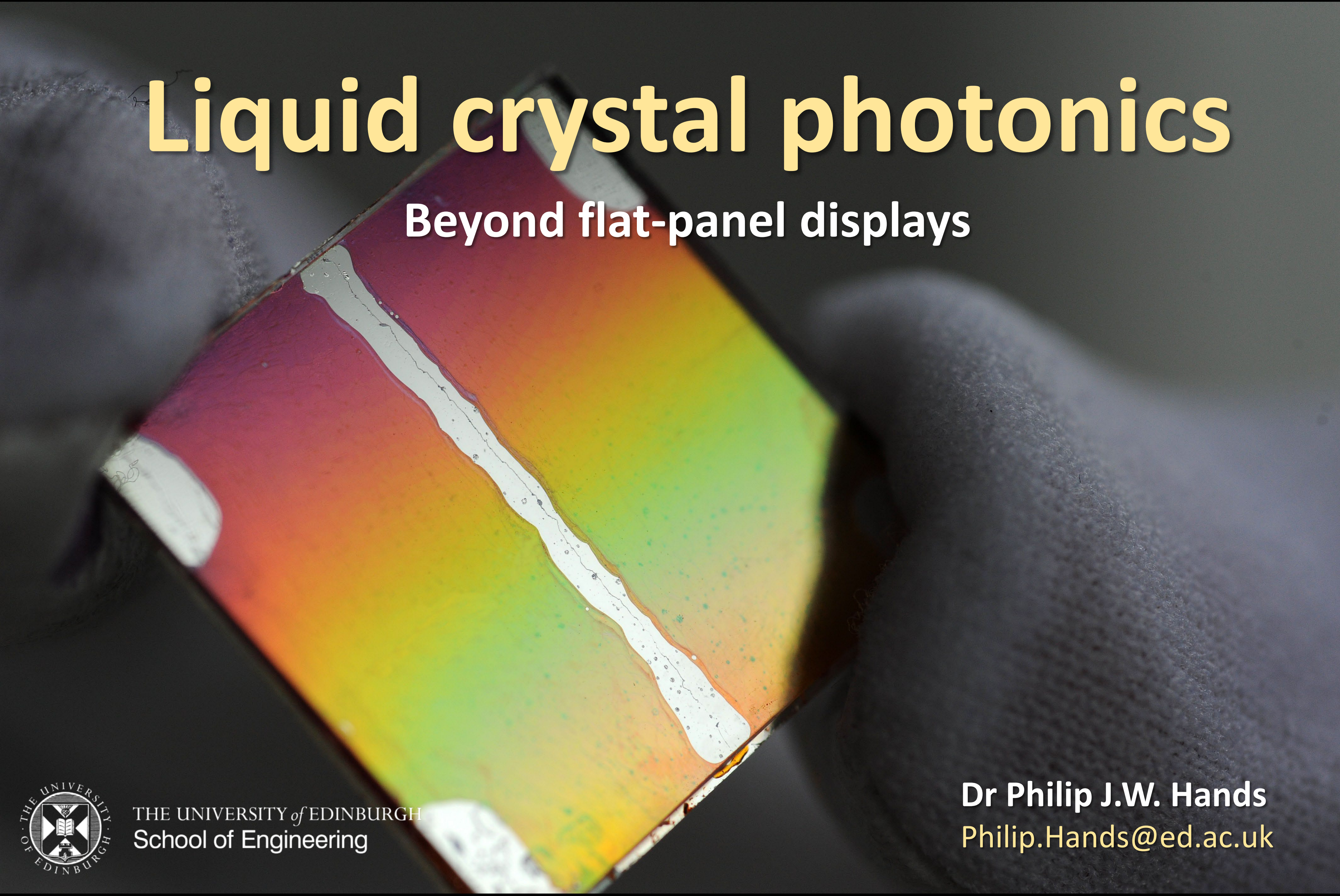
Liquid crystal photonics

Beyond flat-panel displays



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Dr Philip J.W. Hands
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www.thinglink.com

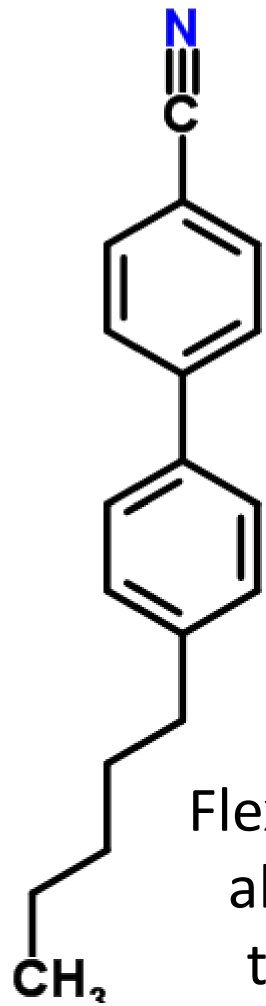
Liquid crystals

Sausage-shaped molecule

–

+

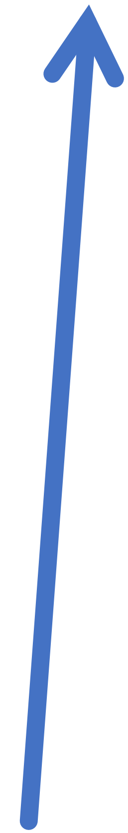
Electric
(& magnetic)
dipole



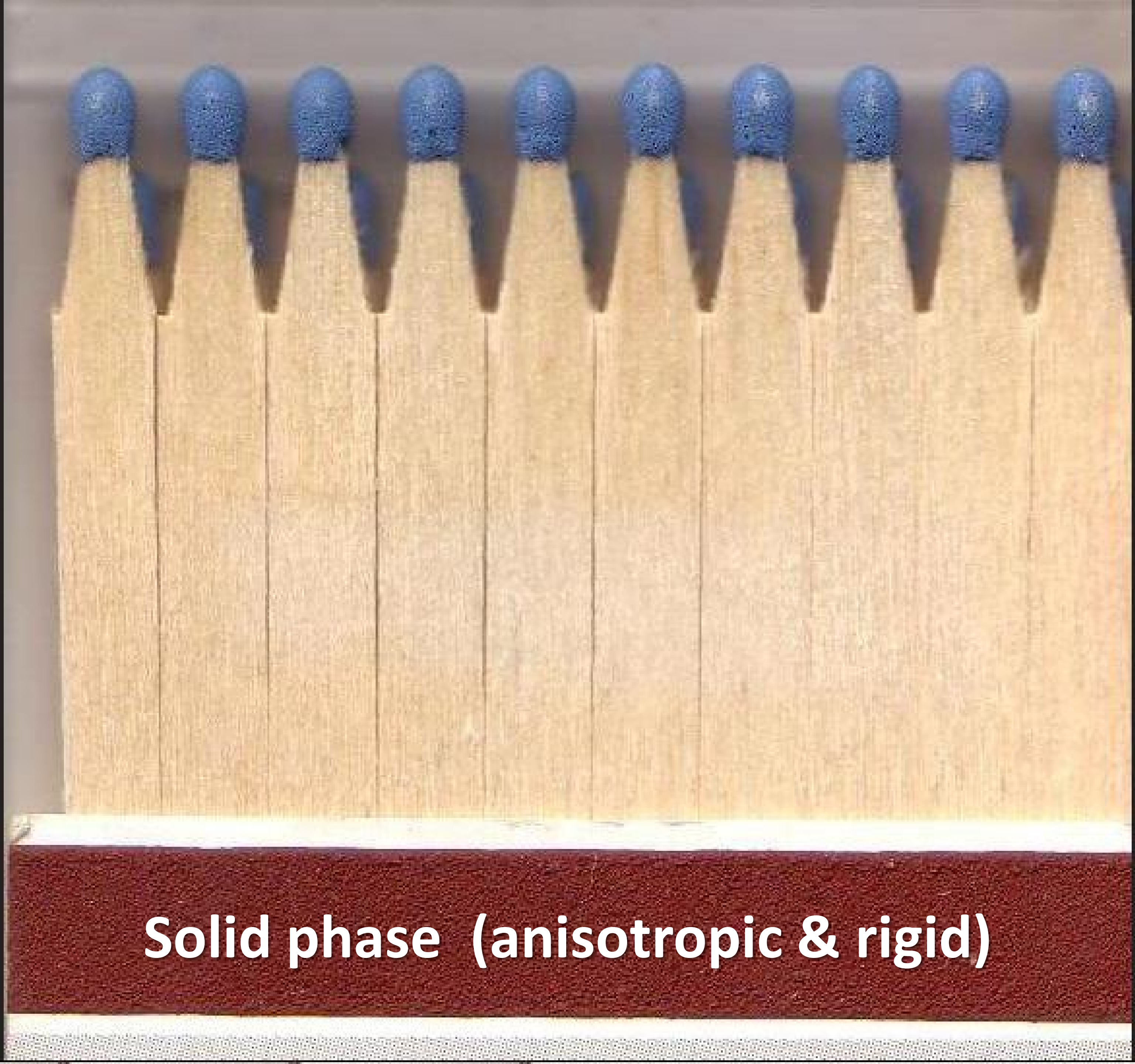
Rigid
aromatic
core

Flexible
alkyl
tail

director, **n**




Liquid phase
(isotropic & fluidic)


Solid phase (anisotropic & rigid)

Liquid crystal phase (anisotropic & fluidic)

Commonly used for modern LC displays

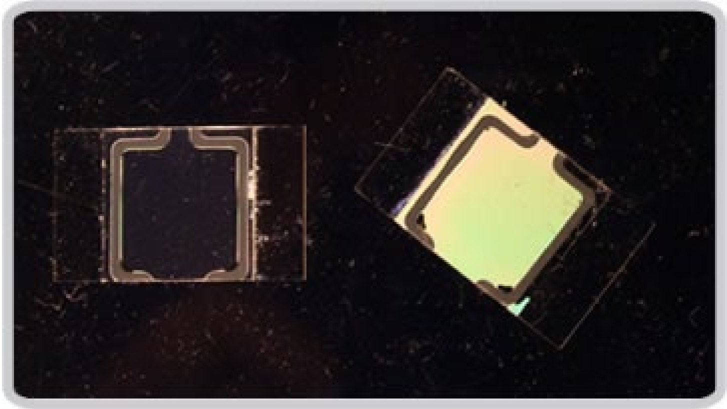
Nematic phase: Orientational order, but no positional order

LC properties: Optical anisotropy

Angle of LC molecules determines the refractive index
(for linearly polarised light)

Rotate a nematic LC cell between cross-polarisers:

(or rotate nematic molecules by applying an electric field):

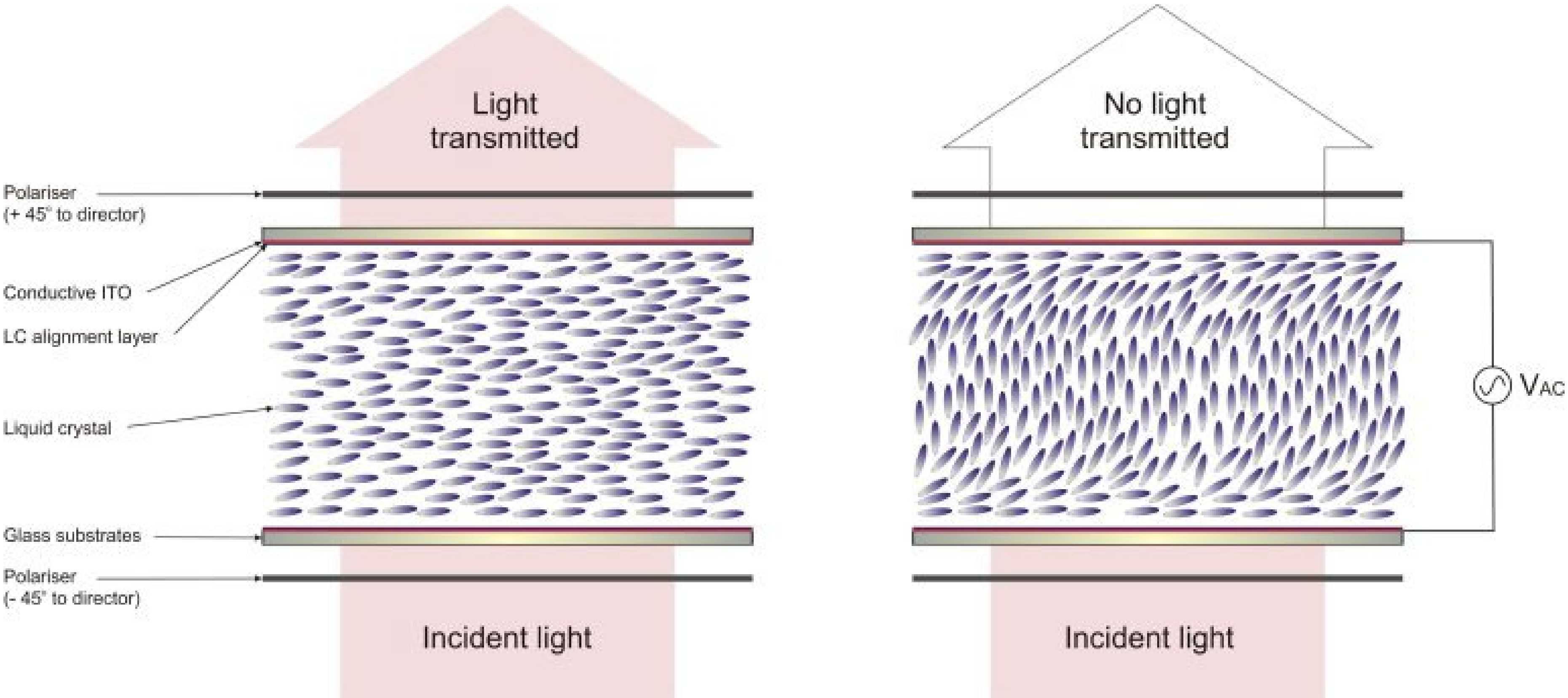


→ Modulation of phase, polarisation & intensity of transmitted (or reflected) light

→ Electrical control of light

LC properties: Fréedericksz transition

Simple nematic LC cell (e.g. a single pixel):



- Combine with red/green/blue filters for full colour control
- Forms basis of nearly all LC display switching mechanisms
- Remove upper polariser for phase modulation only (variable waveplate)

LCD research & development: The end of the road for LCs?

- In recent years, LCD manufacture has become dominated by a very small number of companies.
- Most display manufacturers have taken a strategic decision to halt R&D activities in LCD technology (and are beginning to sell off this part of their business).
- LCDs will still be manufactured and will have a place in the market, but no new R&D funds will be invested at the current time.
- R&D funds instead diverted to OLED and Qdot technologies.
- Is this the end of liquid crystal research and development?

No!

But the field must diversify and find new applications.

Liquid crystal lenses

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Department of Engineering

Durham University

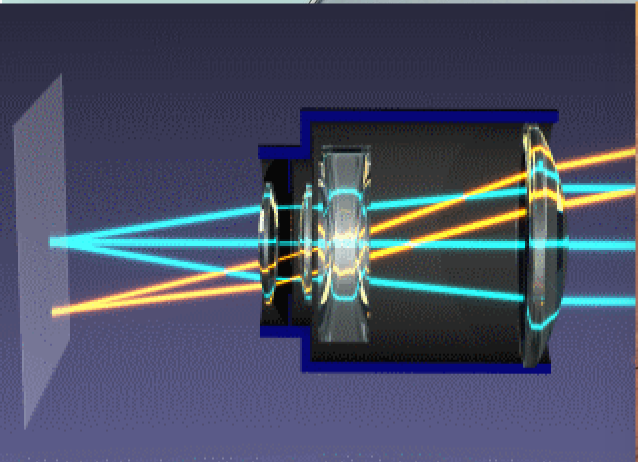
Adaptive lenses: Motivation

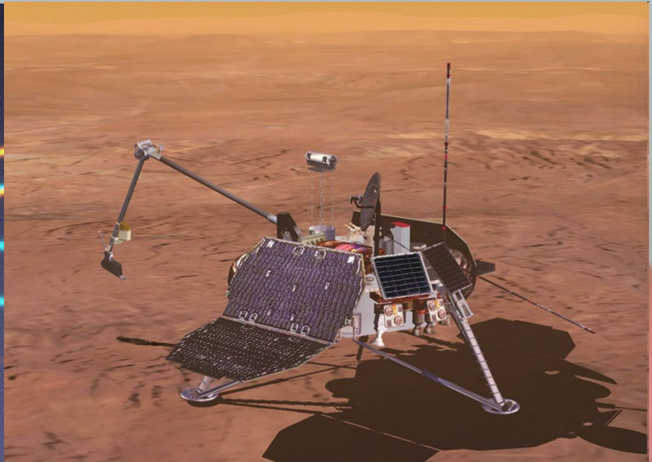
Improvements in:

Weight
Size
Reduced complexity
Cost
Power consumption

Enables:

3D displays

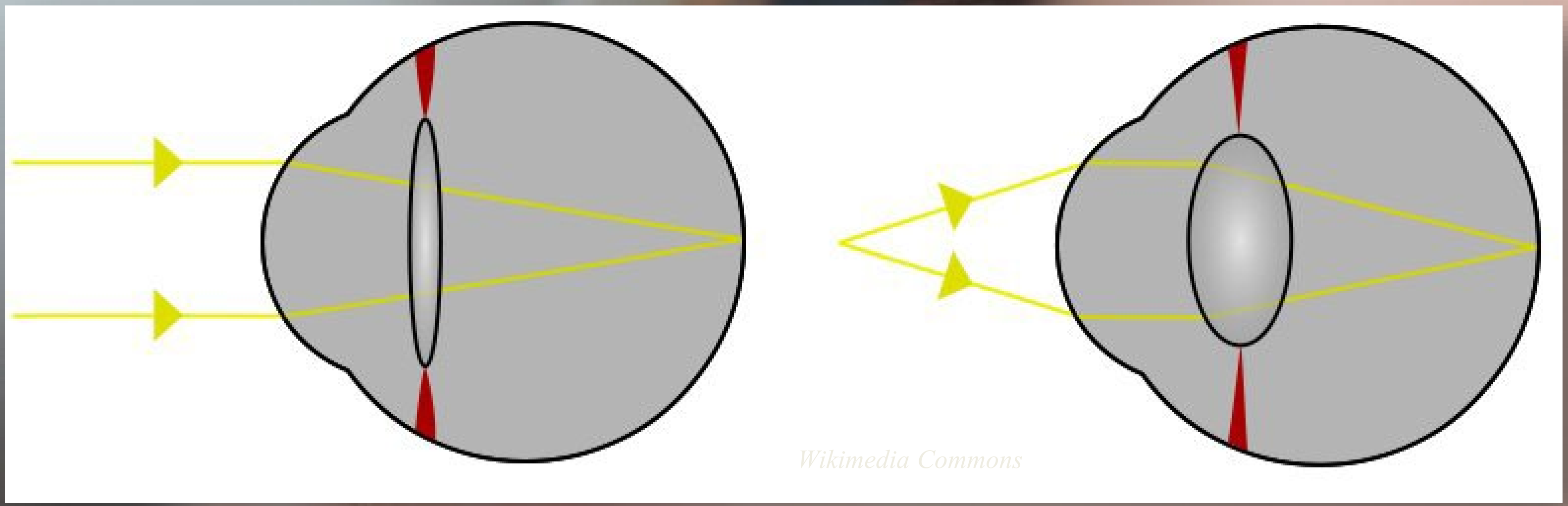




Adaptive lenses: Inspiration from nature

Human eye

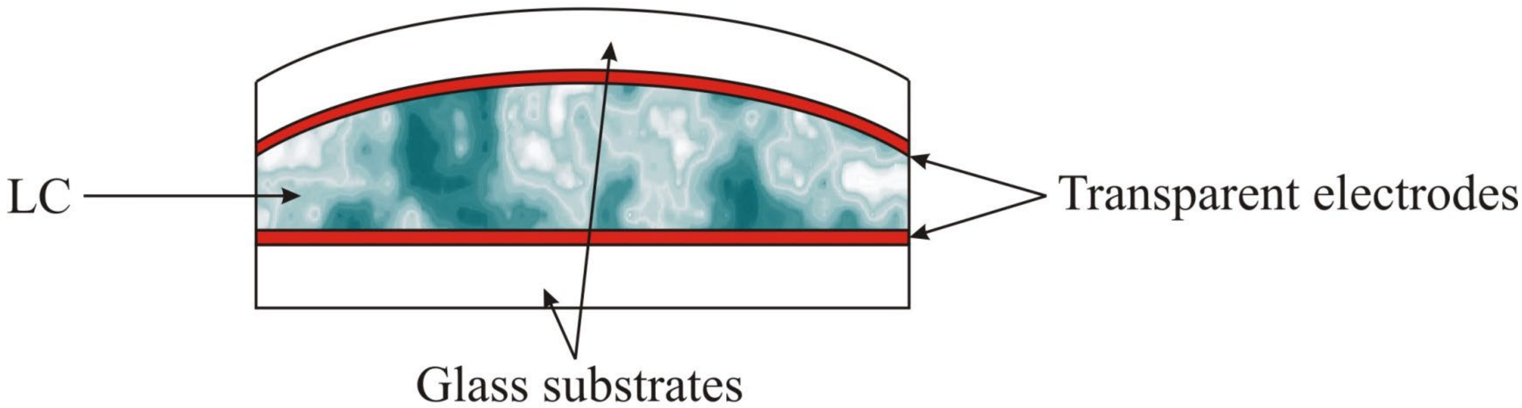
Adaptive lens facilitated by muscular-controlled variable thickness profile



LC lenses: Surface relief approach

Surface relief approach

Conventional lens: Variable thickness, constant n.



- Positive or negative
- Strong lenses

- LC alignment on curved surfaces difficult
- Off-axis aberrations
- Thick cells – slow switching, haze

Normal lens: S. Sato, Jap. J. Appl. Phys., 18 (9), 1679-1684, (1979)
Fresnel lens: S. Sato, Jap. J. Appl. Phys., 24 (8), L626-628, (1985)
Phase-separation microlens: H.-S. Ji *et al*, Optics Letters, 28 (13), 1147-1149, (2003)

LC lenses: Surface relief approach

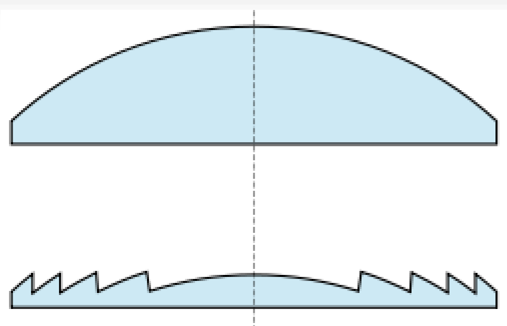
+/- 2.0 D switching, 2-3 V applied potential

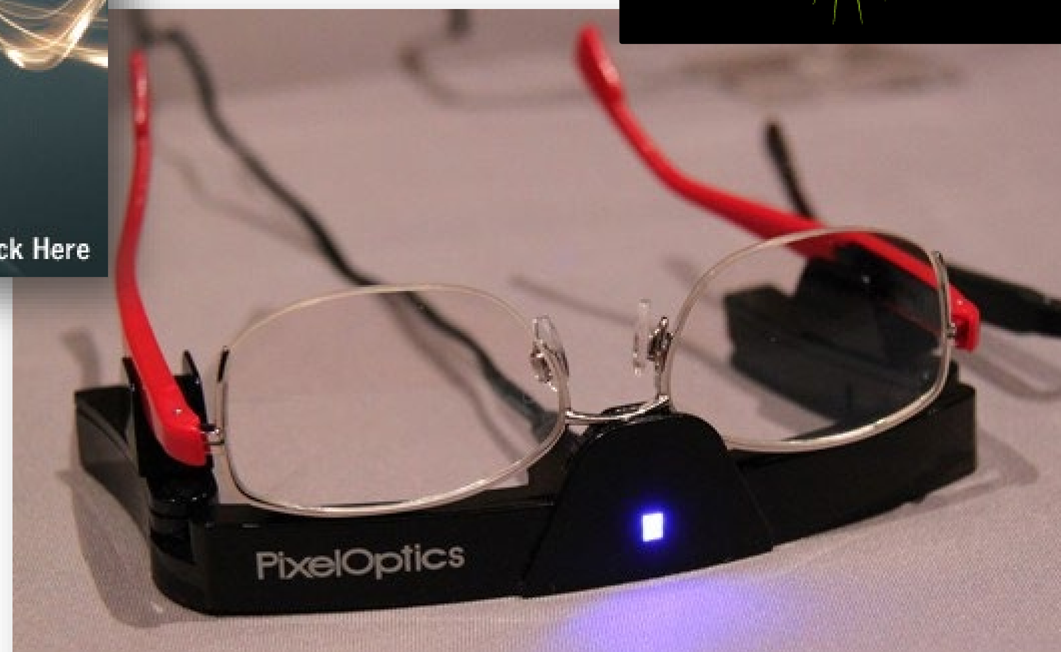
H.E. Milton, P.B. Morgan, J.H. Clamp, H.F. Gleeson,
Contact Lens & Anterior Eye, Volume 35, Supplement 1, 1 December 2012, Page e14

H.E Milton, PhD thesis, (2013), University of Manchester

H.E Milton, P. Morgan, H.F. Gleeson, (2013), Proc. BLCS, Cambridge, P13

LC lenses: Surface relief approach



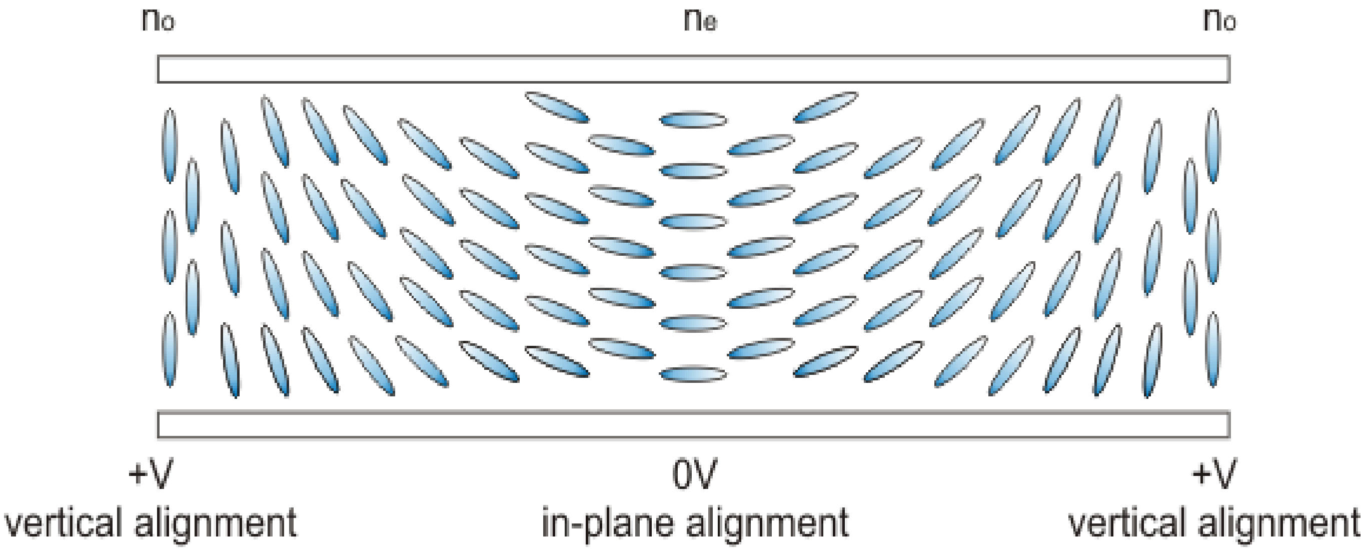


Fresnel lens relief pattern in substrate, in-filled with chiral nematic LC
Switchable bifocal region, for reading glasses
Charging docking station
Includes accelerometer for detection of downwards head movement when reading

LC lenses: Variable index approach

Variable index approach

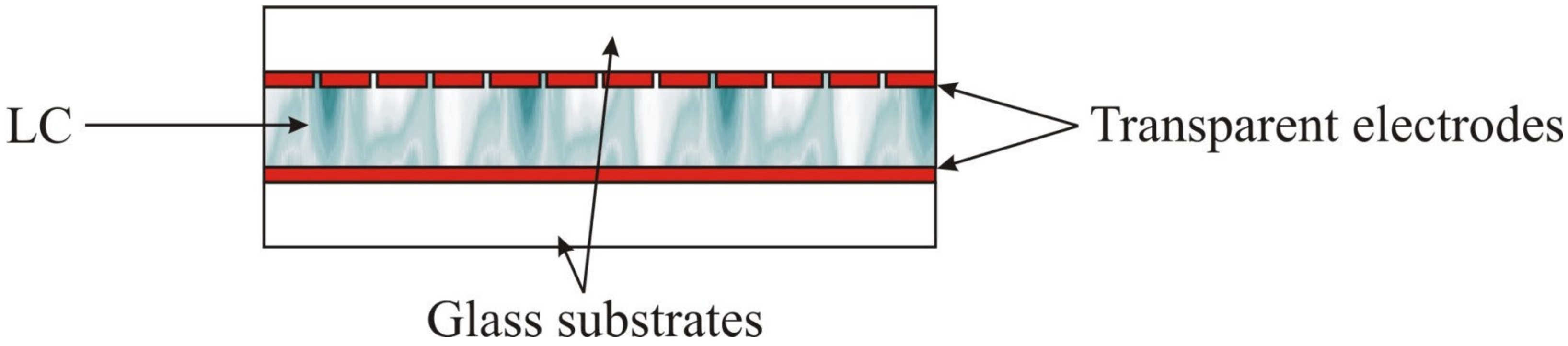
Conventional lens: Variable thickness, constant n.
Alternative lens: Constant thickness, variable n.



Phase difference across cell: $$\Delta\Phi = \frac{2\pi}{\lambda} d.\Delta n$$

LC lenses: Variable index approach

Zonal addressing:

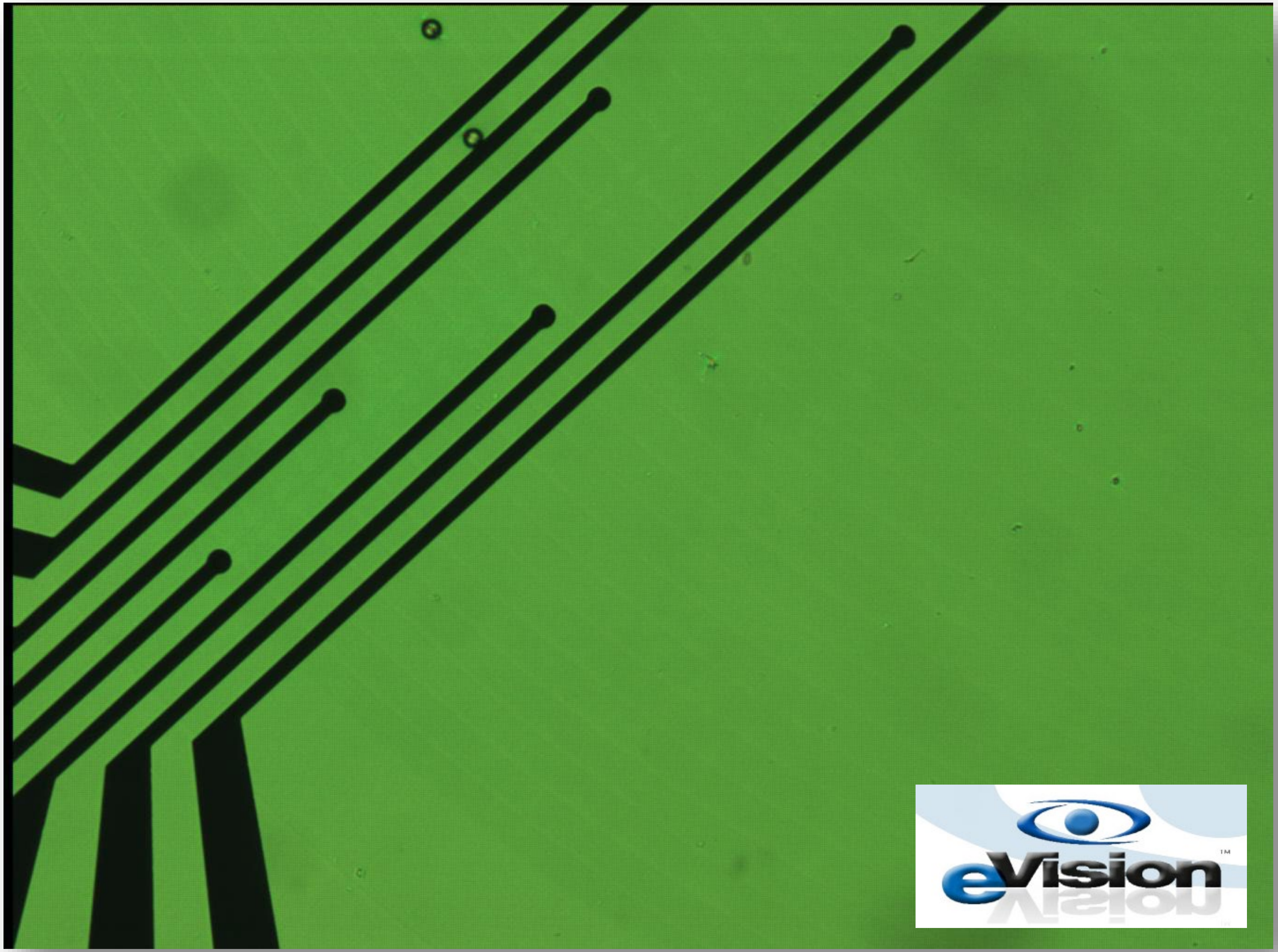


- Utilises existing display/SLM technology
- Good control of lens profile
- Positive and negative lens
- Aberration correction

- Stepwise approximation (diffraction)
- Complicated structure & fabrication
- Complicated driving electronics

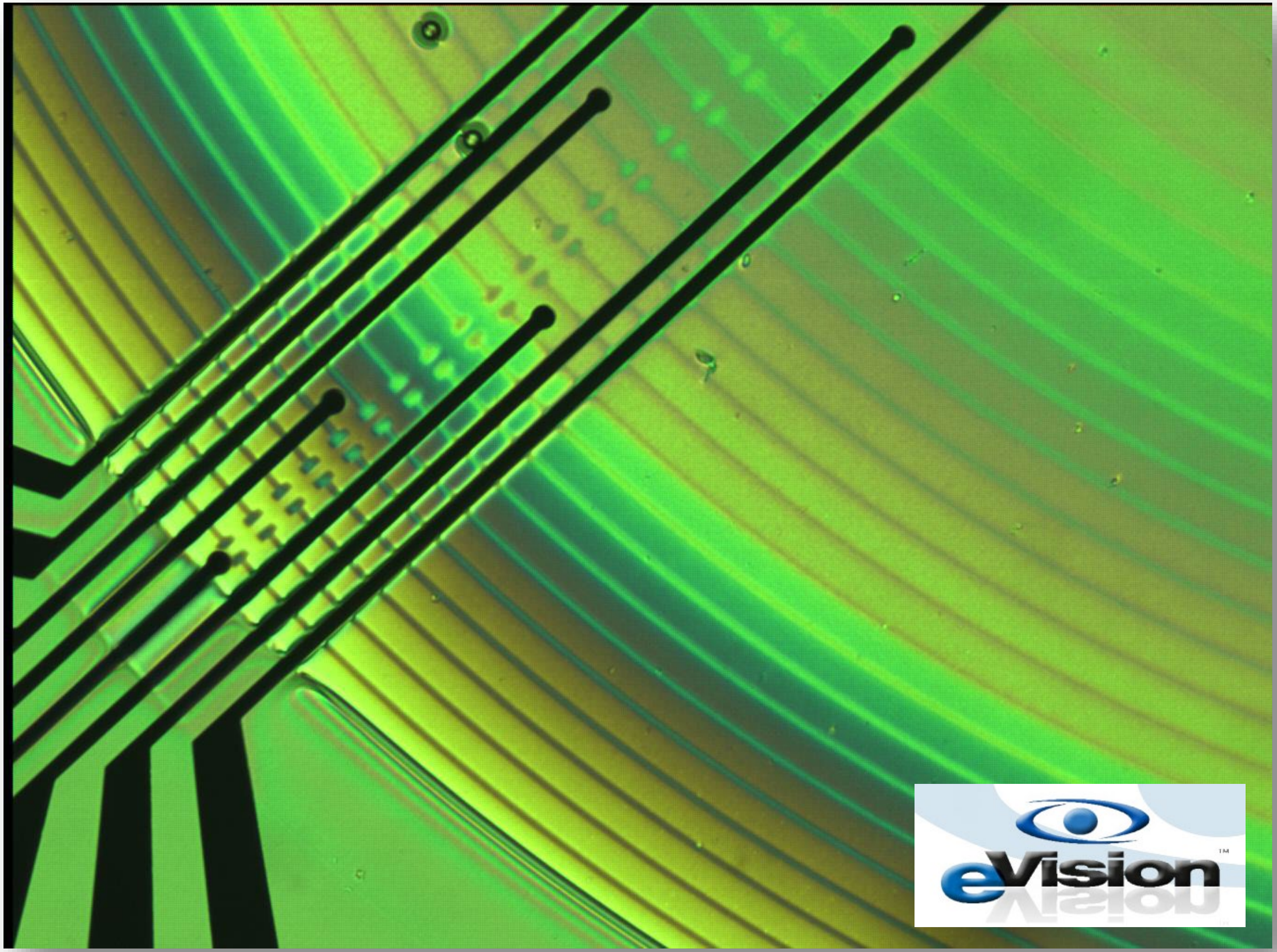
Strip electrodes:	S.T. Kowel *et al*, Applied Optics, 23 (2), 278-289, (1984)
Resistor network:	N. Riza, M. DeJule, Optics Letters, 19 (14), 1013-1015, (1994)
SLM:	E.C. Tam, Optics Letters, 17 (5), 369-371, (1992)
Concentric rings:	L. Li , *et al,* Proc. SPIE 79440S (2011)

LC lenses: Zonal addressing



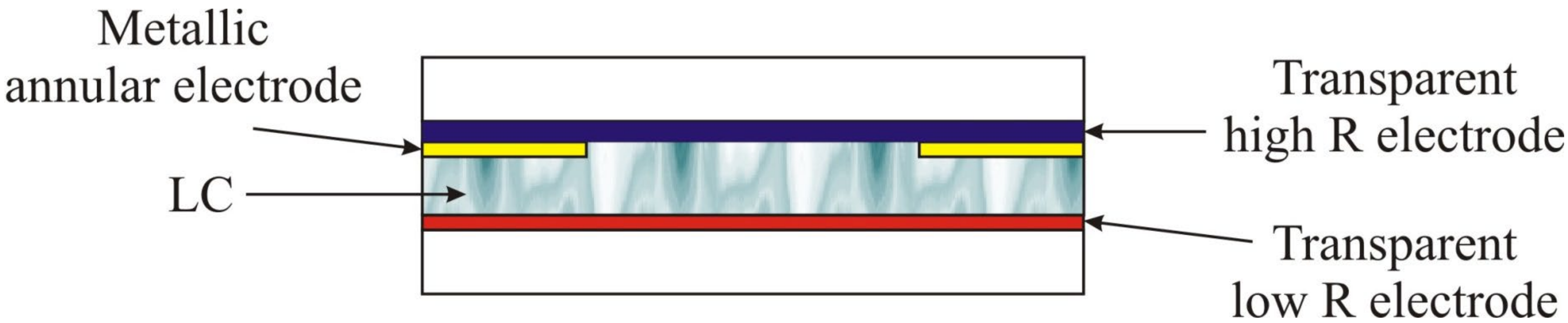
L. Li, L. Shi, D. Bryant, T. Van Heughten, D. Duston and P. J. Bos, Proc. SPIE **79440S** (2011).

LC lenses: Zonal addressing



L. Li, L. Shi, D. Bryant, T. Van Heughten, D. Duston and P. J. Bos, Proc. SPIE **79440S** (2011).

LC lenses: Modal addressing

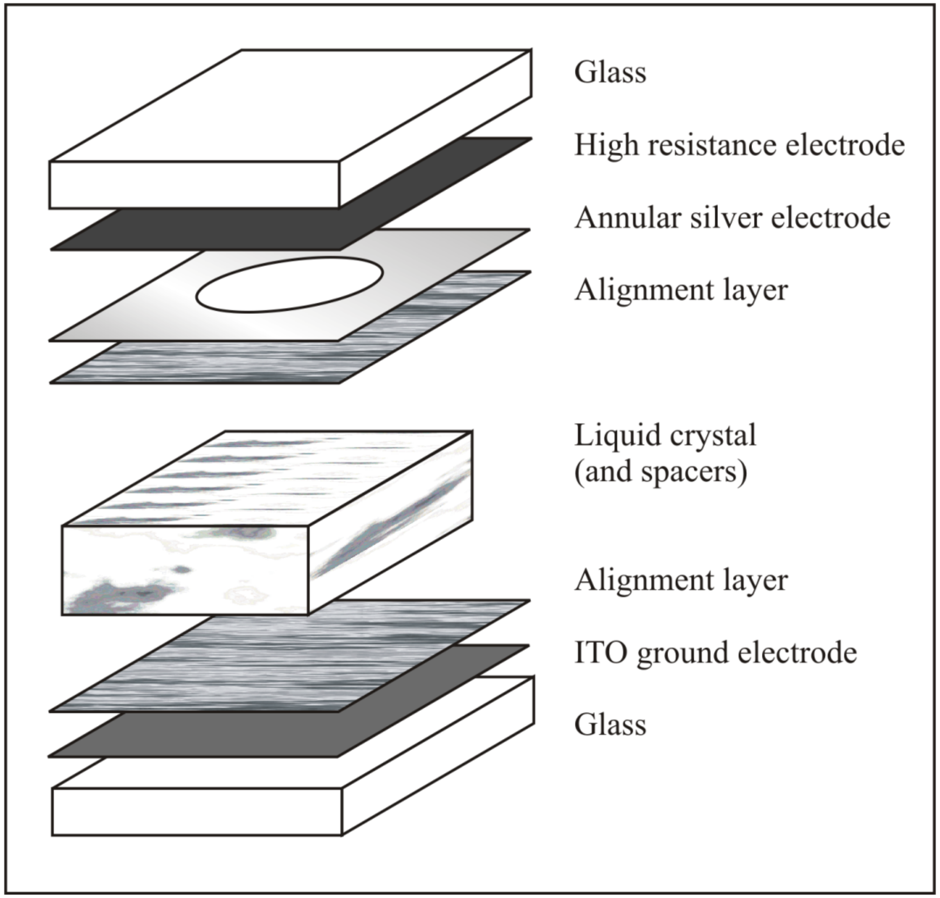


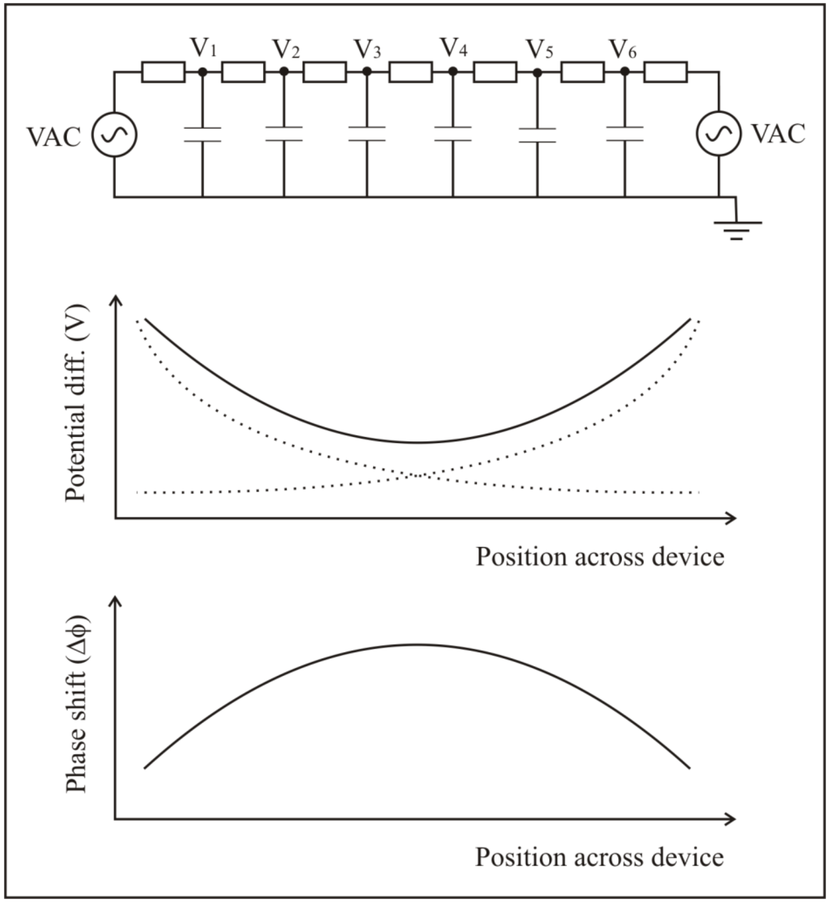
- Simple structure
- Good control of lens profile
- Arbitrary aperture size
- Smoothly varying index profile
- Lens arrays

- Positive lens only

Naumov, A.F., *et al.,* Optics Letters, 23 (13), 992-994, (1998)
Naumov, A.F., M.Y. Loktev, et al. (1998) Optics Letters 23(13): 992-994.
Naumov, A.F., G.D. Love (1999) Optics Express 4(9): 344-352.
Love, G.D., A.F. Naumov (2000) Liquid Crystals Today, 1-4.
Hands, P.J.W., G.D. Love, et al. (2004) Liquid Crystals VIII, Proc. SPIE 5518.

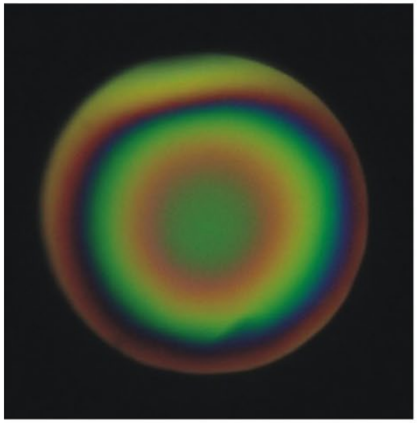
LC lenses: Modal addressing

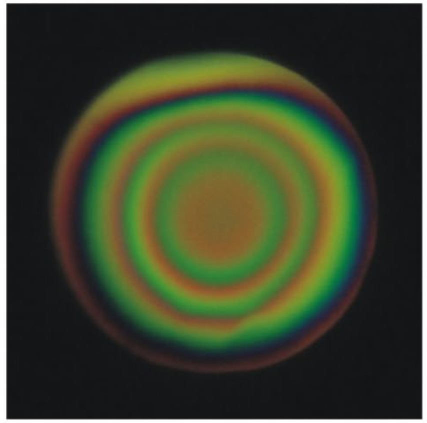


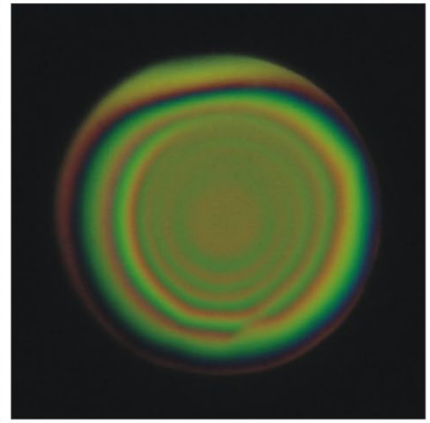


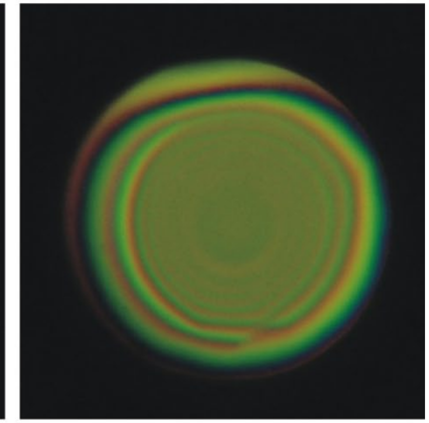
Transparent “high R” layer: TiO_2, ZTO, PEDOT

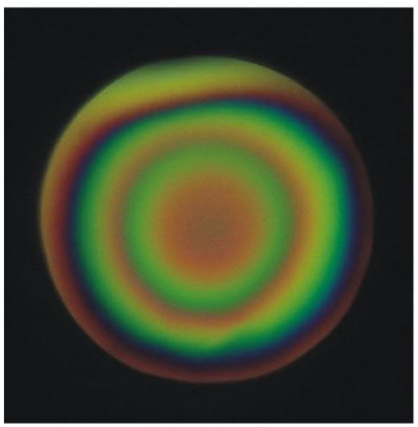
LC lenses: Modal addressing

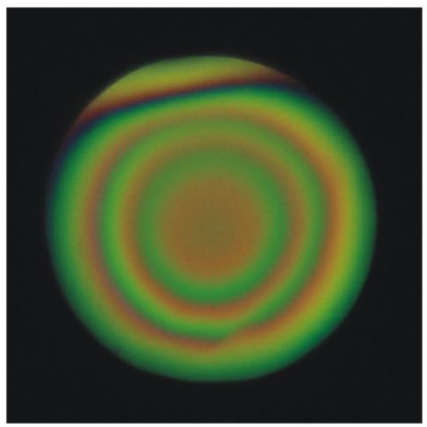

20 V, 15 khz

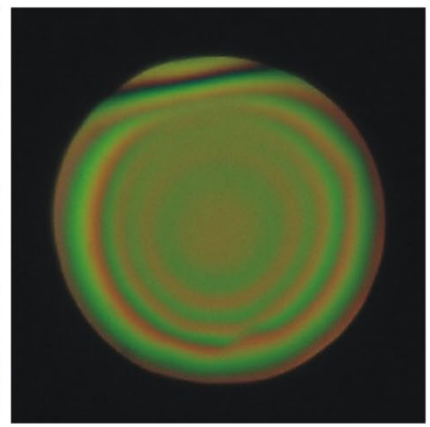

20 V, 25 khz

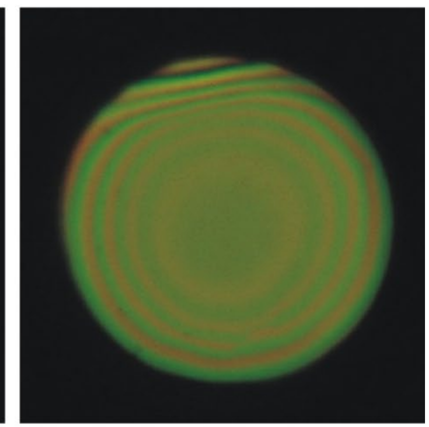

20 V, 35 khz


20 V, 45 khz


0.7 V, 20 khz


10 V, 20 khz


15 V, 20 khz


20 V, 20 khz

Control of focal length (and lens shape) with applied voltage AND frequency.

Focal length: approx. 1m → ∞
(7mm aperture)

Hybrid liquid crystal lenses

3D displays

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Berkeley
UNIVERSITY OF CALIFORNIA

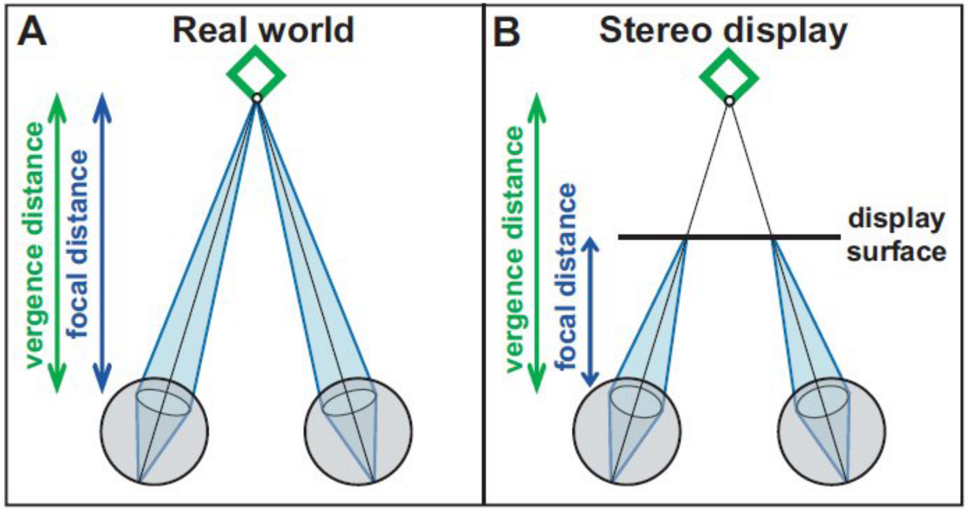
Durham
University

3D displays: The need for adaptive lenses

Vergence-accommodation mismatch

Problem:

Most "3D" (stereoscopic) displays only provide vergence (parallax) cues



Stereoscopic "3D" film/TV:
2 cameras used.
Only 1 image plane in focus at any given time (controlled by film director).

Result: Eye cannot refocus other areas of screen.

Depth cue mismatch
- nausea, unconvincing 3D

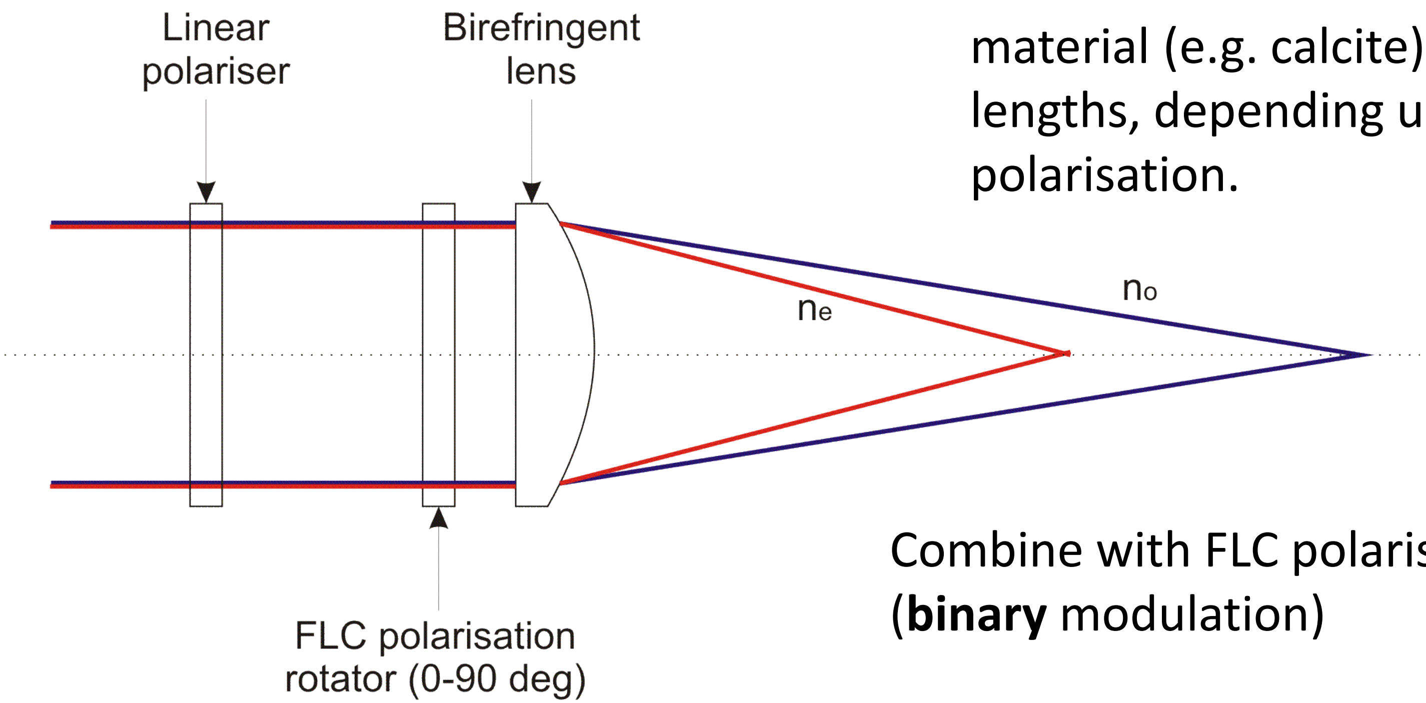
We require 3D displays with vergence AND accommodation cues.

LC lenses: Hybrid birefringent/LC lens

Hybrid approach:

Discrete focal planes

Lens made from birefringent material (e.g. calcite) has 2 focal lengths, depending upon input polarisation.



Thin ~2µm
Fast

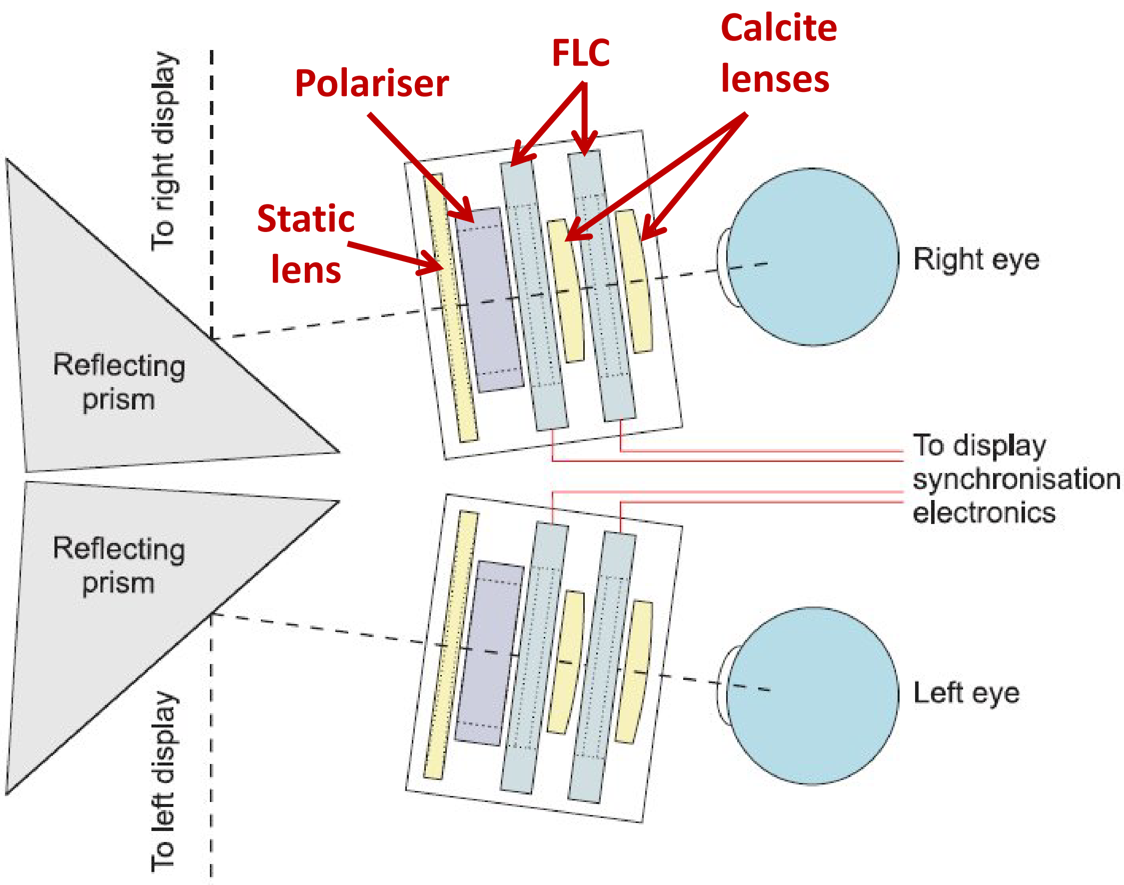
Combine with FLC polarisation rotator (**binary** modulation)

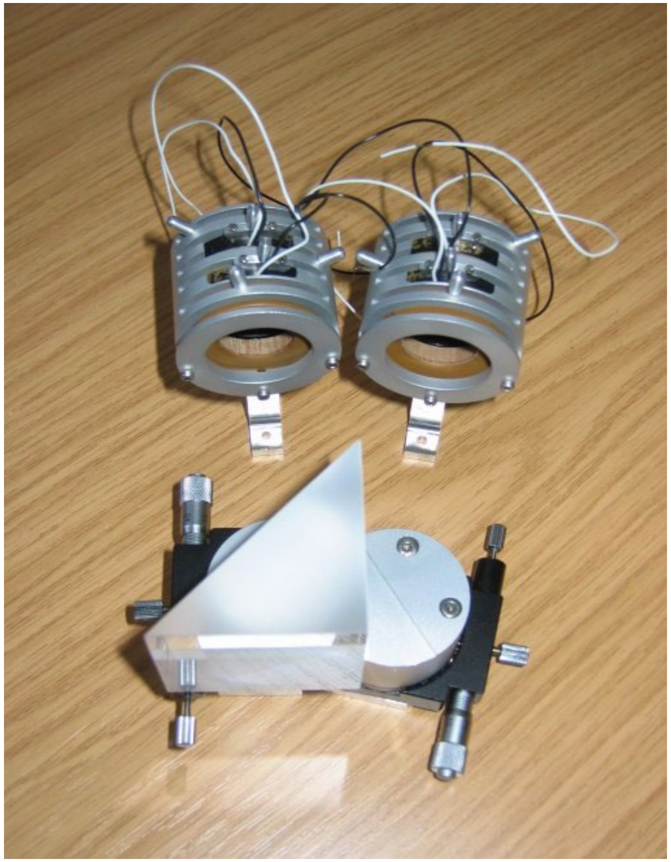
- **Fast** adaptive lens.
- **Strong** focussing power (+ or -)

A.K. Kirby, P.J.W. Hands, G.D. Love, Adaptive Optics for Industry & Medicine, Proc. SPIE 6018-14 (2005).

3D displays: Stacked hybrid birefringent/LC lenses

- Lens (FLC) 1 switches at 2x frequency of lens (FLC) 2
- 4 selectable focal planes

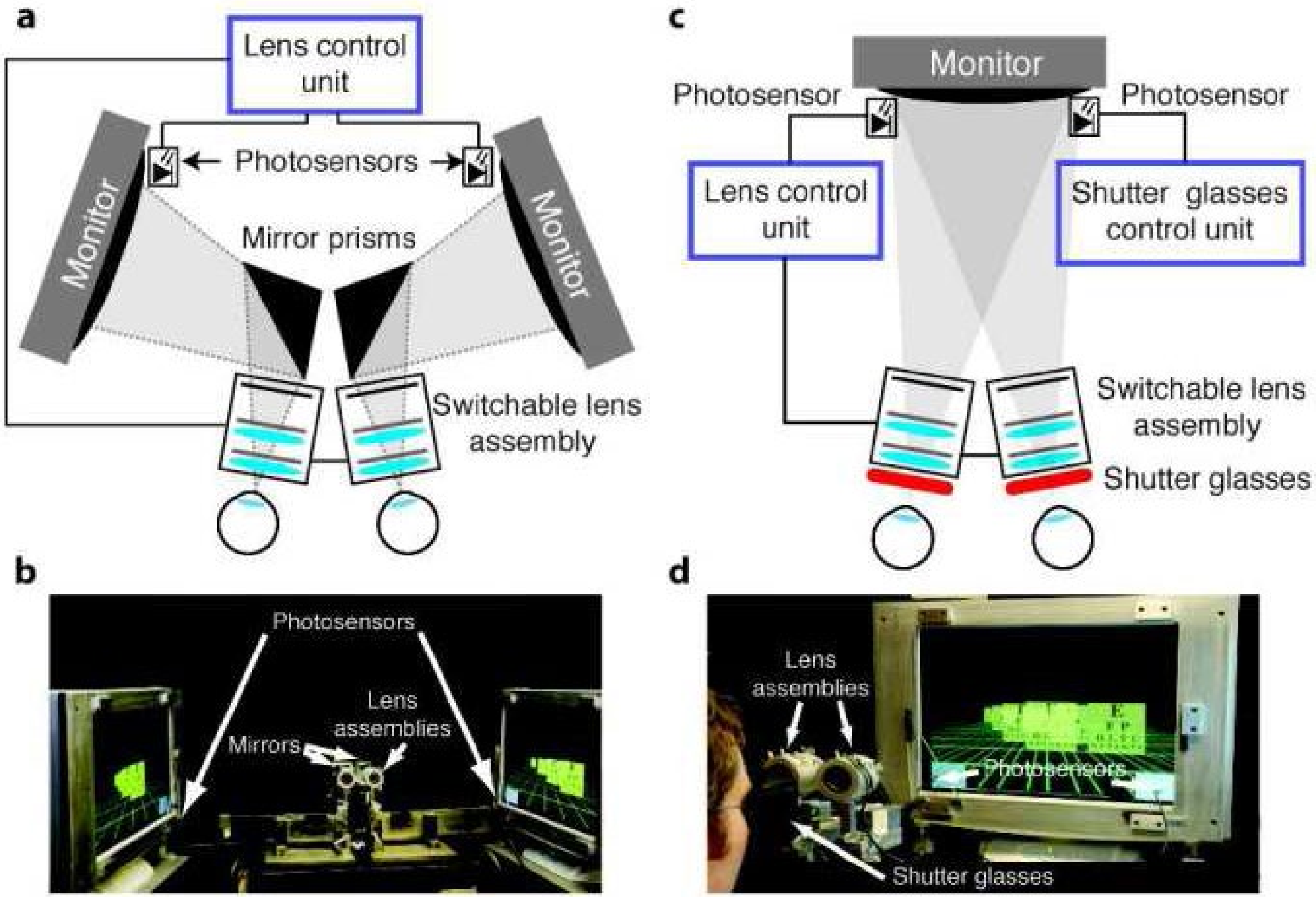




G.D. Love, D.M. Hoffman, P.J.W. Hands, J. Gao, A.K. Kirby, M.S. Banks, Optics Express, 17 (18), 15716, (2009).
D.M. Hoffman, P.J.W. Hands, A.K. Kirby, G.D. Love, M.S. Banks, Proc. SPIE, 7237, 72370R, (2009).
M.S. Banks, G.D. Love, D.M. Hoffman, P.J.W. Hands, A.K. Kirby, Frontiers in Optics 2009, 93rd OSA Meeting, (2009).

3D displays: Volumetric display

Two-screen approach | **Single-screen approach**



Liquid crystal lasers

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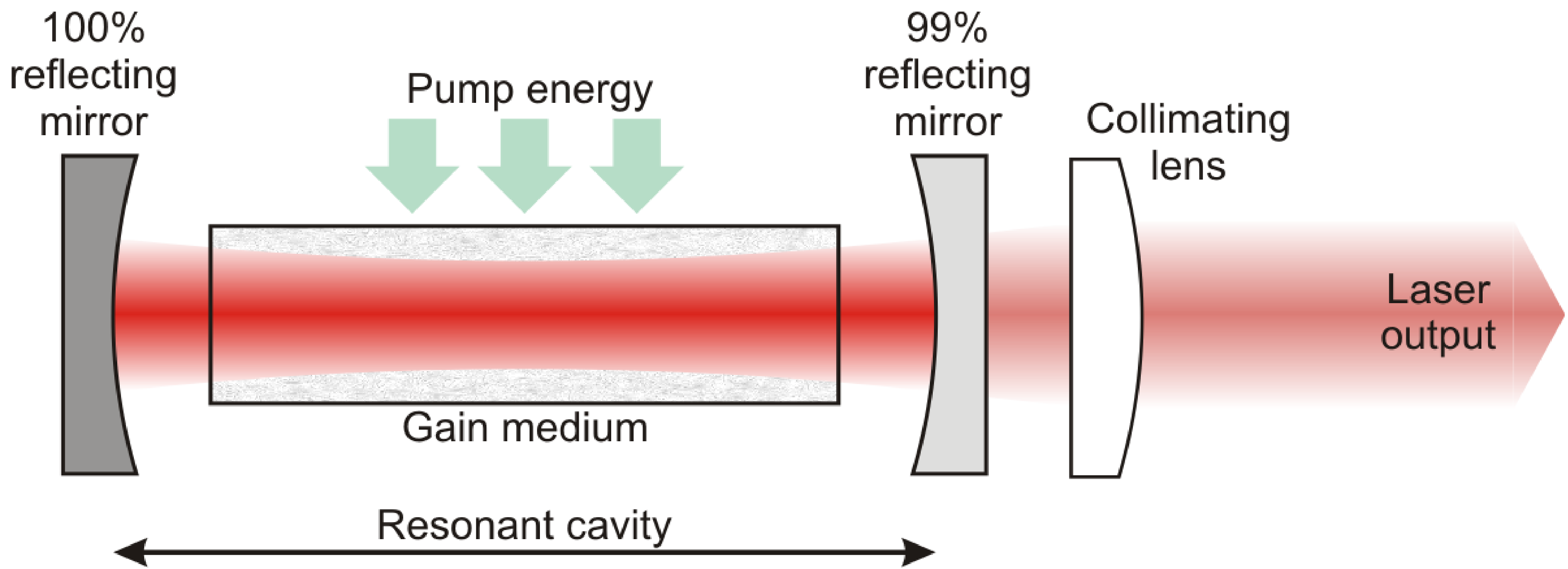
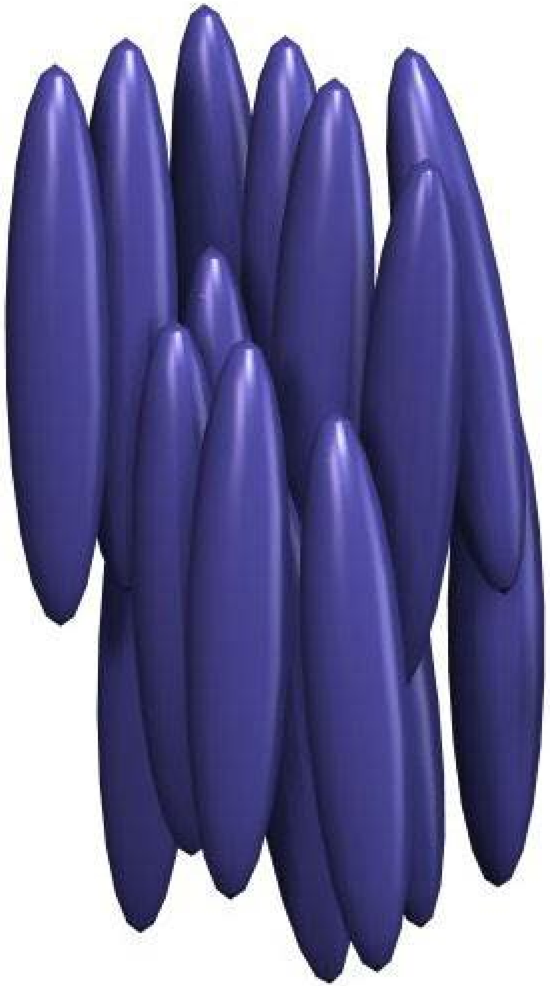
Department of Engineering

Laser checklist



- ✓ Resonant cavity (Fabry-Perot)
- ✓ Gain medium (e.g. HeNe, Ruby, etc)
- ✓ Pump/Excitation source (e.g. flash lamp)

Liquid crystal



Nematic phase: Orientational order, but no positional order

Chiral nematic (cholesteric) phase:

Helicity

F&F Tower, Panama

Cayan Tower, Dubai

Chiral nematic (cholesteric) phase:

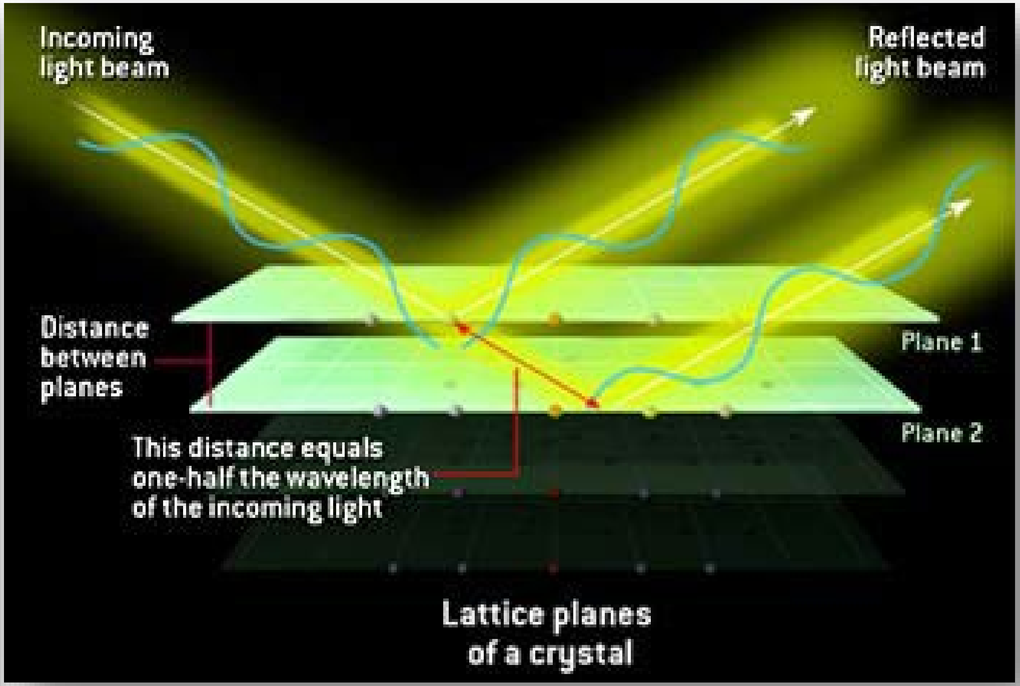
Helicity

Photonic band gaps: Chiral nematic LCs

Nematic LC + Chiral dopant = <u>Self-assembled</u> PBG with tuneable reflection

University of Wisconsin-Madison

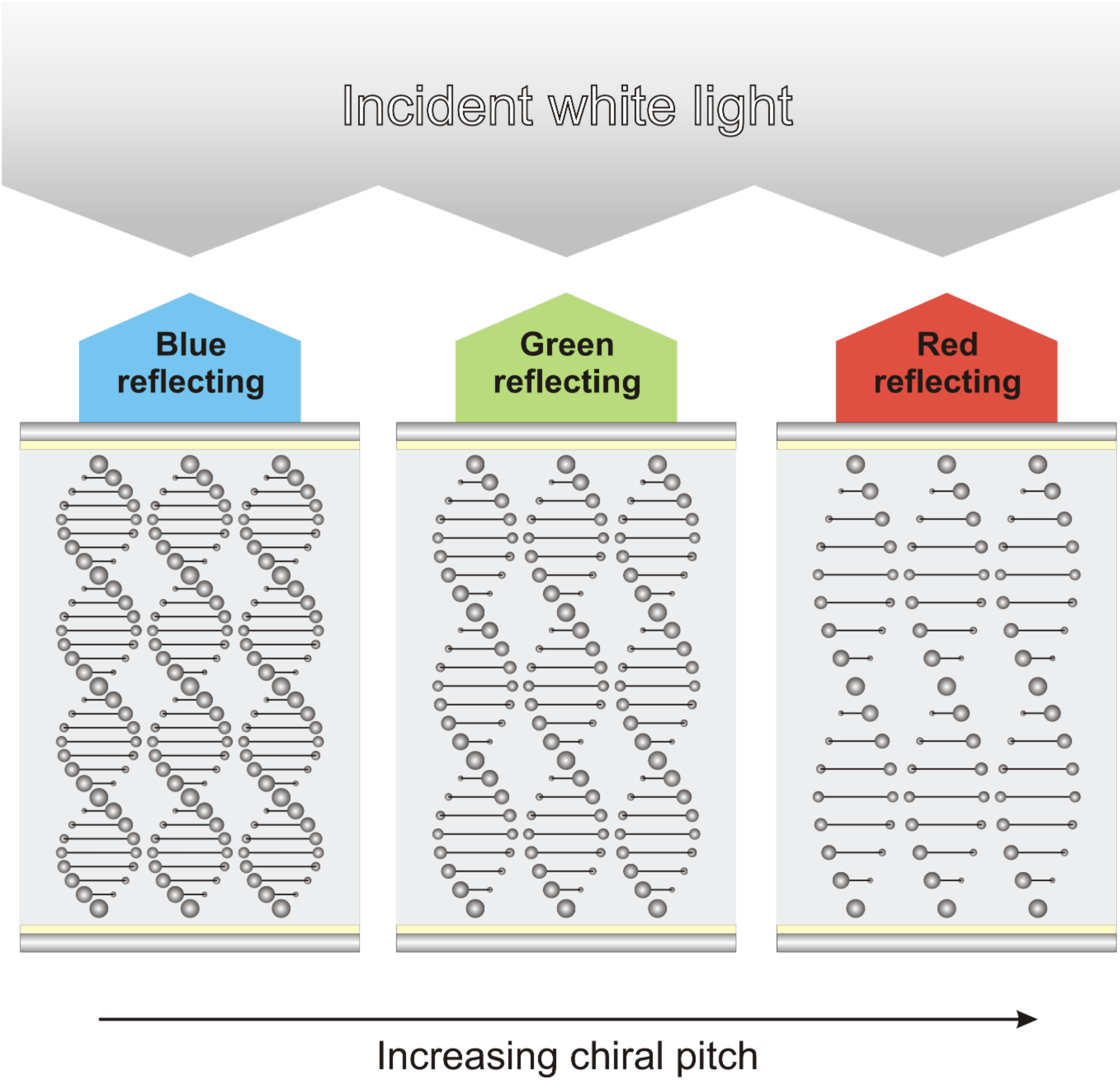
Photonic band gaps: in nature



Bragg's law: $m\lambda = 2d\sin\theta$

Periodic layered nanostructure leads to selective reflection of optical radiation.
Causes iridescence in certain insects and birds.
Colour through nanostructure alone.

Photonic band gaps: Chiral nematic LCs



Twisted structure provides sinusoidally varying refractive index (1D photonic band gap).

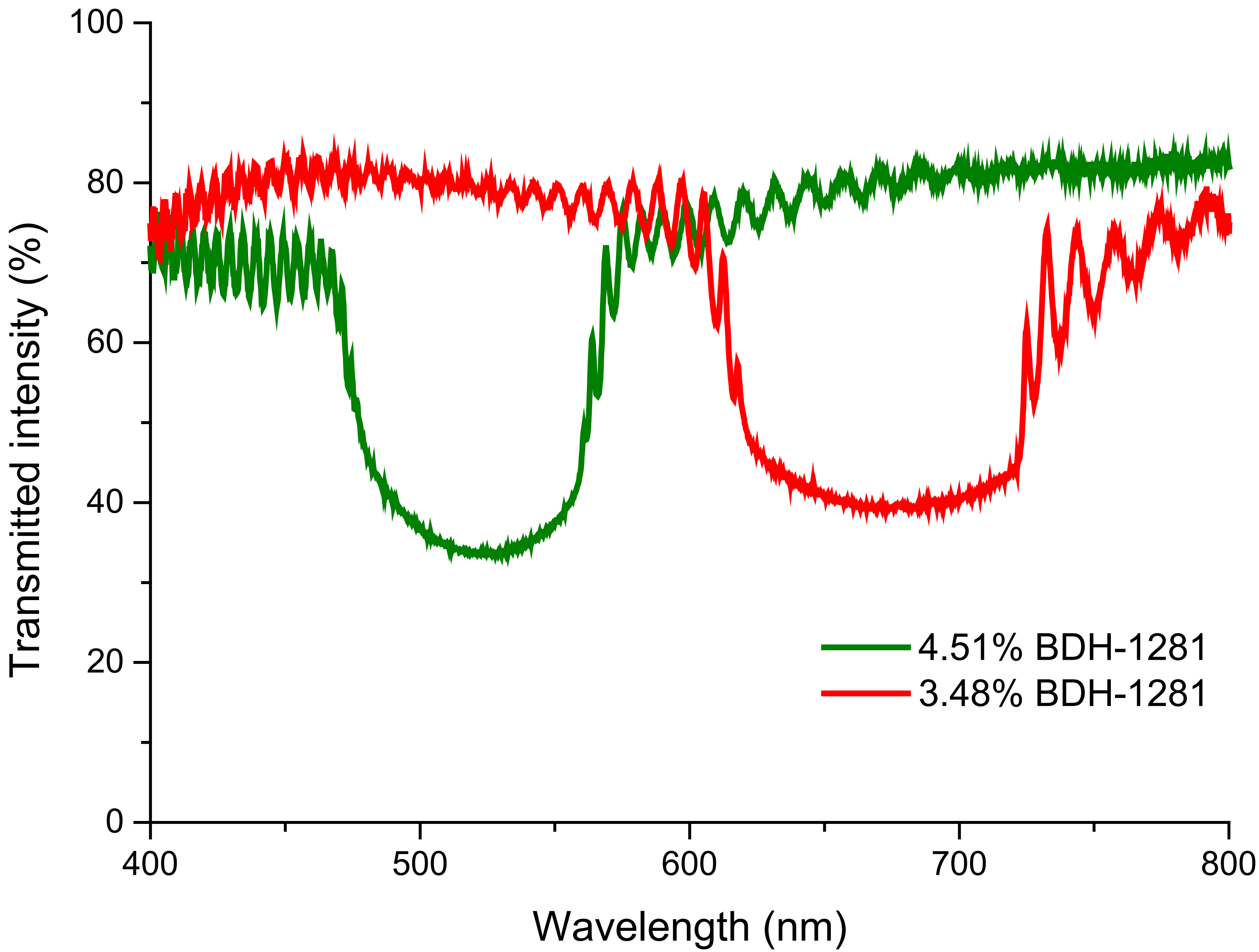
Wavelength-selective reflection:

Short helical pitch: Blue reflecting

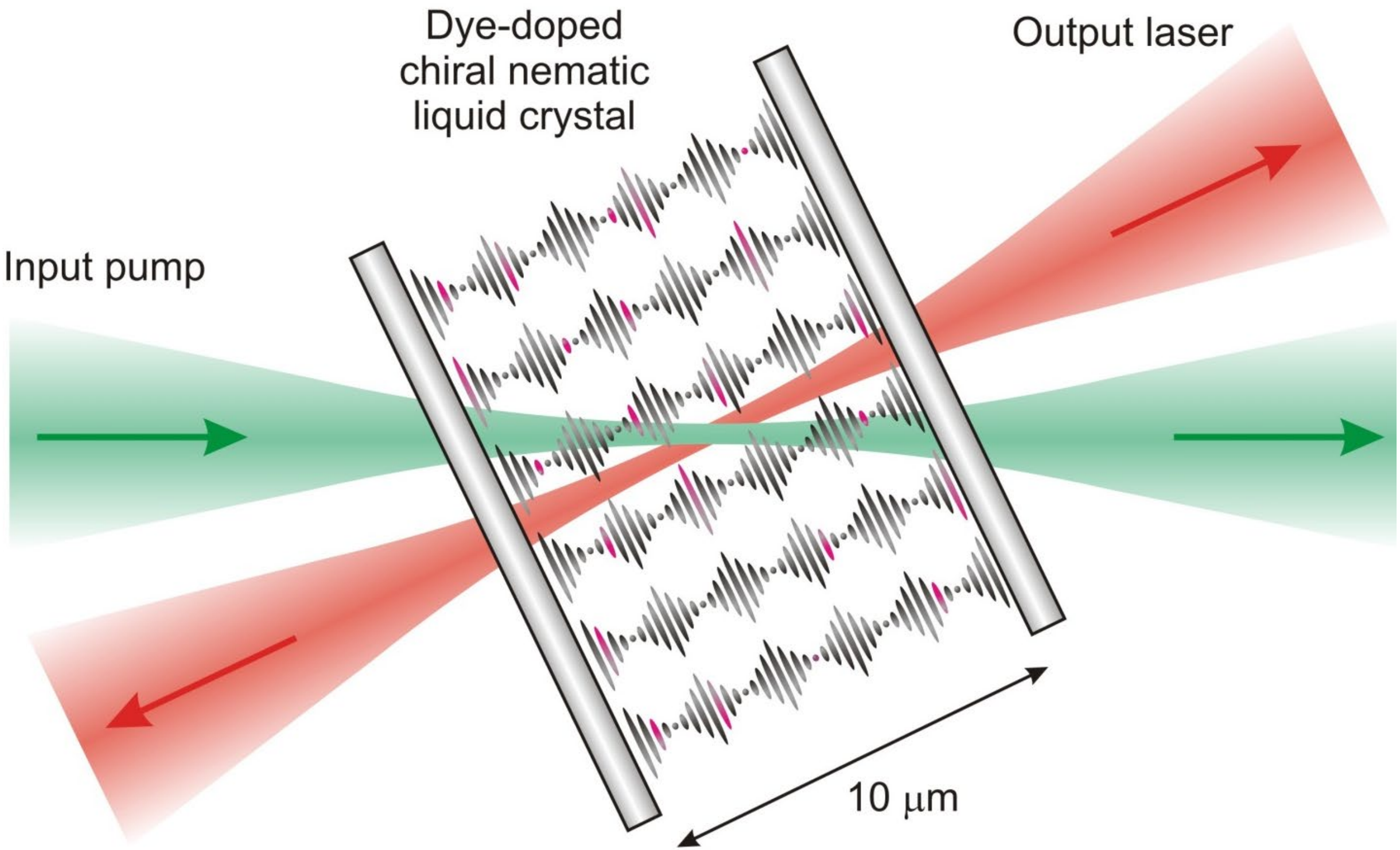
Long helical pitch: Red reflecting

Photonic band gaps: Chiral nematic LCs

Nematic LC + Chiral dopant = <u>Self-assembled</u> PBG with tuneable reflection

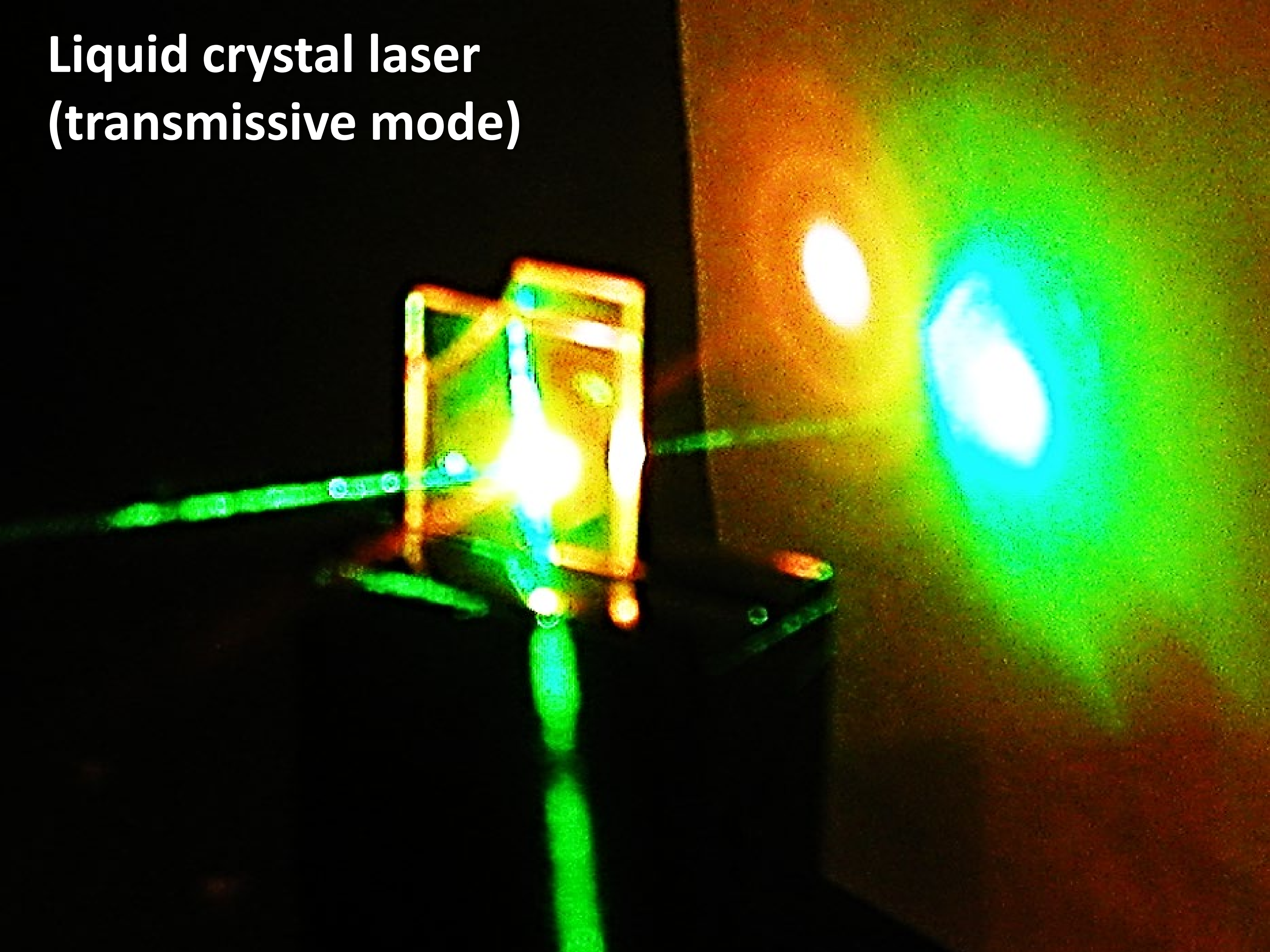


Liquid crystal laser

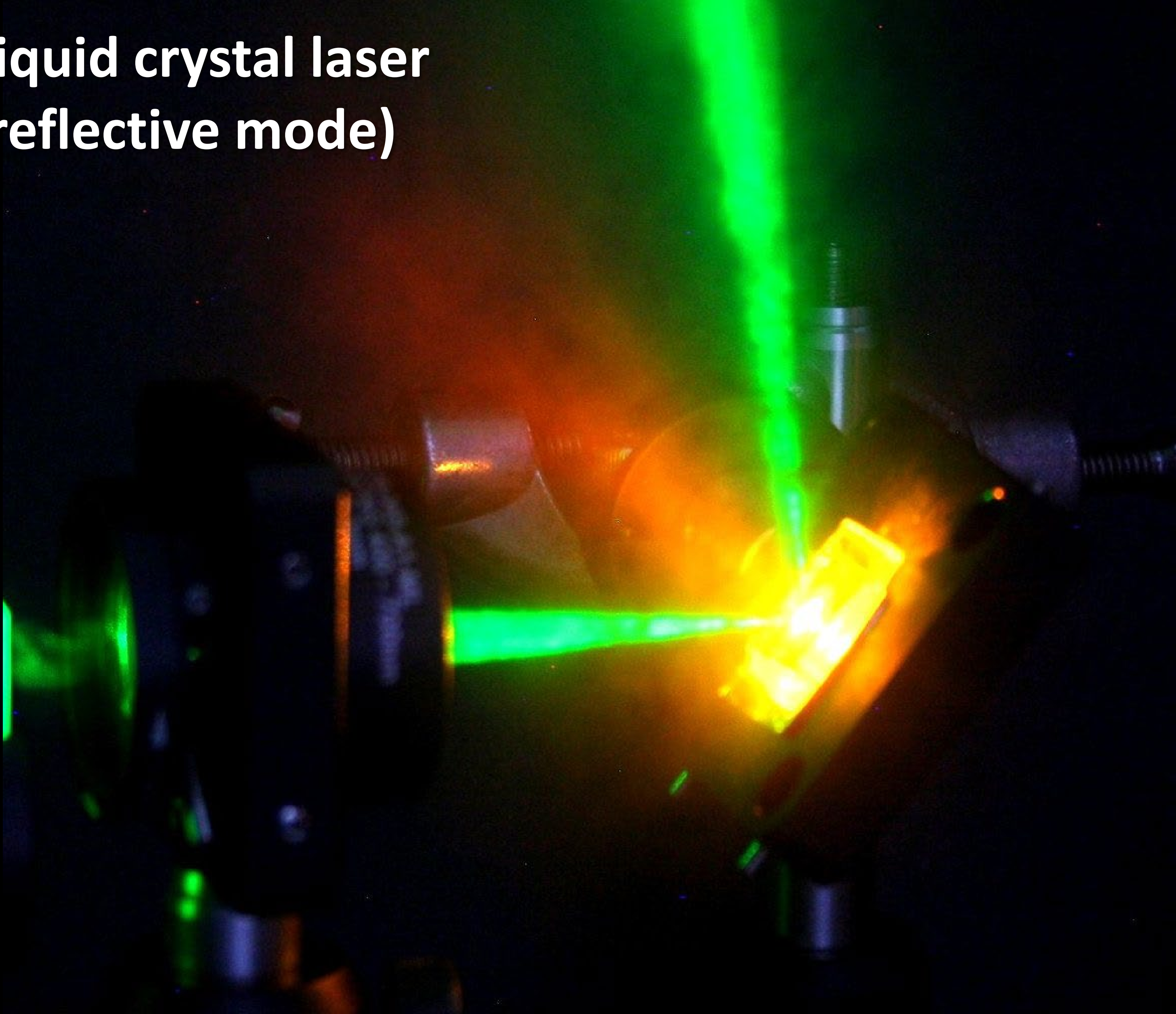


- ✓ Resonant cavity (LC photonic band gap)
- ✓ Gain medium (organic dye)
- ✓ Pump/Excitation source

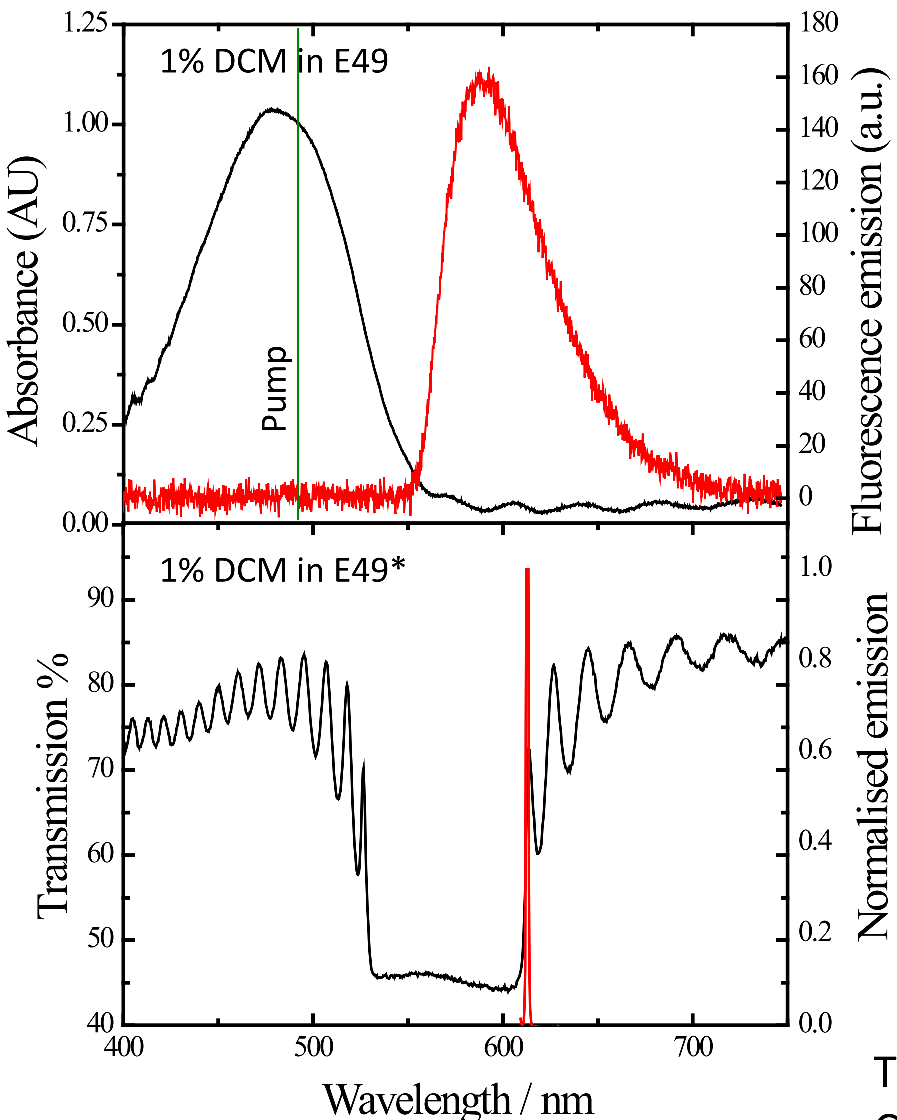
Liquid crystal laser (transmissive mode)

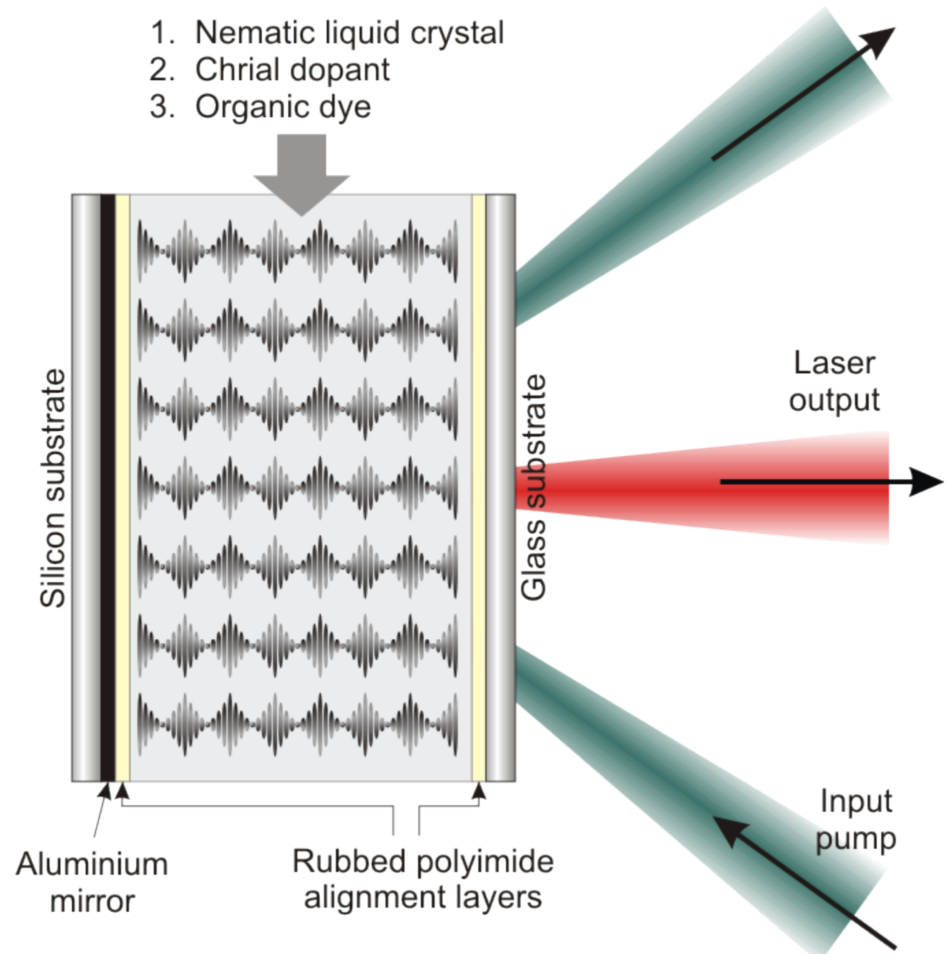


Liquid crystal laser (reflective mode)



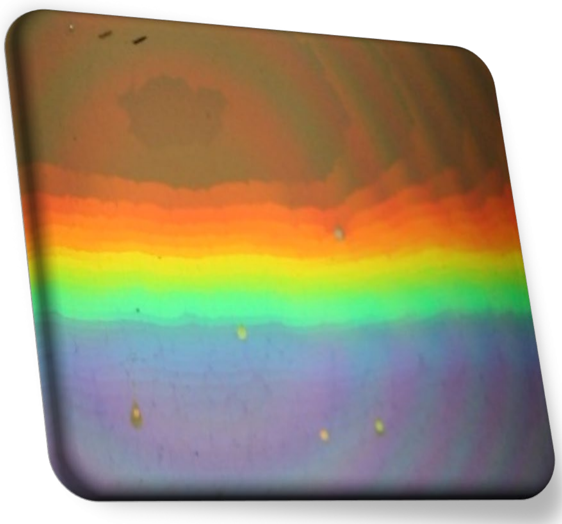
Liquid crystal laser

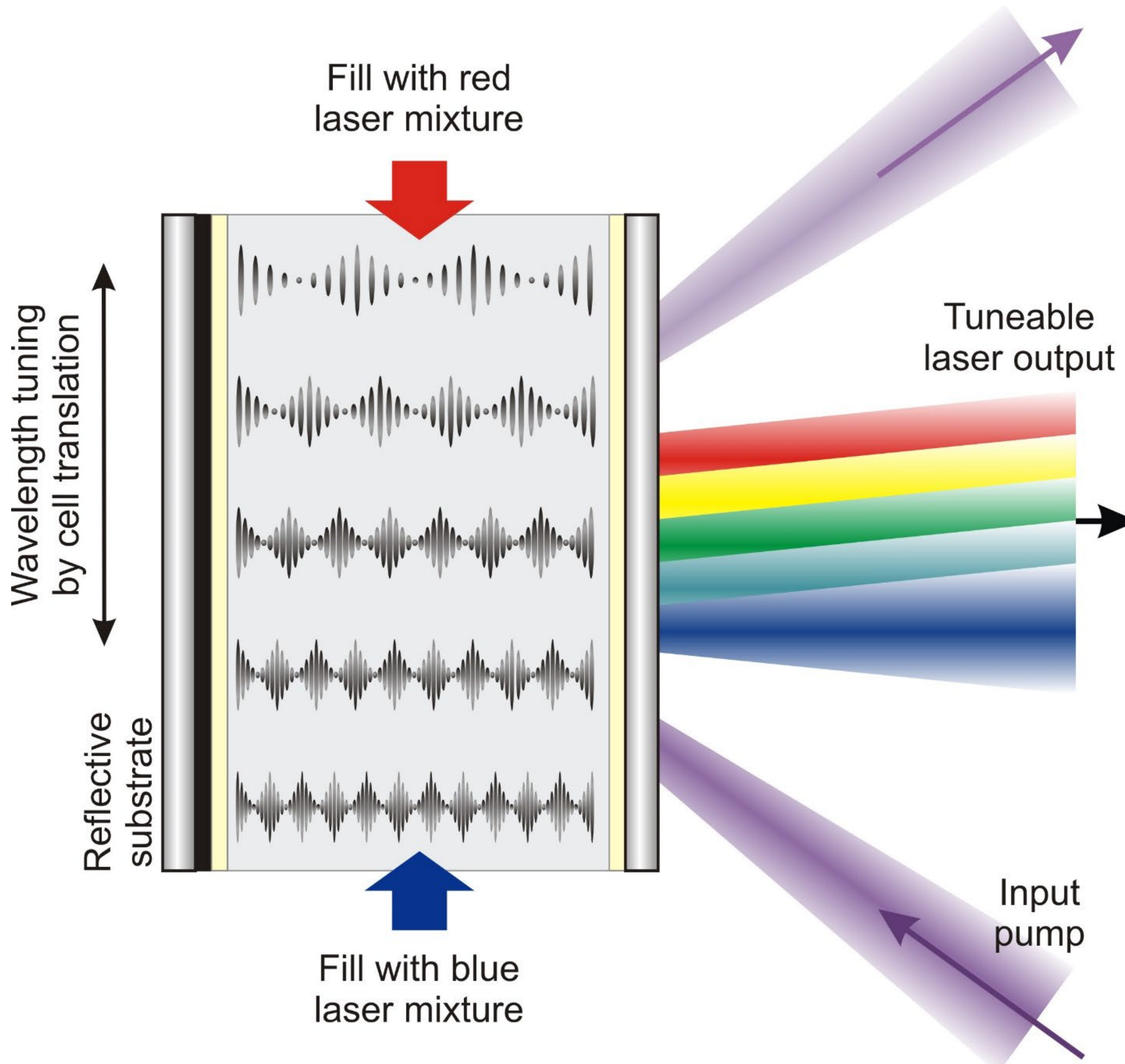




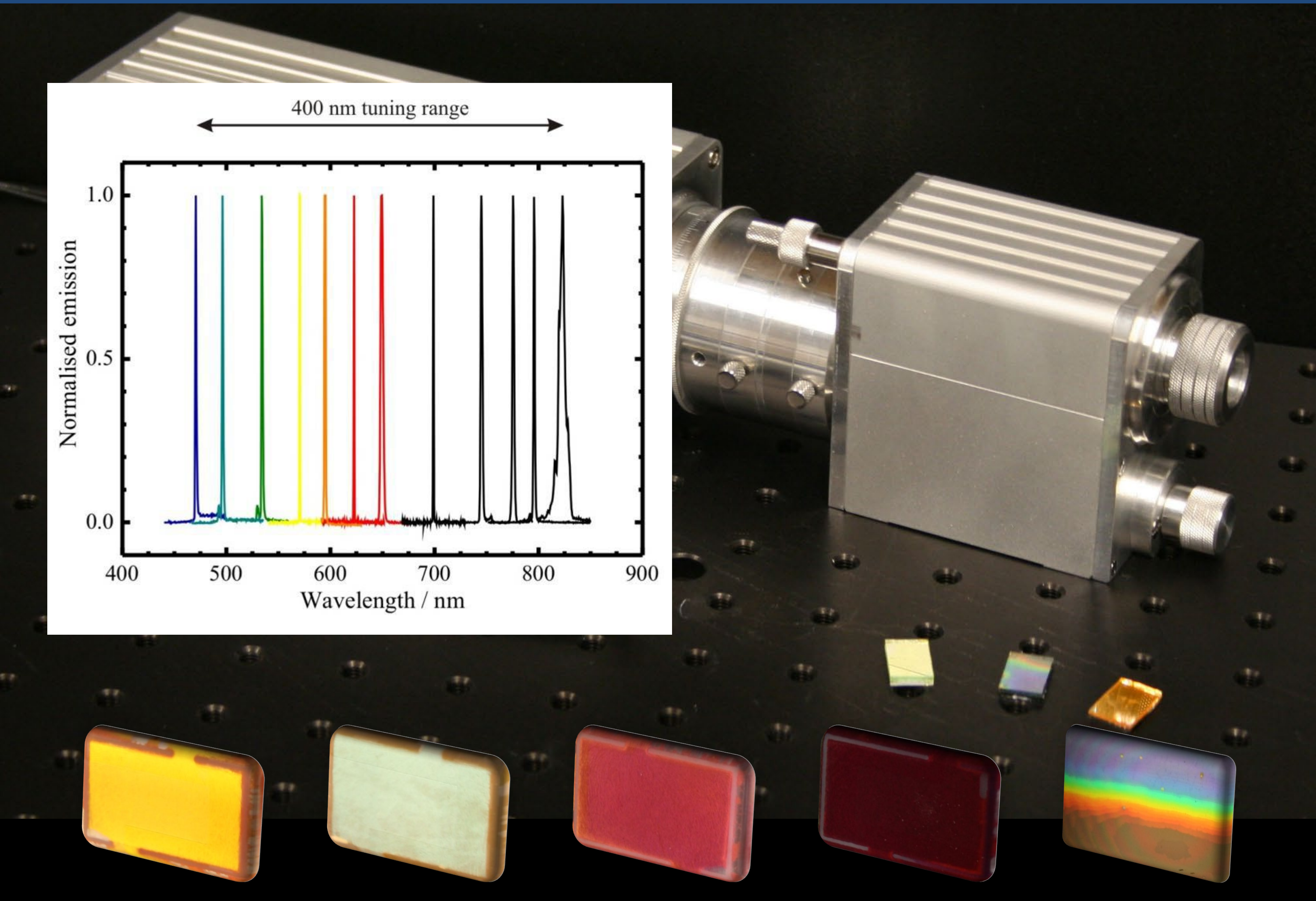
Tune chirality to match PBG with dye fluorescence
Choose pump laser to match dye absorbance

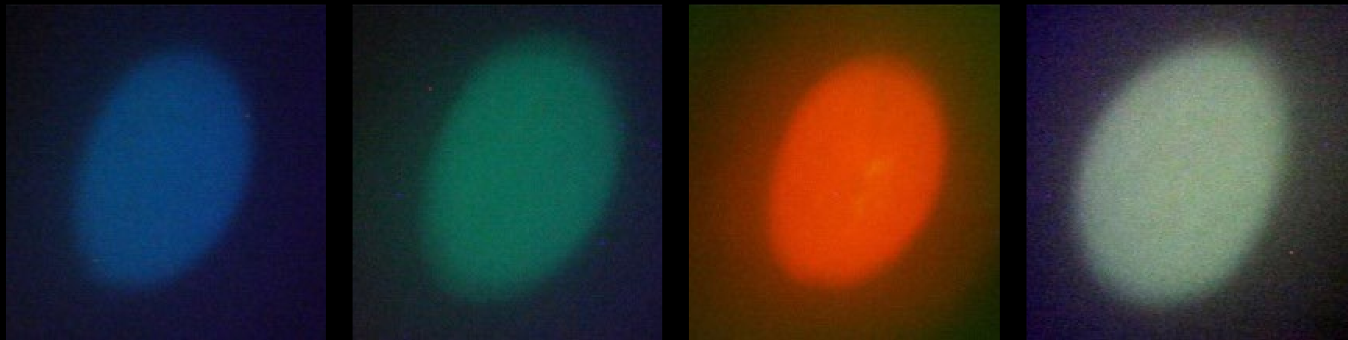
Liquid crystal laser: Gradient pitch



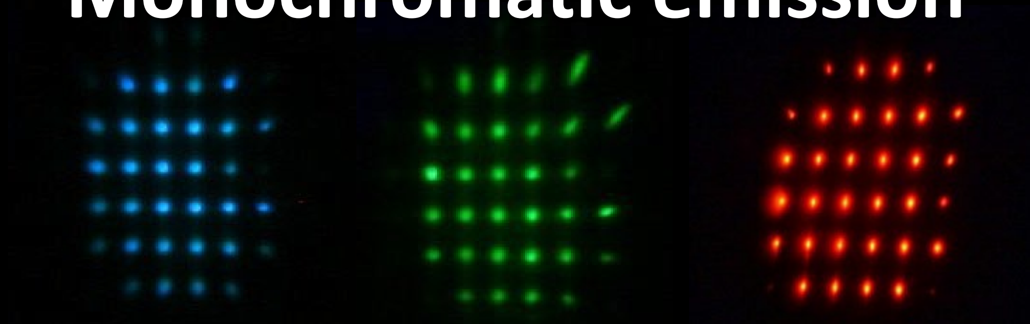


Liquid crystal laser: Portable demonstrator

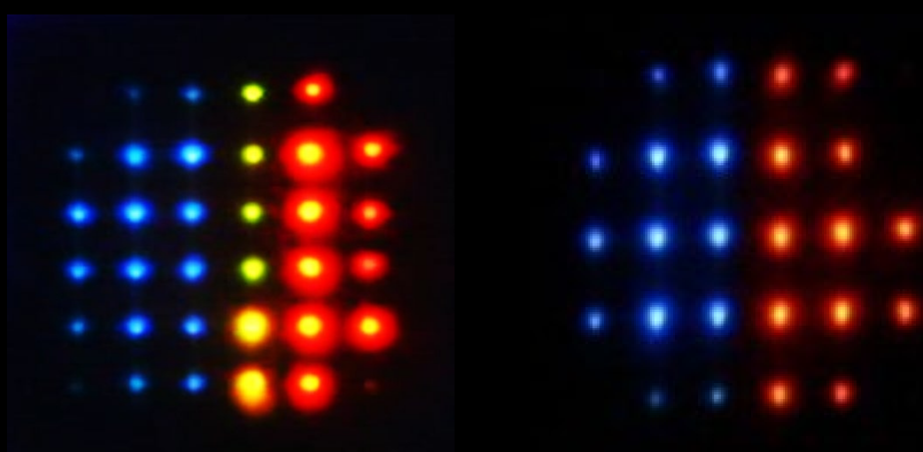




Monochromatic emission

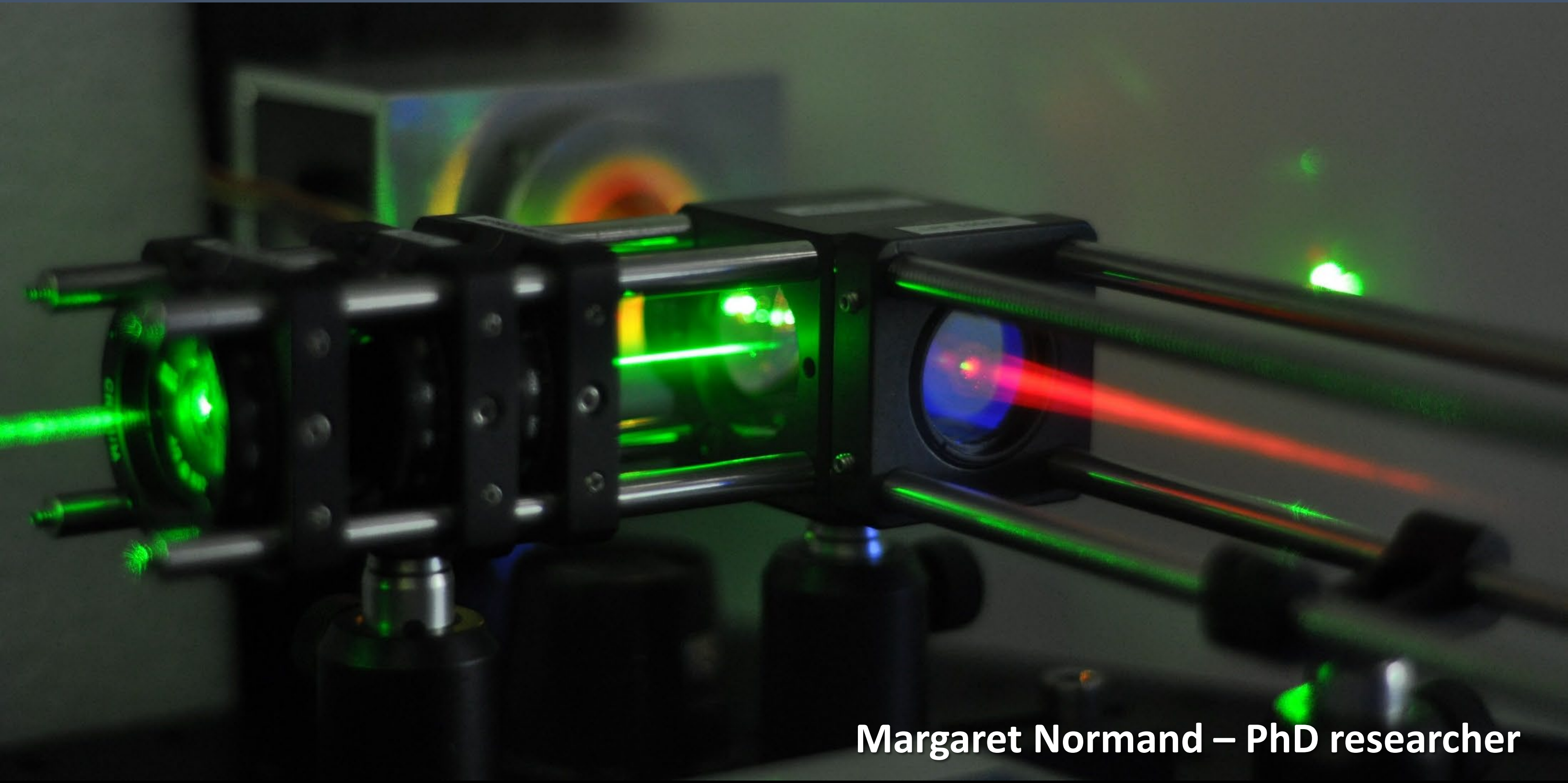


Single-beam, arrays, beam-shaping



Simultaneous polychromatic emission

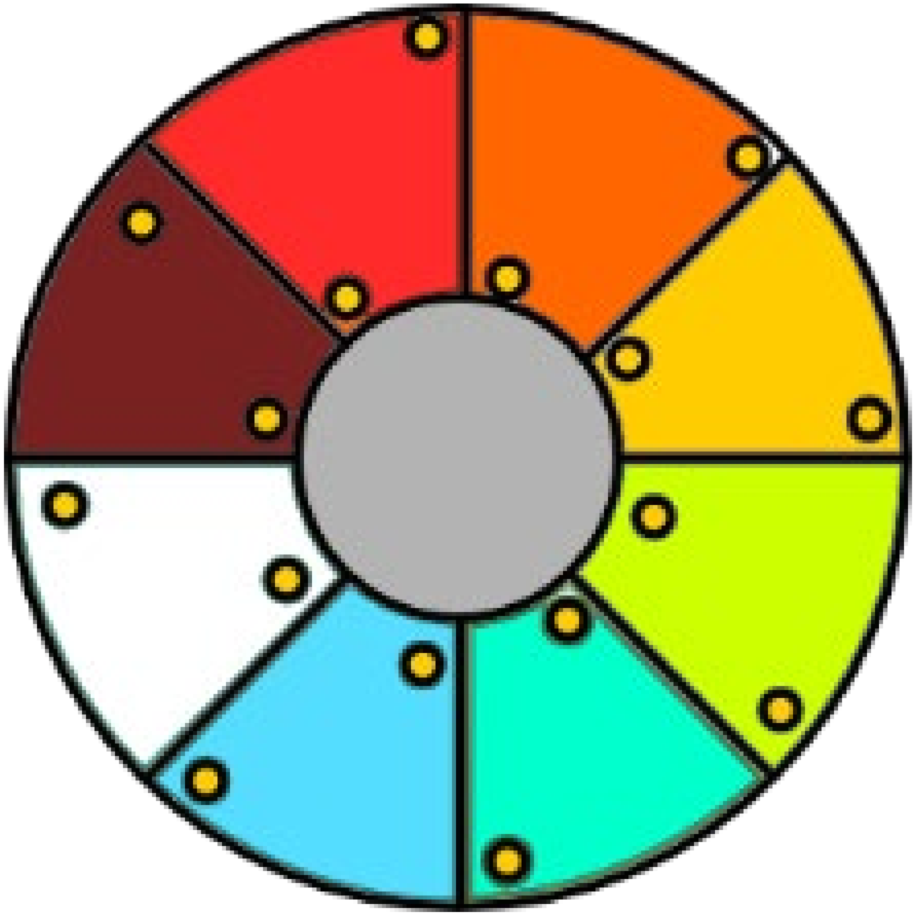
Liquid crystal laser: Spinning lasers



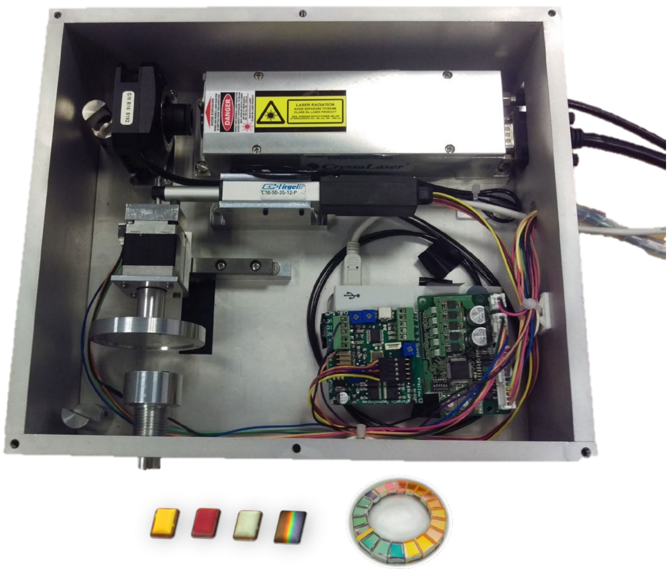
- Overcome repetition rate limitations (static <500Hz, spinning >10kHz)
- Distribute optical and thermal energy of pump
- Enable fast colour-switching

Liquid crystal laser: Spinning laser for colour-switching

- “Colour wheel” approach.
- **Avoids gradient diffusion problems.**
- Radial glue lines create segmented cell.
- **Provides discrete colour-sequential outputs** when cell rotated (including off-state).



Liquid crystal laser: Prototype system development



2012 → 2017 → 2022

2012

DPSS 532 nm pump
Static & translating cell

Output: ~ 1 mW, 550-850 nm
1 ns, < 1 kHz

~ £10k

2017

DPSS 532/440/355 nm pump
Spinning & translating cell

Output: ~ 6 mW, 550-850 nm
1 ns, < 10 kHz

~ £15k

2022

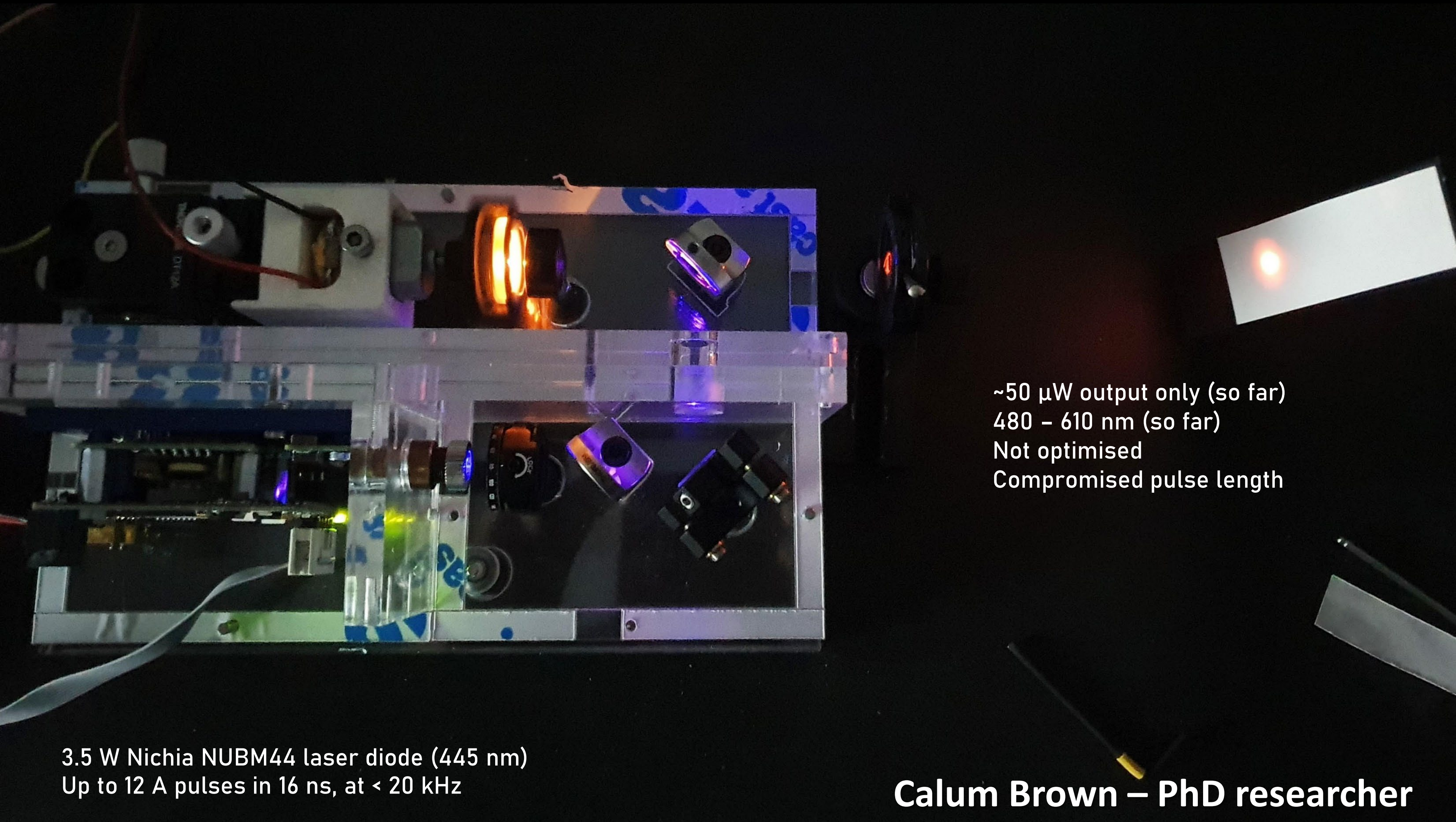
LD 445 nm pump (modular)
Spinning & translating cell

Output: ~ 100 µW, 470-850 nm
4 ns, > 100 kHz

~ £2k

C.M. Brown *et al*, Optics & Laser Technology 140, 107080, (2021).
C.M. Brown *et al*, Proc SPIE 11987, 1198703, (2022).

Liquid crystal laser: Prototype system development



~50 µW output only (so far)
480 – 610 nm (so far)
Not optimised
Compromised pulse length

3.5 W Nichia NUBM44 laser diode (445 nm)
Up to 12 A pulses in 16 ns, at < 20 kHz

Calum Brown – PhD researcher

C.M. Brown *et al*, Optics & Laser Technology 140, 107080, (2021).
C.M. Brown *et al*, Proc SPIE 11987, 1198703, (2022).

Liquid crystal laser: Future directions

Smaller & cheaper?

???

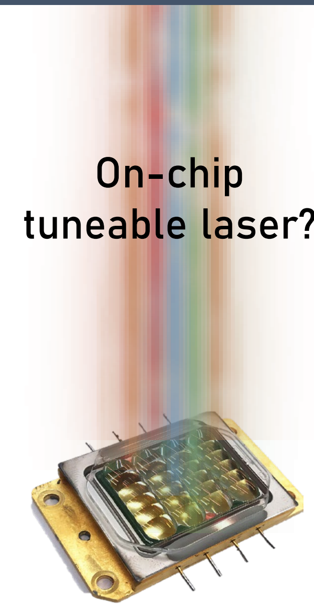
- Free-space micro-optics
- Replaceable LC cartridges

Faster & more powerful?

???

- Multi-diode or DPSS pumping
- Bigger cells
- Faster spinning/beam-steering
- Better focussing optics
- MHz operation
- x40,000 power multiplier
- ~ 1W feasibly possible
- (Compromises in cost & size)

On-chip tuneable laser?

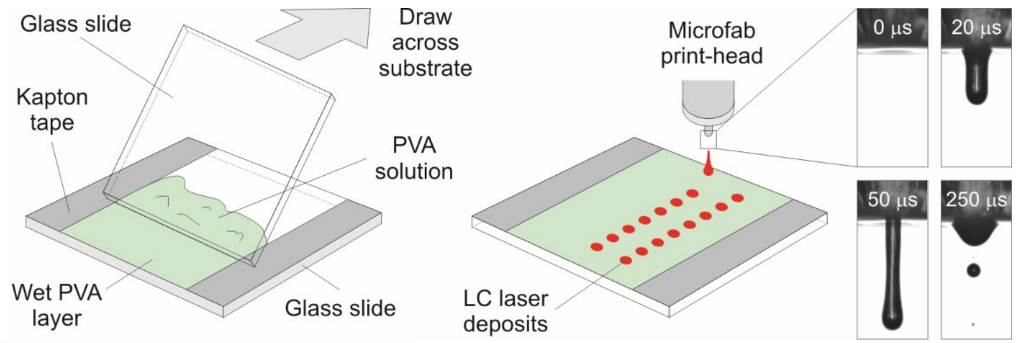


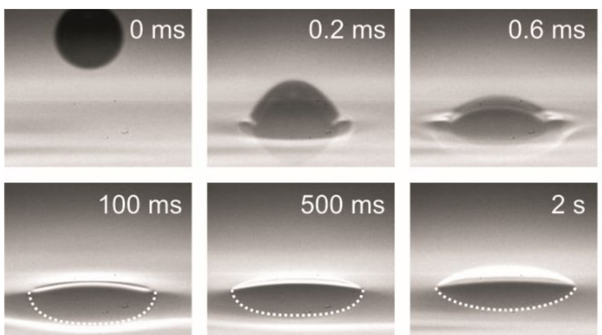
???

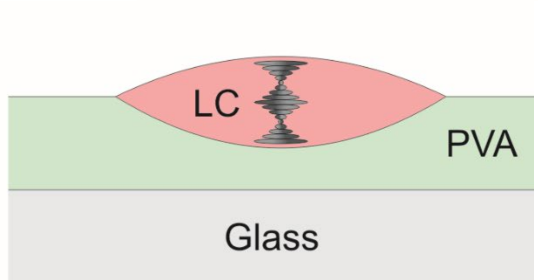
- Monolithic construction
- Integrated LC & diode array

Future directions for LC lasers: Ink-jet printed lasers

Printing of LC laser into wet PVA

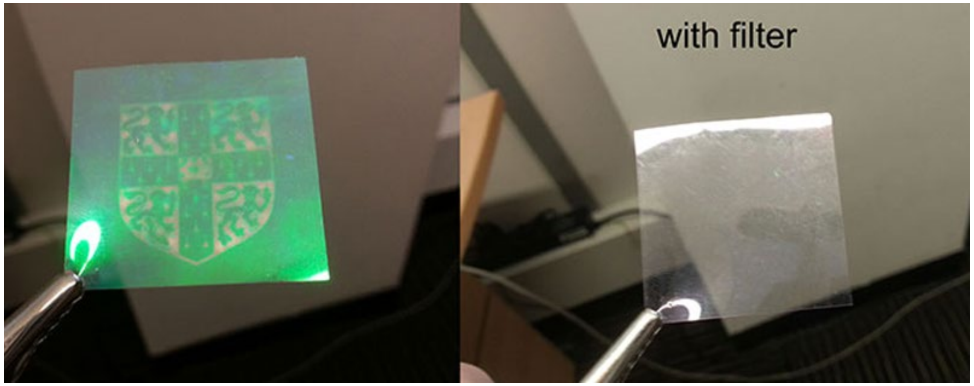






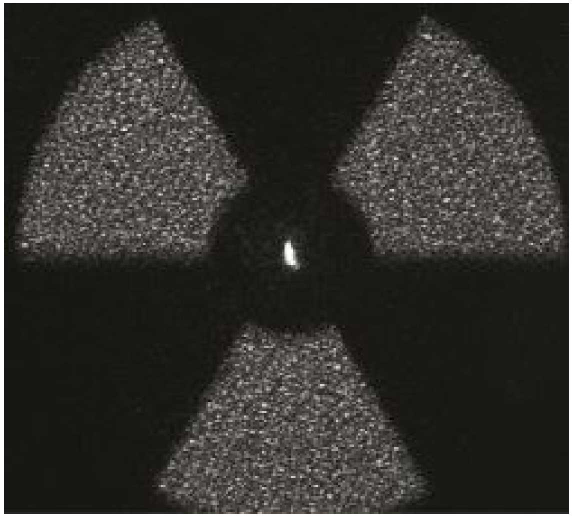
Spin-out from University of Cambridge (2012)
Sold to Tracerco (2015)

ilumink

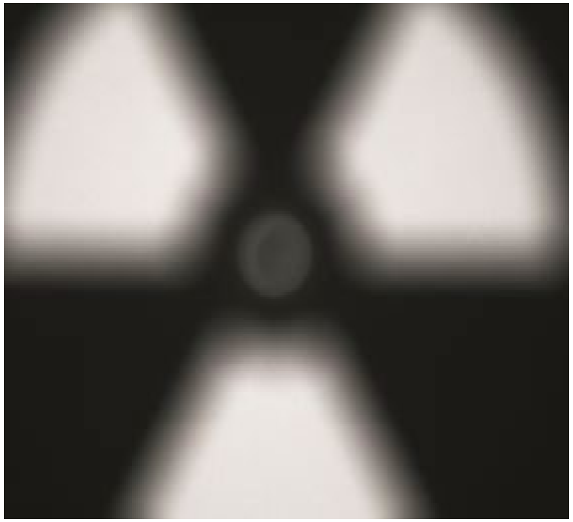


D.J. Gardiner, et al, Soft Matter 8: 9977-9980, (2012)

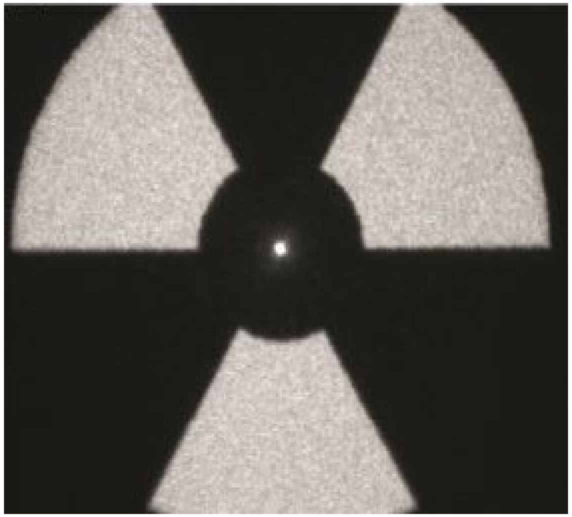
Future directions for LC lasers: Holographic projection



Semiconductor laser
(high coherence)



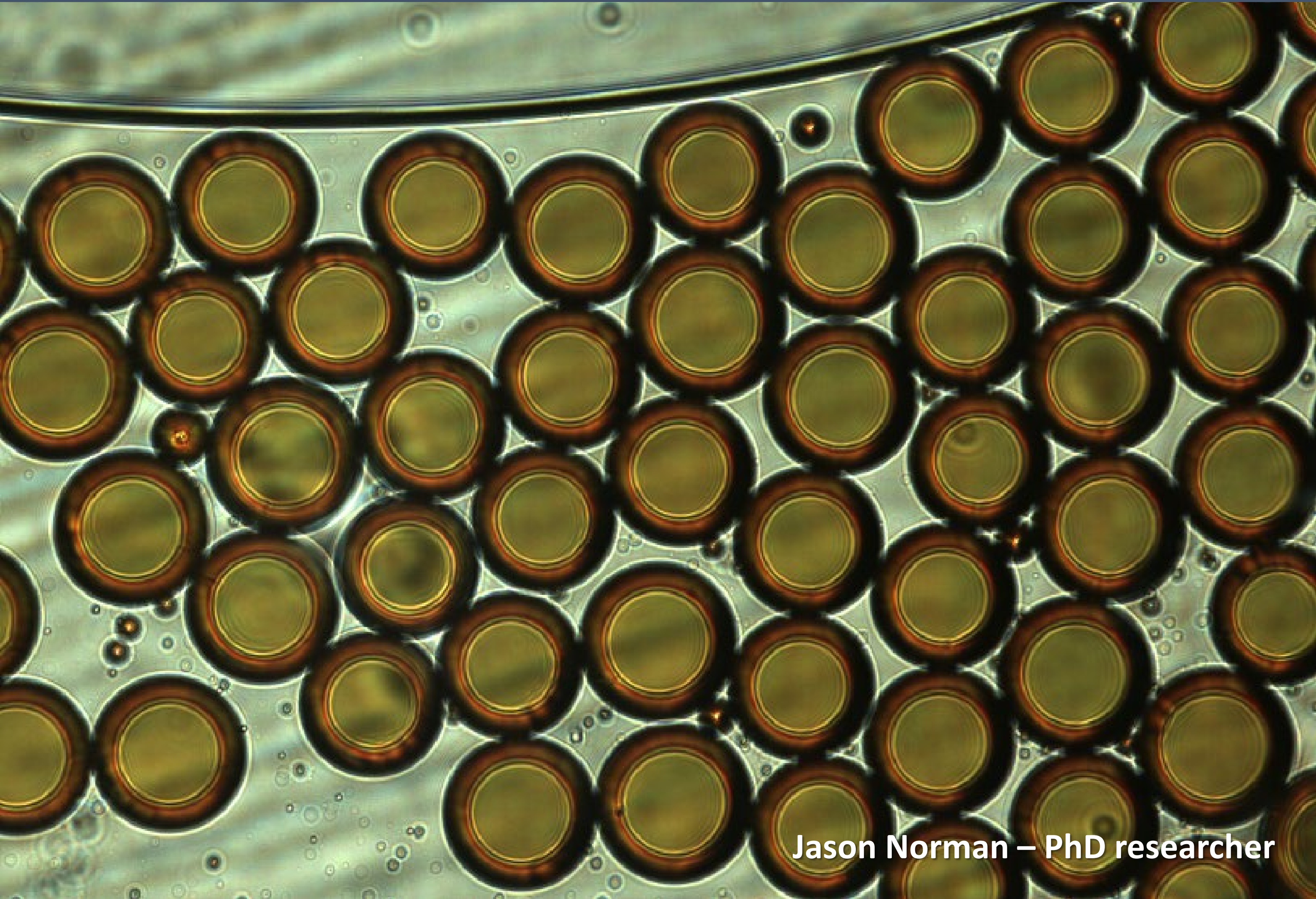
LED
(spatially-filtered)
(low coherence)



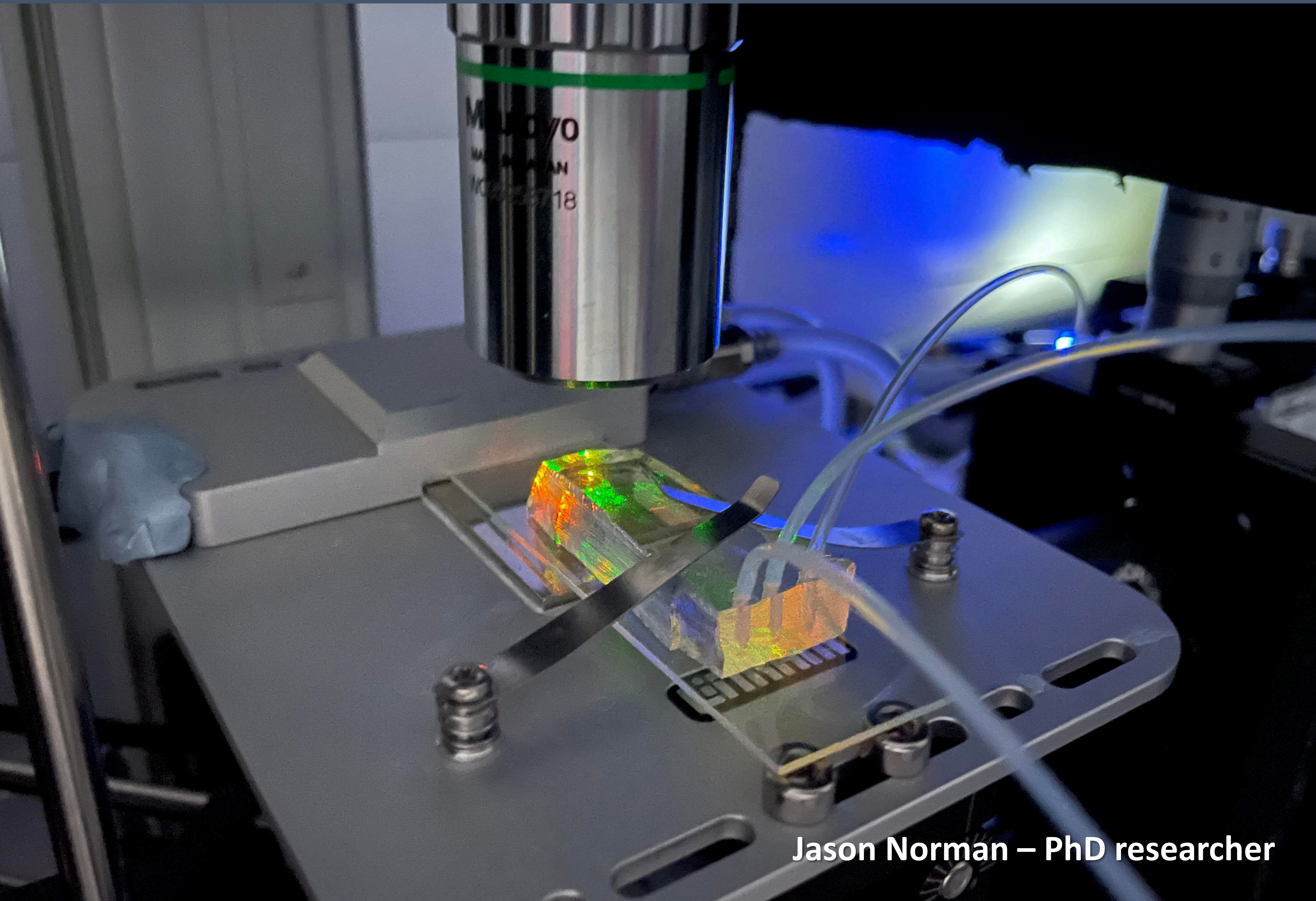
Liquid crystal laser
(mid coherence)

Future 2D and 3D holographic displays for augmented reality?

Future directions for LC lasers: Lasing microfluidic sensors



Future directions for LC lasers: Lasing microfluidic sensors



Jason Norman – PhD researcher

Future directions for LC lasers: Medical imaging

Fluorescence microscopy:

Microscopists currently either:

- Limit their choice of wavelengths & fluorophores (limiting detection capabilities & compromising performance)

or

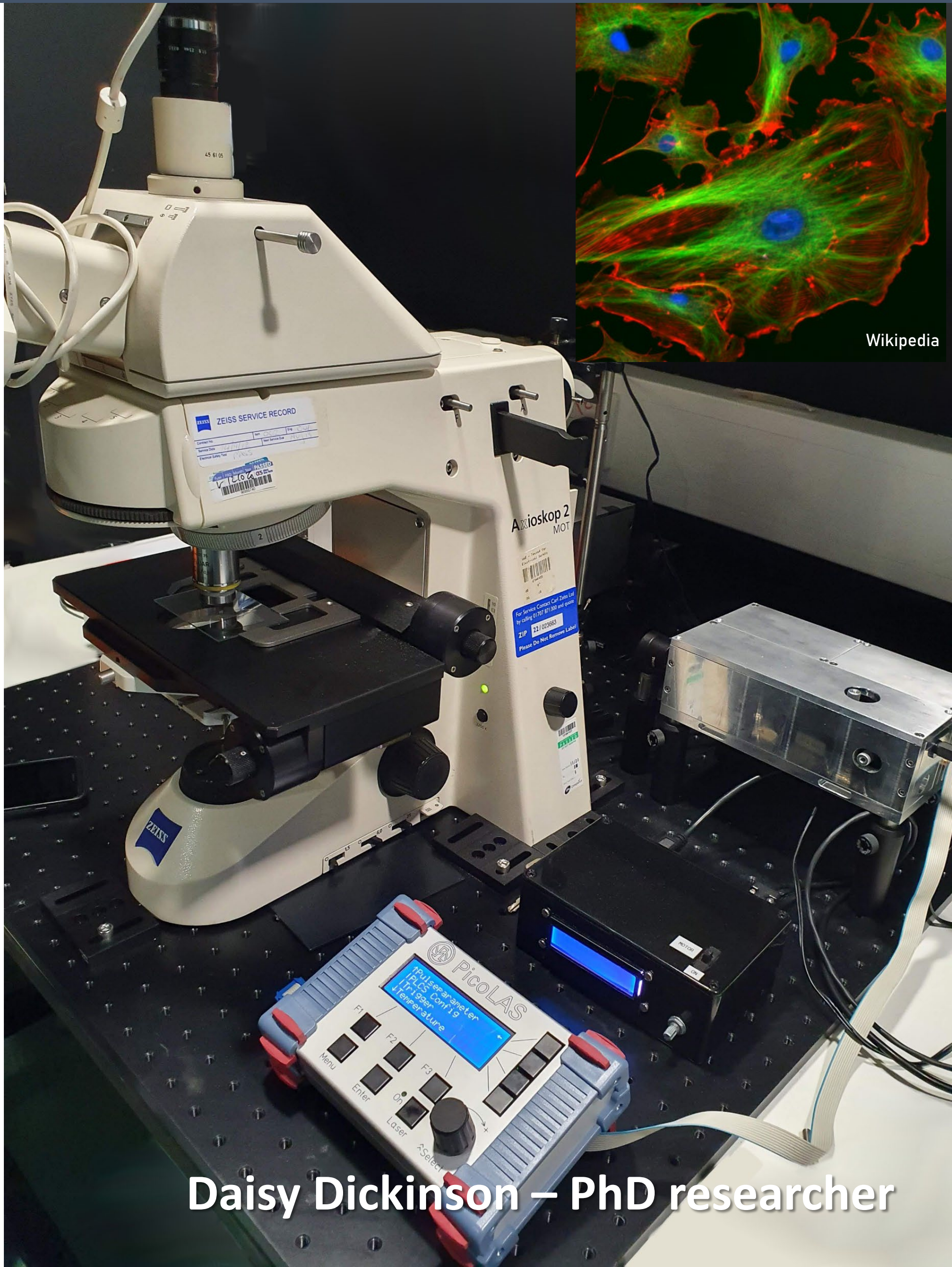
- Add multiple laser sources (adding cost, size & complexity)

Inappropriate excitation wavelengths give rise to:

- Inefficient excitation of fluorophores
- Weakened signal strength
- Increased bleaching (increase excitation source power to compensate for weak signal)
- Cross-talk between fluorophores with overlapping absorbances

Optimised excitation wavelengths from LC laser give rise to:

- Increases signal strength
- Minimises bleaching
- Eliminates cross-talk and enables selectable addressing

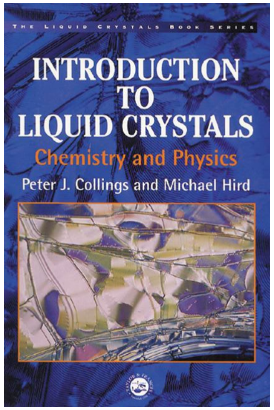


Further reading:

LCs:

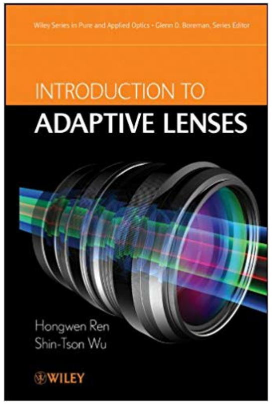
D. Andrienko, *Introduction to liquid crystals*
Journal of Molecular Liquids, 267, 520-541, (2018)

P.J. Collings, M. Hird, *Introduction to liquid crystals*
CRC Press, Taylor & Francis, (1997)



LC lenses:

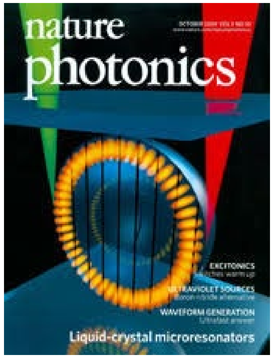
H. Ren, S.-T. Wu, *Introduction to Adaptive Lenses*
Wiley (2012)



LC lasers:

S. Morris, H. Coles, *Liquid crystal lasers*
Nature Photonics, 4, 676-685, (2010)

Jaroslaw Mysliwiec, et al. *Liquid crystal laser: the last decade and the future*
Nanophotonics, 10(9), 2309-2346, (2021)



My papers:

https://www.research.ed.ac.uk/portal/en/persons/philip-hands(0ee0289e-69f3-4af4-a863-ac8c82c0291a).html

Acknowledgements:

University of Durham:
Gordon Love, Andy Kirby

UC Berkeley:
Marty Banks, David Hoffmann

University of Cambridge:
Steve Morris, Damian Gardiner, Tim Wilkinson, Harry Coles

University of Edinburgh:
Mags Normand, Peigang Chen, Calum Brown,
Daisy Dickinson, Jason Norman, Ieva Pakamoryte