Week 9: Liquid Crystal Actuators

Mahmut Selman Sakar

Institute of Mechanical Engineering, EPFL

Lecture Overview

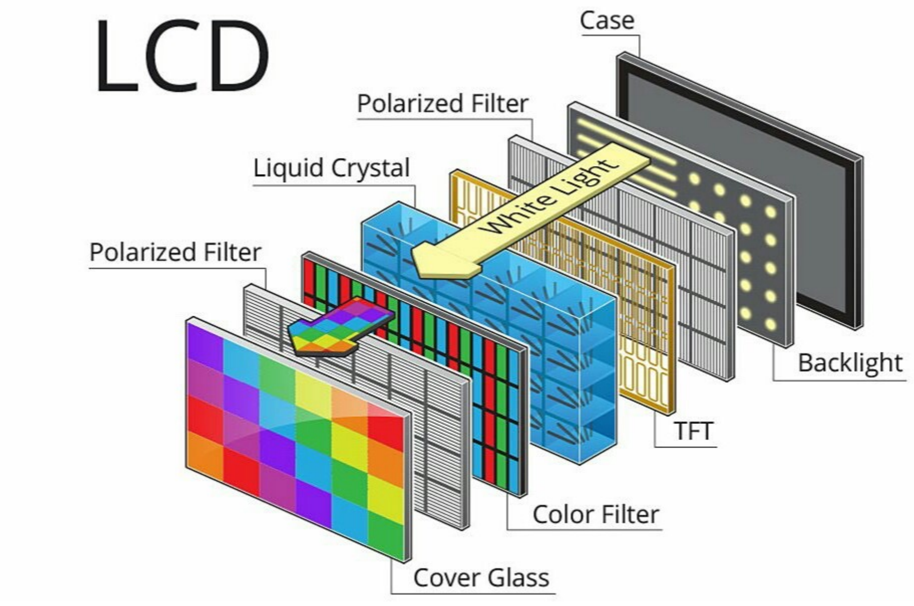
- Topological defects and micromanipulation
- Liquid crystal polymers and elastomers

Liquid Crystals

- **Mesophase**: A state of a matter in between liquid and solid
- Combine the long-range order of crystals with the mobility of liquids (statistical arrangement of molecules)
- Orientational order, no positional order, anisotropy, still can flow
- Reconfigurable materials that optically report information about the environment
  - Electric fields (e.g. smart-phone displays)
  - Temperature (i.e. thermometers)
  - Mechanical shear
  - Sensors for chemical and biological stimuli

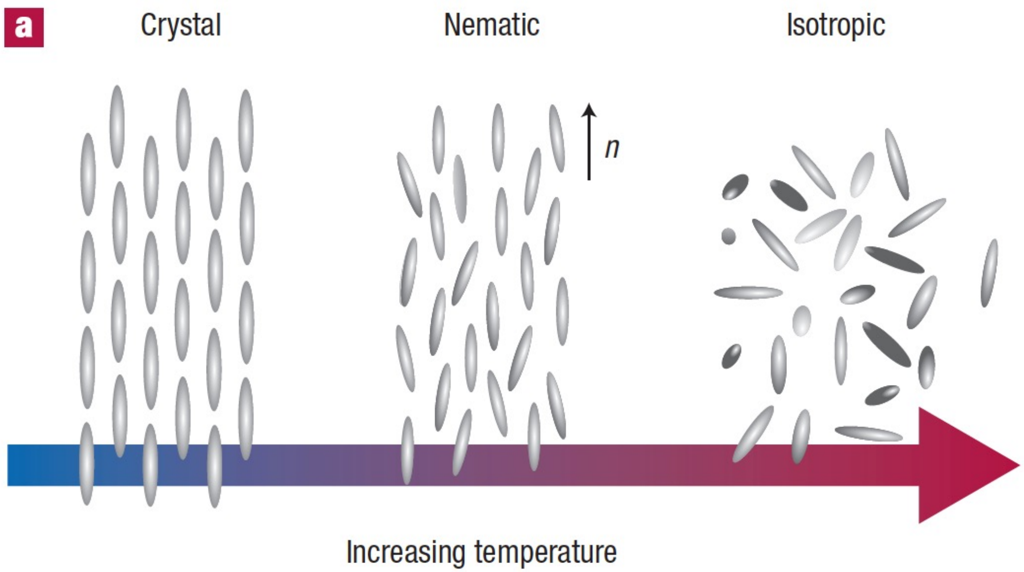
History

- 1890 Otto Lehmann identifies a new and distinct state of matter
- 1904 First commercially available LC (Merck)
- End of 1960s temperature indicators based on cholesteric LCs
- 1968 George Heilmeier builds first LCD prototype
- 1990s LCDs replace conventional display devices



Terminology

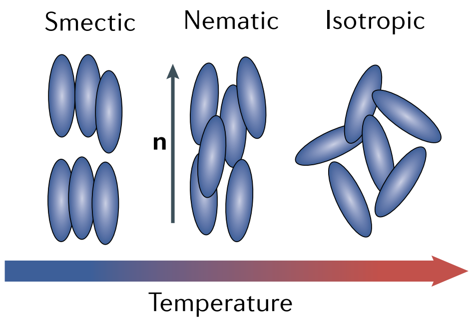
- Formation of the mesophase
  - **Thermotropic**: temperature induced phase formation
    - If the temperature is too high, thermal motion will destroy the cooperative ordering of the LC phase, pushing the material into conventional isotropic liquid phase
    - May exhibit a variety of phases as temperature is changed
  - **Lyotropic**: Order depends on the concentration of the material



Terminology

- Mesogen: Un-crosslinked macromolecules that can organize into liquid crystalline phase through
  - Stiff molecular conformation
  - Intramolecular interactions such as hydrogen bonding

- Structure of the mesophase for rod-like molecules
  - Nematic (tread like)
  - Smectic (soap-like)
  - Cholesteric (chiral nematic)

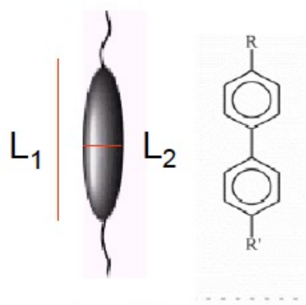


- Structure of the mesogens
  - Calamitic (rod-like), discotic (flat, disc shaped), banana shape, conic

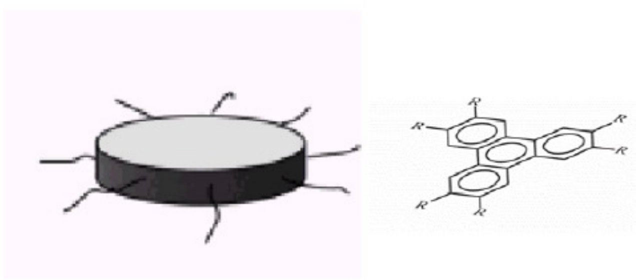
Mesogens: The subunits of liquid crystals

- Rigid molecule or molecule segment with anisometric (geometrical anisotropic) architecture that forms a mesophase

$L_{krit} = L_1/L_2$



calamitic



discotic

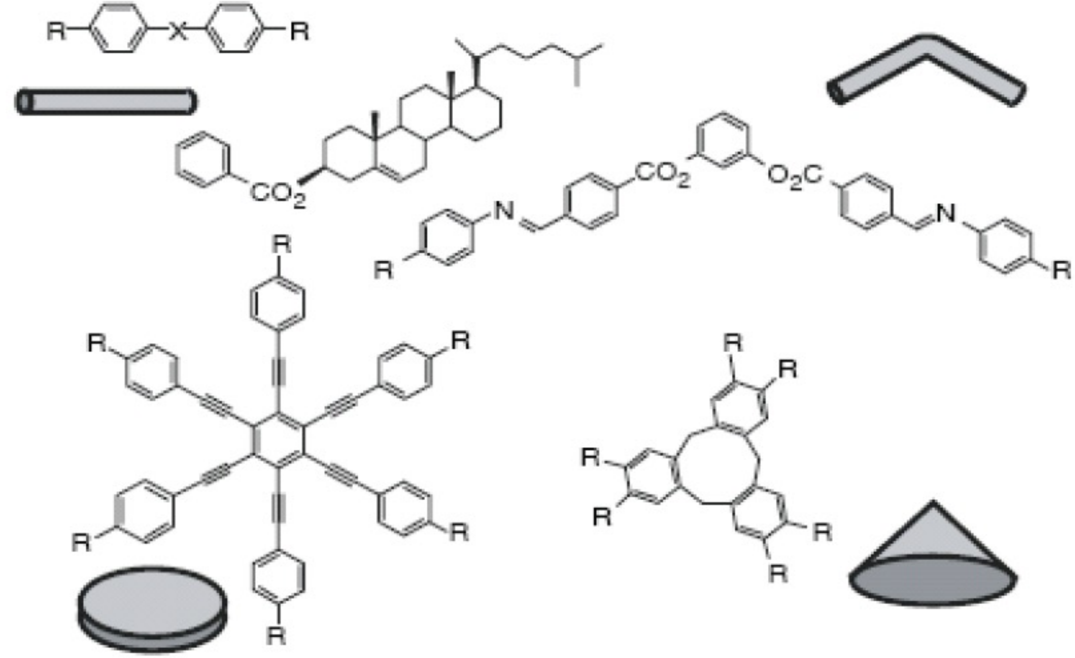
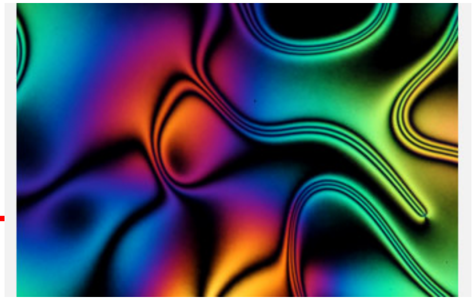
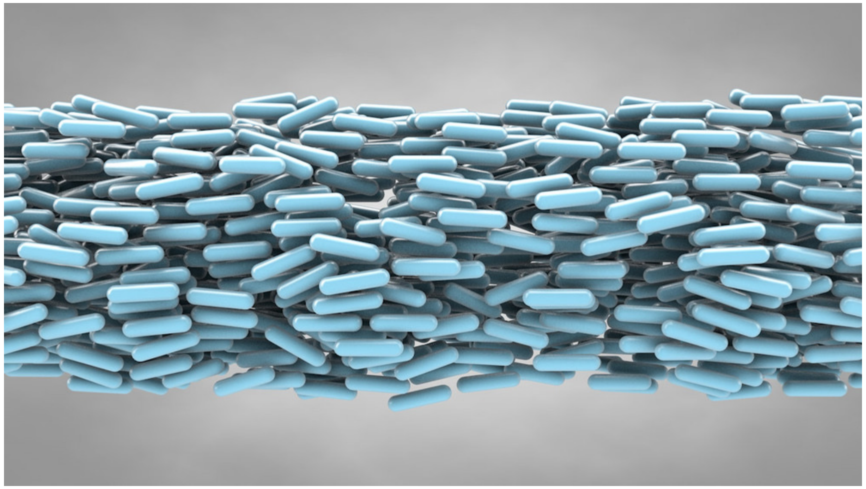


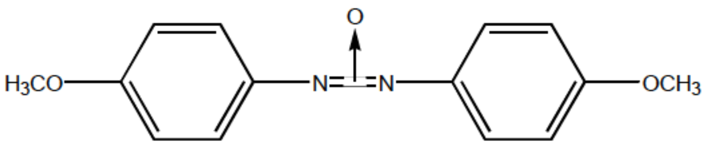
Abbildung 2.2: Bekannte formanisotrope Moleküle, die thermotrope Flüssigkristalle bilden. Links Beispiele für stab- und scheibenförmige Moleküle, rechts ihre gewinkelten Analoga: Oben Bananen-, unten Hutform. Die Reste R können Alkyl-, Alkoxy- oder komplexere, auch chirale Ketten, einzeln auch polare Gruppen wie CN oder NO_2 sein. Die Brückengruppe X kann z. B. eine Esterfunktion, eine Methylengruppe, eine Schiffsche Base oder eine Phenylgruppe sein.

Nematic Liquid Crystals

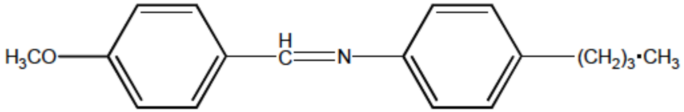


- Comes form the Greek word for thread
- Preferred molecular orientation defines the director **n**
  - Rod-like molecules are spontaneously and collectively aligned into a certain direction
- Director **n** varies from point to point at macroscale
- 1D order where molecule centers are not oriented





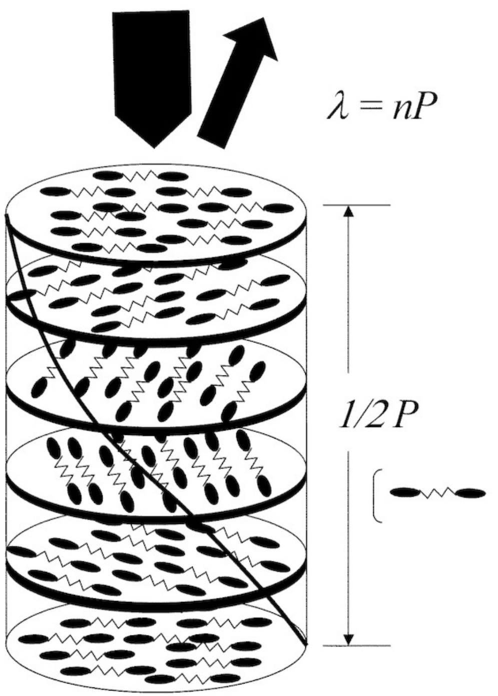
PAA: p-azoxyanisole

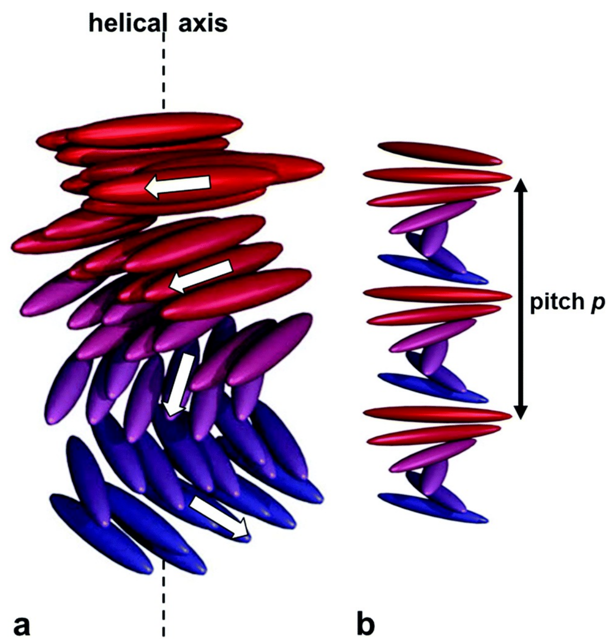


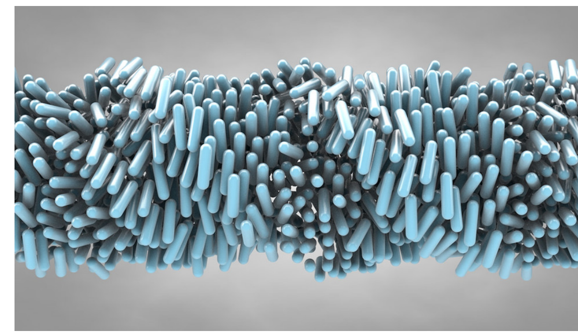
MBBA: n-(p-methoxybenzyidene)-p-butylaniline

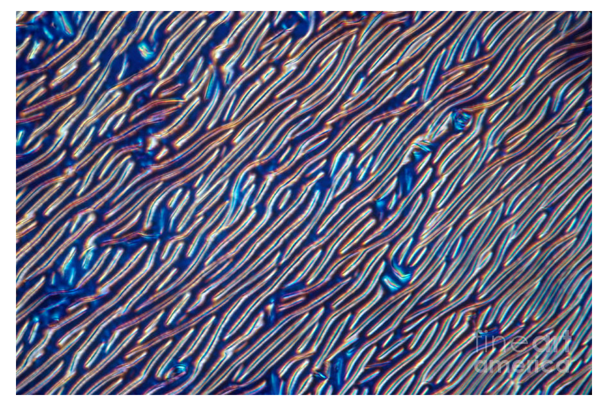
Cholesteric Phase

- The structure acquires a spontaneous twist about an axis perpendicular to the director
  - Also observed in cholesterol derivatives
  - Formed from chiral mesogenic molecules



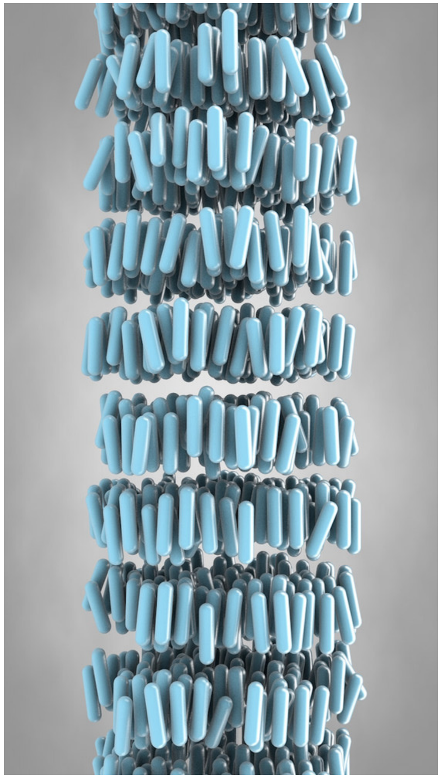


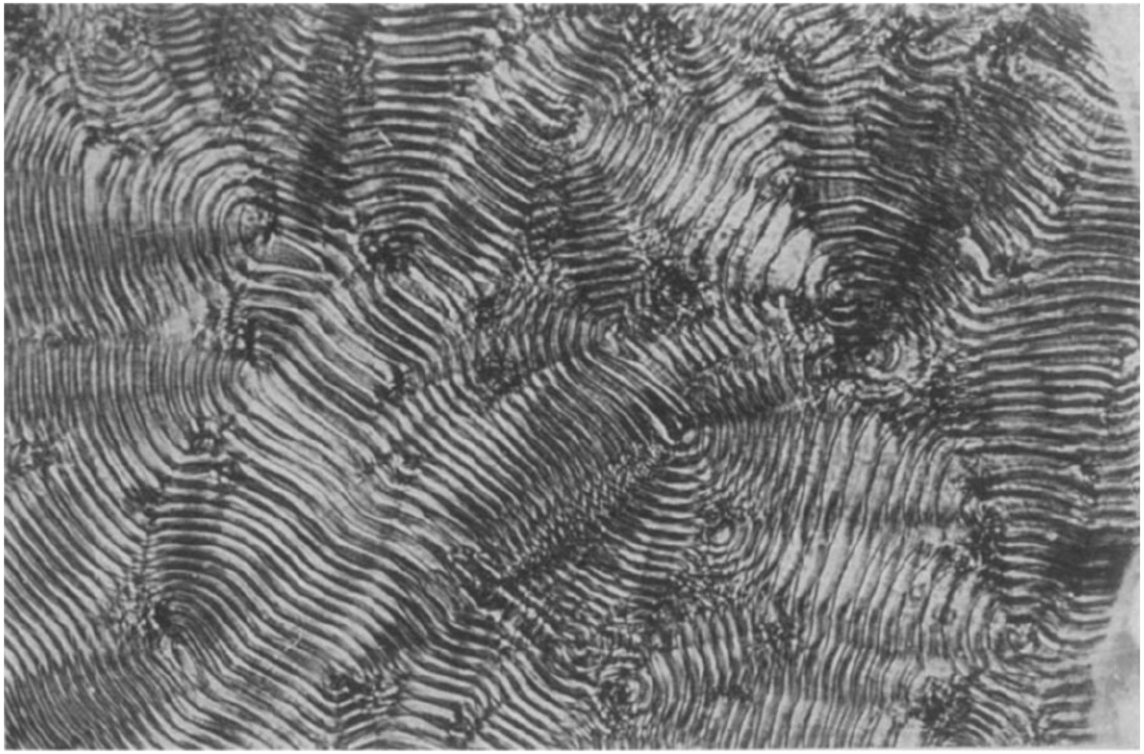




Smectic Phase

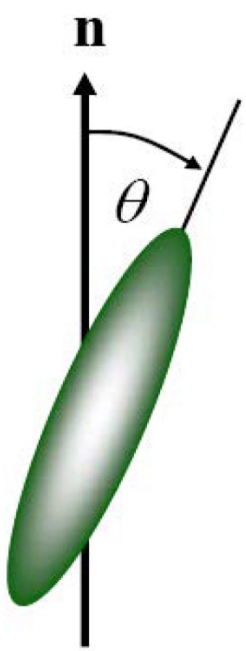
- Smectic phases exhibit a higher degree of order than nematics
- Molecule centers are oriented in the layers
- Mesogenic molecules with terminal alkyl or alkoxy chains





Order Parameter

- Quantitative description of the orientation of the mesogens
- Director **n**: Anisotropy is defined by the symmetry axis of the orientation distribution



$$S = (3\cos^2\theta - 1)/2$$

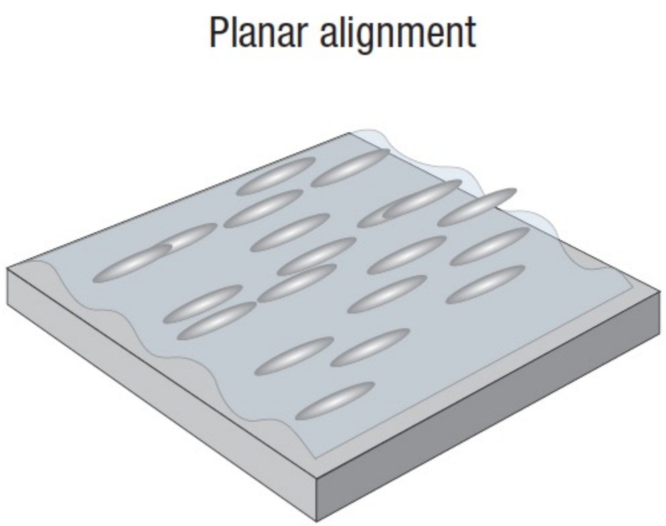
θ = Average deviation angle of the mesogen axes from the director

- All molecules aligned parallel to the director: S = 1
- Random distribution: S = 0

- Nematic phase: 0.45 < S < 0.65
- Smectic phase: 0.85 < S < 0.95

Hierarchy of Orientation

- Orientation of mesogens in domains
  - Domain size in the um range
  - Orientation of the molecular axes with respect to the director inside each domain
- The directors of the domains are statistically distributed
- Uniform alignment of the domains
  - Rubbing
  - Aligned substrates
  - Application of magnetic or electric field
  - Viscous fingering



Frank-Oseen Free Energy

$$g = \frac{1}{2}k_{11}(\nabla \cdot \mathbf{n})^2 + \frac{1}{2}k_{22}(\mathbf{n} \cdot \mathrm{curl}\,\mathbf{n} + t_0)^2 + \frac{1}{2}k_{33}(\mathbf{n} \times \mathrm{curl}\,\mathbf{n})^2$$

This is the famous Frank-Oseen elastic free energy density for nematics and cholesterics.

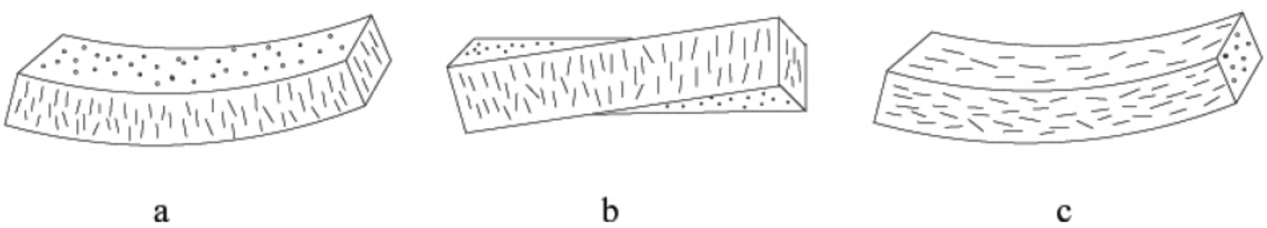


Figure: The three distinct curvature strains of a liquid crystal: (a) splay, (b) twist, and (c) bend.

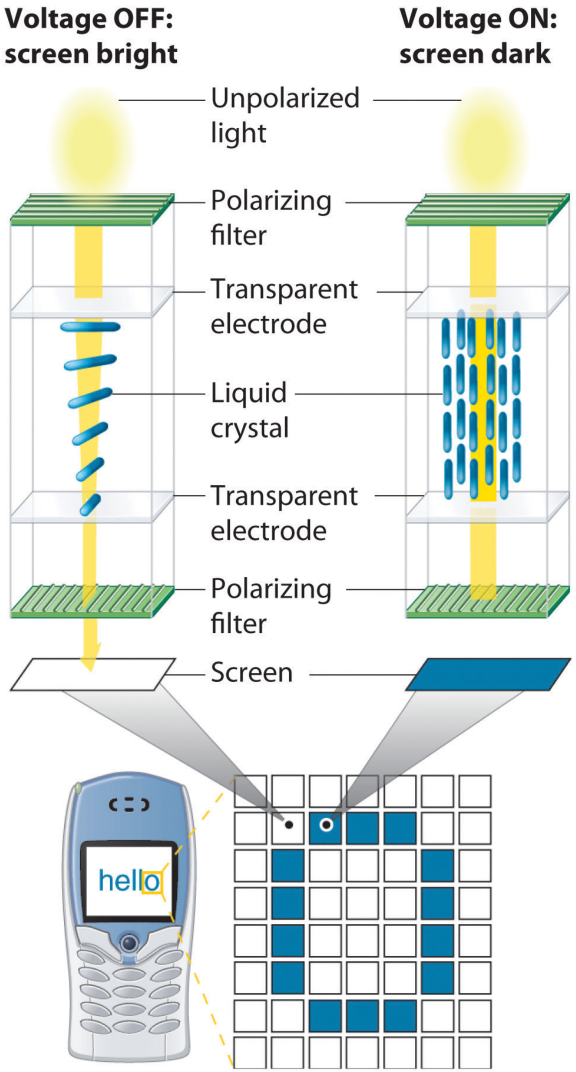
- A nonpolar LC with equal bend, splay, and twist constants

$$g = \frac{1}{2}k\left[(\nabla \cdot \mathbf{n})^2 + (\nabla \times \mathbf{n})^2\right]$$

- The equilibrium value of S is that which minimizes free energy

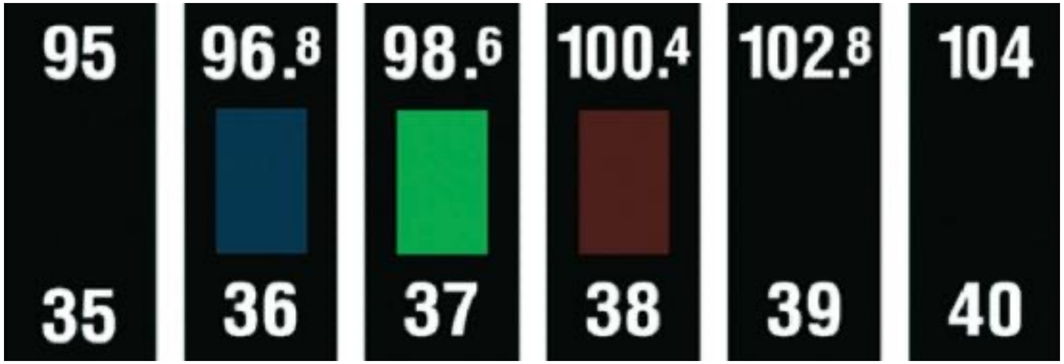
Liquid Crystal Displays

- Mesogens are polar,
  - interact with an electric field
  - change the orientation
- Nematic liquid crystals tend to be relatively translucent
- They become opaque when an electric field is applied and the molecular orientation changes
- This behavior is ideal for producing dark images on a light or an opalescent background



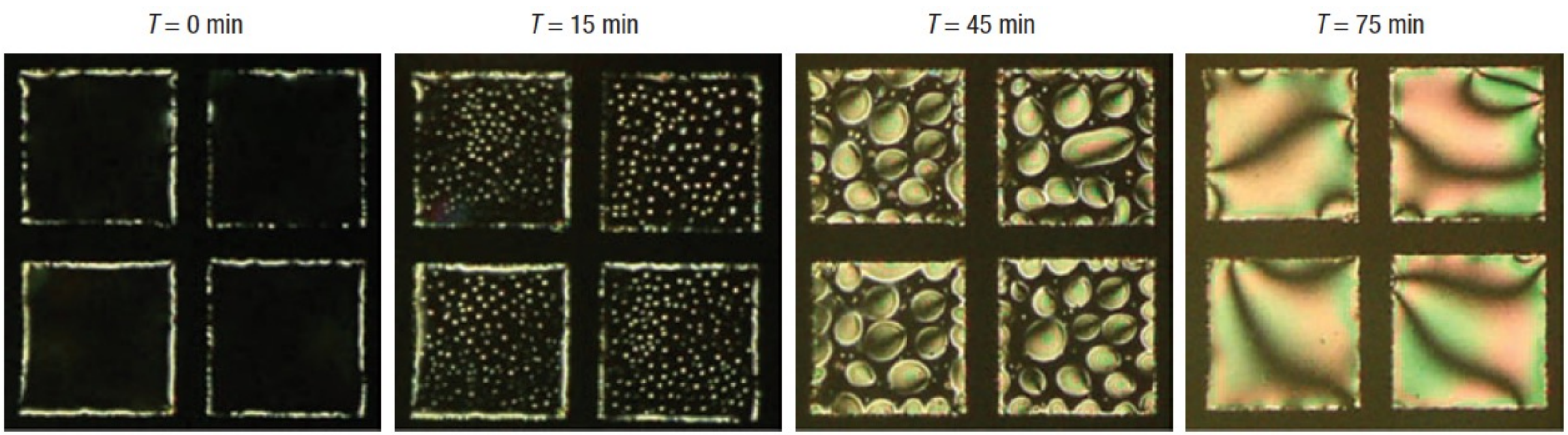
Liquid Crystal Thermometers

- Changes in molecular orientation that are dependent on temperature result in an alteration of the wavelength of reflected light.
- Changes in reflected light produce a change in color, which can be customized by using either a single type of liquid crystalline material or mixtures.
- An LC thermometer that indicates temperature by color

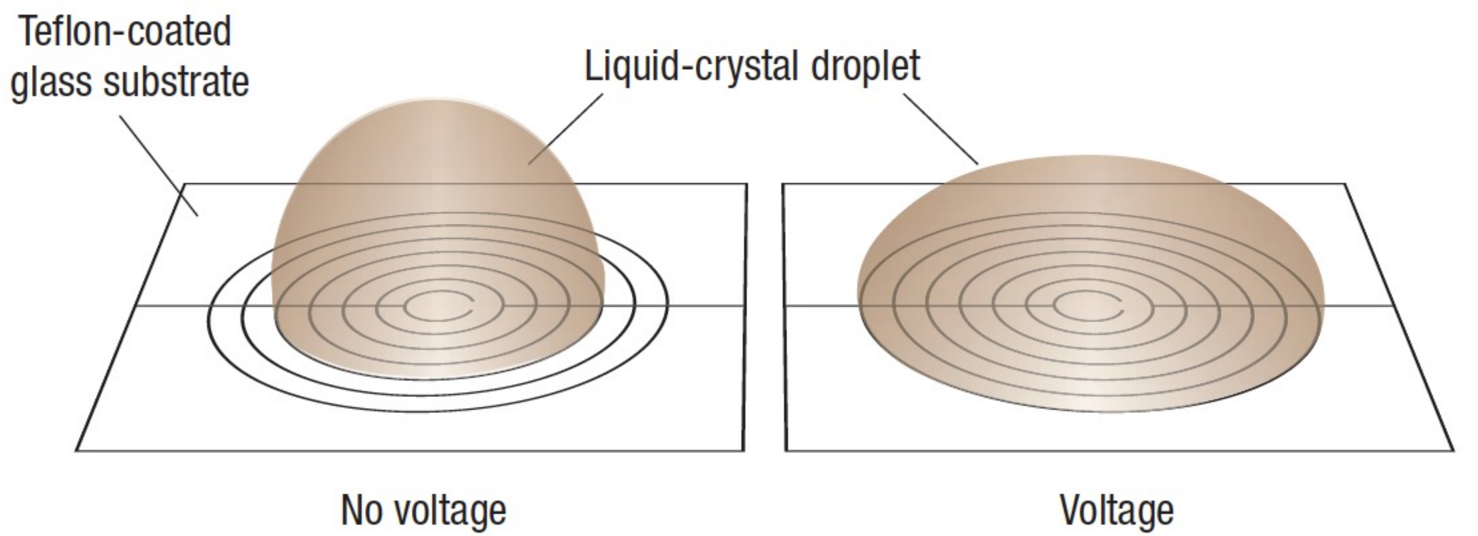


Biosensor

- Many biological systems, including cell membranes, phopholipids, cholesterols, DNA etc. exist in liquid crystal phases
- Liquid-crystal aqueous interface where chemical is applied
- Orientational change with the introduction of the chemical (enzymatic reaction)
- Label free detection



Dynamic Lenses

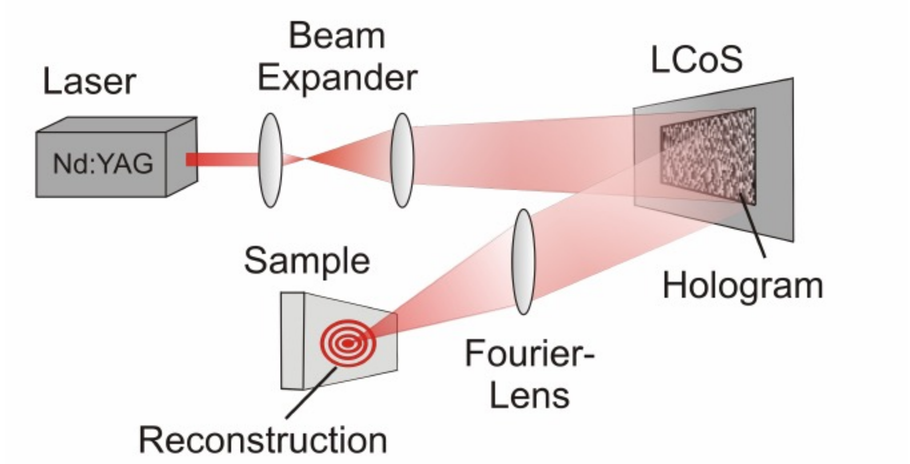


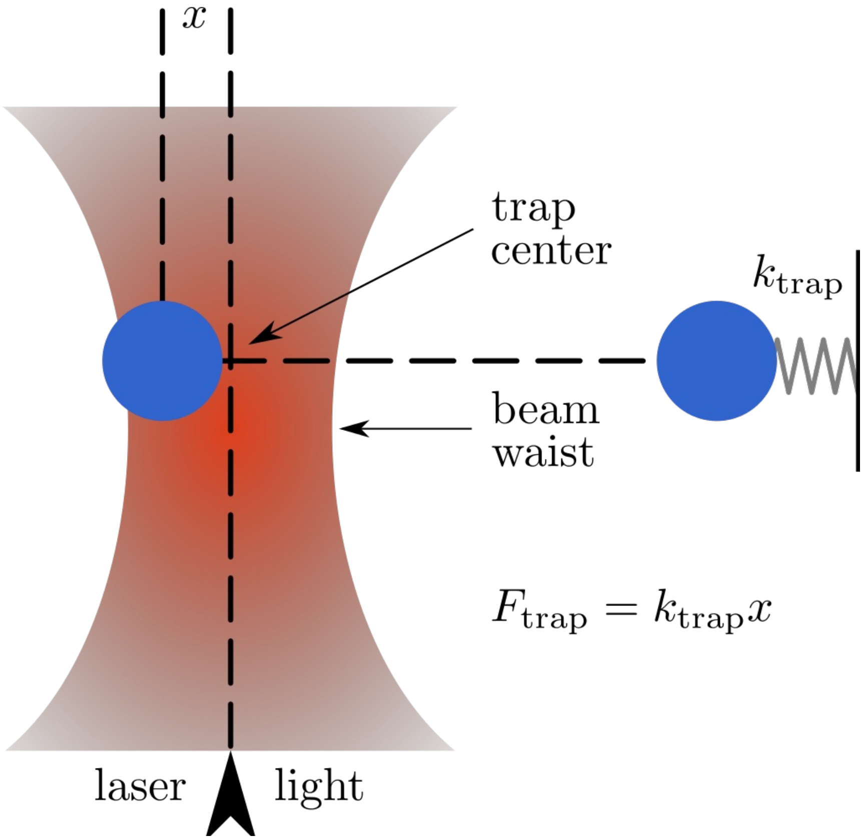
- Focal length of the lens is tuned with an electric field
- Microlens arrays similar to fly's eye
- Bifocal eyeglasses (near and far vision)

Spatial Light Modulators and Optical Traps

movie

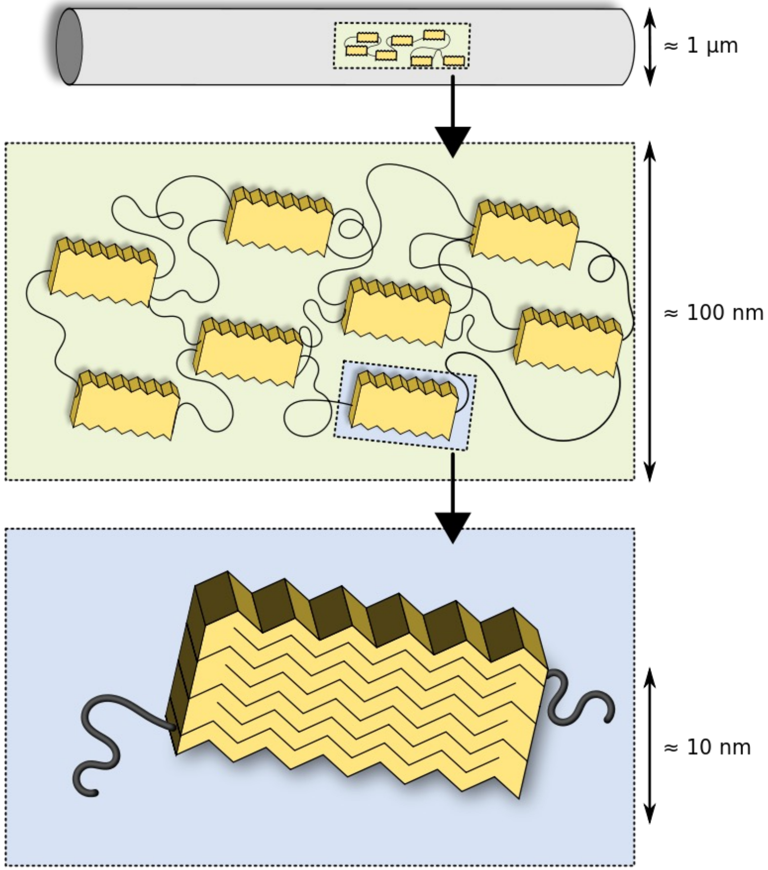
- Spatially varying modulation of light intensity and/or phase
- Holographic display technology
- Holographic optical tweezers

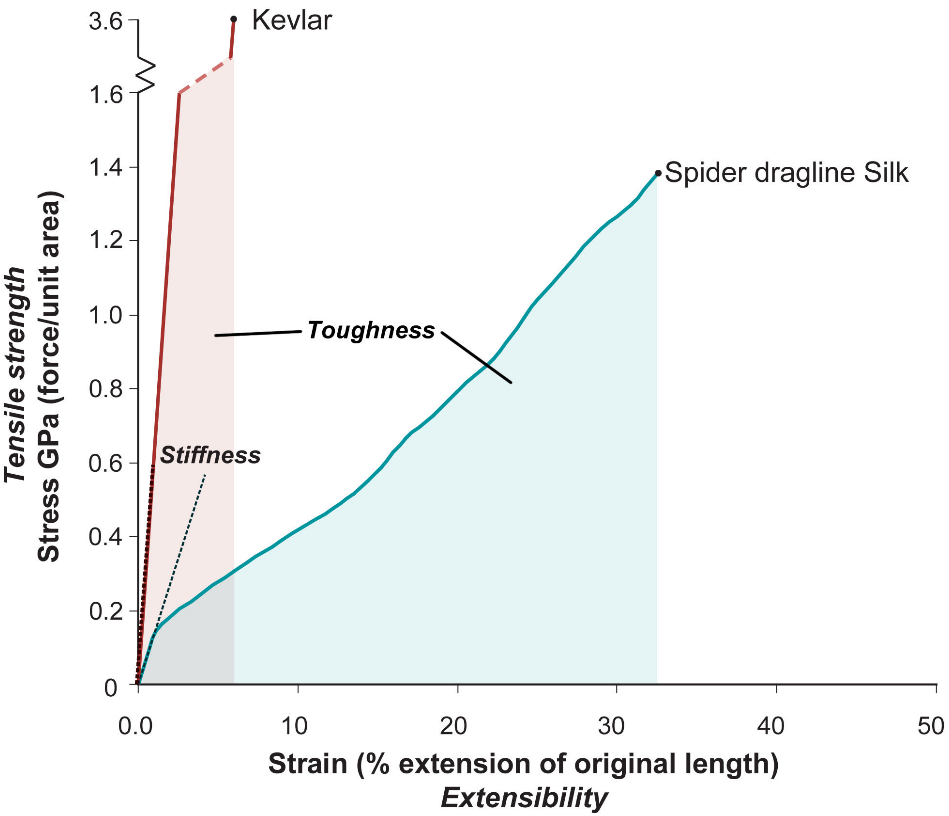




Structural Elements

- Extrusion of fibers with aligned rod shaped mesogens
  - Kevlar, spider silk





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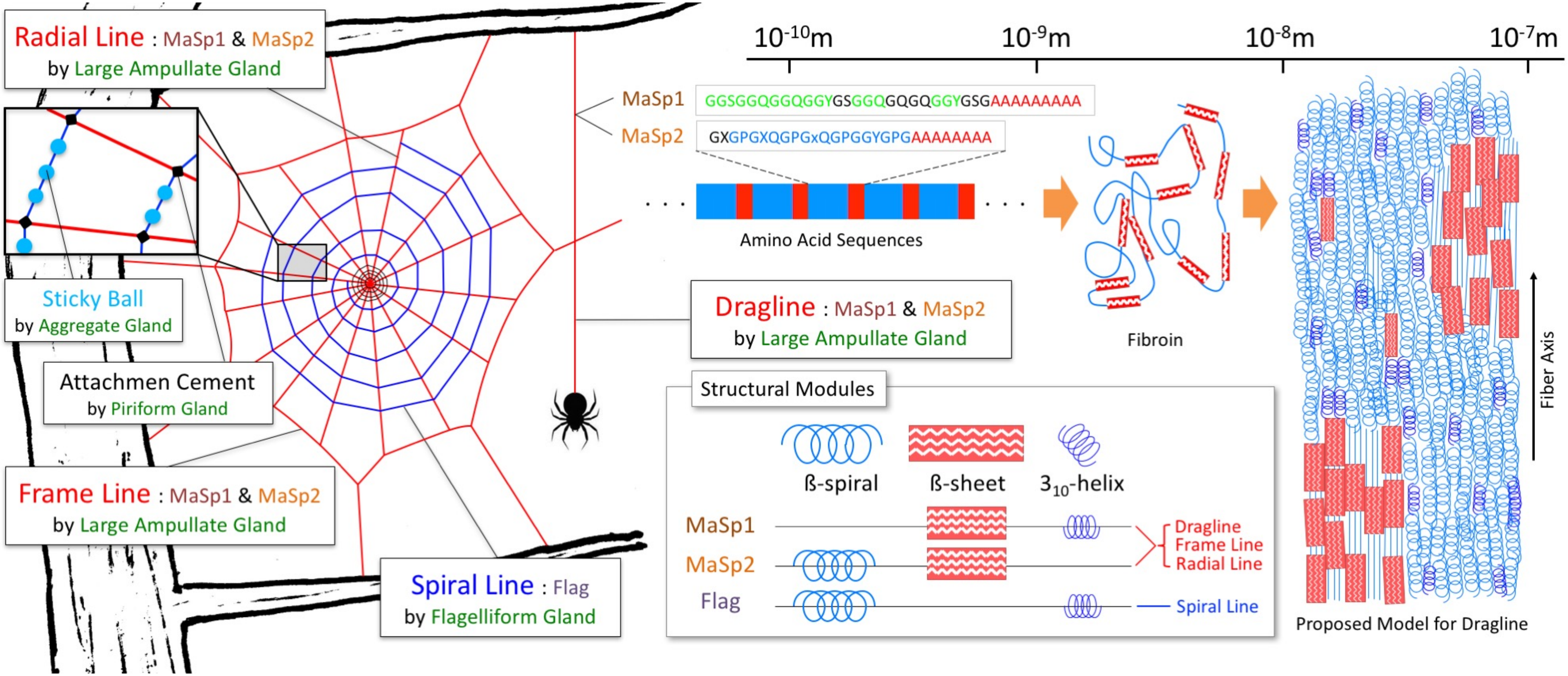
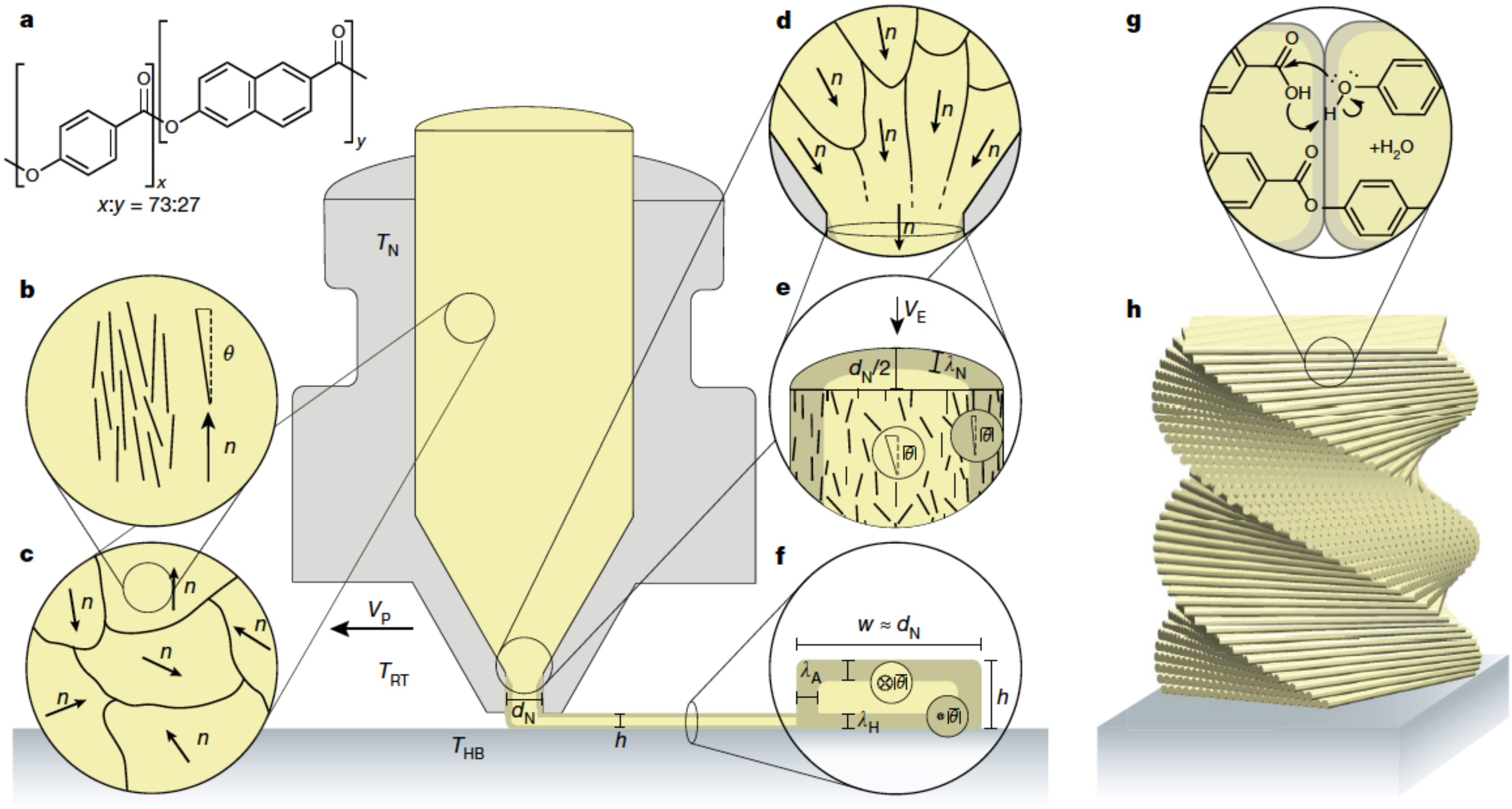
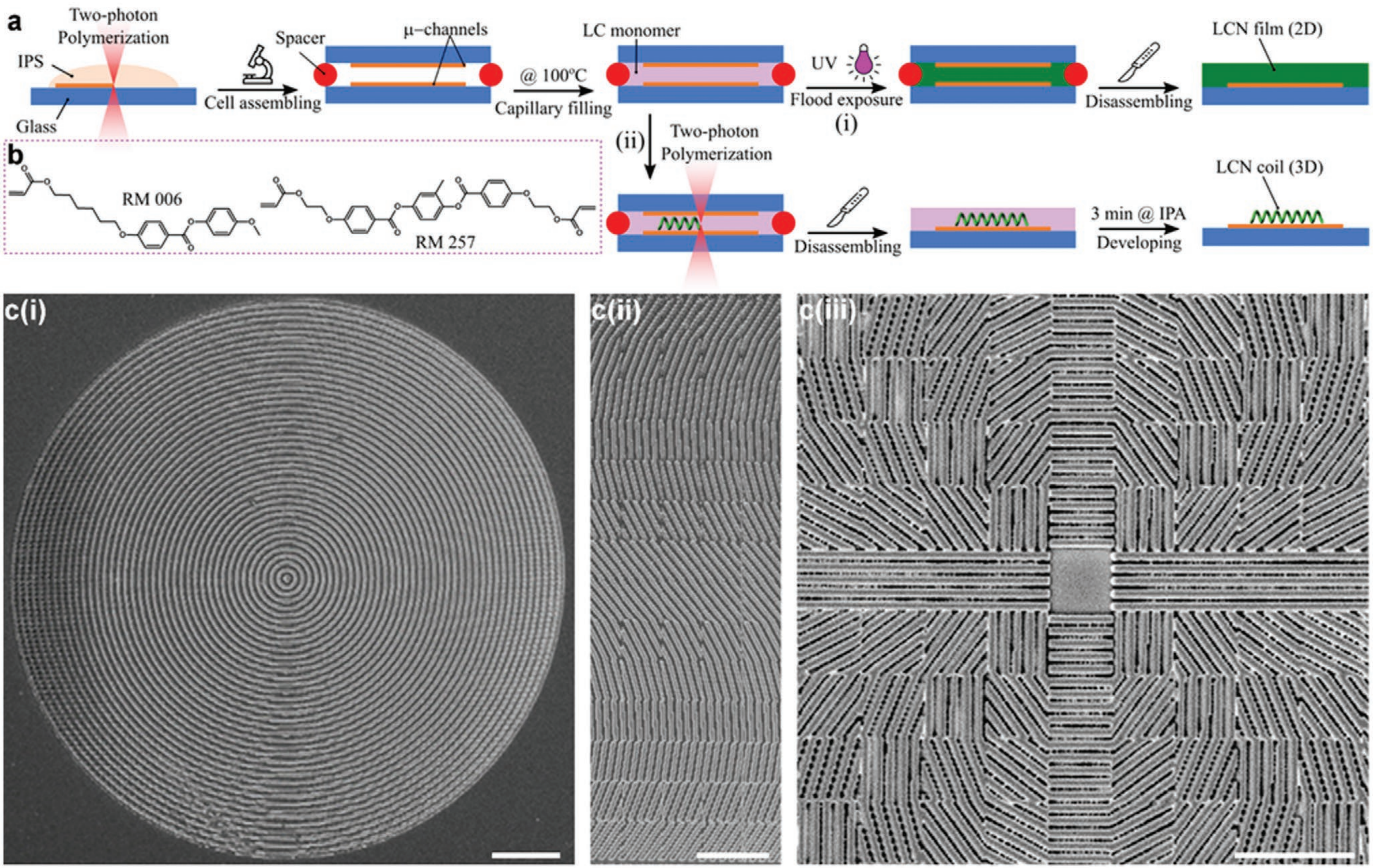


3D printing of liquid crystal networks

- The directors are subjected to elongational and shear forces during the extrusion through the heated nozzle
- Solidification front freezes the nematic order in place

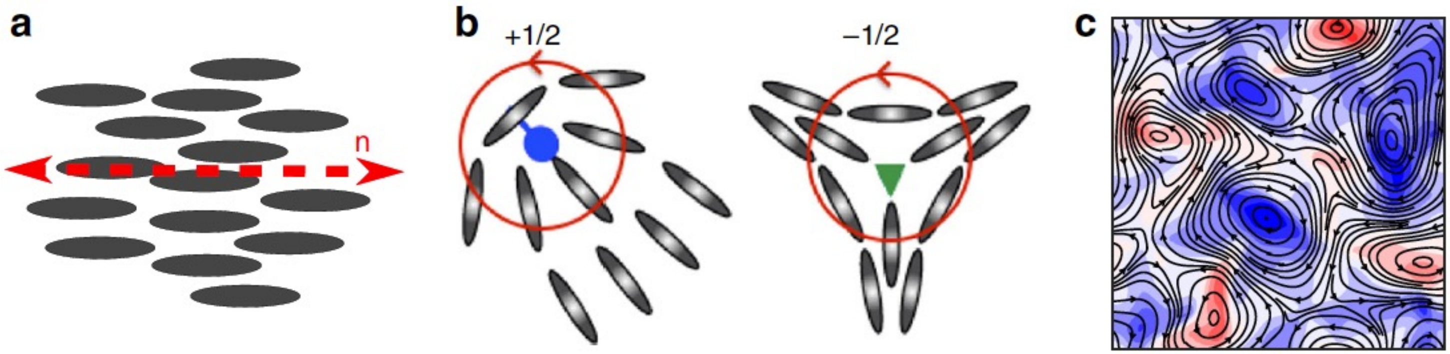


3D printing of liquid crystal networks

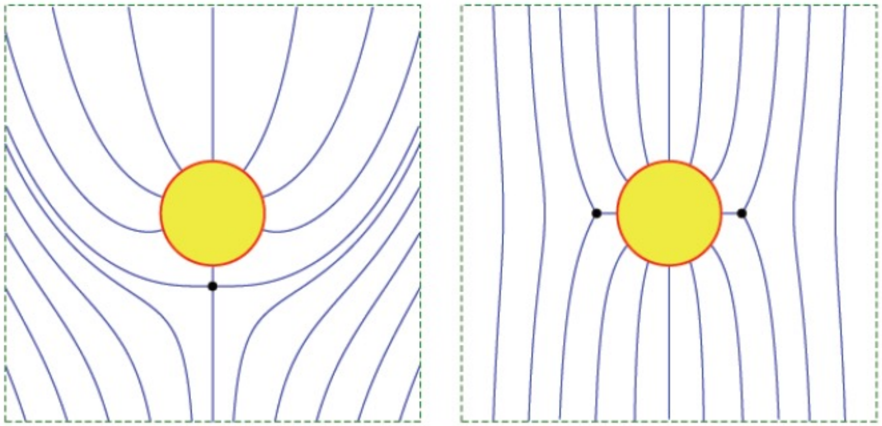


Topological Defects in Nematics

- Active nematic turbulence

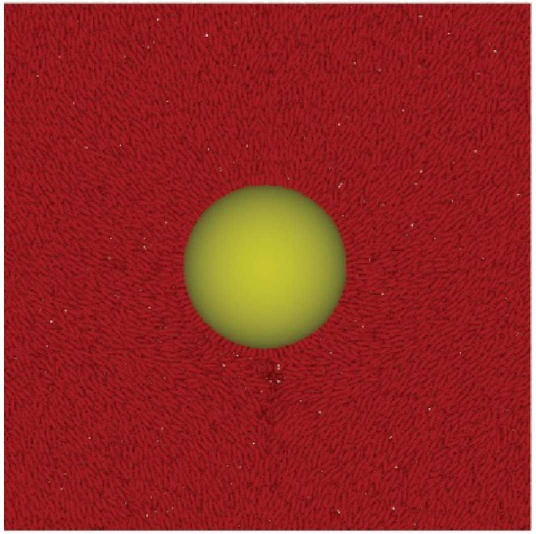


- Topological defects induced by colloidal particle



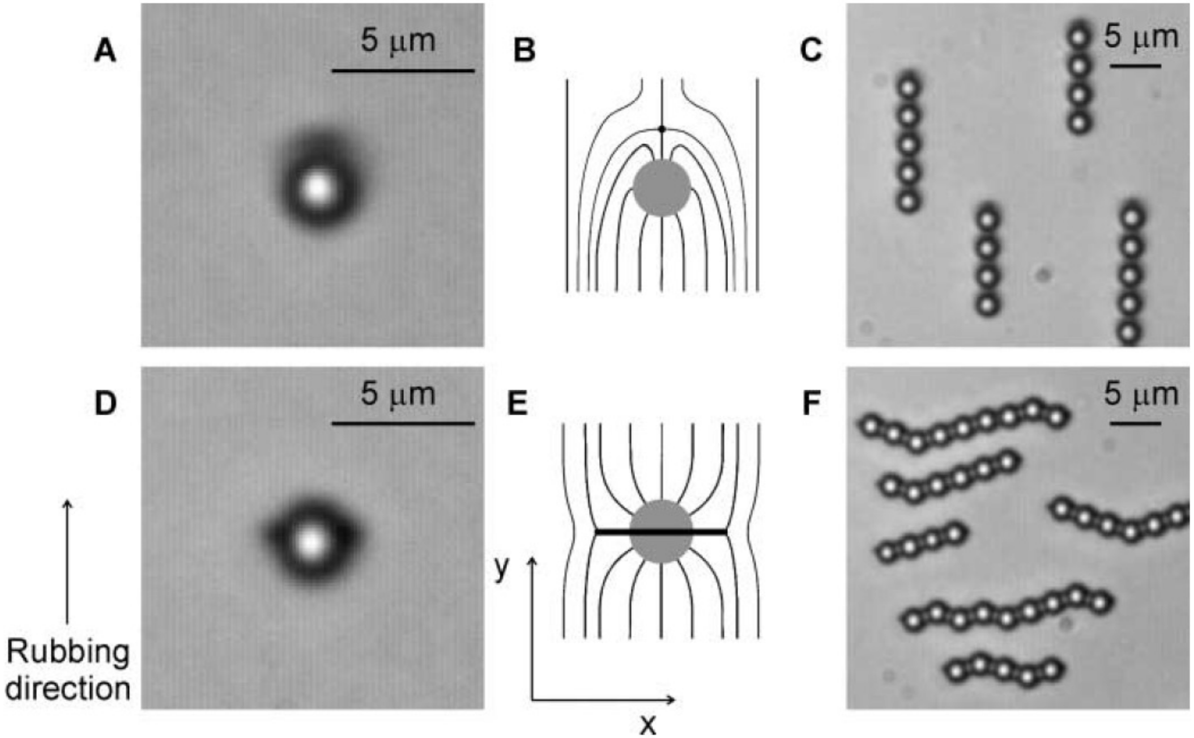
Satellite (dipole)

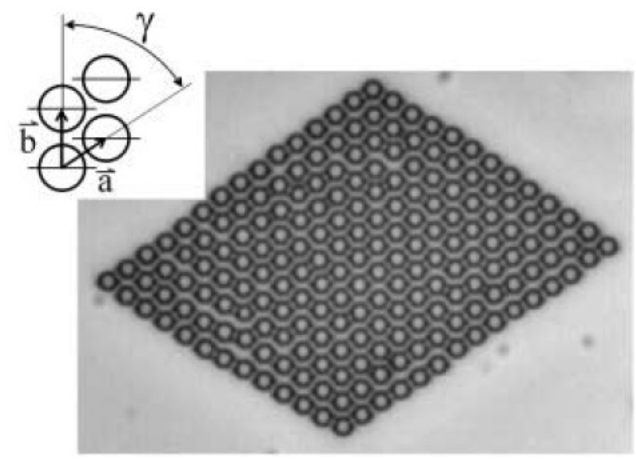
Saturn ring



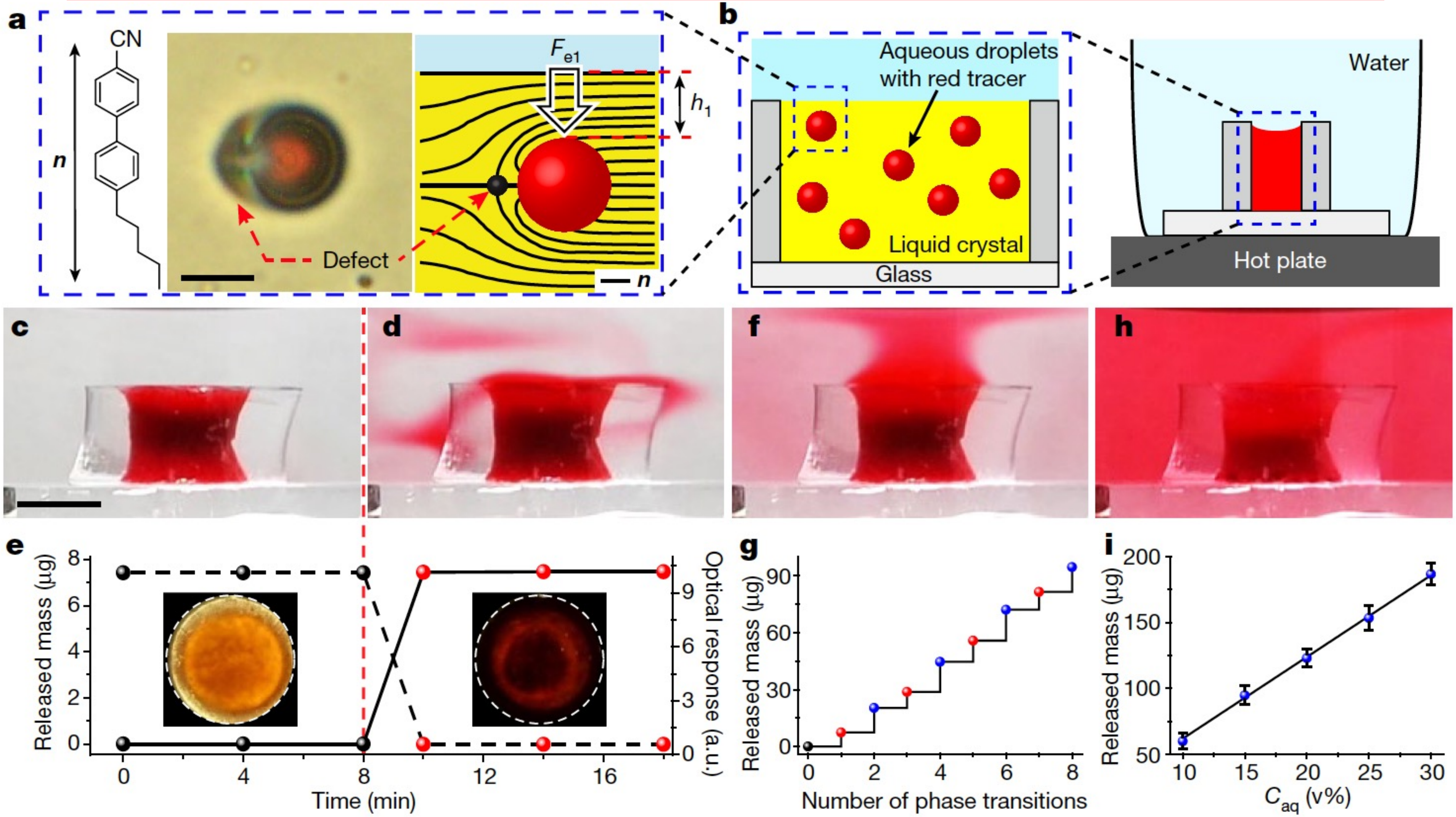
Nematic-mediated interactions

- The orientation of nematic molecules is locally disturbed because of their interaction with microparticle surfaces
- The disturbance can be considered as elastic deformation at microscale
- 2.3 um silica spheres in 5um or 2.5um LC layer



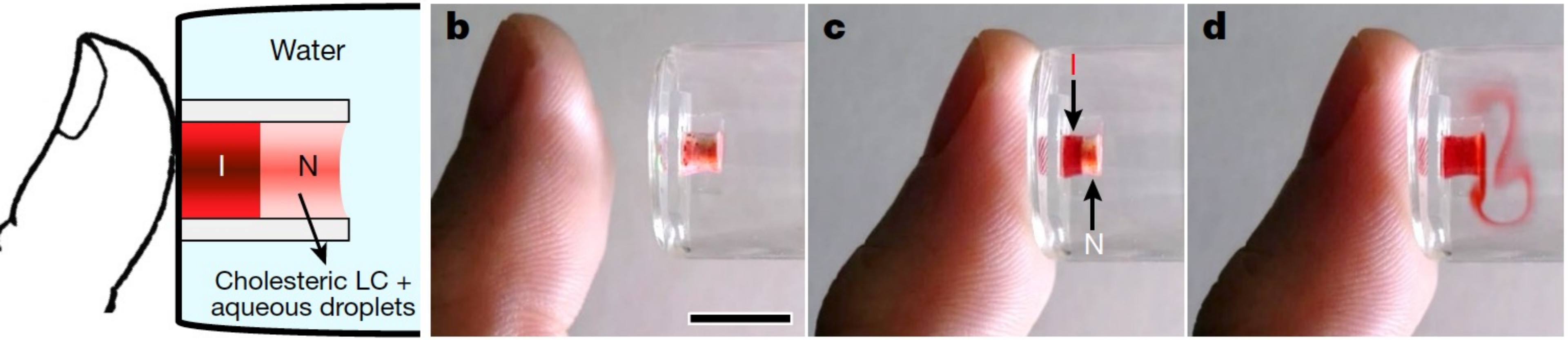


Pulsatile ejection of microdroplets from LCs



Pulsatile ejection of microdroplets from LCs

- Heat released from the human finger



Liquid Crystal Elastomers

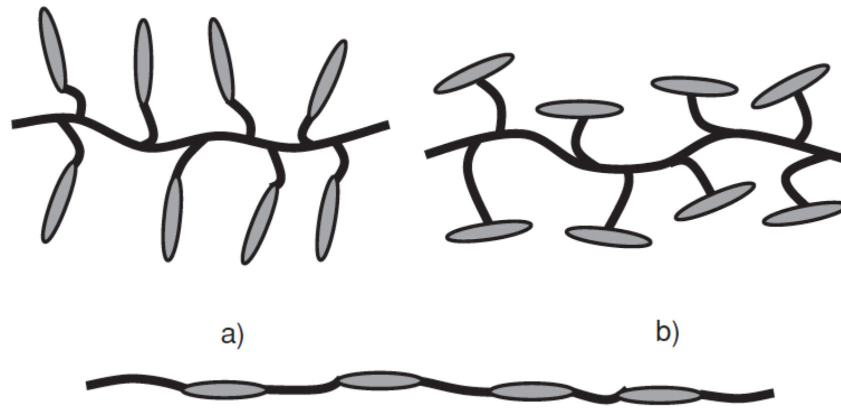
- Mesogenic monomers incorporated into the backbones or sidechains of weakly crosslinked long flexible polymers (i.e. polysiloxane)
  - Anisotropy and large susceptibility of low-molecular mass LCs with rubber elasticity

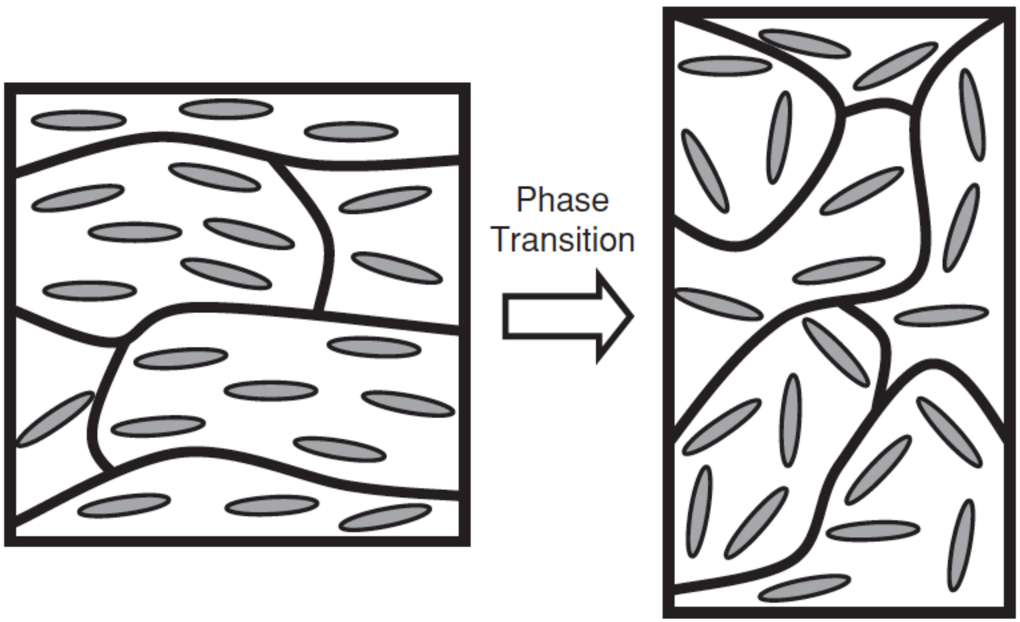
- Strong coupling between the orientational order and mechanical strain
  - Changing orientation order gives rise to internal stresses
  - Deformation and change of shape

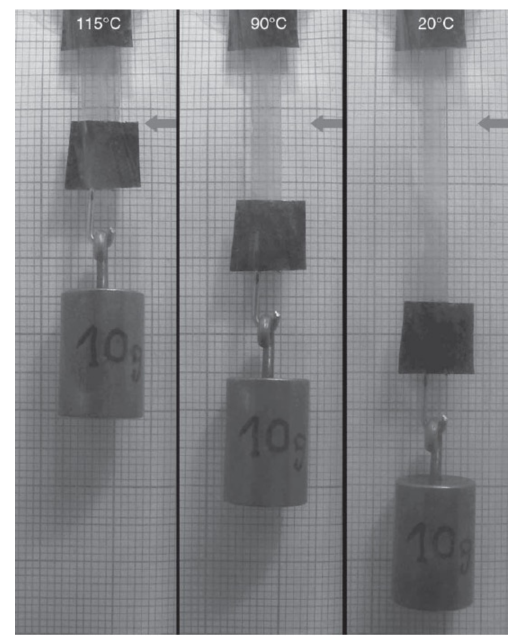
- Molecular structure corresponds to traditional rubber
  - Long chains of molecules that can easily slip past one another
  - Enable the material to be expanded with very little force
  - Strains of several 100 per cent
  - Mechanical response depends on alignment direction and phase

Liquid Crystal Elastomers

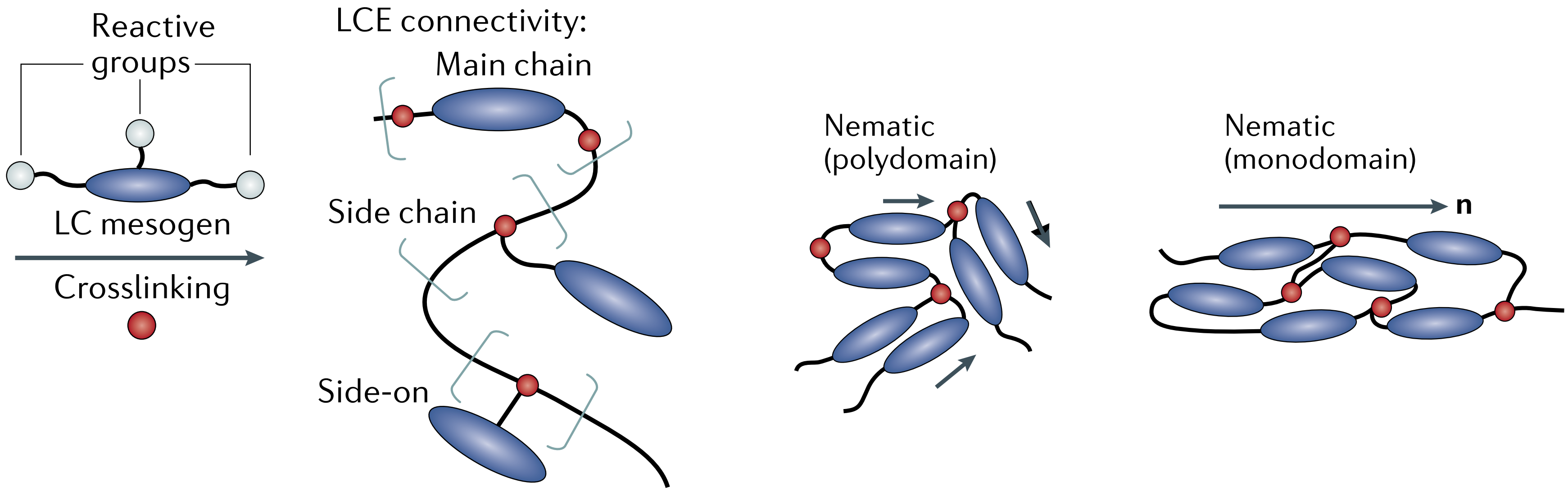
- Coupling between the mesogens and polymer chains
  - (a) end-on
  - (b) side-on
  - (c) main-chain



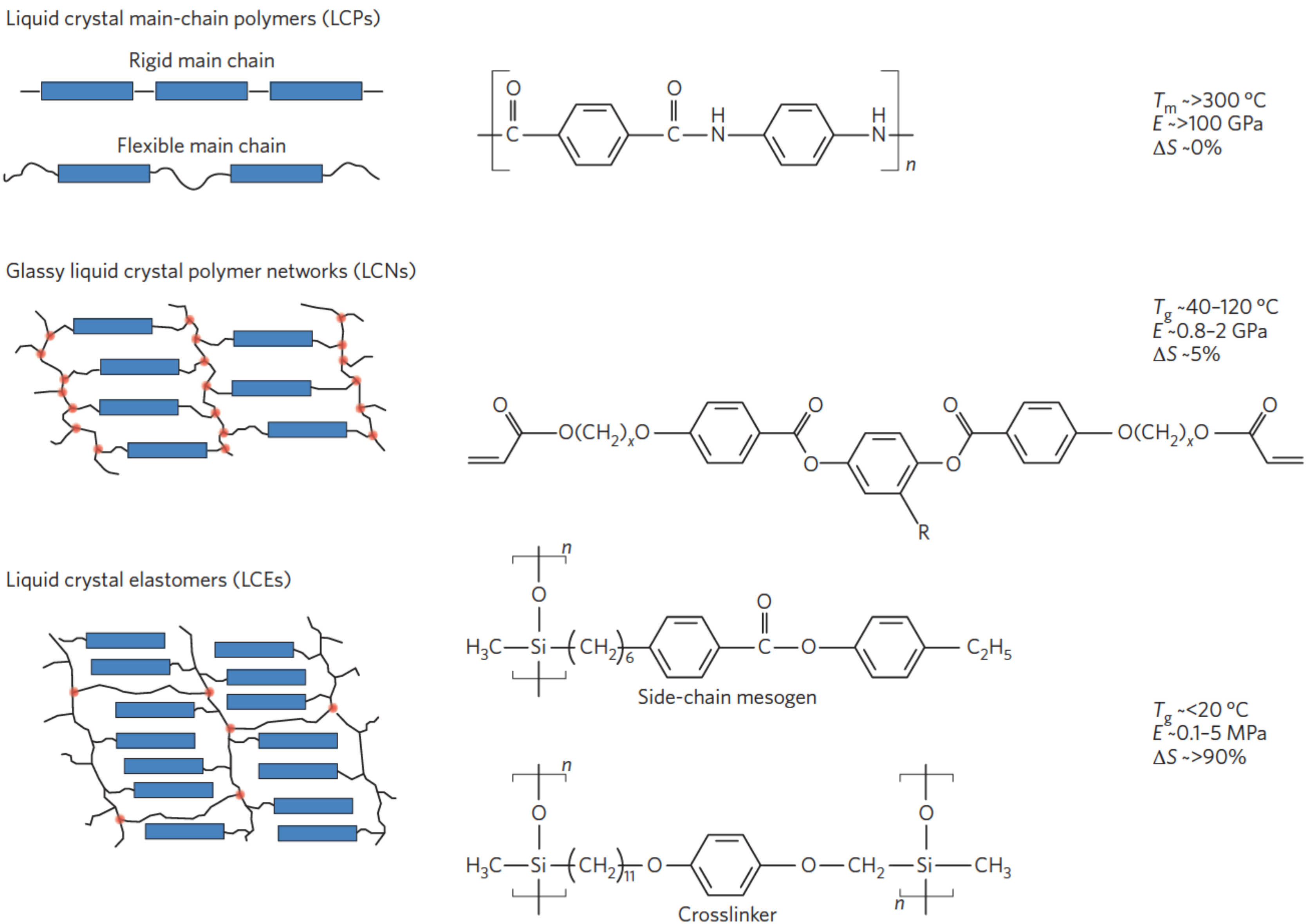




Liquid Crystal Elastomers

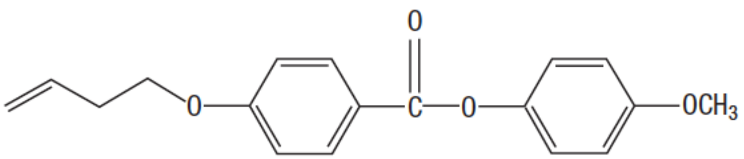


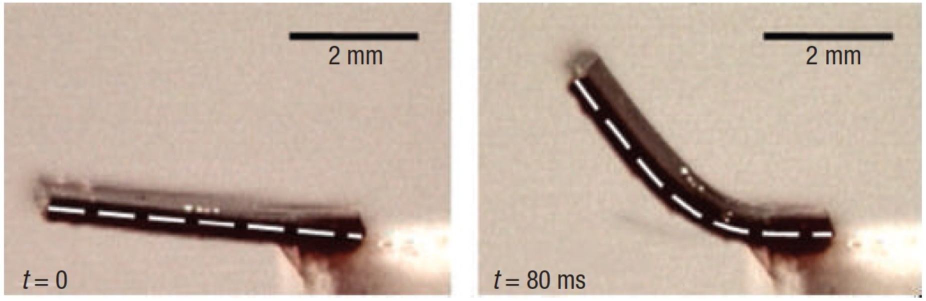
Liquid Crystal Elastomers

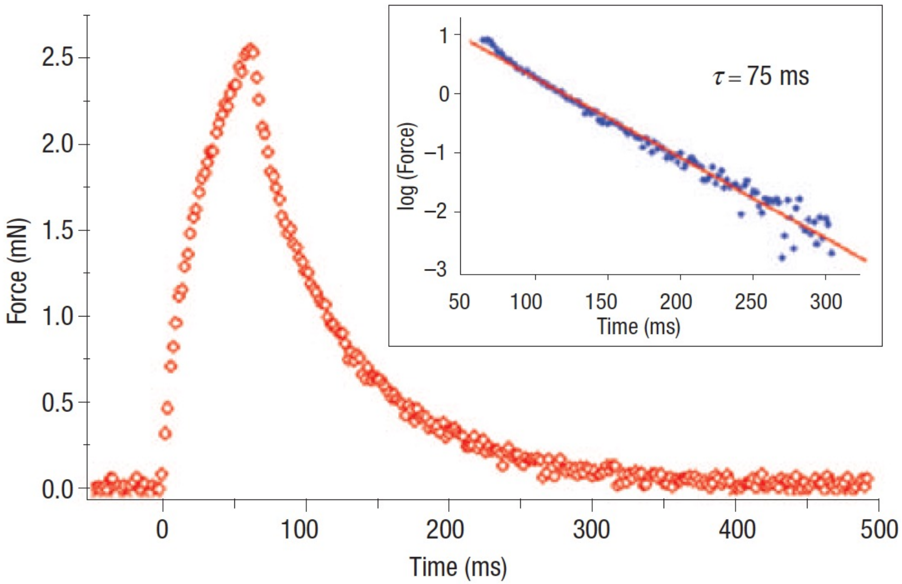


Wireless control with light

- Dopants containing azobenzene moieties: covalent bonding or dissolving
- Change in the degree of order
  - Photoisomerization of the dissolved dye
  - Photoisomerize between trans- and cis-states in the presence of linear polarized light at specific wavelengths

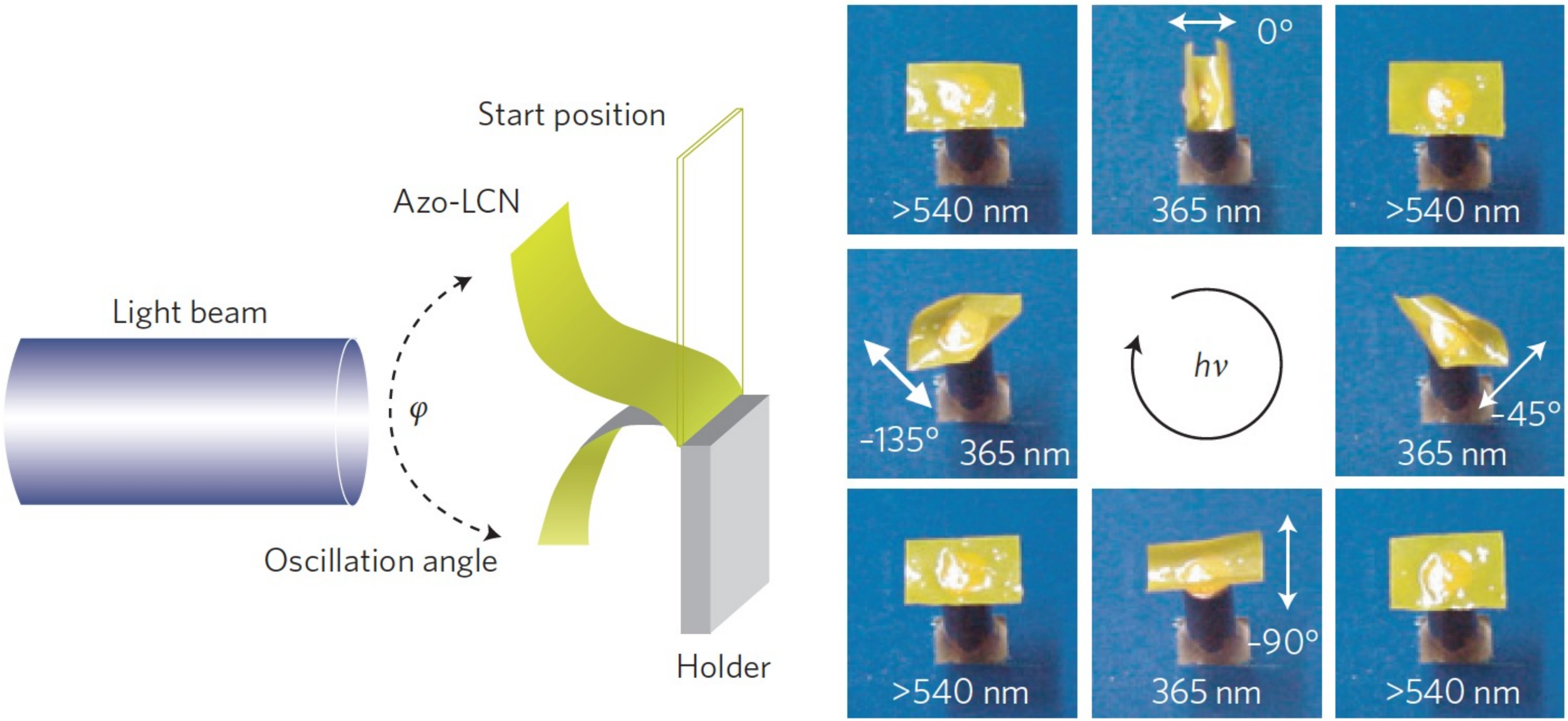






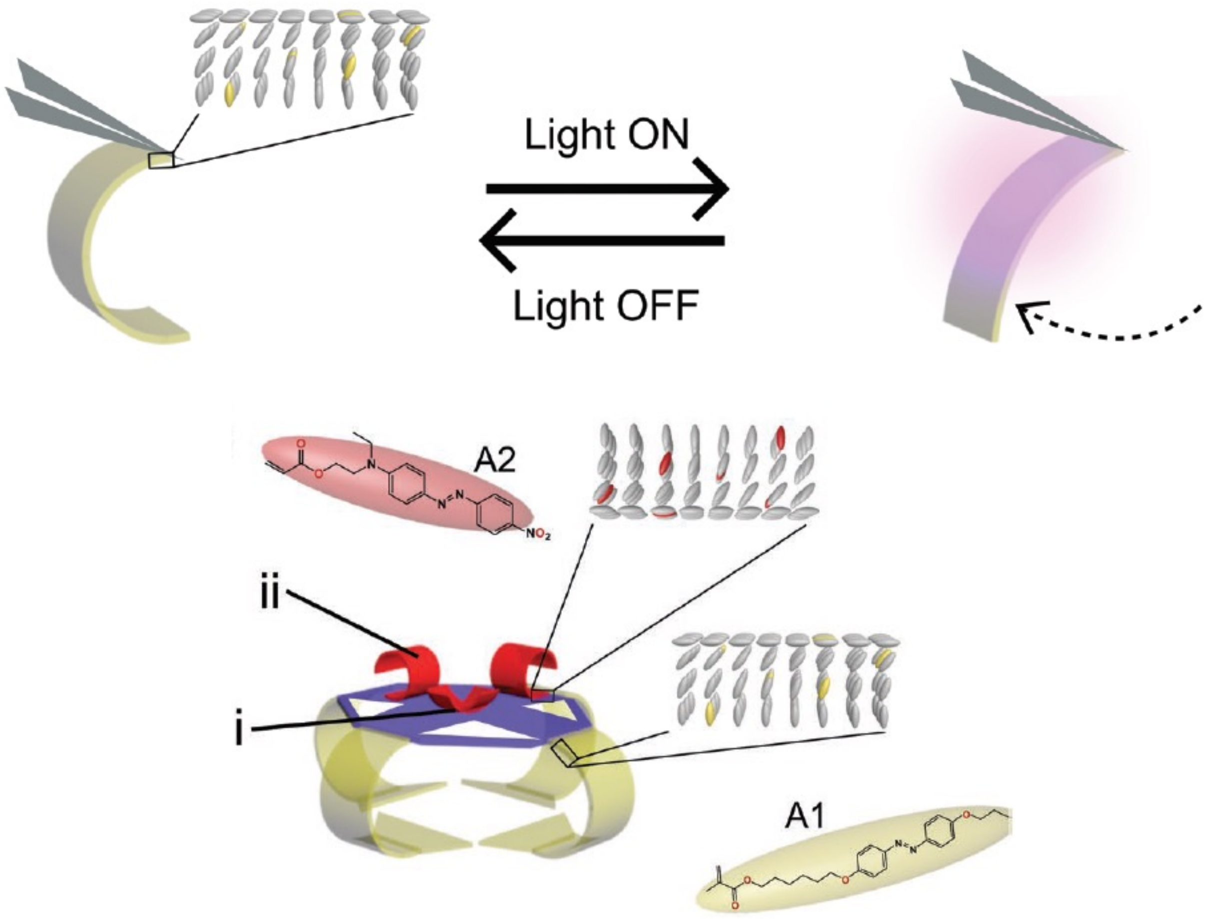
Wireless control with light

- Intensity, polarization, and wavelength of light



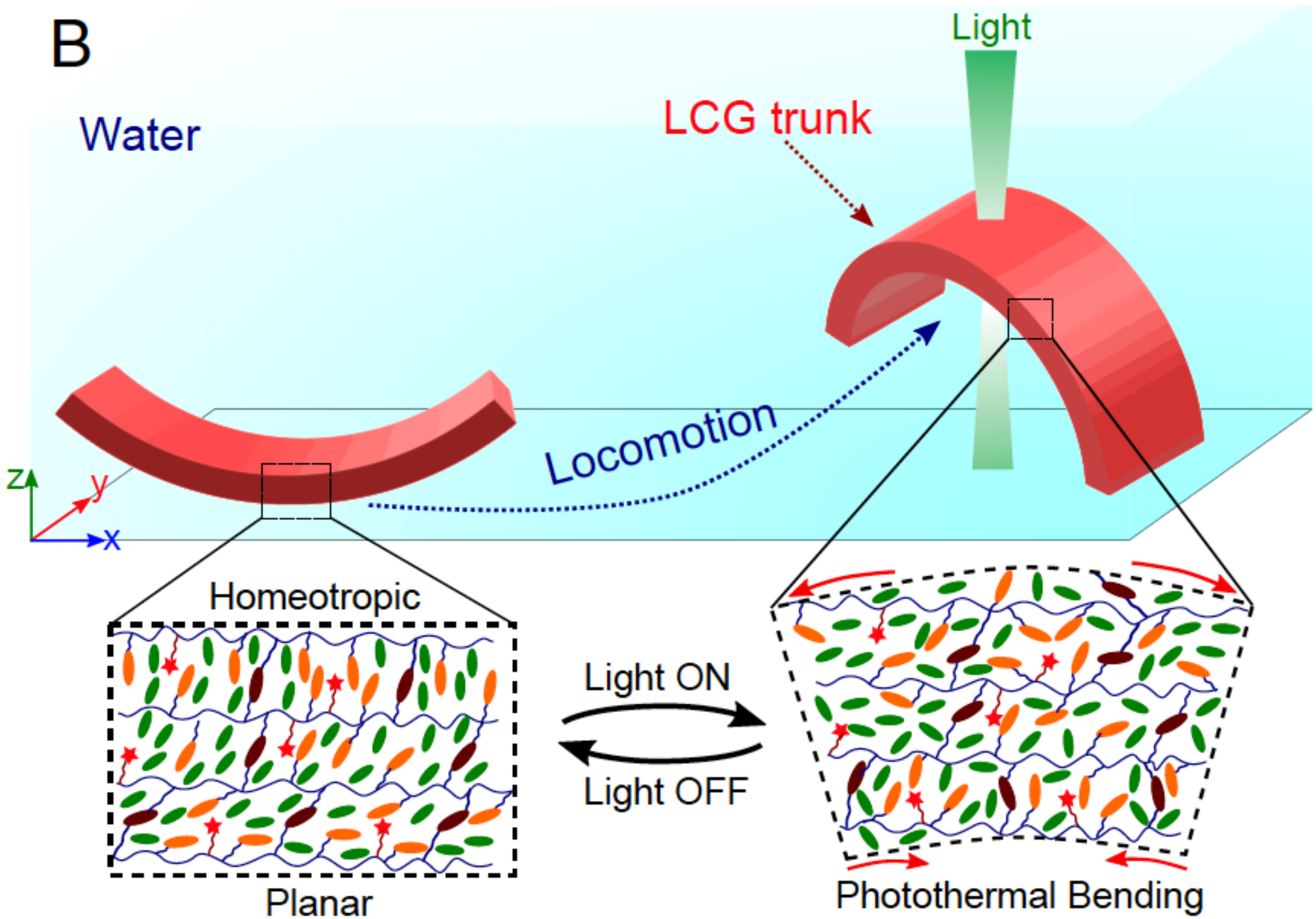
Soft robot

- Two different materials for the legs and the grippers



Soft robot

Soft robot


B
Water
LCG trunk
Light
z
y
x
Locomotion
Homeotropic
Planar
Light ON
Light OFF
Photothermal Bending

Soft robot

Light-fueled Oscillation

Frequency: 1Hz

Sample size: 9 x 1.5 x 0.1 mm^3

The playback speed is 1X.

Soft robot

Swimming in Vertical Direction
based on Undulatory Light-fueled Bending

Light source: Arc Lamp

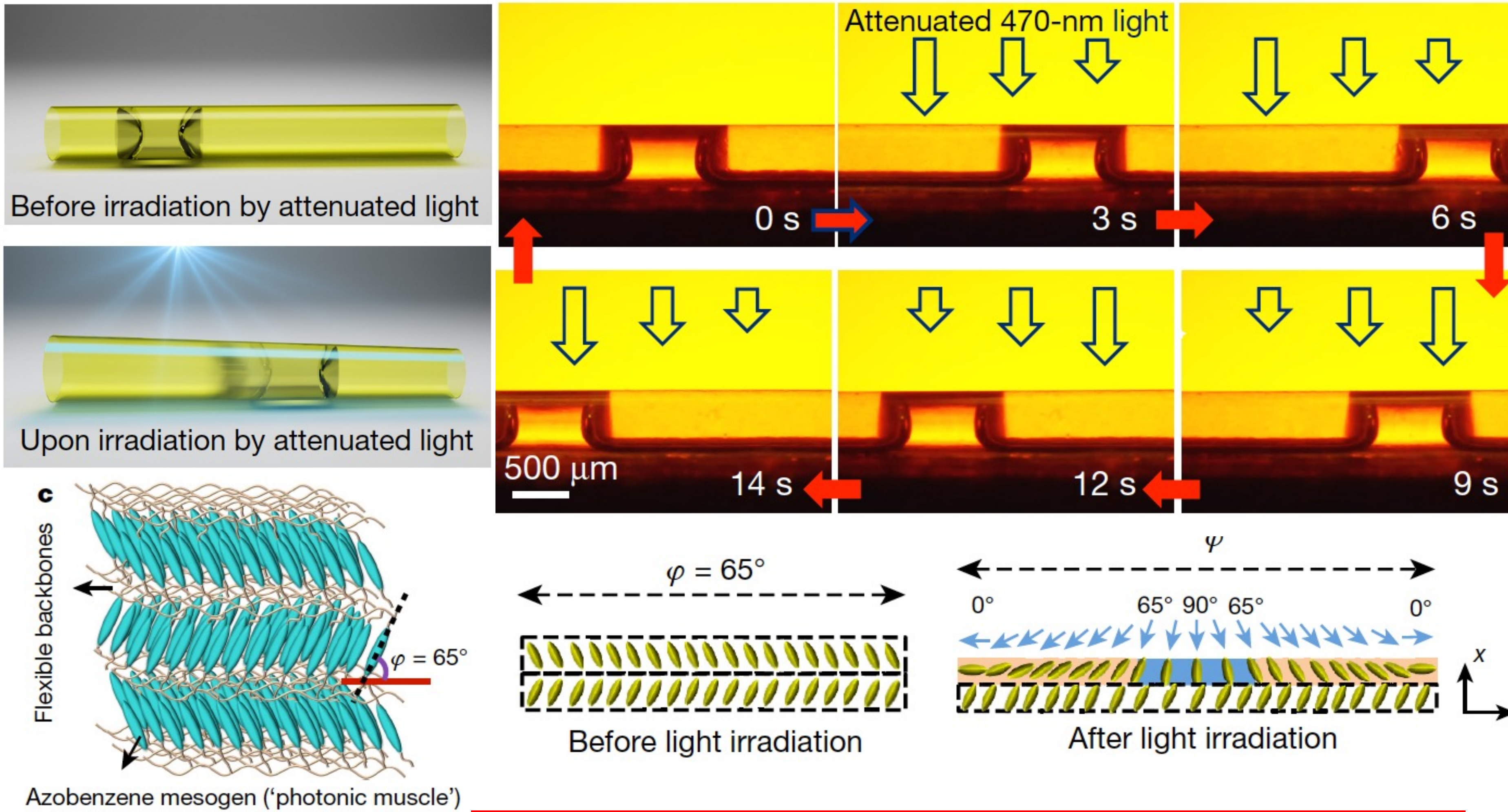
Light intensity: < 1.8 W cm^{-2}

Sample size: 16 x 3 x 0.1 mm^3

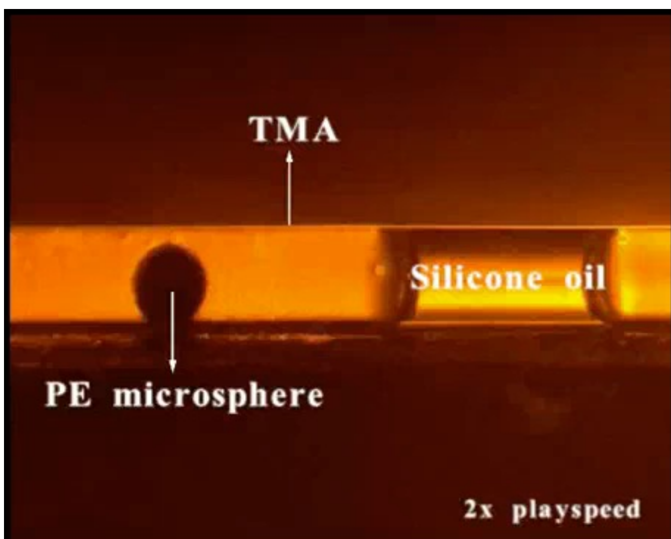
The playback speed is 1X.

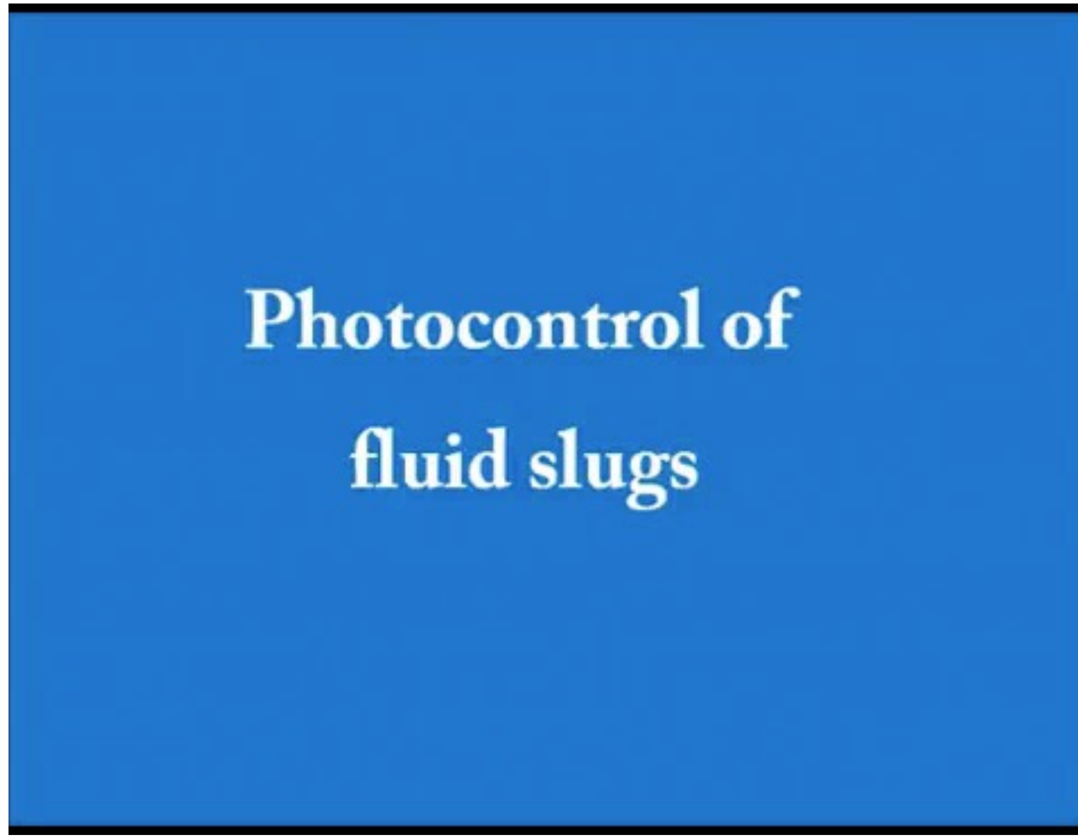
Pumping and transport

- Deformation into a cone-like geometry: capillary force



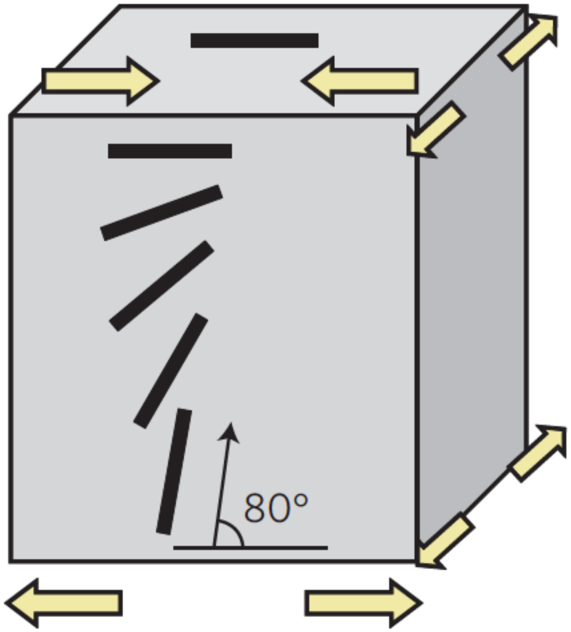
Pumping and transport

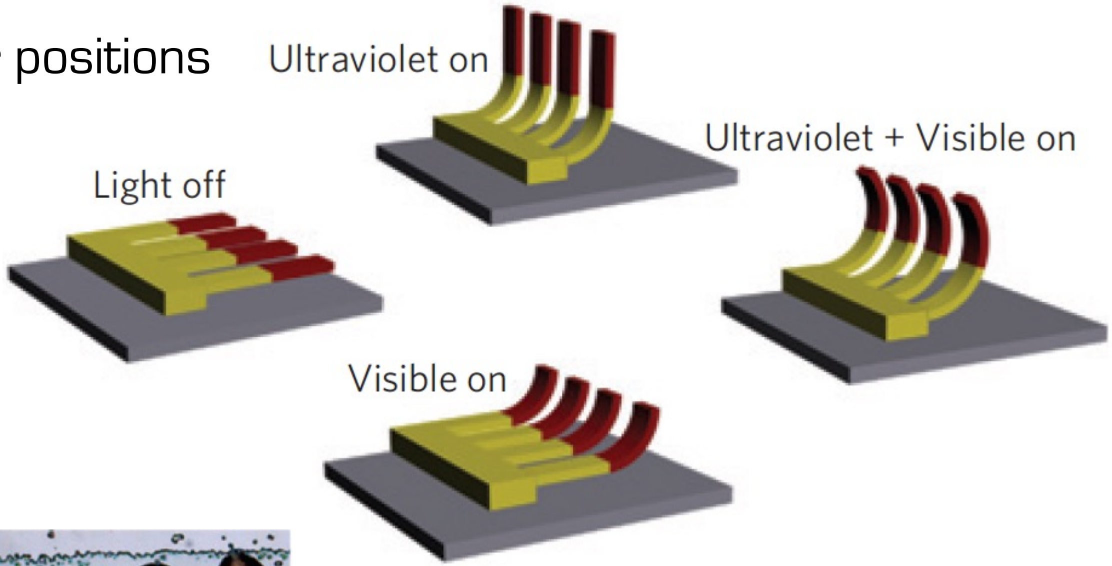


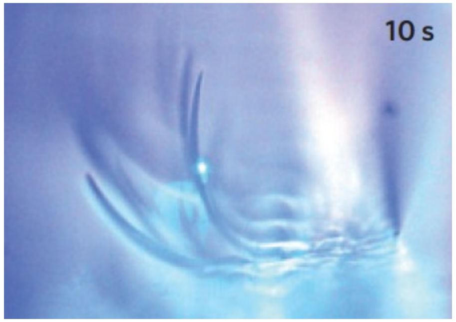


Artificial Cilia

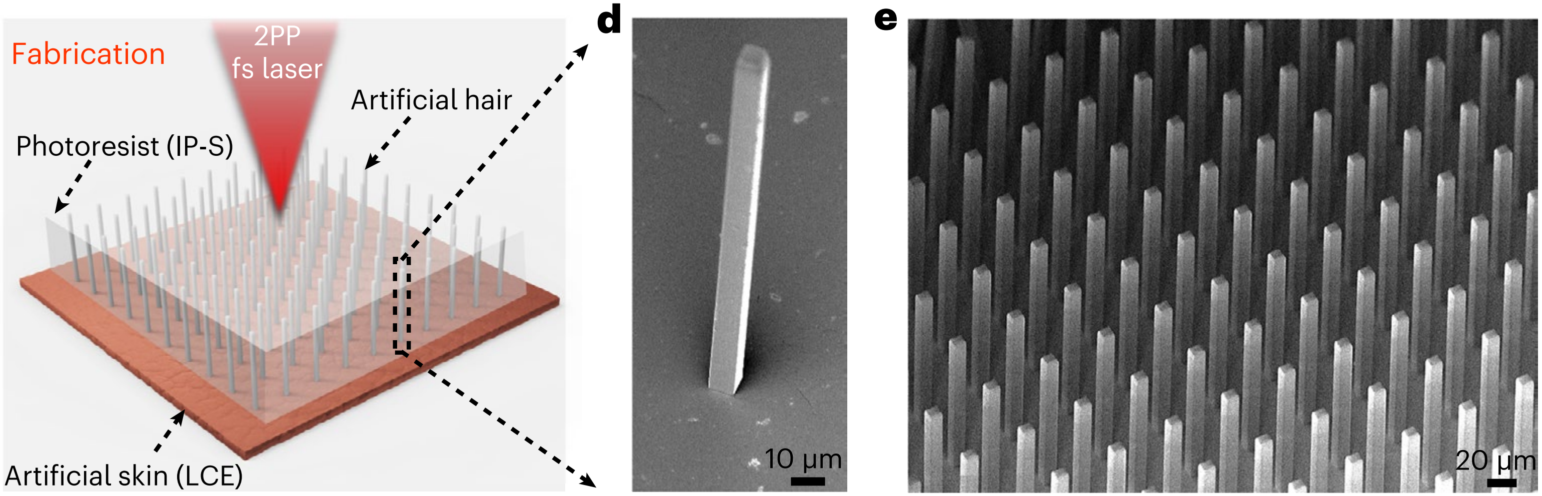
- Asymmetric motion controlled by the spectral composition of light
  - Two different dyes
  - Switching between four positions

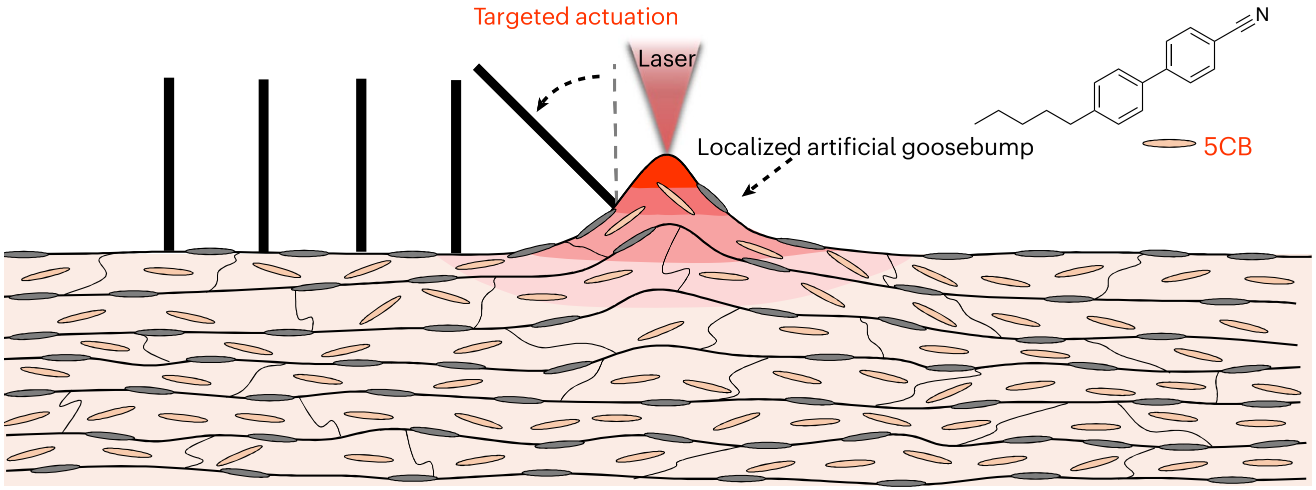




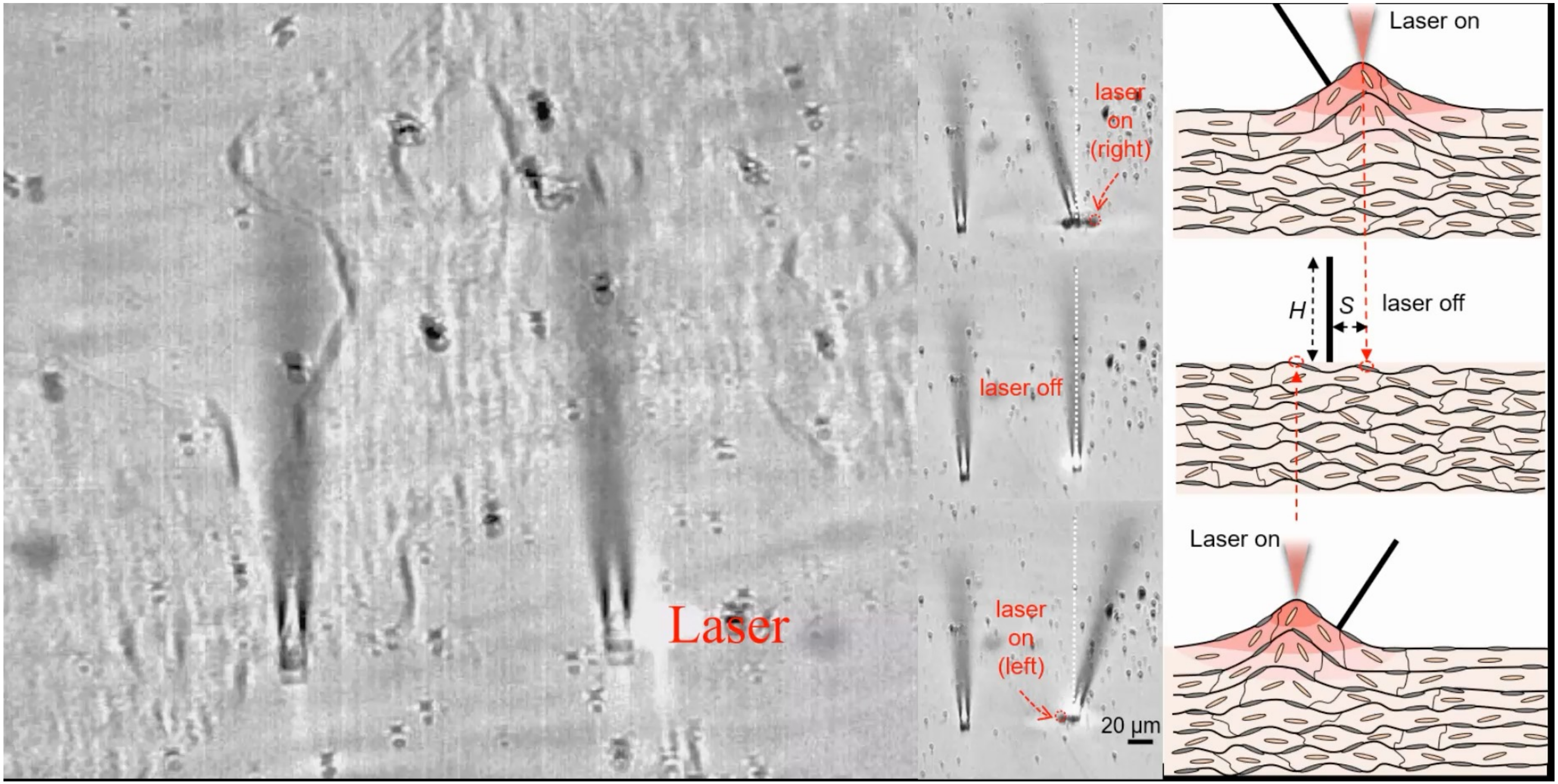


LCE Skin

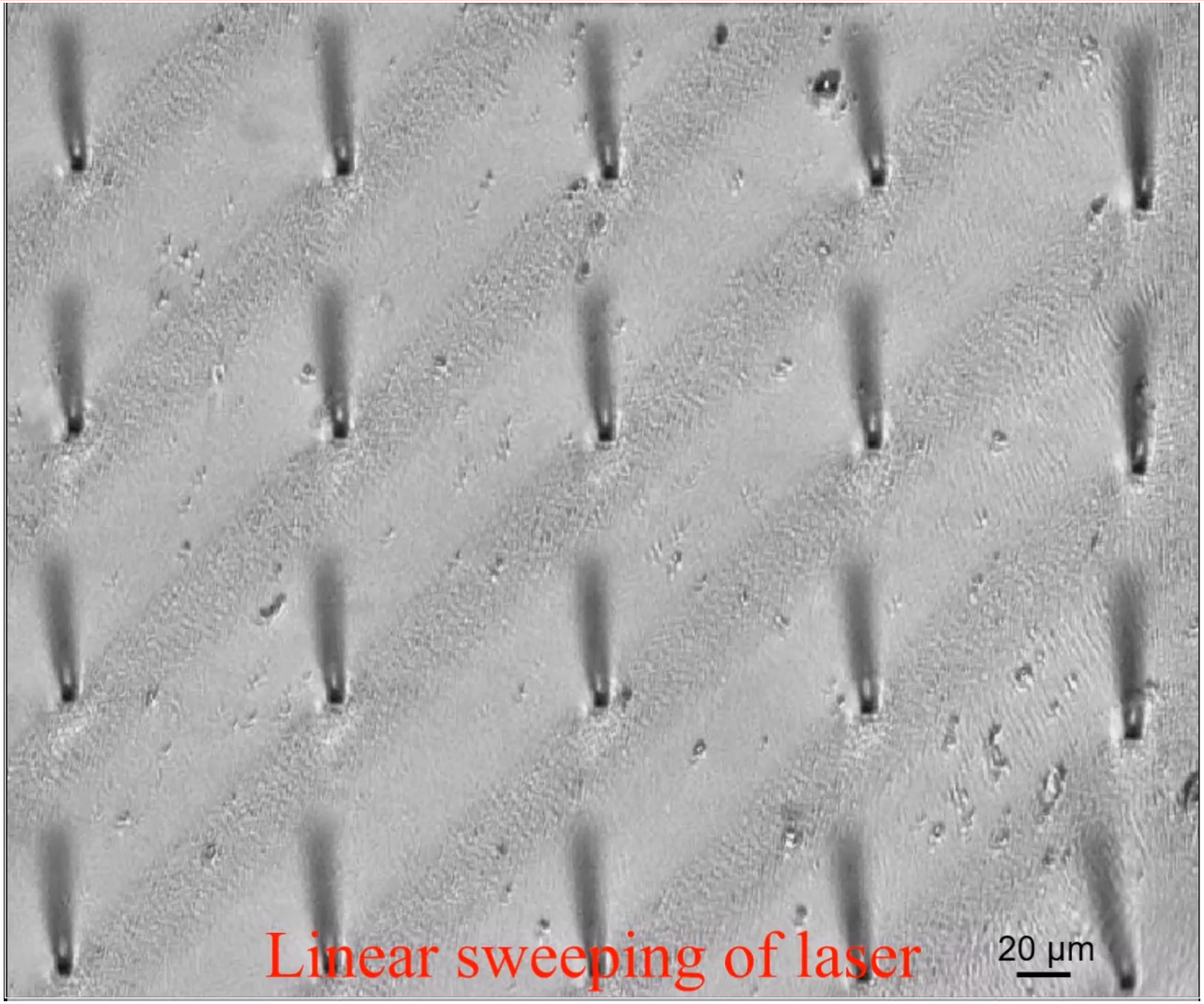

Fabrication
2PP
fs laser
Artificial hair
Photoresist (IP-S)
Artificial skin (LCE)
d
10 μm
e
20 μm


Targeted actuation
Laser
Localized artificial goosebump
N
5CB

LCE Skin

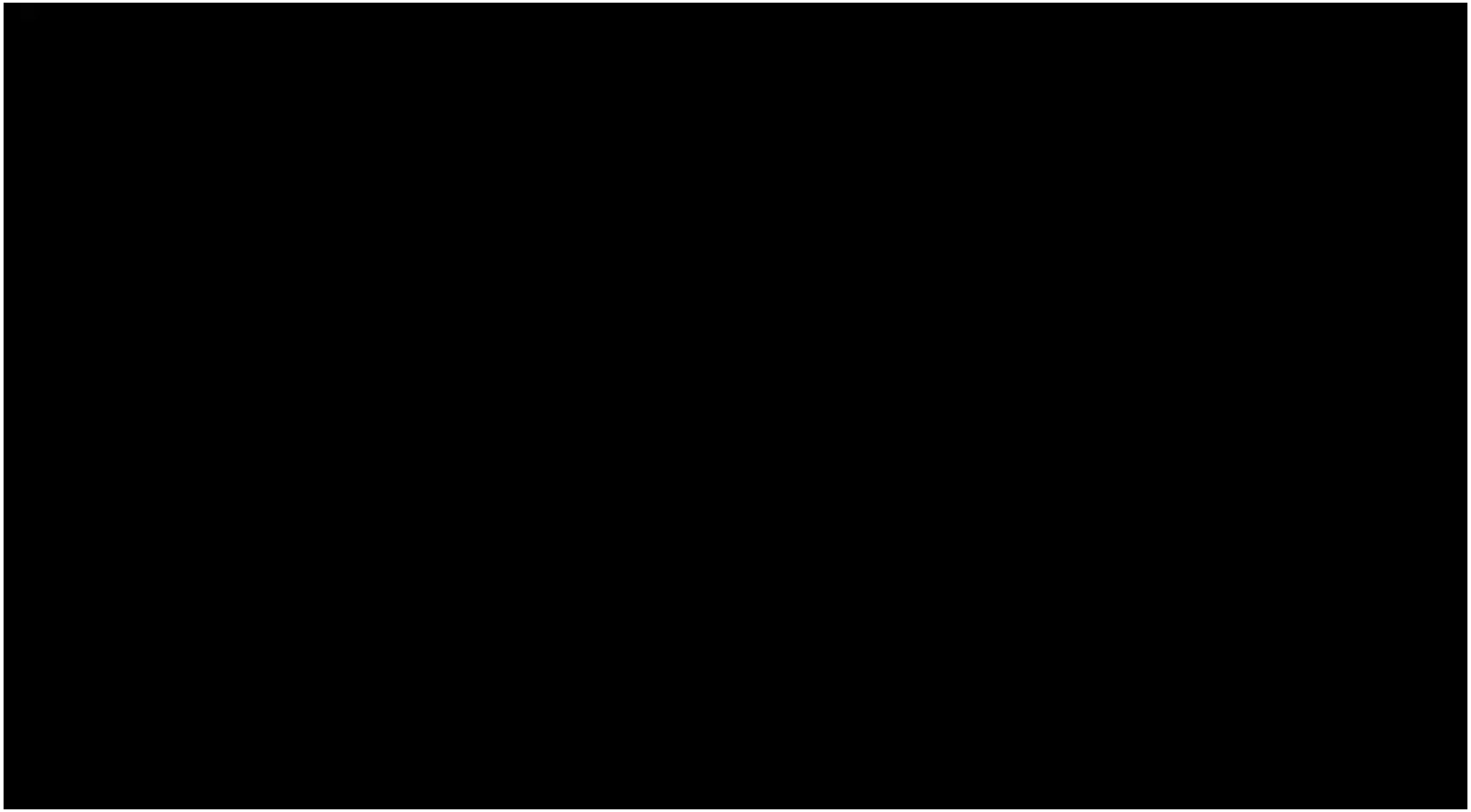

Laser
laser on (right)
laser off
laser on (left)
20 µm
Laser on
H
S
laser off
Laser on

LCE Skin



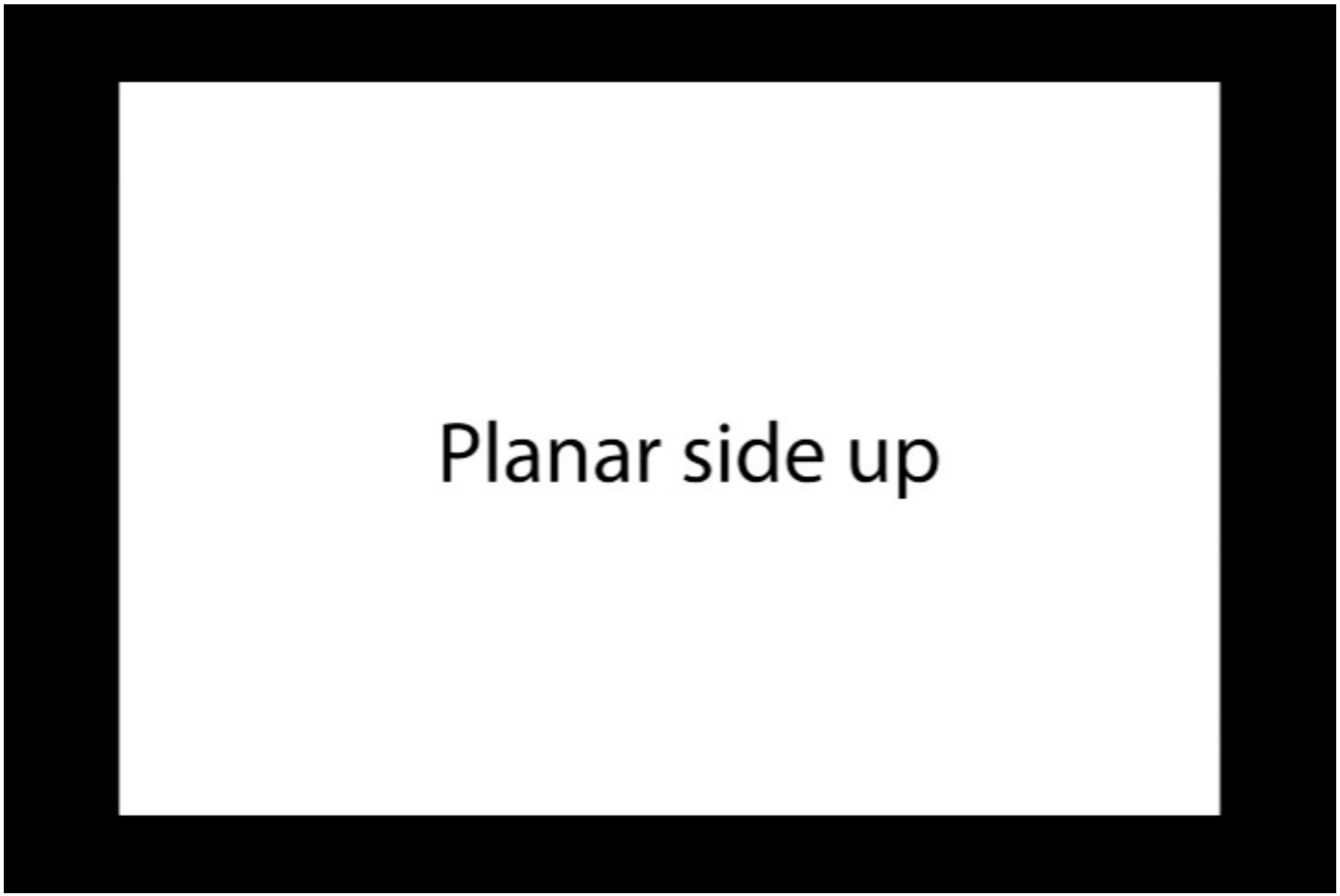
Rotation and rolling

- Shear stress gradients through the thickness



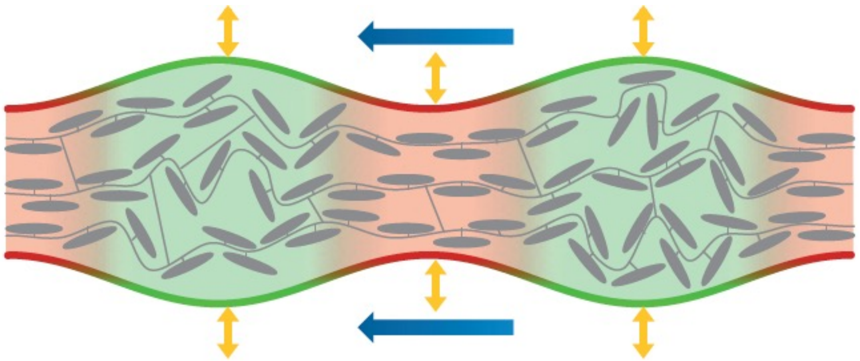
Making waves in a photoactive polymer film

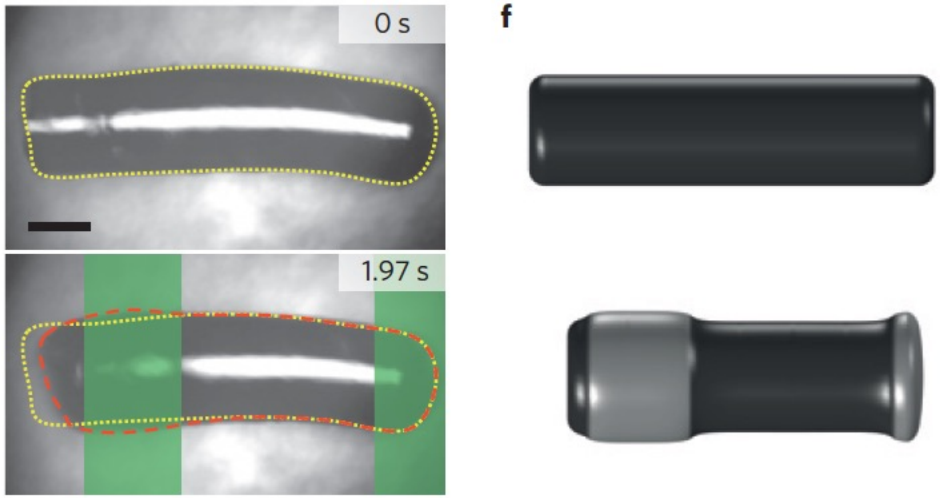
- continuous, directional, macroscopic mechanical waves under constant light illumination



Biomimetic Swimming

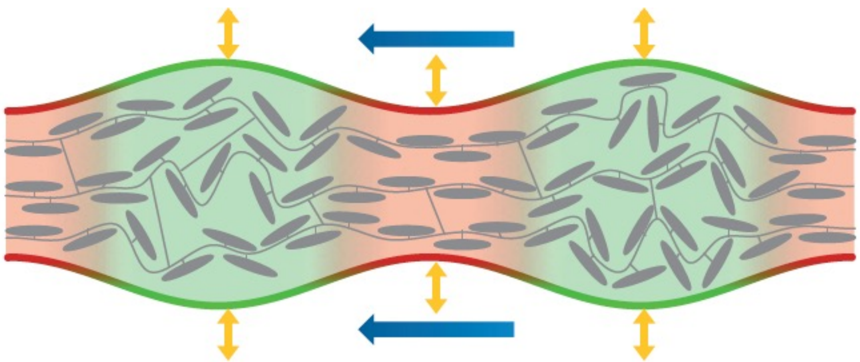
- Generating of a travelling wave under periodic light pattern

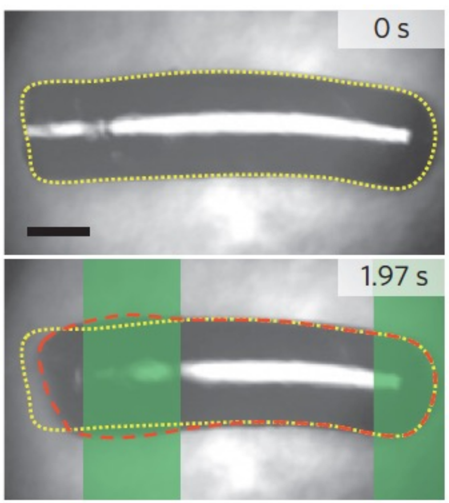




Biomimetic Swimming

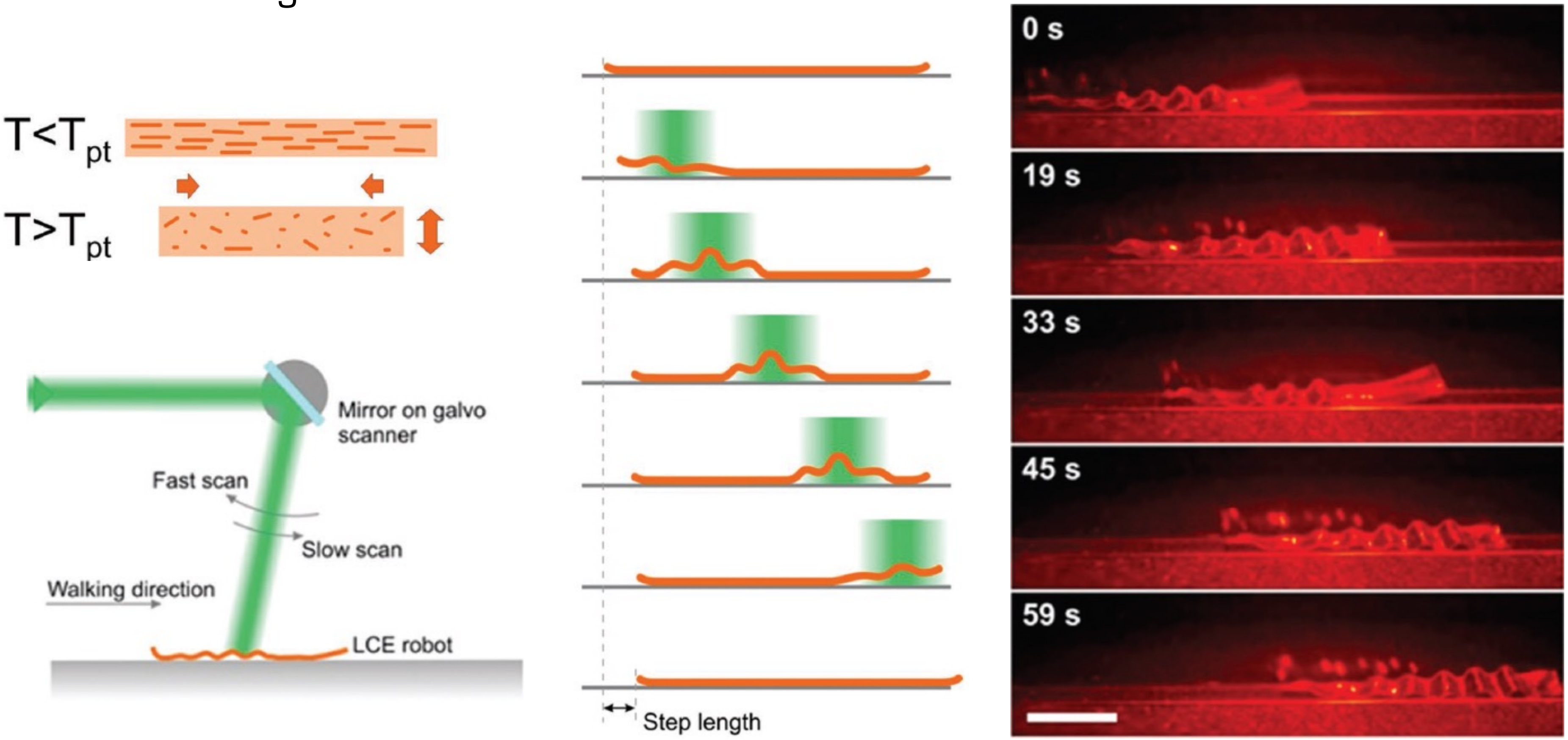
- Generating of a travelling wave under periodic light pattern





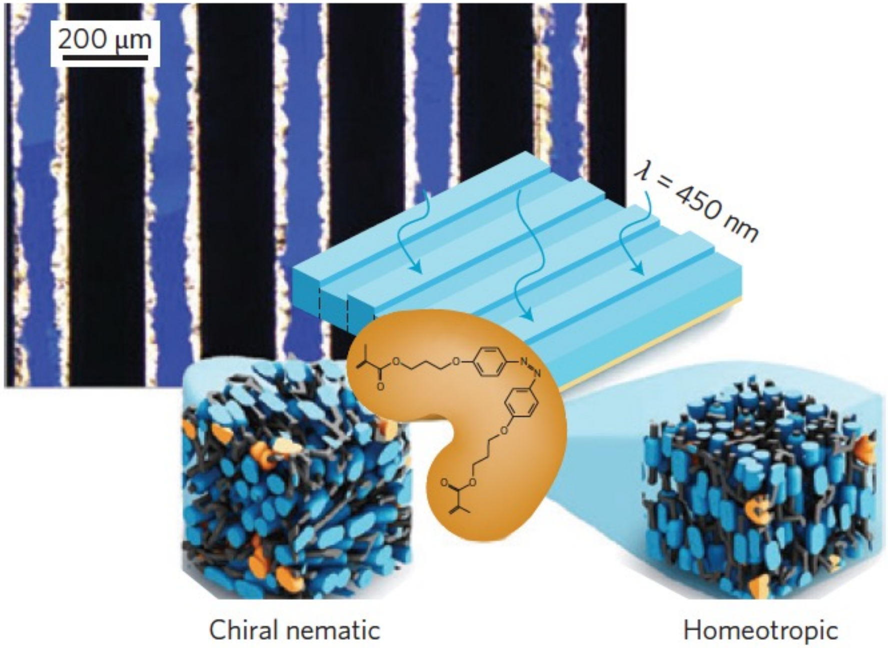
Biomimetic Crawling (movie)

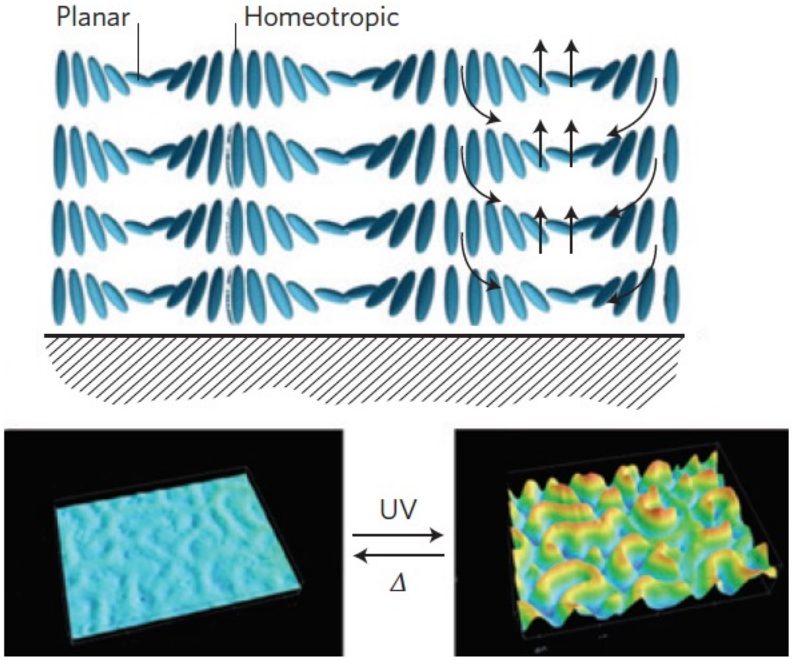
- Spatially modulated light field to trigger synchronized, time-dependent body deformations
- Scanning a laser beam



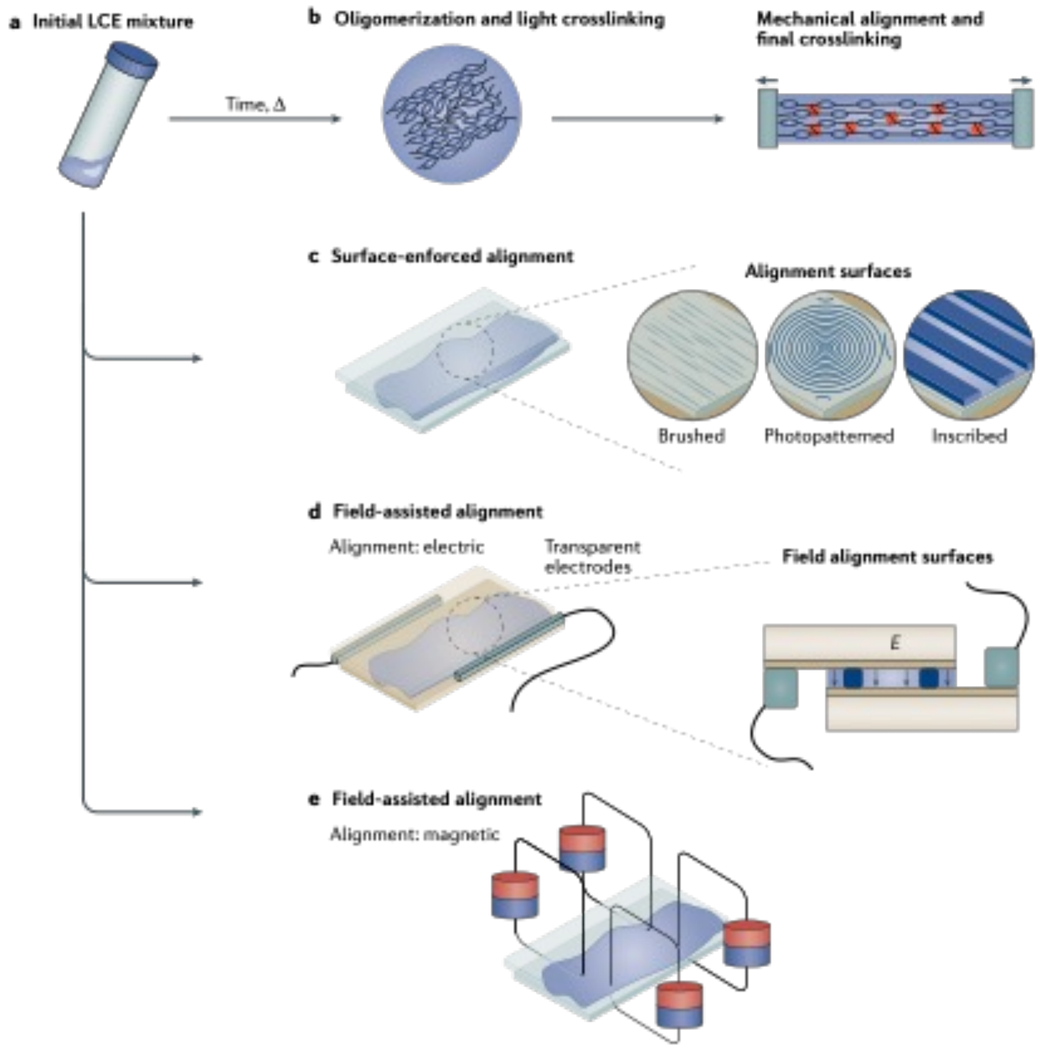
Programming local anisotropy

- Spatially complex shape changes or surface variations
- Electric, magnetic or photoalignment prior to polymerization
- Lock complex orientation in the polymer



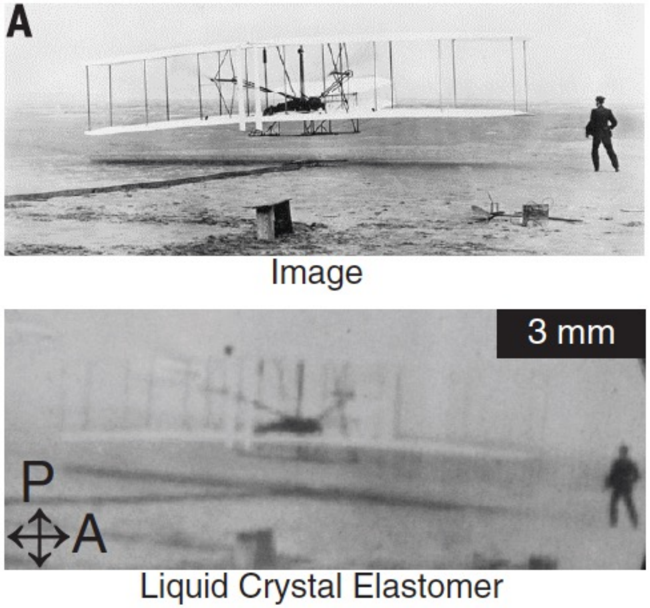


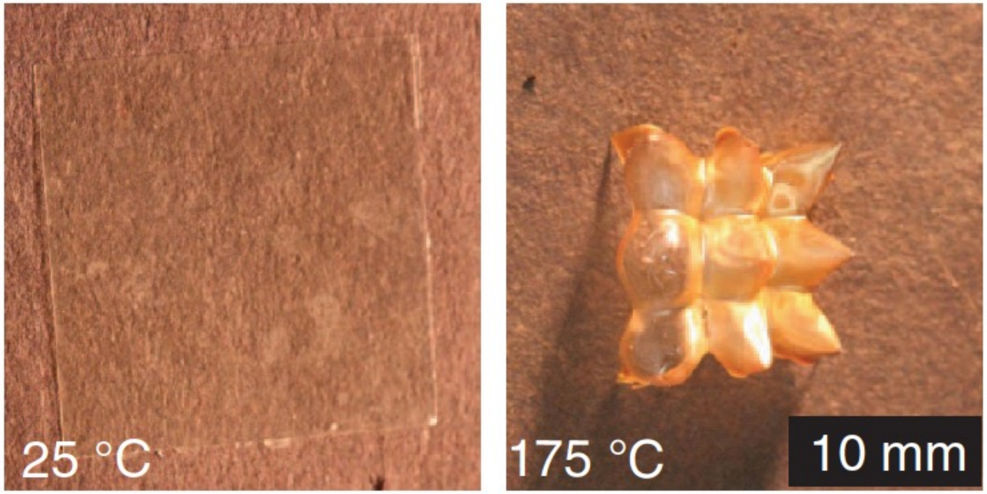
Programming local anisotropy



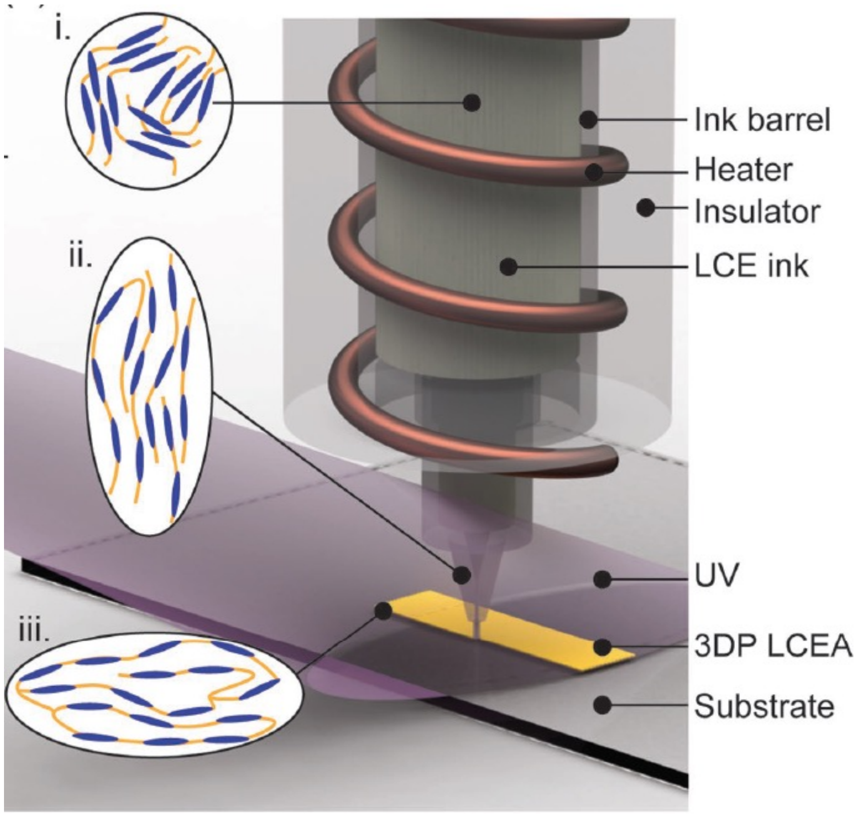
Voxels

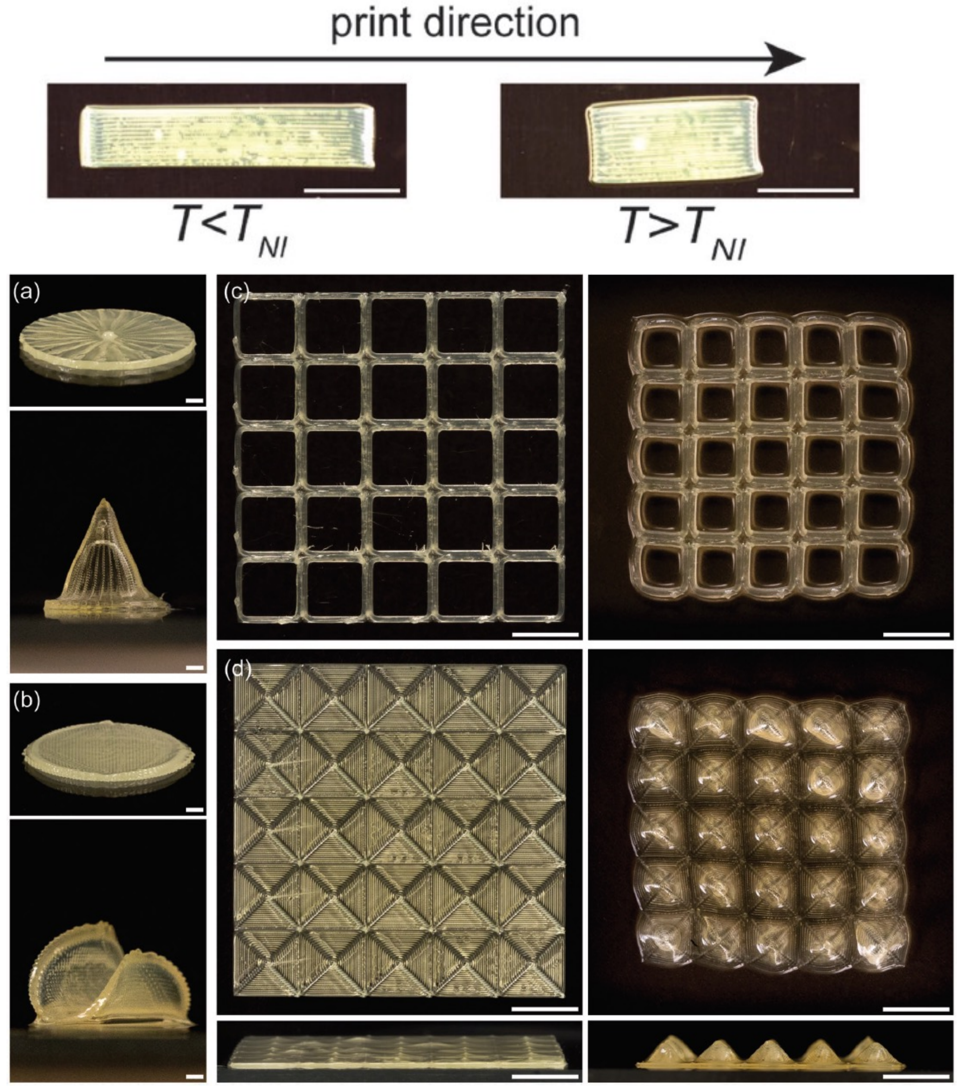
- Complex director profiles within LCE
- Spatial control with high resolution
- Photoalignment surface



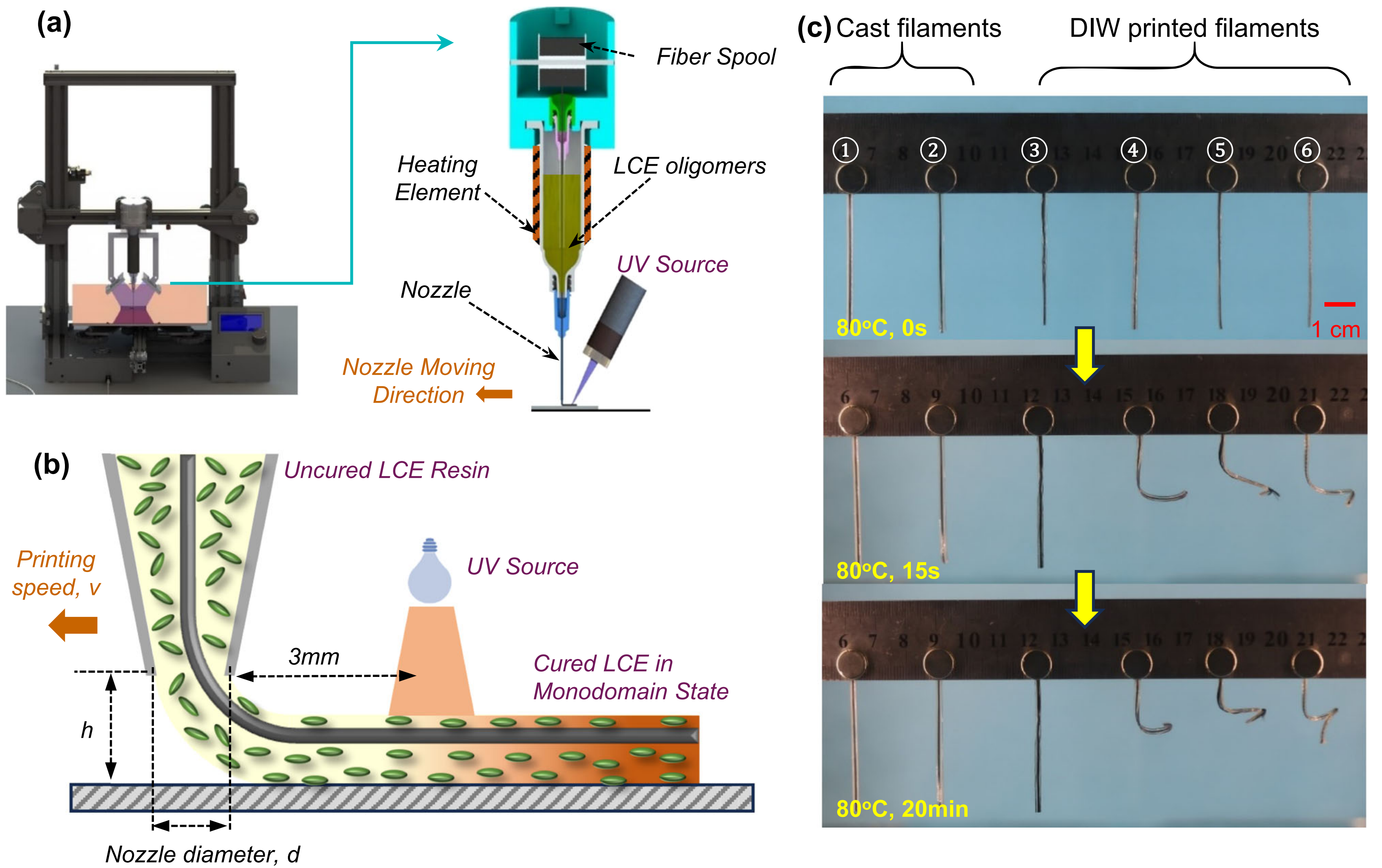


3D Printing LCE Actuators





3D Printing LCE Actuators



3D Printing LCE Actuators

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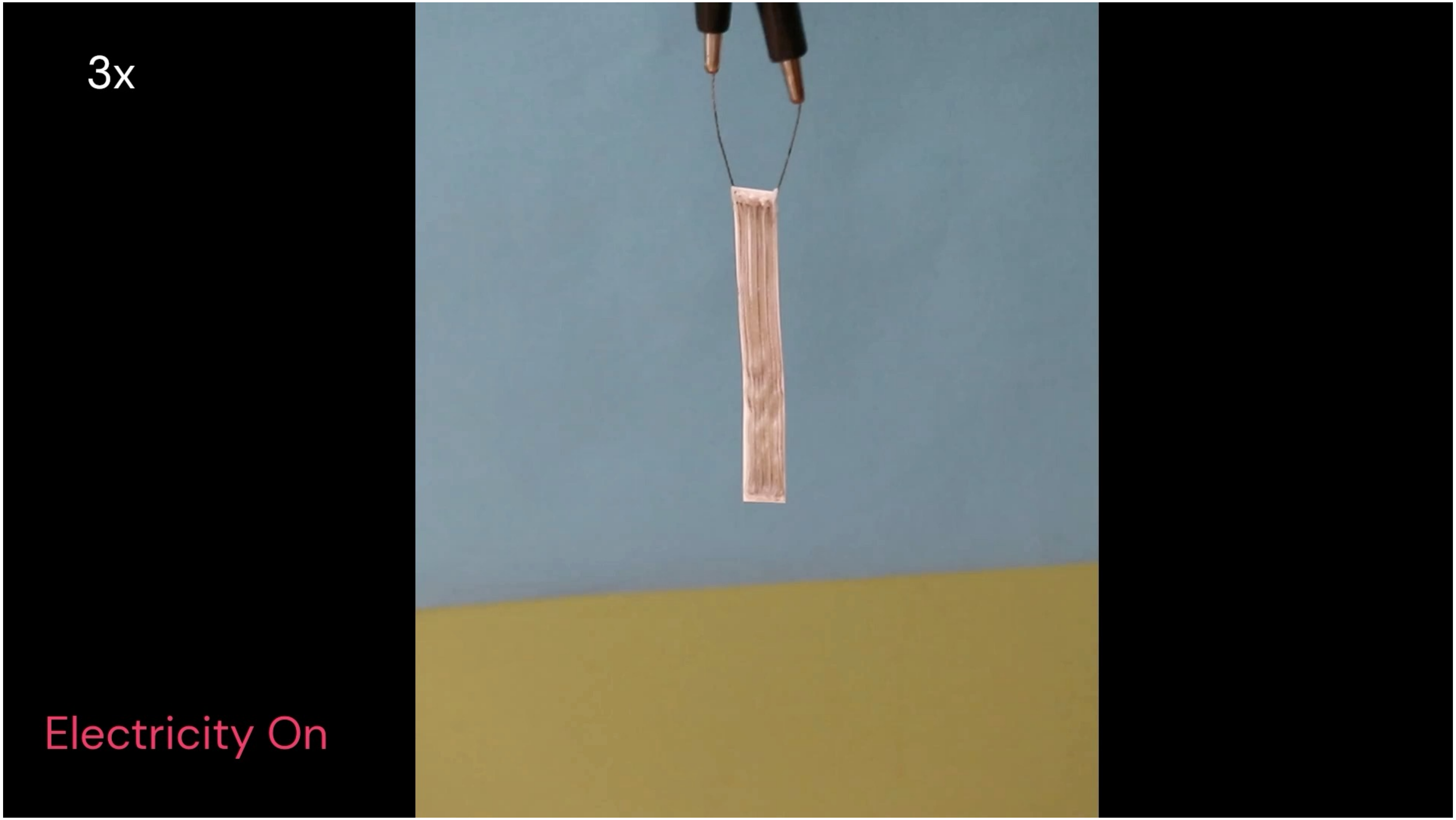
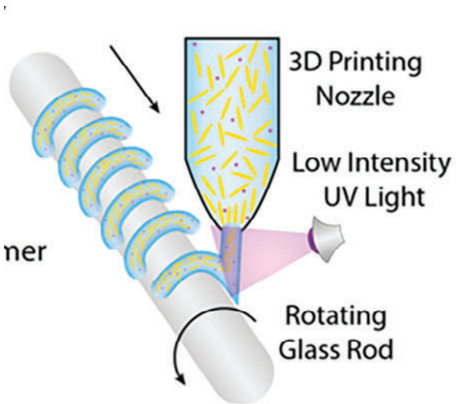
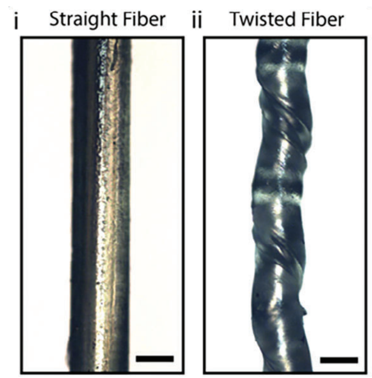
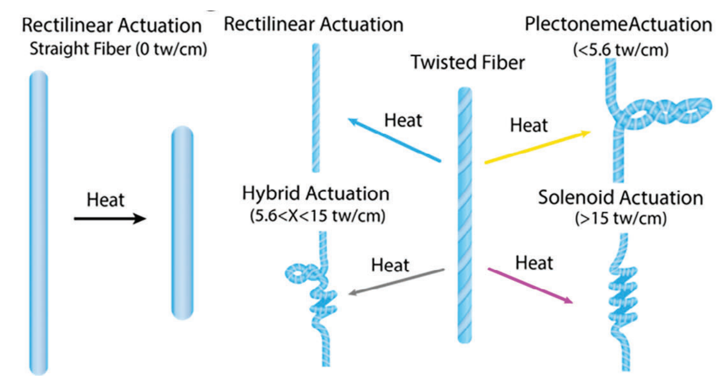
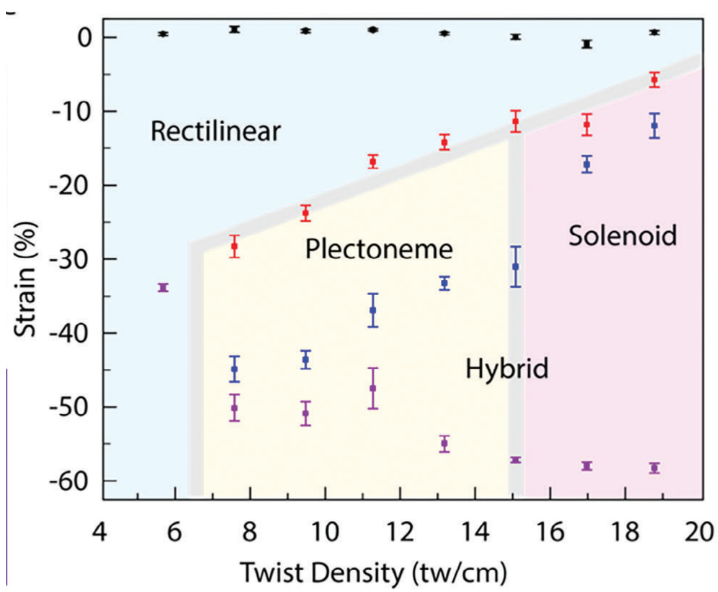


Twisted Liquid Crystal Elastomer Fibers









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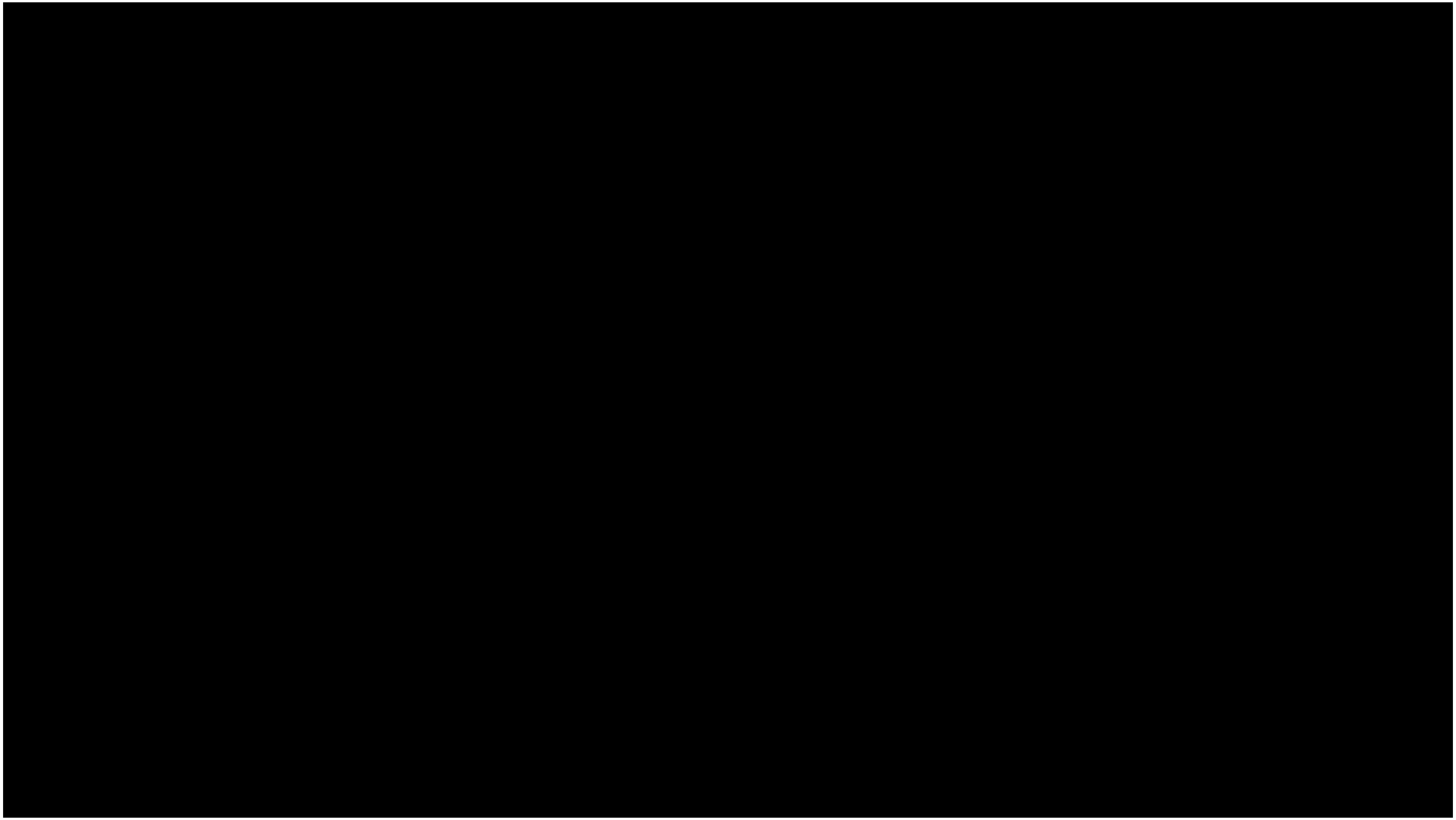
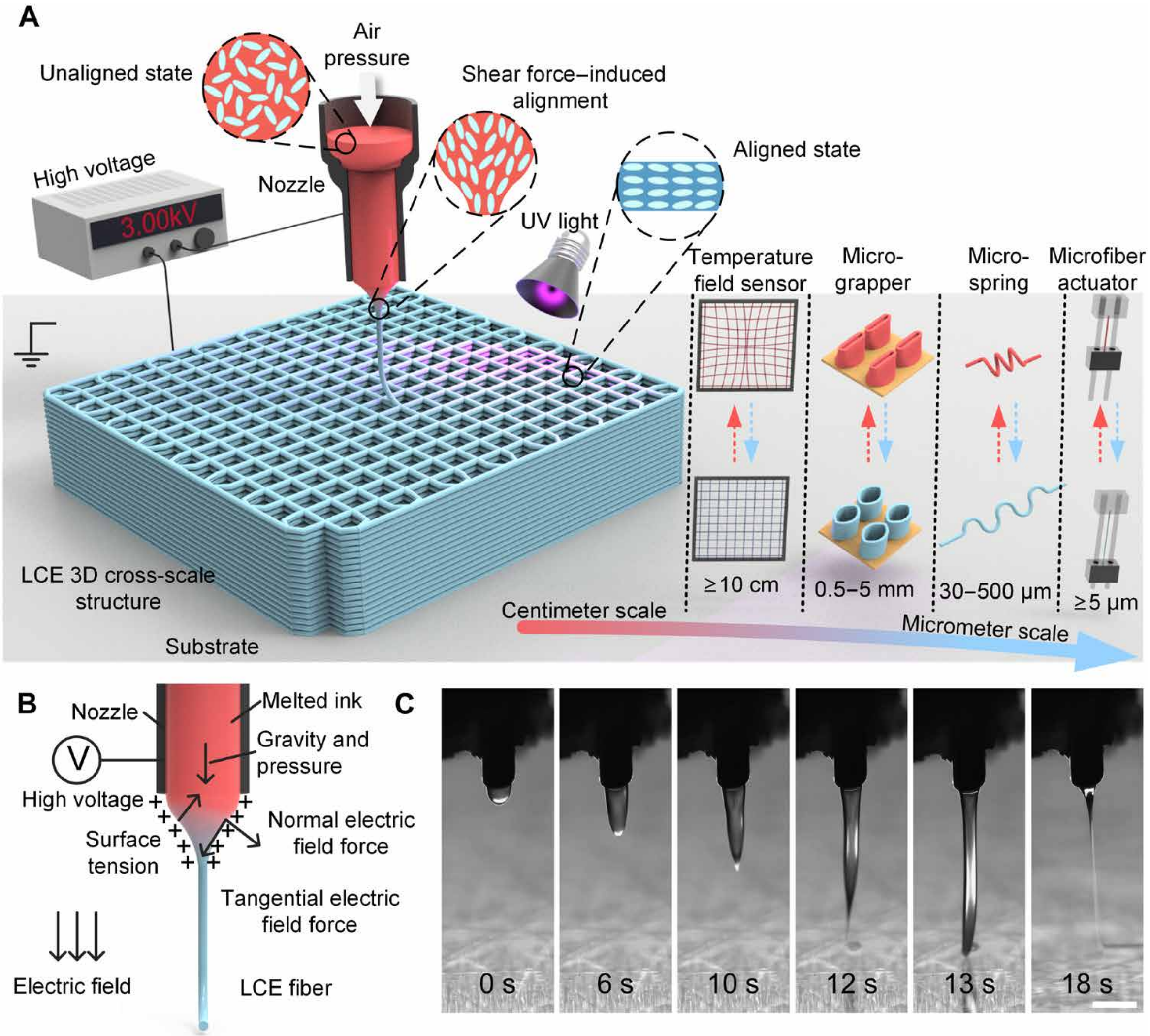
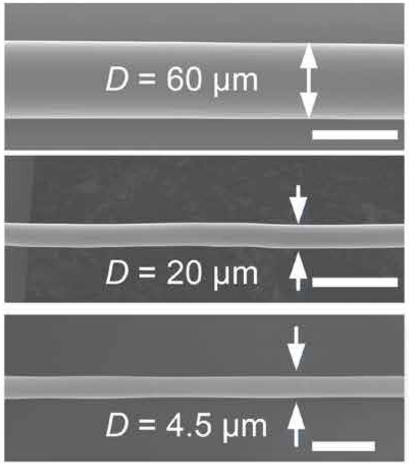


Melt electrowriting





Melt electrowriting

- Melt electrowriting (MEW) is a polymer melt processing technique which involves formation of polymer fibres and their controlled deposition to create complex architectures following additive manufacturing

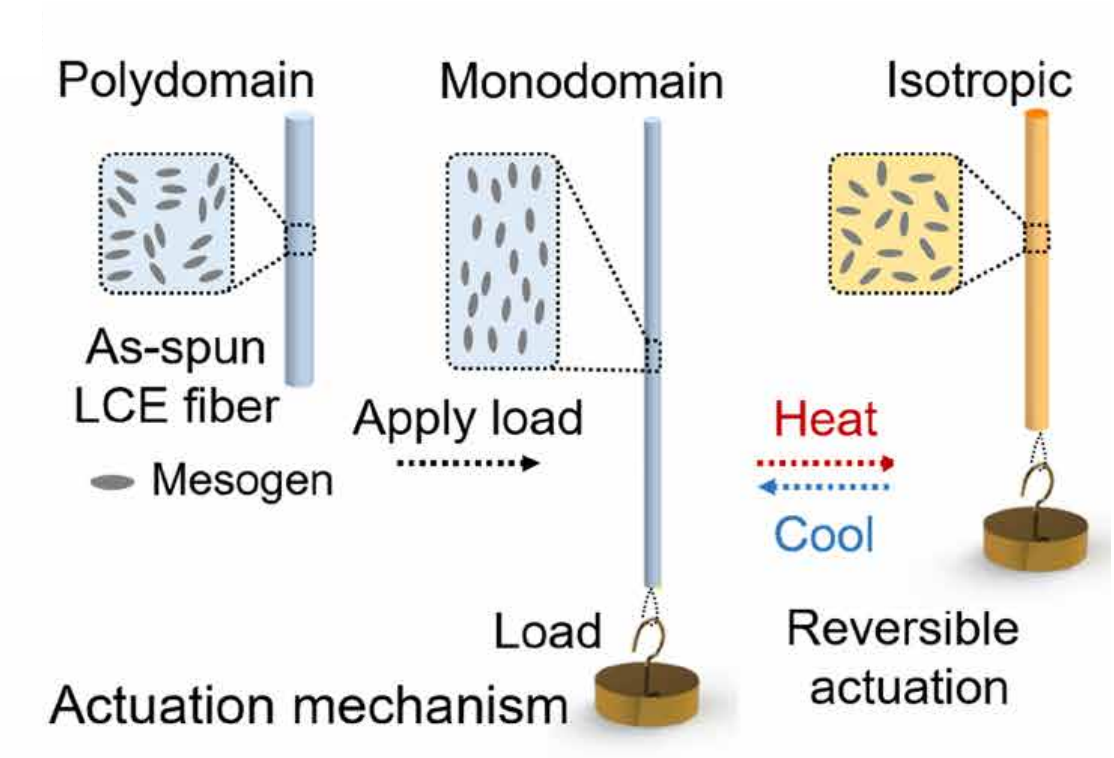
- A high voltage (up to 10 kV) applied across the nozzle-collector gap (0 – 10 mm) leads to the formation of a Taylor cone at the tip of the nozzle which forms into a stable polymer jet

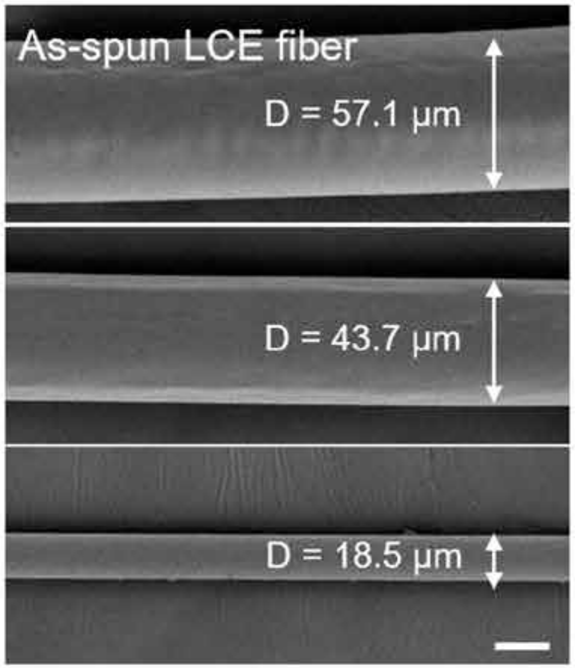
- The electrical forces acting on the jet lead to its thinning as it travels from the nozzle to the collector and fibres in the range of 5 – 50 μm can be formed depending on the parameters used

- Once a stable jet is formed, the nozzle can be moved with respect to the collector at pre-defined speeds to deposit fibres in controlled and layer-by-layer manner

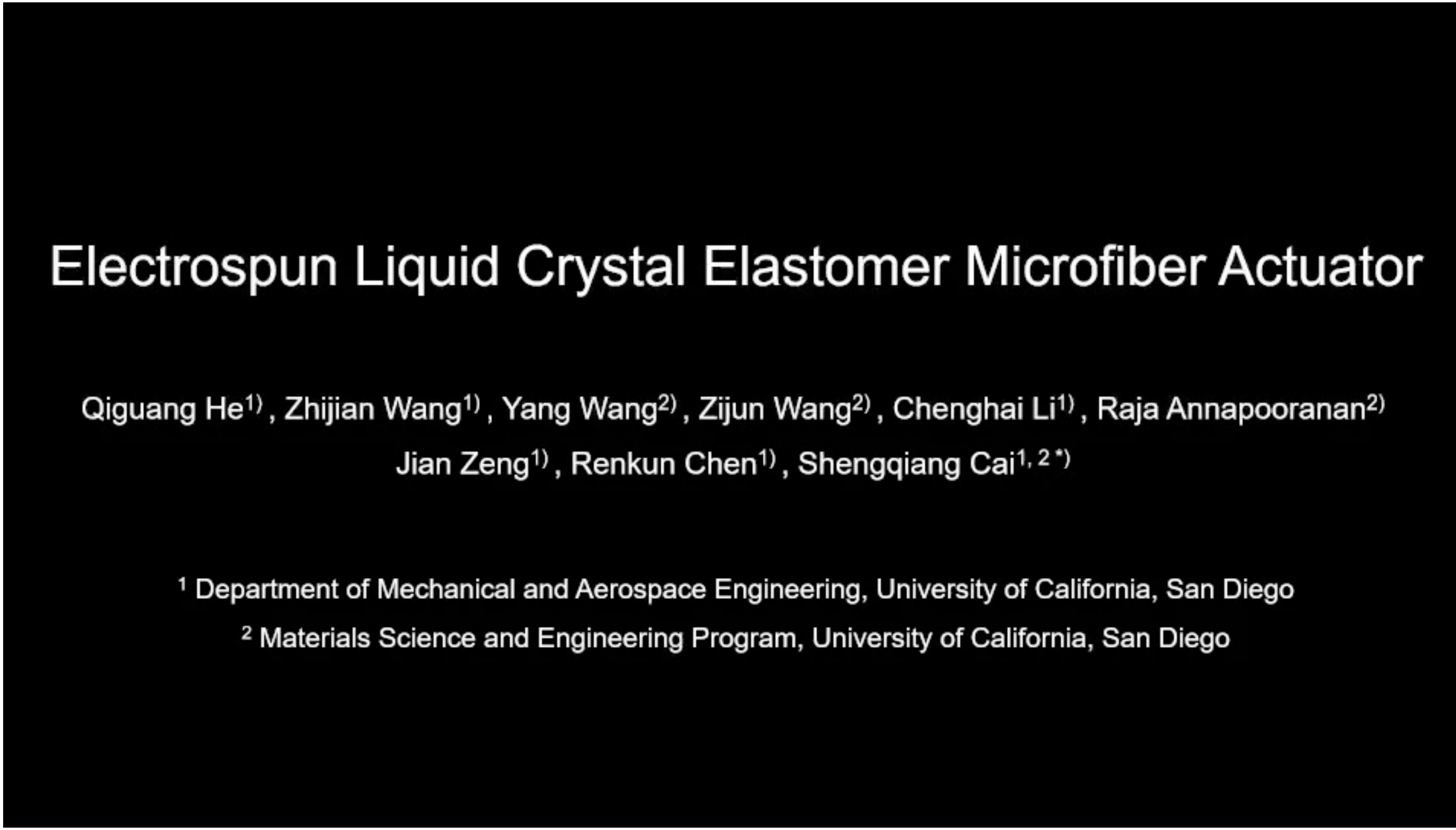
Electrospun LCE Microfiber Actuators

- Large actuation strain (60%), fast response (< 0.2s), and high power density (400 W/kg)
- Nematic isotropic phase transition of mesogens





Electrospun LCE Microfiber Actuators



Electrospun LCE Microfiber Actuators

Electrospun Liquid Crystal Elastomer Microfiber Actuator

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Jian Zeng[1)], Renkun Chen[1)], Shengqiang Cai[1, 2 *)]

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[2] Materials Science and Engineering Program, University of California, San Diego

Electrospun LCE Microfiber Actuators

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