Temperature-controlled polymer nanopatterning for 4D tunable photonics

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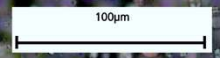
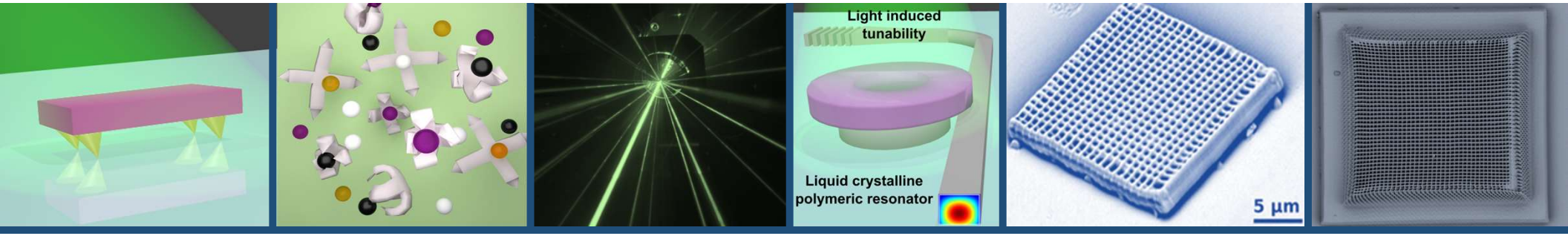
INRiM ISTITUTO NAZIONALE DI RICERCA METROLOGICA

Kopaonik, 14th March 2023

Lens European Laboratory for Non-Linear Spectroscopy

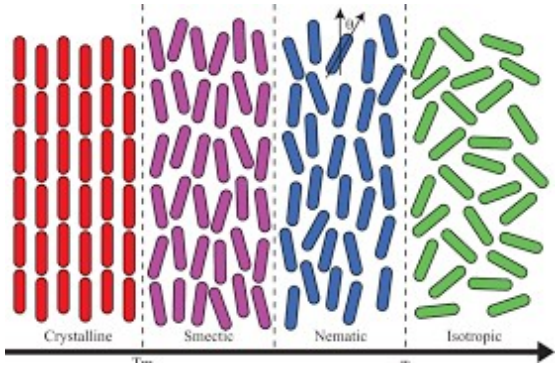


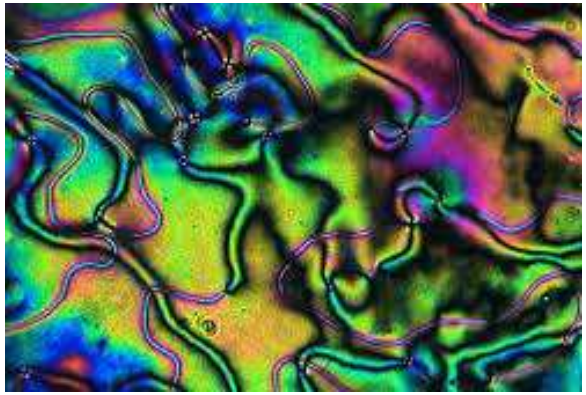


From micro-robotic to photonic applications using 4D responsive nanostructured materials

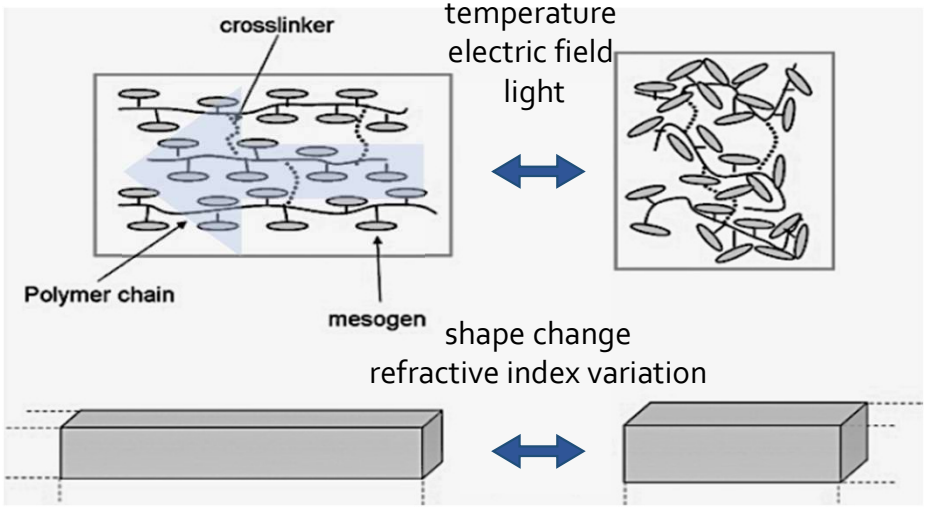
liquid crystals and liquid crystalline networks

Liquid crystals

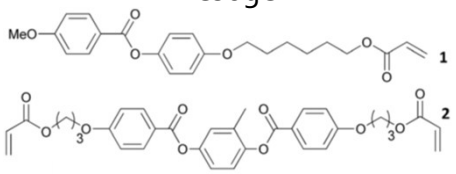




Liquid crystalline networks



Mesogen



Cross-linker

Azo-dye

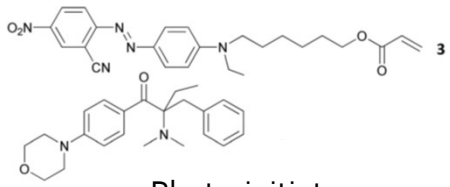
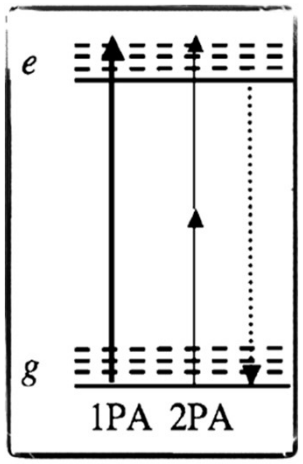


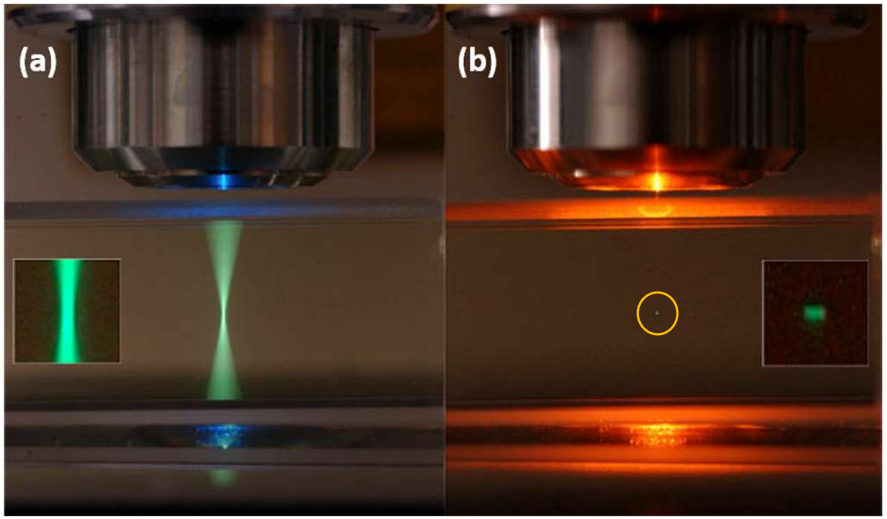
Photo-initiator

two-photon direct laser writing (TP-DLW)

Two-photon absorption polymerization for 3D (or 4D) nano patterning

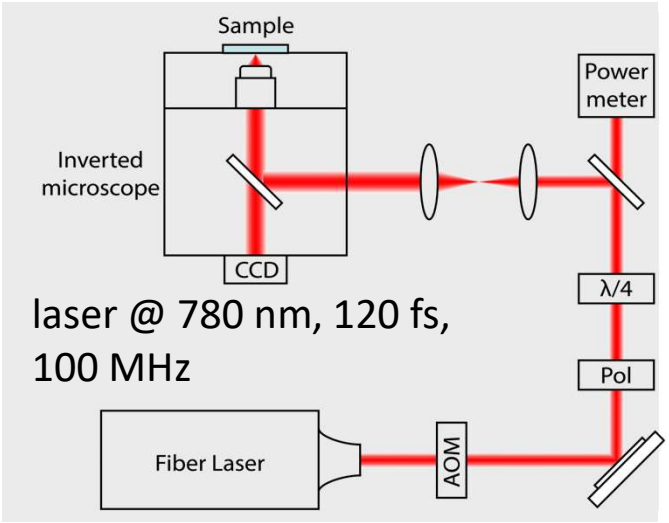


Single photon excitation Two photon excitation



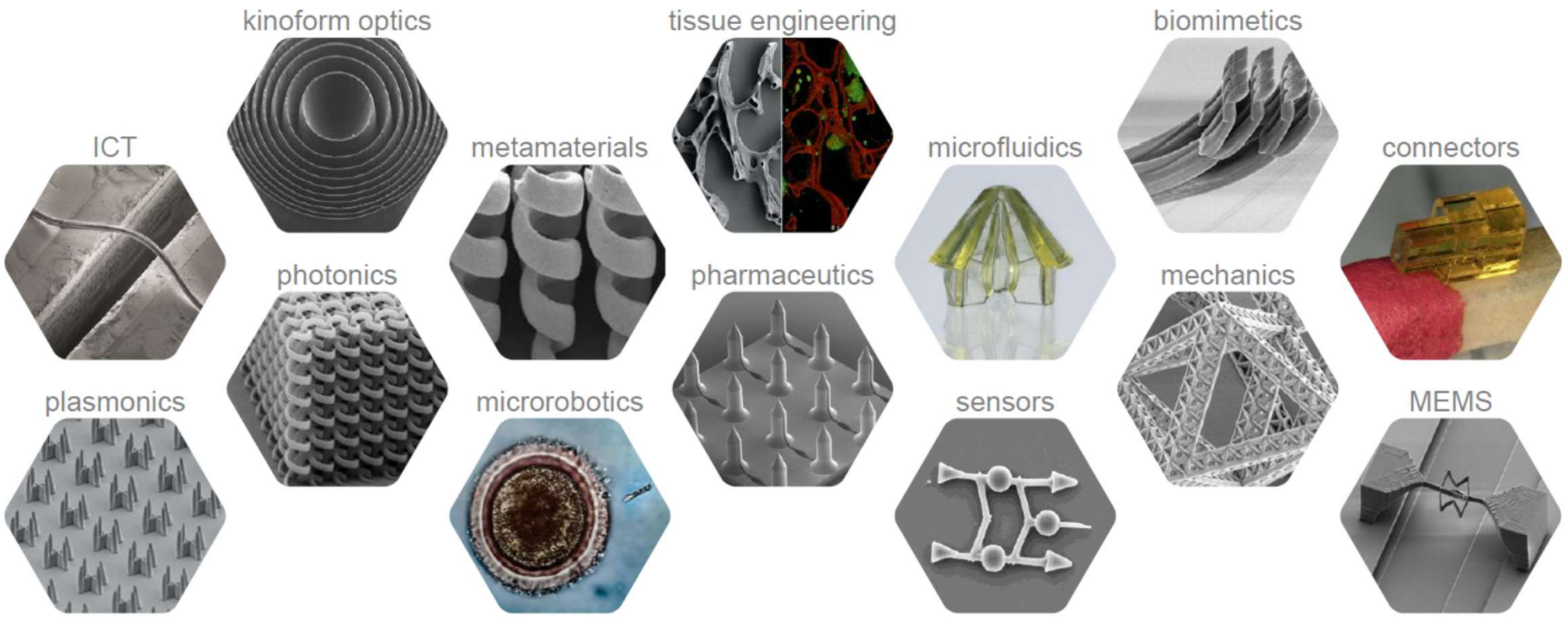
$$n^{(1)} = \sigma(\nu) N_g \frac{I}{h\nu}$$

$$n^{(2)} = \frac{1}{2}\delta(\nu) N_g \left(\frac{I}{h\nu}\right)^2$$

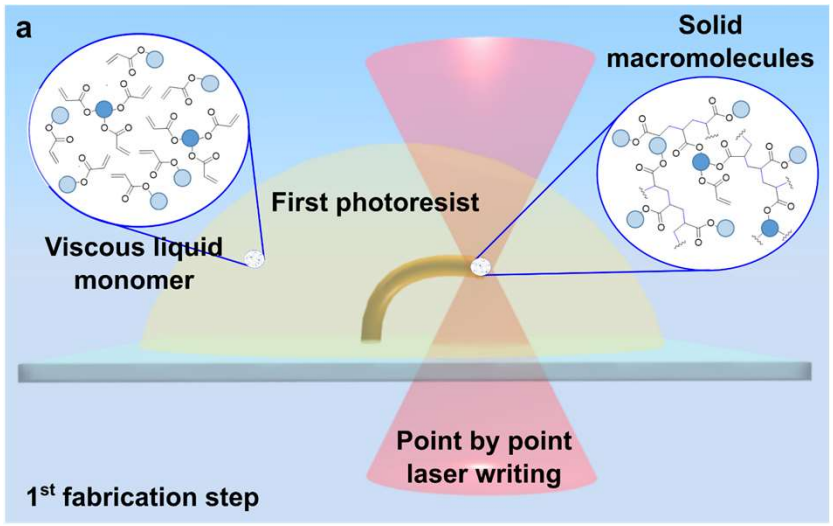


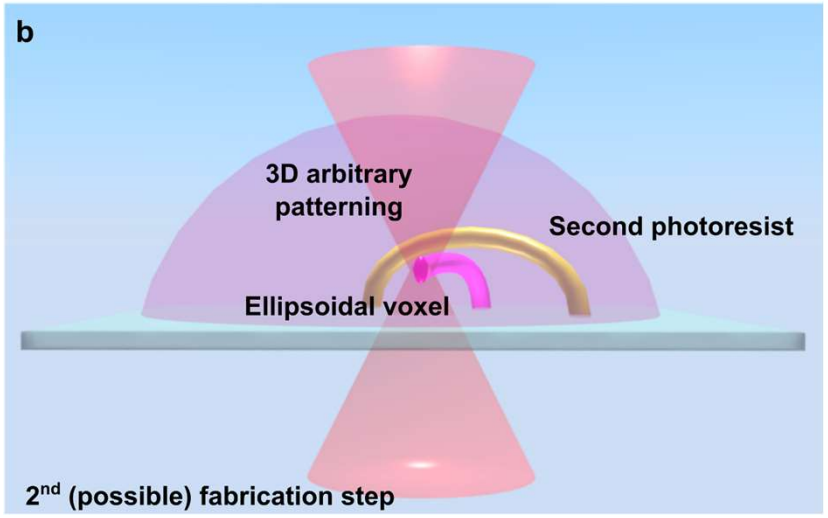
two-photon direct laser writing (TP-DLW)

Glassy resists

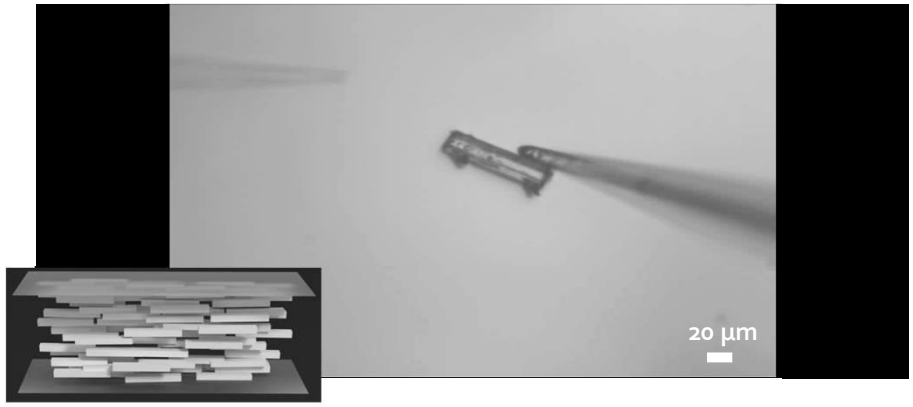


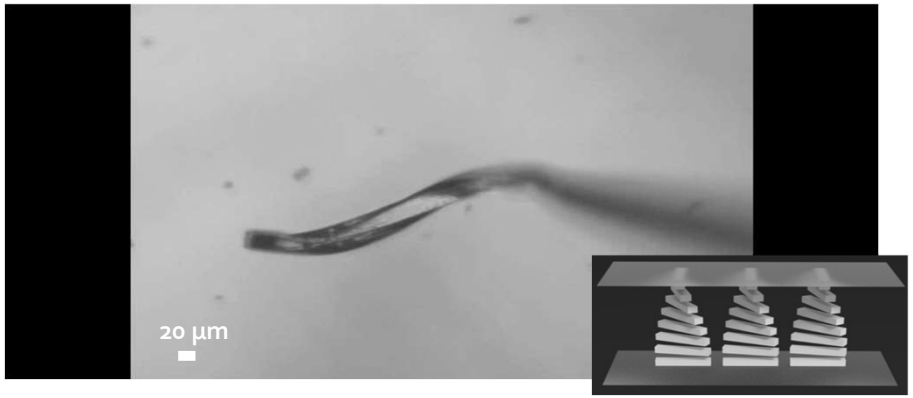
two-photon direct laser writing (TP-DLW)

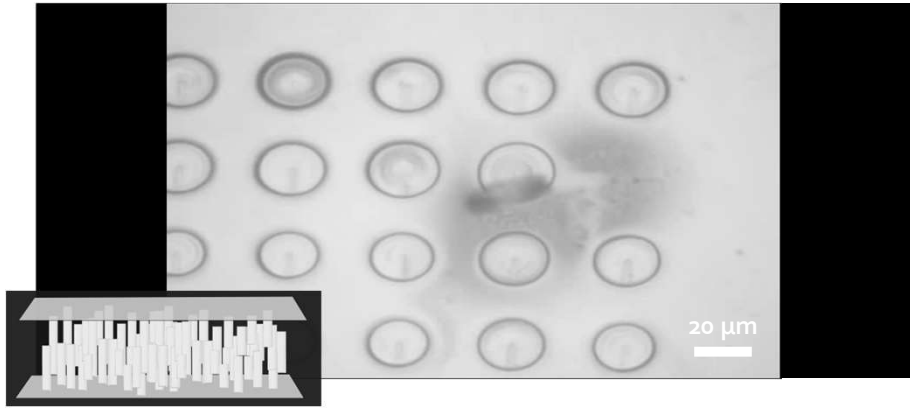


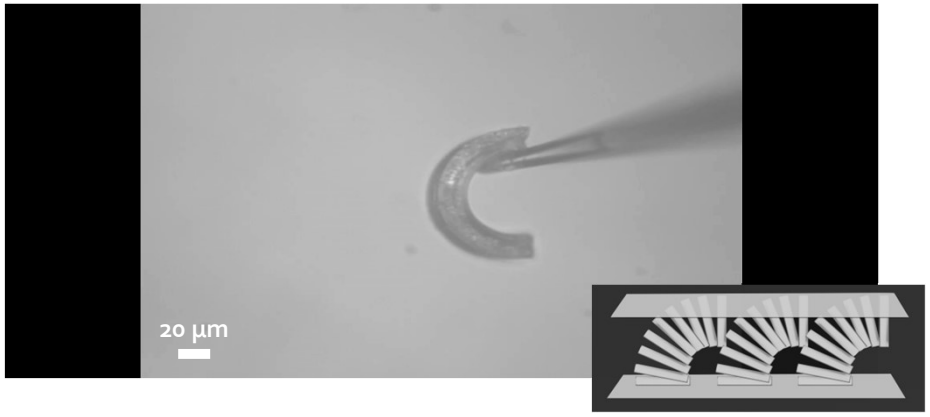


liquid crystalline network: alignment control

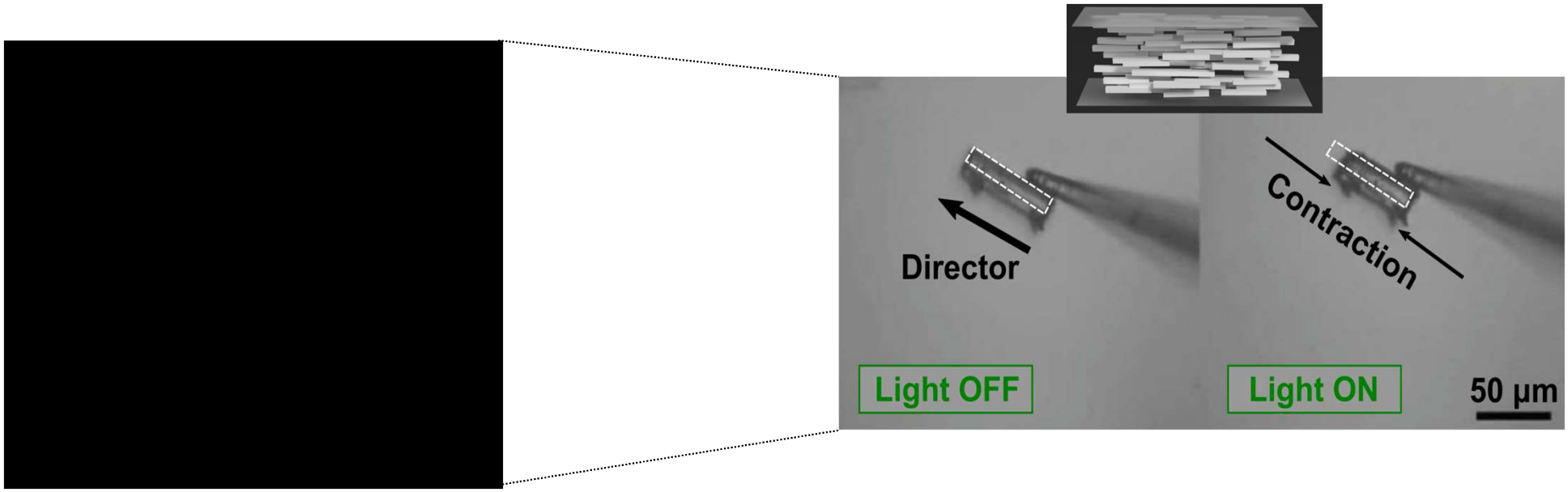






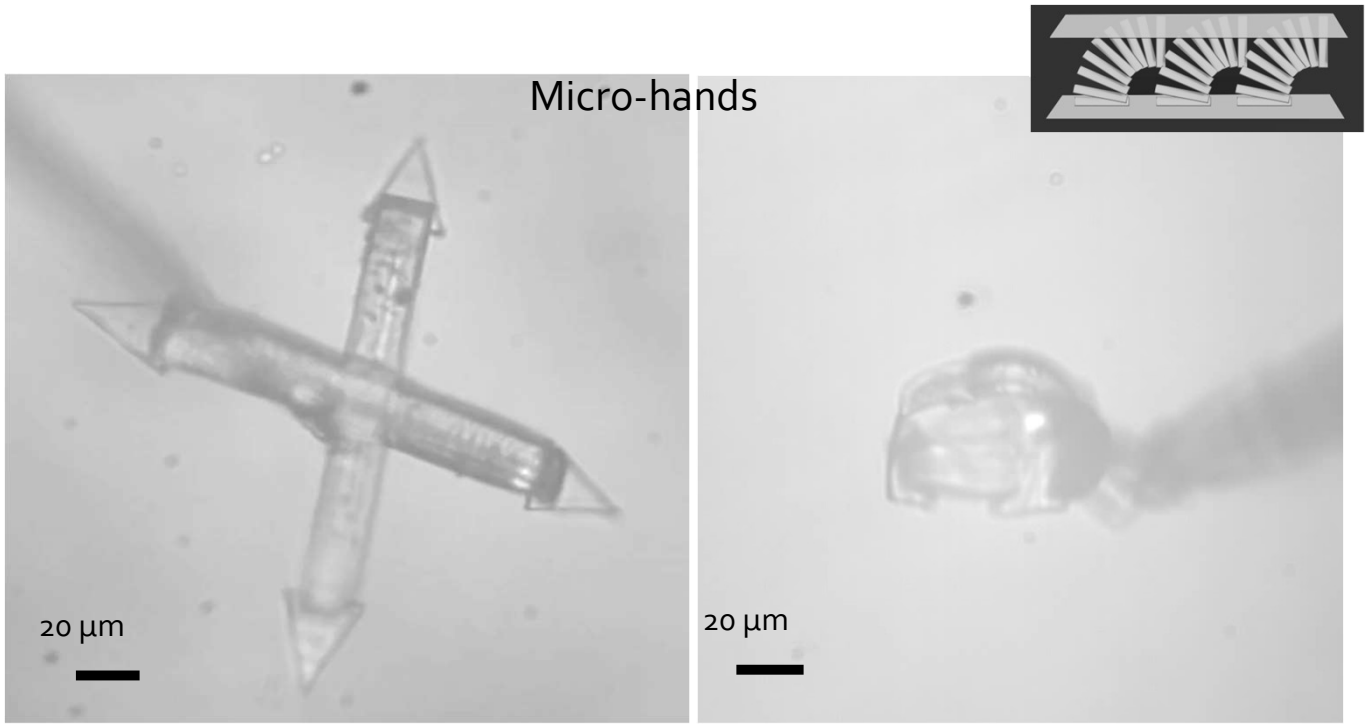


From microrobotics



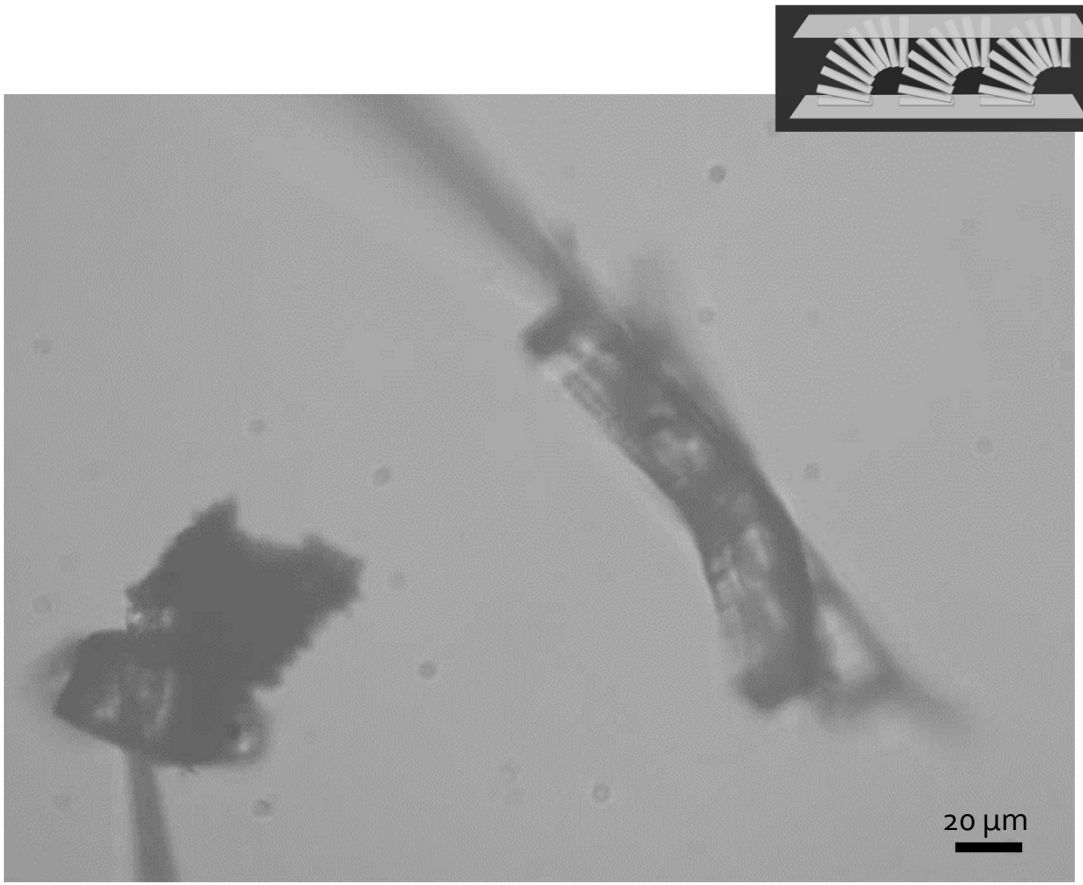
H. Zeng et al., *Adv. Mater.* **2015,** 27.26: 3883

From microrobotics



D. Martella, S. Nocentini et al., *Adv. Mater.* **2017**, *29.42: 1704047;*

From microrobotics



Laser intensity under activation threshold

To polymer photonics

Good optical properties

Easy manufacturing with diverse lithographic techniques

Tailored chemical design

Multifunctional platforms

Cheap

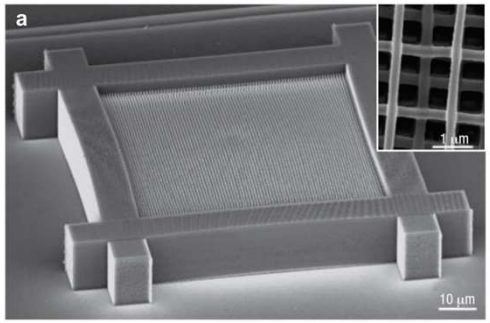
Complementary to Silicon photonics

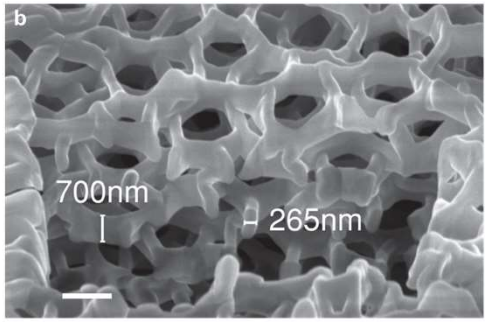
S. Nocentini et al., "3D printed soft materials for photonics", *Adv. Opt. Mater.* **2019,** 1900156.

3D polymer photonics

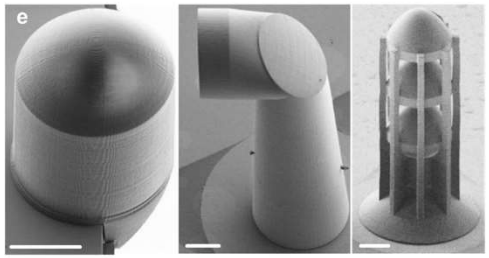
Glassy resists

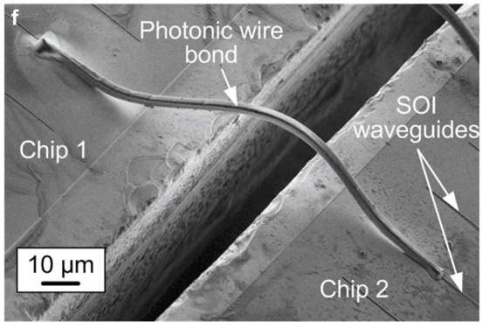
Ordered and disordered photonic crystals

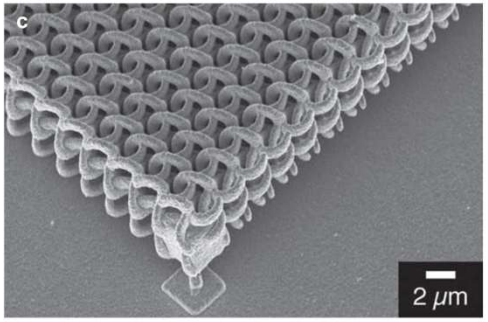


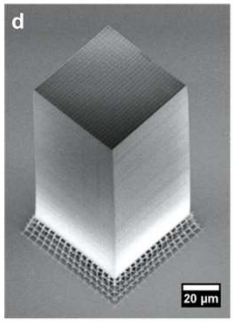


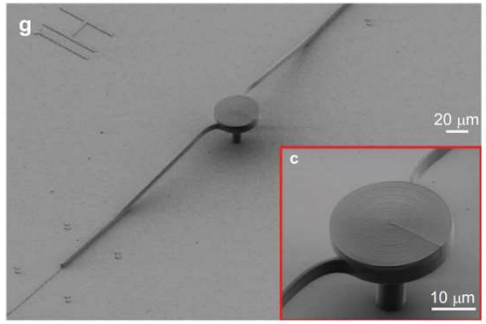
Optical and photonic components for integrated circuits

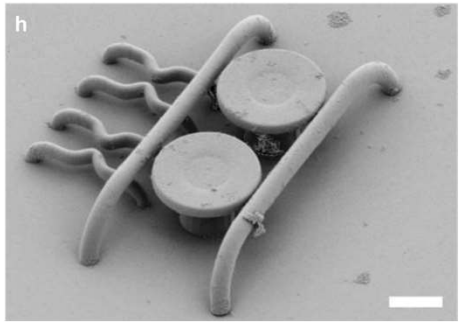








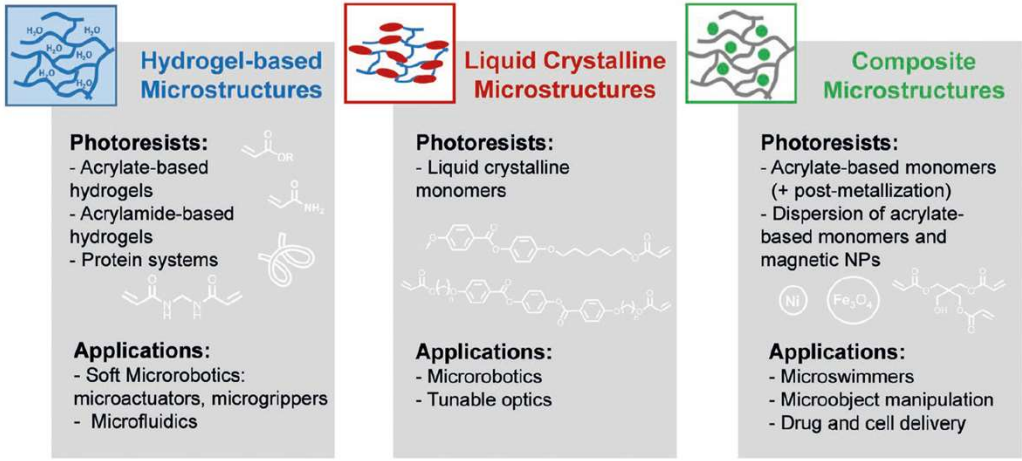


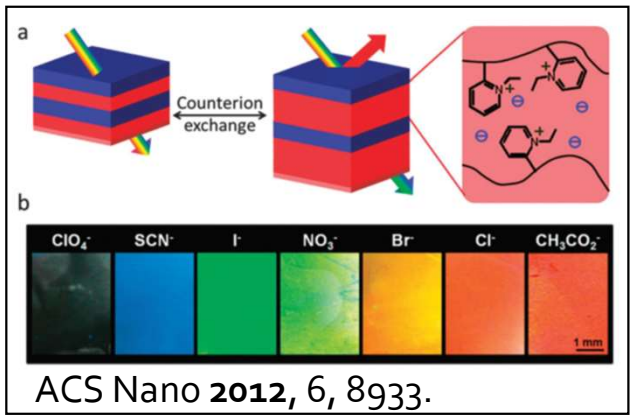


a) *Nat. Mater.* **2004,** *3*, 444. b) *Adv. Opt. Mater.* **2014,** *2*, 115. c) *Adv. Mater.* **2011,** *23*, 3018. d) *Adv. Opt. Mater.* **2014,** *2*, 226. e) *Nat. Photonics* **2018,** *12*, 241. f) *Opt. Express* **2012,** *20*, 17667. g) *Light: Sci. Appl.* **2014,** *3*, e175. h) *Sci. Rep.* **2013,** *3*, 1577.

reconfigurable polymer photonics

Stimuli-responsive polymers for dynamic reconfiguration

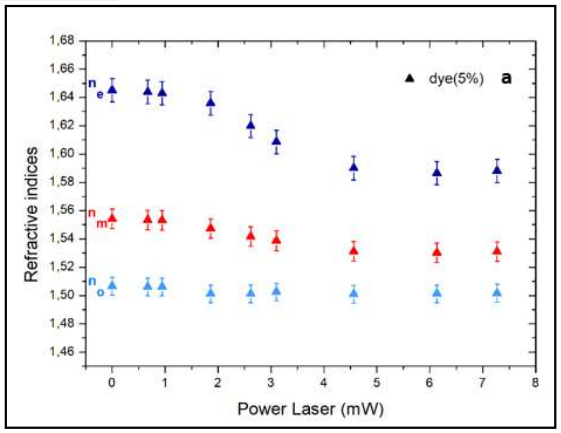




ACS Nano **2012**, 6, 8933.

Geometry or Refractive index

LCN:
Birefringence control
Reversible anisotropic shape change

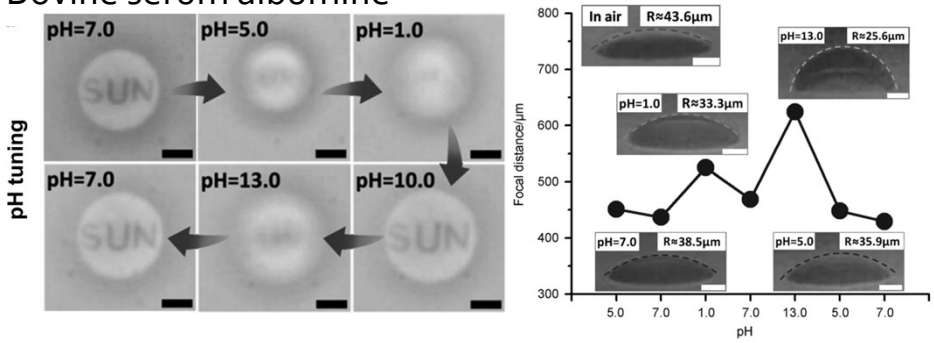


Spiegel, C. et al, (2020). 4D printing at the microscale. *Advanced Functional Materials*, *30*(26), 1907615.

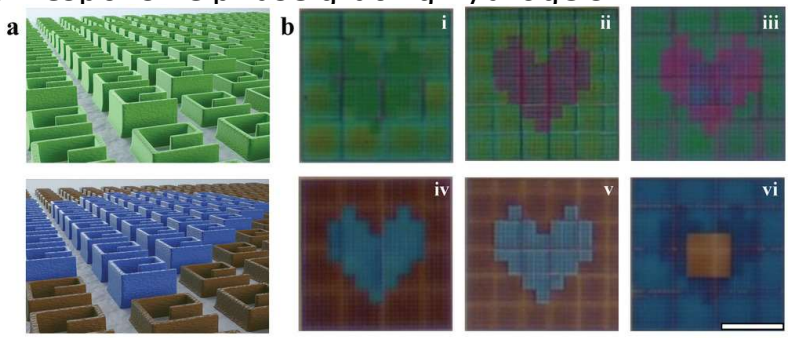
4D polymer photonics

Responsive resists

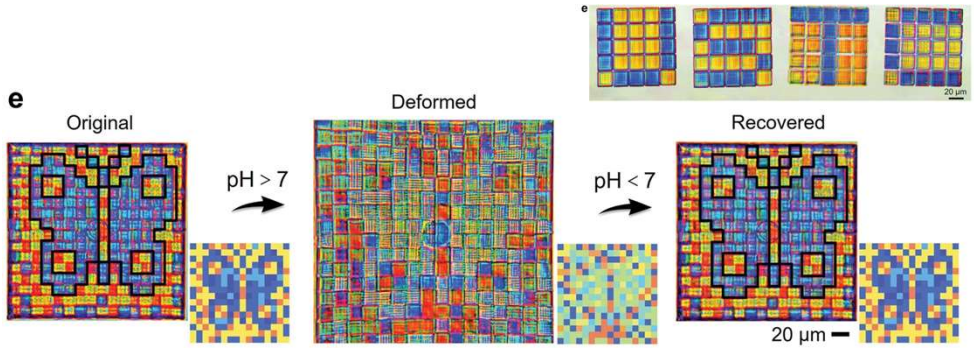
Bovine serum albumine[1]



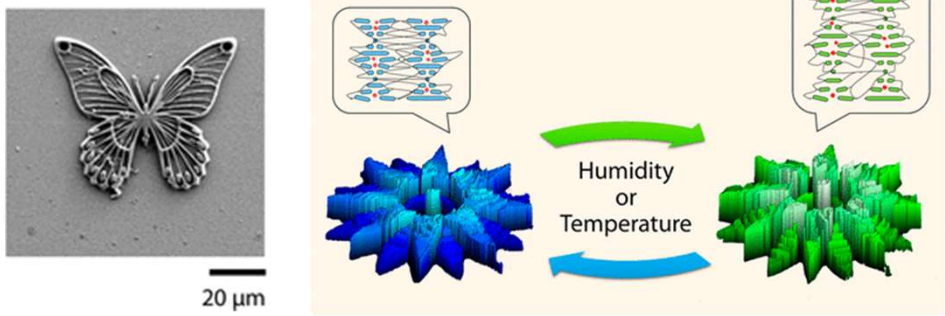
Vapour responsive phase grating hydrogels[2]



3D nanopatterned colored hydrogels[3]



Cholesteric Liquid Crystals[4]

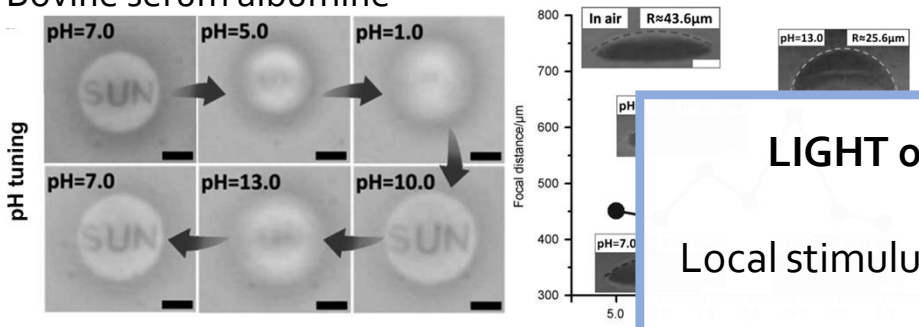


1. *Angew. Chem., Int. Ed.* **2012,** *51,* 1558. 2. *Adv. Funct. Mater.* ***2023,*** 2211735. 3. *Small* ***2022,*** p.2204630.
4. *ACS Nano* **2020,** 14, 8, 9832–9839.

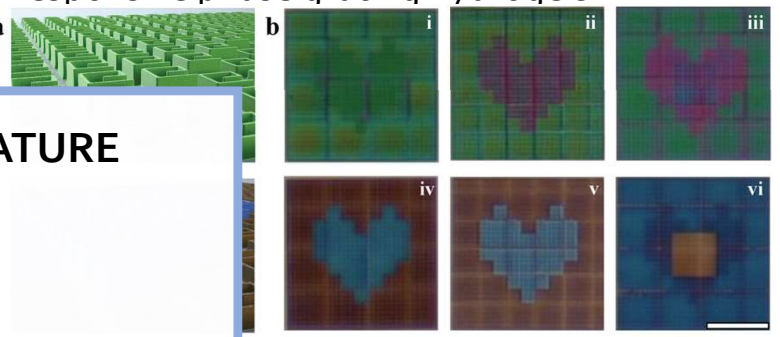
4D polymer photonics

Responsive resists

Bovine serum albumine[1]



Vapour responsive phase grating hydrogels[2]



LIGHT or TEMPERATURE

Local stimulus (L)

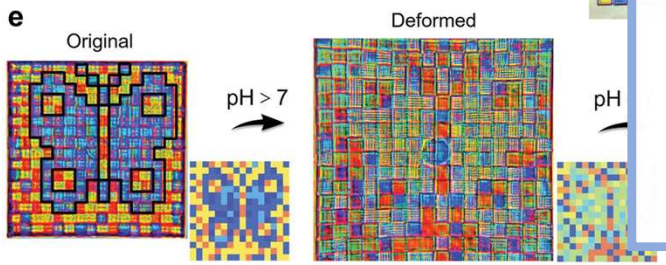
Space and time modulation (L)

Multi-parametric control (L)

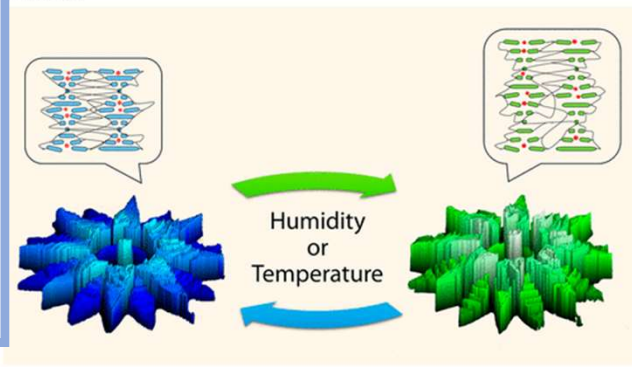
Non-invasive and remote actuation

Dry environments

3D nanopatterned colored hydrogels[3]



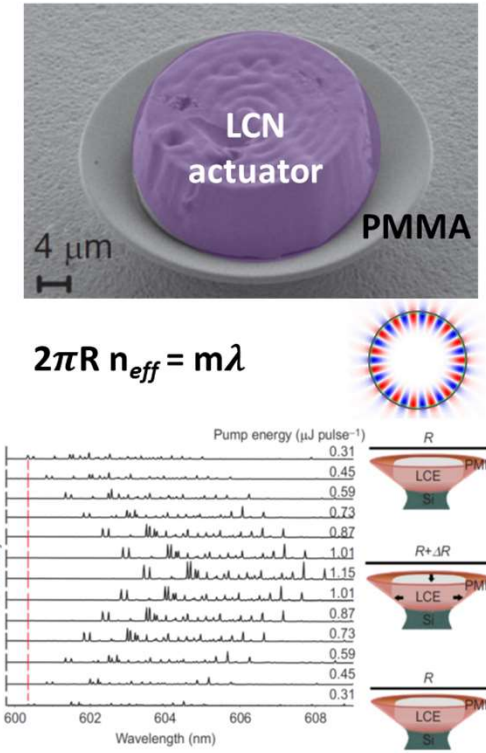
Cholesteric Liquid Crystals[4]



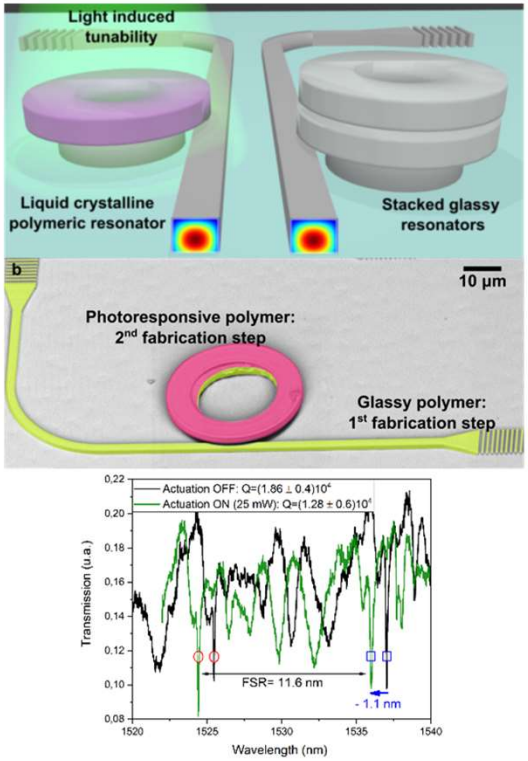
1. *Angew. Chem., Int. Ed.* **2012,** *51,* 1558. 2. *Adv. Funct. Mater.* ***2023,*** 2211735. 3. *Small* ***2022,*** p.2204630.
4. *ACS Nano* **2020,** 14, 8, 9832–9839.

Liquid crystalline networks for photonics

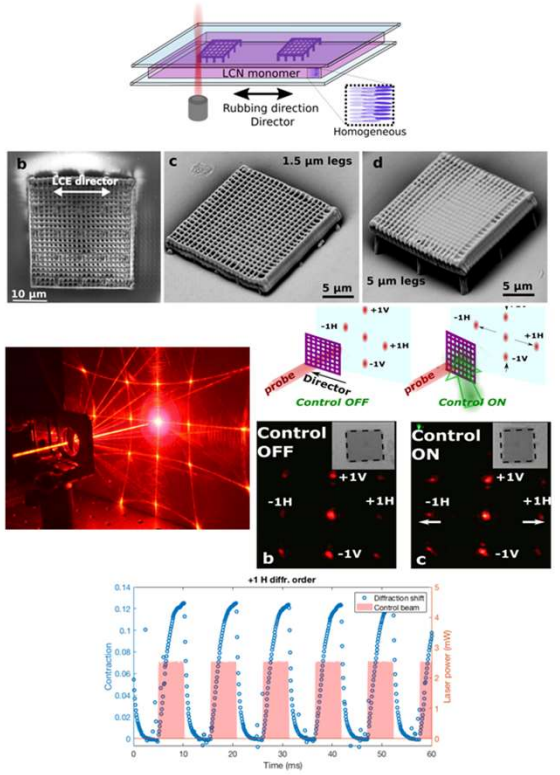
A light tunable microlaser



Optically controlled 3D photonic circuits



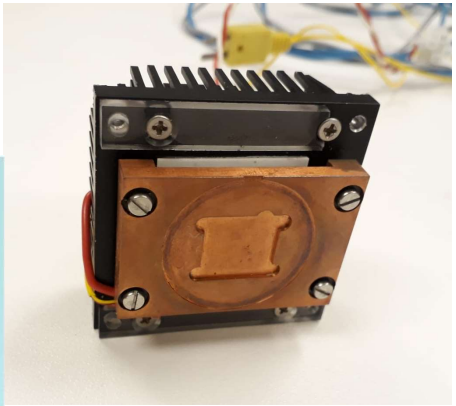
A light controlled beam steerer

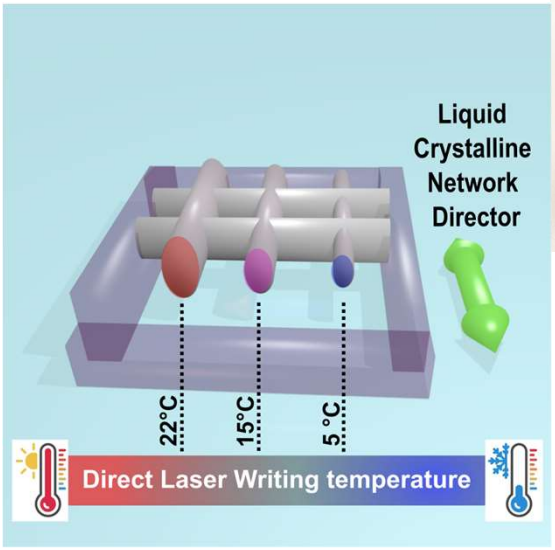


Flatae A. M., et al. "*Light: Science & Applications* **2015,** 4.4, e282; Nocentini S., et al., *ACS Photonics* **2018** 5.8, 3222; Nocentini S., et al., *Advanced Optical Materials* **2018,** 6.15, 1800167

temperature ruled two photon polymerization

NEED: enhance resolution, stability and reduce swelling

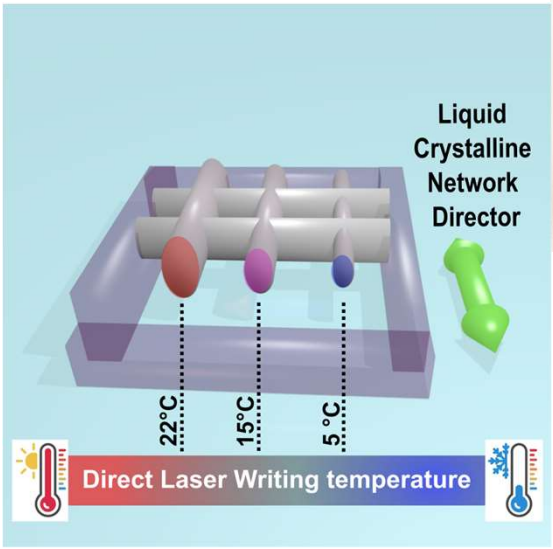


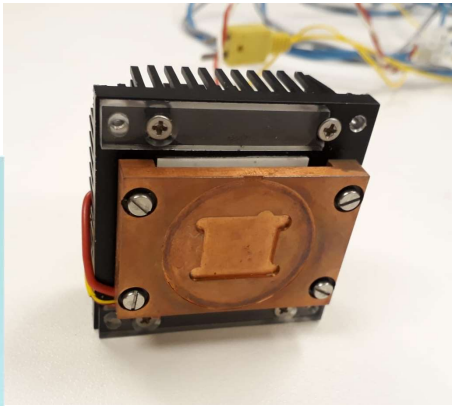


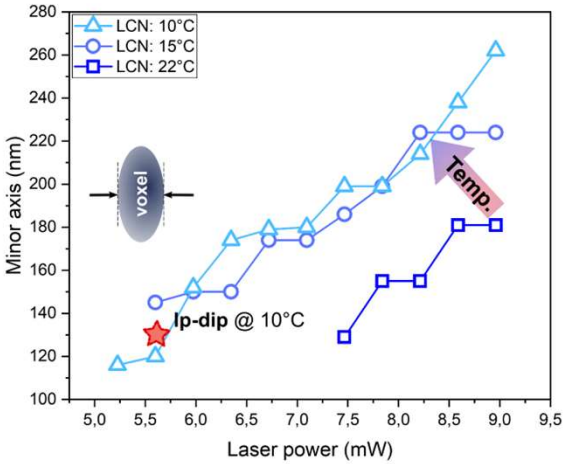
I. De Bellis, S. Nocentini, *et al.*, 2021. "Two-Photon Laser Writing of Soft Responsive Polymers via Temperature-Controlled Polymerization." *Laser & Photonics Reviews*, *15*(8), 2100090, **2021**.

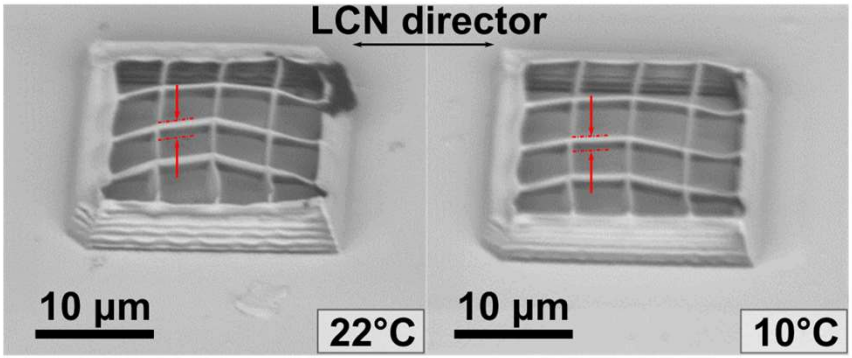
temperature ruled two photon polymerization

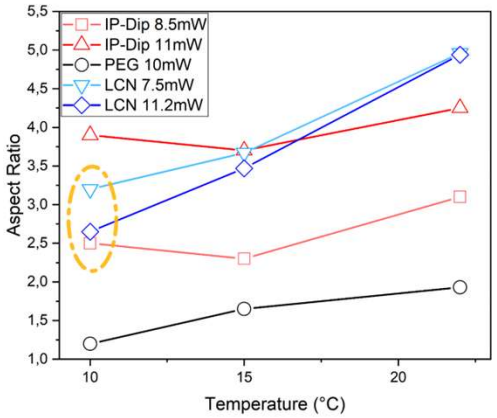
NEED: enhance resolution, stability and reduce swelling





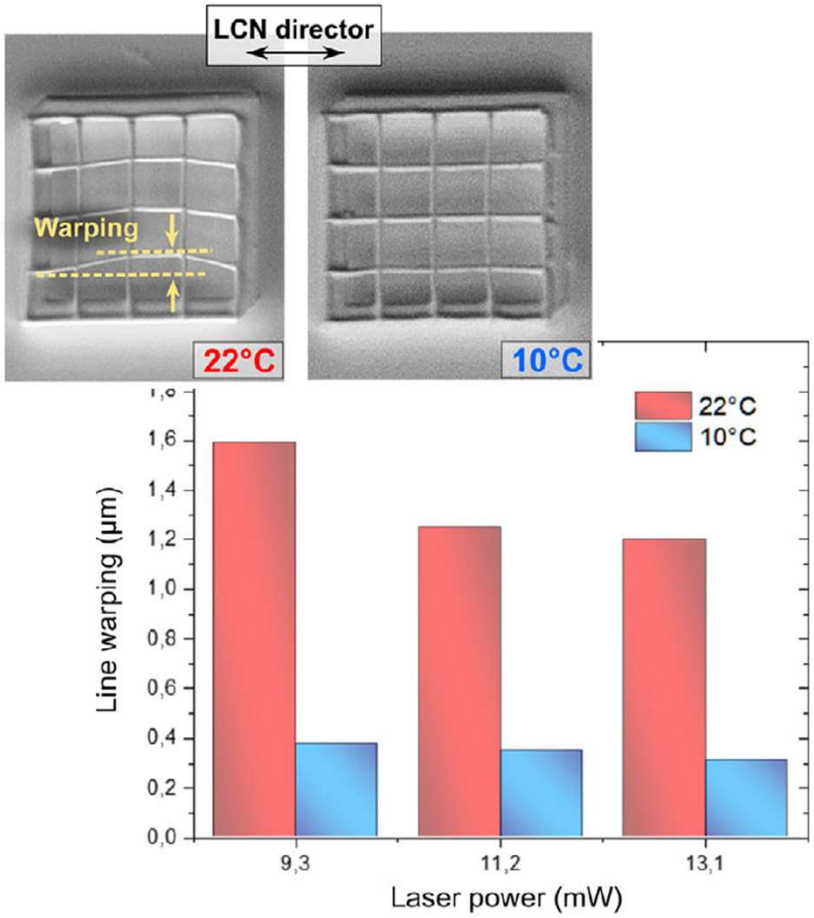


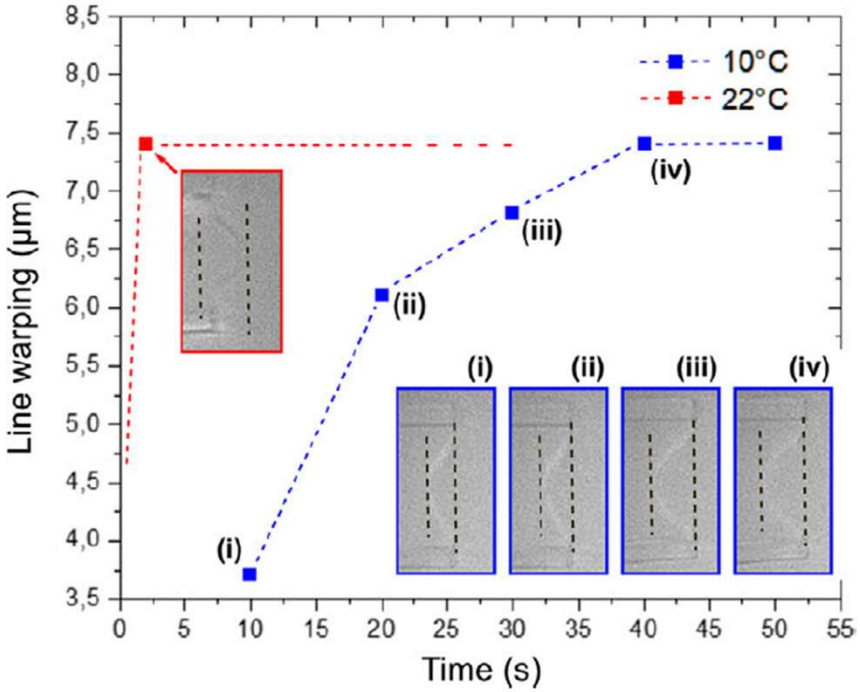




I. De Bellis, S. Nocentini, *et al.*, 2021. "Two-Photon Laser Writing of Soft Responsive Polymers via Temperature-Controlled Polymerization." *Laser & Photonics Reviews*, *15*(8), 2100090, **2021**.

temperature ruled two photon polymerization



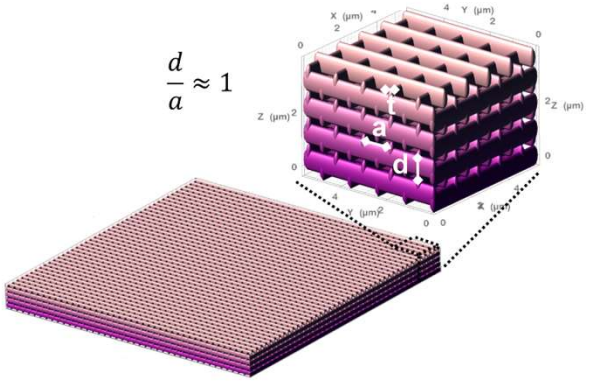


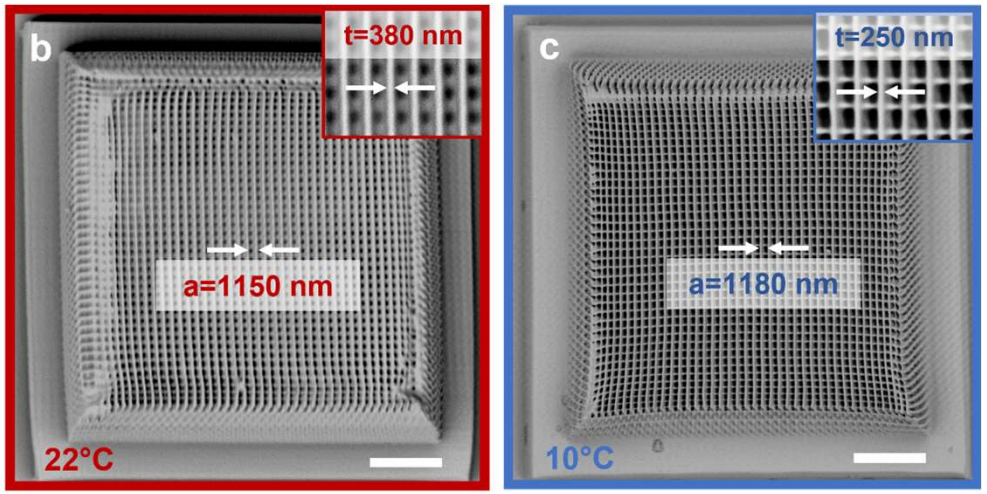
Slower monomer diffusion and larger Young Modulus @10°C

Improved resolution and mechanical stability

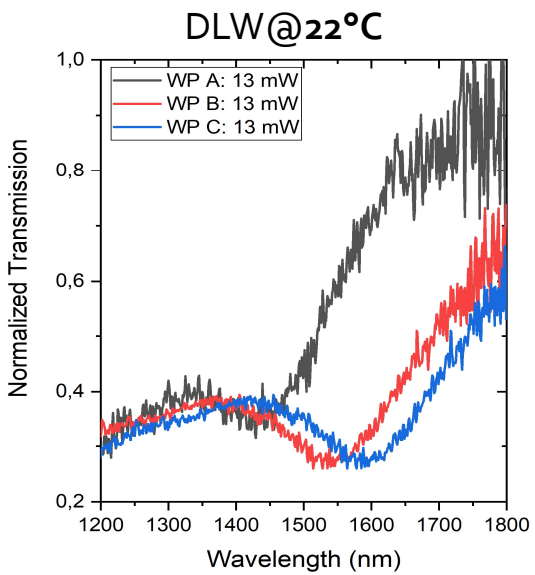
I. De Bellis, S. Nocentini, *et al.*, 2021. "Two-Photon Laser Writing of Soft Responsive Polymers via Temperature-Controlled Polymerization." *Laser & Photonics Reviews*, *15*(8), 2100090, **2021**.

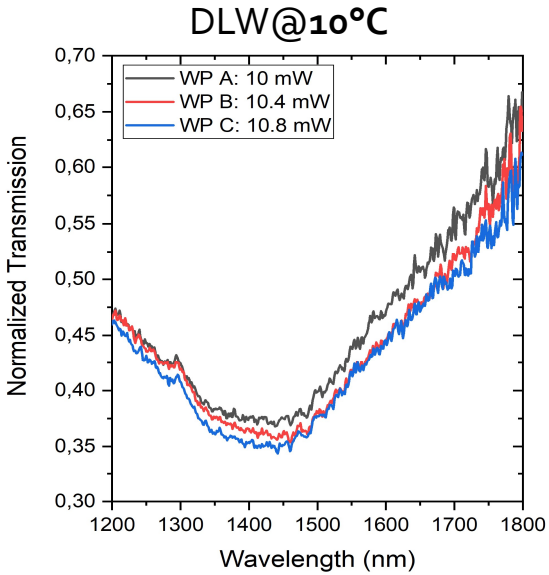
temperature responsive photonic crystals





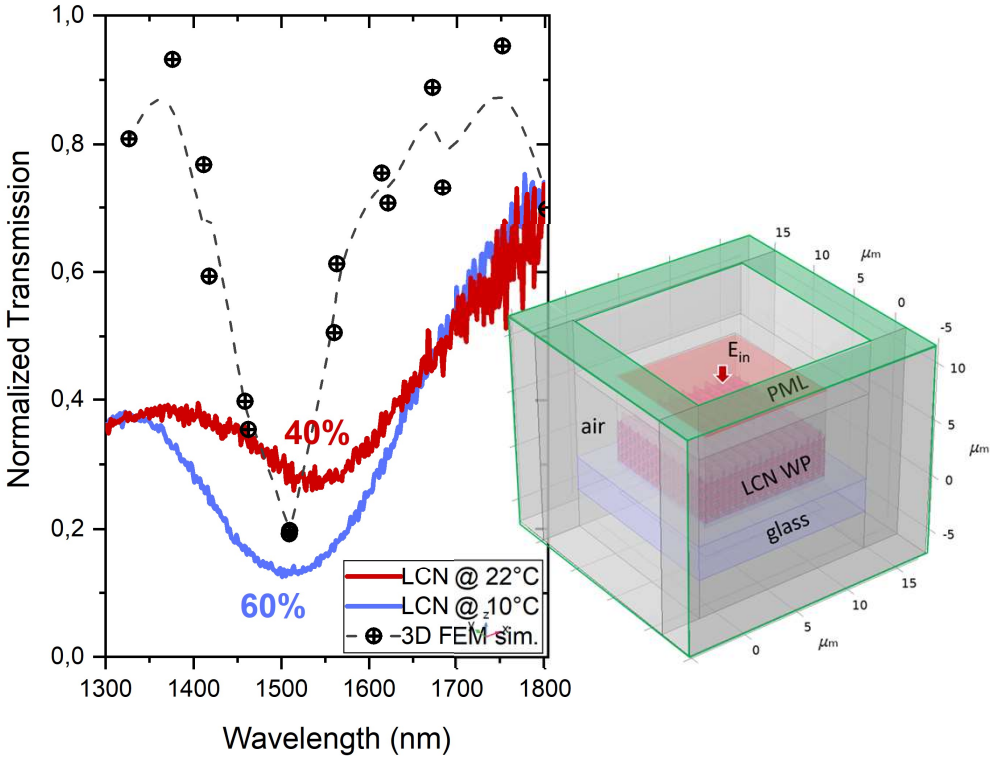
Reproducible optical feature: stop band in the telecom range

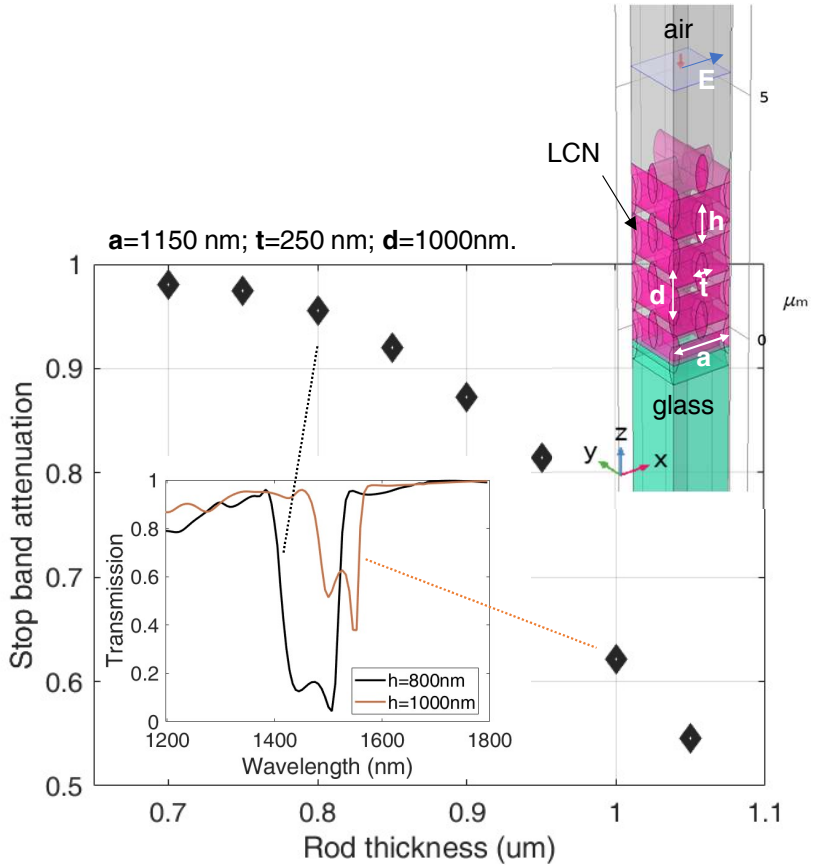




I. De Bellis, S. Nocentini, *et al.*, "Temperature Tunable 4D Polymeric Photonic Crystals ." *Adv. Funct. Mater*, doi:10.1002/adfm.202213162.

temperature responsive photonic crystals





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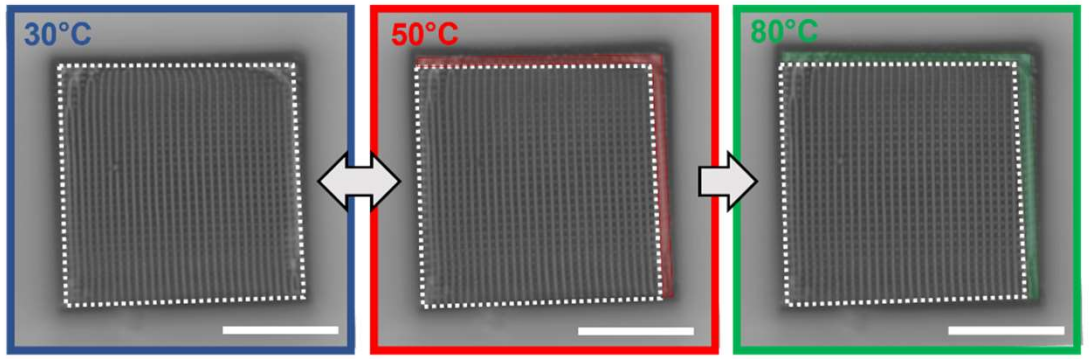

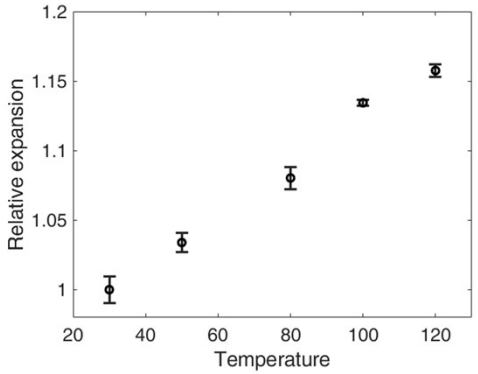

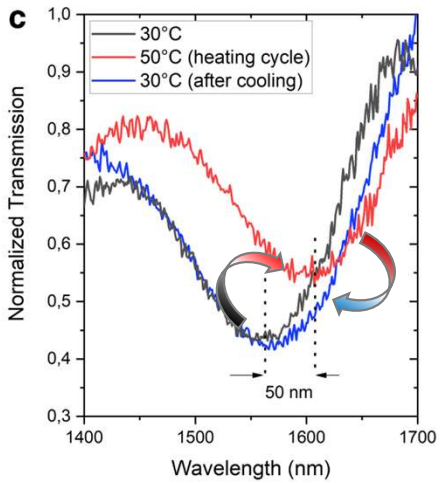

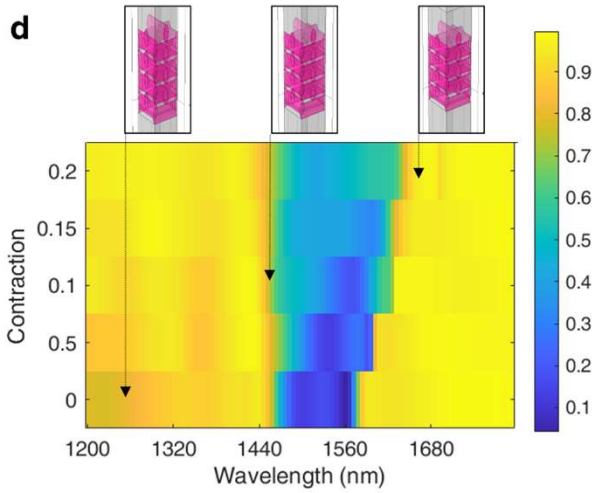

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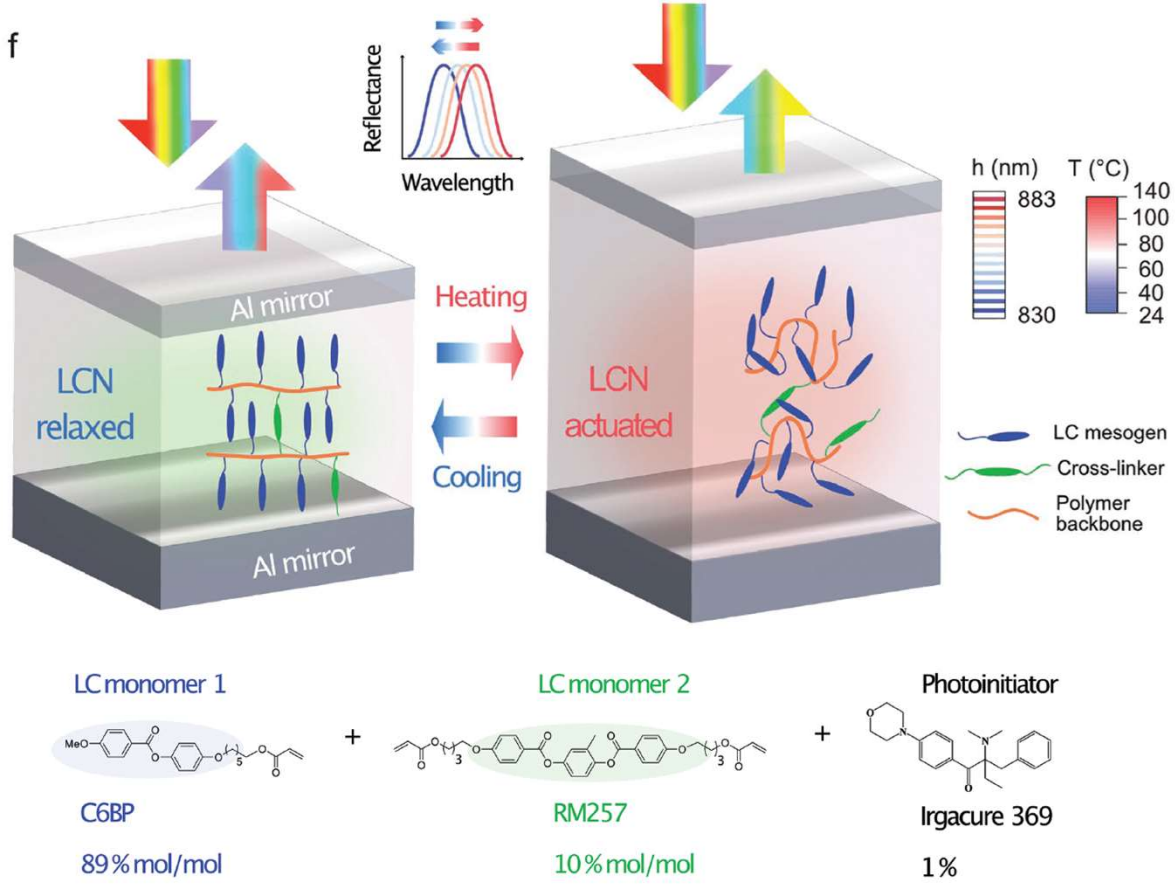
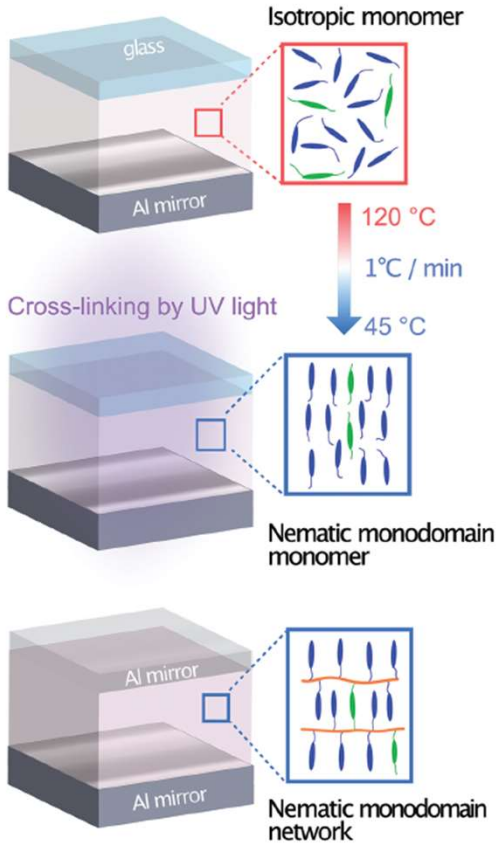
Dynamically Tunable Planar Optical Cavities





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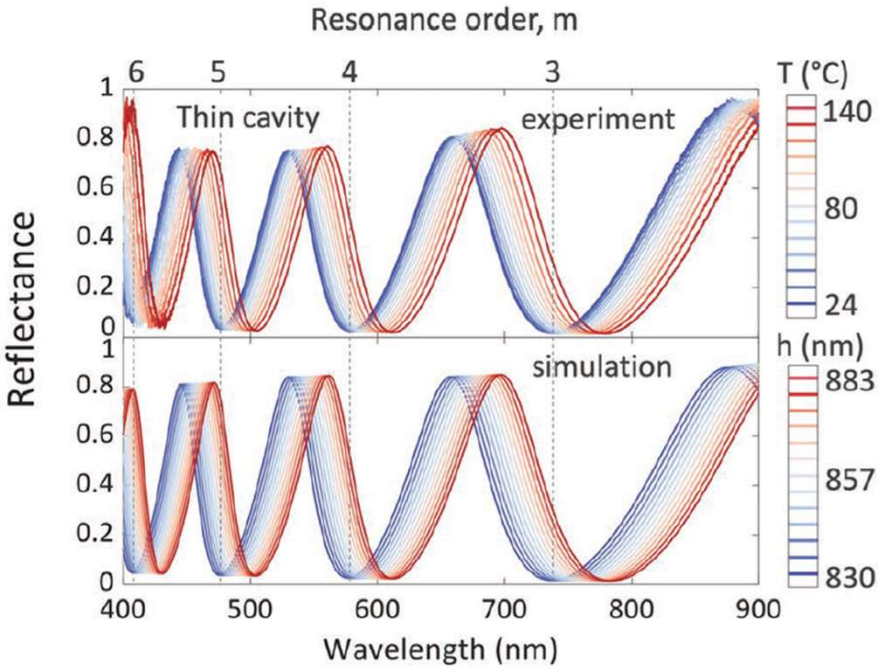

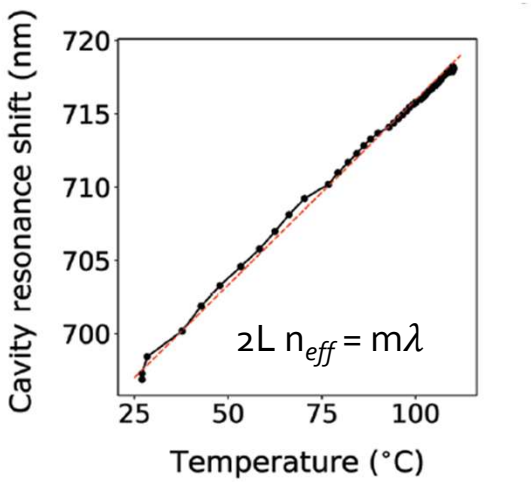

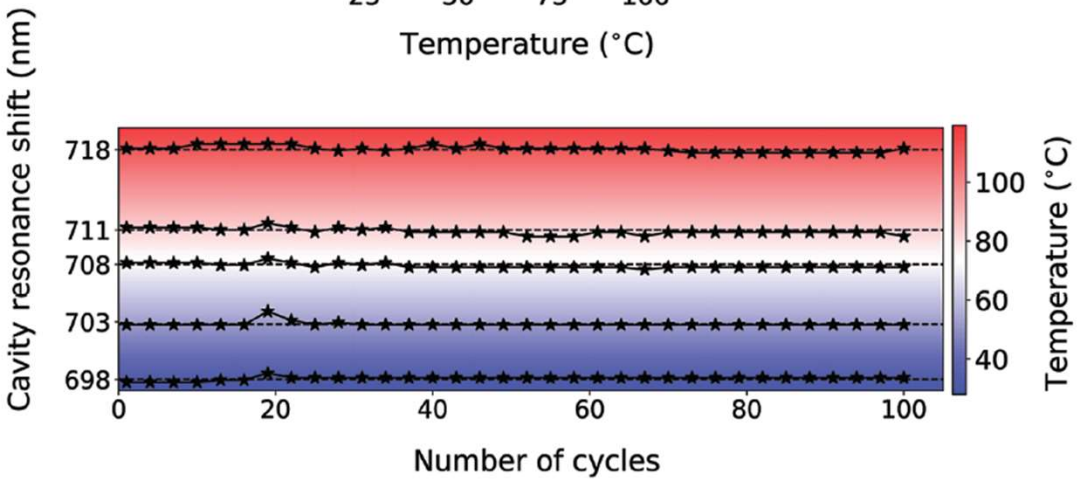

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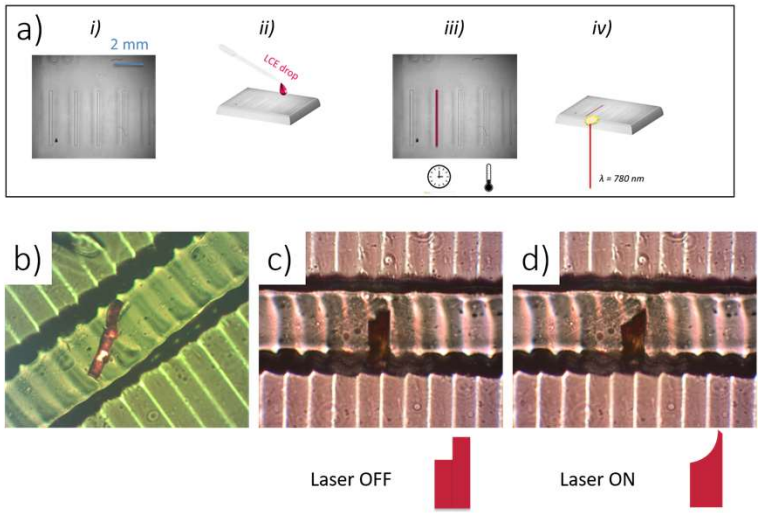
Twinning for excellence of the Serbian Research Center for quantum biophotonics



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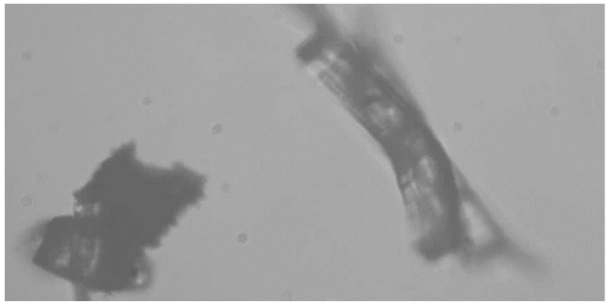
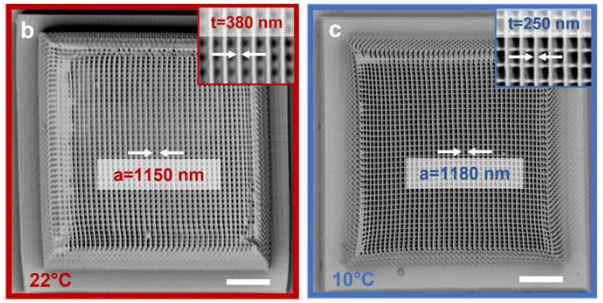
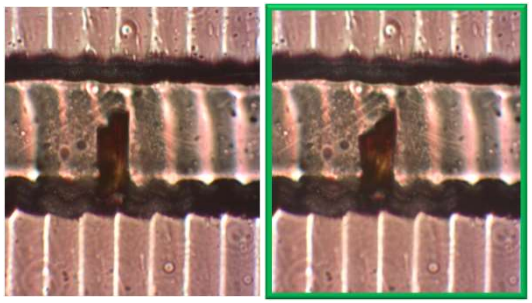
100µm

Temperature-controlled polymer nanopatterning for 4D tunable photonics

nocentini@lens.unifi.it, s.nocentini@inrim.it







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Thank you

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European Commission

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Temperature-controlled polymer nanopatterning for 4D tunable photonics

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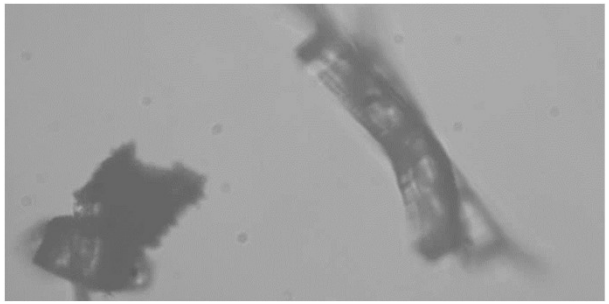

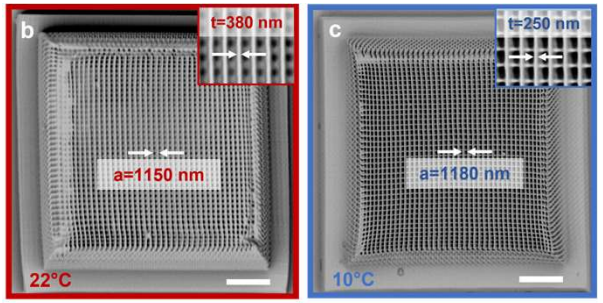

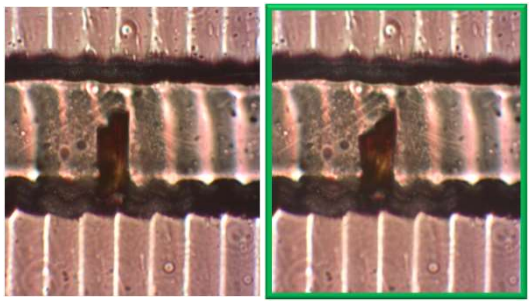

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