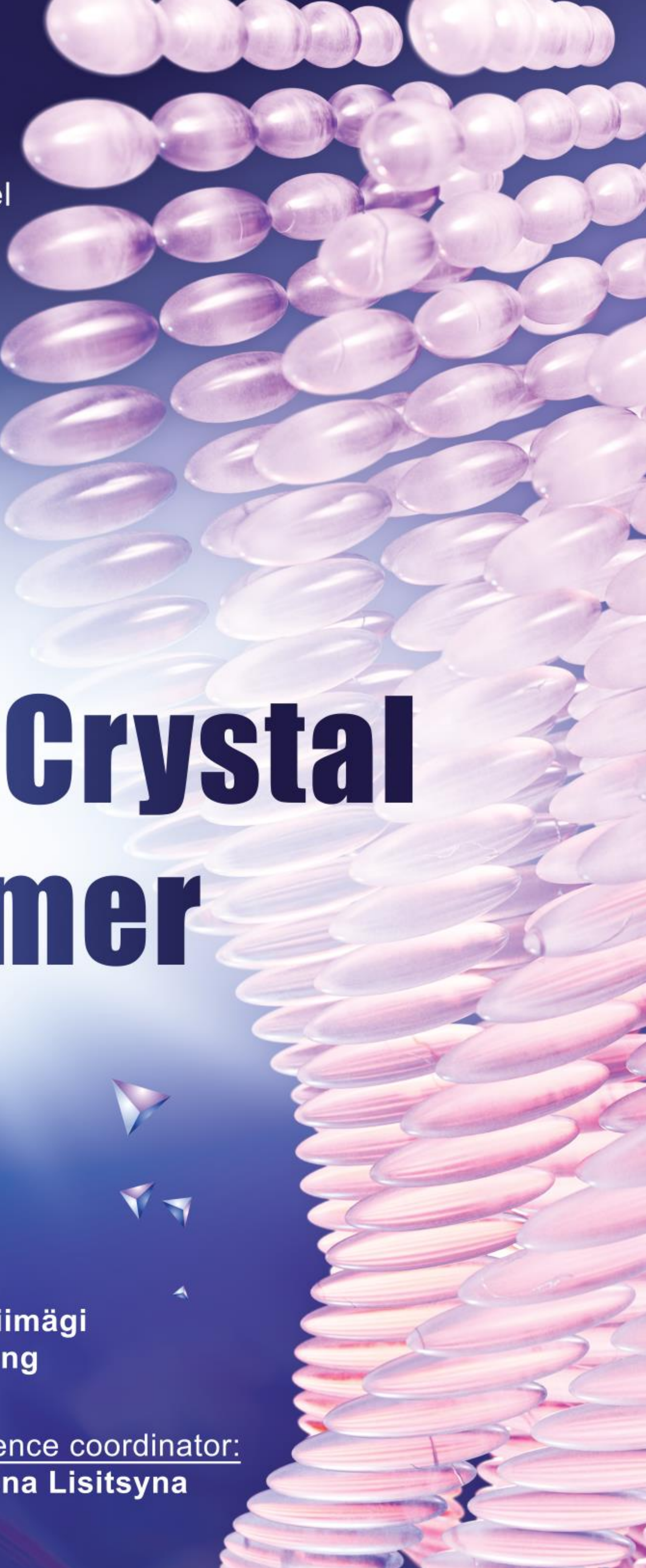
11-15 August 2025
Scandic Rosendahl Hotel
Tampere, Finland



International Liquid Crystal Elastomer Conference

Chairs:
Arri Priimägi
Hao Zeng

Conference coordinator:
Ekaterina Lisitsyna

International Liquid Crystal Elastomer Conference

11-15 August 2025
Tampere, Finland

Dear friends and colleagues,

It is a great pleasure to welcome you all to Tampere for the International Liquid Crystal Elastomer Conference – ILCEC 2025.

This conference series holds a special significance for the two of us, Arri and Hao. We first met each other in ILCEC in Erice in 2015. That encounter turned out to be a turning point that eventually led Hao to move from Florence to Tampere and brought our academic paths together.

The following editions in Houston (2017) and Eindhoven (2019) were full of optimism and excitement, thanks to the rapid progress and growing interest in the field. The 2021 virtual meeting, hosted by South China Normal University, was crucial in keeping our community connected in the gloomy pandemic world. Most recently, Boulder 2023, led by Tim White, continued the tradition of excellence we are now proud to carry forward.

Today, we are honored to take the torch and welcome you with a program with 55 oral presentations and 59 posters, offering a snapshot of the vitality, creativity, and impressive breadth of the field.

Our community thrives together. Yet, we are living through a time of global uncertainty and political turmoil, when fences are being built and barriers emerge. Coming together is challenging in these circumstances, and that’s why this gathering matters more than ever. In times like these, we need communication across boundaries, openness, and trust.

To all of you who made the significant effort to be here, thank you! Your presence matters, as do the ideas, collaborations, and friendships that will take shape in the coming days. Let us make the most of these days to learn from each other and push the field forward — together.

Welcome once again to Tampere. Let ILCEC 2025 begin!

Sincerely,

Hao Zeng

____

Arri Priimägi & Hao Zeng

Chairs of ILCEC 2025

Tampere

Tampere is #1 travel destination for Finns in their home country. Numerous events, fascinating cultural experiences and soothing lake views to match the relaxed atmosphere makes the city very appealing all year round.

Tampere is internationally known as a city of technology, often going in the forefront of development. The hometown of innovations has made many world-class breakthroughs and has developed products and services that improve the quality of life of people.

Tampere is defined by a few unique characteristics: it is surrounded by beautiful lakes and eskers, it has a perfect scale for walking and there’s always something new and innovative going on. The centre of the city is dominated by industrial heritage: the national landscape of Tammerkoski rapids and historical red brick buildings. But in Tampere we always look to the future and therefore construction sites are often seen in everyday street life. The tramway route will be extended even further. In December 2021, Finland’s largest multipurpose arena, Nokia Arena opened.

From the cultural point of view, Tampere is defined by our local treats of black sausage with lingonberry sauce and the world’s best doughnuts, morning coffee at Laukontori Market Square enjoyed in a small lake breeze, our imaginative museums, events after events, and the fact that we are the sauna capital of the world.

For further information, visit www.visittampere.fi

Tampere University

Tampere University is one of the most multidisciplinary universities in Finland. We bring together research and education in technology, health and society. The University is known for its excellence in teaching and research and it collaborates with hundreds of universities and organisations worldwide. Our community consists of about 23,200 students and around 4,200 staff members from more than 80 countries.

The University was created in 2019 through a merger between the University of Tampere and Tampere University of Technology. Almost all internationally recognised fields of study are represented in our university. At Tampere University, multidisciplinary research is conducted across the boundaries of fields of science. More specifically, our strength lies in research in the fields of health, technology and society. The topics our Centres of Excellence (CoEs) study range from body-on-chip research to game cultures.

The missions of our research include fostering a just and participatory society, promoting the health and welfare of people at all ages, developing safe living and working environments that are resource efficient, and ensuring socially responsible digitalisation and transformation of work.

General information

Conference venue
Scandic Rosendahl, Pyynikintie 13, 33230 Tampere

Registration desk
Opening hours:
August 11: 8.00 - 8.45
August 12: 8.15 - 8.45

Coffee Breaks
Coffee and tea will be available all day long in Scandic Rosendahl Congress lobby. Smoking is only allowed in designated areas outside the building.

Lunch
Lunch is included in the price of the conference and will be served in restaurant Käpy about 50 meters away from the conference hall every day August 11-14 12:40-14:00, except on Friday August 15 12:00-13:00.

Wi-Fi
Free wireless Internet service is available for the duration of ILCEC2025 at Scandic Rosendahl.

Info on public transport
Bus line 10 connecting Rosendahl and the city center (from Hatanpään valtatie) runs every 10-15 minutes from 6 am to 8 pm, then every 20-30 minutes from 8 pm until about midnight. See the route planner at https://reittiopas.tampere.fi/ for more options on public transport in Tampere.

Single tickets (zone AB, 2.80 €) can be bought in the Nysse Mobiili app or through contactless payment when boarding the bus or tram. The ticket is valid for 90 min for all city buses and trams; make sure to validate your ticket every time you board another bus/tram. Cash payment when boarding is not possible. See more on the Nysse website: https://www.nysse.fi/en/tickets-and-fares.html.

Social Program

City Reception – Monday August 11 18:45-20:45

Buses for the city reception leave at **18:45** from hotel Rosendahl to the old city hall "Raatihuone" (address: Keskustori 10, Tampere). The Renaissance Revival style building located at the central square was finished in 1890 and nowadays serves mostly to house events organized by the city of Tampere.

The **reception starts at 19:00**. Remember to take your Conference badge with you as it will be your pass to the event! Snacks and a glass of sparkling wine will be offered at the city reception. The bus back to hotel Rosendahl leaves after the city reception ends approximately at **20:30**.

Conference dinner – Wednesday August 13 18:30-23:00

The conference dinner is held at a restaurant located on the island Viikinsaari a couple of kilometers from the city center to lake Pyhäjärvi. The boat departs from the pier of hotel Rosendahl at **18:30**. We take a 15-minute cruise on the lake before taking shore to Viikinsaari. Our boat back leaves at **22:30**. Do not wander off too far to the beautiful natural resort in order not to get stranded on the island.

Sauna evening party – Thursday August 14 17:30-23:00

The bus for the sauna evening departs at **17:30** from hotel Rosendahl. The event is held at Hangaslahden sauna (address: Lassinlinnankatu 24, Tampere) at the shore of lake Näsijärvi. The place offers a genuine Finnish smoke sauna as well as an electric sauna for additional capacity. A proper dinner will be served at the sauna starting at **18:00**.

Participants should bring their own bathing suits. We encourage you to have a swim in the lake! Towels should be taken form the Hotel.

The bus back to hotel Rosendahl leaves at **22:30**. If required, the bus will stop at the city center (Keskustori old church) on the way back.

Information for presenters

Oral Presentations

Presentations will have the following durations.

Contributed talks are 20 minutes including discussion and speaker change (17 min talk + 3 min discussion/speaker change)

Invited talks are 25 minutes including discussion and speaker change (20 min talk + 5 min discussion/speaker change)

Keynote lectures are 30 minutes.

Presenters are encouraged to use their own laptops, however the lecture room is equipped with PC supporting PowerPoint (ppt and pptx) and pdf formats. Please make sure to check your equipment before the beginning of your session to avoid unpleasant surprises.

Posters

The posters should A0 size (841x1189 mm) in vertical orientation. The poster boards will be marked with the number according to the poster list. Authors can mount their poster as soon as they arrive to the venue and no less than 2 hours before the first poster session, which is held on Monday 11 August 15:30-17:30. You are welcome to contact the conference assistants on site.

The posters have to be removed at the end of the last poster session on Wednesday August 13 after 17:00. Any posters remaining on display walls after 17:30 will be removed and directly disposed.

There will be **3 poster prizes** 2 of which decided by a dedicated committee and 1 will be voted by all the Conference participants.

Committee

Chairs of the conference:

Prof. Arri Priimägi
Tampere University, Finland
arri.priimagi@tuni.fi

Assoc. Prof. Hao Zeng
Tampere University, Finland
hao.zeng@tuni.fi

Program committee:
Asst. Prof. Devin J. Roach (Oregon State University, USA)
Dr. Morgan Barnes (University College London, UK)
Dr. Jiu-an Lv (Westlake University, China)
Asst. Prof. Mingchao Zhang (National University of Singapore)
Prof. Tayler Hebner (Purdue University, Indiana, USA)
Asst. Prof. Hamed Shahsavan (University of Waterloo, Canada)

Conference organizers:
Dr. Ekaterina Lisitsyna, ekaterina.lisitsyna@tuni.fi
Dr. Suvi Lehtimäki, suvi.lehtimaki@tuni.fi

Keynote speakers

Timothy (Tim) White
University of Colorado Boulder, USA

D1-01
The Contribution of "Liquid Crystallinity" to the Thermomechanical Response of Liquid Crystalline Elastomers

Research of White's group is highly interdisciplinary, bridging chemical engineering, materials science, polymer science, mechanics, optics, and applied physics. He developed a materials chemistry to prepare liquid crystal elastomers and networks with directed self-assembly properties. He is also interested in reconfigurable optical elements and is focused on realizing a new generation of optical elements.

Hong Yang
Southeast University, China

D3-01
Enhanced Mechanical Performances of Liquid Crystal Elastomers Enabled by Mechanophores and Interpenetrating Network

Dr. Yang's research interests are liquid crystal materials, functional polymeric materials, polymer synthesis methodology, organic synthesis, heterocyclic chemistry, and medicinal chemistry.

Carlos Sánchez Somolinos
CSIC, University of Zaragoza, Spain

D5-01
Additive Manufacturing of LCEs: Programming Actuation, Enabling Motility, and Advancing Autonomy in Soft Robotics

Dr. Somolinos's expertise and scientific objectives are focused on developing polymers and their processing through advanced manufacturing techniques in the search for polymeric surfaces or functional systems of interest in optics, biomedicine and soft robotics.

The Contribution of "Liquid Crystallinity" to the Thermomechanical Response of Liquid Crystalline Elastomers

Timothy J. White[1]

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*Corresponding author e-mail: *tim.white@colorado.edu*

Liquid crystalline materials are pervasive in our homes, purses, and pockets. It has been long-known that liquid crystallinity in polymers enables exceptional characteristics in high performance applications such as transparent armor or bulletproof vests. Extensive prior research has examined liquid crystalline polymer networks with suppressed T_g (e.g., elastomers), typically due to an increase in molecular weight between crosslinks. These so-called liquid crystalline elastomers are distinct in exhibiting dramatic stimuli-response associated with order-disorder transitions as well as exceptional nonlinearities to mechanical perturbation. This presentation will summarize the preparation of liquid crystalline elastomers with nontraditional liquid crystalline segments with a special emphasis on functional implications in robotics, optics, and in health care.

Enhanced Mechanical Performances of Liquid Crystal Elastomers Enabled by Mechanophores and Interpenetrating Network

Hong Yang*

School of Chemistry and Chemical Engineering, State Key Laboratory of Digital Medical Engineering, Southeast University, Nanjing, Jiangsu Province 211189, China
*Corresponding author e-mail: *yangh@seu.edu.cn*

Liquid crystalline elastomers (LCEs) have garnered significant attention for their exceptional actuation capabilities, but their practical applications are hindered by insufficient mechanical strength and fatigue resistance. Herein, we introduce our recent advancements in overcoming these limitations through the following design strategies. (1) Mechanophore-enabled energy dissipation: By incorporating a chain extender containing a rigid bicyclic cyclobutene mechanophore and benzene moiety into the LCE backbone, stress-activated cycloreversion releases stored length and dissipates energy, enhancing strength and toughness by over 10-fold compared to pristine LCEs and providing excellent impact absorption (Figure 1a). (2) Nanocomposite reinforcement for mechanical performance: Integrating high-aspect-ratio 2D metal-organic framework (MOF) nanosheets into LCE matrices *via* pore-confined crosslinking creates an interpenetrating network that preserves mesogenic alignment and significantly enhances mechanical performance (Figure 1b). The composite demonstrates an enhanced tensile strength of 89 MPa at room temperature, and even at 200°C, maintains a high tensile strength of 4.2 MPa with excellent stability over 1000 stretching cycles at 15% strain. (3) Dynamic network design for enhanced fatigue resistance: Introducing partial dynamic sacrificial bonds (tetraarylsuccinonitrile, TASN) into LCE matrixes enables reversible dissociation and recombination of central C-C bonds, allowing the LCE-TASN materials to endure 3000 stretching cycles at 100% strain with rapid recovery within 5 min (Figure 1c). Collectively, these strategies promote the development of high-performance LCE systems with enhanced mechanical strength and fatigue resistance, paving the way for their broader application in advanced actuation and impact-dissipating devices.

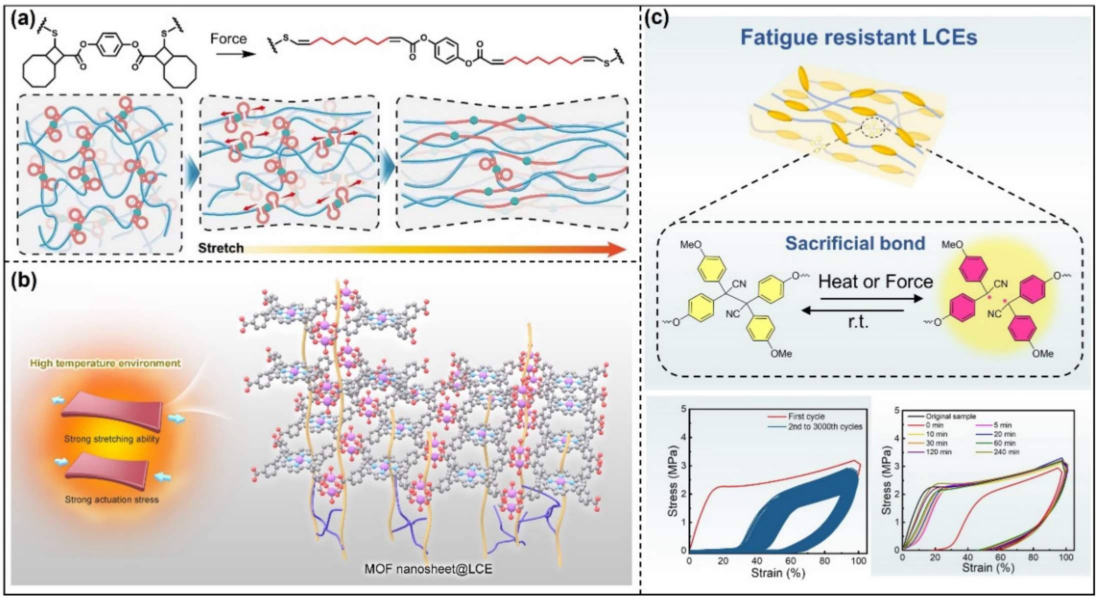

Figure 1. Schematic illustration of three design strategies for enhancing LCE mechanical performance: (a) mechanophore-enabled energy dissipation *via* force-induced cycloreversion of bicyclic cyclobutane, (b) nanocomposite reinforcement through pore-confined crosslinking of 2D MOF nanosheets and LCEs, and (c) dynamic network design incorporating TASN-based sacrificial bonds for improved fatigue resistance of LCEs.

Additive Manufacturing of LCEs: Programming Actuation, Enabling Motility, and Advancing Autonomy in Soft Robotics

Carlos Sánchez-Somolinos[1,2,*]

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[2] *Centro de Investigación Biomédica en Red de Bioingeniería, Biomateriales y Nanomedicina, Instituto de Salud Carlos III, Zaragoza, 50018, Spain*

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Structuring smart materials in three dimensions has brought new possibilities for soft robotics, enabling complex actuation and functionalities. Liquid crystalline elastomers (LCEs) are especially exciting in this field, as they can anisotropically change shape in response to stimuli like heat, light, or humidity. Additive manufacturing in LCEs enables precise control over material alignment to create programmable, highly reproducible, and scalable transformations. This lecture will present recent advancements from the Advanced Manufacturing Laboratory, focusing on the development of multiresponsive systems, biomimetic and self-sustained motions, and multimodal responses, key toward greater autonomous soft robotic devices.

Acknowledgments

The described research is part of the project STORM-BOTS. This project has received funding from the European Union’s Horizon 2020 research and innovation programme under Grant Agreement No 956150 (STORM-BOTS). The described research study was a part of the project PRIME. This project has received funding from the European Union's Horizon 2020 Research and Innovation Programme under grant agreement no. 829010 (PRIME). Funding has also been received from Spanish “Ministerio de Ciencia, Innovación y Universidades (MCIU)” through AEI/FEDER(UE) PID2020-118485RB-I00 project, Gobierno de Aragón project PROY_E28_24, FEDER (EU), Fondo Social Europeo (DGA E15_20R) and by CIBER-Consorcio Centro de Investigación Biomédica en Red (CB16/01/00263), Instituto de Salud Carlos III.

Invited speakers

D1 - 02 **Albert Schenning**
Eindhoven University of Technology, The Netherlands
Stimuli-responsive Functional Materials & Devices
"Cholesteric Liquid Crystal Elastomers"

D1 - 05 **Yue Zhao**
Sherbrooke University, Canada
Polymers and Liquid Crystals Laboratory
"Actuation and Auxetic Behaviors of Stretching-Induced Monodomain Side-Chain Liquid Crystal Elastomers"

D1 - 09 **Antal Jakli**
Kent State University, USA
Jákli Lab
"Shape Changes of Liquid Crystal Elastomers Swollen by Low Molecular Weight Liquid Crystal Drops"

D1 - 12 **Camilla Parmeggiani**
University of Florence, Italy
Complex Photonic
"How to Build Cell Instructive Scaffolds by Liquid Crystalline Networks"

D2 - 01 **Jerry Qi**
Georgia Institute of Technology, USA
Active Materials and Additive Manufacturing Lab
"Additive Manufacturing of Liquid Crystal Elastomers and Multimaterial 3D Printing for Functional Applications"

D2 - 02 **Sara Nocentini**
University of Florence, Italy
Complex Photonic
"Advanced Photonics with 4D Microstructured Liquid Crystalline Networks"

D2 - 03 **Qi-Huo Wei**
Southern University of Science and Technology, China
Qi-Huo Wei
"Photopatterning Liquid Crystal Polymers with Predesigned Director and Shape"

D2 - 05 **Zachariah A. Page**
University of Texas at Austin, USA
ZAP Group
"Sidechain and Mainchain Photoalignment of AzobenzeneContaining Liquid Crystalline Polymers"

D2 - 08 **Atsushi Shishido**
Tokyo Institute of Technology, Japan
Shishido-Kubo Group
"Crosslinked Liquid-Crystalline Polymer Films Patterned by Scanning Light"

D2 - 09 **Zhongqiang Yang**
Tsinghua University, China
Yang's group
"Smart Liquid Crystal Elastomer Fibers"

D2 - 13 **Kevin Chen**
Massachusetts Institute of Technology, USA
Soft and Micro Robotics Laboratory
"Insect-Scale MicroAerial-Robots Powered by Soft Artificial Muscles"

D3 - 02 **John Biggins**
University of Cambridge, UK
Soft Mechanics Group
"Soft Elasticity and Microstructure: Explaining Mechanical Programming and Powering Director Design"

D3 - 04 **Antonio De Simone**
Sant'Anna School of Advanced Studies/SISSA-International School for Advanced Studies, Italy
SISSA mathLab and SAMBA lab (sensing and moving bio-inspired artifacts)
"Self-Oscillations of Submerged Liquid Crystal Elastomer Beams Driven by Light and SelfShadowing"

D4 - 01 **Javier Read de Alaniz**
University of California, Santa Barbara, USA
Read de Alaniz Research Group
"LightDriven Soft Materials that Move, Change Color and “Survive”"

D4 - 02 **Danqing Liu**
Eindhoven University of Technology, The Netherlands
Human Interactive Materials
"Interactive Liquid Crystal Polymers for Soft Robotics and Haptics"

D4 - 06 **Mohand Saed**
University of Cambridge, UK
Dr. Mohand Saed
"Switchable Pressure-Sensitive Adhesion in Liquid Crystal Elastomers"

D4 - 10 **Jeong Jae (JJ) Wie**
Hanyang University, South Korea
Prof. Jeong Jae (JJ) Wie
"Stiffness Patterning of Light-Triggered Jumper for Efficient Snap-Through"

D4 - 14 **Jie Yin**
North Carolina State University, USA
Yin Lab
"Self-Resetting Soft Robot Enables Light-Powered Continuous Leaping"

D5 - 05 **Taylor Ware**
Texas A&M University, USA
Responsive Biomaterials Lab
"Mesomorphic Siloxanes without Mesogens"

The Future of LCEs – invited leaders for the panel discussion

Wednesday 13 August 14:40-15:40

Eugene Terentjev
Professor of Polymer physics at the University of Cambridge (UK)
Fellow and Director of Studies in Natural Sciences at Queens' College.

Helen Gleeson
Cavendish Professor of Physics
at University of Leeds, UK

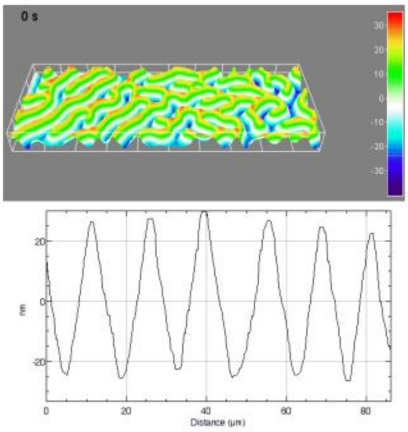
Ivan Smalyukh
Professor of Physics at University of Colorado Boulder, USA
Director of WPI-SKCM2 at Hiroshima University, Japan

Jan Lagerwall
Professor in Physics at the Physics & Materials Science Research Unit
of the University of Luxembourg

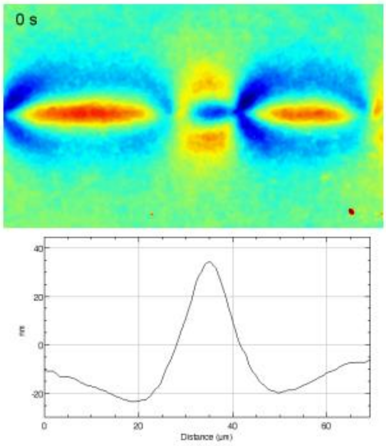
With Digital Holography Microscopes (DHM)

Investigate liquid crystal time-response to:

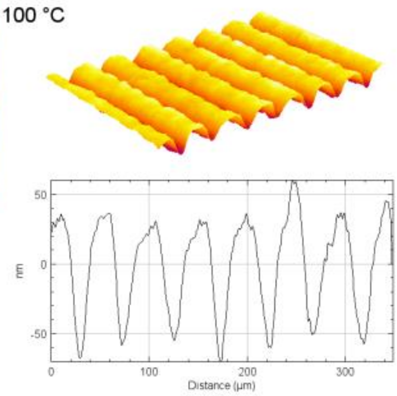
Light irradiance



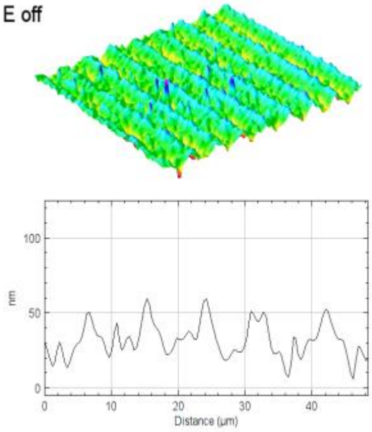
Light Polarization



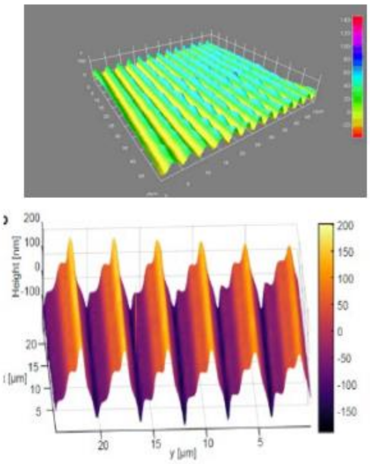
Temperature



Electrical field



Laser texturing



Oral presentations

Monday August 11

D1 - 03 **Force-Trainable Liquid Crystal Elastomer Enabled by Mechanophore-Induced Radical Polymerization**
Shuai Huang, Southeast University, China

D1 - 04 **From Substituents to Actuation: A Chemical-Quantitative Predictor of Contraction Forces**
Jesus Guillen Campos, University of California, Santa Barbara, USA

D1 -06 **Cross-over for Semi-soft or Auxetic Behavior in a Series of LCEs**
Thomas Raistrick, University of Leeds, UK

D1 - 07 **Self-Assembling and Structural Behaviour of Multifunctional Selectively Deuterated Reactive Mesogens Targeted for Photo-active Liquid Crystalline Elastomers**
Valentina Domenici, University of Pisa, Italy

D1 - 08 **Nanomaterial/Polymer based Soft Actuators with Light-Driven Self-Oscillation for Bionic Applications**
Ying Hu, Hefei University of Technology, China

D1 - 10 **Programming Liquid Crystal Elastomers for Multistep Ambidirectional Deformability**
Yuxing Yao, The Hong Kong University of Science and Technology, China

D1 - 11 **Polymer Conformation Changes Observed with the Naked Eye in a Liquid Crystal Elastomer and Their Use to Produce Adjustable and Multidirectional Deformations**
Min-Hui Li, Université PSL, CNRS, France

Tuesday August 12

D2 - 04 **Unlocking New Opportunities in Liquid Crystal Elastomers through Smectic Phase**
Suk-kyun Ahn, Pusan National University, Republic of Korea

D2 - 06 **Enhancement of Photomobile Properties of Liquid-Crystalline Polymers through the Design of Azobenzene Derivatives**
Toru Ube, Shizuoka University, Japan

D2 - 07 **Dynamic Azobenzene Liquid Crystal Elastomers Based on SBS and Their Applications**
Li Han

D2 - 10 **Enabling Active Textiles Using Liquid Crystalline Elastomer Yarn**
Pedro Santos Silva, Aalto University, Finland

D2 - 11 **Reconfigurable Exotic Liquid Crystal Elastomer “Smart” Surfaces via Hot Embossing**
Lansong Yue, Eindhoven University of Technology, Netherlands

D2 - 12 **Optically Controlled Wind-Assisted Flight in Miniature Soft Robots**
Jianfeng Yang, Tampere University, Finland

Wednesday August 13

D3 - 03 **What is Difficult about Printing of Complex Director Patterns?**
Michał Zmyślony, University of Cambridge, UK

D3 - 05 **A Nonlinear Viscoelastic Model for Nematic Elastomers: Coupling Mesogen Order, Director Rotation, and Network Viscoelasticity**
Thao Nguyen, Johns Hopkins University, USA

D3 - 06 **(Re)programming Functionality in Liquid Crystalline Elastomers Using Dynamic Covalent Chemistry**
Tayler Hebner, Purdue University, USA

D3 - 07 **3D Deformation of Liquid Crystals Elastomer for Small-Scale Structural Manipulation**
Mingchao Zhang, National University of Singapore, Singapore

D3 - 08 **Tailorable Energy Damping Using 3D Printed Liquid Crystalline Elastomers**
Devin Roach, Oregon State University, USA

D3 - 09 **Mechanics and Microstructures of Mechanically Programmed LCEs**
Morgan Barnes, University College London, UK

D3 - 10 **Phototunable Self-Oscillating Systems**
Jiuan Lv, Westlake University, China

D3 - 11 **Polymerized Liquid Crystals as Aquatic Robots and Actuators**
Hamed Shahsavan, University of Waterloo, Canada

Thursday August 14

D4 - 03 **Regulating Airflow Using Hybrid LCN for Soft Pneumatic Robots**
Elif Kurt, Eindhoven University of Technology, The Netherlands

D4 - 04 **Functional Blue Phase Liquid Crystal**
Jingxia Wang, Technical Institute of Physics and Chemistry, Chinese Academy of Sciences, China

D4 - 05 **Hierarchical Liquid Crystal Microstructures for Multi-Degree Optical Field Manipulation**
Wei Hu, Nanjing University, China

D4 - 07 **Nematic LCE and Composites for Enhanced Vibration Damping**
Kailing Lin, Cambridge Smart Plastics Ltd, UK

D4 - 08 **Harnessing Extreme Internal Damping in Polyrotaxane-Incorporated Liquid Crystal Elastomers for Pressure-Sensitive Adhesives**
Subi Choi, Pusan National University, Republic of Korea

D4 - 09 **From LC Molecular Alignment to Optical Coupling: Multifunctional LC Materials for Soft Robotics and AR Waveguide Displays**
Yu-Chieh Cheng

D4 - 11 **Control of Magnetic Properties by Photoresponsive Liquid Crystalline Networks**
Neri Fuochi, University of Florence, Italy

D4 - 12 **Magnetically Induced Motion of LCP Microparticles**
Alexandra Gruzdenko, Eindhoven University of Technology, The Netherlands

D4 - 13 **Emergent Locomotion in Dissipative, Closely Connected Soft Matter Rings**
Hongshuang Guo, Tampere University, Finland

Friday August 15

D5 - 02 **Electroactive Liquid Crystal Elastomers with Low Phase Transition Temperature**
Yakui Deng, Chimie ParisTech, PSL, France

D5 - 03 **Flexible Electroactive Ionic Liquid Crystal Elastomers Based on Thiol-Michael Chemistry**
Yasaman Maddah, University of Waterloo, Canada

D5 - 04 **All-Optical Microfluidic Technology Enabled by Photodeformable Linear Liquid Crystal Polymers**
Xiaoyu Zhang, Fudan University, China

Cholesteric Liquid Crystal Elastomers

Albert P.H.J. Schenning

Laboratory of Stimuli-responsive Functional Materials and Devices, Eindhoven University of Technology, P.O. Box 513, 5600 MB Eindhoven, The Netherlands
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Cholesteric liquid crystal elastomers (CLCEs) are appealing due to their elastic properties and their programmable visible structural colors [1]. They exhibit a self-assembled helical superstructure that determines the wavelength of light that is reflected. CLCEs are able to respond to external triggers such as temperature, light, and mechanical force, resulting in a structural color change. This makes them interesting for a variety of applications, including soft actuators, optical sensors, and smart windows.

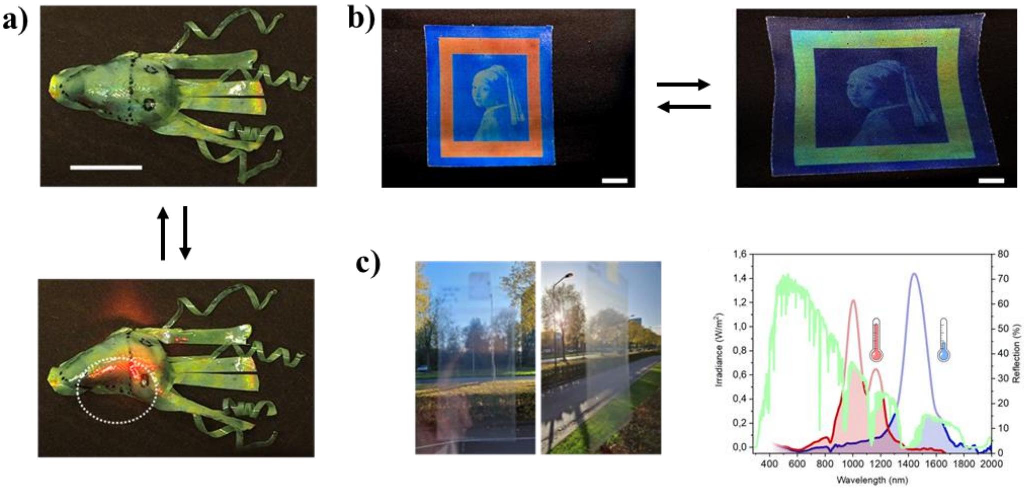

Figure 1. a) A light responsive structural colored CLCE 3D shaped "cuttlefish" actuator, scale bar is 0.5 cm; b) A mechanochromic CLCE containing the portrait of the Girl with a Pearl Earring, scale bar is 1 cm; c) A thermochromic infrared reflective CLCE window foil.

In my lecture, I will discuss CLCE photonic actuators that can simultaneously change color and shape [2], mechanochromic sensors that detect the degree of strain [3], as well as thermochromic infrared reflectors for smart windows [4].

[1] P. Zhang, L.T. de Haan, M. G. Debije, and A. P. H. J. Schenning, *Light Sci Appl,* **2022**, 11, 248.
[2] P. Zhang, M. G. Debije, L. T. de Haan, and A. P. H. J. Schenning, *ACS Appl. Mater. Interfaces* **2022**, *14*, 20093.
[3] L. D. C. de Castro, J. Lub, O. N. Oliveira Jr, and A. P. H. J. Schenning, *Angew. Chem. Int. Ed*, **2025**, *64*, e202413559.
[4] H. Sentjens, A. J. J. Kragt, A. P. H. J. Schenning, and M. G. Debije, *Responsive Mater.* **2023**, *1*, e20230006

Force-Trainable Liquid Crystal Elastomer Enabled by Mechanophore-Induced Radical Polymerization

Shuai Huang[1*], Hong Yang[1*], Quan Li[1*]

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In nature, organisms adapt to environmental changes through training to learn new abilities, offering valuable insights for developing intelligent materials. However, replicating this adaptive learning in synthetic materials presents a significant challenge. This study introduces a feasible approach to train liquid crystal elastomers (LCEs) by integrating a mechanophore tetraarylsuccinonitrile (TASN) [1] into their main chain, addressing the challenge of enabling synthetic materials to exchange substances with their environment. Inspired by biological training, the LCEs can self-strengthen and acquire new functionalities through mechanical stress-induced radical polymerization. The research not only enhances the mechanical performance of LCEs, but also endows them with the ability to learn properties such as flexibility, light responsiveness, and fluorescence.[2] These advancements are crucial for overcoming the limitations of current materials, paving the way for the creation of advanced intelligent soft materials with autonomous self-improvement, akin to the adaptive skills of living organisms.

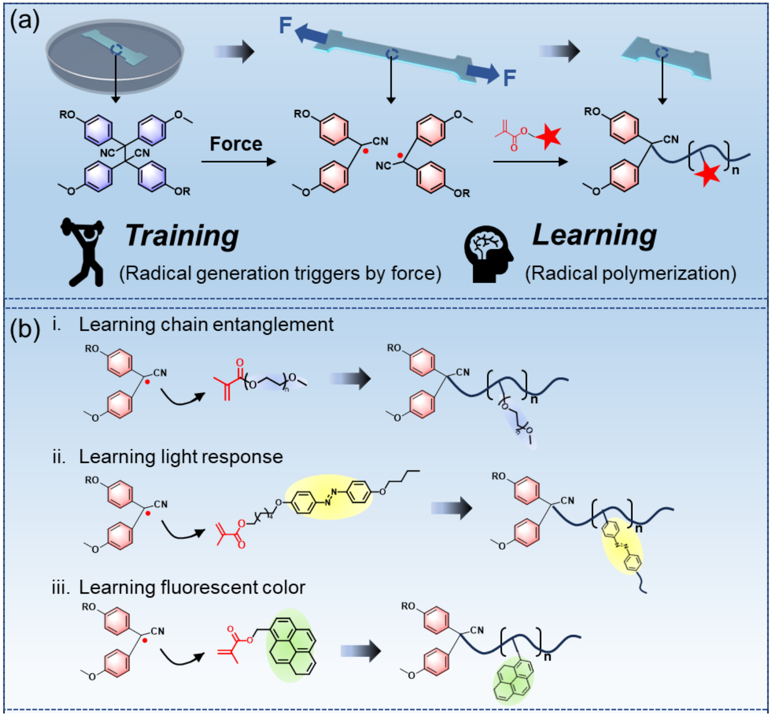

Figure 1. Design of the force trainable liquid crystal elastomer

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From Substituents to Actuation: A Chemical-Quantitative Predictor of Contraction Forces

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Light-responsive liquid crystal elastomers (LCEs) offer unique opportunities for remote actuation, but predicting their mechanical performance remains a major challenge. Here, we present a strategy to chemically program contraction forces in DASA-LCEs by tuning the substituents on the DASA photoswitch. By systematically modifying the electron-donating and -withdrawing character at position-3 of the DASA pyrazolone ring, we modulate the photoswitching efficiency and thermal stability of the chromophore. Remarkably, we demonstrate that these molecular-level modifications lead to predictable, quantitative changes in the actuation force and transition temperature of the resulting LCEs. Using Hammett parameters as electronic descriptors, we establish strong linear correlations between substituent effects and macroscopic LCE performance. This work provides a rational framework for designing high-performance LCE actuators through simple chemical inputs, opening the door to predictive control of soft robotic systems.

Actuation and Auxetic Behaviors of Stretching-Induced Monodomain Side-Chain Liquid Crystal Elastomers

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A series of side-chain liquid crystal polymers (SC-LCPs) are synthesized by grafting side-group azobenzene mesogens onto the polybutadiene backbone, and their monodomain liquid crystal elastomers (SC-LCEs) are prepared by film stretching followed by chain crosslinking. Depending on the flexible spacer linking the side-group mesogens and chain backbone and on the phase in which the film is stretched before cooling to room temperature, different orientation states of the two constituents are obtained in the monodomain films: 1) chain backbone and side-group mesogens are both aligned along the stretching direction (SD), 2) chain backbone is aligned along SD, while mesogens are oriented perpendicular to SD; and 3) both chain backbone and mesogens are aligned perpendicular to SD. The coupling of the oriented chain backbone and mesogens leads to unusual thermal and optical actuation behaviors and affects the auxetic response of the monodomain LCE films upon restretching.

Cross-over for semi-soft or auxetic behavior in a series of LCEs

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Liquid crystal elastomers are lightly cross-linked elastomeric materials containing liquid crystal components. Under deformations perpendicular to the nematic director, LCEs have been reported to display one of two distinct behaviors: semi-soft elastic (SSE) or an auxetic response, previously (and erroneously) described as a mechanical Fréedericksz transition [1,2]. Auxetics are materials displaying a negative Poisson's ratio – they get thicker when stretched.

In the soft elastic response, deformation incurs little-to-no elastic cost due to the continuous in-plane rotation of the director to align with strain. The 'semi' in 'SSE' comes from the initial 'high' modulus region observed in the stress-strain curve, followed by a plateau [1]. In the SSE response, the order parameter is constant and distinctive optical textures known as "stripe domains" form to minimize macroscopic shear [1,3]. In contrast, auxetic LCEs deform with a reduction in uniaxial order and an emergence of biaxial order. Auxeticity arises due to out-of-plane rotations of mesogenic units [4]. Notably, the LCE remains optically clear throughout the deformation [2].

The question still remains as to why certain LCEs deform via the SSE and others deform via an auxetic deformation. Here, a series of sidechain liquid crystal elastomers with varying crosslink density is studied. Higher crosslink density samples display a clear auxetic response [5]. At lower crosslink densities, the behavior is consistent with the SSE response. At intermediate crosslink density, transitionary behavior with similarities to both the auxetic and SSE response is observed. These results are described along with theoretical insight that suggests design rules for each.

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Self-assembling and structural behaviour of multifunctional selectively deuterated reactive mesogens targeted for photo-active Liquid Crystalline Elastomers

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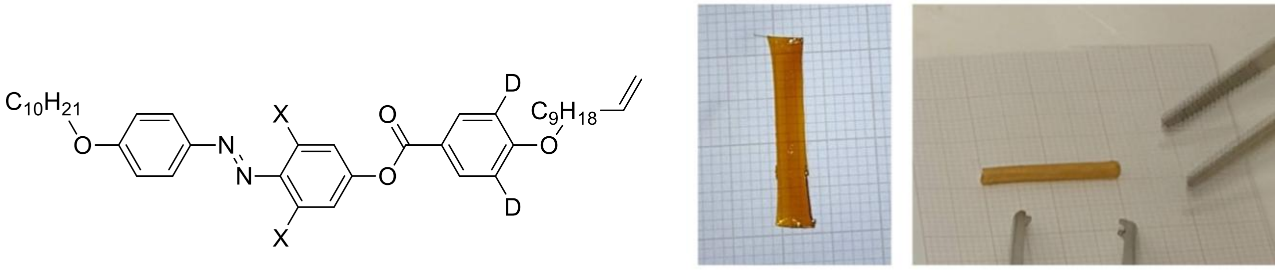
Multifunctional reactive mesogens with lateral methyl substitution in the vicinity of the azo group and selective deuteration on phenyl ring close to the reactive chain were designed and synthesized (see **Fig. 1a**). The self-assembling and structural behaviour was established by polarizing optical microscopy, differential scanning calorimetry and X-ray diffraction techniques. Due to the presence of the selective deuteration, the reactive mesogens were studied by ^{2}H-NMR spectroscopy and the orientational order of the deuterated fragment was investigated and established in the whole mesophase range [1].



(a) **(b)** **(c)**

Fig. 1: (a) Molecular structure of the designed reactive mesogens with double lateral substitution (10 DABU-D$_2$, X = CH$_3$) and without substitution (10 HABU-D$_2$, X = H) on central phenyl ring of the molecular core. (b) photographs of a monodomain LCE film and (c) a PDLCE in the form of a cylinder.

The two photo-active reactive mesogens have been used for the preparation of multifunctional photo-active Liquid Crystal Elastomers (LCEs) in the form of monodomain films (**Fig. 1b**) and Polymer Dispersed Liquid Crystal Elastomers (PDLCEs) [2] (**Fig. 1c**) targeted for light controlled opto-mechanical applications. The mesomorphic and structural properties as well as the thermo-mechanic and elastic properties of the new LCEs and PDLCEs will be reported and discussed in view of possible applications.

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Acknowledgments

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Nanomaterial/Polymer based Soft Actuators with Light-Driven Self-Oscillation for Bionic Applications

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Designing flexible smart devices and soft robots capable of autonomous deformation and movement through bionics is significant in various applications. As an important part of flexible smart devices, soft actuators that convert external energy stimulation into mechanical deformation have been widely developed in recent years. However, most of the current soft actuators only produce single deformations under external stimuli, and cannot achieve continuous mechanical deformation.

In this talk, we will focus on research work about light-driven soft actuator based on nanomaterials/polymer composite with autonomous motions. Firstly, we prepared CNT/polymer film with the curled shape, which can generate continuous self-oscillating wave motion under constant light irradiation. This actuator can autonomously and continuously crawl toward the light source in a wave-like propagation manner, demonstrating the phototactic movement characteristics [1]. Secondly, we fabricated light-driven actuators based on black phosphorus-CNT/polymer composite film and realized the self-oscillation deformation as well as continuously phototropic movement under constant light by introducing a unique negative feedback structure design [2]. Moreover, continuous self-oscillatory deformation under constant light with adjustable amplitude and frequency of oscillations was realized by installing a load on the MXene/polymer film [3]. We also achieved multi-angle light-driven self-oscillating deformation and biomimetic applications using MXene/polymer film actuators without the load [4]. Besides the artificial light source, we have also designed actuators based on gradient-layered structured MXene layer that can utilize natural sunlight as light source [5]; and further developed CNT-nafion/polymer actuators that can realize the autonomous phototropic motion under natural sunlight irradiation [6]. The above works provide simple ways to design light driven actuators with oscillation, and show their prospect for bionic applications.

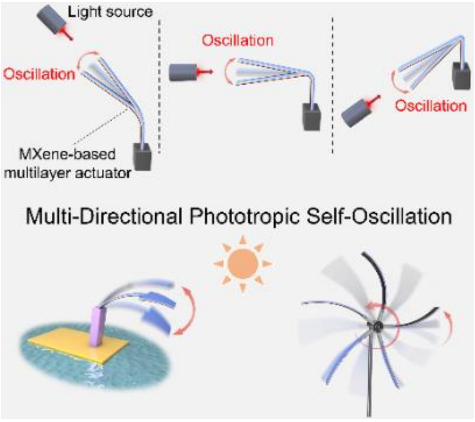

Figure 1. Phototropic self-oscillation and biomimetic applications with MXene actuator [4].

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Shape Changes of Liquid Crystal Elastomers Swollen by Low Molecular Weight Liquid Crystal Drops

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An elastomer swelling actuator deforms by absorbing a fluid, thus generating mechanical movement.[1] We show that depositing small droplets of low molecular weight liquid crystal on liquid crystal elastomer (LCE) films leads to shape changes and bending actuation.[2] It is found that the radially symmetric LCE director alignments provide radially symmetric hat shapes, while swelling LCEs with uniform director structure leads to arch shapes. (see Figure 1) Hybrid samples (different director alignments on two sides) lead to more complicated bent shapes.

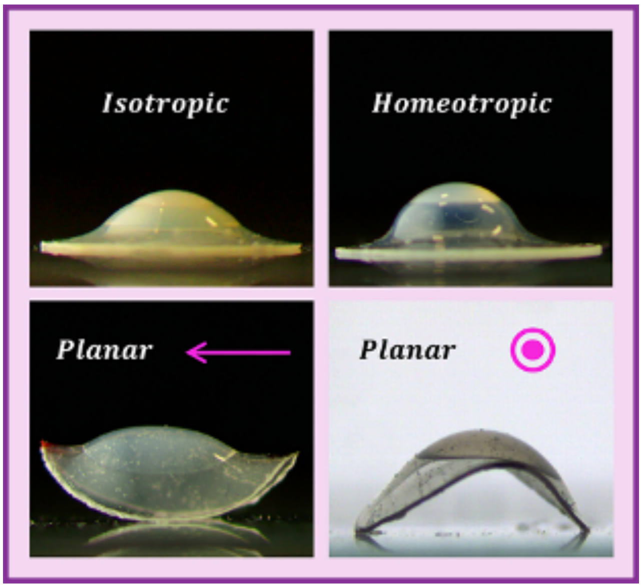

Figure 1. Snapshots of swollen LCE samples at 24 hours after deposition of 0.5 mg 5CB drop at the center of a 6 mm diameter 0.1 mm thick LCE discs. Top -Left: LCE crosslinked in the isotropic phase; Top-Right: LCE sample crosslinked in the nematic phase between homeotropic alignment substrates; Bottom: LCE sample crosslinked in the nematic phase between uniformly rubbed planar alignment substrates. Left: cross-section along the rubbing; Right: cross-section perpendicular to the rubbing.

All the observed shapes can be explained by the diffusion that mainly progresses along the direction normal to the director of the LCE. The swelling induced bending force is elevating the top of the swollen LCE up to a factor of 30, providing a powerful and long-lasting actuation. These observations may lead to applications in various fields, like sealants, soft robotics and biomedical devices.

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Programming liquid crystal elastomers for multistep ambidirectional deformability

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Ambidirectionality, which is the ability of structural elements to move beyond a reference state in two opposite directions, is common in nature. However, conventional soft materials are typically limited to a single, unidirectional deformation unless complex hybrid constructs are used. We exploited the combination of mesogen self-assembly, polymer chain elasticity, and polymerization-induced stress to design liquid crystalline elastomers that exhibit two mesophases: chevron smectic C (cSmC) and smectic A (SmA). Inducing the cSmC-SmA–isotropic phase transition led to an unusual inversion of the strain field in the microstructure, resulting in opposite deformation modes (e.g., consecutive shrinkage or expansion and right-handed or left-handed twisting and tilting in opposite directions) and high-frequency nonmonotonic oscillations. This ambidirectional movement is scalable and can be used to generate Gaussian transformations at the macroscale.

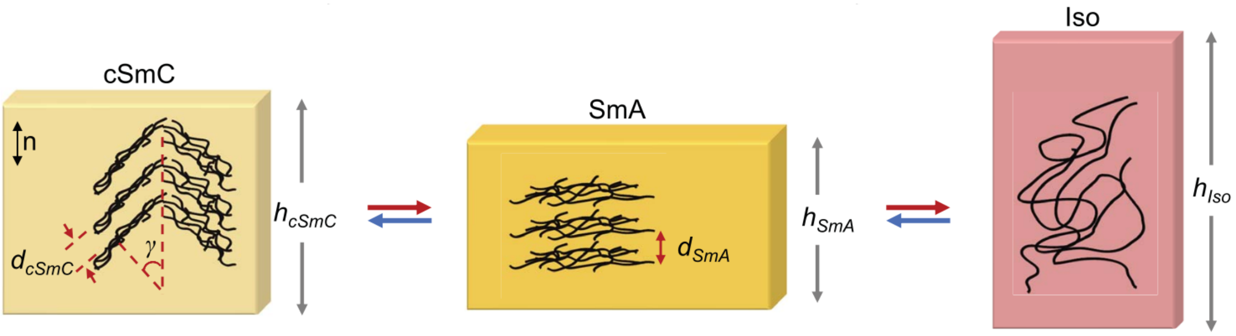

Figure 1. Schematic illustrating polymer chain reconfiguration during cSmC-SmA-Iso phase transitions enabling consecutive opposite deformations in end-on LCEs. The schematic blocks illustrate the dimensions of end-on LCE microplates. h and d denote the height of LCE microplate and lamellar layer thickness, respectively. Black lines inside schematic blocks denote polymer backbones.

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Polymer conformation changes observed with the naked eye in a liquid crystal elastomer and their use to produce adjustable and multidirectional deformations

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The monodomain nematic liquid crystal elastomer (LCE) is a nonporous material with one-dimension (1D) negative thermal expansion (NTE) along the direction of orientation. This stimuli-responsive size change is comparable with the contractile response of a muscle fibre [1], which confirms the early prediction of Pierre-Gilles de Gennes. Recently, LCEs have become more and more popular and increasingly investigated as a full-fledged class of stimuli-responsive materials. However, the nematic LCE is limited to a single, unidirectional deformation unless complex hybrid architectures are made. We develop here a special LCE [2] based on a liquid crystal polymer with an extraordinary phase transition sequence, “re-entrant nematic (N_{Re}) – smectic A (SmA) – nematic (N) – isotropic (I) phase”, along with “prolate – oblate – weakly oblate – spherical” chain conformation evolution [3,4]. In the aligned LCE film, these conformational changes of polymer chain are observed with the naked eye through their macroscopic translations into a unique sequence of “contraction – expansion – second expansion” deformations. Notably, a switch from NTE to positive thermal expansion (PTE) occurs upon heating. Moreover, a bilayer actuator composed of aligned and non-aligned LCE layers can perform 2D to 3D shape transformation with “curling – uncurling – second uncurling” actuation sequence. This LCE capable of multiple deformations in response to a single stimulus paves the way to multimodal single-material actuators. It provides a new strategy for the development of advanced materials with adjustable and multidirectional deformations.

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How to build cell instructive scaffolds by Liquid Crystalline Networks

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The extraordinary features of Liquid Crystalline Networks (LCNs) make them great candidates to address tissue engineering issues [1]. Among them, reproduction of biological tissues *in vitro* require the control of the collective cells organization and their correct differentiation ask for an aligned growth. To date, the main approach is based on the development of complex polymeric scaffolds able to mimic the biological environment, trying to reproduce the mechanical properties or the extracellular matrix composition and topography. However, the complexity of these methodology strongly limits their wide application.

We approached the problem completely differently by taking advantage of acrylate-based LCNs, combining their easy processability (3D printing, electrospinning, etc.) with a demonstrated biocompatibility towards different cell lines, and preparing materials with anisotropic molecular structure and tunable rigidity by photopolymerization. Such materials demonstrated the ability of the LC order inside the materials to influence the living organisms, promoting myoblast differentiation into functional myotubes [2] but also speeding up human induced pluripotent stem cell-derived cardiomyocytes (hiPSC-CMs) maturation[3].

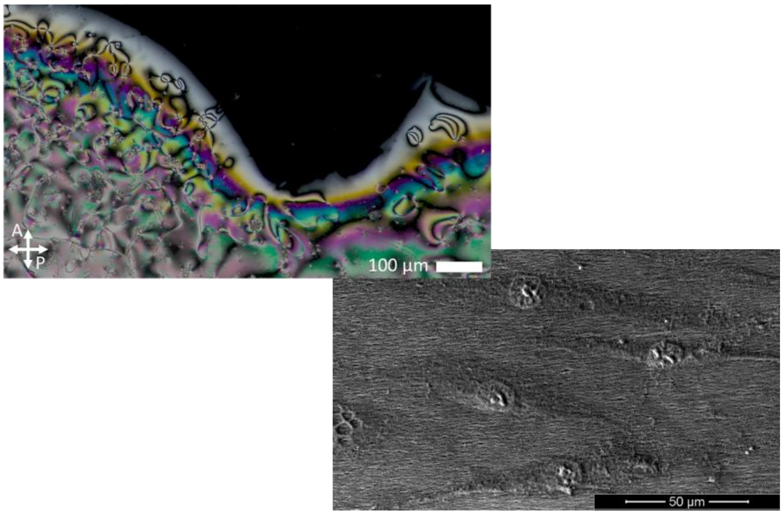

Figure 1. Polarized optical microscope (POM) images of a monomeric mixture and SEM images of aligned fibroblast on a LC scaffold

Acknowledgment: The work has been funded by the European Union - NextGenerationEU under the National Recovery and Resilience Plan (PNRR) - Mission 4 Education and research - Component 2 From research to business - Investment 1.1 Notice Prin 2022 - DD N. 104 del 02/02/2022, from the project “ALICE - light-Activated high-performance actuators by electrospinning of reversibly crosslinked LIquid CrystallinE networks”, proposal code 20224EBZ3Y – CUP J53D23008450006.

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Additive Manufacturing of Liquid Crystal Elastomers and Multimaterial 3D Printing for Functional Applications

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3D printing (additive manufacturing, AM) where materials are deposited in a layer-by-layer manner to form a 3D solid has seen significant advances in the recent decades. The integration of AM with stimuli responsive materials has led to birth of 4D printing, where the printed materials and structures can change their shape and properties over time. Among stimuli responsive materials, liquid crystal elastomers (LCEs) are particularly attractive because of their large reversible dimension change upon external stimuli, such as temperature. In addition, LCE can be printed by direct ink write (DIW) 3D printing. Because of the shear force and stretching during the DIW process, mesogens can be aligned and the printed LCEs can have actuation immediately after printing. In this talk, we introduce our efforts in integrating 3D printing of LCEs with other functional materials to create shape changing structures and devices. We integrated digital light processing (DLP) 3D printing process with DIW method such that we can combine the advantage of DIW printing of LCEs with a rapid printing of DLP to create functional structures. In addition, we present our efforts in using DIW to fabricate LCE fibers to increase their application potentials.

Advanced Photonics with 4D Microstructured Liquid Crystalline Networks

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Materials responsive to external stimuli or environmental changes are crucial for emerging applications in sensing, photonics, and cryptography. To realize their potential, nanoscale and microscale integration is essential. We leverage two-photon direct laser writing, enabling 3D polymeric printing with nanometric resolution, and digital light processing, a scalable technique for 2D+1 microstructures to pattern liquid crystalline networks (LCN) and demonstrate 3D-printed microstructures for reconfigurable photonics, secure information encoding, and sensing.

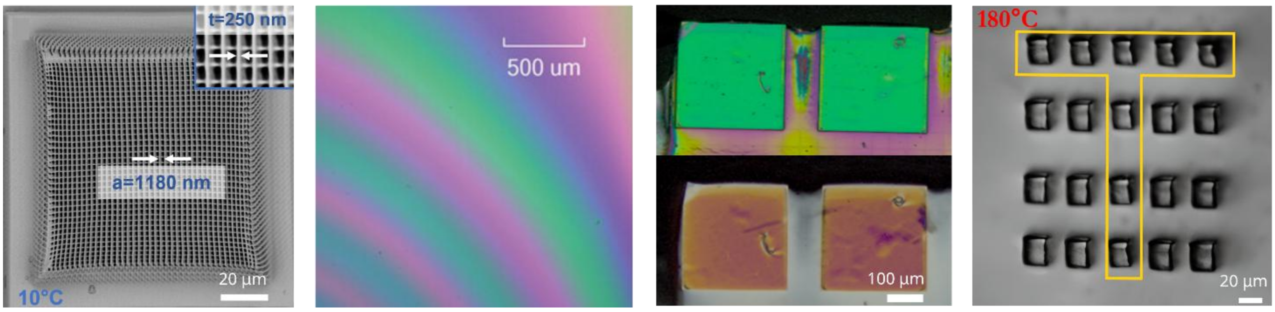

Figure 1. Examples of tunable LCN microstructures for photonics, sensing and anticounterfeiting.

I will present our latest advancements in 4D nano and micro structuring (3D design with controlled temporal deformation) of LCNs for various tunable photonic structures: from a 3D deformable photonic crystal with sub-diffraction limited resolution [1,2] to highly reproducible tunable optical filters based on metal-responsive dielectric-metal structures [3], from polarization color pixels for solvent sensing [4] to hidden micro tags that can be unveiled under proper stimuli [5].

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Photopatterning Liquid Crystal Polymers with Predesigned Director and Shape

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Precisely controlling the geometric shape and the director field of liquid crystal polymers is central to many emerging applications, ranging from flat optical elements, active matter manipulation, stimuli-responsive soft actuators and soft robotics. This talk will report research progresses of my group in developing techniques for photopatterning molecular orientations in both 2D and 3D, understanding their physical limits on spatial resolutions, and demonstrations of their practical applications including diffractive optical elements, ultracompact optical microscopes, deep diffractive neuron networks, programmable stimuli-responsive microstructures.

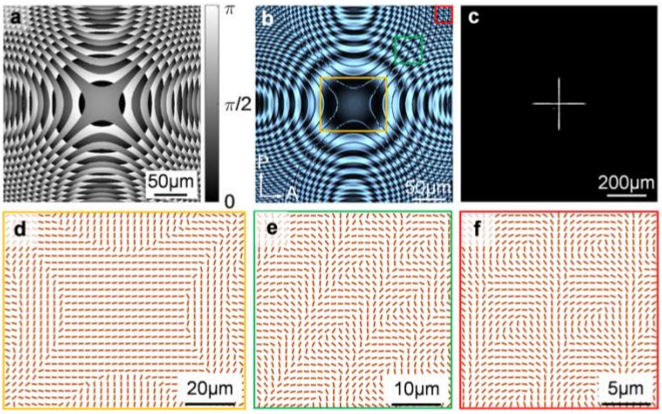

Figure 1. Flat optical elements enabled by precise photopatterning molecular orientations in 2D. (a-c) Designed molecular orientation profile (a), polarized optical microscopic image of a fabricated liquid crystal optical element (b), and intensity distribution measured at the focal plane (c), respectively. (d-f) Measured molecular orientations of the orange, green and red areas in (b), respectively.

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Unlocking New Opportunities in Liquid Crystal Elastomers through Smectic Phase

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Liquid crystal elastomers (LCEs) have made a significant progress in recent years, demonstrating great potential in various fields such as soft actuators, robotics, smart textiles, damping, adhesives and biomedical applications.[1] Traditionally, nematic LCEs have been preferred for applications like soft actuators and artificial muscles due to their ability to generate larger actuation strains compared to smectic LCEs. In addition, the internal rotation of mesogens in nematic LCEs occurs more easily under mechanical stress, leading to enhanced energy dissipation relative to smectic LCEs. While smectic LCEs have received less attention, their intrinsic layered structure offers unique alignment characteristics that can be harnessed to control actuation modes. In this talk, I will present our recent works on smectic LCEs in both 1D fiber and 2D films geometries. Thanks to orthogonal orientation of mesogens relative to smectic layers, we could achieve unconventional actuation modes, unlocking new opportunities in creating active textiles and dynamic haptics.[2]

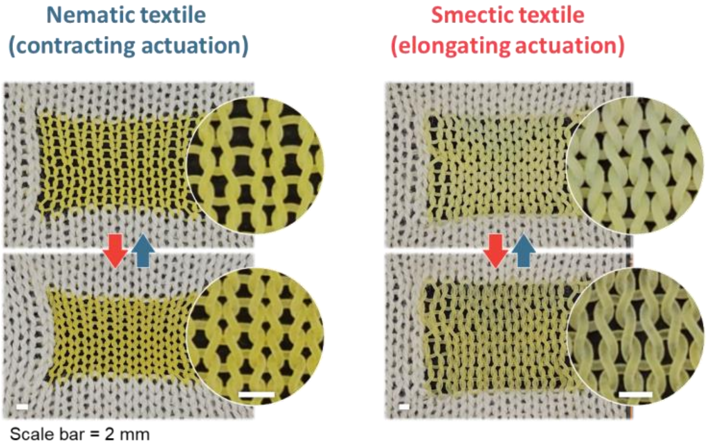

Figure 1. Nematic (left) and smectic (right) LCE textiles with showing thermotropic contraction and elongation, respectively.

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Sidechain and Mainchain Photoalignment of Azobenzene-Containing Liquid Crystalline Polymers

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The incorporation of light-responsive components into liquid crystalline polymers has enabled spatiotemporal control over dramatic changes in physical properties, including volumetric changes for actuation and (meso)phase changes for adhesives. Moreover, microscopic control over directors for monodomain molecular ordering of liquid crystals has enabled programable anisotropy, from optical to mechanical properties. In the ZAP research group, we have been developing new structure-process-function relationships to better understand and control molecular alignment within liquid crystalline polymers. This presentation will describe our recent findings regarding the influence that polymer architecture, composition, and molecular weight have on the rate and degree of molecular photoalignment, along with the corresponding processing conditions (i.e., temperature and light exposure wavelength and intensity). These fundamental findings are anticipated to facilitate future research into stimuli-responsive liquid crystalline polymers and polymer networks with applications in soft robotics, electronics, and more.

Enhancement of Photomobile Properties of Liquid-Crystalline Polymers Through the Design of Azobenzene Derivatives

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Liquid-crystalline polymers (LCPs) containing photochromic moieties show macroscopic deformation upon irradiation with light [1–3]. Various reversible motions of LCPs such as contraction, bending and rotation have been reported so far. Azobenzene derivatives have been extensively studied as photochromic components for photomobile polymer materials. Typical azobenzene derivatives show *trans-to-cis* and *cis-to-trans* photoisomerization upon irradiation with UV and visible light, respectively. These photoisomerization behaviors are directly correlated to the macroscopic deformation of photomobile materials. In this study, we develop LCPs containing various types of azobenzene moieties to control their photoresponsive behaviors.

Introduction of electron-donating and -withdrawing groups to azobenzene core (push-pull structure) leads to red-shift of light absorption properties. Push-pull azobenzene derivatives show photoisomerization upon irradiation with sunlight, and fast thermal back isomerization after the cease of irradiation. LCP films containing push-pull azobenzene moieties exhibit reversible bending in response to sunlight without the need of artificial optical elements, such as color filters and lenses (Figure 1a). Another way to allow red-shift of absorption spectra is extension of π-conjugation length. Reversible deformation of LCP films containing azotolane moieties can be induced by visible light. Furthermore, azotolane shows two-photon absorption upon irradiation with femtosecond laser pulses. We demonstrate three-dimensionally selective actuation of the films via two-photon absorption processes [4]. Localized strain in a continuous body leads to sophisticated motions with a tremendous degree of freedom.

Bridged azobenzene also exhibits reversible photoisomerization in response to visible light. *Cis*-isomers are thermodynamically more stable than *trans*-isomers in bridged azobenzene due to the ring strain in molecular structure. Reversible deformation of the films with bridged azobenzene moieties can be induced upon irradiation with visible light even in liquid nitrogen, where thermal molecular motions are severely restricted (Figure 1b) [5]. Adequate design of photochromic components greatly contributes to control photoresponsive properties of LCPs.

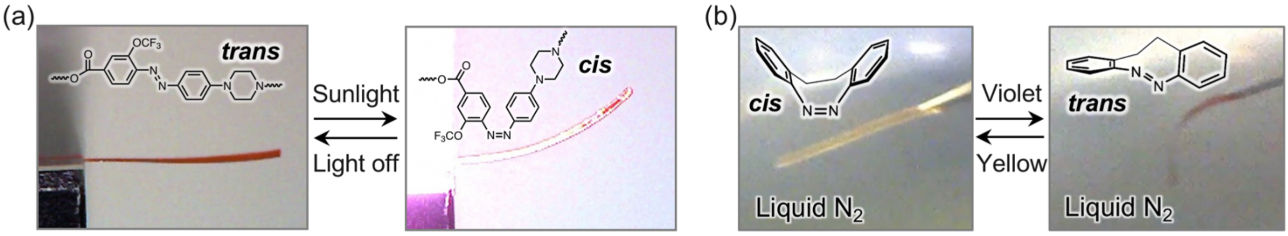

Figure 1. Photoinduced deformation behaviors of photomobile polymer materials containing (a) push-pull azobenzene and (b) bridged azobenzene moieties.

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Crosslinked Liquid-crystalline Polymer Films Patterned by Scanning Light

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The effects of external force on polymers have been actively studied for a long time. Initially considered a primary factor leading to polymer degradation, it has recently been re-evaluated as crucial for imparting advanced functionalities to polymers. However, the effect of mechanical stimuli deliberately applied to the growing polymers is still unknown. Recently, we developed a novel photopolymerization process using spatiotemporal lighting, which causes molecular flow during the photopolymerization [1-5]. We report efficient polymerization behavior under photoinduced molecular flow fields [6,7]. Photopolymerization with scanning UV light exhibited higher-molecular-weight polymers, with a reduction of 90% of exposure dose compared to photopolymerization with static uniform light. The efficient polymerization behavior is attributed to the spatially reduced radical concentration due to the photoinduced molecular flow. Our proposed approach holds promise for an innovative polymer synthesis process. In addition, our recent progress on molecular alignment patterning in the crosslinked liquid-crystalline polymer films produced by scanning photopolymerization is introduced.

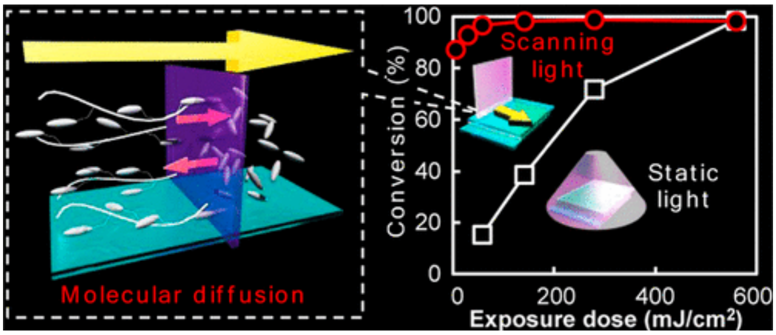

Figure 1. Schematic illustrations of the polymerization behavior under photoinduced molecular diffusion (left) and monomer conversion of a liquid-crystalline polymer obtained by scanning light as a function of exposure dose (right) [7].

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Smart liquid crystal elastomer fibers

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Liquid crystal elastomers (LCEs), consisting of liquid crystal mesogens coupled with polymeric chains to form a cross-linked network, exhibit anisotropic optical and mechanical properties due to their phase transitions under external stimuli such as light, electricity, magnetic field, and heat [1]. LCE fibers, owing to their high aspect ratios, superior responsive properties, and one dimensional material geometry, have emerged as outstanding candidates for constructing soft actuators in recent years [2].

This talk will first introduce the fabrication of LCE fibers, including dry spinning, melt spinning, template method and rotational 3D printing. It will also explicate how to obtain solid and hollow fibers, control their size, structure, component and liquid crystal orientation. Finally, soft actuators based on LCE fibers, responsive to heat, electricity, and air pressure, will be demonstrated, highlighting their diverse functionalities.

For example, (i) LCE fibers can simulate pumping function of heart muscles [3], lifting heavy objects akin to biceps brachii [4], and achieving rapid ball throwing similar to triceps brachii [5]. (ii) LCE fibers with programmed alignment enriched responsive modes of LCE actuators and have achieved not only common shrinkage and bending deformations, but also developed complex deformations such as elongation, torsion and rotation [6,7]. (iii) Incorporating liquid metal into LCE fibers can integrate sensing and actuating in a single fiber with a simple design [8,9]. (iv) Additive manufacturing of LCE actuators based on knitting technology can bring about advanced geometry, integrated multi-functions and efficient recyclability [10]. The porous structure and soft elasticity of LCE knitted actuators will facilitate the development of ergonomic and comfortable wearable devices. Knitted LCE actuators incorporated with other functional fibers and smart textiles can act as a deformable, multifunctional platform. The above works provide new design concepts for constructing a new type of simple, intelligent, and miniaturized soft actuators.

The LCE actuators based on fiber structure is expected to be applied in fields such as wearable devices, including motion assistance and human computer interactions.

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Enabling active textiles using liquid crystalline elastomer yarn

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In almost everyone's life, a piece of cloth ended up washing or drying under conditions that cause it to shrink, making it no longer fit. Consequently, the textile industry commonly uses processes and materials to minimize such permanent dimensional changes.[1] However, the possibility of using new materials capable of recovering their original shape, upon a specific trigger, opens the door to potential applications where dynamic shape adaptation is desirable – from apparel that adjusts to body movements or temperature, to structural elements that reconfigure under changing environments.[2] In this context, liquid crystal elastomers (LCEs) have long been considered promising base materials for large-stroke reversible actuation. Yet, until recently, it was not possible to produce LCE filaments compatible with standard textile production methods. We present the crafting of active fabrics incorporating LCE yarns, based on recent developments in LCE fiber spinning.[3,4] By combining these LCE yarns with conventional passive yarns under different design frameworks, we investigated how specific arrangements might influence the overall actuation performance – namely the amount of stroke, the generated force, and out-of-plane deformations. The created prototypes that seamlessly combine active LCE yarns into the rich portfolio of existing passive yarns depict a world where textiles are not just passive entities, but active accomplices responding to environmental stimuli, paving the way for adaptive, shape-changing systems

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Reconfigurable Exotic Liquid Crystal Elastomer “Smart” Surfaces via Hot Embossing

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Smart surfaces, distinguished by their dynamic responses to environmental changes, may enhance the functionality, interactivity, and efficiency of materials and devices. Liquid crystal elastomers (LCEs) are ideal candidates for creating smart surfaces, allowing reversible topographical changes in response to environmental stimuli. However, traditional thermoset LCE preparation methods require complex manufacturing processes, including photopolymerization, and the resulting surfaces (often pillars) are nonreprogrammable and nonrecyclable.[1-3]

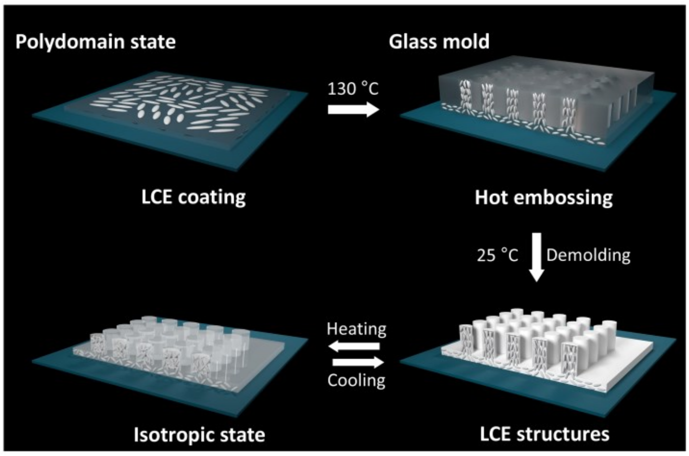

Figure 1. Schematic representation of the hot embossing process to prepare surface structures atop the LCE coating.

In this work, hot embossing is used in combination with a thermoplastic LCE for creating self-healing and reprogrammable exotic surfaces capable of reversibly responding to environmental stimuli, significantly simplifying fabrication (Figure 1).[4] It is demonstrated that hot embossing can be effectively applied to fabricate surfaces with arrays of pillars, cones, tubes, or mushroom shapes. The exotic surface structures exhibit reversible and programmable shape changes in response to heat and can be erased and rewritten to alternate complex topographies. As an additional feature, the LCE can be recycled and reused to create photo-responsive surface topographies that can be spatiotemporally addressed by light. Light-responsive LCE surfaces are prepared by incorporating a photothermal dye without loss of reconfigurability. Demonstrators are fabricated such as locally controlled object movement on a surface by light.

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Optically Controlled Wind-Assisted Flight in Miniature Soft Robots

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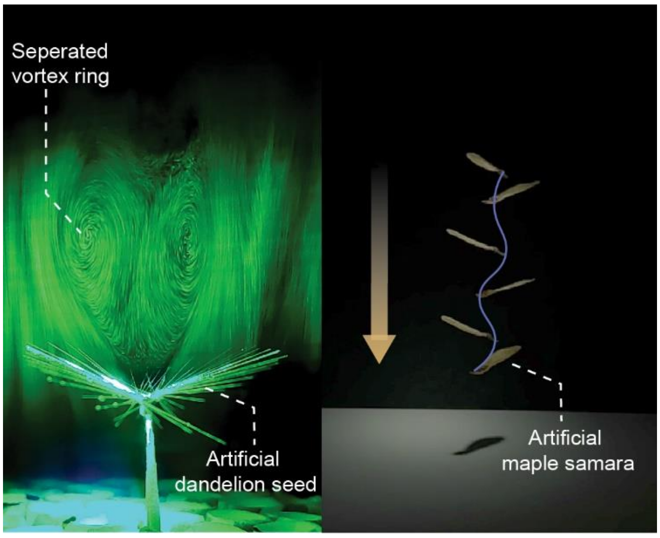
The integration of stimuli-responsive polymers into soft robotics has enabled diverse forms of autonomous motion. However, achieving controlled flight—beyond walking, swimming, and jumping—remains a challenge due to stringent requirements on actuation, weight, and aerodynamic design. Here, we present a class of light-responsive soft actuators capable of wind-assisted dispersal and controlled gliding, inspired by biological plant such as dandelion seeds [1] and maple samaras [2]. By leveraging liquid crystalline elastomers (LCEs) and azobenzene-crosslinked liquid crystal networks, we achieve reversible and bistable shape morphing, allowing precise modulation of aerodynamic parameters [3-4]. Our designs enable optically controlled lift-off, landing, and gliding, surpassing natural analogs in tunability. We demonstrate light-driven manipulation of descent pathways, terminal velocity, and rotational dynamics in both indoor and outdoor environments. These findings open new avenues for wirelessly controlled microfliers, expanding the potential of soft robotics in environmental monitoring and distributed aerial systems.



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Agile and robust micro-aerial-robots powered by dielectric elastomer actuators

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Recent advances in microrobotics have demonstrated remarkable locomotive capabilities such as hovering flights [1], impulsive jumps, and fast running in insect-scale robots. However, most microrobots that are powered by power-dense rigid actuators have not achieved insect-like collision resilience. In this talk, I will present our recent effort in developing a new class of microrobots – ones that are powered by high bandwidth soft actuators and equipped with rigid appendages for effective interactions with environments. Towards improving collision robustness [2] of micro-aerial robots, we develop the first heavier-than-air aerial robot powered by soft artificial muscles that demonstrates a 1000-second hovering flight [3]. In addition, our robot can recover from an in-flight collision and perform a somersault within 0.10 seconds. The robot's maximum lift is comparable to that of the best rigid-powered sub-gram robots. This work demonstrates for the first time that soft aerial robots can achieve agile and robust flight capabilities absent in rigid-powered micro-aerial vehicles, thus showing the potential of a new class of hybrid soft-rigid robots.

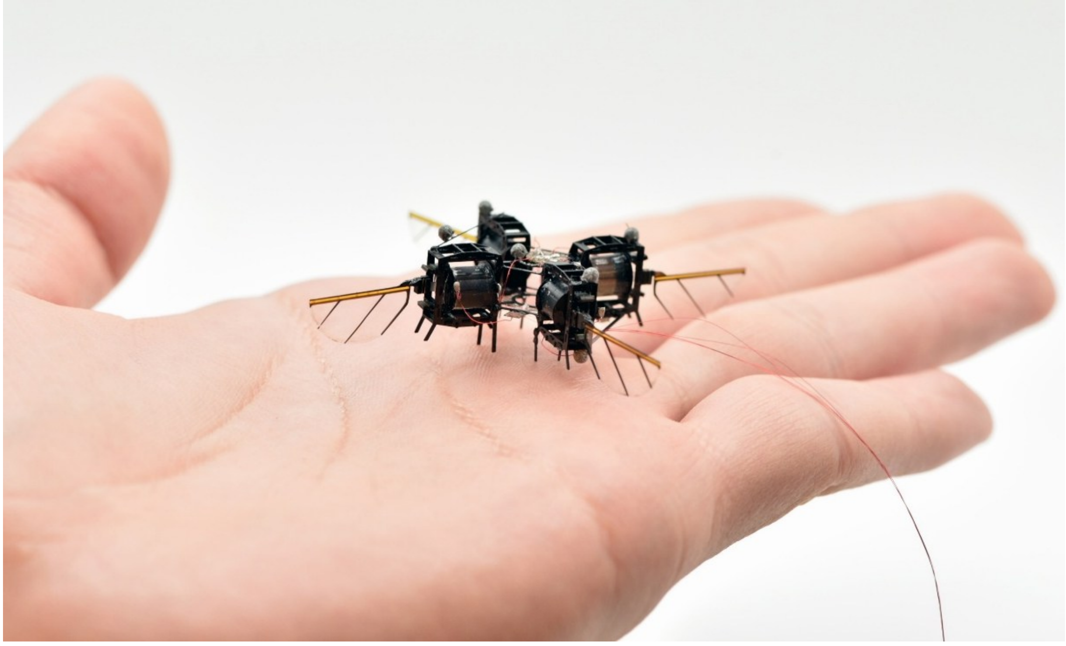

Figure 1. An image of a 0.75 g flapping-wing micro-aerial-robot powered by dielectric elastomer actuators.

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Soft elasticity and microstructure: explaining mechanical programming and powering director design.

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For more than a decade now, it has been possible to create flat nematic LCE sheets encoded with arbitrary planar patterns of alignment [1]. Upon heating, these sheets undergo a corresponding pattern of contraction that morphs them into a complex shape, such as a cone, cap or face. This experimental capacity has provoked much work on designing director patterns to achieve specific shape changes and/or accomplish specific tasks [2]. However, this process of design and fabrication remains quite complex. Furthermore, in reality, once we depart from highly symmetric shapes (surface of revolution, transitionally invariant etc), the experimental realizations tend to be rather disappointing, producing shapes that are rather different than that intended. In contrast, direct mechanical programming of LCEs enables the robust actuation into seemingly arbitrarily complex shapes, without director design or complex fabrication [3]. However, it is rather mysterious why the procedure produces faithful programming of complex deformations.

In this talk, I will combine experimental and theoretical results to explain how and why direct mechanical programming works. Critically, such programming requires the initial formation of an isotropic genesis polydomain, and programming occurs via soft elasticity, director rotation and microstructure formation. Theory suggests the microstructures that form are higher order laminates, which are indeed experimentally observed. Theory also provides a simple prediction about the full set of 3D deformations that can be programmed, which is also validated experimentally.

I will then demonstrate how the mechanism behind mechanical programming can also be used for explicit computational director design, both with and without microstructure. I will use these techniques to design nematic patterns that morph a flat region into a complete wrapping of the sphere, discuss how much actuation is required to wrap a sphere, and demonstrate experimental realizations of the resultant patterns fabricated via extrusion printing.

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What is difficult about printing of complex director patterns?

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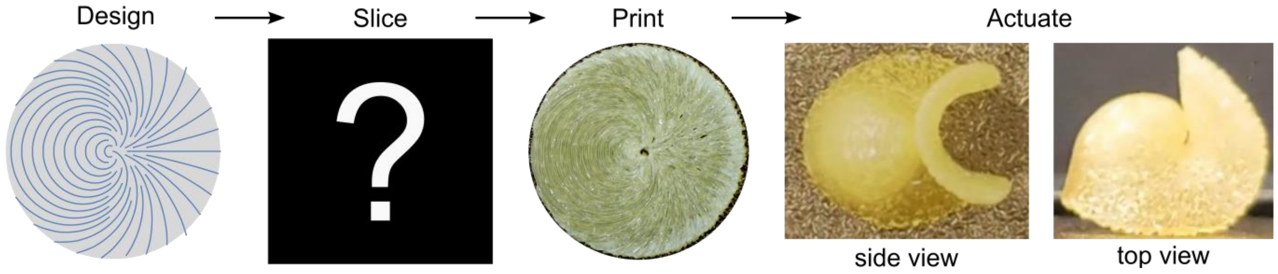

Fig. 1. Workflow of 3D printing of director patterns.

LCEs can famously be fabricated with complex bespoke director patterns, which then encode corresponding patterns of contraction on stimulation that can morph the initially flat LCE sheets into complex three-dimensional shapes. This ability to pattern the actuation has driven the subject of director design, culminating in many analytic patterns for simple target shapes (cones, irises, grippers, and more) and inverse solvers for arbitrary complex geometries (e.g. faces). Many of the director patterns having been experimentally demonstrated using surface alignment techniques.

A relative newcomer to the field of LCEs is extrusion 3D printing, wherein director alignment follows the extrusion direction, offering a new route to fabricating patterned LCE sheets. However, despite the wide range of known director patterns, 3D printing has been almost exclusively limited to uniaxial and azimuthal print paths, or stacks thereof. In contrast, the library of LCE inks has been expanded significantly and includes thermo-, photo- and magneto-responsive materials, together with many more composite materials. Likewise, the printing techniques have been extended to freestanding prints, graded alignment and multi-material printing. How come the director patterning is the only aspect that lags behind the other two? Is there any fundamental barrier to the printing of complex director patterns, or is it purely technical?

To find out, one must first analyse the standard 3D printing workflow. Every 3D object that is to be printed needs to first be sliced, that is, firstly decomposed into layers (2D), which are then further decomposed into paths (1D). The field of slicing is very mature; however, it was developed having in mind isotropic materials, where the printing direction is a degree of freedom that is used to improve the geometry replication and lower the print time. Conversely, for LCEs the direction acts as a constraint, and packing paths together is inherently difficult in regions where the paths diverge. Unfortunately, all known director patterns, apart from uniaxial and azimuthal, contain divergence, and so this problem cannot be avoided without seriously limiting pattern choice.

In this talk, I will give an overview of preexisting director patterns, show the issues that director divergence causes and demonstrate that no perfect solution exists when printing is done at constant width. Then, I will present our slicing approach driven by the divergences in the director pattern [1], that is suitable for printing of any material with patterned anisotropy, and comes with an open-source implementation in the form of *Vector Slicer* [2]. Critically, *Vector Slicer* enables satisfactory printing of LCE sheets with any director pattern, thereby opening this fabrication technique to the whole library of planar patterns developed for photoalignment.

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Self-Oscillations of Submerged Liquid Crystal Elastomer Beams Driven by Light and Self-Shadowing

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Light actuation offers versatile control over LCE properties, enabling complex deformations. A notable phenomenon in LCEs is self-oscillation under constant illumination. Understanding the physics underlying this dynamic response, and especially the role of interactions with a surrounding fluid medium, is still crucial for optimizing the performance of LCEs. In this study, we have developed a multi-physics fluid-structure interaction model to explore the self-oscillation phenomenon of immersed LCE beams exposed to light. We consider a beam clamped at one end, originally vertical, and exposed to horizontal light rays of constant intensity focused near the fixed edge. Illumination causes the beam to bend towards the light due to a temperature gradient. As the free end of the beam surpasses the horizontal line through the clamp, self-shadowing induces cooling, initiating the self-oscillation phenomenon. The negative feedback resulting from self-shadowing injects energy into the system, with sustained self-oscillations in spite of the energy dissipation in the surrounding fluid. Our investigation involves parametric studies exploring the impact of beam length and light intensity on the amplitude, frequency, and mode of oscillation.

Our findings indicate that self-oscillation initiates above a certain critical light intensity, which is length-dependent. Also, shorter lengths induce oscillations in the beam with the first mode of vibration. Applying higher light intensity may trigger composite complex modes, while the frequency of oscillation increases with the intensity of the light if the mode of oscillation remains constant.

A Nonlinear Viscoelastic Model for Nematic Elastomers: Coupling Mesogen Order, Director Rotation, and Network Viscoelasticity

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Liquid crystalline elastomers (LCEs), composed of mesogens bound in an elastomeric network, combine the anisotropic self-ordering behavior of liquid crystals with the dissipative viscoelastic behavior of the polymer network. This combination produces unique behaviors, including temperature-activated large reversible shape change, a rate-dependent soft stress response, and enhanced dissipation compared to traditional elastomers. Previously, we developed a nonlinear viscoelasticity model for LCEs based on a viscoelastic micropolar theory that incorporated the coupled mechanisms of viscous director rotation and viscoelastic network deformation.[1] The model assumed a constant order parameter and thus could not describe the deformation response of the nematic-isotropic transition nor mesogen ordering from deformation. To capture these effects, we developed a thermoviscoelastic model for LCEs based on a novel viscoelastic microstretch theory that described the coupled mechanisms of viscous mesogen ordering, viscous director rotation, and viscoelastic network deformation. To demonstrate the behavior of the coupled theory, we specified linear flow rules for the order parameter, director orientation, and viscous deformation gradient, applied the neoclassical potentials for the equilibrium and nonequilibrium free energy densities of the network, and the Frank energies for the gradient of the director and order parameter fields. The model was implemented in COMSOL and applied to investigate the effect of the heating/cooling rates and preload on the stretch response to the nematic-isotropic transition (Fig.1A), the heterogeneous evolution of the order parameter and strain field through the nematic transition (Fig.1B), and the effect of thermal history on the stress response (Fig. 2).

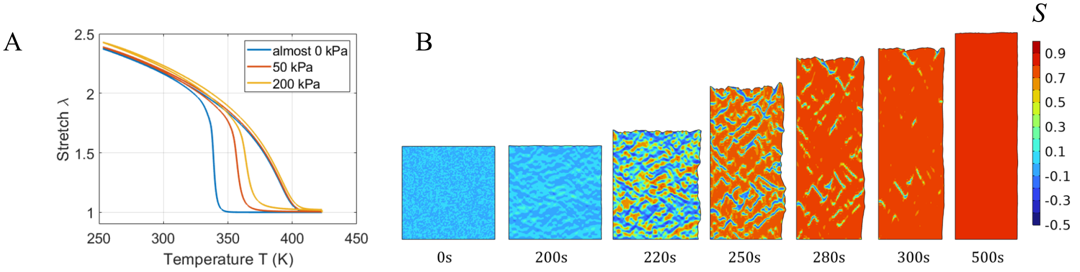

Figure 1. (A) FEA simulations of the strain response to a cooling and heating cycle through the nematic-isotropic transition temperature T_{ni} under different pre-stress. A larger pre-stress led to a higher nematic-isotropic transition temperature during cooling but did not affect the stretch response during heating. (B) The heterogeneous evolution of the order parameter S at different times following a quench from T_{ni} to room temperature. The mesogens initially formed a +/-45° pattern of domains aligned with the director ($S=0.8$) and perpendicular to the director ($S= -0.5$) before becoming uniformly aligned along the director.

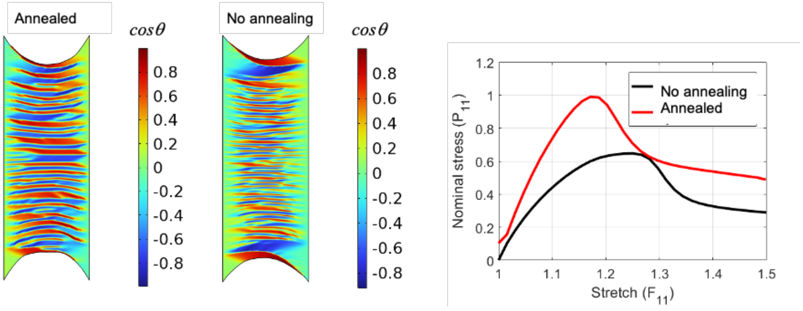

Figure 2. FEA simulations of stretching an LCE strip perpendicular to the director comparing the effect of simulating the thermal history of cooling from T_{ni} to room temperature (Annealed) before calculating the stress response. The Annealed case showed coarser stripe domains and a stiffer stress response.

(Re)programming functionality in liquid crystalline elastomers using dynamic covalent chemistry

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The ability of liquid crystalline elastomers (LCEs) to undergo complex stimuli-responsive shape-change relies on the patterning of mesogens within the polymer network. Deformation results from the disruption of the patterned anisotropic structural order upon the application of stimulus such as heat or light. Typically, orientation of mesogens within the LCE is enforced during the initial synthesis of a polymer network by methods such as surface anchoring or mechanical stretching. As a result, the network retains the programmed orientation and assumes the corresponding shape-morphing behavior. However, this approach leaves minimal opportunities for reprogramming due to the permanence of the covalent crosslinks. Therefore, dynamic covalent bonds are often leveraged within the polymer network of LCEs to enable reconfigurable anisotropic patterns within the material and, as a result, reprogrammable shape changes as shown in Figure 1.

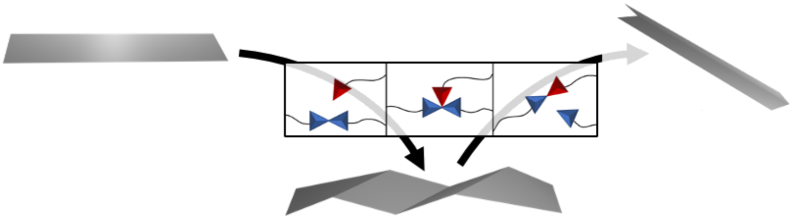

Figure 1. Dynamic covalent chemistry enables reprogramming of LCE actuation properties.

Since both actuation and dynamic bond exchange are stimuli-responsive properties, it is important to consider orthogonality of stimuli for each component when designing a network that integrates both moieties. Programming these functionalities with orthogonal stimuli-responsiveness enables independent activation of their corresponding function. In this work, we demonstrate one approach in which the intrinsic thermal phase transitions are leveraged for actuation and light-responsive chemistry, namely radical-mediated allyl sulfide exchange, is used for dynamic bond reorientation. [1] We demonstrate that the orthogonality of these responsive attributes enables programming via combination of surface alignment and mechanical stretching to access complex thermally-actuated shape changes. In a second demonstration, the functions of these two stimuli are reversed; LCEs are programmed for photoresponsive actuation and thermally activated bond exchange using thiol-anhydride chemistry. [2] Notably, in these LCEs, diarylethene is used as the photoresponsive moiety to enable thermally stable photomechanical actuation, allowing for thiol-anhydride bond exchange to take place in the nematic phase without compromising photoresponsive properties. We demonstrate both programming of orientation and shape-locking in these materials, further emphasizing the power of combining the functionality of dynamic covalent bonds with stimuli-responsive liquid crystalline networks.

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3D deformation of liquid crystals elastomer for small-scale structural manipulation

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The three-dimensional (3D) deformation of liquid crystal elastomers (LCEs) upon thermal stimulation has been extensively explored in macroscopic applications, often seen in constructing various soft robots. However, their potential for manipulating micro-/nanoscale structures remains largely untapped. Here, we harness the spatial 3D deformation of LCEs to achieve precise and dynamic control over small-scale structures, unlocking new possibilities for microactuation. Two distinct deformation modes—planar and thickness expansion—enable innovative actuation strategies. The first approach[1] exploits in-plane expansion of LCEs to drive micro-metastructures (kirigami structures), enabling programmable and reconfigurable transformations of different patterns upon heating and cooling. The second approach[2] leverages out-of-plane thickness expansion, where LCEs actuate microhairs, mimicking artificial goosebumps. This dynamic surface control opens up exciting applications in adaptive interfaces, tunable adhesion, and high-density information storage. By demonstrating the power of LCEs' spatial 3D deformation at micro- and nanoscales, these works establish a new paradigm for programmable small-scale structural manipulation. We believe this breakthrough will propel the development of next-generation microfluidic devices, bioinspired adaptive materials, and microscale robotics, expanding the frontiers of intelligent, multifunctional systems.

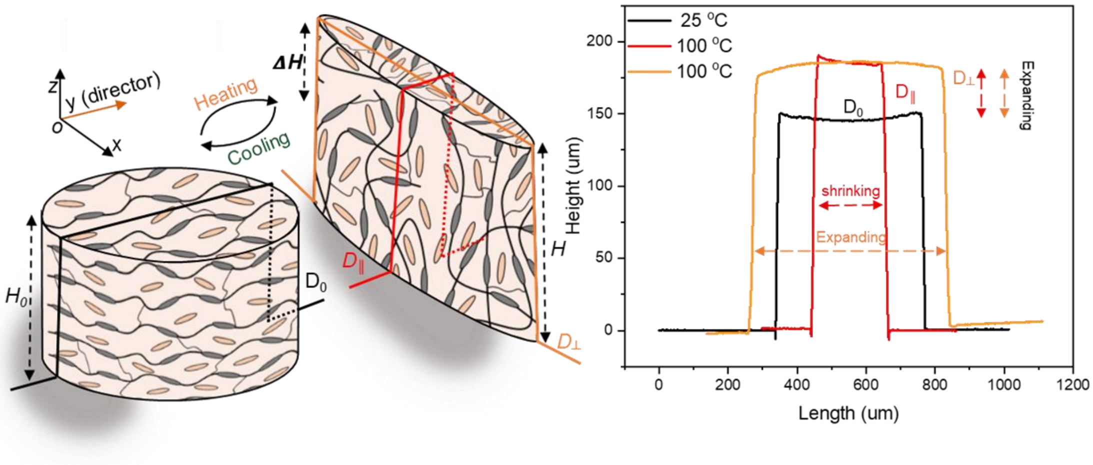

Figure 1. Schematic and profile showing the 3D deformation of liquid crystal elastomers upon heating/cooling.

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Tailorable Energy Damping using 3D Printed Liquid Crystalline Elastomers

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Liquid crystalline elastomers (LCEs) are remarkable materials with anisotropic properties useful for shape morphing, adhesion, optics, energy or damping. However, without effective manufacturing techniques, these materials will remain confined to laboratories. Recent advances in additive manufacturing (AM), also known as 3D printing, have demonstrated that by tailoring fabrication strategies, we can also tailor LCE properties, form, and function. One compelling application of LCEs is in the design of energy-dissipating structures capable of mitigating mechanical loads across a broad range of strain rates, including shock, vibration, and compression. Due to their anisotropic polymer backbone alignment, LCEs exhibit a soft elastic response that enhances energy dissipation [1]. By leveraging direct ink write (DIW) 3D printing, we fabricate monodomain LCE lattice structures designed to optimize damping performance. Our results show that these lattices match traditional elastomeric materials in quasi-static environments while offering superior damping under high strain-rate impacts. Furthermore, monodomain LCE lattices improve dynamic mechanical vibration damping, particularly at structural resonance, and provide high-frequency attenuation [2].

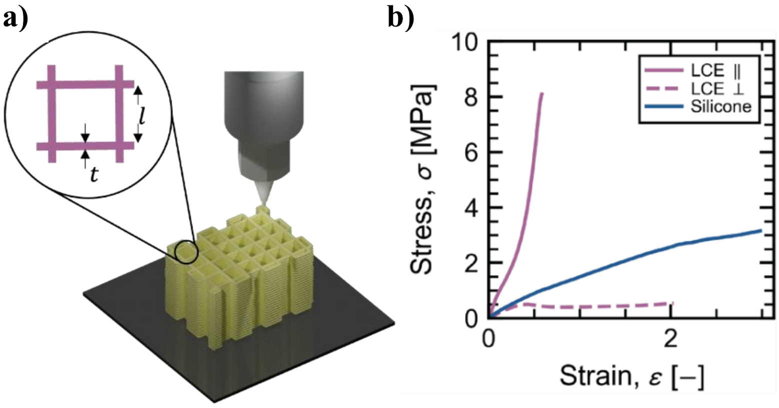

Figure 1. a) 3D printing of tailorable LCE lattice architecture. b) Exceptional anisotropic compression response of monodomain LCEs.

Beyond damping, we also explore the tunability of LCE-based lattice structures to enhance their mechanical adaptability. Soft, high-aspect ratio architected LCE lattices with programmable stiffness and energy absorption are fabricated using Bouligand-inspired designs with varying relative density. Under strain rates spanning from 10^{-3} to 10^{3} s^{-1}, we find that LCE-based lattices greatly outperform non-mesogenic silicone counterparts, particularly at high strain rates, where they absorb up to 40 times more energy. Thermal actuation further expands the tunability of these structures, where initial softening occurs below the nematic-to-isotropic transition temperature (T_{NI}), followed by significant stiffening above T_{NI}.

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Mechanics and Microstructures of Mechanically Programmed LCEs

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The mechanical behavior and shape transformation of liquid crystal elastomers (LCEs) are governed by their microstructure. While various manufacturing techniques exist to control the director orientation within LCEs, designing microstructures for complex, arbitrary shape changes remains challenging. However, mechanically programmed LCEs have been shown to self-organize into complex microstructures that accommodate external stresses, enabling shape transformations without prior knowledge of the microstructure [1,2].

Here, we investigate the microstructures that emerge in mechanically programmed LCEs and establish a connection between experimentally observed programmable strains and theoretical predictions. This study provides a framework for understanding the intricate microstructures formed through mechanical programming, offering insights into how they can be harnessed for tailored mechanical responses and advanced shape transformations. These findings can guide the design of sophisticated director orientations, ultimately advancing manufacturing techniques such as 3D printing.

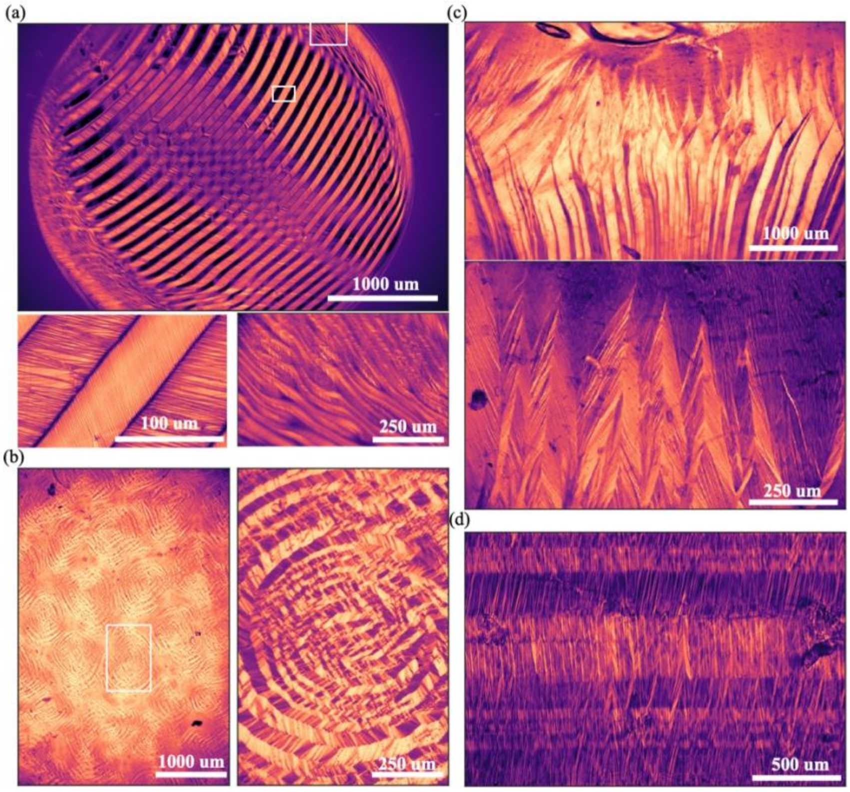

Figure 1. Gallery of experimentally observed microstructures in mechanically deformed LCEs.

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Phototunable Self-Oscillating Systems

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Abstract

Self-oscillating systems that enable autonomous, continuous motions driven by an unchanging, constant stimulus have great potential for transforming intelligent machines, advanced robotics, and biomedical devices. Despite great efforts to gain self-oscillations that have been made through artificial systems using responsive soft materials of gels or liquid crystal polymers, these systems are plagued with problems that restrict their practical applicability: few available oscillation modes due to limited degrees of freedom, inability to control the evolution between different modes, and failure under loading. Here we present three phototunable self-oscillating systems, and each system possesses diverse oscillation modes, controllable evolution between diverse modes, and loading capability. These self-oscillating systems enable not only controllable generation of multi-modal self-oscillations but also production of diverse complex oscillatory motions. We envision that these systems with controllable self-oscillations, loading capability, and mechanical robustness will be useful in sophisticated autonomous devices and systems, autonomous energy extraction from solar irradiation, compact wireless scanners, and beyond.

Keywords: Phototunable Oscillation; Soft Actuators; Non-equilibrium Systems; Photodeformation

Polymerized Liquid Crystals as Aquatic Robots and Actuators

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Small-scale soft swimmers have provided scientists active in biomedical engineering and environmental science out-of-the-box solutions for targeted, non-invasive, and untethered procedures in their respective fields. Despite great advances in developing such swimmers, their efficient, untethered, and integrated powering, actuation, and control remain a challenge due to the out-of-equilibrium and dissipative nature of the driving physical and chemical phenomena. At the heart of the design of such swimmers typically lies a soft polymer, such as hydrogels or polymerized liquid crystals, that swims with undulatory shape-changes in response to external stimuli, such as light, heat, and magnetic field. Locomotion via these means depends on the constant exposure to stimulation, which makes this mechanism inefficient. However, self-propulsion is the main mechanism behind the locomotion, for instance, of many small aquatic insects. Indeed, nature had provided its tiny swimmers, with locomotion mechanisms where powering and steering are decoupled.

Inspired by this, we have designed small-scale, bioinspired aquatic locomotors with programmable deterministic deformation, and trajectories that integrate self-propelled chemical motors and photoresponsive shape-morphing structures. A Marangoni motor system is developed integrating structural protein networks that self-regulate the release of chemical fuel with photochemical liquid crystal network (LCN) actuators that change their shape and deform in and out of the surface of water. While the diffusion of fuel from the motor system regulates the propulsion, the dissipative photochemical deformation of LCNs provides locomotors with control over the directionality of motion at the air-water interface. This approach gives access to different but interchangeable modes of deformation and locomotion within a train of connected soft gears as well as single swimming robots via morphing of the soft structure. The proposed design, which mimics the mechanisms of surface gliding and posture change of semiaquatic insects such as water treaders, offers solutions for autonomous swimming soft robots via untethered and orthogonal power and control [1-3].

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Light-driven soft materials that move, change color and "survive"

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Photons have multiple enabling advantages to control chemical reactions, processes and stimuli-responsive materials. Here I will discuss our group's efforts to design and develop a new class of negative photochromic molecules termed donor-acceptor Stenhouse adducts (DASA), their incorporation into liquid crystal elastomers and subsequent effort to unlock their potential to create photoresponsive materials.

Interactive liquid crystal polymers for soft robotics and haptics

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We propose the utilization of a liquid crystal polymer network (LCN) for soft robotic fucntions, where diverse molecular components are arranged within a two-dimensional coating. Notably, the LCN surface exhibits dynamic deformations into predefined topographic patterns triggered by factors such as temperature, light, and electric fields (1). These microscopic alterations have a significant impact on macroscopic aspects like tribology, haptics, laminar fluid mixing in microchannels, and guided cell growth. Additionally, our LCN coating incorporates a robotic-relevant function, allowing controlled liquid secretion under UV irradiation or through an AC field (2). This controlled release capability opens avenues for applications such as lubrication, regulated adhesion, drug delivery, and agricultural, antifouling in marine and biomedical devices, as well as personal care and cosmetics. This comprehensive toolbox forms the basis for designing two-dimensional soft robots tailored for environments where human-machine interactions occur.

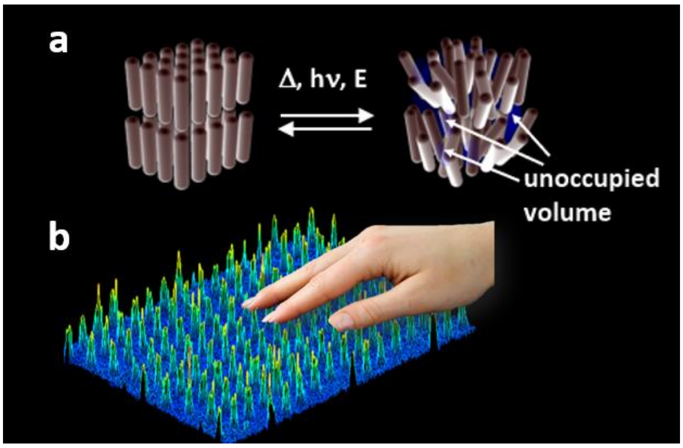

Figure 1: Liquid crystal polymer networks used for haptics. (a) principle of the anisotropic deformation of liquid crystal polymer. (b) surface structures generate touch feedback.

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Regulating Airflow Using Hybrid LCN for Soft Pneumatic Robots

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Being capable to produce complex and adaptive motions resulting from large and non-linear deformations, pneumatically-driven soft robotics continues to be one of the leading technologies in the soft robotics field. However, achieving autonomy in soft pneumatic systems remains challenging since the structures used mainly consist of passive materials [1], limiting the possibility to be responsive to environmental cues. To advance in responsive soft pneumatic robotics, developing and integrating active responsive elements is essential to impart responsiveness in the fluidic circuits. Herein, we present liquid crystal network (LCN)-based fluidic regulators that can be manipulated through multi-physical stimuli. We design thermo-responsive hybrid bilayer LCN films by introducing active (radially-aligned nematic) and passive (non-aligned isotropic) layers. By creating slits in the center and confining in a holder for further integration into fluidic circuits, we control their open-and-close behaviour with heat, which is also verified by computational simulations. Incorporating this newly developed LCN regulators within fluidic circuits, we successfully demonstrate their regulating behaviour by altering the fluidic resistance of the hybrid LCN, where the actuation of the regulator is triggered by controlled thermal stimuli under air flow [2].

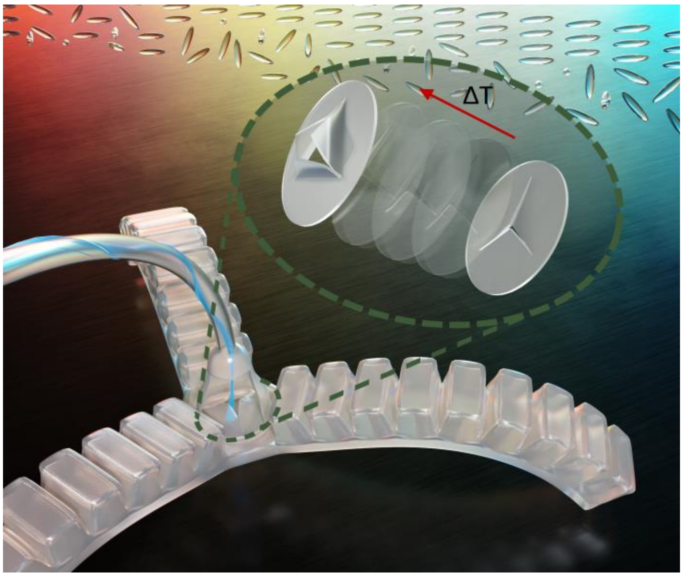

Figure 1. Representative drawing of hybrid LCN fluidic regulator within soft pneumatic robot. Actuation of the LCN is triggered by controlled thermal stimuli.

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Functional Blue Phase Liquid Crystals

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Blue-phase liquid crystals have attracted extensive attention owing to their unique three-dimensional self-assembled superstructure, multiple external stimulus responsiveness, real-time reconfigurability, and excellent optical properties. However, the functional characteristics of blue-phase liquid crystals are still not sufficiently understood, thus limiting their practical applications. We have achieved large-area, high-quality, free-standing multicolor single-domain blue-phase liquid crystal film with broad temperature window (-190~310 °C)[1] based on a suitable polymer stabilized system, the martensite transition of BPII to BPI was discerned via multiple approaches such as small angle X-ray scattering and transmission electron microscopy[1]. The excellent stability[2] of the polymerized stabilized blue phase was characterization. The multi-color fine blue-phase "live" patterns[3-5] were developed in combination with the inkjet printing technology; high-quality blue-phase lasing[6-8,] was realized with extended laser temperature range over 400 °C (-180~240 °C), the stretching lasing[9] behavior was demonstrated from Blue phase liquid crystal elastomer. These works have greatly contributed to the practical application of functional blue-phase liquid crystals in the fields of display, anti-counterfeiting, and laser.

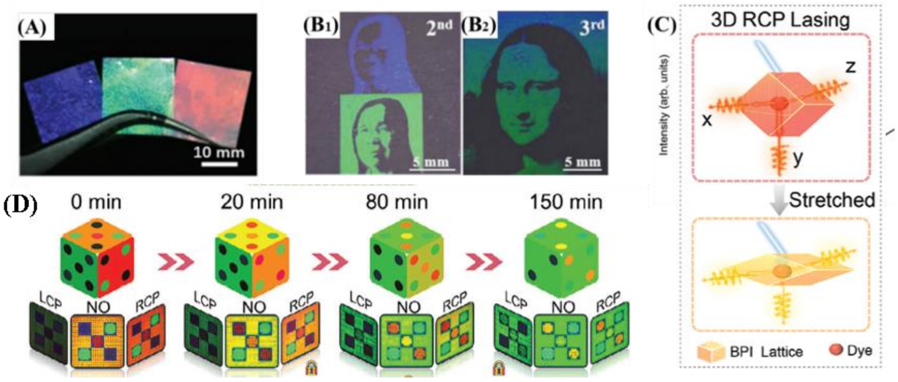

Figure 1. **The application of functional blue phase liquid crystals.** (A) The large area multi-color blue phase liquid crystal films prepared; (B,D) The high-resolution blue-phase liquid crystal patterns based on inkjet printing technology; (C) the scheme for 3-dimensional stretching lasing based on bluse phase liquid crystal elastomer.

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Hierarchical liquid crystal microstructures for multi-degree optical field manipulation

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Keywords: liquid crystal, helical superstructure, photoalignment, planar optics, optical edge detection

Vital fields such as supercomputing, constellation satellite & 5G/6G communications, virtual/augmented reality, and holographic displays desire super-large-capacity information processing. Photon informatics exhibits superiorities to electronic techniques due to its intrinsic multi-dimensional and large-scale parallel processing. Thus accurate, efficient, and orthogonal manipulation of the multi-dimensional parameters of light, especially the on-demand tailoring on working frequency and spatial phasefront, is highly pursued. Here, a dynamic polarization photo exposing system is adopted to record the polarization distribution to the spatial orientation of a photoalignment agent, and further guide the self-organization of cholesteric liquid crystals. Via preprograming the initial orientation of the helixes, spatial geometric phases can be arbitrarily encoded to the reflected light in a reconfigurable way. These planar optics exhibit unique properties such as spin dependency and broadband tolerance. Via electrically driving the nano helix of a photopatterned heliconical cholesterics, the reflective Bragg band can be precisely selected in the range from 380 nm to 1550 nm reversibly. Spin-decoupled transflective spatial light modulations are demonstrated in a piecewise-twisted anisotropic monolayer. Besides the wavelength selection and geometric phase modulation, spatial amplitude modulation and spin reversion can be further expected. It enriches the fundamental understanding of soft matter photonics and may upgrade optical informatics.

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Switchable Pressure-Sensitive Adhesion in Liquid Crystal Elastomers

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Nematic liquid crystal elastomers (LCEs) are known for their exceptional viscoelastic dissipation and energy damping properties,(1) which are believed to contribute to their unusually strong pressure-sensitive adhesion (PSA).(2,3) In this study, we explore the mechanism behind this enhanced PSA by fabricating thin adhesive tapes with LCEs of different chemical formulations, analyzing their material and surface properties, and evaluating their adhesion performance through standard tests, including peel, lap shear, and probe tack tests. Our results confirm that the LCE adhesive exhibits high adhesion strength and tackiness in the nematic phase, while showing low adhesion strength and tackiness in the isotropic phase. Furthermore, we demonstrate that by modifying the LCE polymer network architecture, it is possible to fine-tune the viscoelastic properties to meet the Dahlquist Criterion for ideal PSA, which requires a glass transition temperature around 0°C and a shear modulus of approximately 0.1 MPa at room temperature.

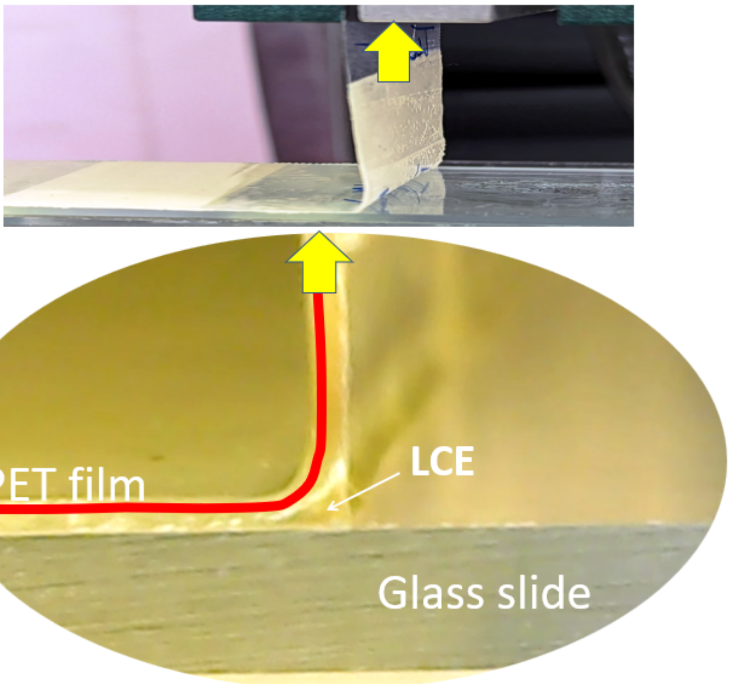

Figure 1. LCE adhesive tape under 90-degree peeling test

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Nematic LCE and composites for enhanced vibration damping

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The enhanced vibration damping in nematic LCE has been discovered a long time ago [1], with the most prominent mechanical loss at higher frequencies. One of the important features of vibration damping in soft materials is the comparison of mechanical impedance between the damping layer and the vibrating substrate: in order to pass as much mechanical energy into the dissipating LCE as possible, but if the substrate is metal or other solid – the impedance mismatch is too big and very little vibration energy would have a chance to dissipate. To address this, we work in the 'constrained layer geometry' when the dissipating soft material is fully enclosed within the metal structure, and the vibrations are forced into the polymer [1,2]. Here we investigate this effect at high frequencies, comparing the 'classical' thiol-acrylate main-chain nematic LCE with various traditional damping materials (of which, Sorbothane® is the most promising).

One of the ways to characterize the mechanical loss is to consider the natural resonance peaks in a vibrating construction (in our case: metal plate) and assess the Q-factor, which is the ratio of the resonance peak frequency to the peak width. High Q-factors mean very sharp resonance peaks, i.e. low dissipation (in another representation, the Q-factor is the inverse of the loss factor of dynamic-mechanical analysis: $\tan\delta=1/Q$). As an illustration, the Q-factor of bare metal plate vibration resonance is around Q=15, damping with Sorbothane® reduces this to 6-7, but the isotropic-genesis nematic LCE achieves Q-factors below 1 (i.e. the elastic material is in the overdamped regime: a unique feature in vibration analysis).

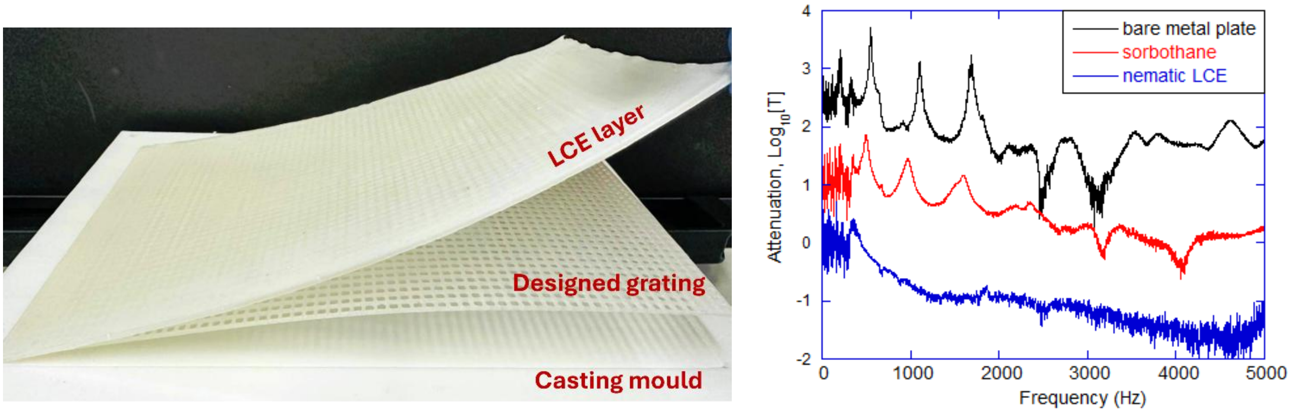

Figure 1. (a) An illustration of our LCE metamaterial assembly for acoustic damping: the mould, the printed grating for scattering compression waves, and the LCE layer incorporating it. (b) A comparison of vibration resonance damping in constrained layer geometry, indicating the unique 'overdamped' nature of LCE medium.

In order to further optimize the vibration damping efficiency, we not only seek new LCE systems with a higher dynamic-mechanical $\tan\delta$, but also construct 'metamaterials' – composites of LCE and designed rigid structures aiming to scatter elastic waves in the system and enhance the fraction of dissipative S-waves [3] even when the incoming deformation was predominantly a P-wave, as is the case with most acoustic signals.

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Harnessing Extreme Internal Damping in Polyrotaxane-Incorporated Liquid Crystal Elastomers for Pressure-Sensitive Adhesives

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Liquid crystal elastomers (LCEs) exhibit exceptional energy dissipation compared to amorphous elastomers due to their dynamic soft elasticity.[1, 2] In this study, we develop a new class of LCEs incorporating polyrotaxane (PRx-LCEs) as slidable crosslinkers.[3] Surprisingly, PRx-LCE displays much enhanced energy dissipation, surpassing even glass transition (T_g), as evidenced by the tan delta curve in viscoelastic measurements.[4] Such unprecedented high energy dissipation ability together with enhanced stress-relaxation observed in PRx-LCE leads to superior adhesion in both probe tack and peel tests, outperforming conventional LCEs and commercial adhesives. In addition, PRx-LCE demonstrates temperature responsive adhesion, facilitating residue-free removal at elevated temperatures. The synergy between LCE and slidable crosslinks enables the development of robust and switchable pressure-sensitive adhesives with versatile applications.

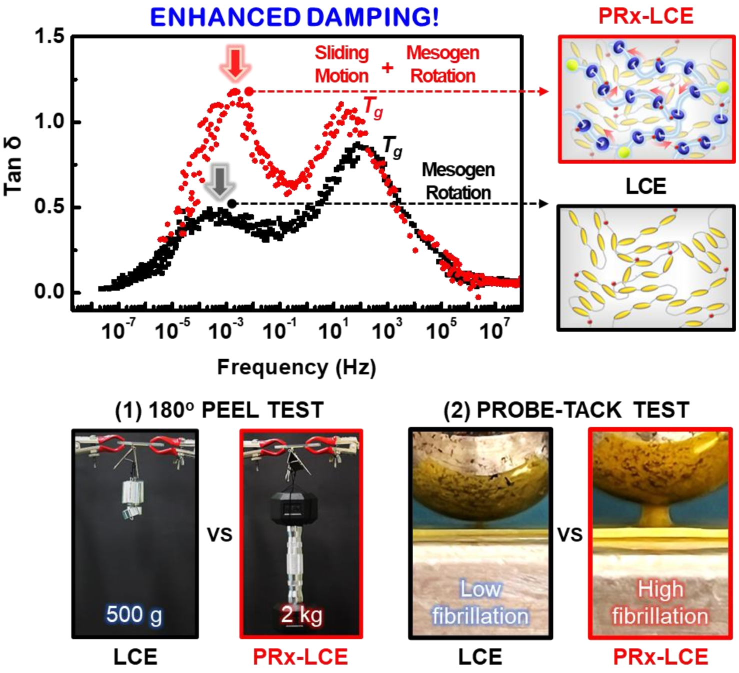

Figure 1. Master curves of loss factor versus shift frequency for pristine LCE and PRx-LCE, constructed from frequency sweep measurements at various temperatures (top). Comparison of adhesion strength between LCE and PRx-LCE adhesives (bottom).

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Stiffness Patterning of Light-Triggered Jumper for Efficient Snap-Through

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The jumping motion provides rapid maneuverability and energy-efficient hurdling over large obstacles. By topological conversion between bistable morphologies via snap-through, polymeric film consisting of azobenzene-functionalized liquid crystalline polymers (azo-LCP) can demonstrate photomechanical jumping through energy accumulation and instantaneous energy release [1]. For efficient jumping, large stress and strain responsivity of the film are beneficial. However, photomechanical jumping of polymers is governed by stress-strain correlation of viscoelastic polymers, which exhibit an inherent trade-off. To circumvent this trade-off and achieve highly efficient snap-through, we sought to spatially pattern mechanical stiffness of azo-LCP. By using stiffness mismatches, we broke the symmetry of the curvature during photomechanical deformation, shifting contact points during the millisecond-scale jumping process. As a result, directional jumps are achieved with an initial angular velocity of 5,000 rpm. Through the combined simultaneous effects of high rigidity and strain response, the patterned azo-LCPs were able to reach a jump height of 24.5 BL.

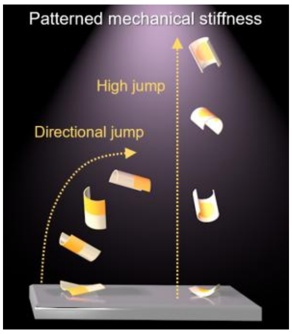

Figure 1. Illustration demonstrating photomechanical jumps of azo-LCPs by encoding two different mechanical stiffness.

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Control of magnetic properties by photoresponsive Liquid Crystalline Networks

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Magnetostrictive materialsare widely utilized in sensors, actuators, and energy storage devices, owing to their capability to interconvert mechanical stress and magnetic property variations. Their integration with Liquid Crystalline Networks (LCNs) presents a compelling research challenge. In this context, we demonstrated the feasibility of inducing mechanical stress in magnetostrictive devices—thereby modulating their magnetic properties—without direct physical contact. This was achieved through the incorporation of magnetostrictive FeGa thin films into photoresponsive LCNs. [1]

By embedding photo-switchable molecules such as azobenzenes within the polymeric matrix of LCNs, we enabled light-mediated control over the material's structural dynamics, facilitating remote and reversible shape modulation. Specifically, upon UV or visible light irradiation, the azobenzene-functionalized LCN undergoes deformation, exerting mechanical stress on the FeGa layer. This interaction results in optomechanical touchless regulation of the system's magnetic and electrical properties, which can be precisely tuned based on illumination duration and wavelength. The resulting fully reconfigurable magnetic platform offers significant potential for next-generation sensor technologies and smart material applications.

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Magnetically induced motion of LCP microparticles

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Liquid crystal polymers (LCPs), well known for shape morphing, hold great potential as remotely powered and controlled actuators for microdevices, with many applications envisioned, especially in the biomedical field. However, LCPs also possess another promising property - the anisotropic magnetic susceptibility that leads to a magnetic torque aligning LC molecules with external magnetic fields [1]. Since inertial forces are negligible in liquids at the small scale, the magnetic torque may prove sufficiently strong to define the orientation of LCP-based microdevices in space and even propel them, for example, by means of a rotating flagellum, similar to bacteria and sperm cells. Notably, no magnetic additive would need to be incorporated in the LCPs, meaning advanced micromachines could be built using a single material that provides both shape morphing and magnetic response.

While magnetic manipulation of LCP microobjects is possible in theory, it has been rarely demonstrated [2]. The aim of this work is to closely investigate this process and the extent to which it may be useful for applications at the small scale. We build a permanent magnet-based setup creating rotating magnetic fields and use it to study magnetically induced spinning of LCPs. We look at particles with different molecular alignments, shapes, and sizes suspended in water, one of the most biologically relevant liquids. To confirm the observed motion is caused by the magnetic anisotropy of LCPs, the magnetic properties of the materials are characterized in terms of magnetic susceptibilities and possible ferromagnetic contamination.

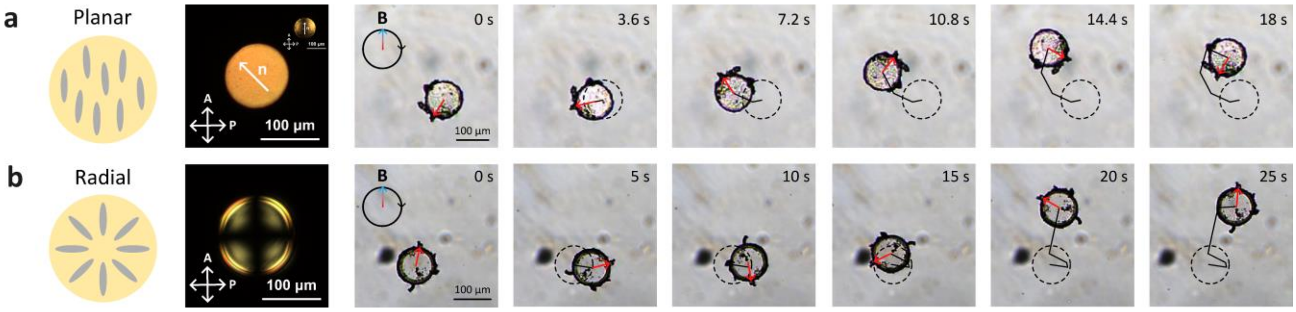

Figure 1. LCP microdisks with planar (a) and radial (b) alignments spinning in the presence of a rotating magnetic field (0.33 T).

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Emergent locomotion in dissipative, closely connected soft matter rings

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Abstract. In nature, interplay between individual organisms often lead to the emergence of complex and sophisticated biological functions. Synthetic materials research has focused on mimicking the natural complexity, *e.g.*, by harnessing non-equilibrium states to drive self-assembly processes. However, it is highly challenging to understand the interaction dynamics between non-equilibrium entities and to obtain collective behavior that can arise autonomously through interaction.[1] In this study, we use thermally fueled, twisted rings exhibiting self-sustained movements as fundamental units and investigate their interactive behaviors and emergent functions (Figure 1). The rings are fabricated from connected thermoresponsive liquid crystal elastomer (LCEs) strips that undergo zero-elastic-energy-mode, autonomous motions upon a heat gradient.[2] We study single-ring structures with various twisting numbers and nontrivial links, and connected knots where several LCE rings (N = 2,3,4,5) are linked. We show that The observations uncover that controlled locomotion of the structures can emerge when N $\geq$ 3. The locomotion can be programmed by controlling the handedness at the connection points between the individual rings. Our findings illustrate how group activity emerges from individual responsive material components through their mechanical coupling, offering a model for programming autonomous locomotion in soft matter constructs.

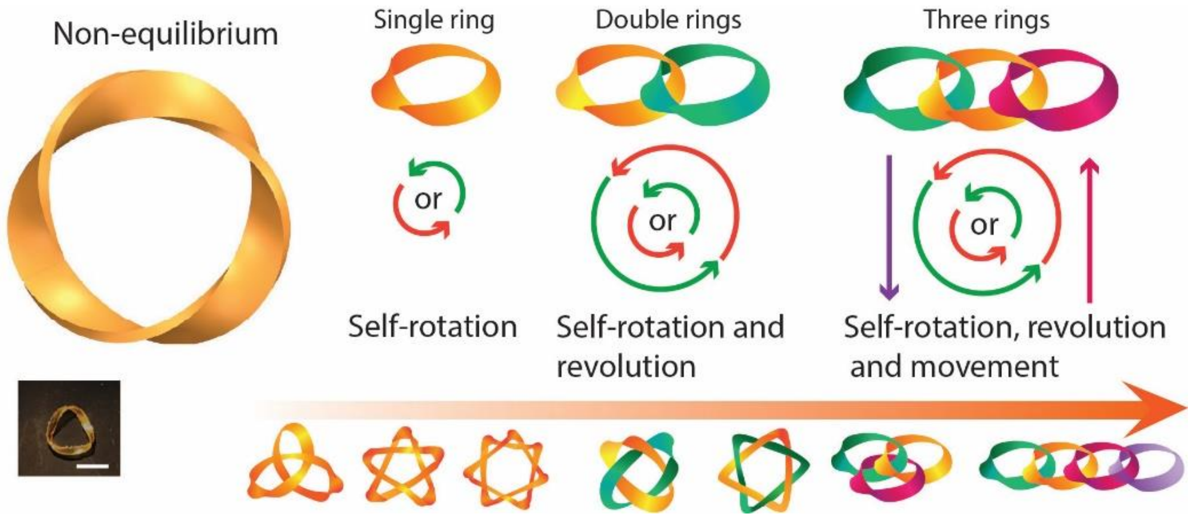

Figure 1. A schematic diagram illustrating the structures of a single ring, two connected rings, and three or more connected rings.

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Self-Resetting Soft Robot Enables Light-Powered Continuous Leaping

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Continuous leaping is ubiquitous in biological organisms, yet replicating this behavior in untethered soft robots remains challenging due to limited onboard energy storage and actuation strategies. We present a soft autonomous millimeter-scale robot capable of sustained jumping and leaping under constant photothermal actuation [1]. The robot consists of a ring-shaped liquid crystal elastomer (LCE) body that functions as both the energy harvester and storage unit, coupled with a passive stiff tail that strikes the ground to trigger propulsion. When exposed to continuous light, the system self-resets during its airborne phase and re-engages upon landing, enabling repetitive motion without the need for external control or recharging. By tuning the tail design and photothermal energy density, the robot transitions between crawling, directional leaping, and vertical jumping. Optimized configurations yield remarkable performance—vertical jumps exceeding 50 body heights and horizontal leaps over 5 body lengths, with a total body size of just 1.5 mm in height and 20 mm in length. Demonstrations in cluttered, uneven environments highlight the robot's ability to navigate debris and obstacles autonomously. This work introduces a new class of self-sustained, photothermally powered soft robots with potential for search-and-rescue missions and exploration in unstructured terrains.

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Electroactive Liquid Crystal Elastomers with Low Phase Transition Temperature

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Over the past decades, liquid crystal elastomers (LCEs) as stimuli-responsive smart soft materials have attracted more and more attention. Most LCE-based materials use heat or light as external stimulus, where the LC order and the anisotropy of liquid crystal polymer (LCP) chain conformation are changed by temperature variation or light illumination. However, electrical energy is the most convenient and the most in demand stimulus in real applications. Nowadays, research on electroactive LCEs (eLCEs) has become a compelling direction.

Recently, our group have elaborated ionic eLCEs by incorporating ion-conducting materials inside LCEs [1,2]. We have reported the first bifunctional ionic eLCE device (i-EAD-LCE), where an ion-conducting LCE is sandwiched by two electrically conducting polymer electrodes composed of formulated PEDOT:PSS [1]. The i-EAD-LCE can perform both bending deformation and linear contraction/elongation by controlling electrical stimulation of low voltages (±2 V at 0.1 Hz or ±6 V at 10 Hz). Further, to enhance the mechanical properties of eLCE, the central ion-conducting LCE of the device has been replaced by two interpenetrating polymer networks (IPN) composed of a LCE and an ionogel to prepare a new trilayer device i-EAD-IPN-LCE [2]. This i-EAD-IPN-LCE can function not only as electroactive bending and linear actuators by controlling electrical stimulation of low voltages (±5 V at 0.1 Hz or ±10 V at 10 Hz), but also as a mechanical bending sensor to output electrical signals. Nevertheless, in both i-EAD-LCE and i-EAD-IPN-LCE, the N-I phase transition temperatures (T_{NI}) are above 80 °C, which limits its practical application in many fields. The objective of this work is then to reduce the value of T_{NI}. We have achieved to prepare a new central ion-conducting IPN layer with interpenetrating ionogel and LCE with T_{NI} as low as 43 °C. LC monomers with two-benzyl-rings and three-benzyl-rings were mixed to adjust the π–π interaction between mesogen cores to reduce T_{NI} of LCE. The trilayer ionic electroactive device elaborated with this new IPN-LCE can function as bending or linear actuator by controlling electrical stimulation of very low voltages (±2 V at 0.1 Hz or ±3 V at 10 Hz). This system is promising for future real applications.

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Flexible Electroactive Ionic Liquid Crystal Elastomers Based on Thiol-Michael Chemistry

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In recent years, Liquid crystal elastomers (LCEs) have received attention in soft robotic applications and healthcare equipment due to their sensitivity to a variety of external stimuli such as heat, light, electric and magnetic fields, among which the electric field is a convenient means of actuation for portable devices. Ionic LCEs are a class of these electroactive materials that benefit from the movement of counter ions under an applied electric field as the actuation mechanism, i.e., expansion (contraction) at the side where large positive ions (small negative ions) have moved to [1]. In this work, we have synthesized flexible ionic LCEs by a two-step reaction mechanism including the click reaction of bifunctional mesogenic acrylates with bi- and tetra-functional thiols which forms a weakly crosslinked elastomer (thiol-Michael addition) and a subsequent stretching and UV polymerization of the excess acrylate groups to maintain the alignment. The ionic liquid used in this study (1-Butyl-1-methylpyrrolidinium dicyanamide) exhibits a dual role which includes not only the large electric susceptibility of the produced iLCE but also the catalysis of the thiol-Michael addition. This is due to the basic nature of ionic liquid which can replace the regular basic catalyst of the thiol-Michael addition mechanism (e.g., dipropyl amine). In addition to the thermal actuation which includes the significant amount of 28% strain at 100°C, the produced flexible iLCE strip with 20 wt.% ionic liquid and the initial dimensions of $18mm \times 2mm \times 120\mu m$ exhibits a $1.5\,mm$ end displacement equal to 0.12% strain, under an $f = 16.6\,\mathrm{mHz}$, $U = 2\,V$ square wave voltage. In another experiment with $U = 100V$, we demonstrated that the flexible iLCE film with 28 wt.% ionic liquid and the initial dimensions of $18mm \times 8mm \times 180\mu m$ is capable of producing a one-time end displacement of $7\,mm$, which is the highest value reported so far for the electric actuation of ionic LCEs. SEM studies of the cross-section of the LCE films reveal nano and micro-phase separation in the presence of the ionic liquid.

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All-Optical Microfluidic Technology Enabled by Photodeformable Linear Liquid Crystal Polymers

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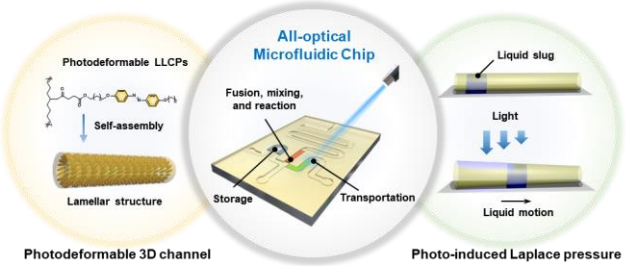
Microfluidic chip technologies advance from original devices that can conduct a single task to integrated systems capable of performing complex jobs. The core of the system is the microfluidic chips which are typically constructed with non-responsive materials such as silicon, glass, and rigid plastics, thus requiring complex external air/liquid pumps to manipulate the samples. The external equipment renders the microfluidic systems cumbersome and increases the risk of bio-samples contamination. The all-optical microfluidic chip (AOMC) integrates all necessary microfluidic units and uses light to manipulate microfluids, which is prospective to completely solve the major problems of miniaturization and integration in the microfluidic systems. However, impeded by photo-controlled principles and appropriate materials, AOMCs and photo-controlled biochemical/immunoassay analyzers have never been created.



In this work, we report the new conception of the all-optical microfluidic technology enabled by the photodeformable linear liquid crystal polymers (LLCPs), and the essential principle for the development of AOMCs. By innovating the chain structures and condensed structures, we developed a new kind of photodeformable liquid crystal polymer (LCP) materials without any chemical crosslinking, LLCPs, through ring-opening metathesis polymerization, which transformed traditional photodeformable LCPs with polyacrylate main chains and low-ordered nematic phase into LLCPs with polyolefin main chains and high-ordered smectic phase. Polyolefin LLCPs performed as the cutting-edge photodeformable materials that integrated excellent mechanical, processing, and deformation properties, comprehensively satisfying the applicable requirements of micro-actuators from one to three dimensions. Furthermore, we constructed AOMCs by replacing the conventional chip materials with newly designed polyolefin LLCPs and proposed a novel mechanism to drive microfluids by photoinduced Laplace pressure, thus creating a conceptually new microfluidic technology. Finally, we emphasized the first set of the true AOMC utilizing light as the only supplied energy to facilitate liquid manipulations including transport, mixing, fusion, and separation processes on a single microfluidic chip, which demonstrated its potential as an innovative platform for conducting biochemical/immunoassay detection at the micro-nano scale with low sample consumption, reduced reaction time, and enhanced portability.

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Mesomorphic Siloxanes without Mesogens

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Liquid crystal elastomers have substantial promise in a wide range of applications from biomedical devices to soft robots. In many of these applications, environmental stability is critical to future translation of liquid crystal elastomers. However, many current liquid crystal elastomers are susceptible to oxidative and/or hydrolytic degradation as both the mesogens and the polymer network have functional groups susceptible to degradation. Here, we synthesize mesomorphic silicone rubbers based on polydiethylsiloxane (PDES) without any mesogens. A series of PDES-based elastomers with a range of mechanical properties were prepared by controlling crosslink density. These amorphous PDES elastomers undergo phase transition to aligned mesomorphic state under tension[1]. The strain-induced mesophase of these elastomers allows the synthesized elastomers to have excellent toughness. The toughness of highly crosslinked PDES elastomers was eight times higher than neat control amorphous silicone elastomers and four times greater than Sylgard 184 with comparable Young's modulus. Additionally, uniaxially stretched mesomorphic PDES elastomers function as thermally responsive actuators. The elastomers undergo reversible shape changes in response to temperature with a blocking stress of up to 530 kPa and maximum strain of 17 % on heating from 0 to 40 °C. While these elastomers exhibit inherent hysteresis during heating and cooling cycles, we will discuss a strategy to control the hysteresis by partially melting the materials during heating. PDES elastomers have good hydrolytic and oxidative biostability during *in vitro* degradation studies, with no changes in mass and actuation performance. Toughness, low actuation temperature, and inherent biostability, suggest that soft actuators based on PDES could be attractive for diverse applications where the material must interact with uncontrolled environments.

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Poster session

P-1 **Biaxial Deformations in Monodomain Liquid Crystal Elastomers**
Stuart Berrow, University of Leeds, UK

P-2 **Reactive Fluid Ferroelectrics: Towards the Next Generation of Ferroelectric Liquid Crystal Networks**
Stuart Berrow, University of Leeds, UK

P-3 **Shape Programming of Liquid Crystal Elastomers by Two-Stage Wavelength-Selective Photopolymerization**
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P-4 **Liquid Crystal Elastomer Hollow Fibers as Artificial Muscles with Large and Rapid Actuation Enabled by Thermal-Pneumatic Enhanced Effect**
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P-57 **A Computational Model for Halogen Bond-Based Stimuli-Responsive Polymer Networks**
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P-58 **Leveraging Catechol Chemistry to Tackle Toughness-Softness-Work Capacity Tradeoff in Reprogrammable Liquid Crystal Actuators**
Enjian He, Tsinghua university, China

P-59 **Thermally Gated Covalent Adaptivity in Liquid Crystal Elastomers for Stable Actuation**
Yixuan Wang, Tsinghua University, China

Biaxial Deformations in Monodomain Liquid Crystal Elastomers

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Liquid crystal elastomers (LCEs) can, depending on the sample, display one of an array of mechanical responses when subject to a strain. The majority of LCEs reported in the literature tend to exhibit the so-called ‘semi-soft elastic’ response when mechanically strained, in which the mesogens reorient in the direction of applied strain[1]. This mechanism is often employed to obtain alignment during LCE synthesis[1]. Another deformation mechanism is the emergence of biaxiality upon the application of strain due to an increasing population of mesogens oriented in both transverse axes to the strain axis, a phenomenon previously known as the ‘Mechanical Fréedericksz Transition’ (MFT)[2]. This evolution of biaxial order has been observed to coincide with, and drive, auxetic behaviour in a family of LCEs[2,3]. Auxetic behaviour, more formally known as a negative Poisson’s ratio (i.e thickening in one or both transverse axes upon application of strain), is typically observed in porous structures, whose pores deform under strain[4]. In the case of auxetic LCEs, the auxetic response is attributed to an out-of-plane rotation of the nematic director under strain, i.e. the biaxial deformation.[2,3].

This talk will discuss work investigating the effect of changes to the chemical composition of the LCEs on the emergence of biaxial order, and thus the auxetic response the LCEs exhibit. Within these investigations, the emergence of smectic ordering, despite the polymerization being conducted in the nematic phase, has been observed[5]. When subject to mechanical strain, these smectic LCEs too show biaxial character, contrary to many of the deformation mechanisms reported previously for smectic LCEs[6,7], however did not show an auxetic response[5]. This talk will therefore also discuss these biaxial deformations in smectic LCEs.

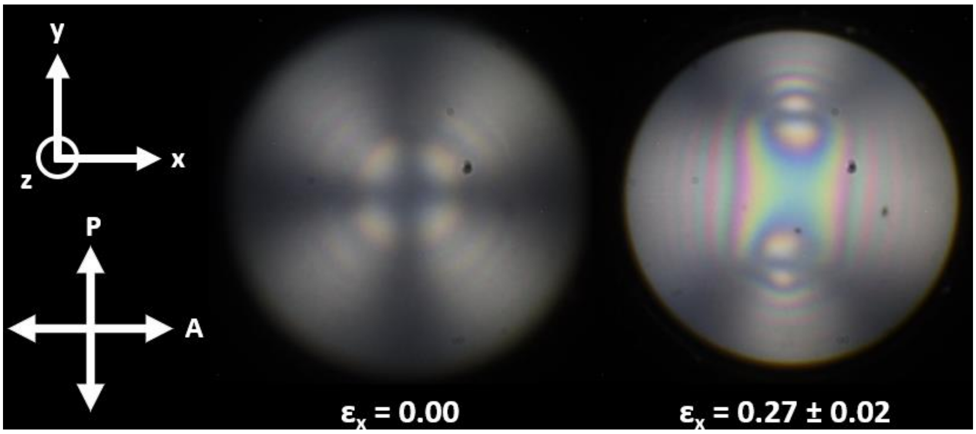

Figure 1 – The emergence of biaxiality in and LCE visualized by the splitting of the melatopes in the conoscopic figure upon the application of an applied strain, adapted from Berrow *et al*[5].

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Reactive Fluid Ferroelectrics: Towards The Next Generation of Ferroelectric Liquid Crystal Networks

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Reactive mesogens (RMs) are materials displaying liquid crystalline structural characteristics whilst also possessing reactive functional groups. First designed to overcome buckling instabilities in optical fibers[1], they have now become staples of several technologies and research areas, including liquid crystal displays[2] and liquid crystal elastomers (LCEs)[3]. Currently, the majority of RMs employed are polyfunctional (have multiple reactive groups), and are used to impart nematic ordering into network systems.

The ferroelectric nematic (N_F) phase is a relatively recent discovery, that has attracted significant research interest. Like in the nematic phase, molecules in the N_F phase have orientational order, however they differ from the nematic phase in that the molecular dipoles align in one direction, thereby eliminating inversion symmetry (**Figure 1**)[4]. N_F phase materials therefore have almost perfect parallel polar order, a property which gives promise for several applications.

Naturally, whilst the fluidity of low molar mass N_F phase materials yields potential, there is interest regarding macromolecular N_F materials, particularly networks, to further the scope for applications of N_F phase materials. Investigations into oligomers and polymers displaying an N_F phase have shown some success[5,6], however as yet a network structure displaying an inherent N_F phase has not been achieved, with the closest example being an isotropic network swollen with N_F droplets[7]. To that end, RMs that display the N_F phase would be desirable as they could facilitate polymerization within the N_F phase, thereby locking the polar order into the network. In this work, we discuss investigations into the synthesis of RMs displaying the N_F phase, analysis of their properties, and examine some potential use cases[8].

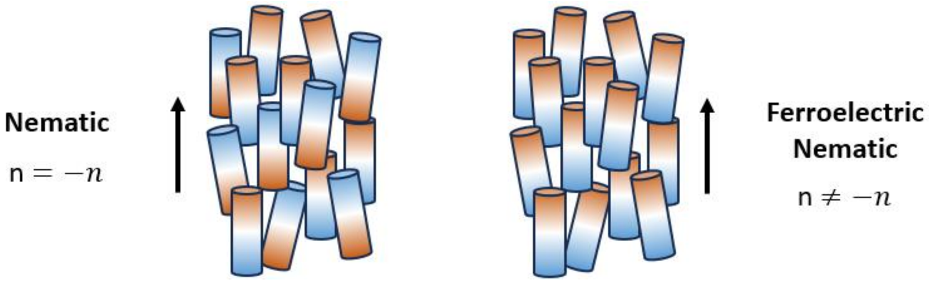

Figure 1 - Schematic representing the nematic and ferroelectric nematic phases, with dipole moments displayed by a colour gradient from white to orange.

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Shape Programming of Liquid Crystal Elastomers by Two-stage Wavelength-selective Photopolymerization

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A widely employed method to create liquid crystal elastomer (LCE) actuators is based on the use of two consecutive crosslinking steps. In a first crosslinking step, a loosely crosslinked, usually disordered elastomer is formed. This material is mechanically deformed to induce alignment and crosslinked a second time to permanently program the instilled director pattern [1]. The resulting actuators can switch between their programmed state and their initial state in response to temperature and have applications in soft robotic systems and human interactive technologies. However, the first crosslinking steps in these systems are often base catalyzed, which induces a time-dependency in its production and restricts the use of many coating methods. To increase the processibility and add spatio-temporal control to the first crosslinking step, we propose a two-stage wavelength selective photopolymerization (TWSP) method [2]. By adding a bifunctional crosslinker with an acrylate group and an oxetane group (Figure 1.a) to a liquid crystal oligomer mixture, we can first make a loosely crosslinked LCE by selectively polymerizing the acrylate groups using blue light. After this, the material can be deformed to instill alignment, which is then permanently programmed using UV-light to polymerize the oxetane groups, producing reversible actuators (Figure 1.b). This can be used to program complex deformations as shown in Figure 1.c.

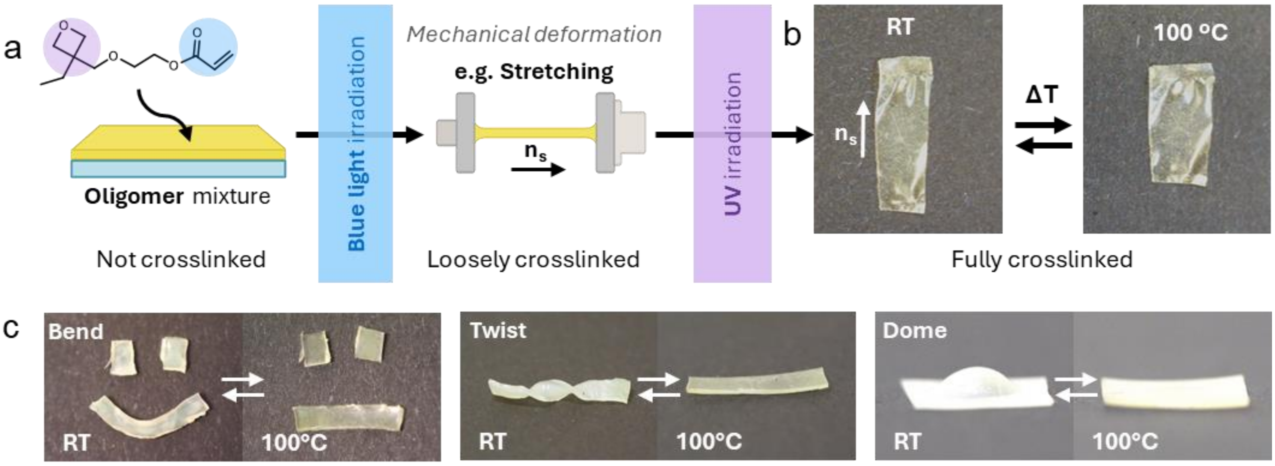

Figure 1.a, schematic of the TWSP procedure using an acrylate-oxetane crosslinker. b, an actuator that was programmed by stretching in between the two crosslinking steps, showing a contraction in response to an increase in temperature. c, actuators that were programmed by bending, twisting and stretching the loosely crosslinked LCE over a dome shaped mold. When heated these materials return to their initial flat state.

As a proof of concept, we demonstrate the enhanced control in the first crosslinking step by producing 4D printed actuators as well as actuators produced through selective polymerization with a photomask, which both undergo an additional shape programming step. We believe that the added control will enable the production of more complex initial states to produce new types of actuators and facilitate the upscaling of existing technologies.

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Liquid Crystal Elastomer Hollow Fibers as Artificial Muscles with Large and Rapid Actuation Enabled by Thermal-Pneumatic Enhanced Effect

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Liquid crystal elastomer has large and reversible deformation under stimulation, making it an ideal material for artificial muscles. We develop a novel solvent evaporation-assisted template method to prepare axially aligned liquid crystal elastomer hollow fibers (LCEHF). Taking advantage of the enhanced effect of heat-induced phase transition and mechanical force-induced orientation transition of mesogens, the LCEHF under both heat and pressure can produce a large contraction ratio of about 50%, which is higher than 42% of thermal stimulation or 27% of pneumatic stimulation. The dual response enhances actuation speed by 300- and 3700-fold. Moreover, the actuation temperature is significantly lowered, enhancing mechanical performance. The dual thermal-pneumatic LCEHF mimics human muscles, enabling rapid and reversible bending of artificial arms. This new methodology advances LCE actuation performance and broadens its applications.

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Harnessing the Orders of Liquid Crystal Molecules at the Microdroplet Interfaces for Bio-inspired Intelligent Materials

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The programmable responsiveness and functionality of liquid crystal (LC)-based materials, such as shape morphing and color change under external stimuli, have attracted broad interest in designing intelligent materials. Methods such as mechanical stretching and shearing, surface alignment, and field-assisted alignment have been developed to program the order of LC molecules for the desired responsiveness. However, the huge size mismatch between the nanometer-sized LC mesogens and the targeted macroscopic objects calls for questions about how to delicately control molecular order for desired performance. In nature, the responsive materials are built from molecules that assemble into microdomains, and the materials are constructed by using the microdomains as active components.

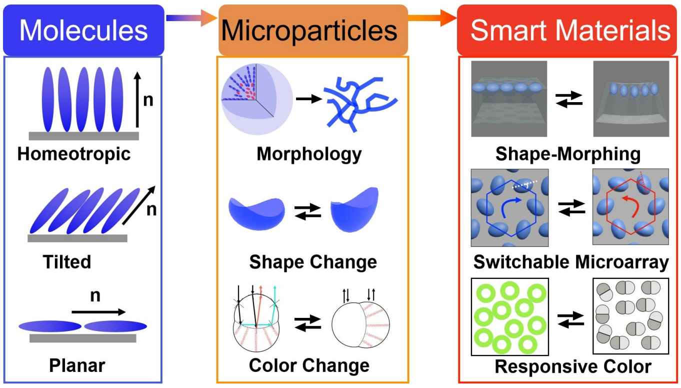

Figure 1. Summary of the talk.

Inspired by this hierarchical design strategy, LC microparticles are used to bridge the gap between molecular scale and macroscopic scale for the synthesis of intelligent materials based on LCs. The molecular order of LC molecules inside microdroplets is tuned by adjusting the surface anchoring effect governed by surfactants, which can be combined with chiral dopant addition to generate microdroplets with reflective structural colors. The alignment configuration can be fixed by polymerization for the synthesis of microparticles with reversible shape-morphing properties, and nanoparticles can be incorporated to introduce new functionalities. The shape-changing microparticles are exploited to program shape-morphing behaviors of inactive elastomer films via magnetic field-guided embedding and fabricate microarrays with switchable optical polarization via template-assisted embedding. Microparticles capable of color switching can be used for camouflage and information encryption. The molecule-microparticle-macroscale hierarchical design provides a strategy for designing LC-based intelligent materials, paving the way for various unforeseeable applications.

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Welding Complex-shaped Actuators from Dynamic Liquid Crystal Elastomers

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Liquid crystal elastomers (LCEs) are highly promising materials for developing soft actuators and small-scale robotic systems due to their exceptional stimuli responsive properties. In terms of soft LCE actuators, most effort has been dedicated to molecular alignment engineering or 4D printing to yield complex 3D deformations.[1,2] LCEs incorporating dynamic bonds, in turn, enable features like reconfigurable actuation and self-healing.[3] However, achieving programmable actuation and distinct control over shape transformations of different parts of the LCE construct remains challenging. To address this, we introduce a welding strategy for fabricating multicomponent LCEs with advanced shape-morphing capabilities, while preserving the distinct functional properties of each component. This approach is enabled by incorporating dynamic disulfide bonds into surface-aligned, chain-extended LCEs, which facilities robust adhesion between LCE segments without disrupting their molecular orientation during the welding process. The resulting construct, consisting of seamlessly integrated, differently oriented LCE segments, enables diverse shape-morphing behaviors, as shown in Figure 1. These capabilities are showcased through soft robotic applications, such as a rolling robot exhibiting positive and negative phototaxis based on its assembly configuration. This work establishes an effective platform for designing and programming LCE-based actuators, expanding their potential in advanced applications.

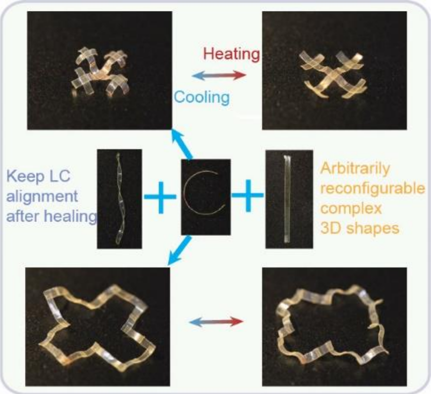

Fig. 1: The versatile shape changes of actuators assemblies by welding of splayed, twisted and planar-aligned LCE strips.

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Acknowledgments
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Dual Physically Crosslinked Azobenzene Liquid Crystal Elastomers Programmable for Multi-modal Information Encryption

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Dynamic interactions endow liquid crystal elastomers (LCEs) with network rearrangeability. Nevertheless, the need for high stability networks used to fix the orientation of liquid crystal (LC) remains an inherent problem [1-3]. To address this, we developed azobenzene liquid crystal elastomers (Azo-LCEs) with dual physical crosslinking via 2-ureido-4-pyrimidone (UPy) hydrogen bonds and glassy polystyrene (PS). Our UPy dissociation occurs below $T_{\text{LC-iso}}$, prompting the proposal of a novel mechanism for locking in LC orientation. The reversible UPy network exhibit continuous dynamic equilibrium under mild condition, enabling locking in LC actuation domains, where Azo mesogens align perpendicular to the stretching direction. By systematically investigating the dynamic mechanisms of UPy and structure-property relationships, the thermomechanical, photochromic and photomechanical behaviors are optimized. These Azo-LCEs exhibit thermo-induced anomalous reversible deformation, erasable photolithography imaging and photo-programmable deformations.

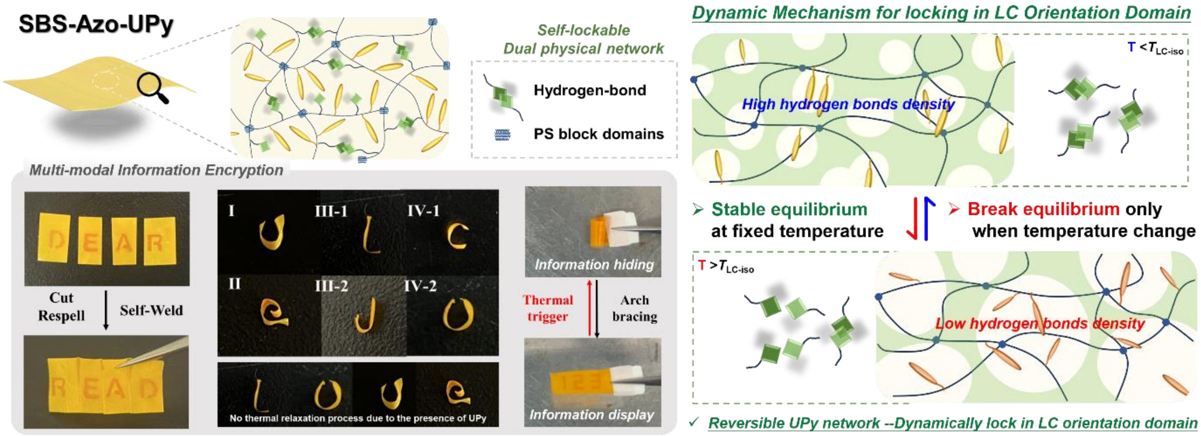

Figure 1. Schematic representation of LCEs programmable for multi-modal information encryption with self-lockable physical network and the novel dynamic self-locking mechanism

To showcase multifunctionality, we designed an information system using patterned Morse code masks, enabling encryption and decryption through thermo-induced anomalous actuation. Combining heating with photo-programing parameters, the pre-stored deformation can be decrypted into different meanings for multidimensional information encryption. A movable-type information encryption system is achieved by cooperating water-assisted UPy self-healing and Azo erasable photolithography imaging. Exploiting the synergistic interplay of photochromic and photomechanical properties, we developed a snap-ring wristband-like device capable of dynamically displaying and concealing information. Producing the effect of 1+1>2, this work highlights the synergistic potential of multifunctional materials and innovative processing strategies, offering multiple information encryption modes and advancing the design of intelligent materials.

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Plant Tendril Inspired Liquid Crystal Elastomer Fiber Actuators

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Inspired by recent studies of tendril anatomy and the mechanism of translating morphological asymmetry into macroscopic motion, we have 4D-printed a biomimetic LCE artificial tendril, which is not only capable of mimicking the nastic motions of natural tendrils but also able to perform evolutionary (evolving from an artificial tendril to an artificial flagellum) biomimetic locomotion similar as the behaviors of natural flagellum (Figure 1a). To further study the influences of actuator structures and molecular alignments on the shape-morphing behaviors of the LCE fiber actuators, the printing parameters (including filament number, width, thickness, and core-sheath morphology) are adjusted to achieved various deformations, such as contraction, bending, and helical twisting (Figure 1b). The underlying mechanism of helical deformations of the LCE fiber actuators is revealed by using theoretical models and finite element simulations.

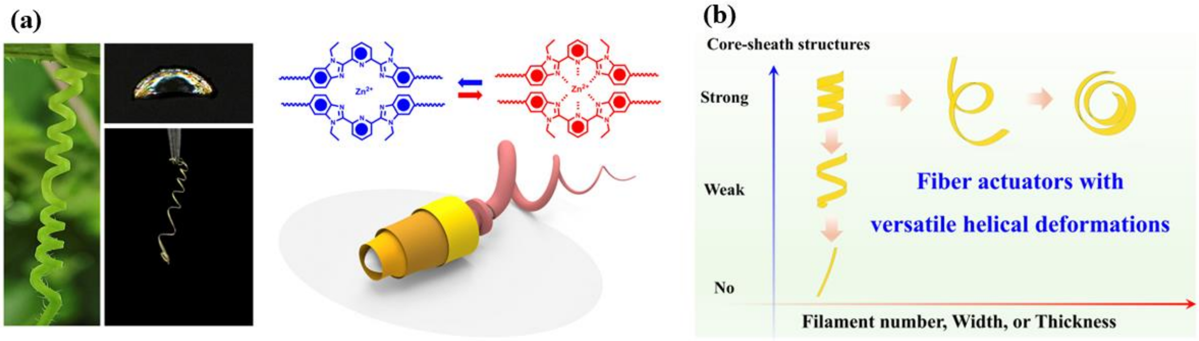

Figure 1. (a) Digital images and schematic illustration of the LCE artificial tendril and artificial flagellum. (b) Various helical deformations of the LCE fiber actuators achieved via changing their 3D structures and asymmetric core-sheath configurations.

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Multi-Functional Liquid Crystal Polymers via Combining Ring-Opening Metathesis Polymerization and Post-Polymerization Modification

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Advanced liquid crystal polymers (LCPs) with diversified functionalities have aroused many interests due to their ability to achieve multiple responses and complex shape changes [1,2]. To date, the commonly used method to synthesize a multifunctional LCP is copolymerizing mesogenic monomers with demand functional groups. However, this direct polymerization method suffers from limited group tolerance because many functional groups may lead to side reactions or hinder the polymerization, which inevitably limits the attained functional type of LCPs.

Post-polymerization modification (PPM) offers a competitive candidate [3,4] for engineering multifunctional polymers, but its advantage has not been fully exploited to fabricate multifunctional LCPs. Here, we design a facile synthetic approach [5,6] towards multifunctional LCP by combining the ring-opening metathesis polymerization (ROMP) with PPM, in which ROMP helps to prepare a reactive LCP precursor with high molecular weight, and PPM provides a facilitation to introduce functional groups into the precursor. Accordingly, a photo- and humidity-responsive linear LCP is demonstrated to show the potential of this synthetic strategy to diversify functions of the LCPs. Under light irradiation and humidity changes, the deformation modes of the LCP films are converted to complex shapes (bending, twisting, and curling). Subsequently, we advance this approach to design an LCP capable of thermally-induced deformation and fluorescence switching [7]. Upon heating, the obtained LCP films and fibers undergo contraction, bending, unfolding and rolling, with the fluorescence weakening simultaneously.

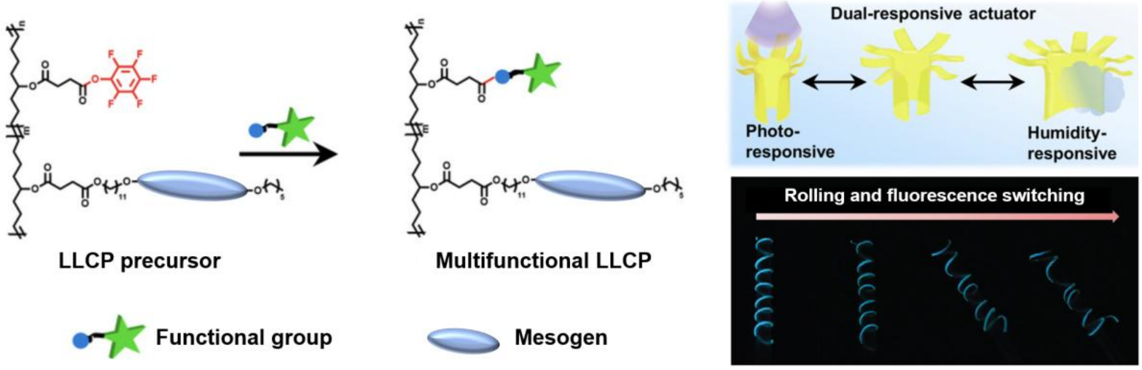

Figure 1. The mechanism of the novel strategy for synthesizing multifunctional LCPs, and the demonstration of the obtained actuators.

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PEDOT impregnated liquid crystal elastomers for multimodal sensing

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Soft flexible electronics are currently of great interest due to their ability to interface with biological tissues. Elastomers, with their flexible nature, serve as an ideal foundation, while the integration of liquid crystals imparts the ability to undergo dynamic shape changes. Liquid crystal elastomers (LCEs) are particularly promising as they can react to a plethora of stimuli with reversible deformations. These stimuli include heat, light, humidity and electrical current [1]. However currently electrical responsiveness of LCEs have limitations depending on the manufacturing methods. Common limitations are small deformations when relying on ionic migration [1], high required voltage if actuating by Maxwell stress [2], long response times [3] or non-reversible deformations due to incorporation of rigid elements.

To combat these issues, we plan to impregnate PEDOT:PSS into a porous LCE matrix. The electronic conductivity of PEDOT:PSS allows for fast response times while retaining its properties over cycling and exhibiting a considerable physical deformation as a response to electrical current due via Joule heating. In addition, a photothermal dye will be doped into the LCE matrix to give light sensing properties as well. This will allow for multimodal sensing of electrical current, light and temperature.

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Temperature Controlled Adhesion in Monodomain Liquid Crystal Elastomers

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Elastomeric pressure-sensitive adhesives (PSAs) are common class of materials that form an adhesive bond under light pressure. Recently, liquid crystal elastomers (LCEs) have been asserted to impart anisotropy onto the adhesion of PSAs, even at the same temperature [1,2]. In fact, in 2013, Corbett and Adams predicted theoretically that there should be a difference between the adhesion of planar and perpendicularly aligned nematic LCEs [3]. In this work, chemically identical side-chain elastomers are produced as isotropic or nematic films [4]. We present the adhesive properties of these differently formed, chemically identical LCEs through a 90° peel test [5].

Measurement of the contact angle of freestanding water is identical for all samples and remains constant under linear strains, confirming that the adhesive properties are dictated by the bulk alignment of the LCE rather than the surface effects.

A temperature-dependent adhesion factor, $\mathcal{A} = \tan\delta/G'(\omega)$, can also be evaluated using dynamic mechanical methods. This was determined at $\omega = 1\ Hz$ for each of our LCE alignment systems at temperatures from 0°C to 80°C. [4] The adhesion factor determined in this way is shown to be in excellent agreement with the peel data at room temperature.

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Electrically Responsive Knitted Structural Liquid Crystal Elastomers for Underwater Drives

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Soft actuator materials are well-suited for underwater applications due to their inherent flexibility, which enables them to resist pressure and operate quietly. Among all, liquid crystal elastomers (LCEs) exhibit significant reversible deformation in response to specific stimuli, making them promising for various underwater applications. To address the rapid heat dissipation of water, current underwater LCE actuators typically utilize a heatless photochemical effect to prevent heating or a high-power photothermal effect to counteract water cooling. However, the use of light is limited in situations where obstacles such as muddy water affect light propagation. In this study, we propose a method for developing a fabric-structured underwater LCE actuator based on LCE-liquid metal (LM) coaxial fiber combined with knitting technology. In this design, the LCE-LM coaxial fiber, as the building block, provides stable and large-scale underwater deformability, while the knitted structure enables diverse deformation modes and structural adjustability. Under electrical trigger, the actuator can deform underwater reversibly in controlled extent and frequency to perform designed functions, such as grabbing and crawling. This strategy presents new ideas for the design of LCE underwater actuators and holds significant potential for applications in underwater exploration, marine resource development, and other related fields.

Multidimensional, Multilevel Information Storage and Encryption Based on Intrinsic Auxetic Liquid Crystal Elastomers

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With the booming development of information technologies, tremendous attention has been paid to information storage and security applications based on soft materials [1–4]. In 2018, a unique LCE–intrinsic auxetic LCE (IALCE) was discovered [5]. Its optical and morphology features that occur during the auxetic response [6] offers great potential for information applications.

In this talk, we report a novel and simple strategy to achieve multidimensional, multilevel information storage and encryption (M^2ISE) with IALCEs. Through polymerization under various electric fields, the Fréedericksz transition alignment is induced to manipulate the director in the plane of the elastomer film. A small voltage (<2.00 V_{rms}) can tune the threshold strain of the auxetic response within the range of ~0.58 ± 0.05 to ~0.91 ± 0.05. Based on the distinct optical and morphological properties of these tuned auxetic responses, we have realized M^2ISE for not only 2D optical information but also 3D tactile information with IALCEs. This study paves a new way for the development of encryption soft materials with high security and versatility for extensive applications.

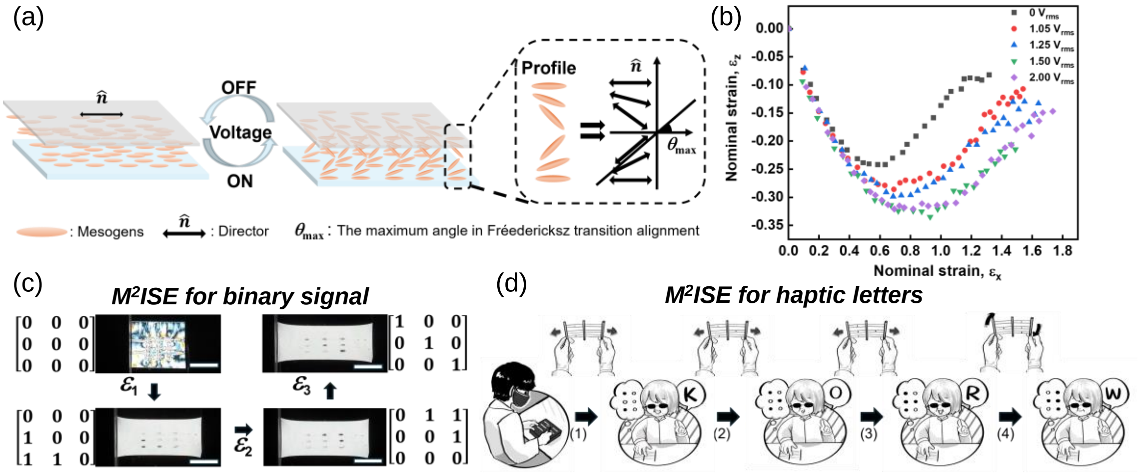

Figure 1. (a) The schematic of the Fréedericksz transition alignment. (b) The nominal strain ε_z-ε_x of IALCEs polymerized under different voltages. (c) The decryption process of multilevel 2D optical information (binary signal) under crossed polarizers. (d) The concept schematic of using a set of 3D tactile M^2ISE IALCEs to show the multilevel 3D tactile information (haptic letters).

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Photo-responsive biomimetic functions by light-driven molecular motors in 3D printed liquid crystal elastomers

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Photoreactive molecular machines are single-molecule devices capable of converting light energy into mechanical energy [1]. However, converting and amplifying molecular motion from the nanoscale across multiple length scales to induce motion in three-dimensional macroscopic objects remains a significant challenge. The key to addressing this challenge lies in the effective organization of molecular machines within a well-defined environment. In this paper, we demonstrate the photoresponsive biomimetic functions of liquid crystal elastomers (LCEs) by embedding light-driven molecular motors into their main chains to serve as photoactuators [2]. Utilizing 3D printing technology, we fabricate LCEs with complex structures that can undergo controlled shape changes. Under UV light stimulation, the unidirectional rotation of molecular motors induces deformation of the LCEs, enabling diverse motions such as bending, helical coiling, petal closure, and butterfly wing flipping. This work provides a new avenue for designing intelligent materials with advanced biomimetic functions.

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Photoinduced Deformation of Polyurethane Fibers with Bridged Azobenzene Crosslinked by Hydrogen Bonds

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Polymer materials that can convert external stimuli such as light, electricity and heat into macroscopic deformation are attracting attention as soft actuators. Among them, crosslinked liquid-crystalline polymer (CLCP) films containing azobenzene moieties that exhibit macroscopic deformation under irradiation with light have attracted much attention because of their remote controllability and ability to be made miniature [1].

However, these CLCPs are difficult to be remolded due to their crosslinks formed by covalent bonds. If the processability of CLCPs can be improved and they can be made into fibers, it is possible to use CLCPs as artificial muscles. Currently, the mainstream artificial muscles are those that use air pressure as a driving source using rubber tubes. Therefore, by replacing rubber tubes with thinner fibers, we can expect movement that is more similar to that of a living body. To develop highly processable materials, one of the effective ways is to use polymers with hydrogen bonds to crosslinks, such as polyurethanes [2].

If fibers are to be used as artificial muscles, it is also possible to take advantage of the property of nylon, which stretches when heated and returns to its original shape when cooled [3]. In that case, there is a problem that it cannot be used under cryogenic conditions because it requires heating. Therefore, the purpose of this research is to create fibers that can be deformed by light over a wide temperature range, including cryogenic conditions. So far, we have shown that films with a bridged azobenzene exhibit high photoresponsiveness under cryogenic conditions [4].

In this study, we synthesized polyurethanes incorporating a bridged azobenzene. We fabricated polyurethane fibers by taking advantage of moldability and evaluated their photodeformation behavior under cryogenic conditions.

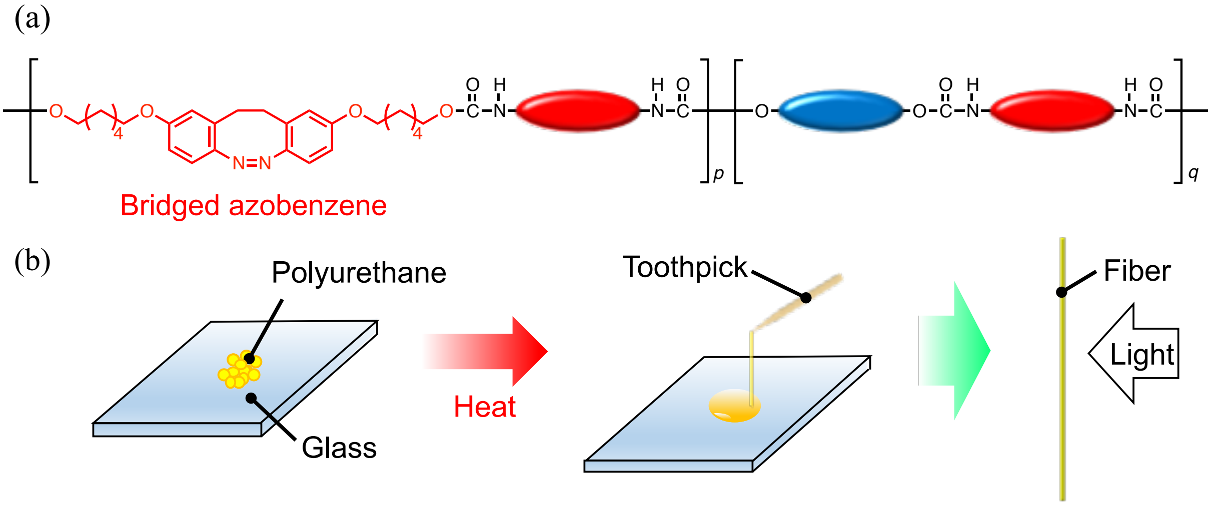

Figure 1. (a) One of the chemical structures of polyurethanes with bridged azobenzene, (b) Preparation of fibers.

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Sunlight-Driven Smart Windows Combining Polymer Network Liquid Crystals and Chiral Azobenzene

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Smart windows can change their transmittance in response to external stimuli such as light and electricity. These devices adjust the sunlight that enters a room and maintain a comfortable indoor environment. So that they attract much attention for energy saving devices, which lead to reduction of energy consumption in air conditioning. Many approaches have been developed for the control of light transmission such as hydrogels, metal oxides, and liquid crystals (LCs). Here, we focused on LCs materials.

LCs have been studied as optical materials due to the controllability of molecular alignment through external stimuli such as heat, electricity and light. Whereas uniaxially aligned LCs are transparent, chiral nematic LCs show light scattering states. Push-pull azobenzenes with chirality were developed as photochromic chiral dopants to allow changes in mesostructures of LCs in response to sunlight. Photochromic and photoinert chiral compounds can realize optical switching by doping in LCs.

We focused on push-pull chiral azobenzene as a material which shows transparent-scattering transition upon solar irradiation, and we fabricated the sunlight-driven smart window (Figure 1) [1]. This smart window aimed for reducing the amount of sunlight that enters the indoors on sunny days, however it showed light-scattering state even cloudy days with low sunlight intensity.

Herein, uniaxially oriented polymer network liquid crystals (PNLCs) can stabilize the orientation of LCs in the transparent state. In this study, we aimed to create a sunlight-driven smart window that changes to a scattering state only clear skies by combining PNLCs with push-pull chiral azobenzene (Figure 2).

The sample with PNLCs showed transparent-light scattering transition upon irradiation with sunlight and kept a transparent state on cloudy days in low sunlight intensity.

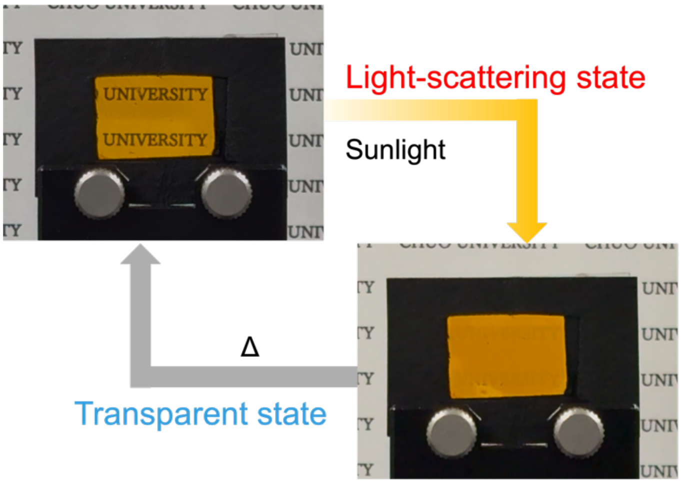

Figure 1. Sunlight-driven smart window with push-pull chiral azobenzene.

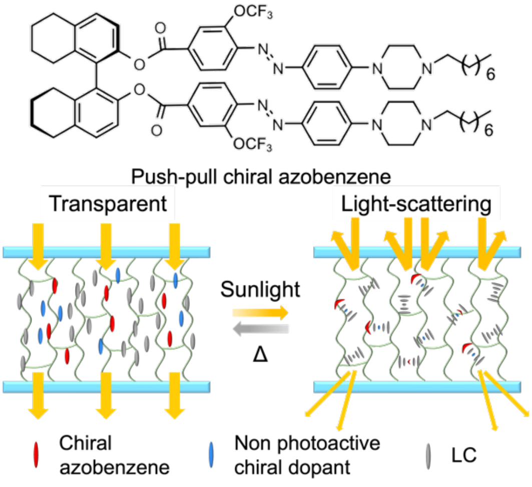

Figure 2. Working mechanism of the sunlight-driven smart window with PNLCs.

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An Effective Strategy to Improve the Scalability of Liquid Crystal Elastomers

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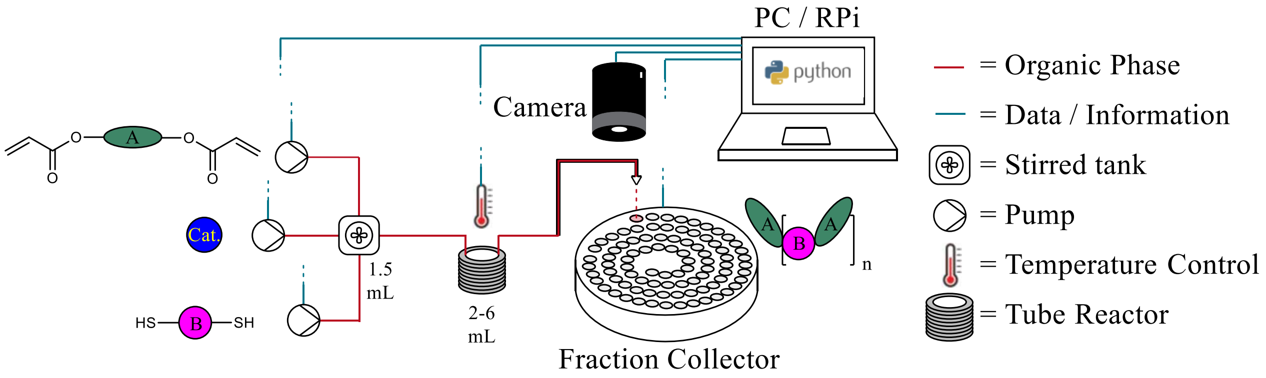
Liquid crystal elastomers (LCEs) are stimuli-responsive polymers with promising applications in soft robotics [1,2]. Advances in processing techniques like direct ink writing (DIW) have enhanced printing ink functionalities, enabling graded structures and customizable actuation [3]. Modifications have further improved response speed, stroke, and sustainability [4,5]. However, despite these innovations, scalable industrial production remains a challenge [6].

Flow chemistry as a powerful platform provides benefits including efficient heat and mass transfer, effective mixing, accelerated kinetics and precise control over reaction parameters [7]. These advantages could be leveraged to consistently produce printing inks [8]. Additionally, flow chemistry allows high-resolution micro-dosing, offering a miniaturised and automated strategy for product design and optimisation [9]. A simple flow system with feeding pumps, mixing tank, reaction and collection sessions is shown in scheme 1. By varying the reaction conditions, for instance the pumping ratio of reagents, the structure, molecular weight and its distributions of the LC oligomers can be tailored and ultimately influence the thermomechanical properties of the final LCE product. With on-line or off-line analytical equipment integrated, a structure-property library can be built efficiently. Overall, flow chemistry presents opportunities for more efficient and scalable production of LCEs.



Scheme 1. An automated flow system setup.

Here, we demonstrate the first continuous flow system to our knowledge for base-catalysed thiol-acrylate Michael addition main-chain LCE precursors. We will discuss the effect of mixing level, flow rate, reactor length and temperatures on the molecular weight and transition temperatures of LCE main chains.

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4D Printed Adaptive Soft Actuators Enabled by Gradient Deformation of Liquid Crystal Elastomers

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Soft actuators achieve lifelike mechanical intelligence by mimicking the asymmetric contraction of muscles and play an irreplaceable role in specific applications such as wearable devices and exploration in extreme environments [1,2]. Liquid crystal elastomers (LCE) combine the entropic elasticity of polymer networks with the anisotropy of mesogens, capable of reversible deformation under external stimuli such as heat and light [3-5]. By controlling the orientation of mesogens, gradient deformation of LCE can be achieved, thereby imitating the asymmetric contraction of muscles to construct soft actuators [6,7]. In the fabrication methods of LCE, 4D printing enables simultaneous programming of mesogen orientation and structural design via shear force application [8]. However, due to the symmetric shear action within the nozzle during printing, achieving gradient orientation poses a challenge. In this report, we introduced the non-uniform exterior nozzle tip shearing to induce the mesogens forming gradient orientation in the thickness direction, achieving large curvature bending deformation. Further imitating the alternating arrangement of caterpillar's muscle and exoskeleton, we constructed segmental soft crawling robots through multi-material 4D printing and realized adaptive locomotion via light-controlled curvature changes of specific segments, including bidirectional crawling, curling into a loop and rolling downhill, as well as correcting their postures through self-righting behavior when losing balance. This work provides a new insight into smart soft actuators.

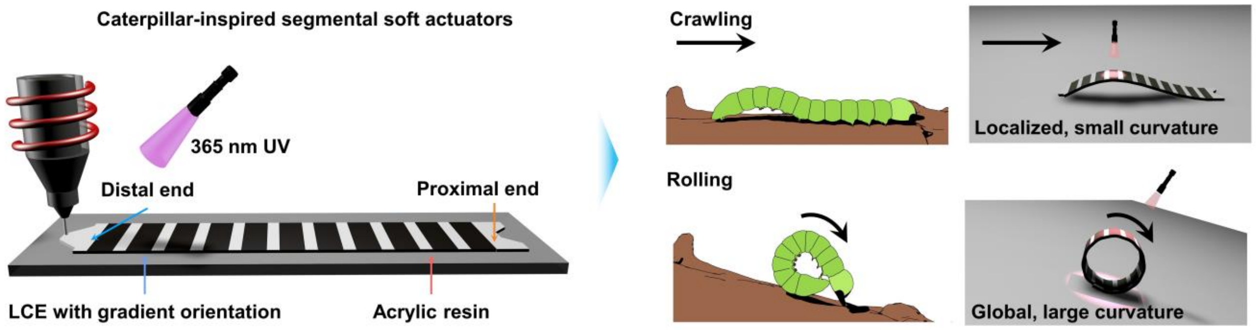

Figure 1. Schematic diagrams of the 4D printing strategy in the preparation of segmental liquid crystal elastomers actuators and caterpillar-inspired locomotion mode switching.

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Synthesizing asymmetric monodisperse mesogenic oligomers towards ordered and tunable liquid crystalline networks

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The thermo-induced actuation and soft elastic behavior of liquid crystal (LC) elastomers have led to their use in emerging applications from thermomechanical actuator to elastocaloric devices. However, their properties, such as the sharpness of the transition, are dictated by their network topology [1,2], including features such as dispersity in interjunction distance and loops. For conventional main chain LCEs, these defects are inherent to currently available synthetic methods: step-growth polymerization results in a relatively broad molecular weight distribution, while the symmetric end groups for the precursor LC oligomer result in the formation of first-degree loops. To prepare a more ordered LC network, we developed a new synthetic strategy based on iterative exponential growth (IEG) synthesis to yield monodisperse oligomers. We subsequently characterized the phase behavior of these oligomers, which crystallize into hierarchical assemblies with both Gaussian and cylindrical curvature. Copolymerization of these oligomers has been demonstrated to stabilize the liquid crystalline phases. Furthermore, as a result of the IEG strategy, these oligomers are inherently asymmetric and possess orthogonally deprotectable end groups. By deprotecting one terminus, one side of the oligomers can be selectively coupled to a tetrafunctional core. We characterize the degree of substitution of the functionalized junctions and optimize the coupling reaction to approach that of a tetrafunctional macromonomer. Through preparing two complementary tetrafunctional macromonomers with end groups amenable to click chemistry, we develop a path towards LC networks with controlled interjunction distance and a reduced number of first-degree loops.

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Development of a dynamic alveolar cell culture platform using light-controllable liquid crystal elastomer materials

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Pulmonary fibrosis is a chronic, progressive lung disease associated with a poor prognosis, and an average life expectancy between three and five years following diagnosis. The prevalence of pulmonary fibrosis increases with age and can reach up to 20 cases per 100,000 people in Europe; however, the etiology and mechanistic events leading to the condition often remain unclear [1].

Currently, pulmonary research faces a lack of effective, human-relevant *in vitro* models to investigate the pathophysiological mechanisms of pulmonary fibrosis and to test potential therapeutic interventions. In vivo, the functional units of the lungs are alveoli, which are responsible for gas exchange and composed of alveolar epithelial cells, immune cells, fibroblasts, and capillary endothelial cells. The epithelial surface functions as an important barrier towards airborne pathogens and pollutants, since it is exposed to the air we breathe. In addition to this unique cellular environment, the alveolar cells are subjected to constant cyclical stretching and shrinking due to respiration. Therefore, replicating both an air–liquid interface and the mechanical cues of breathing is crucial for creating a physiologically relevant alveolar model. However, many existing models either omit mechanical stimulation completely or rely on complex devices that can limit scalability.

The PHOTOBREATHE project aims to address the current alveolar *in vitro* model challenges by integrating light-responsive liquid crystal elastomers (LCE) into air-liquid-interface human cell culture platforms. Specifically, azobenzene-based LCEs are harnessed to convert light into frequency-adjustable stretching movement without invasive contact or complex machinery. The project's central objective is to develop a biocompatible soft-material growth platform that mimics respiratory movements under various physiological and pathological stages, while maintaining long-term stability for co-cultured human alveolar cells. By bridging the gap between static *in vitro* systems and the dynamic in vivo environment, this work aims to facilitate safer, faster chemical testing, toxicology assessments, and more informed regulatory decision-making. Moreover, a key focus is to apply the 3R principles (Replacement, Reduction, and Refinement) in the development process, ensuring ethical and sustainable research practices.

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Investigating Motion of Coupled Structures with Liquid Crystal Elastomers

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The aerodynamic behavior of freely falling structures is significantly influenced by their geometric asymmetry [1]. In our wind tunnel experiments, we investigated the rotational and orbital motion of paper snowflakes by introducing controlled asymmetry through the connection of two individual pieces. Our results indicate that the transition from symmetry to asymmetry plays a crucial role in the observed aerodynamic response.

To further explore dynamic control over aerodynamic performance, we propose integrating liquid crystal elastomers (LCEs) as adaptive connectors between paper snowflakes. LCEs exhibit shape transformation under external stimuli such as light or heat, allowing real-time tuning of structural parameters, including the relative position and orientation of connected elements. This approach enables the investigation of actively tunable aerodynamic properties, mimicking natural flyers like seeds and insects that dynamically adjust their structures for optimal flight [2].

Our findings suggest that LCE-based deformable structures could provide a novel method for studying aerodynamic adaptation and may inspire future applications in bio-inspired flying robots, soft micro-air vehicles, and tunable aerodynamic surfaces.

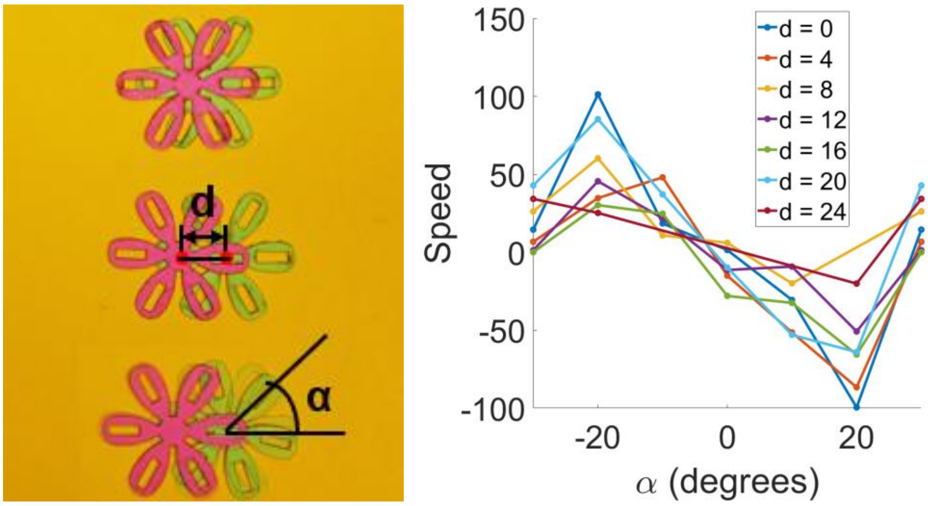

Figure 1. Rotation speeds effected by asymmetry of coupled structure

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Micron Waveguide Arrays Enabled by Direct Laser Writing for Efficient Light-Driven Liquid Crystal Elastomer Soft Robots

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Liquid crystal elastomers (LCEs) have emerged as promising dynamic materials for soft robotics due to their capacity for reversible and programmable shape transformations under external stimuli [1, 2]. Conventional light-driven actuation of LCEs typically relies on laser illumination to induce photothermal effects, triggering molecular reorientation and material deformation. While normal-incidence (near zero angle of incidence) laser actuation theoretically offers the highest efficiency, maintaining consistent normal incidence during operation is impractical, especially in dynamic microrobotic systems. In practical applications, side-incident laser illumination is often employed; however, reflection at the LCE surface reduce energy transfer efficiency, leading to suboptimal actuation performance. To address this challenge, we propose a novel approach that integrates direct laser writing (DLW) [3] fabricated micron-scale waveguide arrays onto the LCE surface (Figure 1). These waveguide arrays significantly enhance light coupling into the material, ensuring efficient and precise actuation even at 90 degrees incident angle.

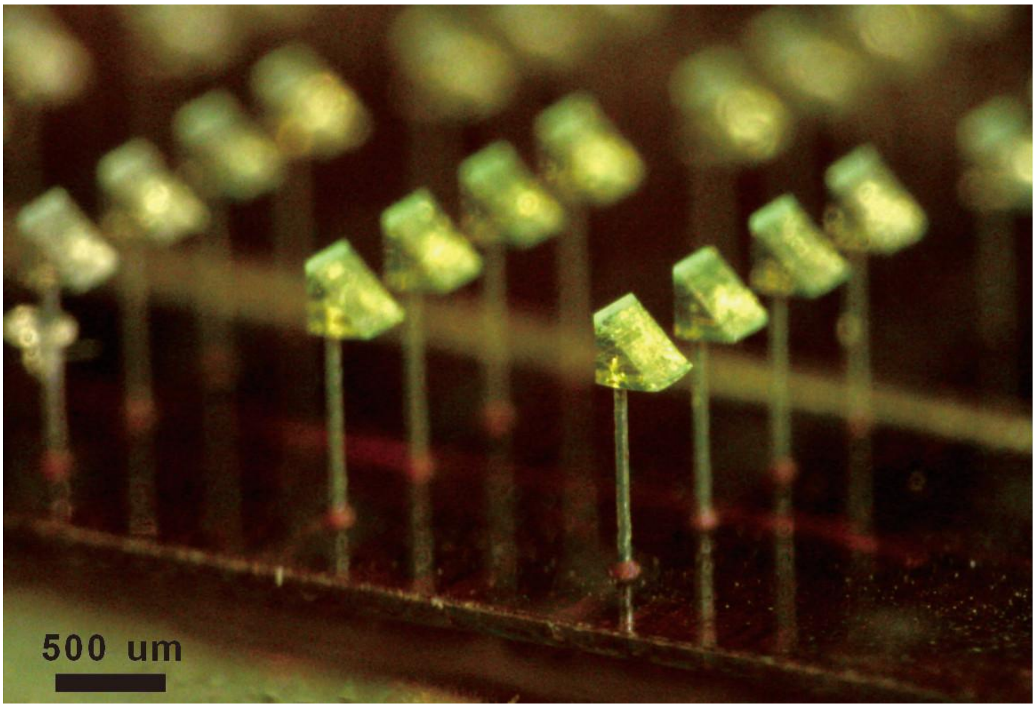

Figure 1. Optical image of micron-scale waveguide arrays on LCE surface

This work highlights the transformative potential of DLW-fabricated micron waveguide arrays in advancing light-driven LCE actuators for soft robotics. By enhancing LCE integration into robotic systems, our method significantly increases the flexibility and adaptability of LCE-based actuators, allowing them to operate effectively under diverse optical conditions.

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Visible Light Actuation in 3D-Printed Liquid Crystal Elastomers using Donor Acceptor Stenhouse Adducts

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3D Printing photo responsive LCEs is a growing research area. Incorporating photoresponsive molecules, for example azobenzene, enables spatio-temporal and orthogonal control over the actuation. However, these molecules interact with light only at the surface, thus restricting their practical applications to thin films. In contrast, negative photochromes lose color upon irradiation, allowing light to penetrate through the entire sample. Leveraging these photoswitches enables LCEs to interact and respond to light beyond the surface, which is key for larger-scale, 3D-printed architectures. Recent work shows photoactivation of DASA, a negative photochrome, through thick LCEs [1]. However, incompatibility with 3D printing remains a challenge. To address this, we incorporate DASA into 3D-printed LCEs using a straightforward functionalization technique. This enables spatial photoswitch patterning and light interactions at a scale meaningful for deployment of soft robots.

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A soft, isotropic mesogenic material with reversible electricity-responsive molecular alignment and corresponding shape deformation

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Liquid crystal polymers are a prime candidate for the preparation of stimuli-responsive materials. Especially interesting are systems which respond to electric fields, as such materials are highly applicable in the development of useful products[1]. Realignment of the mesogenic units in a liquid crystal polymer network by DC electric fields leads to large shape deformations of the material[2][3], which is an interesting effect with many potential applications. However, the materials need to be above the glass transition temperature for this effect to be observed, which is well above room temperature for the polyacrylate liquid crystal materials which are generally used.

In this project, new electricity-responsive soft polymer materials based on liquid crystals are developed. The materials are made through a Michael addition reaction between an electricity-responsive monoacrylate reactive mesogen, a diacrylate linker, and a tetrathiol. The diacrylate and tetrathiol form the network, while the monoacrylate mesogen provides the electricity responsiveness. Due to a lack of a high T_g polymer backbone, the materials have a T_g well below room temperature and can easily deform without the need for heating. The new materials are synthesized as thin films on glass surfaces bearing ITO electrodes, which are used to apply in-plane DC electric fields and study their effect on the material.

Performing the synthesis with a certain specific ratio between the three components results in a material that appears to be a soft isotropic solid. Polarized optical microscopy images before and after applying an electric field show that birefringence is present only when an electric field is applied. This effect is reversible, which suggests that a liquid crystal phase is only present when the electric field is applied. In addition, contactless 3D surface profilometry shows a deformation of the film surface in line with earlier observations in the electricity response of isotropic-genesis multidomain films despite being initially isotropic. The ratio between the components in the formulation has dramatic effects on the behavior of the final film and is systematically studied. As the material does not seem to be initially liquid crystalline, the findings presented here could take these materials out of the field of liquid crystal materials and into the broader scope of non-LC responsive polymers.

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Liquid crystal semi-interpenetrating polymer network for energy-dissipation

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The development of modern industry calls for superior energy-dissipation materials to efficiently eliminate unwanted vibration and absorb the impact energy. Among the polymer systems serving as energy-dissipation materials, liquid crystal network (LCN) is considered as an outstanding candidate for the new generation of energy-dissipation materials, due to its distinctive “soft elasticity” property, which originates from the re-orientation of mesogenic moieties [1-2]. Semi-interpenetrating polymer network (semi-IPN) consists of linear polymers and crosslinked network, where internal chain friction between linear polymers and crosslinked network would promote to dissipate more energy [3]. However, liquid crystal semi-interpenetrating polymer networks (LC-semi-IPN) have been seldomly reported. Herein, we reported LC-semi-IPN consisting crystalline LC polymers (c-LCP), which demonstrates a superior synergistic performance in both mechanical and energy-dissipation properties, surpassing all currently reported LCNs [4]. The crystallinity of c-LCP endows LC-semi-IPN with a substantial leap in Young’s modulus (1800% higher than single network). Moreover, its effective damping temperature reaches up to 130°C, which is the widest reported for LCNs. By leveraging its exceptional synergistic performance, LC-semi-IPN can be further utilized as a functional architected structure with exceptional energy-dissipation density and deformation-resistance.

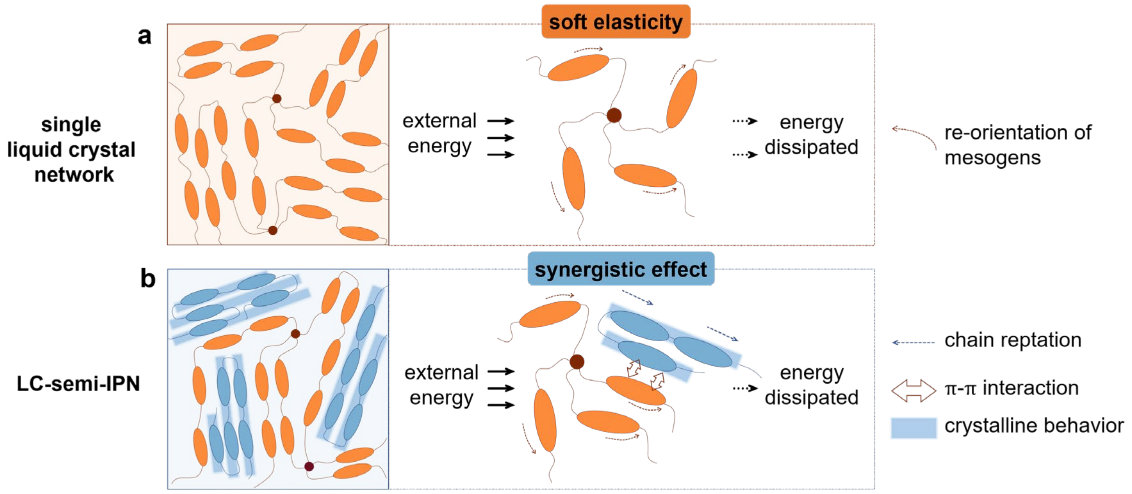

Figure 1. Scheme of the energy-dissipation behaviors and mechanical enhancement of LCN and LC-semi-IPN. a) Schematic illustrating structure of single liquid crystal network and its soft elasticity. b) Schematic illustrating structure of LC-semi-IPN.

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Modulating Polymerization Stresses via Backbone Modifications in Liquid Crystalline Elastomers

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Stresses-induced upon UV-polymerization can lead to volumetric shrinkage, often limiting the performance of synthetic materials in applications such as dentistry and coatings by causing mechanical failure and undesired deformations [1]. While significant progress has been made in mitigating these stresses, they may also serve as a pathway for expanding the design space of directional polymers that would otherwise be inaccessible. In liquid crystalline elastomers (LCEs) - anisotropic materials exhibiting shape programmability and phase-transition-driven mechanical deformations [2] – such stresses are governed by molecular anisotropy and influence the mesophase formation. In single-component end-on LCEs, they contribute to the emergence of chevron-like Smectic C structures, leading to complex motion behavior [3].

Herein, we exploit backbone modifications by introducing a methacrylate unit in *end-on* liquid crystalline elastomers of nematically-aligned acrylate backbones. The reduced build-up of the intrinsic stresses induced upon UV curing under magnetic field result in distinct liquid crystalline phases dependent on the nature of polymer backbone. We further investigate how such molecular packing influences the macroscopic behavior by preparing and analyzing microstructures, aiming to elucidate the balance between intermesogenic interactions, stresses upon polymerization and preparation conditions. Understanding this interplay and advancing such stress-guided mesophase engineering offers insights into optimizing LCEs for soft robotics actuators.

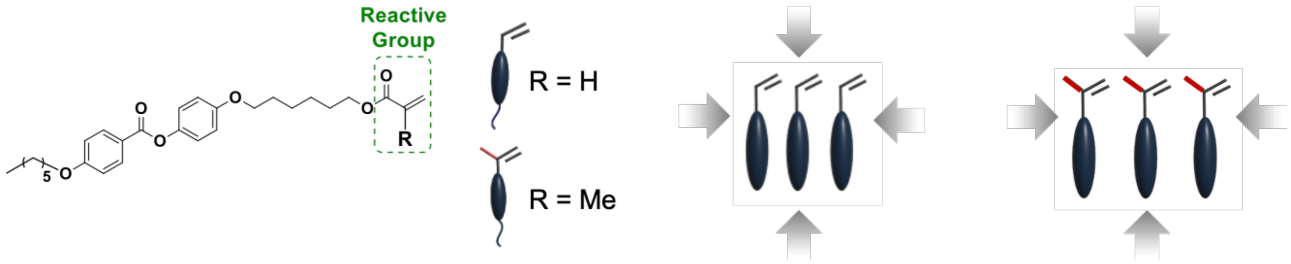

Figure 1. Investigating backbone modifications' influence on the polymerization stress build-up.

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Creation of Visible Light-Responsive Smart Windows with Chiral Bridged Azobenzene

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Smart windows have gained attention for their ability to change transparency in response to external stimuli. Smart windows are candidates for energy saving devices, which allow to control energy flow between inside and outside of a building, leading to reduction of energy consumption in air conditioning. The control of light transmission has been achieved with liquid crystals (LCs) containing azobenzenes. We have focused on smart windows that show the change in alignment of LCs by photoisomerization of azobenzenes.

Various azobenzene derivatives have been developed to improve the functionality of smart windows. One example is chiral azobenzene. LCs doped with the chiral azobenzene exhibit chiral nematic phases and when irradiated, they show a phase transition by changing the helical pitch of the chiral azobenzene. The smart windows based on this mechanism have a wide temperature range for driving, however the drawback is their unpleasant coloring. To overcome this drawback, bridged azobenzene was used. When it was incorporated into LCs, and irradiated with light, a similar phase transition was observed through the isomerization of the bridged azobenzene. The small molar absorption coefficient of the bridged azobenzene allowed for the creation of smart windows with very low coloration. However, they exhibited a narrow range of driving temperature.

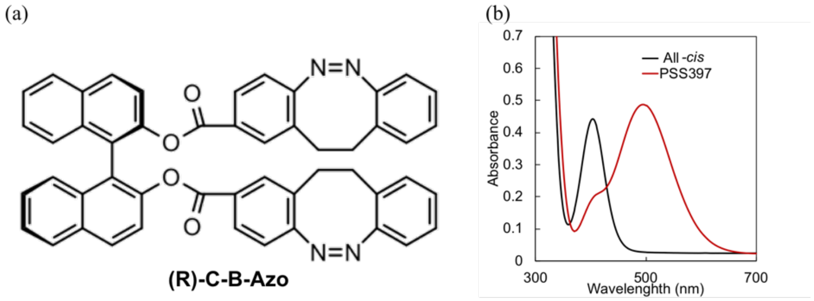

Figure 1. (a) (R)-C-B-Azo. (b) Absorption spectra of (R)-C-B-Azo in toluene.

Thus we designed and synthesized a chiral bridged azobenzene shown in Figure 1 (a) to create a smart window with very low coloration and a wide range of driving temperatures. The smart window with this chiral bridged azobenzene showed transmission-scattering switching by *trans-cis* isomerization upon irradiation with visible light. This system exhibited less coloration (Figure 2) than conventional systems, and enabled transmission-scattering switching over a wide temperature range of -7°C to 55°C.

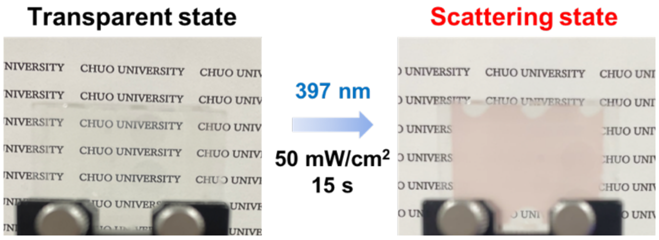

Figure 2. Transmission-scattering switching of the sample.

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Photomobile Materials Responsive to Near Infrared Light with BF$_2$-coordinated Azo Compounds

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Crosslinked liquid-crystalline polymers (CLCPs) with azobenzene show macroscopic deformations when irradiated with UV and visible light [1]. CLCPs have advantages such as greater flexibility compared to metals, and they do not require external wiring, allowing for miniaturization and weight reduction. However, conventional photomobile polymer materials with azobenzene are powered only by UV light, which limits their available wavelength ranges. To expand the range of applications, an effective approach is the introduction of donor and acceptor units into azobenzene structure, which increases the HOMO and decreases the LUMO levels, causing the absorption wavelength of azobenzene to shift toward visible regions. We focus on BF$_2$-coordinated azo compounds (BF$_2$-Azo). The *trans-cis* isomerization of BF$_2$-Azo can be effectively induced using NIR (Figure 1) [2]. Since NIR has high transparency and low energy, photomobile polymer materials with BF$_2$-Azo could be used for in vivo applications.

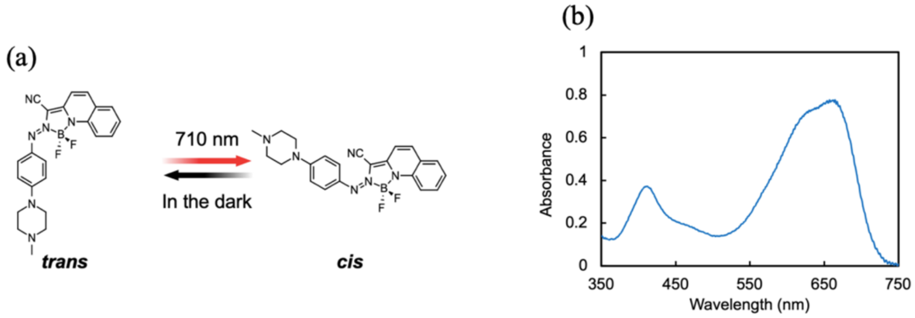

Figure 1. (a) *trans-cis* isomerization of BF$_2$-Azo. (b) Absorption spectrum of BF2-Azo in chloroform.

In this work, we prepared photomobile polymer materials with BF$_2$-Azo and evaluated their photoinduced bending behavior. Upon irradiation with NIR, the BF$_2$-Azo film bent toward a light source. We also examined the change in temperature of irradiated films: the film without BF$_2$-Azo showed no change, while the film with BF$_2$-Azo exhibited a rise in temperature (Figure 2).

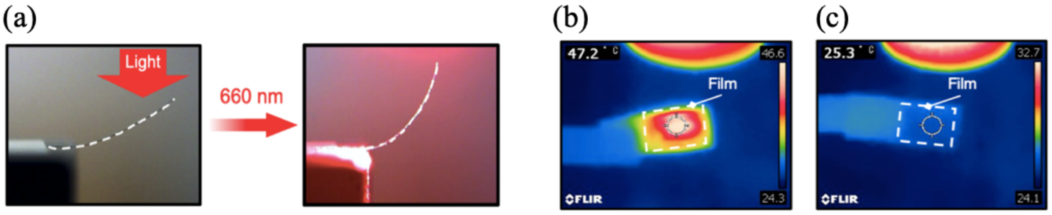

Figure 2. (a) Photoinduced bending behavior of the film when irradiated with NIR light. The change in temperature of the films (b) with BF$_2$-Azo and (c) without BF$_2$-Azo when irradiated with NIR light.

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Liquid Crystal Fibers for Remote Haptic Interaction

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This work presents interactive liquid crystal fiber (LCF) arrays that can actuate in a way perceptible by human touch. The fibers are electrothermally actuated, the input for which can be provided digitally. The combination of these properties enables a remote haptic interaction of users with an immersive virtual environment, or with other users.

In prior work [1] we demonstrated how LCFs could be directionally actuated (Fig. 1A) by localized addressing of an in situ formed radially aligned segment (Fig. 1B). This induces reduction in the scalar order parameter and leads to deformation of the fiber base, causing bending toward the activated region. An exploration of the possibilities for interaction (Fig. 1C,D) with the LCFs allowed us to identify material, engineering and design challenges that the present work has addressed, leading to the design of a fully-functional wearable haptic device (Fig. 1E).

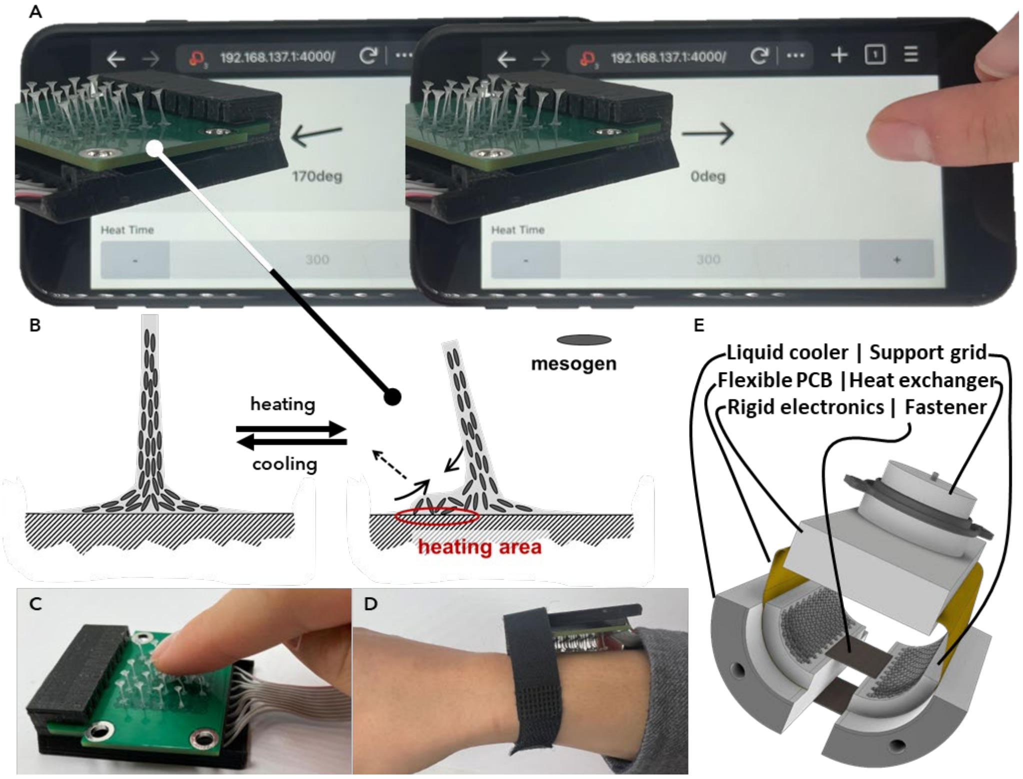

Figure 1. Digital and human LCF interface. A) Snapshots of periodic LCF array bending in the direction swiped by the user, for a heat time of 300 ms. B) Schematic illustration of how local heating can induce directional bending due to disturbing mesogen alignment. C) Active user interaction with LCF array. D) Wearable prototype of LCF array brushing a user's arm. E) 3D design of remote haptic wearable. Figure adapted from [1].

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Viscoelastic relaxation of stress and orientation in nematic LCE

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We present an early-stage theoretical analysis of the viscoelastic response in liquid crystalline elastomers (LCEs), aimed at constructing a consistent model that captures the coupled relaxation of stress and orientational order. This work also seeks to provide a theoretical foundation for understanding the anomalous damping of high-frequency vibrations in nematic LCEs. The absence of a comprehensive theoretical framework for LCE dynamics remains a major impediment to both practical applications and a deeper understanding of high-frequency mechanical behavior. Despite the initial discovery of anomalous vibrational damping over 25 years ago [1] and substantial subsequent efforts [2,3], a working theoretical model has yet to be established.

A persistent misconception in the field links anomalous damping to "dynamic soft elasticity", an equilibrium effect associated with the softening of the shear modulus. However, experimental observations indicate that dissipation peaks at kHz frequencies: far beyond the regime where equilibrium soft elasticity plays a role. At these frequencies, not only is the ‘soft plateau' absent, but higher-order Rouse modes are expected to dominate chain fluctuations. This suggests that the viscoelastic response is primarily governed by the motion of individual mesogenic units (chain segments) rather than collective network-level processes.

To probe the microscopic mechanisms underlying this behavior, we developed a Brownian dynamics simulation framework for network chains incorporating mesogenic rods. This approach extends the conventional Rouse model of "balls and springs" to a main-chain nematic polymer topology, explicitly accounting for both translational and rotational dynamics of anisotropic mesogens in the presence of thermal fluctuations, external stress, and a nematic ordering field. The simulation evolves from an arbitrarily deformed initial state toward equilibrium, allowing us to track both the magnitude and orientation of nematic order as it evolves towards the equilibrium. This computational approach serves as an *in-silico* experiment, providing key insights to guide the development of an analytical theory describing stress and orientational relaxation in nematic LCEs.

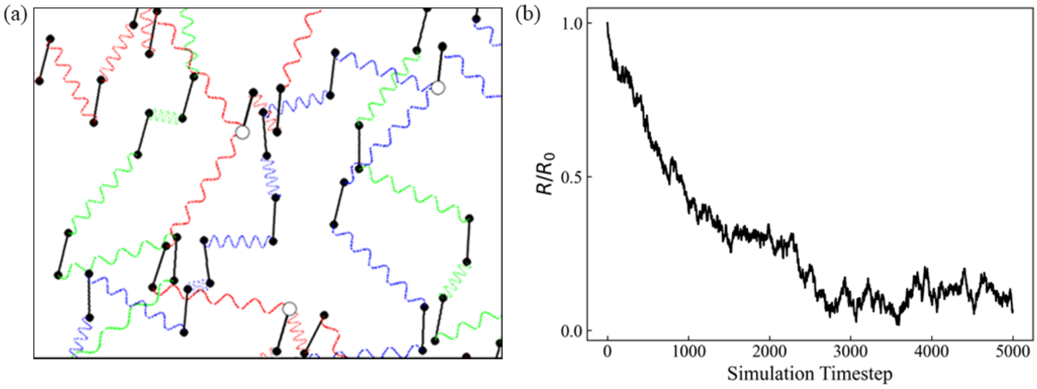

Figure 1: (a) A snapshot of our network simulation, illustrating our mesogen representation, in which frictional drag and thermal noise act on the two ‘balls' of a rigid dumbbell. Crosslinks between chains are marked in white. (b) An illustration of relaxation dynamics of the end-to-end distance, R, of a network chain equilibrating after starting in a highly stretched state with $R=R_0$.

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Architected LCE Structures with Programmed Alignment: Recent Advances in 3D Printing Techniques

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We will report an overview of new methods and applications that Lawrence Livermore National Laboratory and collaborators have developed in recent years to further improve additive manufacturing of architected LCE structures with programmed alignment. The first topic discussed will be recent advancements in magnetic alignment combined with digital light projection (DLP) to build high resolution 3D parts with programmed discreet shape changes. This can be completed by aligning the LCE mesogens themselves[1] or incorporating actuating LCE microparticles[2] into a photocurable resin of choice. The quick magnetic responsiveness allows for alignment to be programmed in three-dimensions and assembled layer-by-layer, resulting in a part with selective areas of shape change at elevated temperature as shown in Figure 1. Printing and resin optimization will be discussed as well as mechanical and thermal responsiveness of the cured parts.

The second topic will focus on using direct ink writing (DIW) to architect 3D lattices with predictable alignment, porosity, and stiffness allowing for increased directional energy absorption. These architected lattices perform exceptionally well at high strain rates when applying compressive loads with the LCE structures outperforming silicone lattices by absorbing 40x more energy. An example lattice made with DIW as well as energy absorption results at increasing strain rates can be seen in Figure 1.

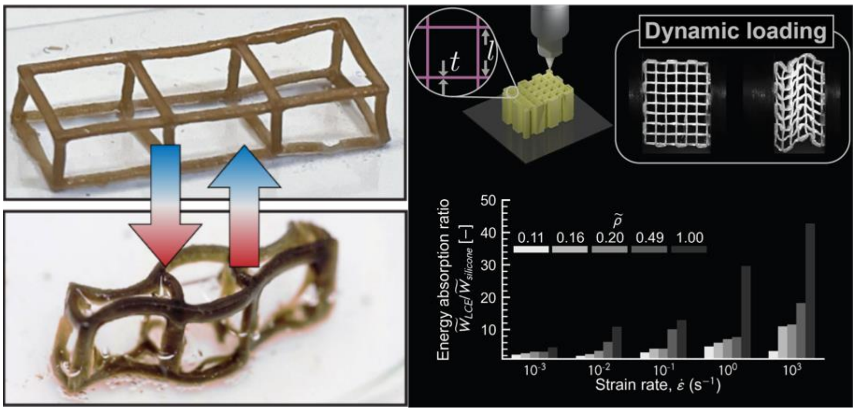

Figure 1. (Left) Temperature induced shape change of DLP printed lattice with selectively aligned magnetic LCE microparticles. (Right) DIW printing of LCE lattices with architected alignment and their energy absorption properties.

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Dependence of elastic characteristics of acrylate-based liquid crystal elastomers on mesogenic content

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Liquid Crystal Elastomers (LCEs) are exceptional materials that merge the rubber-like elasticity of polymer networks with the anisotropic properties of liquid crystals. Similar to conventional liquid crystals, LCEs have orientational properties because they contain molecules that can be aligned in the desired direction during the fabrication process. Once polymerized, the orientation of these molecules can be changed, particularly through a mechanical Fréedericksz transition [1]. This feature makes LCEs particularly attractive for optical applications [2-3]. In particular, LCEs are perfect for designing optical devices that can be mechanically switched and adjusted, utilizing the anisotropic nature of elastomers. Consequently, a thorough understanding of their elastic properties is essential for optimizing these advanced materials for next-generation optical systems.

Here, we report measurements of the elastic properties of acrylate-based LCE samples with mesogenic content ranging from ~60 to ~75 %. We show that the Young's moduli of LCEs increase non-linearly with the increase of the mesogenic content. Furthermore, the elasticity coefficients entering the elastic free energy density expression for these materials have been calculated and are shown to display a similar trend. We have also carried out comparison of the obtained results with our previous calculations for acrylate-amine based liquid crystal elastomers [4].

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Switchable Whiteness in Liquid Crystal Polymer Networks

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Approaches focused on mimicking the natural structures to produce multiple scattering and high whiteness at a low thickness have gained interest in recent decades[1]. Light scattering in response to external stimuli is commonly observed in hydrogels[2] and liquid crystal[3] (LC) materials due to their phase transitions. However, the drawback of these systems is that thick material is required in the case of hydrogels to achieve sufficient whiteness, and thin film LC material have limited capacity in whiteness change. Here, we present a liquid crystal polymer network that switches between transparent (initial) and white (opaque) states when immersed in a polar solvent, most commonly water. By utilizing LC mesogen and balanced moieties of carboxylic acid and amine, light scattering up to 85% can be achieved in the wet state (**Fig. 1a**). The polymer shows reversible and fast switching between transparent and white states, usually in seconds, even with low thickness (~ 5 μm). The whiteness in the wet state can be characterized by a CIE plot, where the co-ordinate is at the centre of the plot (**Fig. 1b**). The scattering can be enhanced by introducing a hydrophobic dopant that can form a halogen bond with the tertiary amine to modify the hydrophilic–hydrophobic ratio. The scattering efficiency in the wet state and the switching speed can also be influenced *via* acid and base treatment. We demonstrate the application of such switchable polymer networks in a privacy system where fingerprinting can be done with a wet finger on dry transparent film (**Fig. 1c**), and on heating, it can be erased. We believe that liquid crystal polymer networks with switchable whiteness open up prospective applications as stimuli-responsive screens, smart windows, and sensors to detect the polarity of solvents.

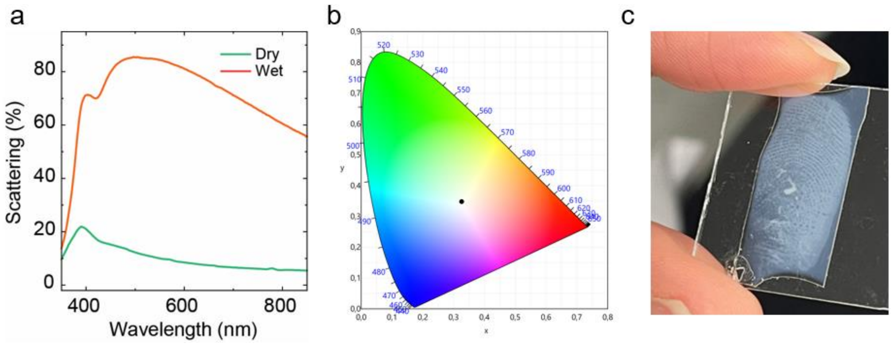

Fig. 1: (a) Total scattering of dry and wet state. (b) Calculated color coordinate of wet state on the CIE chromaticity diagram. (c) Fingerprinting by wet finger on dry transparent film.

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Nematic liquid crystal- Carbon dot Composites: Role of Functionalization of Carbon dot

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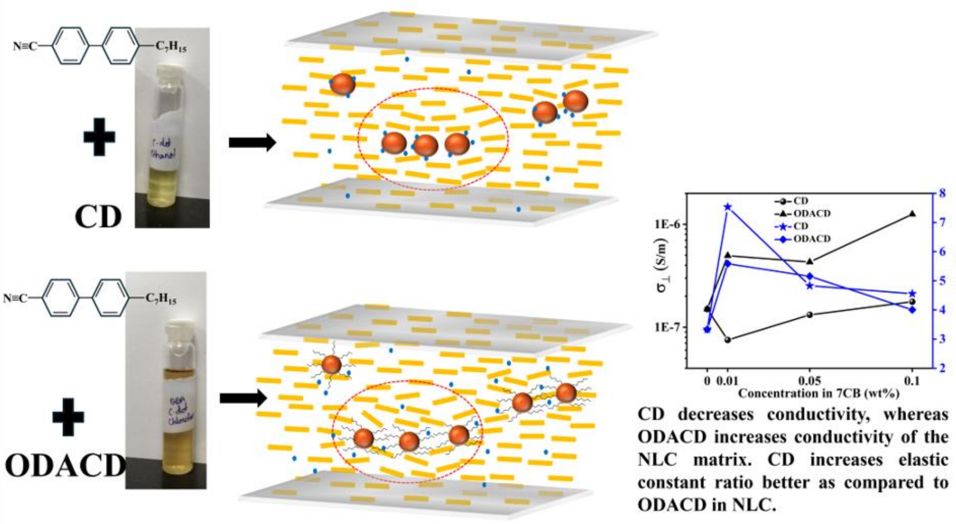
Dispersion of nanoparticles in nematic liquid crystal (NLC) matrix for improved device applications is an active area of research worldwide. Functionalization of nanomaterials is an efficient way to prevent the aggregation of particles and improve its dispersibility in solvents. In the following study, we propose that if unfunctionalized nanoparticles are capable of forming stable dispersions in solvents and miscible in the LC matrix without aggregation or accumulation at interfaces, they could be a better alternative than their functionalized counterparts for improving the physical properties of NLC. In this experimental investigation, the effect of functionalization of nanomaterials on various physical properties, such as dielectric, electro-optic and conductivity properties, of nematic liquid crystals is investigated. To explore the validity of our hypothesis, we investigated the properties of NLC, 7CB incorporated with carbon dots and octadecylamine-functionalized carbon dots.



CD decreases conductivity, whereas ODACD increases conductivity of the NLC matrix. CD increases elastic constant ratio better as compared to ODACD in NLC.

Figure 1. Schematic showing behavior of functionalized and unfunctionalized carbon dot in host nematic matrix

Dielectric permittivity and elastic constant measurements suggested that quantum dots were rearranged in the nematic matrix in such a way to minimize the free energy of the composite, and functionalization did not significantly affect the global ordering of NLC molecules. We also observed that the conductivity of C-dot composites decreased when compared to pure NLC but increased with the dispersion of ODA C-dot in NLC compared to pure NLC. It was observed that the ligand molecules of the functionalized quantum dots did not add to the conductivity of the dispersions but act as a trap for ionic impurities, and the partial release of these impurities upon interactions of the ligand shell with the uniaxial nematic host could be the source for the increased conductivity. This study is expected to impart substantial insights into designing high-performance nanocomposites of LCs for device applications [1].

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The fabrication of liquid crystal networks microstructures using two-photon polymerization

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Liquid crystal networks (LCNs) have been extensively researched due to their unique ability to change shape in response to external stimuli, such as light or heat, through anisotropic expansion resulting from the arrangement of liquid crystal molecules. Traditionally, microstructures are polymerized from the surface of the substrate, limiting their ability to achieve shrinking deformation at the microscale. This paper proposes using two-photon polymerization to fabricate shrinking micro-pillars supported by an LCN wall, avoiding restrictions from the substrate surface. In this study, the fabricated LCN pillars with lengths of 30 microns and thicknesses of 5.5, 8.5, and 11.5 microns achieved a maximum shrinking ratio of 17.33%.

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Magneto-Photochemically Responsive Liquid Crystal Elastomer

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Magnetic and light-driven actuation are widely used in soft robotics due to their remote controllability and adaptability. Magnetic fields enable actuation in optically obstructed environments, while light-driven mechanisms allow precise and localized control of material deformations[1]. Light actuation can be either photothermal or photochemical, with the latter being particularly suitable for underwater applications due to its efficiency and independence from heat dissipation. Despite these advantages, the combination of magnetic and photochemical actuation within a single monolithic liquid crystal elastomer (LCE) system has not been previously explored.
In this work, a dual-responsive LCE system is developed by incorporating hard magnetic microparticles and azobenzene derivatives into the elastomer network, enabling simultaneous magnetic and photochemical actuation[2].Photochemical actuation occurs through the cis–trans isomerization of azobenzene, leading to reversible molecular rearrangements and macroscopic shape deformations. Magnetic actuation is achieved by applying an external field, which generates torque on the embedded microparticles, with the response further controlled by programmed magnetic domains. The system is demonstrated in two key applications (Figure1). First, in underwater object manipulation, where magnetic fields position the actuator while photochemical stimuli enable controlled gripping and release. Second, in the optical reconfiguration of magnetically synchronized cilia, where photochemical actuation modulates the oscillatory behavior of the cilia in response to external mechanism to control periodic motion in dynamic actuation systems.

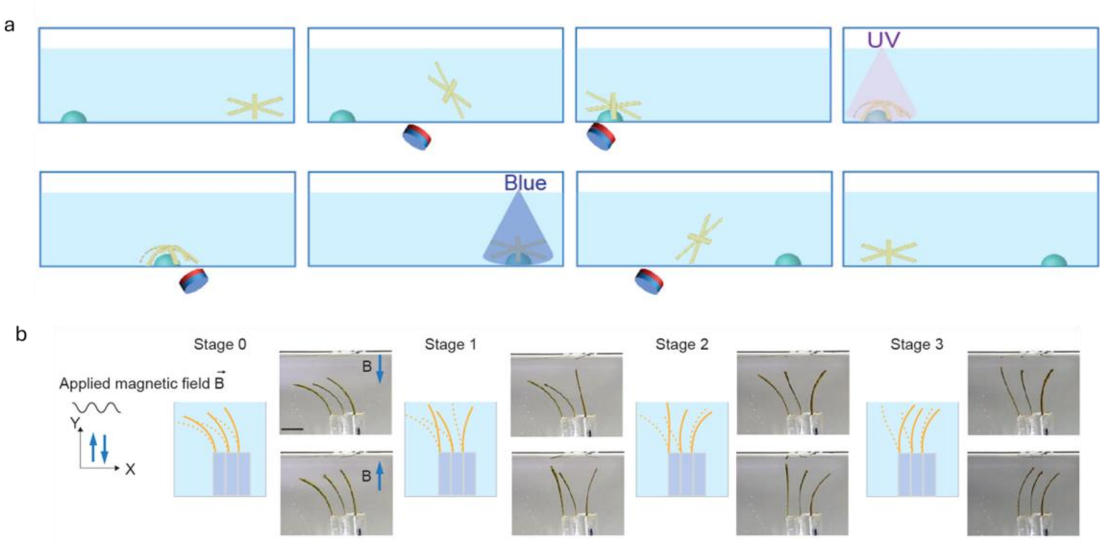

Figure 1. (a) Magneto-photoinduced object translocation. (b) Photocontrolled oscillations of magneto-photoresponsive LCE cilia under oscillating magnetic field.

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Reprogrammable All-Solid-State Ionic Liquid Crystal Elastomers as Electroactive Actuators

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Over the past few decades, liquid crystal elastomers (LCEs) have been successfully developed in the context of artificial muscles, artificial skins, or soft robotics, which can produce extremely sensitive deformations in response to various external stimuli such as heat and light. However, electrical energy is the most convenient and the most in-demand stimulus. Nowadays, electroactive LCEs (eLCEs) have thus attracted the attention of more and more researchers. In our previous work [1], we have reported the first bifunctional ionic eLCE device (i-EAD-LCE), where an ion-conducting LCE is sandwiched by two electrically conducting polymer electrodes composed of formulated PEDOT:PSS. The i-EAD-LCE can perform both bending deformation and linear contraction/elongation under low voltage of different frequencies. However, this device still has some issues such as ionic liquid leakage and poor mechanical performance.

To inherently solve the ionic liquid leakage issue, the polymeric ionic liquid (PIL) network can be designed, in which either ionic liquid-like anions or cations are fixed to the elastomer backbone [2]. Moreover, the hydrogen bonds can be introduced into the device to improve mechanical properties and endow reprogrammable properties as reported [3]. In this work, the chain extender monomers charged with ions and with hydrogen-bond-forming moieties are synthesized. The all-solid-state ionic LCE will be prepared and the eLCE device will be elaborated by adding formulated PEDOT:PSS electrodes. We hope to provide improved electroactive actuators for future real applications in portable devices and soft robotics.

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Modulation of domain sizes of polydomain nematic elastomers

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Nematic liquid crystal elastomers (LCEs) crosslinked at their isotropic phase, when they are quenched to the nematic phase, show polydomain patterns, in which nematic microdomains with different orientations self-organize into a three-dimensional mosaic with characteristic correlation patterns [1-3]. The orientational correlation length of the domain, which is usually in the micrometer range, is believed to emerge as a result of a competition between liquid crystalline ordering and frozen network inhomogeneity. Although polydomain patterns show potentials as the basic platform for optical and mechanical devices, no study exists regarding how they are modulated by experimentally accessible parameters. Here, using confocal polarized fluorescence microscopy, we study the effects of a solid-wall or open boundary on the domain size in conjunction with effects of cross-link density [4]. The LCE bounded by a solid glass shows the reduced domain size near the boundary. In contrast, increased domain size appears at the free surface. With increasing cross-link density, the domain size decreases, also exhibiting the boundary effects. Guided by theoretical considerations, the results are explained by a picture that the effective strength of the inhomogeneity frozen in the polymer network, i.e., the effective disorder strength, varies depending on the cross-link density and constraint states at boundaries [3]. The results offer the first experimental approach to global and local modulation of the polydomain pattern in cross-linked nematic LCEs.

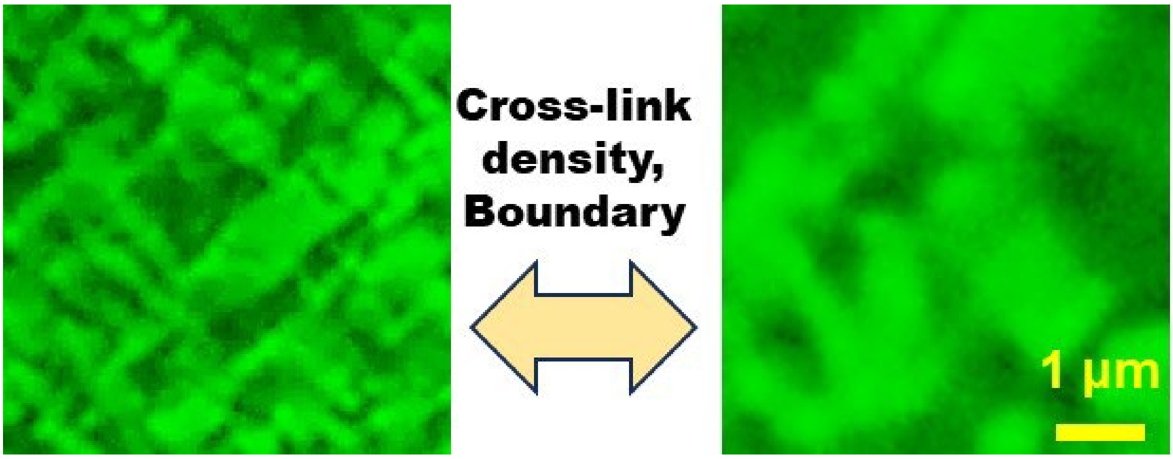

Figure 1. The tangible effects of the interfaces and cross-link density on the domain size of the polydomain structures of nematic liquid crystal elastomers.

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Programming Mechanochromic Responses in Spiropyran-Incorporated Liquid Crystal Elastomers via Direct-Ink-Writing

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Mechanoresponsive polymers have received significant attention for their potential applications in stress and strain sensing, as well as damage detection. Among them, spiropyran (SP)-based polymers, which exhibit force-induced color changes, are widely studied, but most studies are limited to isotropic polymer matrices.[1] In this study, we use UV-assisted direct-ink-writing to print SP-incorporated liquid crystal elastomers (LCEs) and investigate how LC alignment influences their mechanochromic response. Unlike conventional SP-based polymers, the mechanochromic behavior of SP-LCEs is strongly dependent on the stretching direction relative to the nematic director. To gain deeper insight into this behavior, we employ finite element analysis (FEA) simulations and in-situ X-ray measurements, which reveal a direct correlation between the nematic director and mechanoresponsive characteristics. The ability to program the mechanochromism in SP-LCE monolith opens new possibilities for advanced anti-counterfeiting materials and strain sensors.

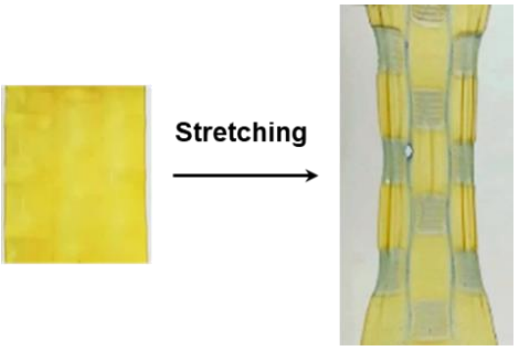

Figure 1. Spatially programmed mechanochromic response of the SP-LCE monolith with a checkerboard pattern.

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Encoding Actuation Modes in Smectic Liquid Crystal Elastomers

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Smectic order offers significant potential for enabling unique actuation mode in liquid crystal elastomers (LCEs), yet it has been less explored than its nematic counterpart [1, 2]. Here, we demonstrate a strategy to encode two distinct actuation modes—contraction and elongation—within a single smectic LCE material by controlling the director orientation during the direct-ink-writing (DIW). Our results reveal that the alignment of the director and the resulting actuation direction of the printed LCEs are affected by printing parameters such as temperature and speed, which we attribute to changes in the rheological behavior of the smectic melt. Our approach provides a simple yet powerful method for programming multimodal actuation in LCE-based devices.

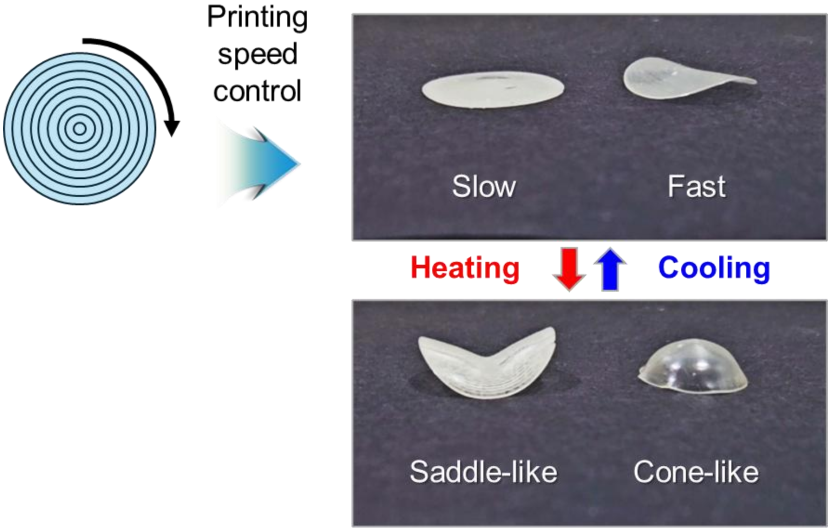

Figure 1. Controlling actuation modes through printing conditions in concentric-patterned smectic liquid crystal elastomers.

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Light-fueled self-sustained soft robotics

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Driving light-responsive materials far from equilibrium via dissipative mechanisms offers a promising route toward autonomous, self-sustained robotic motion [1-2]. This approach is essential for developing next-generation "life-like" materials whose responses are intrinsically self-regulated and adaptive. Despite significant progress in biomimetic devices, clear gaps persist between synthetic systems and their natural counterparts, particularly regarding dynamic interactions with the ambient environment. In our work, we present three distinct strategies for violating thermodynamic equilibrium, namely, the self-shadowing effect, force-assisted shadowing, and zero-elastic-energy modes (ZEEMs). When continuously energized by steady light, these systems exhibit spontaneous motion and dynamic structure-environment interactions that enables diverse functionalities (Figure 1), such as sensitivity to mechanical cues [3], fluid coupling between sustained cilia-like oscillators [4], and autonomous torus swimming in viscous fluids [5]. We believe these results offer new perspectives on the design of stimuli-responsive soft robots that operate in non-equilibrium states and emulate the complex, adaptive behaviors of living systems.

Figure 1. Schematic of three strategies employed in light-fueled self-sustained motions, facilitating a variety of autonomous functionalities.

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Studying the Structure of Liquid Crystal Elastomers using Small- and Wide-Angle X-ray Scattering

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The optimization of optical and physical properties is critical for material design, particularly for applications such as glass laminates, in which both good optical transparency and impact resistance are required [1]. Furthermore, understanding the temperature-dependence of the material properties is particularly important for real-world applications.

Liquid Crystal Elastomers (LCEs) are a form of material that have demonstrated good potential over a wide range of optical and mechanical applications. These types of materials are formed of loosely crosslinked liquid crystal polymers and the coupling of liquid crystalline and polymeric properties gives rise to highly ordered and birefringent soft materials.

Here, we will discuss the influence of molecular packing on a unique family of acrylate-based LCEs first developed by Mistry *et al* [2] which exhibit auxeticity (negative Poisson's ratio under strain). LCE properties such as refractive index and density are temperature-dependent [3,4] and have been previously investigated for LCEs of systematically varied liquid crystalline content [1]. We previously demonstrated the role of temperature-dependent density on optical properties; however, a change in density was not directly measured.

Small-Angle and Wide-Angle X-ray Scattering (SAXS and WAXS) are well understood techniques to provide information on the order and structure of a system and have previously been used to characterize the phase of a range of LCEs within this acrylate family [5].

In this work, X-ray Scattering has revealed the ordering and the structure of a series of LCEs with systematically altered compositions. Using these techniques, we report that the internal spacing of LCEs are dependent on both the liquid crystalline content and phase (isotropic or nematic) of the network. Indeed, for an increase in liquid crystalline content, we see a reduction in internal spacing, signifying an increase in density. Specifically, we observe a 4% increase in density for a 16 mol% increase in the mesogenic content of the network.

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Low-Energy-Driven Autonomous Actuators Enabled by Diels-Alder Crosslinked Liquid Crystal Elastomers

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Autonomous actuators powered by ubiquitous, low-energy natural sources (e.g., ambient sunlight or body heat) offer significant potential for outdoor autonomous soft robotics and biomedical devices. While advances in liquid crystal elastomers (LCEs) have enabled solar-driven self-oscillators and heliotropic tracking systems [1,2], critical challenges remain in expanding the autonomous motion modes of LCE actuators while reducing their energy thresholds. These challenges arise from the inherent trade-off between low-temperature responsiveness and large actuation strain in LCEs, as well as thermal transport constraints, which together impede the realization of high strain rates within a narrow thermal window near ambient temperatures.

Herein, we present a material-structure synergy strategy to overcome these challenges [3]. We develop a dynamic LCE-carbon nanotube composite (DALCE-CNT), incorporating C6BAPE and RM257 mixed mesogens [4] to achieve a low nematic-to-isotropic transition temperature (T_{ni}) of 32 °C while being crosslinked via Diels-Alder reactions for mild-temperature reprogrammability and high reprocessability [5]. Crucially, this reprogrammability enables freeform reconstruction of specific geometries with deformation-amplification effects—including twisted-and-coiled fibers with linear or closed-ring topologies—leading to significant enhancements in actuation strain rate (e.g., 487.5%/s at 30 °C) within biologically relevant thermal ranges.

Leveraging this platform, we demonstrate multi-mode autonomous actuation under natural energy gradients: (i) horizontal self-rolling on human skin (up to 3.8 mm/s) or under 48 mW/cm² simulated sunlight (0.9 mm/min), (ii) downward self-rolling under natural sunlight (2.7 mm/s) that stops in the shade, (iii) self-breathing and autonomous untwist-twist movements at ambient temperatures, and (iv) 83 mW/cm² simulated sunlight-powered autonomous cargo transportation. This integration of material innovation with architectural design advances autonomous soft robotics powered by mild natural energy sources, opening new avenues for LCE-based biomedical applications and autonomous outdoor systems driven by ambient thermal gradients.

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Oligomer-Derived Photoresponsive Liquid Crystal Elastomers with Biocompatible Operating Temperature

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Photoresponsive liquid crystal elastomers (LCEs) that can undergo light-induced actuation at a selected operating temperature range are highly useful functional materials that can be applied in diverse contexts, from autonomous responsive architectural elements via soft robotics to biotechnology [1]. Recent advances in LCE research highlighted the benefits of oligomeric precursors, which enable the use of 3D-printing, microfluidic or other shear-based processing to shape and simultaneously program the LCE, but the majority of light-responsive LCEs are derived from low molar mass precursors. Here we report the synthesis of photoresponsive nematic liquid crystal oligomers (LCOs) functionalized with azobenzene moieties, followed by processing and crosslinking into aligned LCE sheets thanks to a 2-stage network formation. By varying the chemical composition of the oligomers we can tune both the operating temperature and the photoresponsiveness of the final LCE. We conduct a systematic analysis of LCE actuation as a function of temperature with and without UV light irradiation.

By quantifying the LCE actuation around the nematic–isotropic transition, before, during and after UV irradiation, and fitting a simple analytical model to the experimental data, we identify the optimum photoactuation operating temperature with high accuracy. We discuss how this method can be employed as a general tool for identifying the right operating temperature for a certain LCE under specific UV exposure conditions. For one of our three LCO-derived azo-functionalized LCEs, we find the optimum temperature to be as low as 30°C, with near-identical performance at 37°C. The photoresponsiveness is strong, with a UV-induced reduction of clearing point by about 17°C. This renders the LCE ideal for application in biotechnological contexts, as it offers isothermal actuation at a temperature suitable for biological cells. Our next target is to mold these LCEs into very thin tubes, which can then function as light-driven peristaltic pumps to support organoid growth [2]. We will discuss how this can be achieved without exposing the cells to harmful UV light.

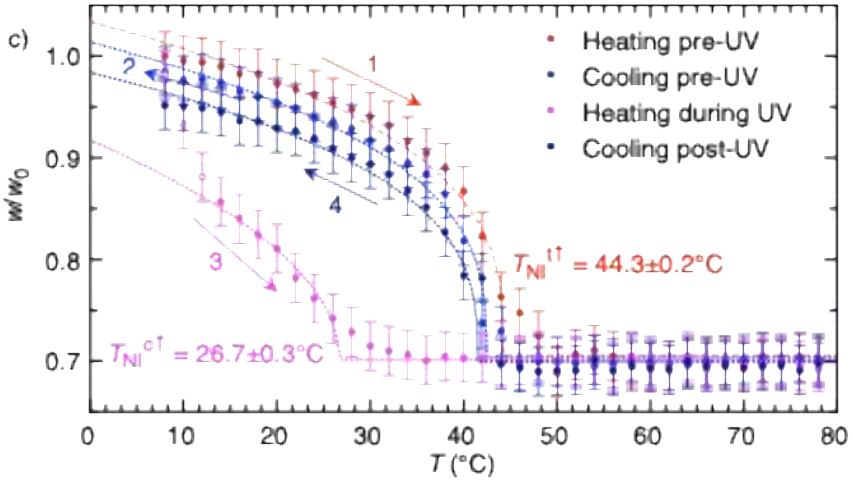

Figure 1. Actuation (as quantified by width w, as measured along the director, divided by ground state width w_0) upon heating and cooling without and with UV irradiation.

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Investigation of the Photomechanical Effect in Guest-Host azopolymers

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Azobenzene molecules and their derivatives exhibit remarkable properties, particularly their reversible cis-trans isomerization, which induces macroscopic deformations due to angular rotation between the phenyl rings. Light-responsive polymers incorporating azobenzene show strong potential for applications due to their photo-responsive behavior driven by light-induced isomerization [1].

Beyond molecular switching, photoinduced mass transport modifies the surface morphology of azobenzene-containing films, enabling the formation of surface relief gratings (SRGs) under interference patterns [2]. These structures have applications in optical data storage [3] and soft robotics [4]. The formation and stability of SRGs depend on the polymer matrix, azo chromophore structure, and concentration, making the design of new azobenzene derivatives an ongoing area of research. In this study, we used Ultem polymer as a host, incorporating various azo chromophores in different concentrations to investigate their photomechanical properties.

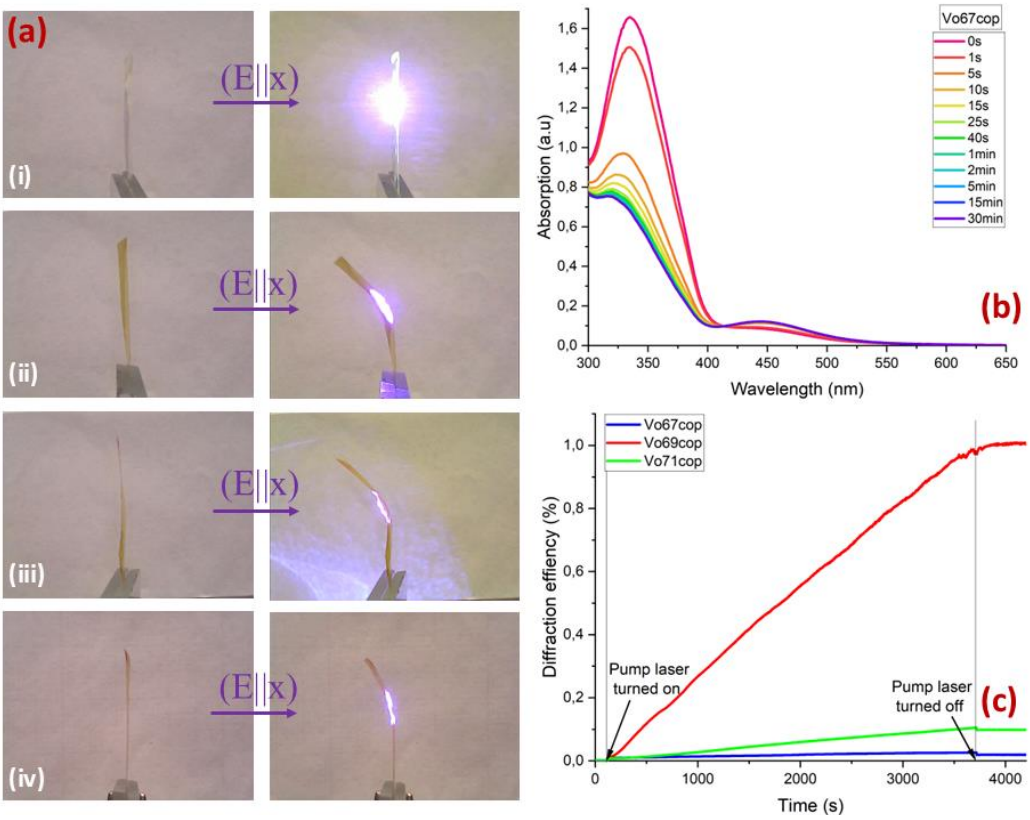

Figure 1. **(a)** Photoinduced bending of cantilevers composed of (i) Ultem, (ii) UNVo60, (iii) UNVo66, and (iv) UNVo87 upon exposure to linearly polarized 405 nm light (E||x) at 100 mW/cm^2 for 2 min. **(c)** Normalized UV–vis spectra before irradiation (pink spectra), and after 30 min of UV light irradiation (purple spectra). **(d)** The first order diffraction efficiency as a function of time azobenzene containing polymers, using 532 nm laser source, with RCP-LCP polarization configuration, Intensity was 150 Mw/cm^2.

We will present our research on photoinduced deformations in azobenzene-based polymer cantilevers using a 405 nm laser. We systematically varied laser intensity, polarization, and exposure time, analyzing photoisomerization through absorbance measurements. Our findings demonstrate that deformation is directly linked to cis-trans isomerization, with polarization-dependent molecular alignment dictating the bending direction-toward the laser under parallel polarization and away under perpendicular polarization. The deformation extent was strongly influenced by laser parameters. Additionally, we will discuss SRG formation, recorded using a two-beam interferometric setup and confirmed via atomic force microscopy. Both photoisomerization and SRG formation showed results consistent with photoinduced deformation, reinforcing the reliability of our findings.

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Encoding actuation anisotropies in magneto-active LCE nanocomposite resins for Digital Light Processing 3D printing

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The field of 4D printing is revolutionizing the manufacture of intelligent objects capable of adapting their shape and properties in response to external stimuli. This project explores the design and printing of a resin combining a liquid crystal elastomer (LCE) matrix and magnetic nanoparticles to create structures with a programmable response.

To address this point, we present a patented magnetic device based on the concept of the Halbach array that can be easily adapted to most of light-driven 3D printers [1]. This device enables the generation of various magnetic field configurations, from homogeneous to quadrupole and higher-order patterns, with adjustable intensity, spatial orientation and gradients. The effectiveness of the device has been demonstrated in several applications [2]. Firstly, precise control of the rotation of printed objects was achieved using a magnetic field. Secondly, we have demonstrated the possibility of inducing a selective folding movement by locally controlling the orientation of the nanoparticles, thus enabling specific areas of an object to be activated. Finally, we have developed an angular magnetic switch whose state can be modulated the magnetic rotation, illustrating the potential of this technology for the creation of advanced functional devices.

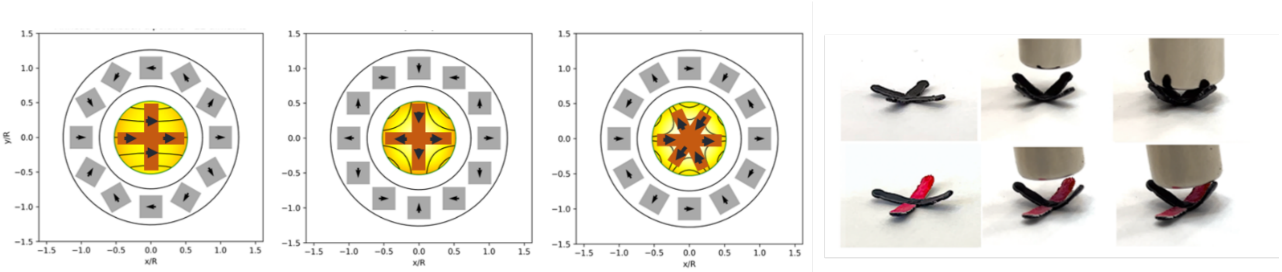

Figure 1. Selective bending movement of the object's branches. a) Quadripolar orientation of the nanoparticles, all four branches bend. b) Dipolar orientation of the nanoparticles, only two of the four branches bend.

These results open up new perspectives in the additive manufacturing of intelligent structures, with potential applications in the fields of biomedicine, soft robotics and adaptive sensors. The integration of this magnetic control into 3D printing processes represents a major advance towards the production of dynamic and reactive materials, capable of interacting with their environment in a programmable and predictive manner.

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P-47

Liquid Crystal Elastomer Actuator Matrix for Large-area Applications

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In recent years, main-chain liquid crystal elastomers (LCEs) have found widespread use in soft robotics research [1][2]. A current challenge is the fabrication of large-scale soft actuator assemblies and the local addressing of individual actuators. Here, we describe a scalable method for the fabrication of flexible foils with thermally driven active LCE elements. LCE and heaters were fabricated on a thin and flexible carrier substrate. Four different heater designs were patterned on two different foil types, and all combinations were investigated and characterized in terms of electrothermal properties, power consumption and resulting actuation behavior. By combining conventional thin film electronics manufacturing of metallic heaters made by sputtering of MoCr then patterned by photolithography [3] and direct ink writing of the active LCE [4], a 150 mm by 150 mm matrix of 25 elements was realized. The device functions by thermal actuation of the LCE by Joule heating of flexible resistive heaters, used simultaneously to interconnect the elements and operate the device. Such a device produces local on-demand actuation, with large flexibility in terms of the overall size of the matrix and of the size of the active elements, while operating at low power, below 400 mW per actuator. Besides demonstrating scalability of LCE-based devices, the presented concept shows potential for applications in texture-changing, smart surfaces and haptic displays.

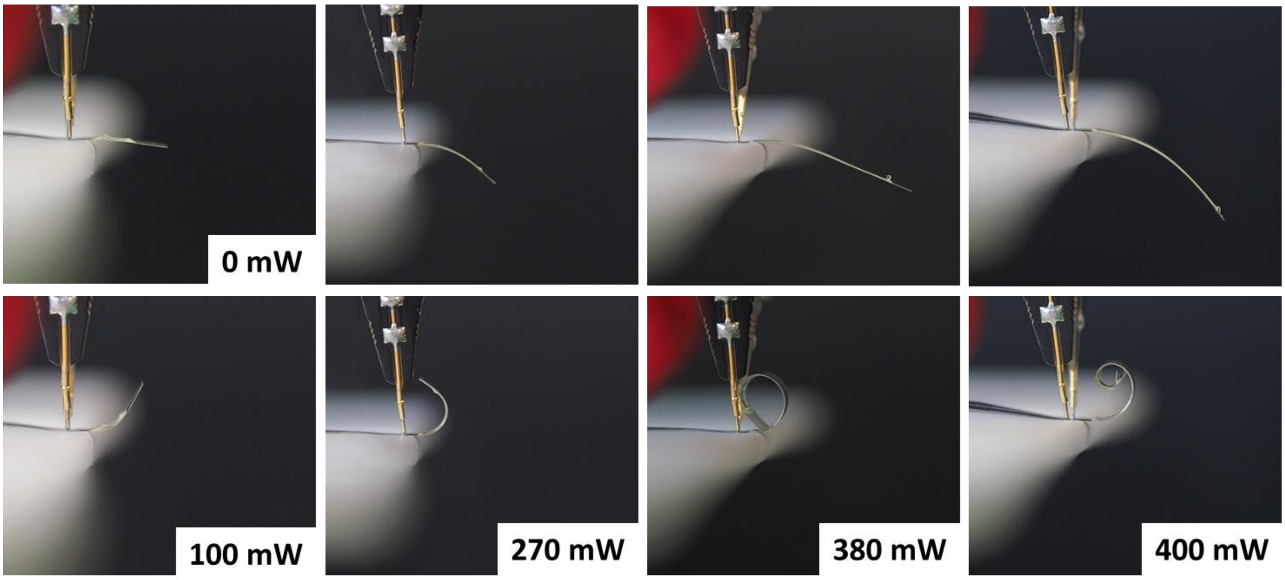

Figure 1. Cantilever actuation of single multilayer elements, fabricated with different geometries on PEN foil upon application of 0 mW (top) and maximum electrical power (bottom).

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Shape-Morphing Printed Electronics Enabled by Liquid Crystal Elastomers

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Haptics, soft robotics and human-machine interfaces are gaining more and more attention in the research panorama as new technologies contributing to enable more conformal and seamless integration with the physical world [1]. From this perspective, combining hybrid printed electronics with innovative substrate materials, capable of responding in predictable and programmable ways to one or more stimuli, is highly desired. These new materials will enable multifunctional soft hybrid electronic devices able to adapt to changes in the environment. In this work, we develop a process to use polydomain nematic liquid crystal elastomers (LCEs) as substrates for printed electronics. The mechanical response — soft-elastic plateau [2], actuation amplitude and temperature — of LCEs can be tuned by varying the chemistry of the synthesis reaction, and of the liquid crystal content, in particular [3]. By carefully co-developing the two-step crosslinking process and direct shape programming of the LCE [4] with the screen printing, curing and transfer of the electronic circuitry, we can create shape-shifting, soft electronic devices, capable of large reversible shape change upon the application of a thermal stimulus, being it external or produced by the embedded circuitry. This process is compatible with conventional printed electronics materials and techniques. Beyond design and optimization of the fabrication procedure, we also characterize the device's durability for longer-term use.

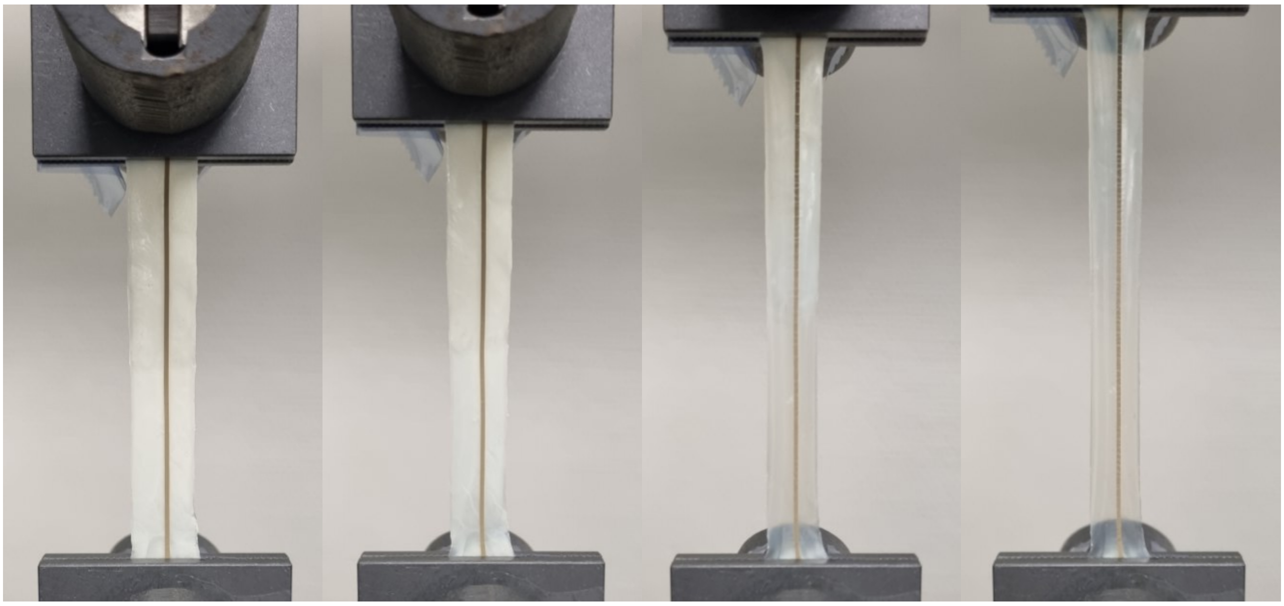

Figure 1. Tensile test frames at 0, 13, 20 and 26 %strain (left to right) of a 76 mm-long sample made of a conductive silver ink and encapsulant trace fabricated on the LCE substrate.

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When Liquid Crystal Networks Meet Chromonic Lyotropic Liquid Crystal Hydrogels

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While liquid crystal elastomers and networks (LCE/Ns) have shown great utility in soft robotics as artificial muscles, their potential in biomedical applications – such as tissue engineering and drug delivery – remains largely untapped. This can be partly attributed to two features of LCE/Ns: 1) the limited compatibility of LCE/Ns with biological environments filled with fluids, cells, and biomolecules, and 2) the typically non-porous nature of most LCE/Ns. This study focuses on actuators with improved biological compatibility and porosity by developing constructs composed of LCNs hybridized with liquid crystal hydrogels (LCHs). In our design, LCNs provide mechanical integrity and stimuli-responsiveness, while LCHs introduce structural porosity, enhance biocompatibility, and enable precise control over deformation. To manipulate LCHs' microstructure and program the deformation of hybrid actuators, we used magnetically aligned templates of chromonic lyotropic liquid crystals (CLLC) from disodium cromoglicate (DSCG) aggregates with positive magnetic susceptibility [1][2]. The desired morphology and alignment of LCHs were achieved by the polymerization and cross-linking of mixtures of acrylic acids and CLLCs, which were coated on LCN substrates, under external magnetic fields.

Our results revealed that the integration of LCHs into LCNs dramatically increases the porosity of the construct. Interestingly, the distinct alignment and stimuli responsiveness of LCN and LCH layers could be leveraged to obtain complex programmable deformation. For instance, LCHs aligned parallel to the planar director of splay LCNs increase their natural bending when exposed to external stimulation, while LCHs aligned with offset from the LCNs' director field induce dynamic twisting deformations. We believe that the inherent porosity and biocompatibility of LCHs can be used to expand the applicability of LCNs in biomedical applications, particularly in drug delivery, where precise stimuli-responsive actuation can enable controlled and localized release of therapeutic agents. Additionally, the ability of the system to safely interact with biological tissues offers significant promise for use in minimally invasive medical devices and adaptive implants [3][4].

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Photo-switchable ferronematic liquid crystal materials

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The recent discovery of ferroelectric nematic liquid crystals (NFLCs) has opened new possibilities in soft matter research.[1,2] A key feature of NFLCs resulting from their polar order is their high dielectric permittivity, which influences their response to electric fields.[3] Our research exploits the unique combination of high dielectric permittivity and fluidity in NFLCs to develop soft materials with tunable dielectric properties.[4] We developed a photo-responsive NF blend that allows for reversible tuning of permittivity upon light irradiation.[5] The compound DIO undergoes a nematic (N) to ferronematic (NF) phase transition via an intermediate liquid crystal phase classified as SmZ_A. In this material, the NF to SmZ_A phase transition is accompanied by a significant change in dielectric permittivity. Therefore, by synthesizing LC blends in which the NF and SmZ_A phases can be reversibly interchanged by light stimuli, we can achieve large and reversible changes in dielectric permittivity. The photo-responsive nature of these NFLCs combined with their efficient switching capabilities makes them suitable for creating dynamic surface topographies. This property is particularly relevant for soft robotics applications, where stimuli-responsive surface actuation is beneficial. Additionally, the ability to control the dielectric properties of LCs using light opens possibilities for the non-contact manipulation of soft materials which could lead to advances in adaptive surfaces.

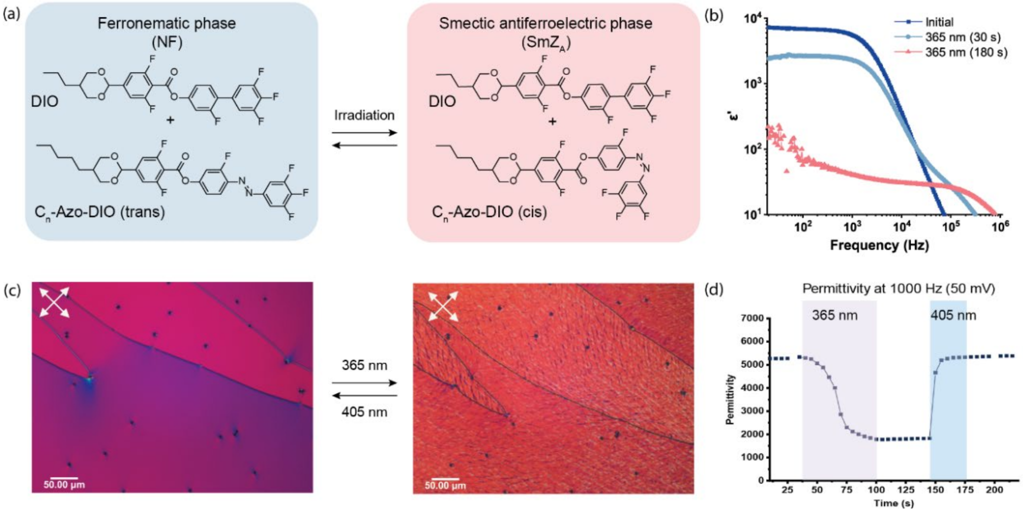

Figure 1. (a) Schematic of a liquid-crystal blend consisting of a ferroelectric nematic LC (DIO) and a phototunable DIO analogue (C_nAzo-DIO). (b) Decrease in permittivity in 4% C_3Azo-DIO:DIO LC blend upon irradiation. (c) Polarized optical images of a planar LC cell upon irradiation. (d) Temperature dependent dielectric permittivity spectrum on cooling of an LC blend after irradiation with 365 nm. (d) Time dependent spectrum of ε′ at 1000 Hz (50mV) upon irradiation of 365 nm and 405 nm.

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Design and Formulation of Liquid Crystal Elastomer Photopolymer Resins for Digital Light Projection Additive Manufacturing

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Liquid crystal elastomers (LCEs) are a novel class of stimuli-responsive materials that can change shape upon exposure to stimuli such as heat, light, and more. Various research has leveraged various additive manufacturing (AM) techniques to simultaneously form LCEs into desired geometries while enabling their alignment, with direct ink write (DIW), digital light processing (DLP), and two-photon polymerization (TPP) amongst the various AM techniques in which LCEs have been fabricated [1]. While the majority of literature has focused on synthesis of LCE feedstocks for DIW, these materials are unsuitable for DLP processing due to their high viscosity. As DLP of LCEs remains a fairly nascent field, many questions about the strategies to synthesize LCE feedstocks with suitable viscosities, thermal transitions, and subsequent actuation capability still remain. Here, we report our findings on development of LCE resins suitable for fabrication with the DLP technique. This includes evaluation into the reactive mesogen and spacer selection, oligomer size, and the use of additives on the actuation and printability of LCE structures. Overall, the tuning of these resins specifically for DLP enables fabrication of structures with finer features and increased complexity over that afford by other techniques, thereby unlocking new capability in LCE fabrication capability.

This work performed under the auspices of the U.S. Department of Energy by Lawrence Livermore National Laboratory under Contract DE-AC52-07NA27344. LLNL-ABS-872497.

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High Power Photo-actuators for Bio-inspired Flapping Wing Motion

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Traditional micro aerial vehicles often rely on tethered power sources or onboard batteries and dedicated control systems, which restrict their mobility and reduce adaptability in diverse environments [1]. To achieve a more lightweight and efficient autonomous flight system, light-driven soft actuators have emerged as a promising solution. Liquid crystal elastomers (LCEs) can undergo photothermal deformation, and when integrated with built-in light shielding for negative feedback, they enable self-sustained oscillations under continuous light exposure [2]. By optimizing the LCE formulation and structural design—including photothermal gradient tuning—we achieved stable oscillatory motion at tens of hertz under constant illumination, with a power density comparable to that of typical insect muscles. Furthermore, we enhanced the aerodynamic efficiency of a bioinspired flapping-wing system by optimizing asymmetric wing motion, reducing energy loss, and improving thrust generation. These results highlight the potential of photo actuated LCEs for high-power density, bioinspired aerial robotics, paving the way for next-generation soft flapping-wing micro air vehicles with improved autonomy and adaptability.

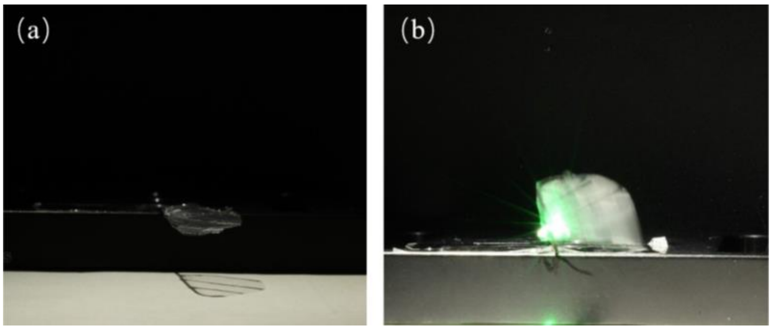

Figure 1.(a) Static and (b) oscillating photo-actuators for flapping wing motion.

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Self-Oscillating Propulsion Discovered via Evolutionary Optimization of Light-Powered Swimming Soft Robots

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Soft robotics offers a promising platform for bio-inspired locomotion, but optimizing their performance remains a challenge, especially when multiple interdependent parameters influence movement in ways that are difficult to model. In this talk, I will present the optimization experiment in which light-powered robots made of liquid crystal elastomers were subjected to an evolutionary selection process, using real-world performance data as a fitness function. Instead of relying on numerical simulations, we directly integrated experimental feedback into two independently conducted evolutionary optimizations, one using Genetic Algorithm (GA) and the other using Particle Swarm Optimization (PSO), to iteratively refine robot designs based on their measured swimming speeds in underwater conditions.

We optimized key parameters defining both the robot's structure (e.g., film thickness, molecular alignment, and dye concentration) and the external actuation conditions (e.g., laser power, scanning frequency). Each optimization cycle consisted of fabricating and testing eight robots, with their measured swimming speeds determining the parameters of the next generation (see Fig. 1). Across four optimization iterations, both GA and PSO significantly improved robot performance, increasing locomotion speed by several times. Interestingly, optimization process led to the unexpected emergence of a self-oscillating mode of locomotion. In this mode, robots exhibited continuous oscillations synchronized with the laser beam, closely following its movement. While this was not the fastest form of propulsion, it presents intriguing possibilities for precision control and adaptive locomotion strategies.

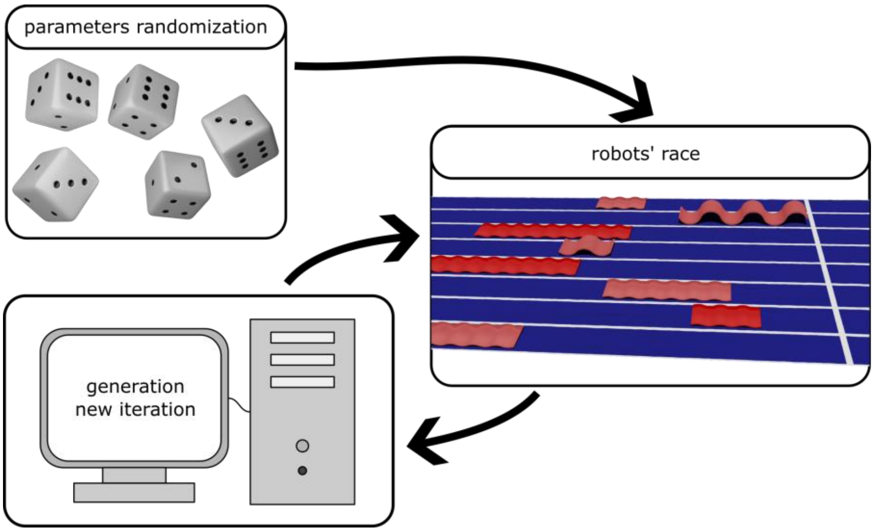

Figure 1. Schematic of the experiment. The optimization began with a randomized set of robots. Their swimming speeds were measured and used as fitness function values in the optimization algorithm, which then generated new robot designs for subsequent measurements.

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Microscale Photolithography of LCE Soft Actuators and Robots with Magnetically Driven, Discretized Alignment Domains

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Abstract:

In the domain of Liquid Crystal Elastomers (LCEs), the effective downscaling of LCEs is essential to unlocking their practical applications as soft robots and actuators in biomedical and MEMS devices. Of equal importance, the alignment-fabrication strategies must be versatile, high throughput, and cost-effective. In recent literature, state-of-the-art photo-printing equipment such as DLW, DMD, and DLP coupled with patterned surfaces or external fields exemplify promising alignment fabrication strategies to achieve downscaling [1-4]. However, they are tremendously expensive and inaccessible to many. Henceforth, the inexpensive prototype developed in the present work showcases an alignment-fabrication strategy that utilizes photolithography and magnetic fields to obtain microscale LCE actuators and soft robots with high throughput. By combining stepwise photopolymerization through a photomask with a variable external field, the careful choice of mask design and director discretization demonstrates versatile programmability. Herein, this straightforward approach is used to produce a variety of LCE constructs with discretized alignment domains from the millimetre to micrometre scale, exhibiting fast photothermal and photochemical actuatable shape-change.

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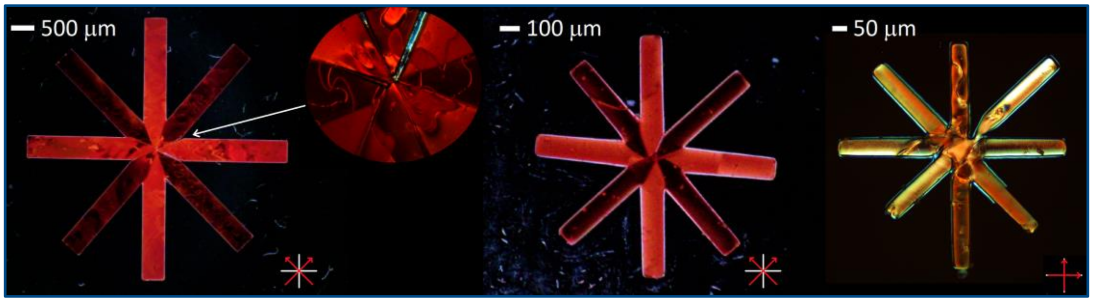

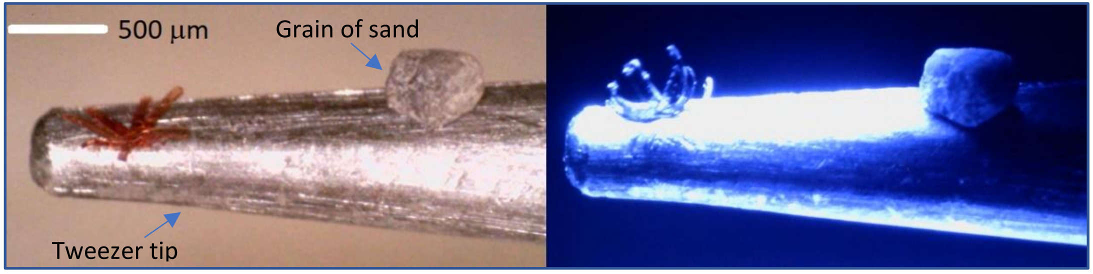

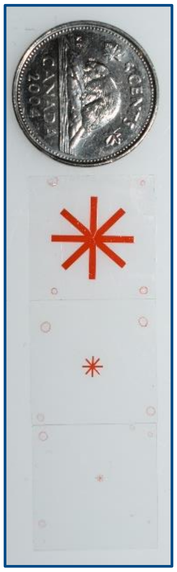

Optical Sensing Enabled by Azobenzene Isomerisation Kinetics

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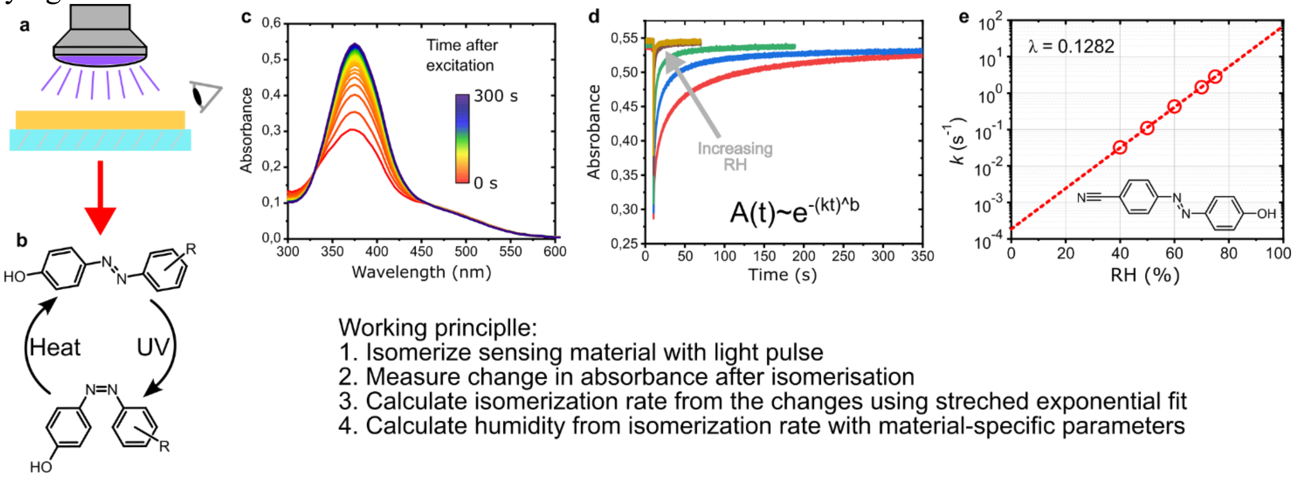
Photoswitches are molecules capable of reversible structural transformation between different states upon exposure to light. When incorporated into materials they enable photocontrol over several material properties and introduce new functions from photoactuation to self-healing with light. [1,2] Azobenzenes are a class of photoswitches that photoisomerize between a stable and a metastable isomer, undergoing large molecular motions. In addition, azobenzene can be relatively easily modified by substitution on the phenyl rings to change the photoswitching properties such as isomerization wavelengths and the thermal isomerization rate of the metastable isomer.

Unrelated to their ability isomerize, azobenzenes have been utilized as colorimetric sensors, where the absorption spectrum changes upon the binding of an analyte to the azobenzene probe molecule. The isomerisation kinetics of azobenzene are known to be sensitive to environmental factors, such as sol-vent polarity, pressure, and pH. Still, the only reported example of sensing using isomerization kinetics is the optical humidity sensing with hydroxyazobenzene-containing polymer thin film demonstrated by Poutanen et al. [3] Remote optical measurement of the isomerisation rate is simple due to large differences in the absorption of the isomers. Following the discovery of humidity-sensing by isomerization kinetics, we have worked towards optical humidity sensing devices, commercialization of the technology, and deeper understanding of the humidity-sensitive azobenzenes.

We present a library of azobenzenes exhibiting varying humidity-sensitive thermal isomerisation rates owing to different substitution and trends among them. In addition, we show how the water absorption characteristics of the polymer matrix affects the sensing performance and in turn how the azobenzene content affects the water absorption. Our findings enable basic strategies to control the photochemical properties of azobenzene thin films to be suitable for optical humidity sensing in varying conditions.



Working principlle:
1. Isomerize sensing material with light pulse
2. Measure change in absorbance after isomerisation
3. Calculate isomerization rate from the changes using streched exponential fit
4. Calculate humidity from isomerization rate with material-specific parameters

Figure 1: a) Illustration of azobenzene thin film, b) isomerisation scheme for hydroxyazobenzene, c) changes in absorption spectra after UV excitation, d) effect of relative humidity on isomerisation kinetics and the form of fitting equation, e) systematic humidity dependency of thermal isomerisation rate for a hydroxyazobenzene with material-specific parameter λ describing the strength of humidity sensitivity.

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Phototunable polarization volume gratings via hydrazone-based molecular chiral switches

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Polarization volume gratings (PVGs) have gained significant research attention recently due to their potential application as diffraction couplers in augmented reality technologies [1]. Additionally, recent studies have highlighted the use of PVGs in spectroscopy applications [2]. In most reported studies, PVGs have fixed optical properties or they are tunable with electric fields. However, since PVGs consist of a slanted cholesteric phase, their optical behavior can be tuned by adjusting the cholesteric pitch that is typically controlled by the concentration of a chiral dopant. This presents an opportunity to modulate PVG properties using light-responsive chiral dopants. Hydrazone-based molecular switches are particularly promising, as they undergo reversible E/Z isomerization upon light exposure (Fig. 1a), enabling precise and reversible control over the cholesteric pitch [3]. Importantly, these isomers exhibit high thermal stability, allowing the material to operate effectively across a wide temperature range.

In this work, we incorporated chiral hydrazone photoswitches into PVGs to achieve light-driven tunability. External irradiation with UV and blue light induced reversible changes in the isomer ratio, resulting in corresponding modulation of the grating's diffraction efficiency across different wavelengths in the whole visible spectrum (Fig. 1b). Notably, while diffraction efficiency is influenced by the cholesteric pitch, the diffraction angle remains determined solely by the period of the anchoring pattern. In order to use the grating without a second photopatterned substrate or control the diffraction efficiency only in a small spot of the sample we also studied the possibility of creating polymer stabilized phototunable PVG.

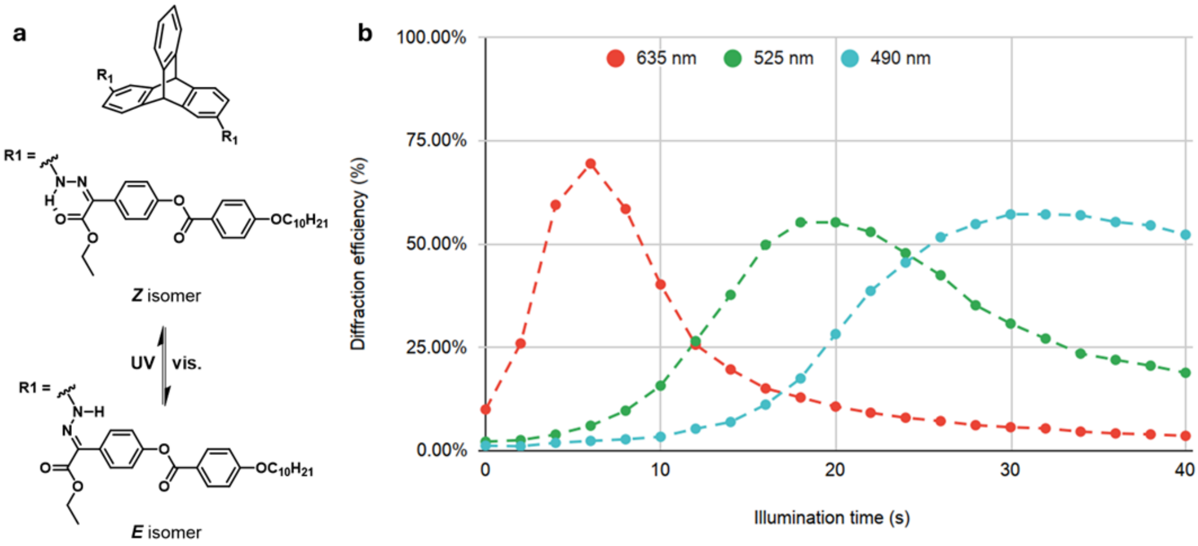

Figure 1. a) The photoisomerization process of the triptycene-hydrazone chiral dopants.
b) Diffraction efficiencies for 490 nm, 525 nm, and 635 nm light reflected from a PVG sample during illumination with 435 nm light.

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A computational model for halogen bond-based stimuli-responsive polymer networks

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Halogen bonding is a means to integrate stimuli responsiveness and self-healability into polymer networks via enabling the formation of dynamic crosslinks sensitive to, e.g., temperature. Motivated by recent advancements by Guo et al. [1-3] in using halogen bonding and by the open questions remaining with the molecular mechanisms involved with the stimuli responsiveness in these dynamic crosslinks, we pursue computational methodology advances in modelling halogen bonding in polymer networks. Specifically, the major challenge is to achieve accurate yet computationally efficient models that would allow computer simulations of large-scale, complex polymer systems while taking the short-range halogen bonding sufficiently accurately into account.

We discuss here the construction and verification of a modelling approach to halogen bonding in polymer networks. Specifically, we combine quantum mechanics (QM) calculations to resolve electronic structure details for halogen-bond donor species in Refs. [1-3]. The QM information is then incorporated into a corresponding all-atom empirical force-field-based model for subsequent classical molecular dynamics (MD) simulations. We report our progress in benchmarking the proposed two-pronged QM-MD approach and address its potential use for further study of molecular mechanisms and effects of halogen bonding in stimuli-responsive polymer networks.

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Leveraging catechol chemistry to tackle toughness-softness-work capacity tradeoff in reprogrammable liquid crystal actuators

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Dynamic chemistry endows liquid crystal elastomers (LCEs) with reprogrammability, enabling the reversible modulation of actuation modes to adapt to diverse tasks and enhancing sustainability and lifecycle management. However, balancing toughness, softness, and work capacity remains challenging due to their inherent tradeoff, as these properties are essential for achieving high-performance and stable actuation. Here, inspired by mussel coordination chemistry, we design a macromolecular crosslinker that combines covalent crosslinking with coordination bonds to tackle this challenge. The optimized LCE achieves exceptional toughness of 28.5 MJ/m³ and low Young's modulus of 3.1 MPa, with high-temperature toughness exceeding 9.3 MJ/m³ at 90°C (25°C above phase transition temperature, T_i) and reaching 5.5 MJ/m³ at 120°C (55°C above T_i), while maintaining work capacity of 416 kJ/m³. Increasing coordination bond content further improves toughness (up to 67.0 MJ/m³) without significantly altering modulus or work capacity. Additionally, incorporating different metal ions provides a strategy akin to stem cell differentiation, transforming a single base material into variants with distinct properties. This enables spatially heterogeneous materials, paving the way for highly integrated actuators with multifunctionality.[1]

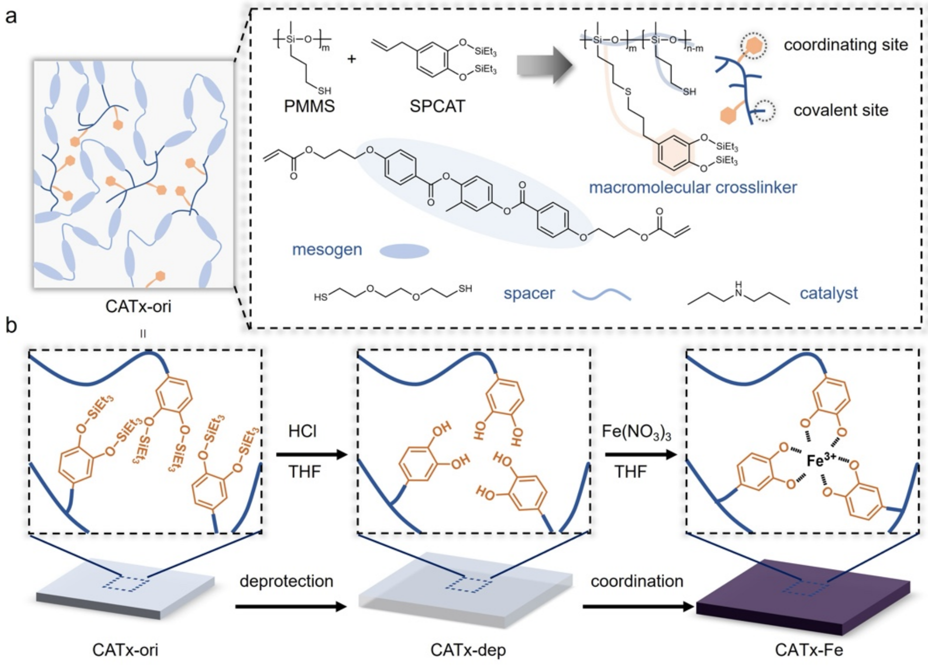

Figure 1. Synthesis and preparation of LCE networks. (a) Overview of the synthesis of macromolecular crosslinker, construction of the original LCE. (b) The process of deprotection and coordination to form the final tough but soft LCE.

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Thermally Gated Covalent Adaptivity in Liquid Crystal Elastomers for Stable Actuation

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Liquid crystal elastomers (LCEs), with reversible actuation of large and anisotropic deformation, have surged in smart materials such as soft robotics, sensors and artificial muscles. LCEs incorporating dynamic covalent bonds (DCBs) endowing network with rearranging ability through reversible bond exchange, facilitating the fabrication of soft actuators with tailored actuation modes and reprogrammability. However, unintended activation of DCBs during actuation, particularly under thermal perturbations, remains a critical challenge, as it damages actuation stability which arises catastrophic failure and potential security risks in practical applications. Present strategies in enhancing actuation stability either achieve only temporary stability or sacrificed reprogrammability or actuation performance. Here, we propose a strategy incorporating catalyst-free α-AC/A DCB of high temperature active-threshold to fabricate stable exchangeable LCE actuators with thermally gated behavior. This design exhibits a “thermal gate” at 120 °C with inert bond exchange below this threshold, yet rapidly activated at 160 °C. The integrated permanent crosslinks further prevent unintended chain slippage, ensuring topological stability. The resulting exchangeable LCE could be fabricated to actuators efficiently and exhibiting unprecedented durability at 120 °C (sustaining 10,000 actuation cycles). The switches between reprogrammability and actuation stability are long-standing reversible, meeting the demands of long-term service without compromising its reprogrammability.[1]

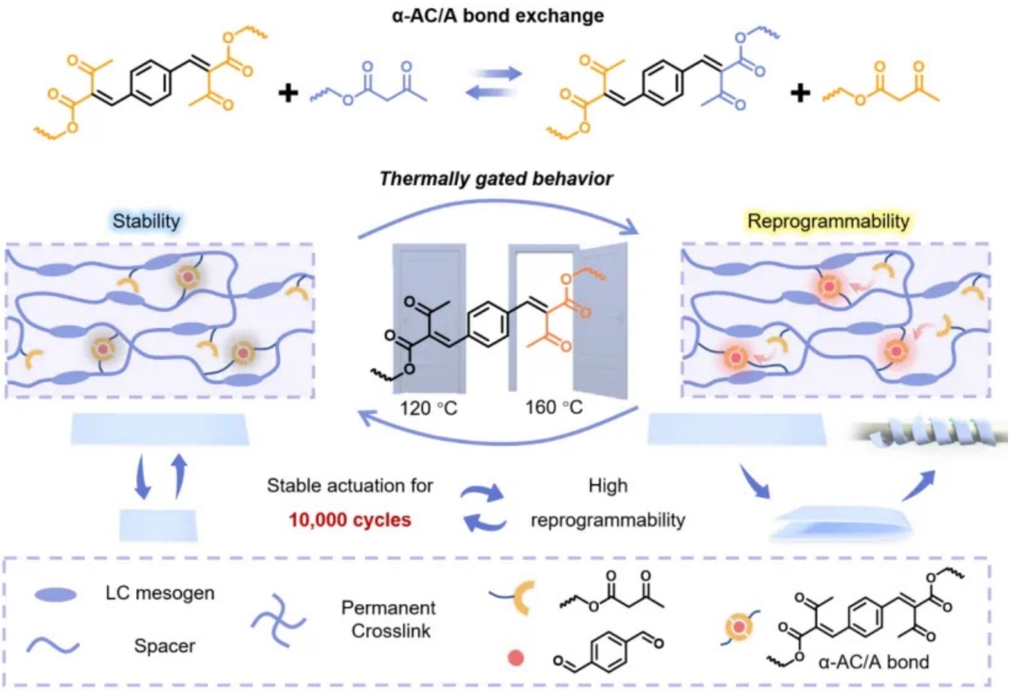

Figure 1. Illustrations of stabilization strategies in xLCE.

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