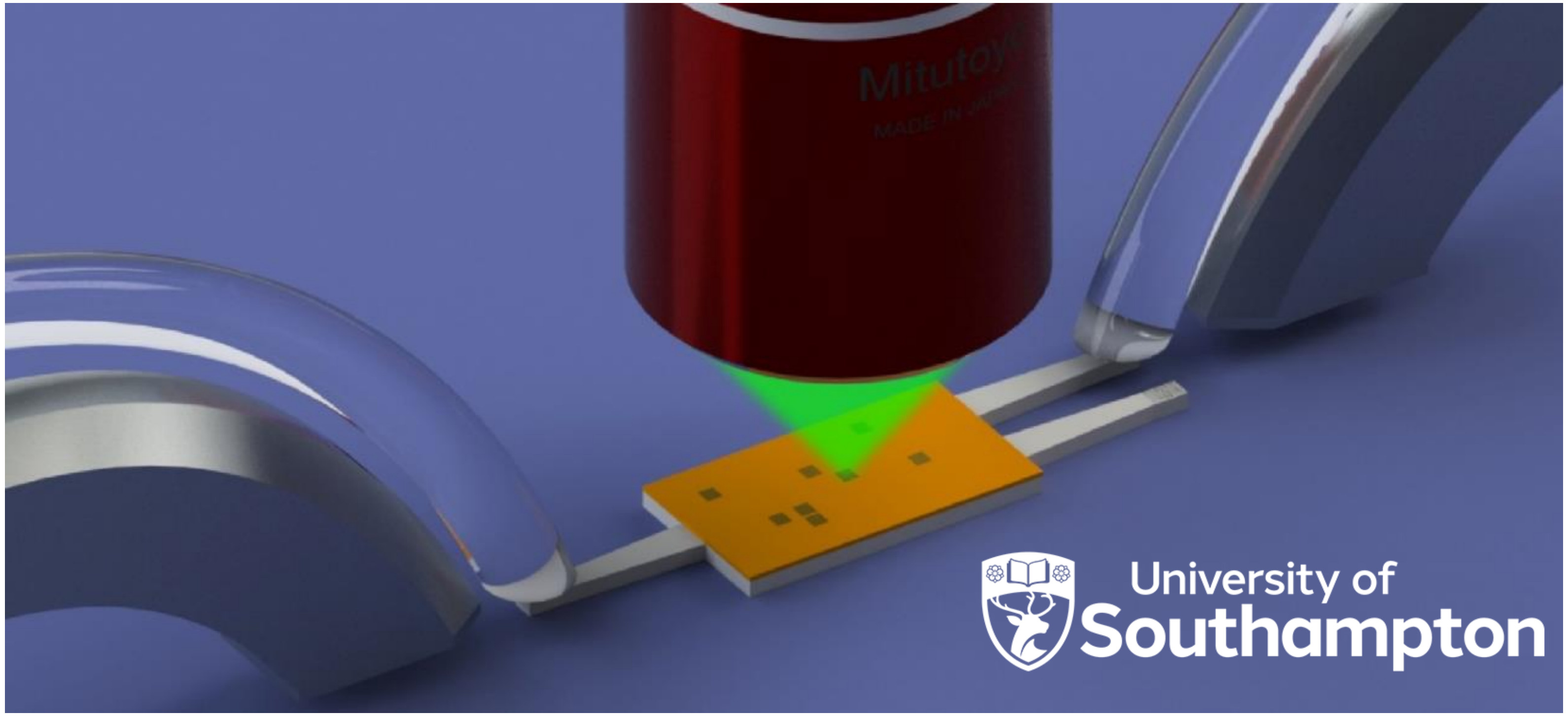
~~Thermochromics and~~ Phase-change technologies for sustainable photonics

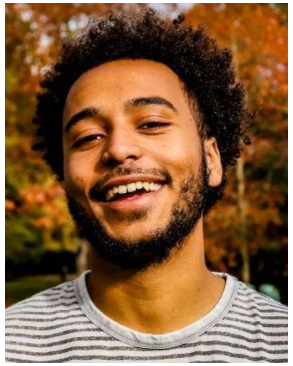
Otto Muskens

University of Southampton, UK



UK Metamaterials Network, 14 June 2023

Acknowledgements








Daniel Lawson | **Callum Wheeler** | **Sophie Blundell** | **Thomas Radford** | **Matthew Delaney** | **Kees de Groot** | **Kai Sun** | **Ioannis Zeimpekis**

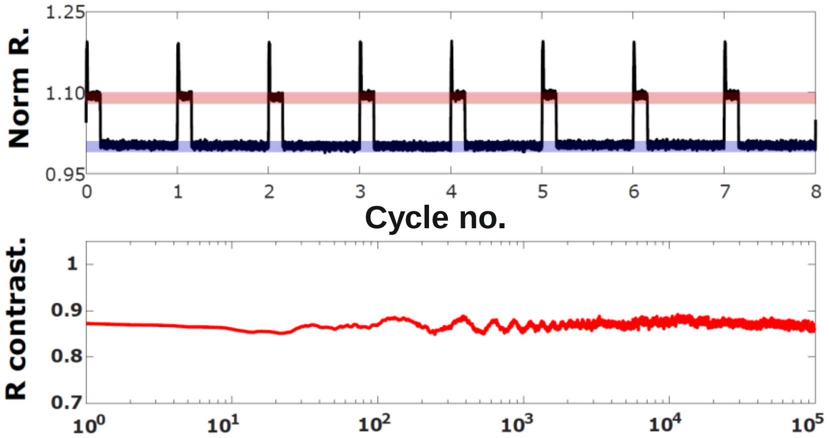
Integrated Nanophotonics group

EPSRC
Pioneering research and skills

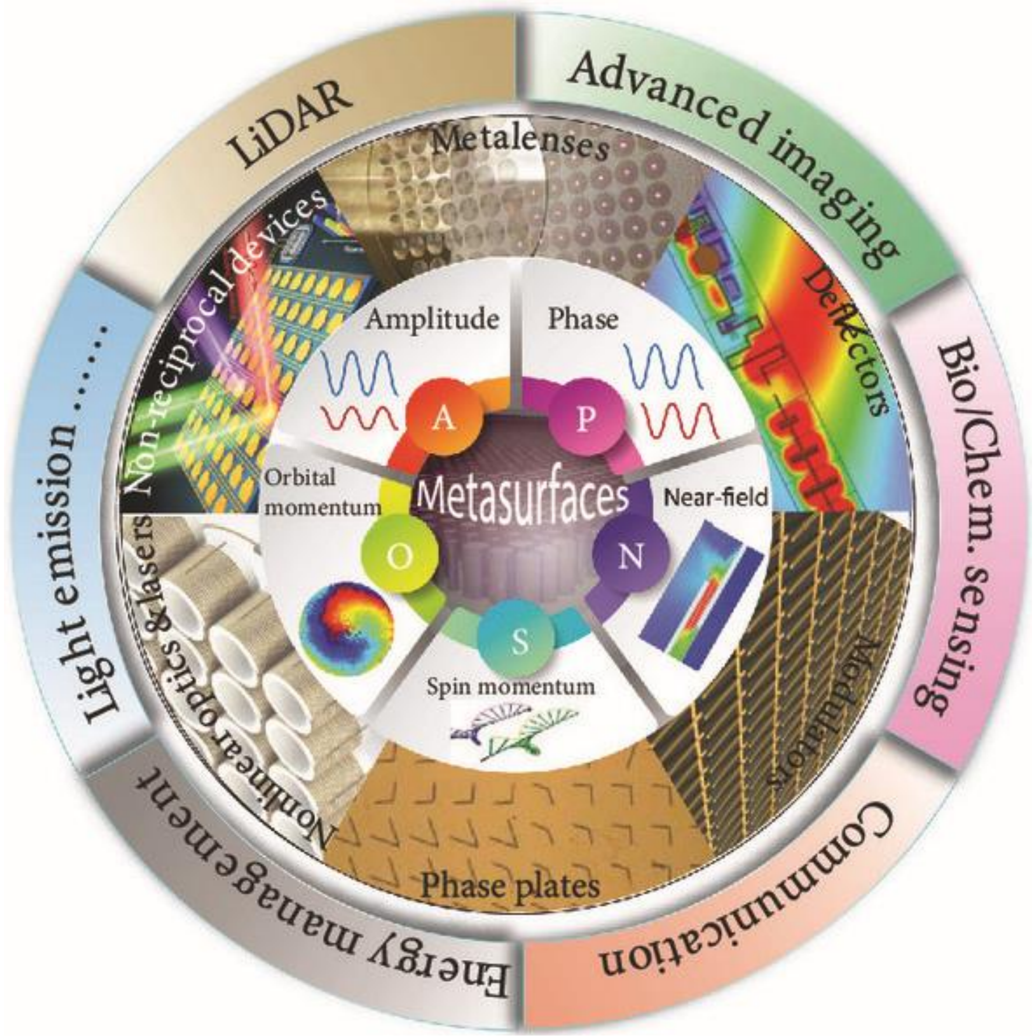
Outline

- New low-loss phase change materials for photonics

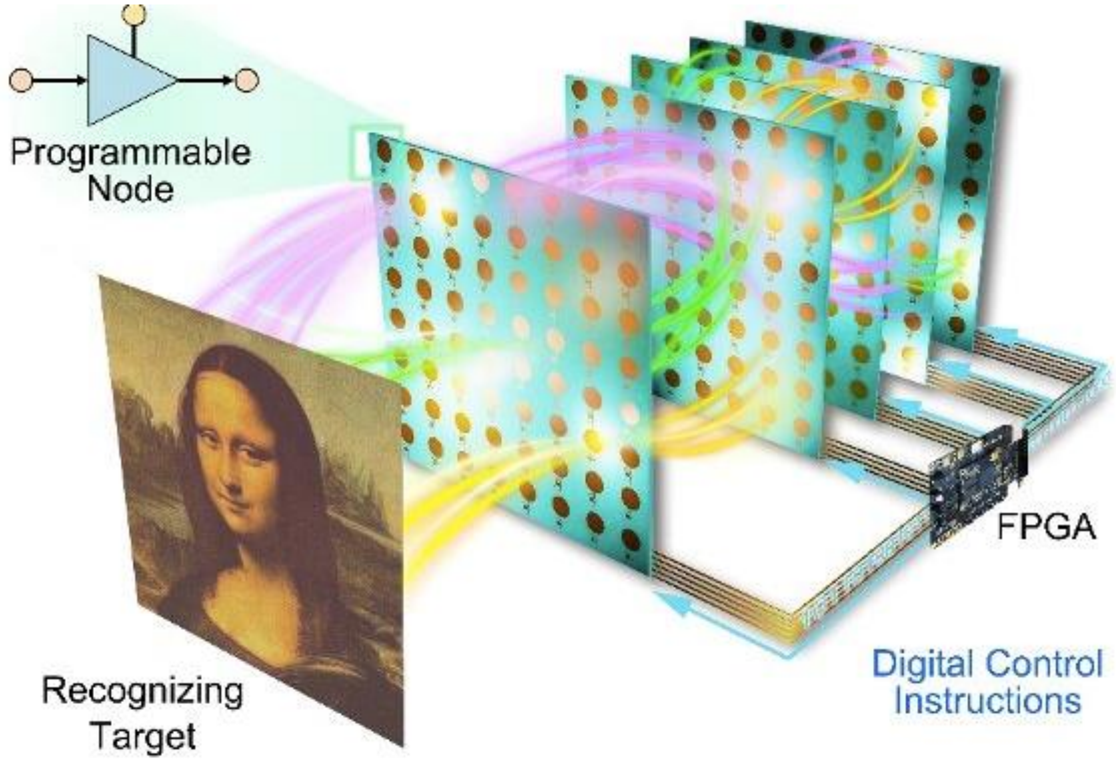
- Optical switching of Sb_2Se_3 films for metasurface applications



Programmable / switchable photonics: application perspective

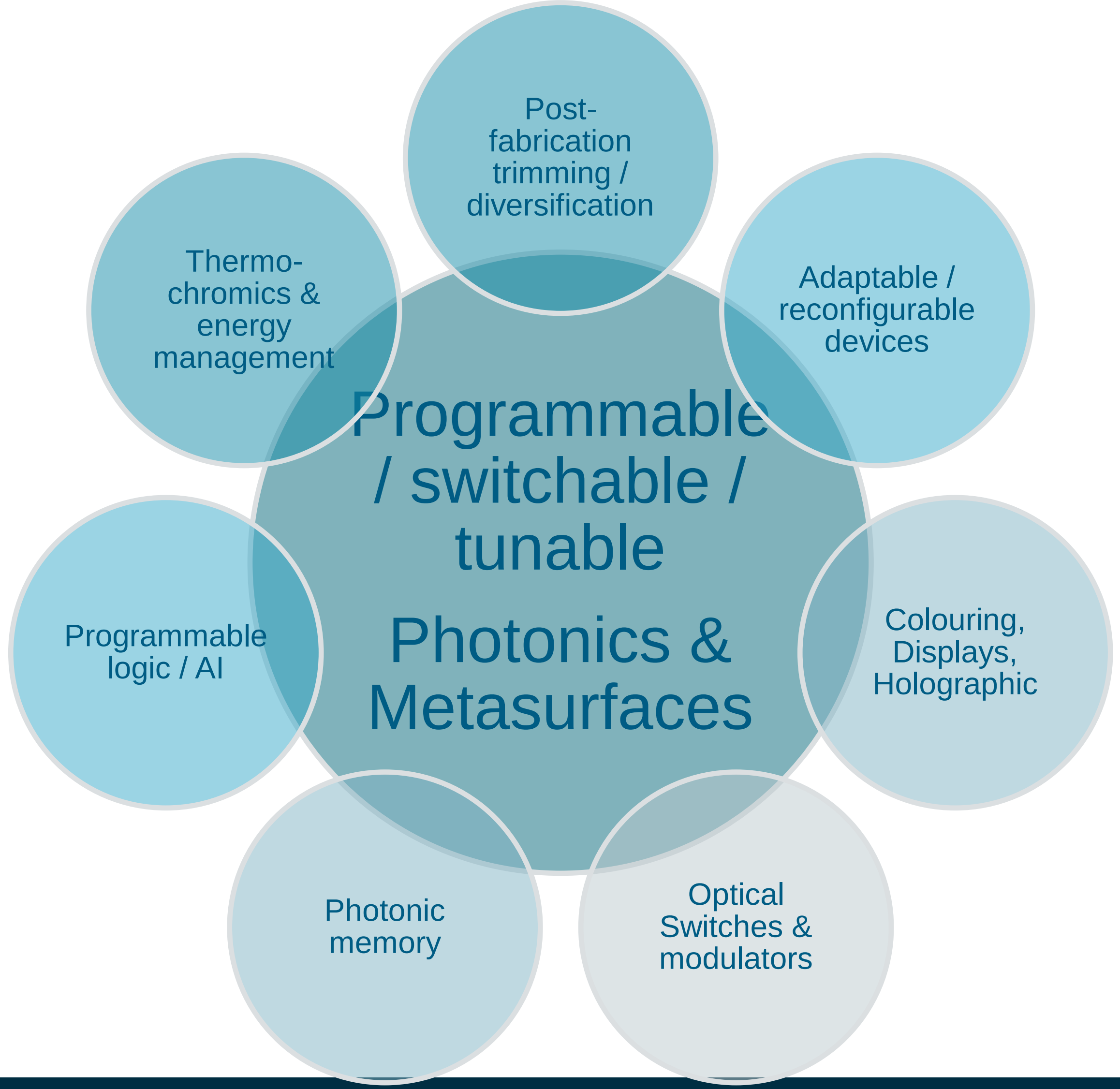


DOI: 10.34133/2022/9765089



DOI: 10.1038/s41928-022-00719-9

Programmable / switchable photonics: application perspective



Optical programming

- Direct (laser) writing
- Offline (in factory), set & forget

Electrical programming

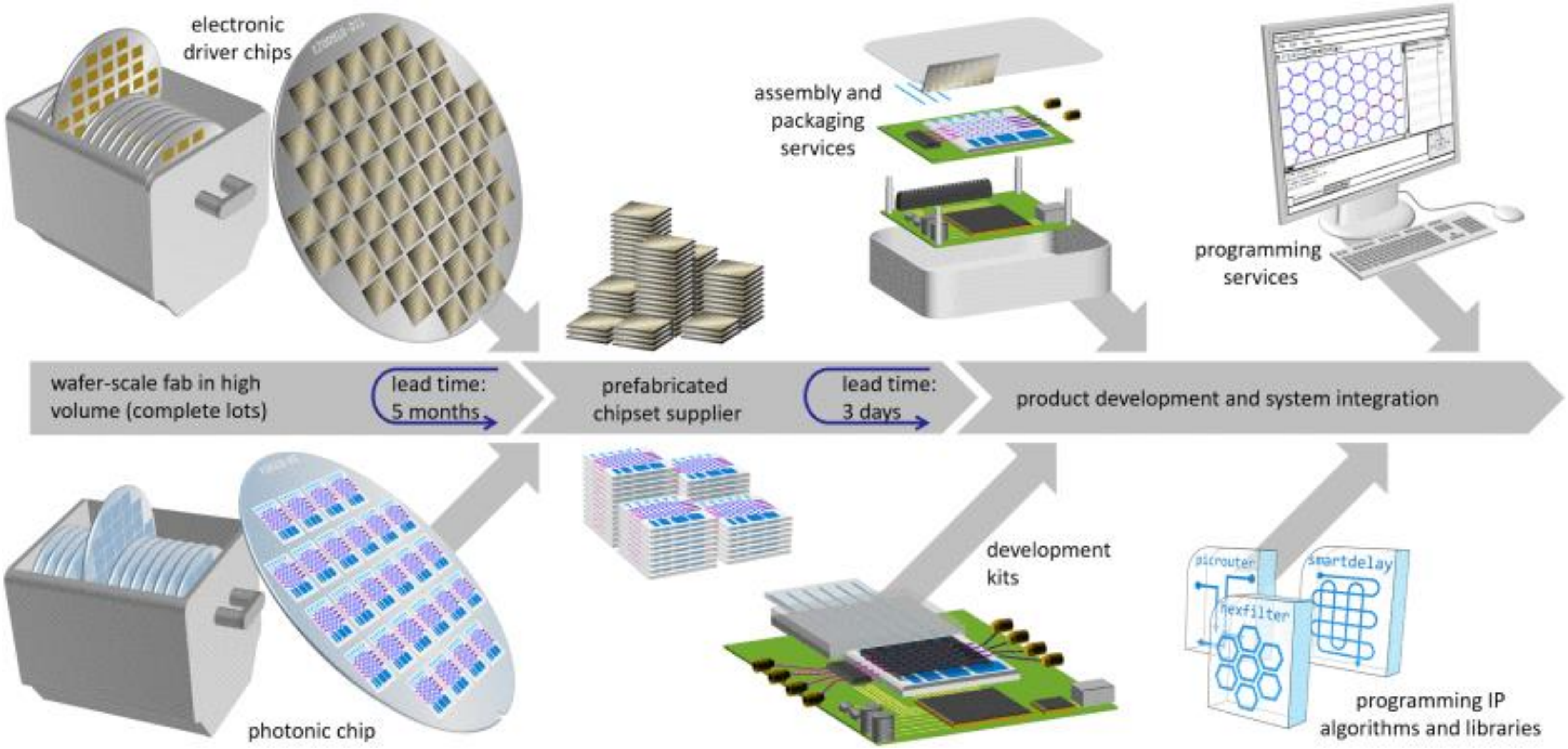
- Device-level actuation
- Requires electrical contacts, interface, regulation

Thermally responsive

- Through local heating or environment
- Passive regulation

…

Programmable photonics: supply chain benefits

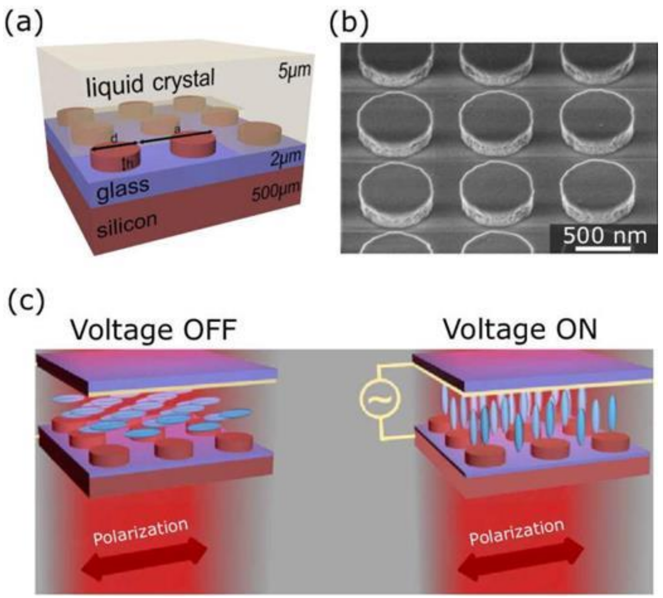


Bogaerts et al., IEEE J Sel Top Quant Electron 26, 8302517 (2020)

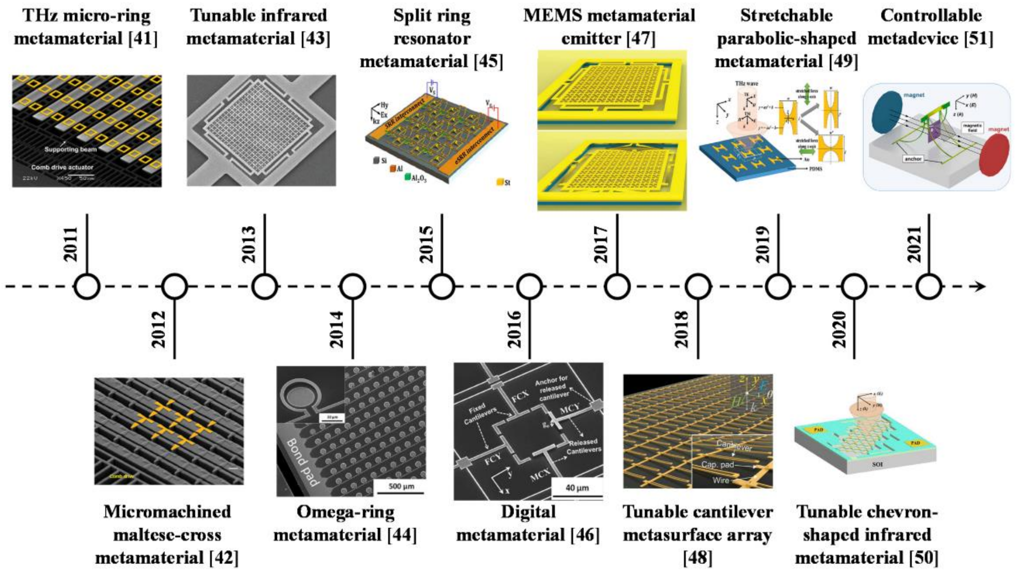
Programmable photonics & sustainability

1. Switching costs energy
2. Actively maintaining a state costs energy

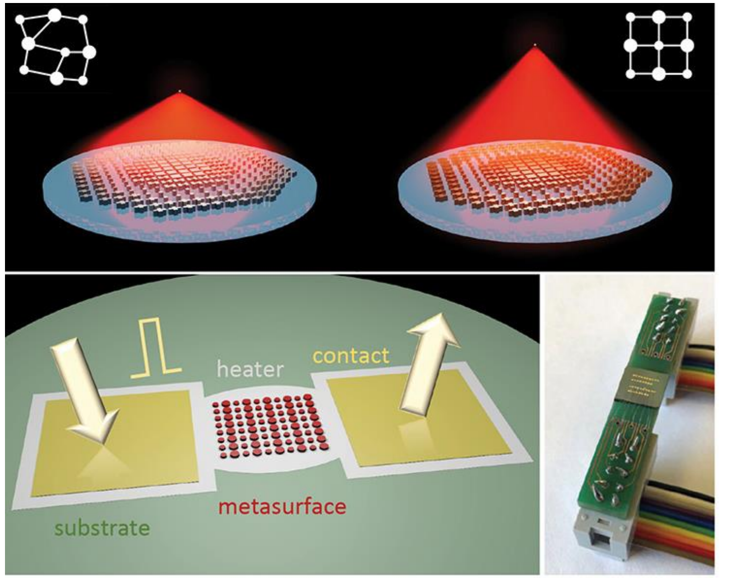
Liquid crystals



MEMS



Phase change



https://doi.org/10.1063/1.4976504

https://doi.org/10.3390/electronics11020243

M.Y. Shalaginov et al. Nat. Commun. 12, 1225 (2021).

Programmable photonics & sustainability

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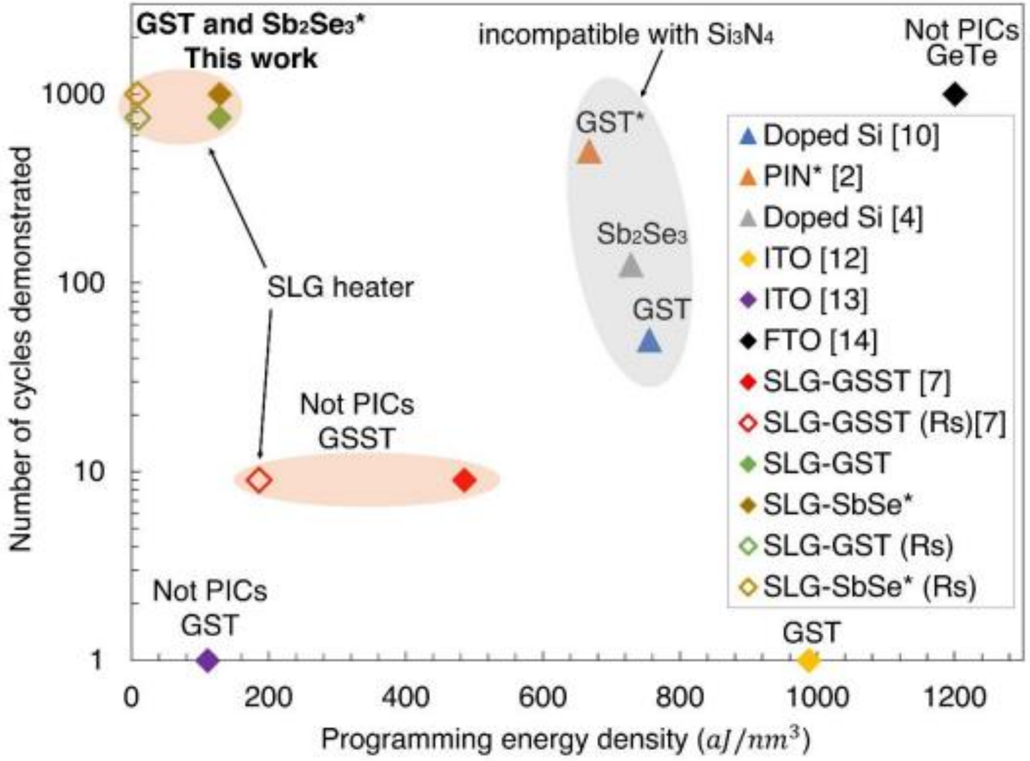

Fang, Z., *et al. Nat. Nanotechnol.* **17**, 842–848 (2022)

PCM switching energy:
- Typically >100 aJ/nm^3
- For a metasurface of 400nm thickness this means:

Energy required:
E_{PCM} = 40 nJ / μm^2 = 4 J/cm^2
This energy is typically applied on a short time scale of 100-1000ns

P_{peak} = 40 mW / μm^2 = 4 MW/cm^2

Can be done easily

Not easy in single-shot

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Programmable photonics & sustainability

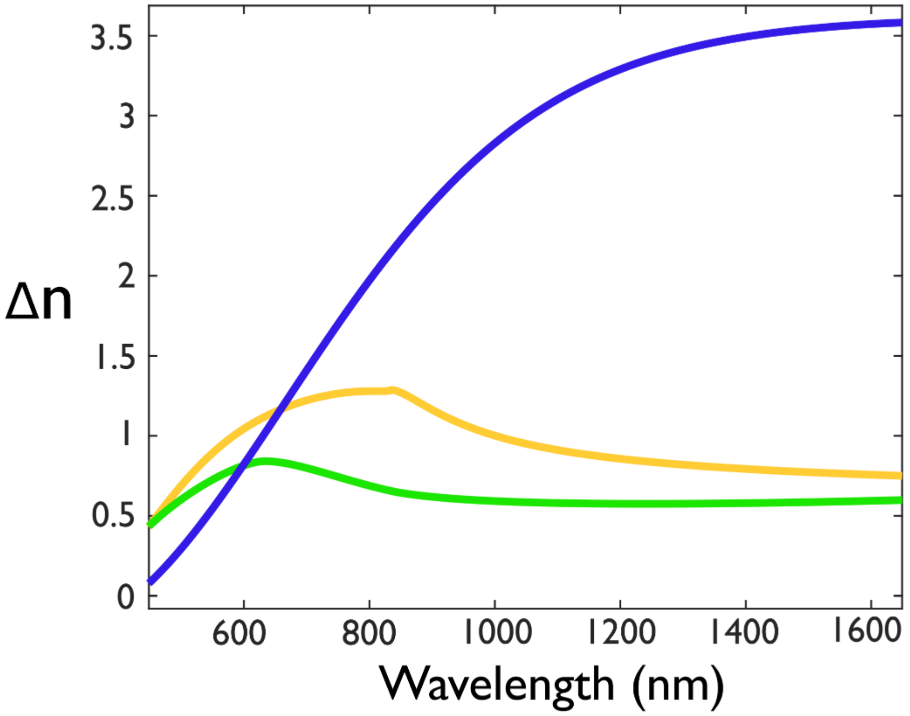
Non-volatile PCMs could be competitive for low-energy programmable photonics compared to volatile technologies:

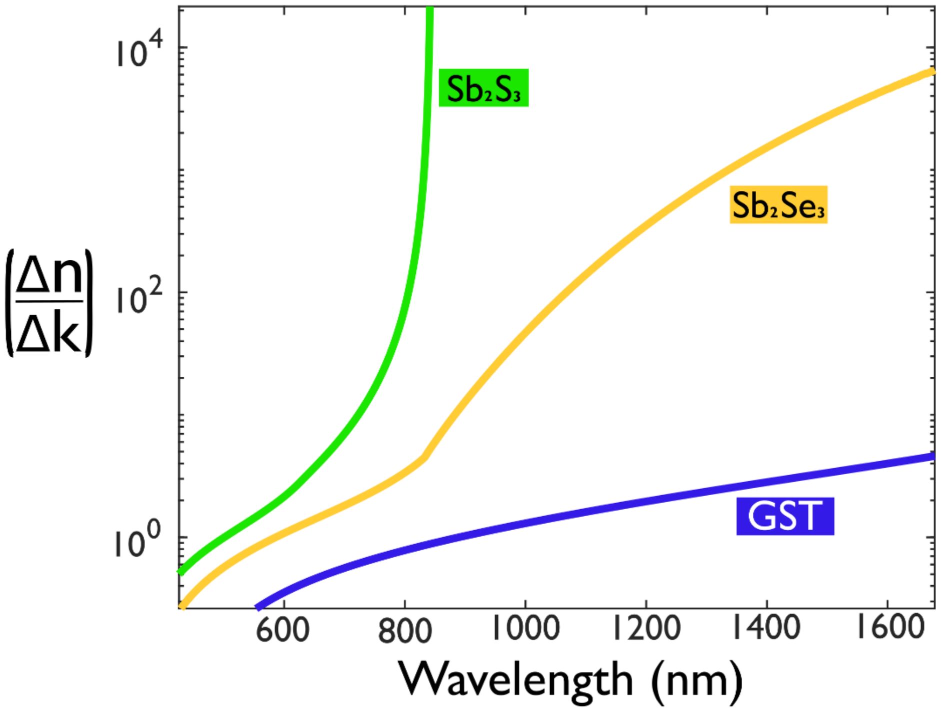
- For applications that require a relatively low rate of changes (defined by write energy < non-volatile retention energy)
- If we can demonstrate good switching of thicker (100s of nm) layers
- Sufficient durability for cycling $>10^6$ (?) cycles
- Thermal stability acceptable for the application

Fang, Z., *et al. Nat. Nanotechnol.* **17**, 842–848 (2022)

Optical switching using Phase change materials

- Antimonide PCMs have a higher Figure of Merit than GST





Sb_2S_3: Dong, W., Simpson, R.E. et al. *Adv. Funct. Mater.* 29, 1806181 (2019)

Sb_2Se_3: Delaney, M., Zeimpekis, I., Lawson, D., Hewak, D. W., Muskens, O. L., *Adv. Funct. Mater.* 2020, 30, 2002447.

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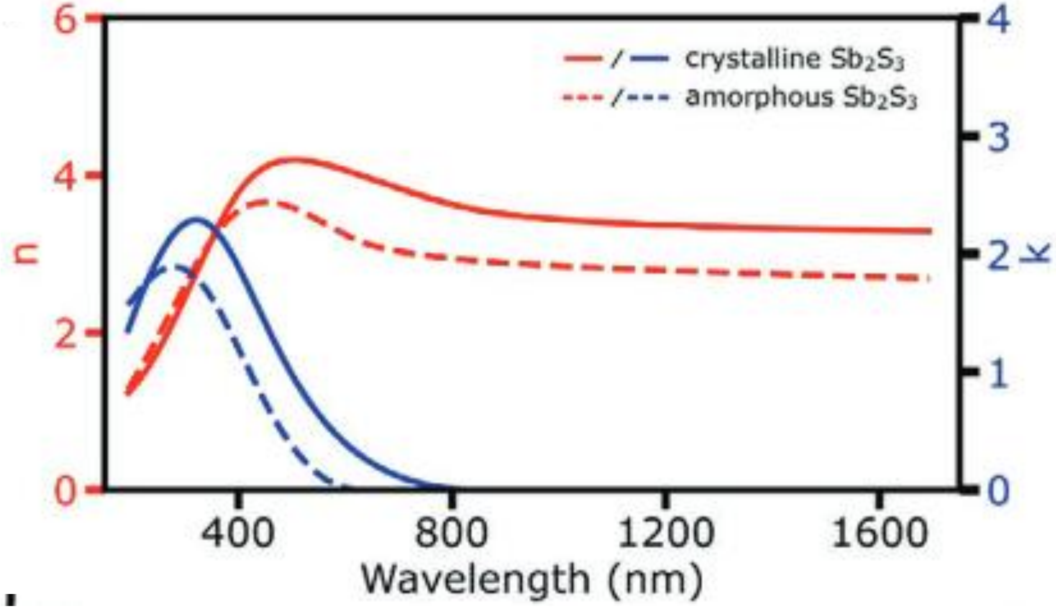
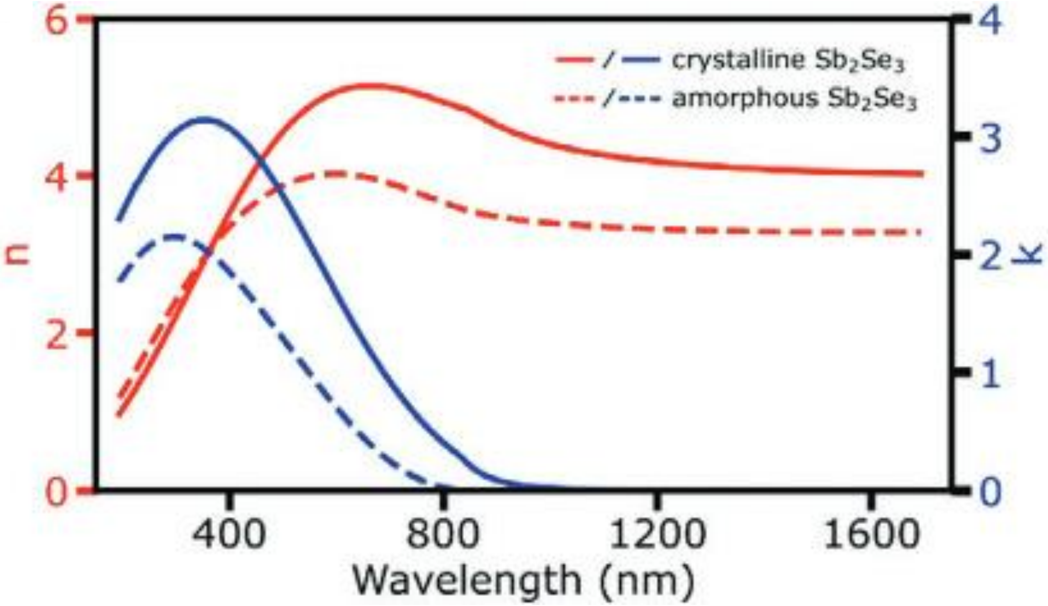
Optical switching using PCMs: Ellipsometry results

- Ultralow optical losses k<10^{-5} in telecom range (1550nm)





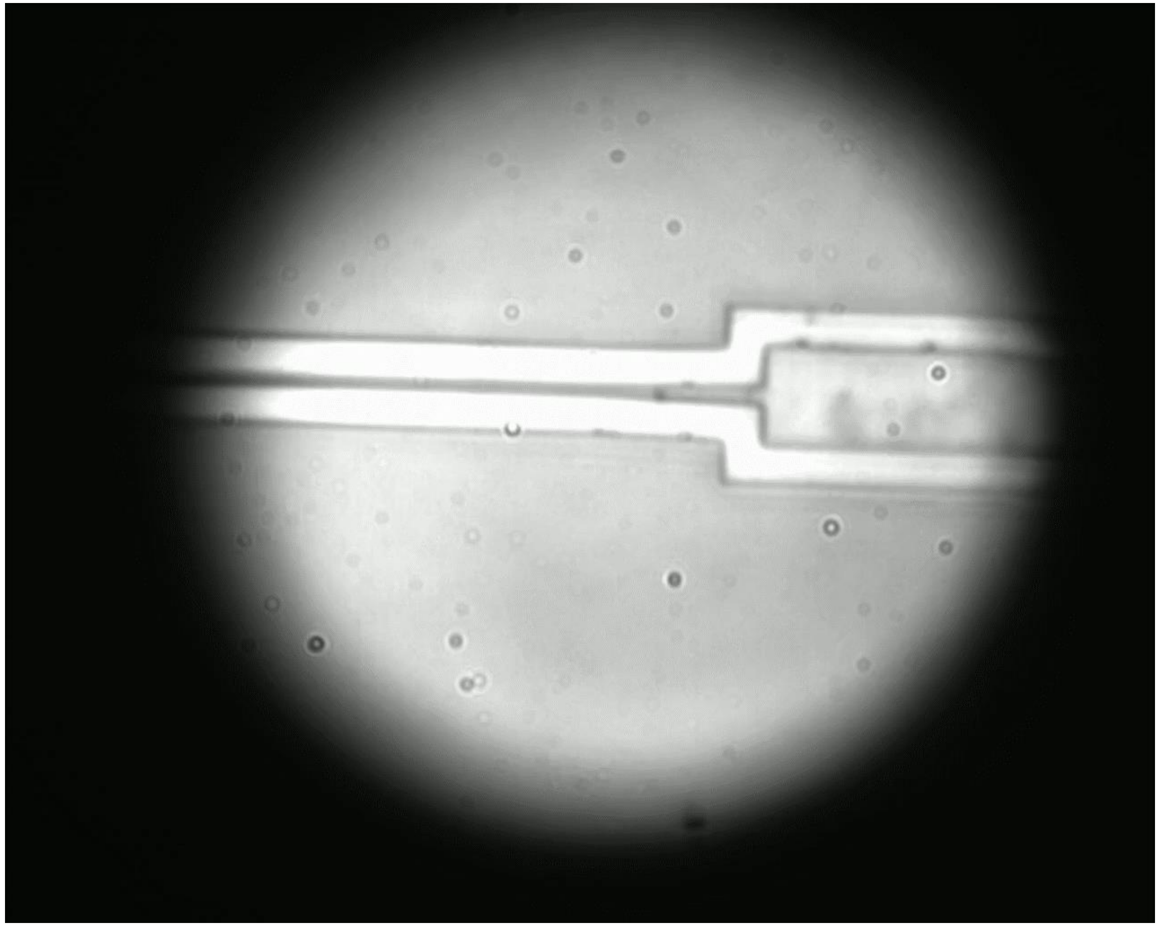
		$\lambda = 633$ nm	$\lambda = 800$ nm	$\lambda = 1060$ nm	$\lambda = 1310$ nm	$\lambda = 1550$ nm
Sb_2S_3	Amorphous	$3.148 + 0i$	$2.943 + 0i$	$2.829 + 0i$	$2.767 + 0i$	$2.712 + 0i$
	Crystalline	$3.989 + 0.276i$	$3.630 + 0.008i$	$3.413 + 0i$	$3.343 + 0i$	$3.308 + 0i$
Sb_2Se_3	Amorphous	$4.013 + 0.532i$	$3.660 + 0.028i$	$3.372 + 0i$	$3.305 + 0i$	$3.285 + 0i$
	Crystalline	$5.132 + 1.403i$	$4.939 + 0.402i$	$4.313 + 0.010i$	$4.121 + 0.001i$	$4.050 + 0i$

Delaney, M., Zeimpekis, I., Lawson, D., Hewak, D. W., Muskens, O. L., Adv. Funct. Mater. 2020, 30, 2002447.

Programmable silicon photonics using Sb_2Se_3

Optical switching of Multimode interference (MMI) device

- Precise 2D control of individual pixels on a MMI was achieved
- Pixels can be set and reset in complex patterns



Delaney et al., Science Advances 7, eabg3500 (2021)

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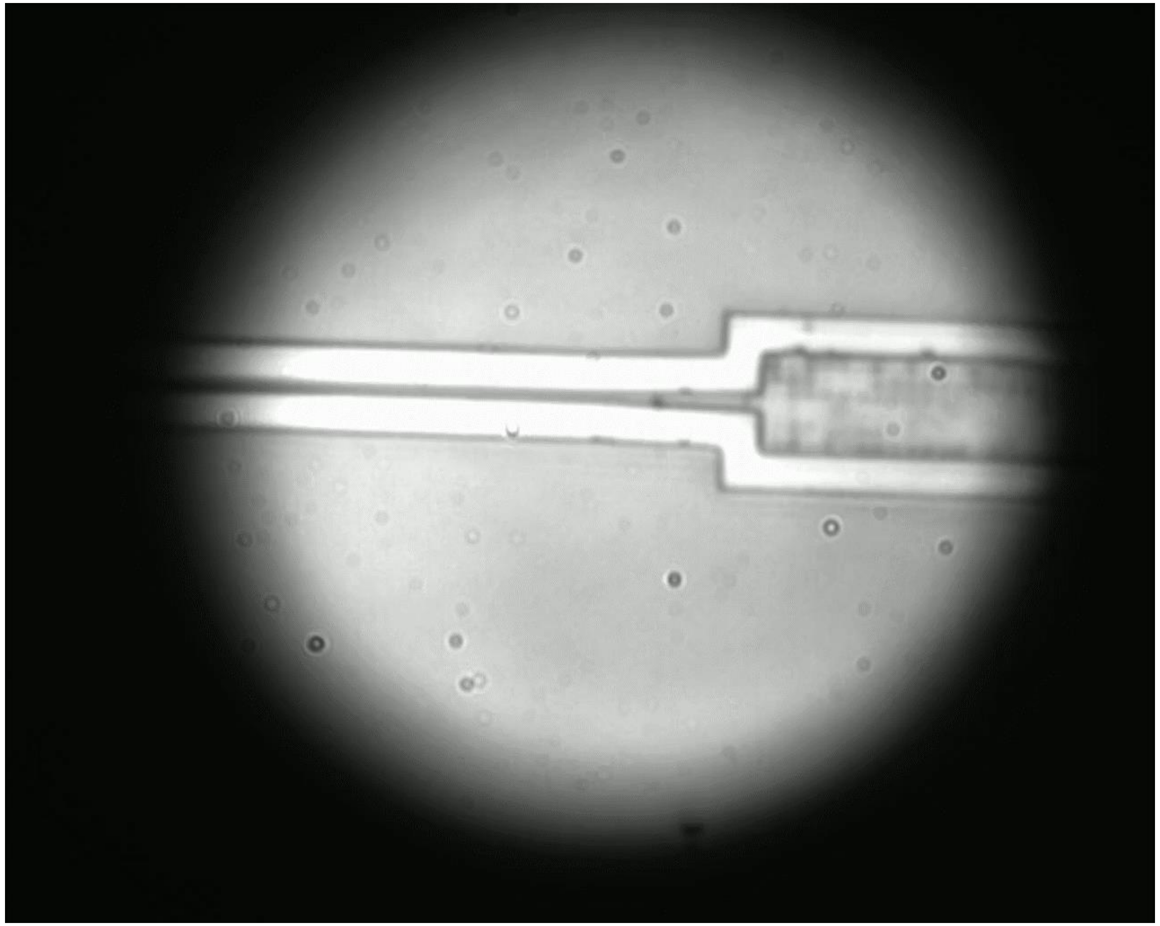
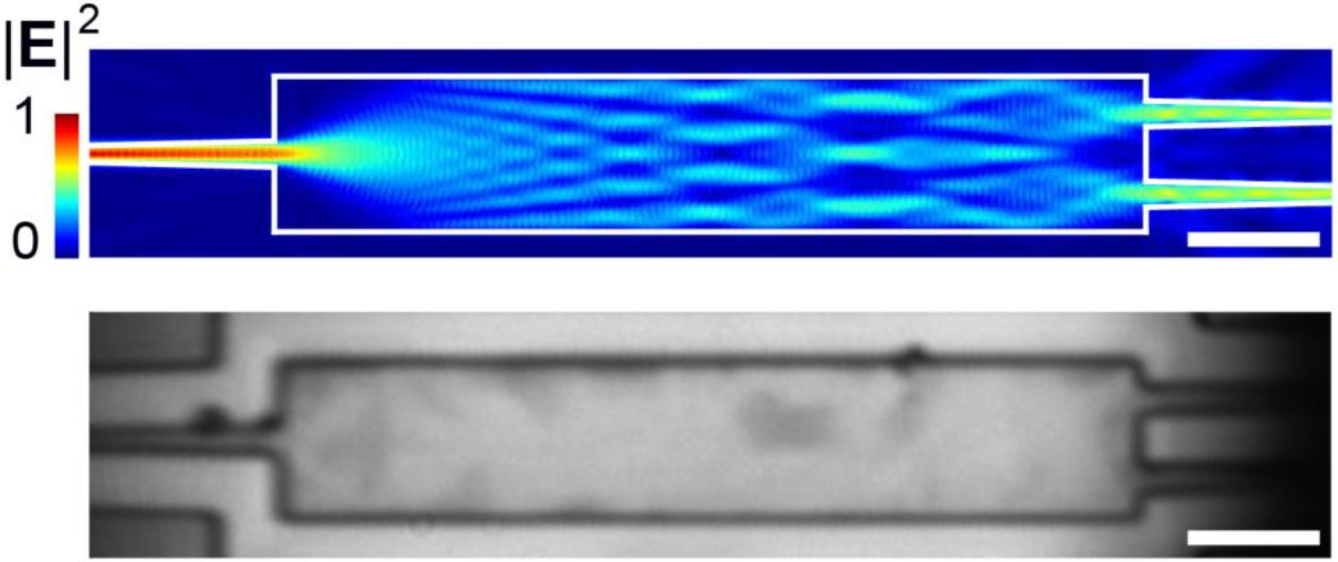


Delaney et al., Science Advances 7, eabg3500 (2021)

Programmable silicon photonics using Sb_2Se_3

Optical switching of Multimode interference (MMI) device

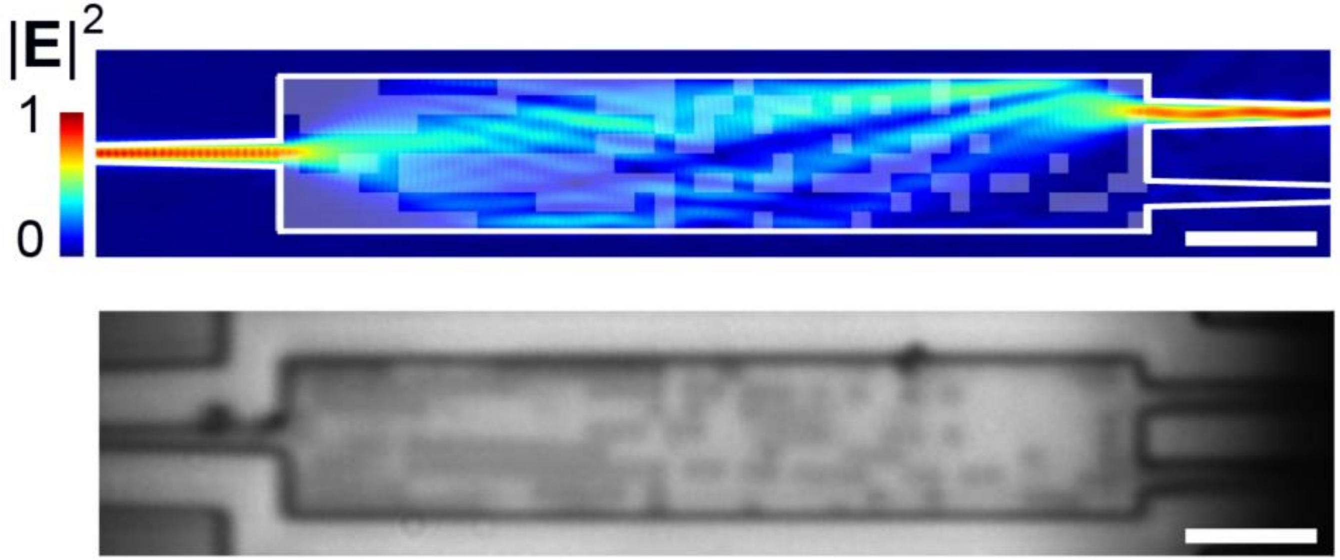
- Unperturbed device acts as a 50:50 power splitter



Programmable silicon photonics using Sb_2Se_3

Optical switching of Multimode interference (MMI) device

- Unperturbed device acts as a 50:50 power splitter
- Patterned device acts as a 92%:8% power splitter



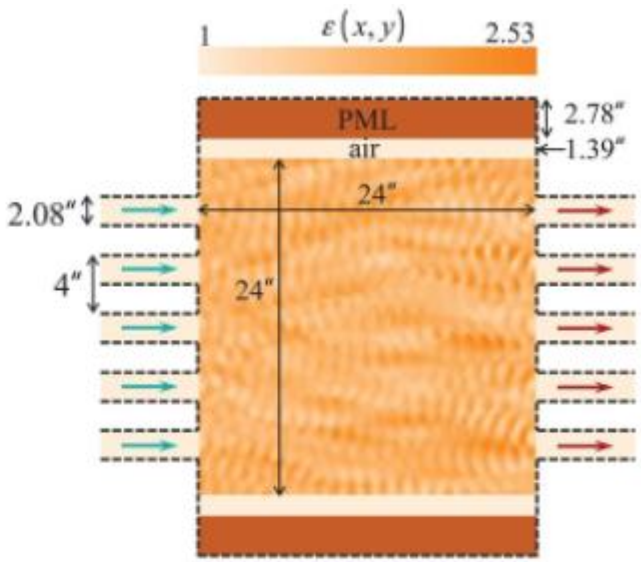
Programmable silicon photonics using Sb_2Se_3

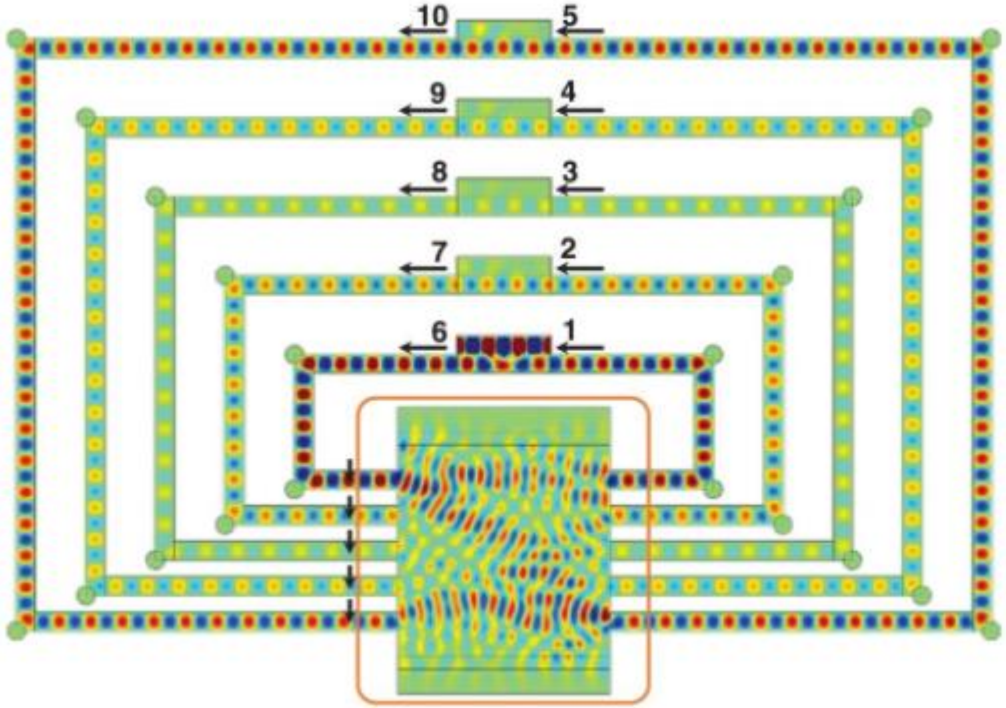
Is it a metamaterial?

Inverse-designed metastructures that solve equations

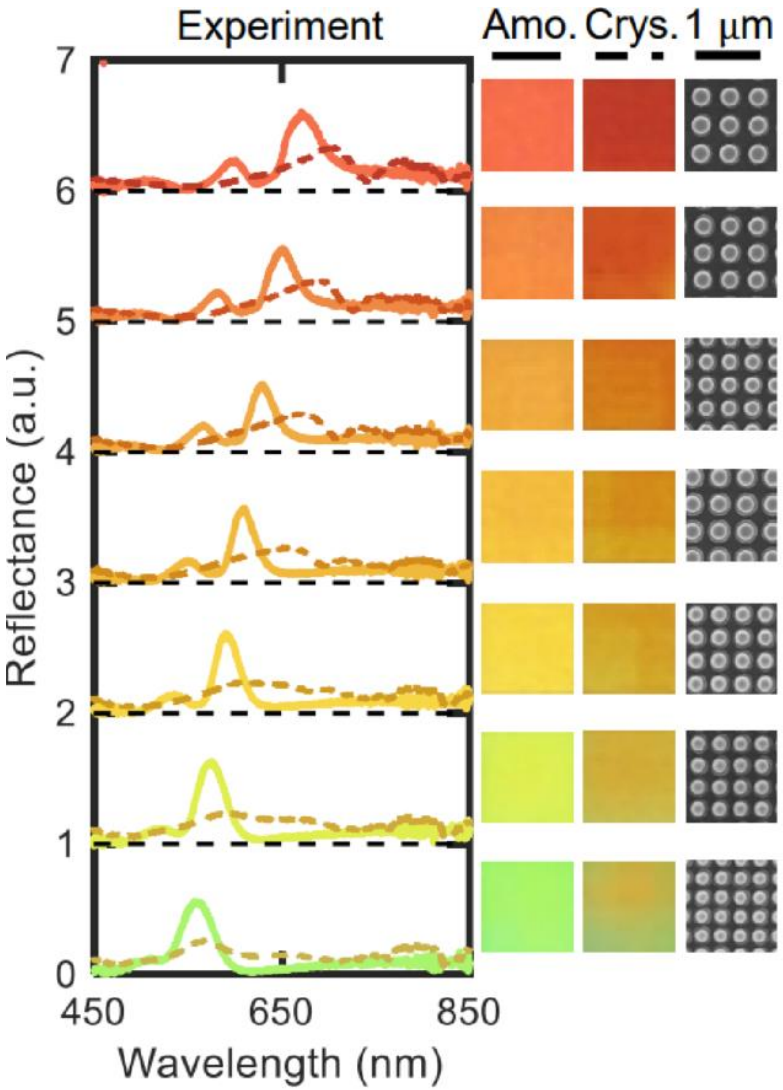
NASIM MOHAMMADI ESTAKHRI , BRIAN EDWARDS , AND , NADER ENGHETA   Authors Info & Affiliations

SCIENCE · 22 Mar 2019 · Vol 363, Issue 6433 · pp. 1333-1338 · DOI: 10.1126/science.aaw2498

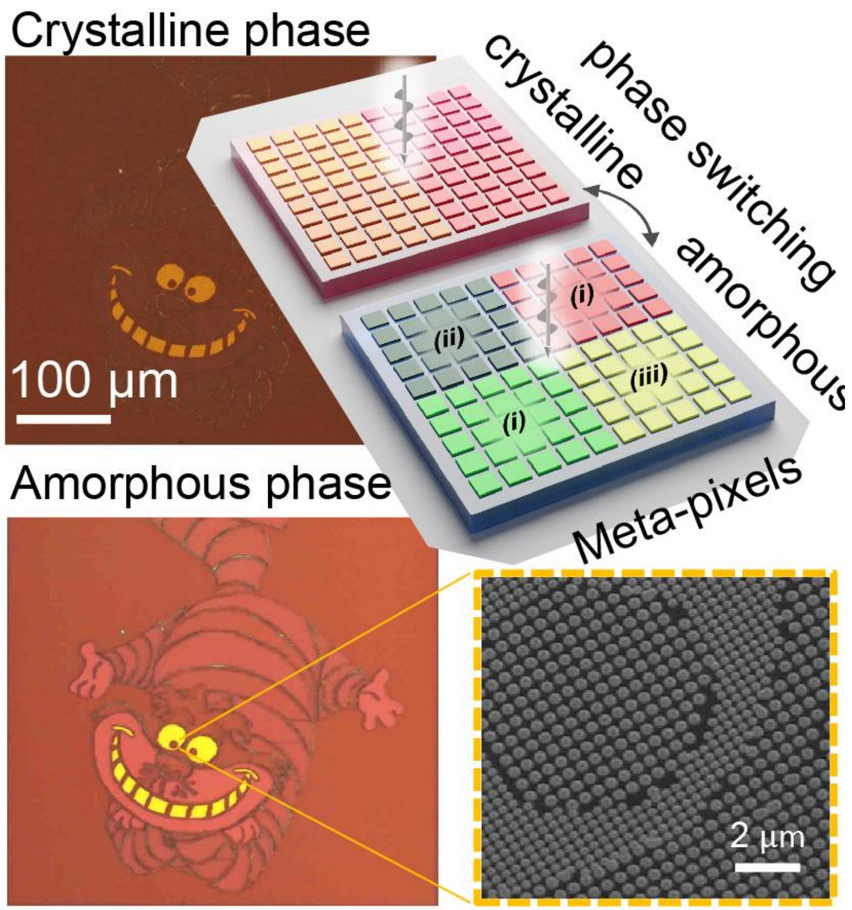




Programmable metasurface structural color using Sb-based PCMs



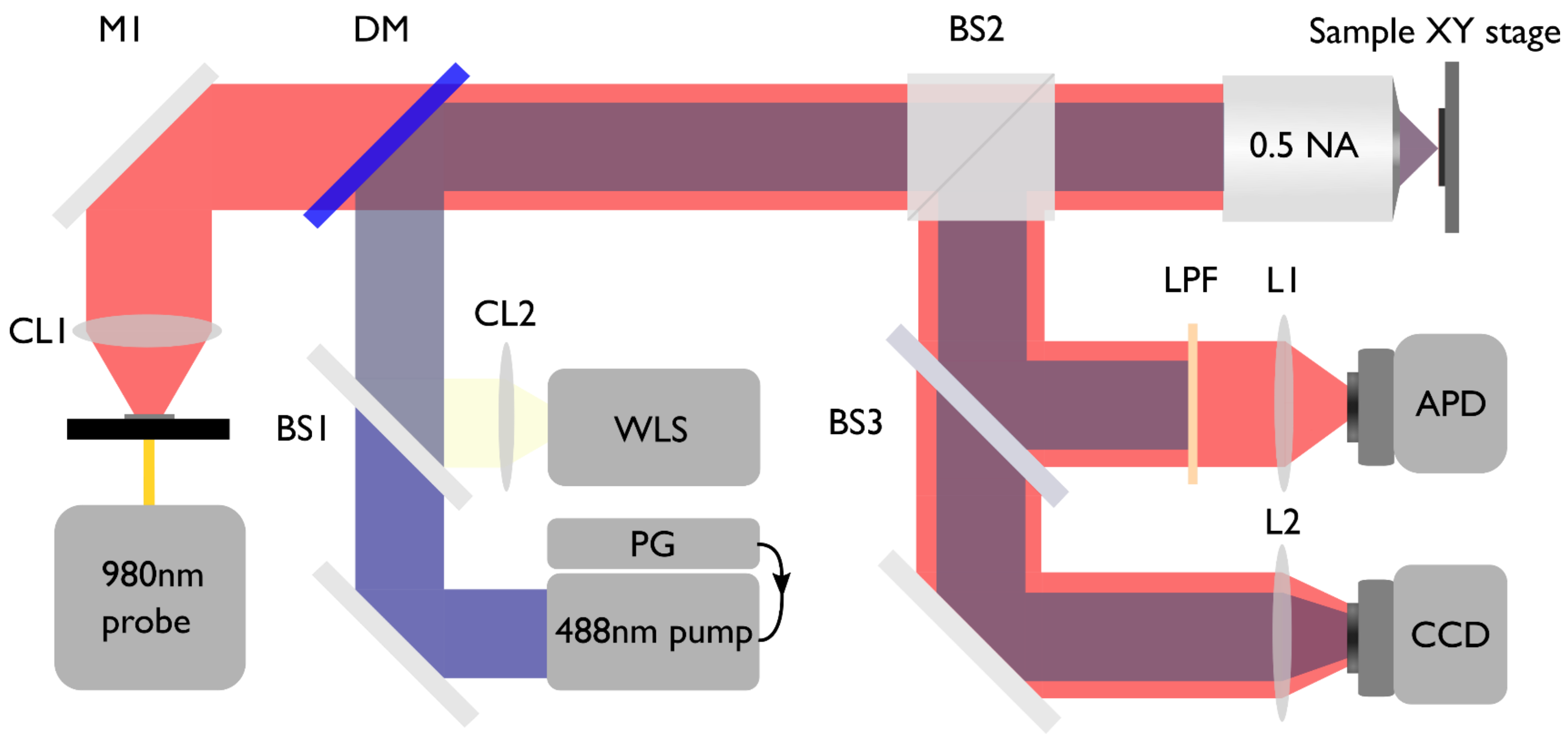
Ali Abidi Group, Georgia Tech.

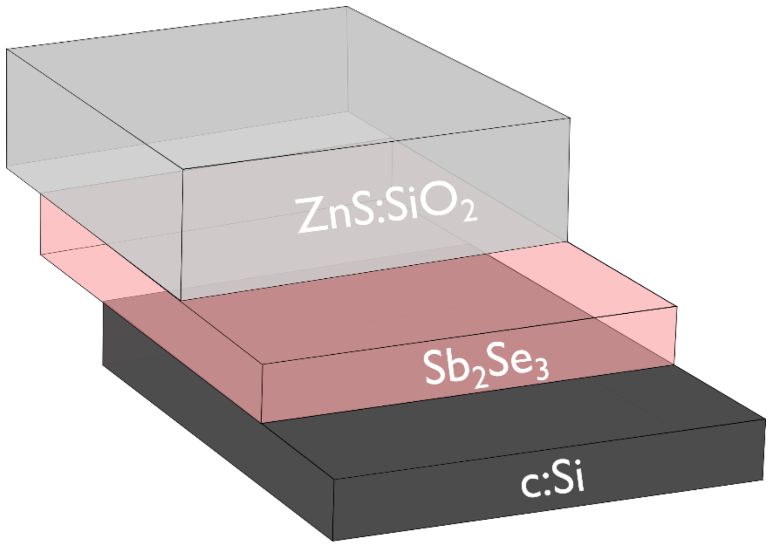


O Hemmatyar et al., arXiv:2107.12159

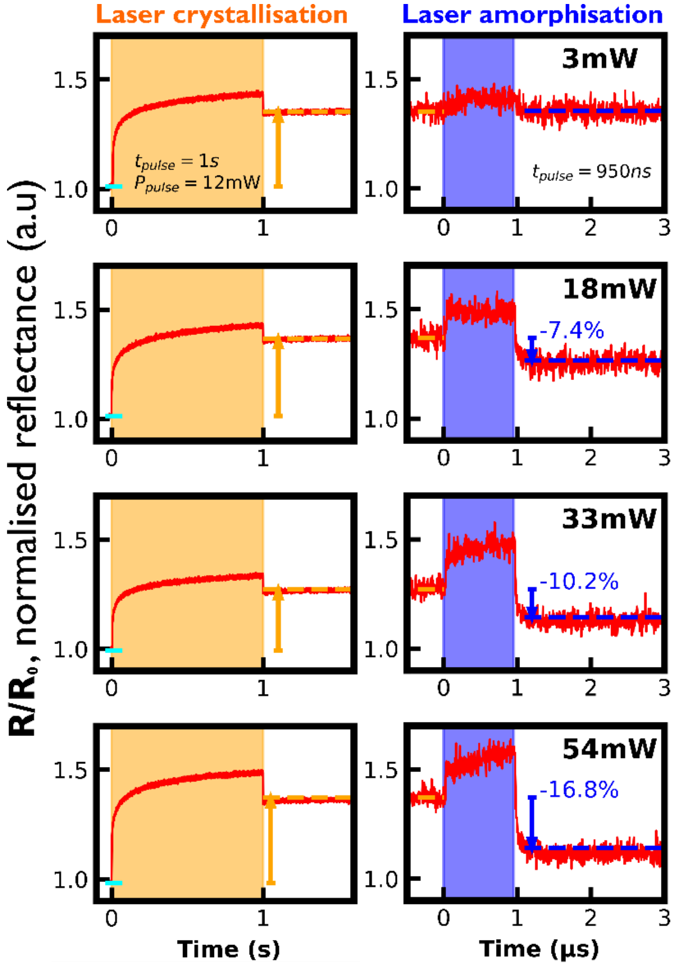
University of Southampton

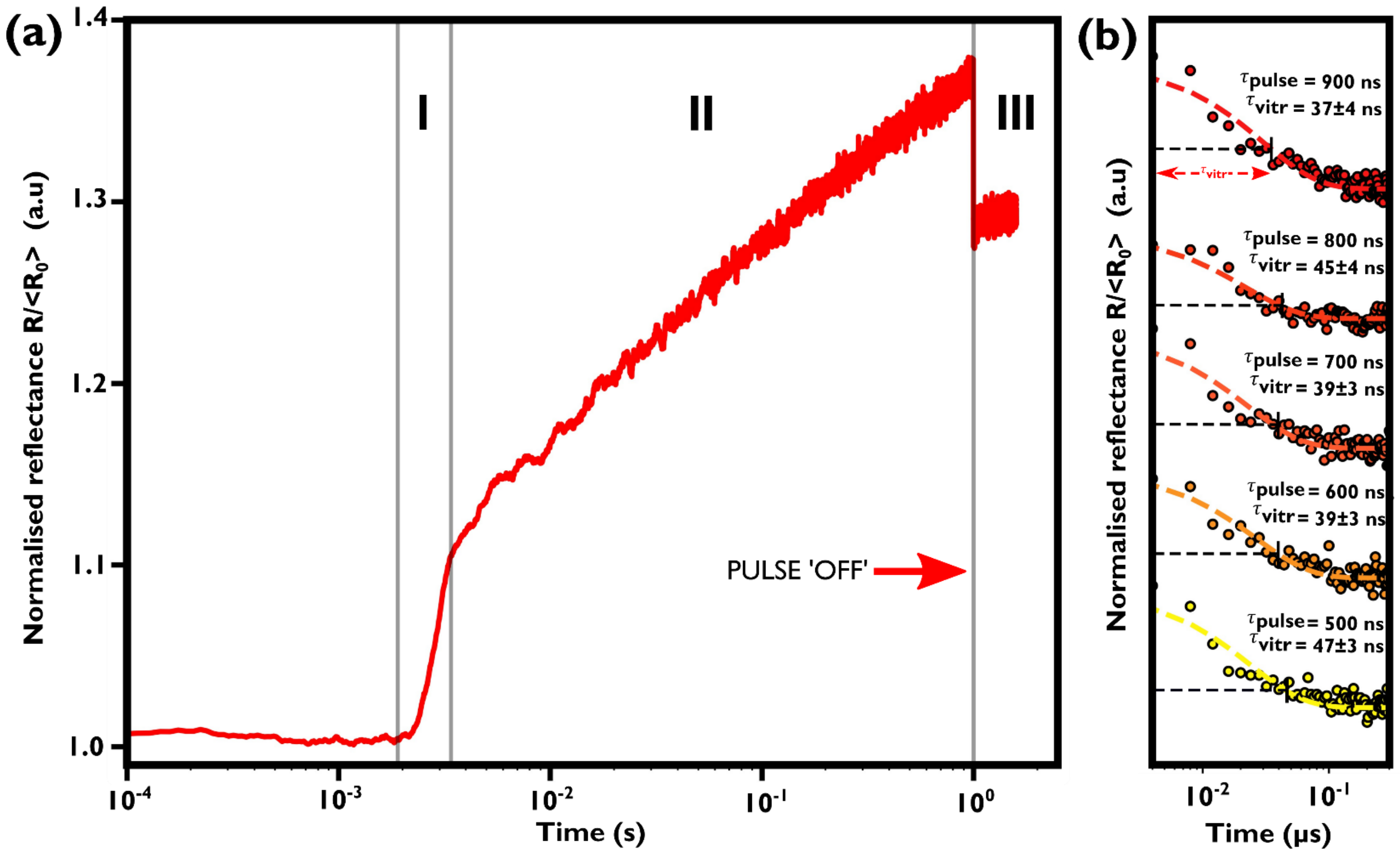
Probing the phase transitions in Sb_2Se_3





Time-resolved optical switching measurements of 20nm Sb_2Se_3





D. Lawson et al, *J. Opt.* 24 064013 (2022)

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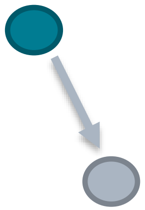
Switching of thicker Sb_2Se_3 layers

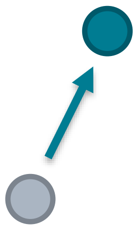


Amorphisation pulse

Pulse length: 10 ns – 100 µs

Pulse power: 4 mW – 60 mW

Aim: Sweep pulse parameters to establish window for reversible switching

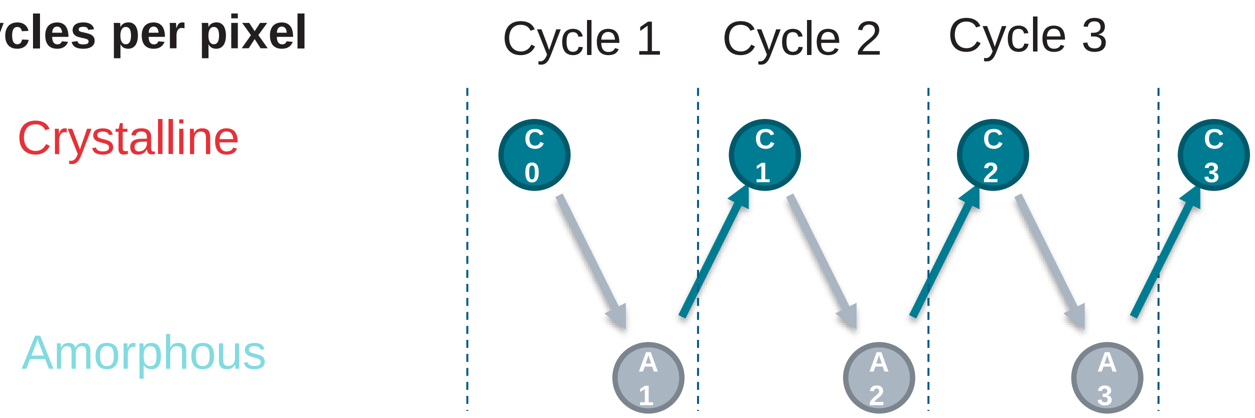


Crystallisation pulse

Pulse length: 1 second
Pulse power: 1mW

Aim: Reset to crystalline state without causing damage

Three Cycles per pixel

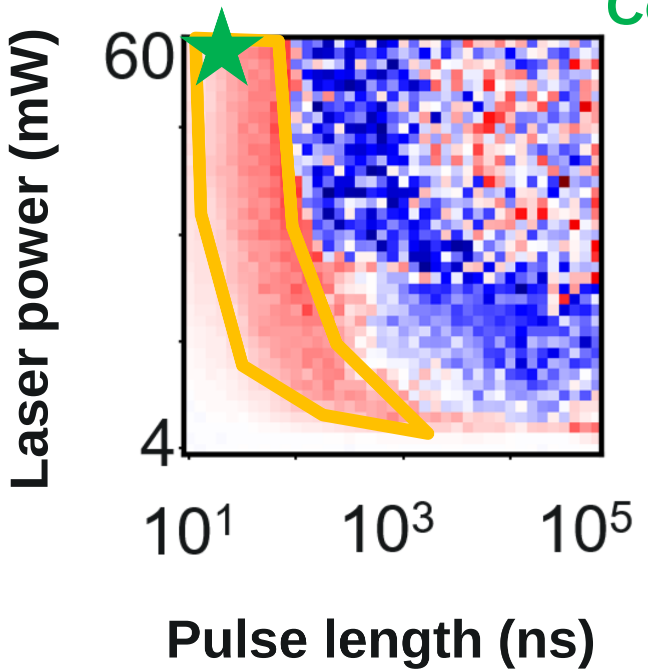


Aim: Identify the initial burn-in and instantaneous damage effects from lack of cyclability

Switching of thicker Sb_2Se_3 layers

Sb_2Se_3 thickness 400nm

Amorphization map

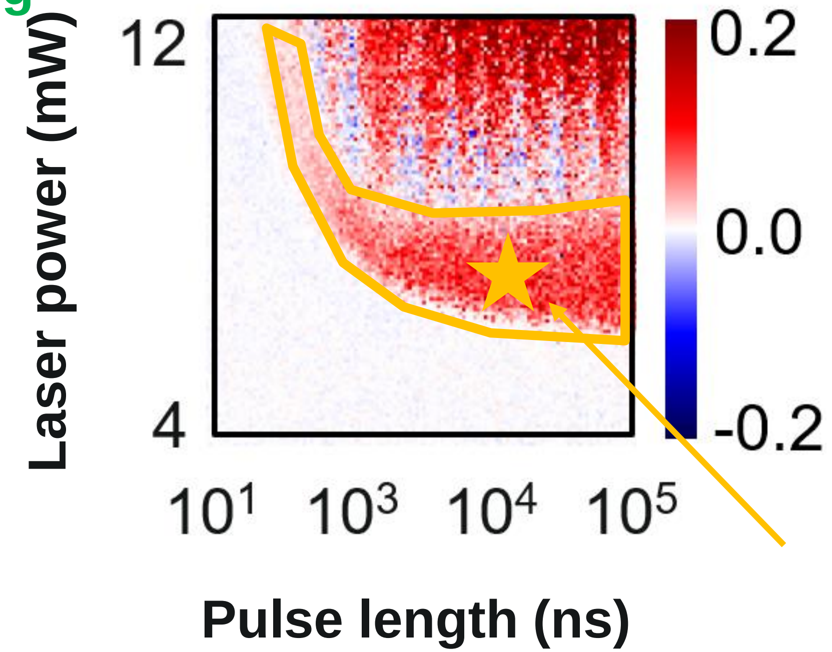


Constant setting

P_{amo} = 60 mW

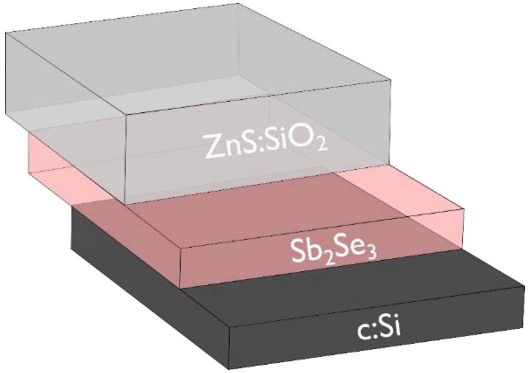
T_{amo} = 50 ns

Crystallization map



80 nm Sb_2Se_3

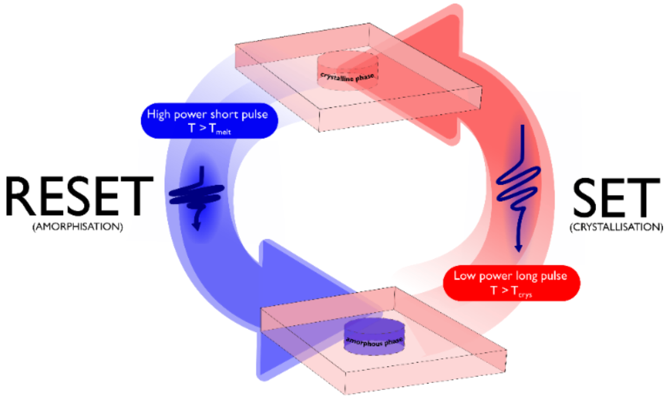
170 nm $ZnS:SiO_2$

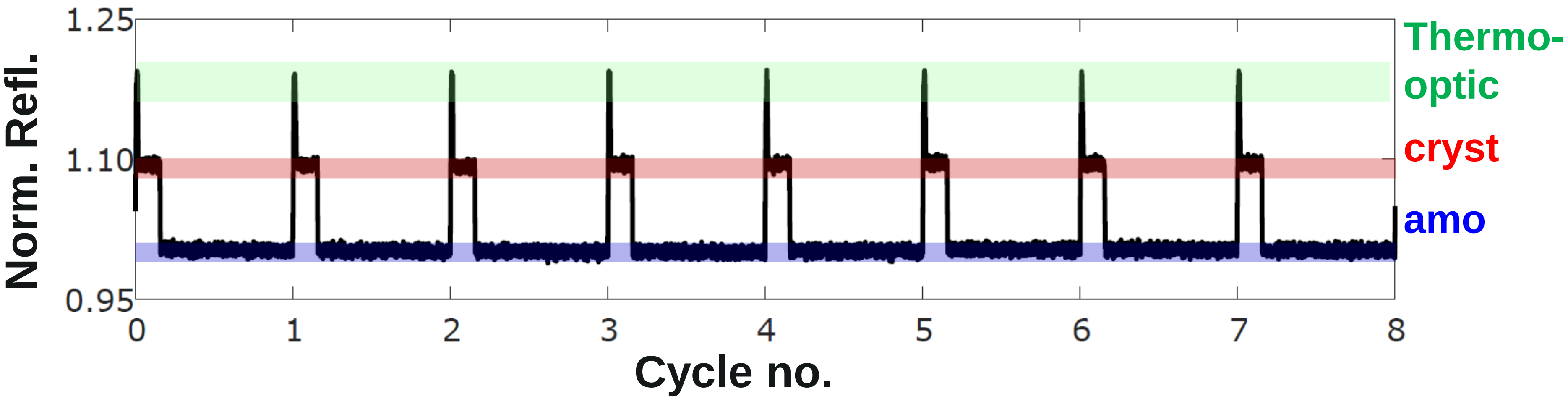


Selected crystallization 'Sweet spot'

P_{cry}=6mW, T_{cry}=12µs

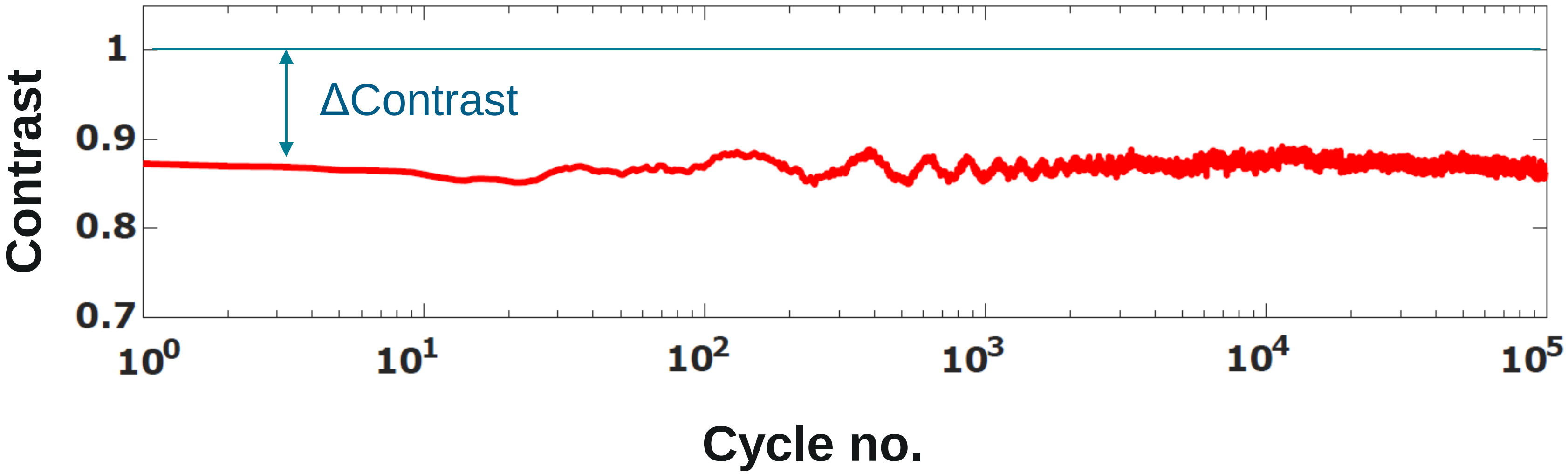
Cycling at 1KHz – 400nm thick Sb_2Se_3 layer



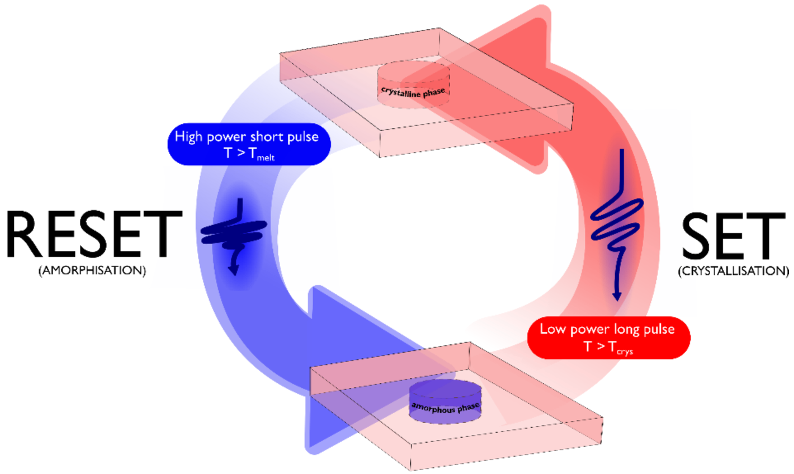


1 Crystallisation pulse:
6mW, 12µs

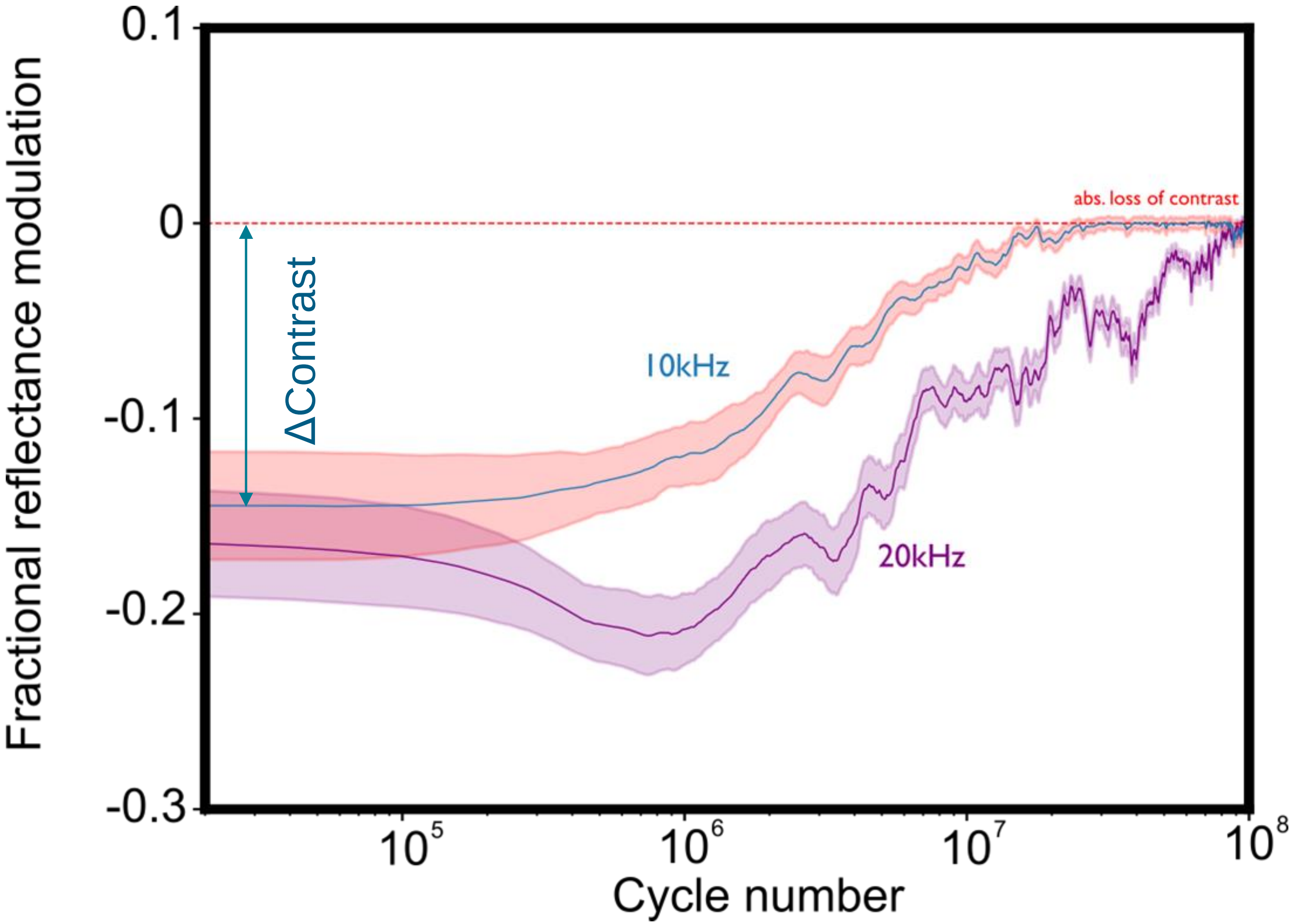
2 Amorphisation pulse:
60mW, 50ns



Driving at 10KHz – faster crystallisation of laser-written glass regions



Around 10^6 cycles reversible switching demonstrated for Sb_2Se_3

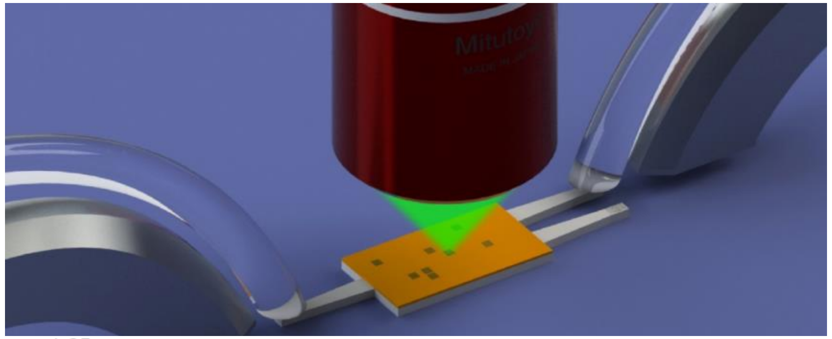


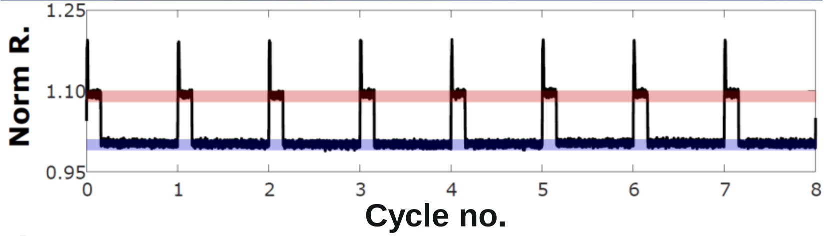
Conclusions

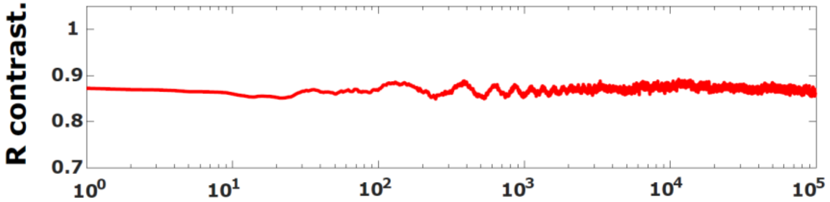
- Introduced Sb_2Se_3 as new optical PCM

- Demonstration of programmable photonics using Sb_2Se_3

- Optical switching of thick (400nm) Sb_2Se_3 films with $>10^6$ cycles







Delaney et al., Adv. Funct. Mater. 2002447 (2020)

Delaney et al., Science Adv 7, eabg3500 (2021)

Lawson et al., J. Opt. 24, 064013 (2022)