National Aeronautics and Space Administration

Advancing metasurfaces towards new frontiers: nonvolatile reconfigurable optics

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LINCOLN LABORATORY
UNIVERSITY OF CAMBRIDGE
Booz Allen

Why is NASA researching reconfigurable metasurfaces?

- “Cutting edge innovations by NASA leaderships seek to refine **scientific instrument into smaller, lighter, more versatile** tools for exploration” – *Karl Hille, chief technologist at NASA’s GSFC*

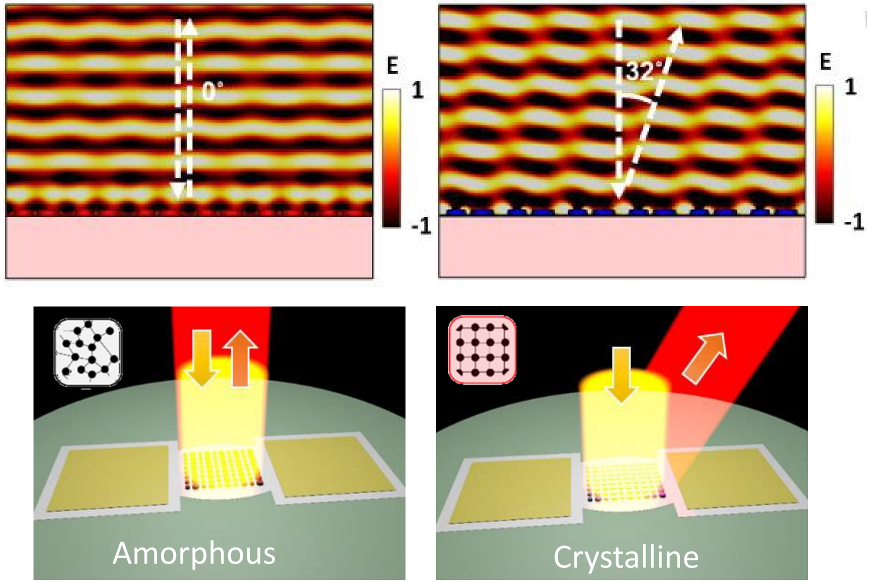
- “**Metasurface optic** technologies are important because of the **precision and versatility** that is offers to LiDAR” – *Cheryl Gramling, assistant chief for technology at GSFC*

- “As recently displayed by the stunning images from the JWST, we often rely on recording the intensity of light (e.g., with a camera) to study the universe. …Metasurfaces enable general manipulations of phase, amplitude, and polarization on the nanoscale, thereby providing **ample opportunity** ….and even **enable functionality not possible using conventional technologies** - *Tobias Wenger, researcher at JPL*

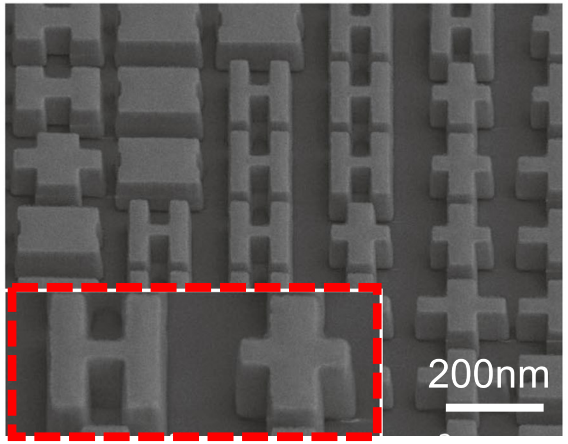
- … “NASA scientists are on the cusp of revolutionizing LEO Earth Observing platforms using novel optical **metamaterials to reduce the size, weight and power (SWaP) of existing architectures**."
  – *Williams Humphreys, chief engineer at LaRC*

- **Metamaterials** are man-made (synthesized) composite materials whose electromagnetic, acoustic, optical, etc. properties are determined by their constitutive structural materials and their configurations. In the field of electromagnetic research and beyond, metamaterials offer **excellent design flexibility with their customized properties and their tunability under external stimuli**

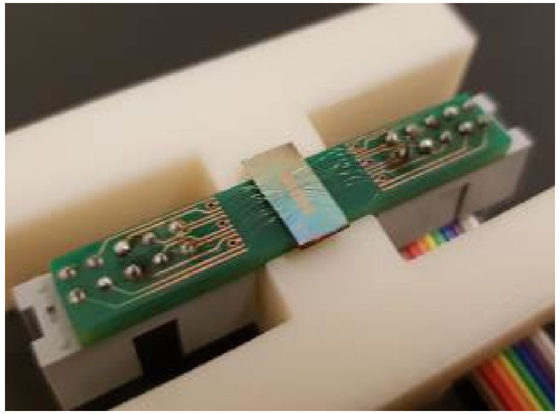
Reconfigurable metasurface optics at NASA LaRC



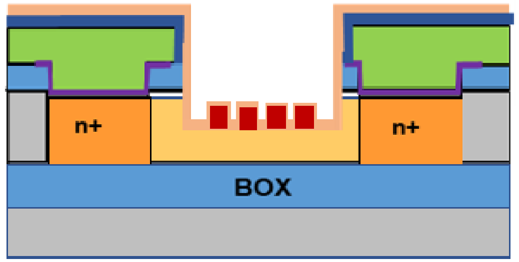
Nature Nano. 16(6), 1-6 (2021)



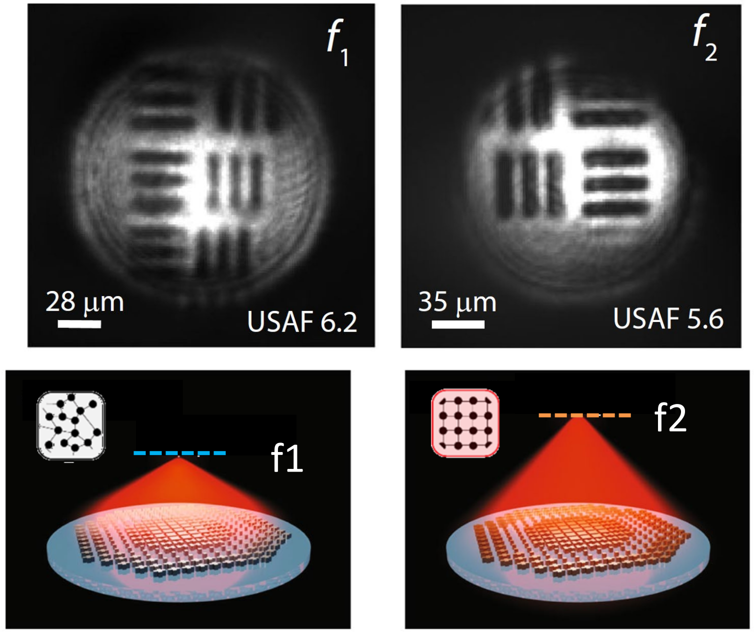
Nature Comm. 12, 1225 (2021)

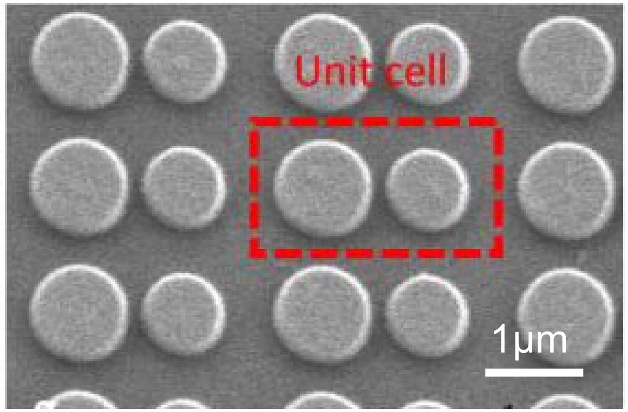


Metasurface pattering on PCM



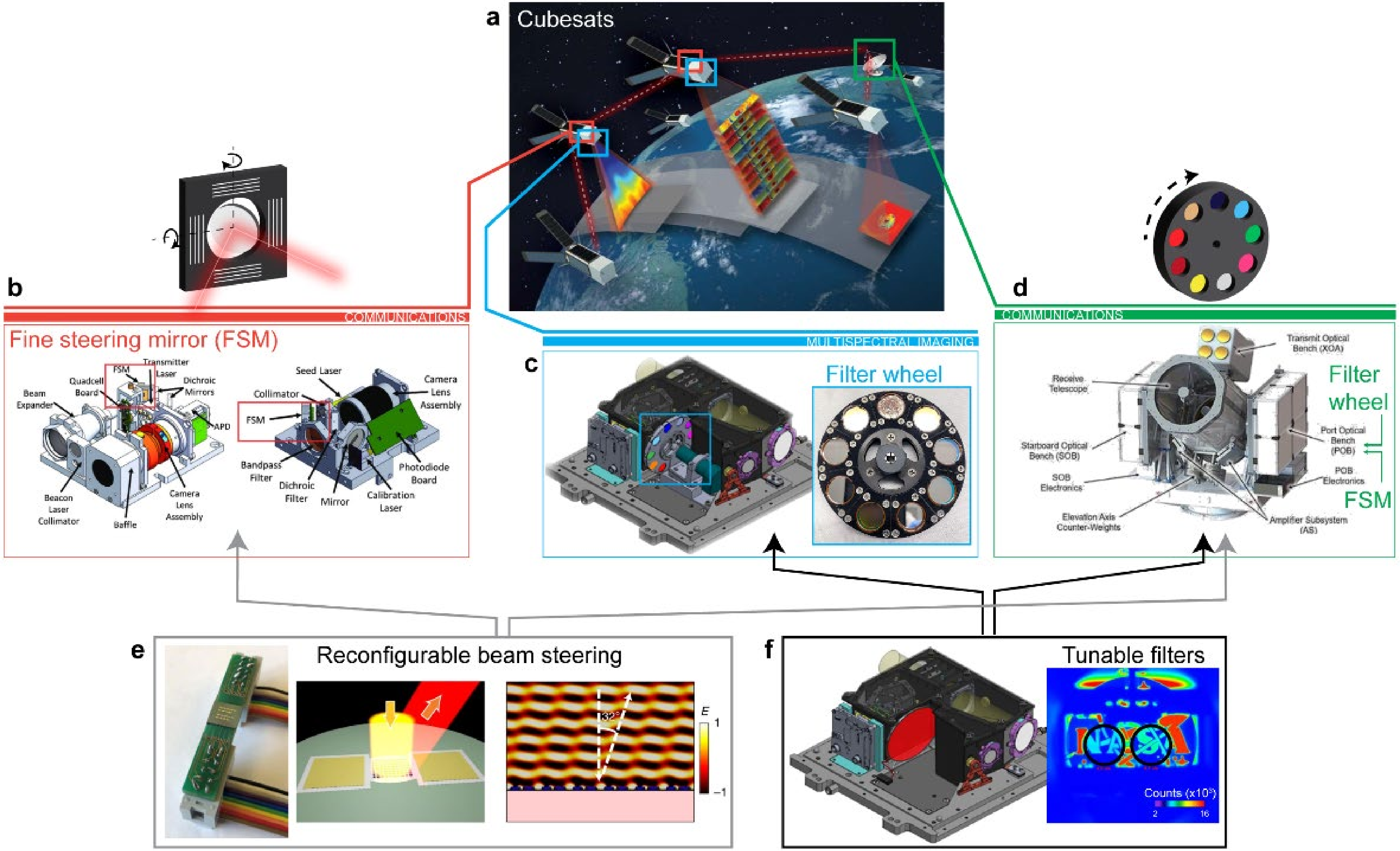
Nature Comm. 10, 4279 (2019)





Nature Nanotech. 16, 661 (2021)

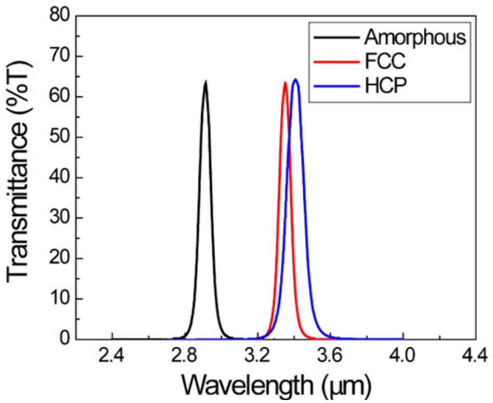
LaRC reconfigurable metasurfaces for spaceborne remote sensing



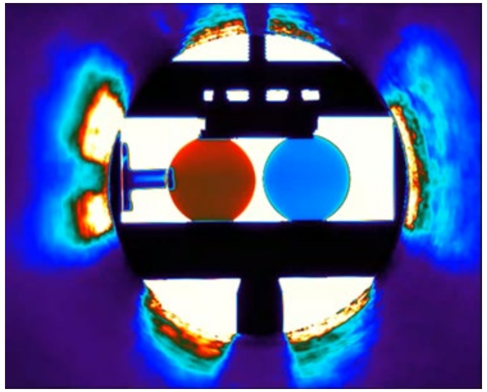
H. J. Kim et al., npj Microgravity (2024)

Technology Development Progress (H. J. Kim *et al.*)

P-ACTIVE tunability & gas sensing

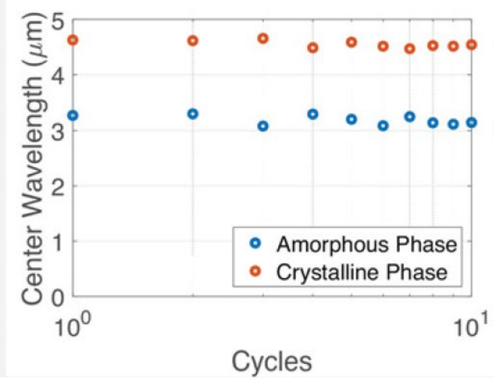


Optica **7**(7) 746 (2020)



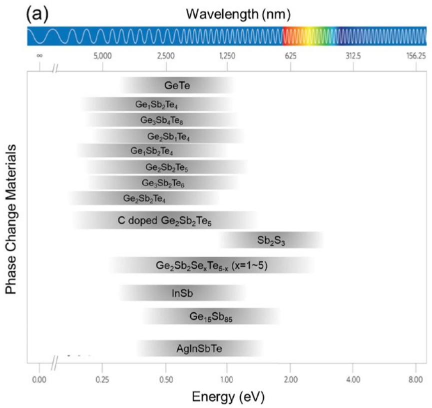
Optics Express **28**(7), 10583 (2020)

Reliability test



Optical Eng. **60**(8) (2020)

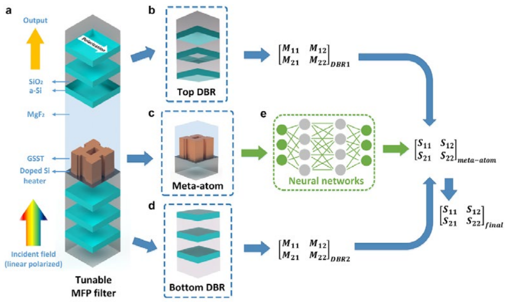
PCM-net database



J. Phys. Photo. **3**, 024008 (2021)

ACS, highlight (2022)

DNN design



Nanophotonics **11**(17), 4149 (2022)

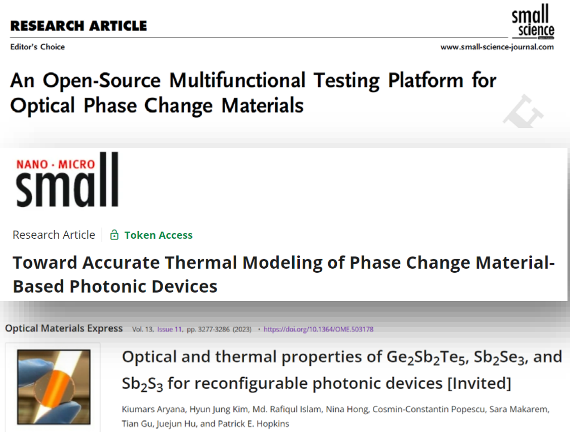
NASA ***TP-20220019141***(2022)

A Multi-Spectral Imaging Pyrometer Patent *Applica.(2022)*

Vision to sub-system

Nature Photonics ***17***(48) (2023)

2023 -



P-ACTIVE for NASA Missions

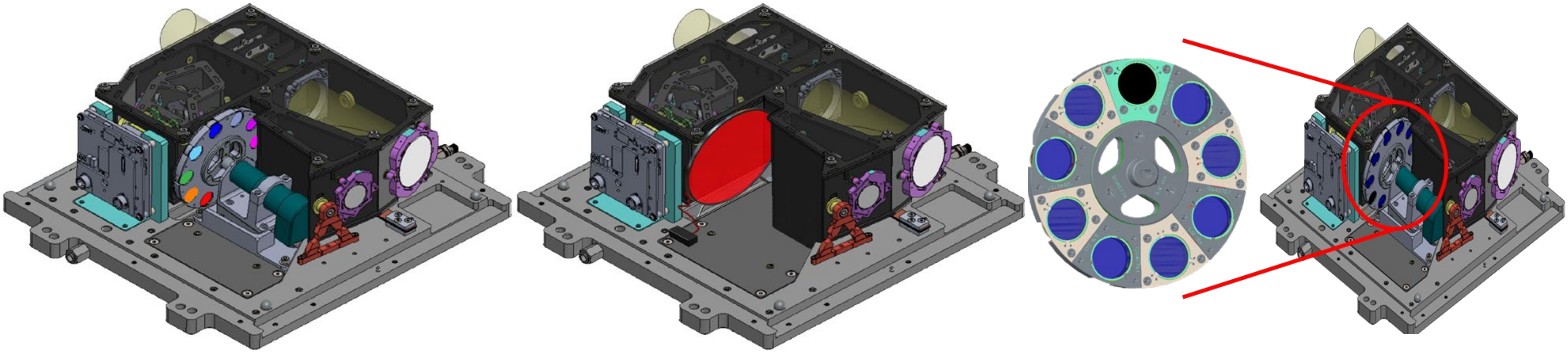
Optical filter wheels are critical components in a plethora of NASA Earth and space science missions, but come with several drawbacks

SCIFLI SLS project

- **Multispectral Performance for Artemis-I**
- **What if? Slow speed** (1500 rpm) limits the in-situ thermal monitoring? Emissivity variation increases the uncertainty?

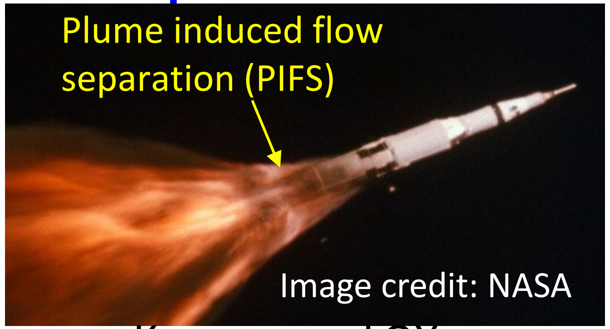
SAGE LIDAR mission

- SAGE (Stratospheric Aerosol and Gas Experiment)
- SAGE-IV: 1/10th the cost of SAGE-III in 6U CubeSat platform for Redeshare launches
- **What if? Filter wheel requires bulky optics and limited spectral tunability**



SWaP + No moving part + More WL tunability = More launch opportunity & More science information

Apollo Saturn V



Kerosene + LOX

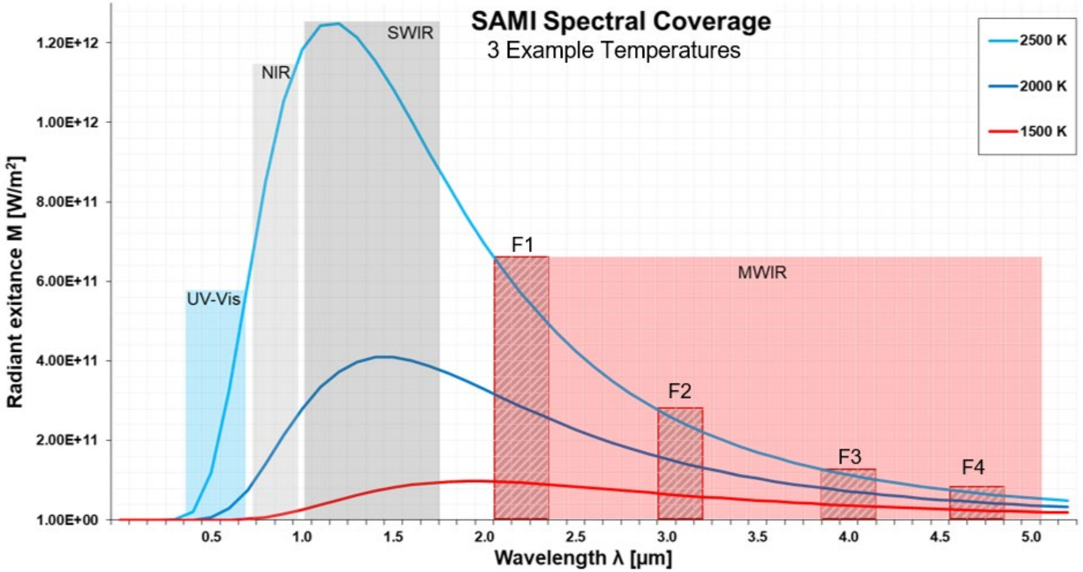
- Plume in VIS spectrum
- No temperature data

Artemis-I Program

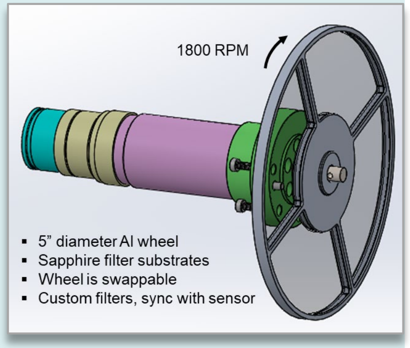
Hydrogen + LOX = H_2O

- Plume in MWIR spectrum
- Temperature retrieval possible

Optimal Wavebands to Meet All Imaging Objectives



- Broadband (2-5 μm):
  - high temp core stage surface data (2 μm) - PIFS imaging (5 μm)
  - Multispectral Imager for observation of plume features and hardbody thermal signatures in temperature retrieval
- Observation requirement of New Airborne Optical System



P-ACTIVE for **SCIFLI Airborne Multispectral Imager (SAMI)**

Extra information

Temporal

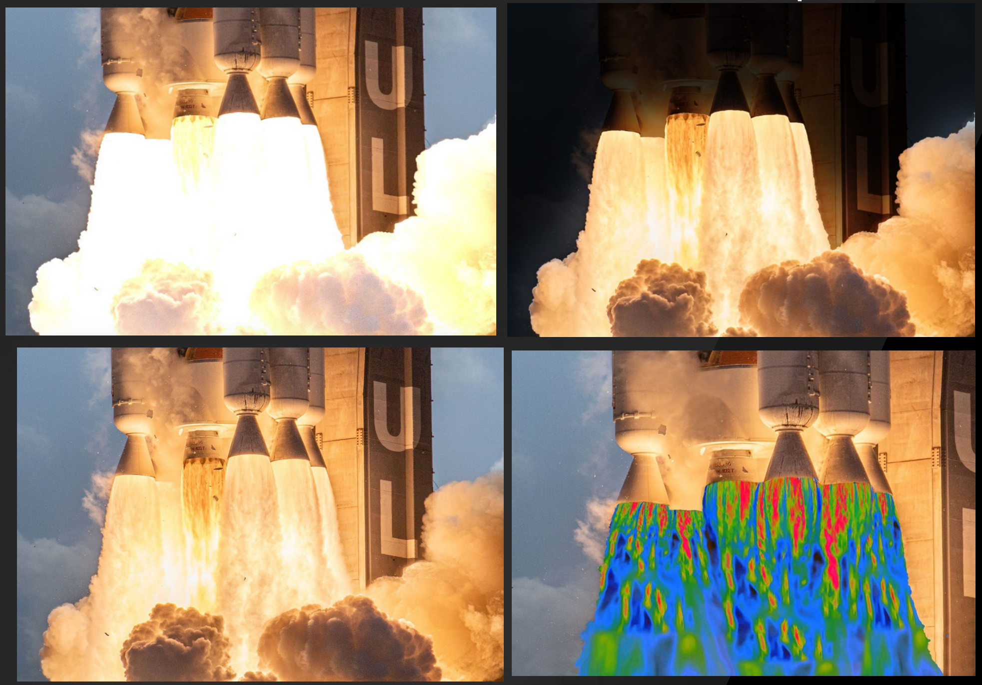
Spectral resolution

Accuracy improvement

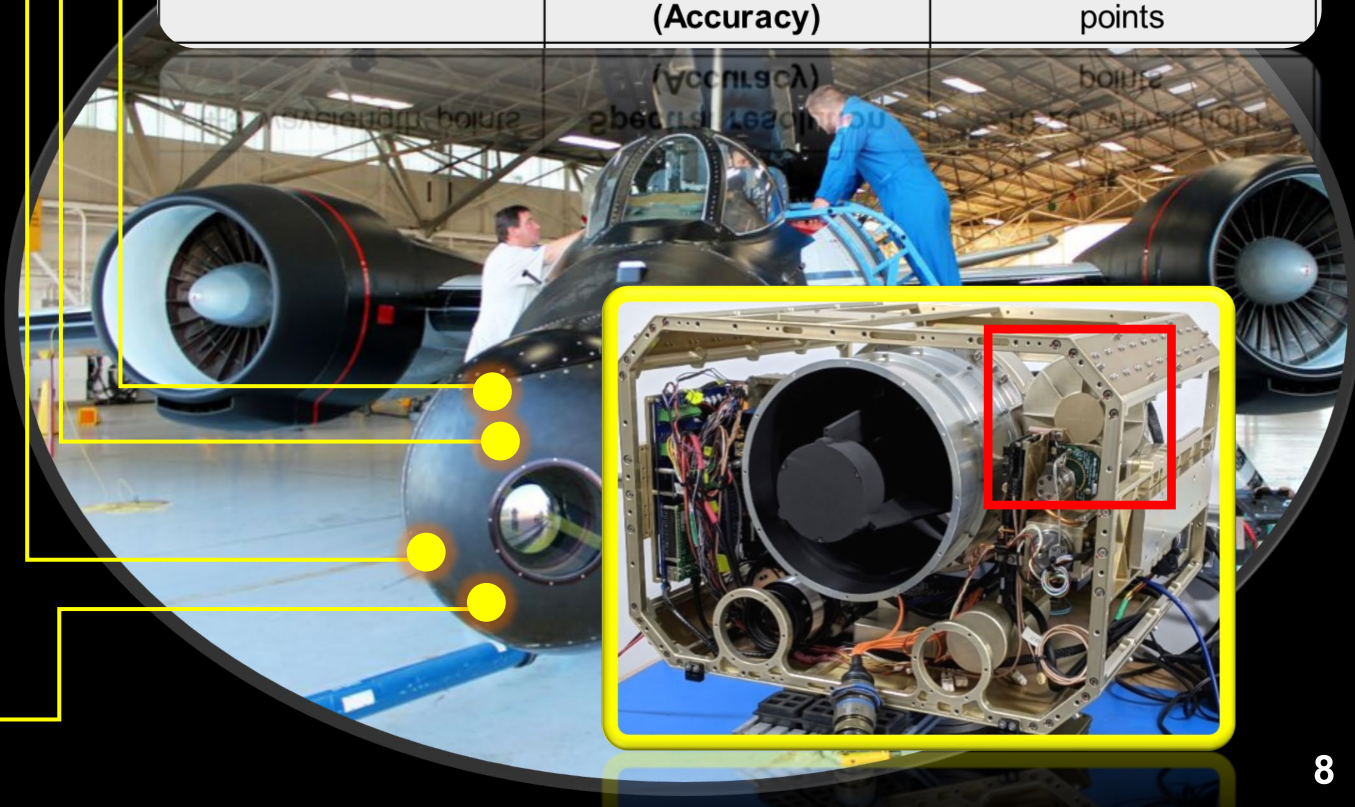
Independent emissivity

Image detail improvement

Dynamic range improvement



Filter wheel		P-ACTIVE filter
800g	**Weight**	10g
725cm^3	**Volume**	0.253cm^3
15W to power motor	**Power**	~mW average power to tune filter
10s of milliseconds (< kHz imaging)	**Temporal resolution (Speed)**	10s of nanoseconds (GHz imaging)
~4-5 wavelength points	**Spectral resolution (Accuracy)**	~10-20 wavelength points

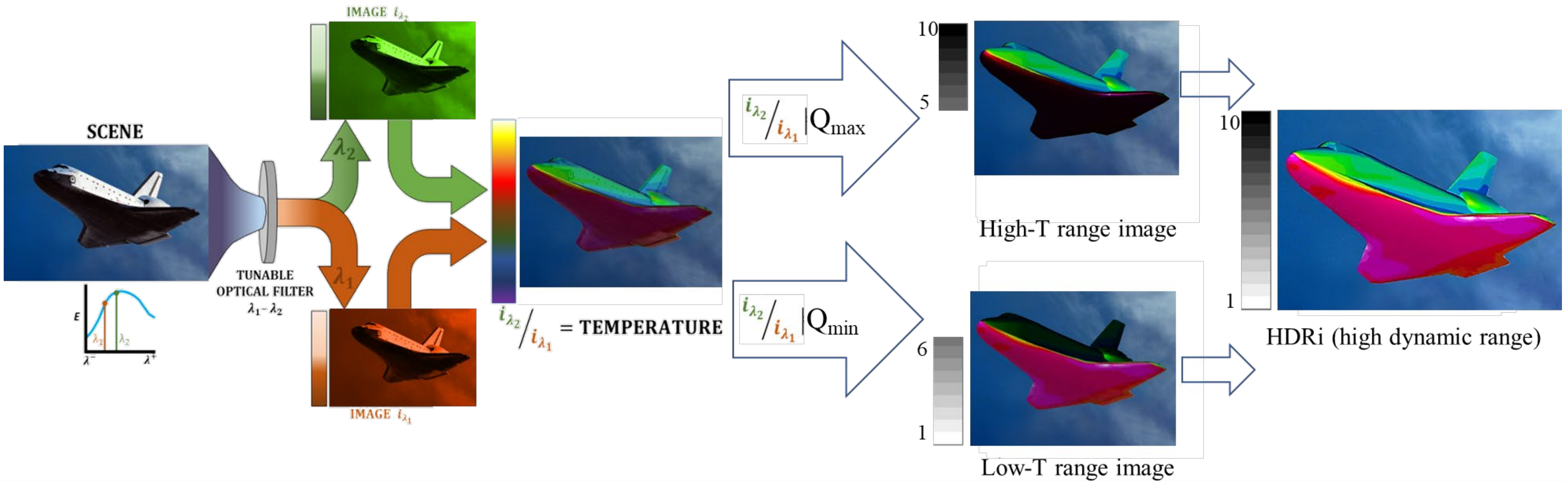


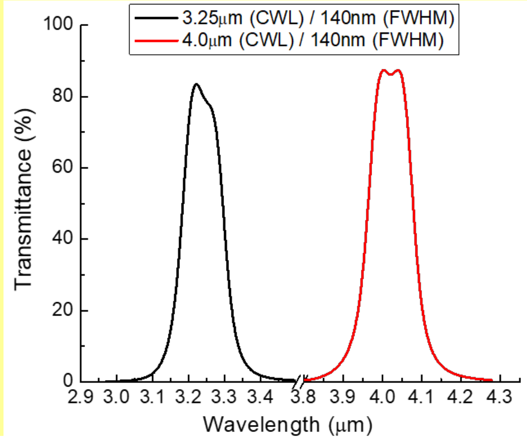
New aircraft opportunity

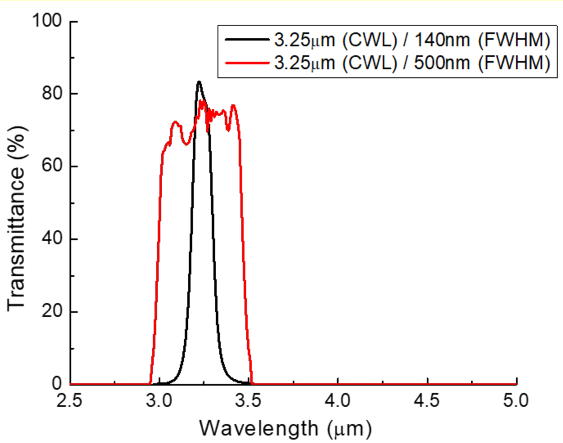
Smaller space

SWaP-C benefits

HDRi for multi-spectral imaging pyrometer



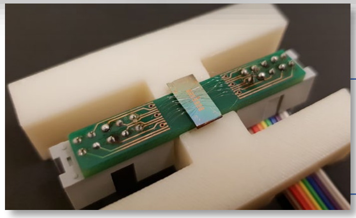




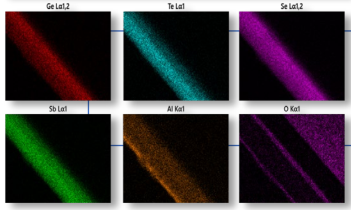
1. Utilizes P-ACTIVE and imaging camera to improve the thermal image
2. Most accurate & enhanced global temperature image of scene
   - Accuracy by eliminating the emissivity uncertainty problematic (CWL tuning) and
   - Details from expanding the dynamic range (FWHM tuning) of the image temperature data.
   - NTR-20119-1, Patent application, 2023

PCM-based Meatasurface Optics (since 2018)

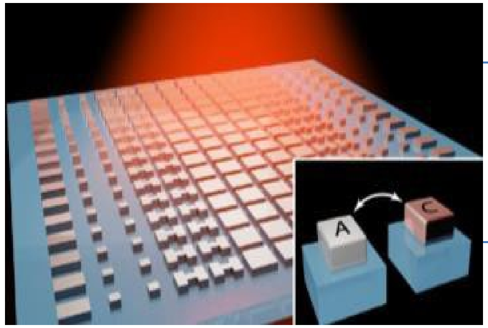
P-ACTIVE



Electrical switching of PCM metasurfaces



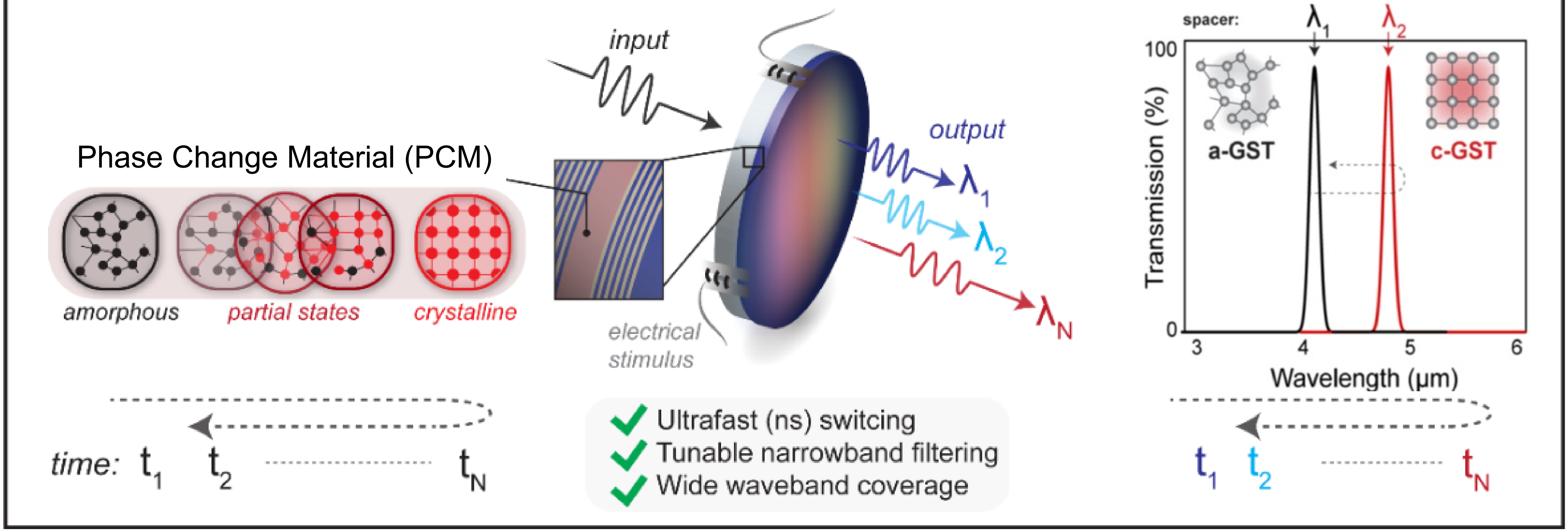
Long live PCMs: Mitigating failure mechanisms for reliability improvement



Reshaping light using PCM metasurfaces

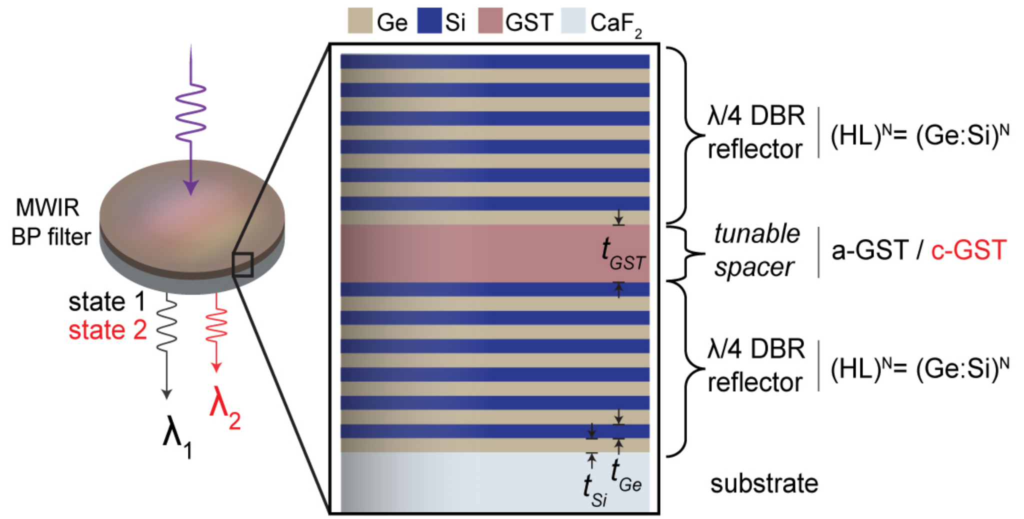
P-ACTIVE – Electrical Switching – Long Live

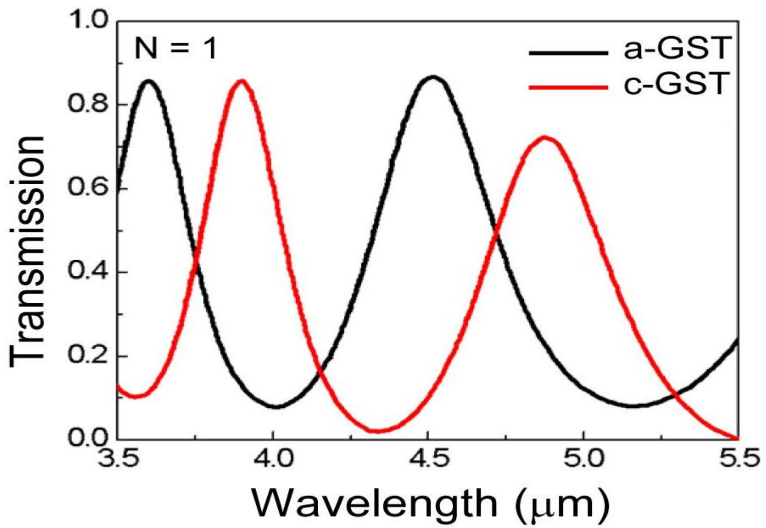
PCM-based Actively Tunable Filter (P-ACTIVE)

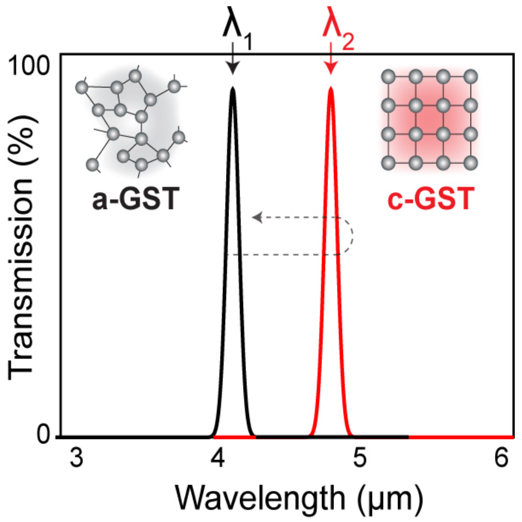


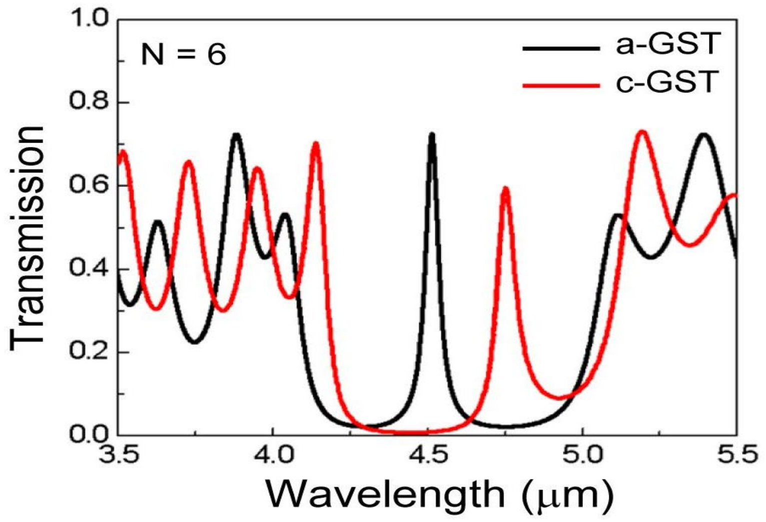
Prototype 1: Fabry-Perot Bandpass Filter with $Ge_2Sb_2Te_5$ cavity

center wavelength (λ_1 or λ_2) shift depending GST crystallinity (refractive index)



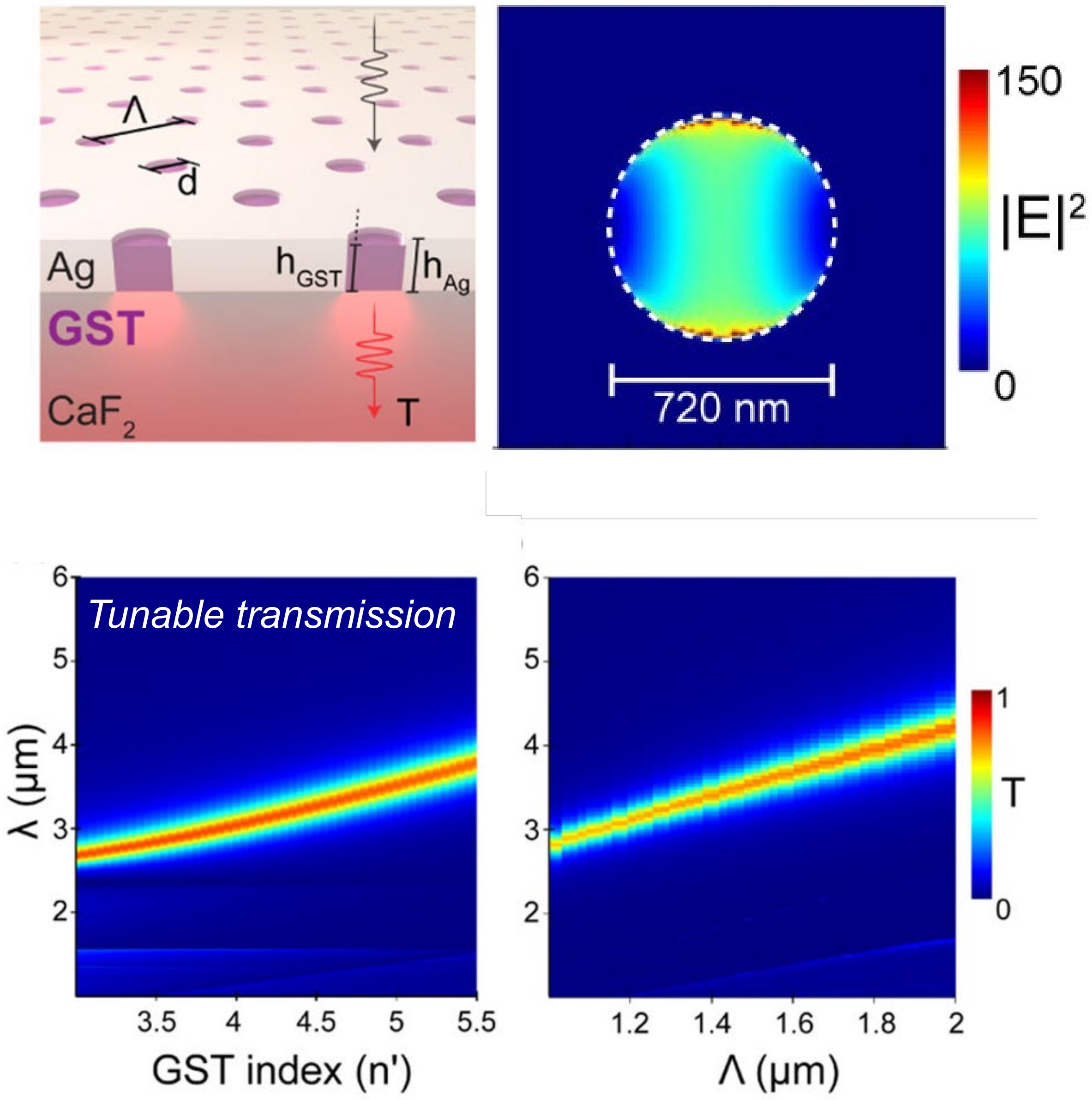






C. Williams. et al, Optics Express 28(7), 10583, 2020

Prototype 2: Metasurface filter with embedded GST



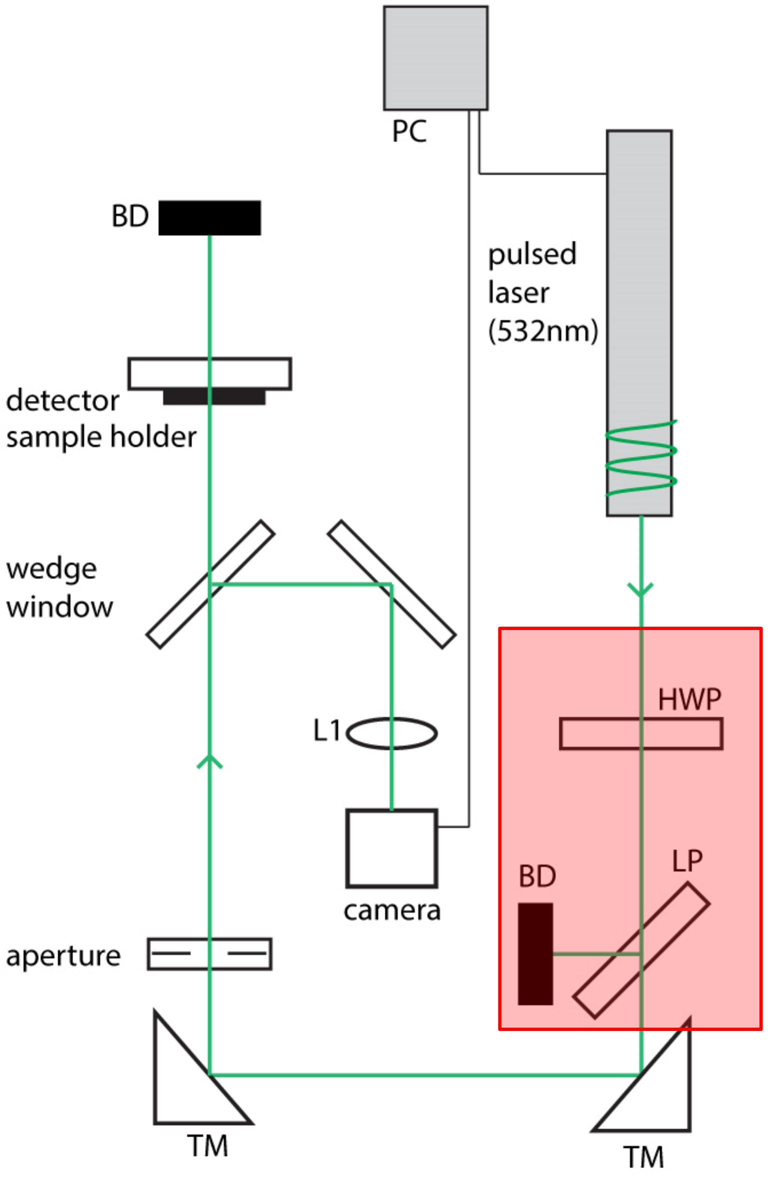
- Metasurfaces are sub-wavelength arrays which can be designed to strongly interact with the light

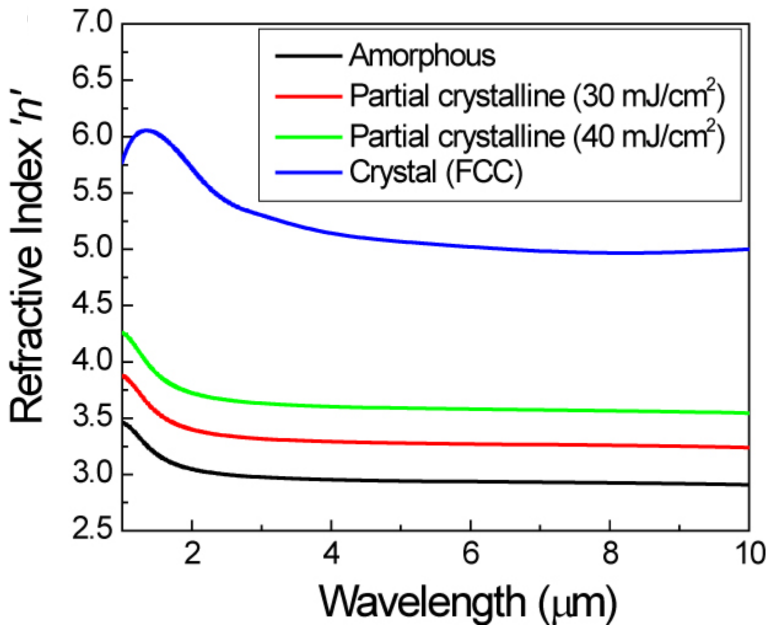
- We utilized a Plasmonic Nanohole Array (PNA) metasurface filter
- Integration of $Ge_2Sb_2Te_5$ (GST) with PNA
- Transmission response dependent on hole index. Holes filled with GST (tunable)

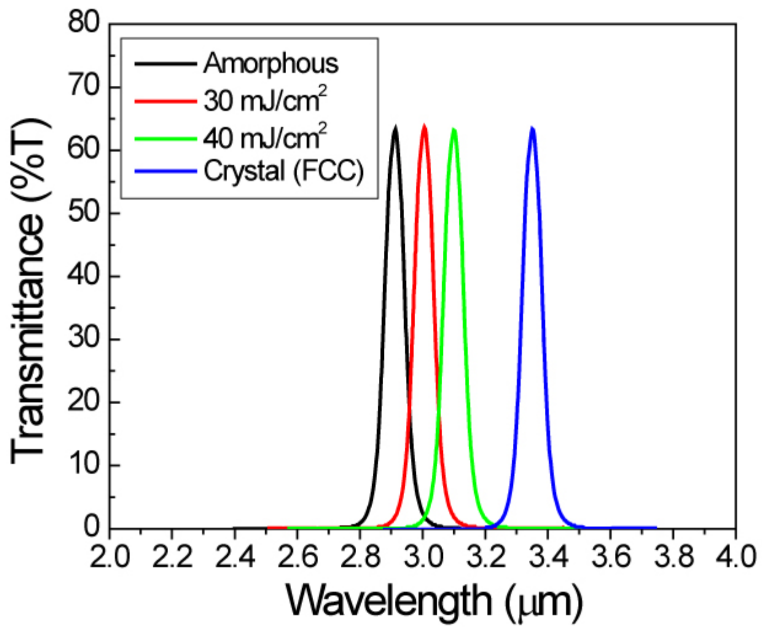
- **GST filled nanohole arrays associated resonance at particular WL in metal film**
  → transmission mode filtering

M. Julian et al., Optica, 7(7), 746-754, 2020

Pulsed-laser switching setup enables rapid center wavelength tuning

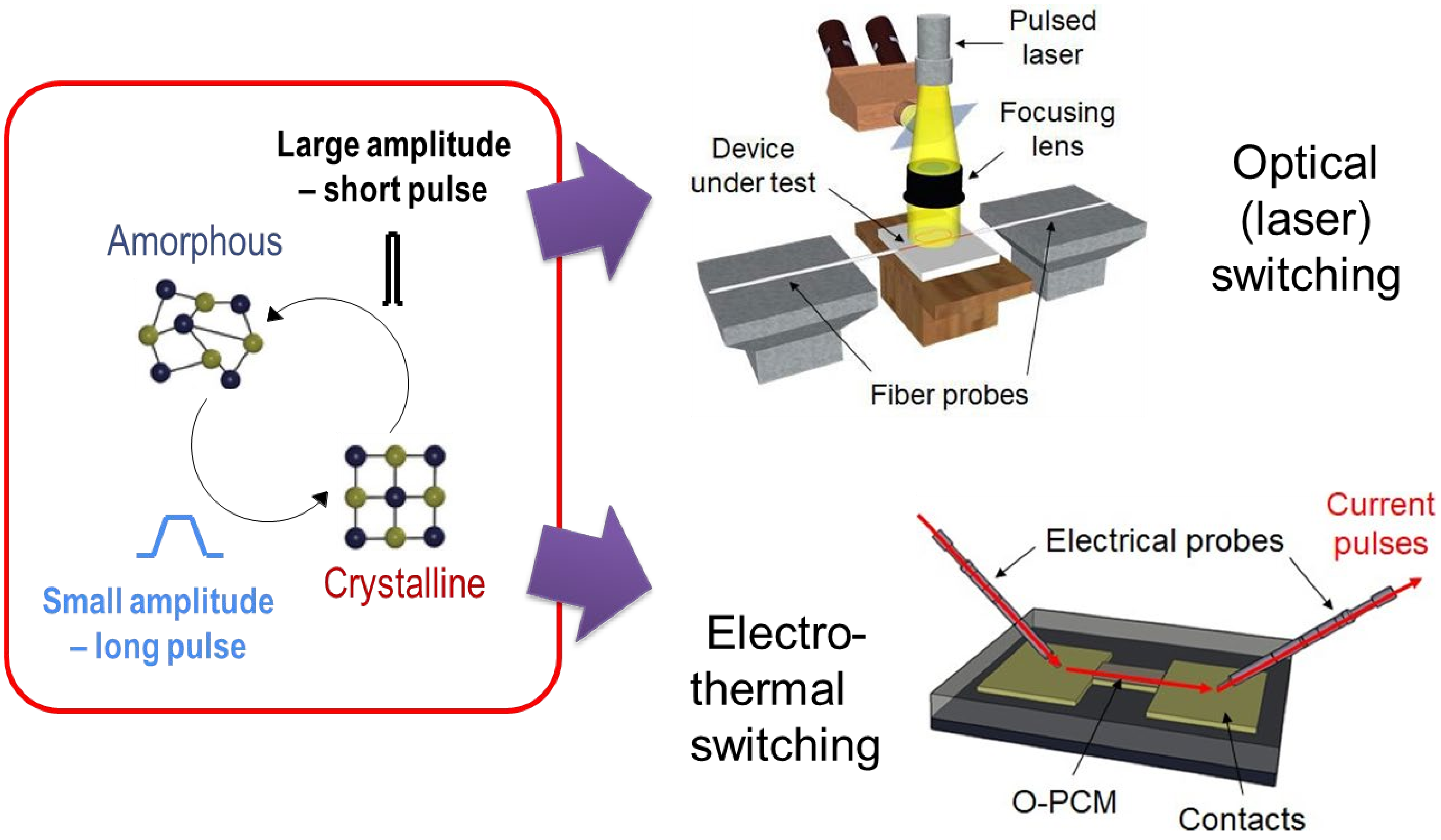




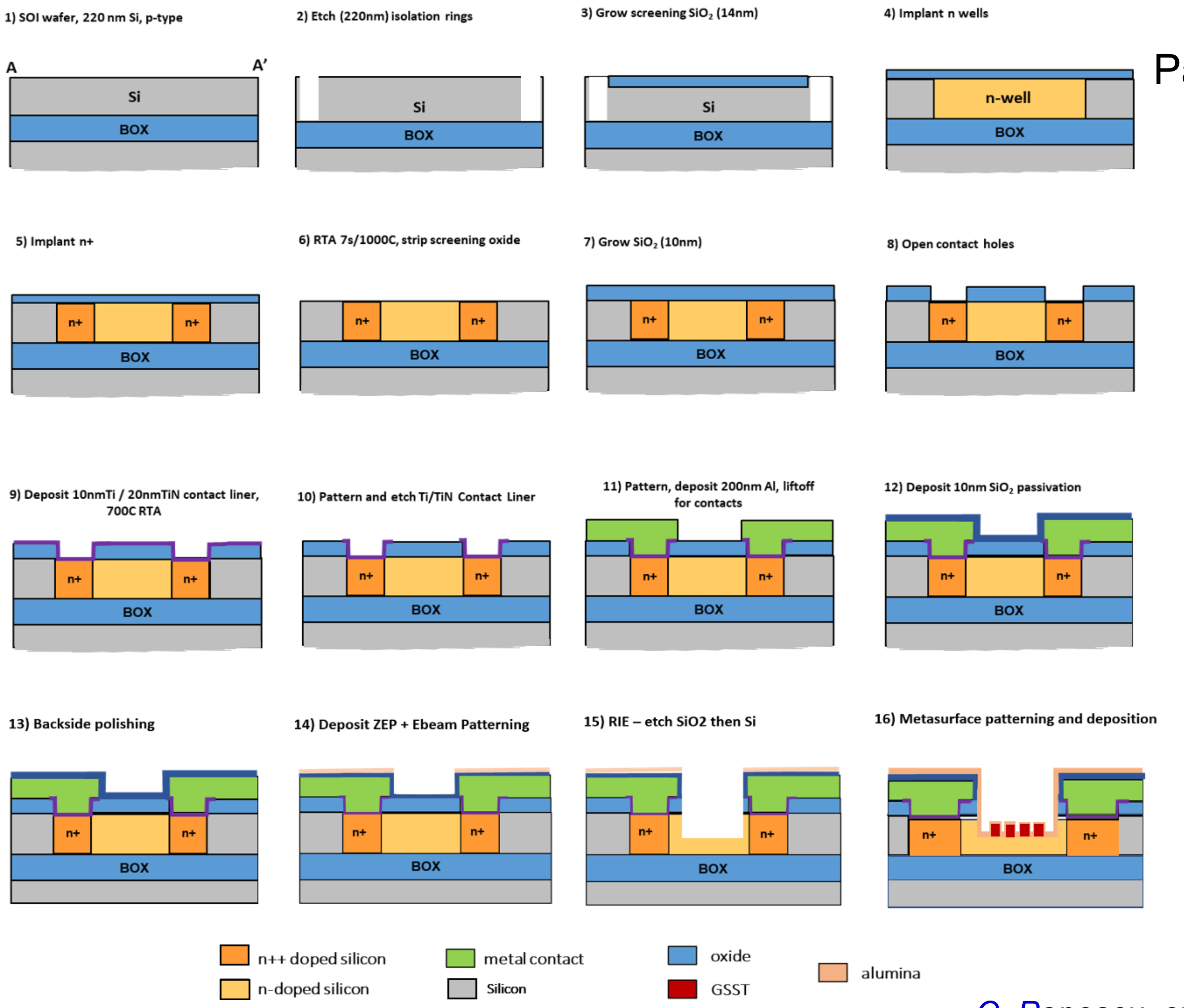


- GST-PCM is generally considered to be a 2-bit material ('0' / '1'), either amorphous (2.9μm) or crystalline state (3.4μm).
- Partial crystallizations of GST-PCM experimental demonstrations

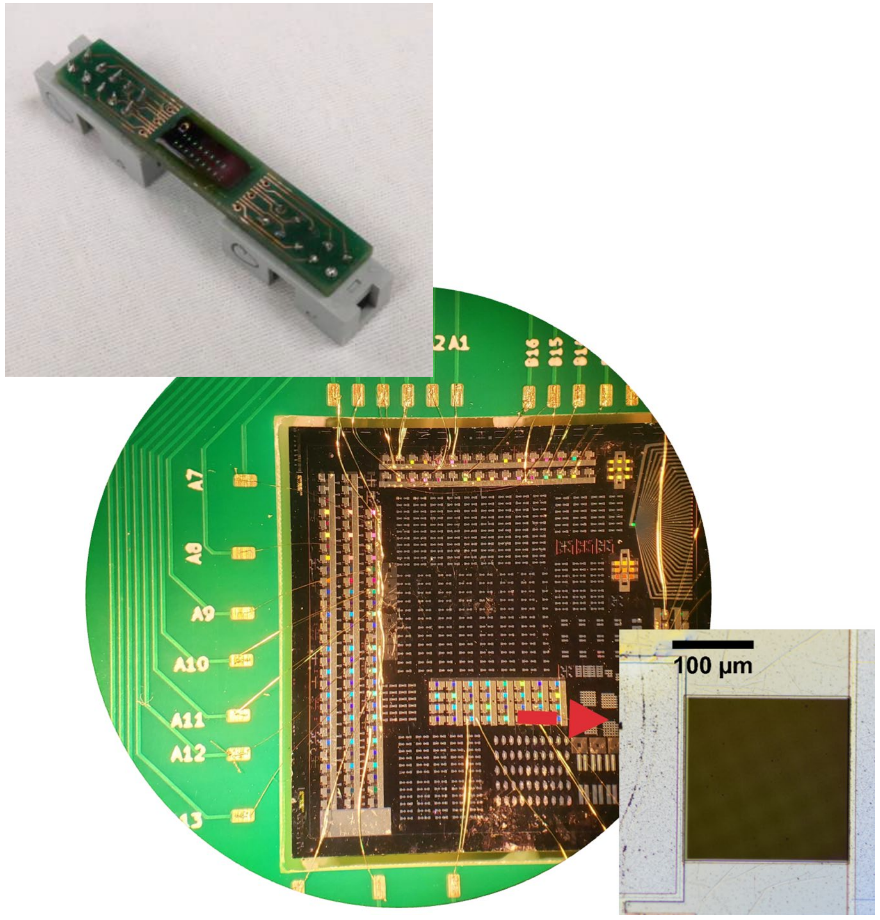
P-ACTIVE – Electrical Switching – Long Live



Electrical switching of PCMs

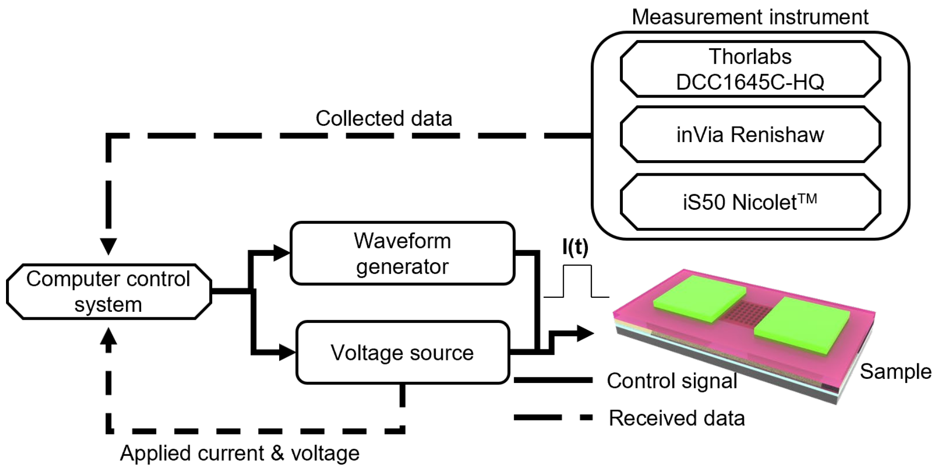


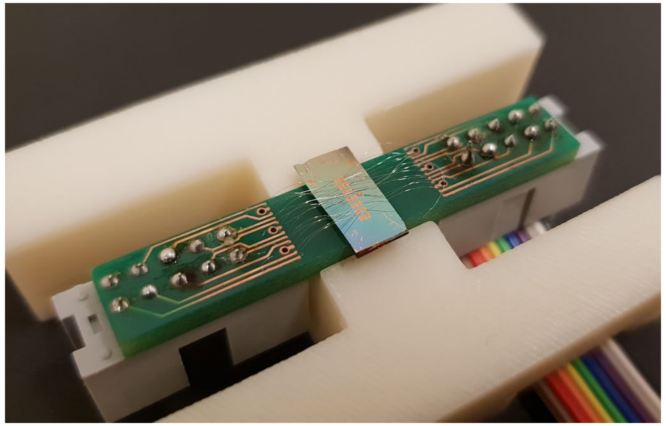
Packaged PCM metasurface devices (source: MIT)

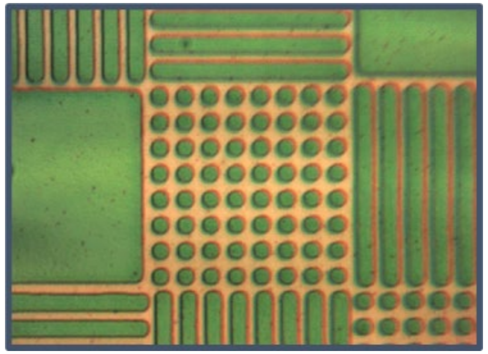


C. Popescu. et al, SPIE Proc. https://doi.org/10.1117/12.2657208 (2023)

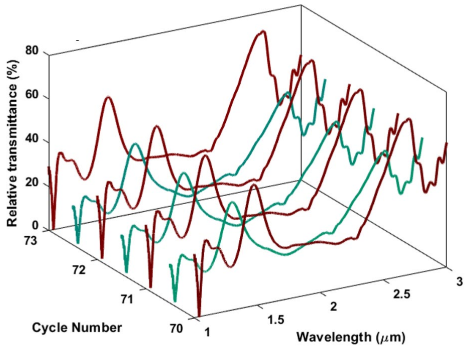
Multimode in-situ characterization platform



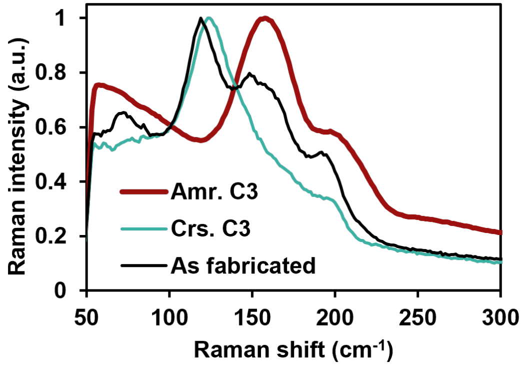




Imaging



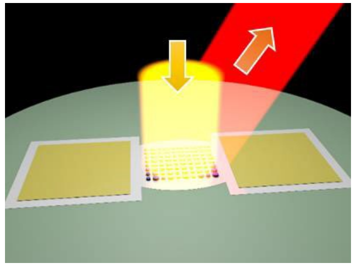
Micro-FTIR

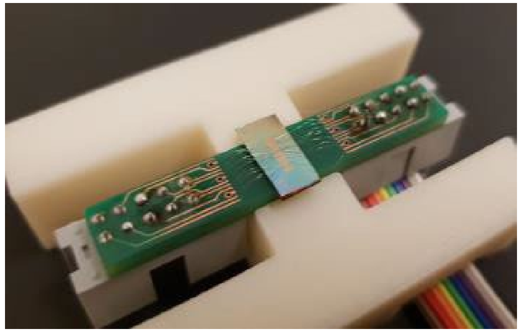


Raman spectroscopy

C. Popescu. et al, Small Science, 2300098 (2023)

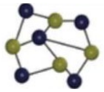
Electrical switching of PCM metasurfaces

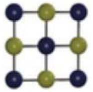




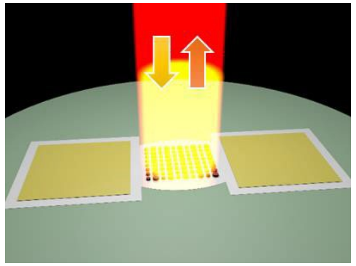
Nat. Nanotechnol. **16**, 661 (2021)

Amorphous





Crystalline



Optics in 2021

Metasurfaces Embracing a Phase Change

mit.edu], Juejun Hu, Tian Gu, Sensong An, Fan Yang and Yifei Zhang, Massachusetts Institute of Technology, Cambridge, MA, USA

Clayton M. Fowler and Hualiang Zhang, University of Massachusetts, Lowell, MA, USA

REFERENCES
1. Y. Zhang et al. Nat. Commun. 10, 4279 (2019).
2. M.Y. Shalaginov et al. Nat. Commun. 12, 1225 (2021).
3. Y. Zhang et al. Nat. Nanotechnol. 16, 661 (2021).

Recent progress in nanophotonics has enabled planar optical systems, termed metasurfaces, that hold potential to enable agile light manipulation and provide size, weight, power and cost (SWaP-C) benefits compared with traditional optics. Active metasurfaces, the optical properties of which can be modulated post-fabrication, have attracted a surge of interest in recent years, given their broad potential applications in imaging, sensing, display and optical ranging. A cohort of non-mechanically switchable meta-devices has

metasurfaces made of optical phase-change materials. More specifically, we have synthesized a new class of nonvolatile chalcogenide alloys, $Ge_2Sb_2Se_4Te_1$, exhibiting giant index contrast as well as broadband transparency in both amorphous and crystalline states.[1]

Capitalizing on this material platform and metasurface design innovation, we demonstrated an all-dielectric varifocal metalens in mid-infrared.[2] By annealing the entire metasurface, we showed that the lens shifted its focal plane between the distances of 1.5 mm

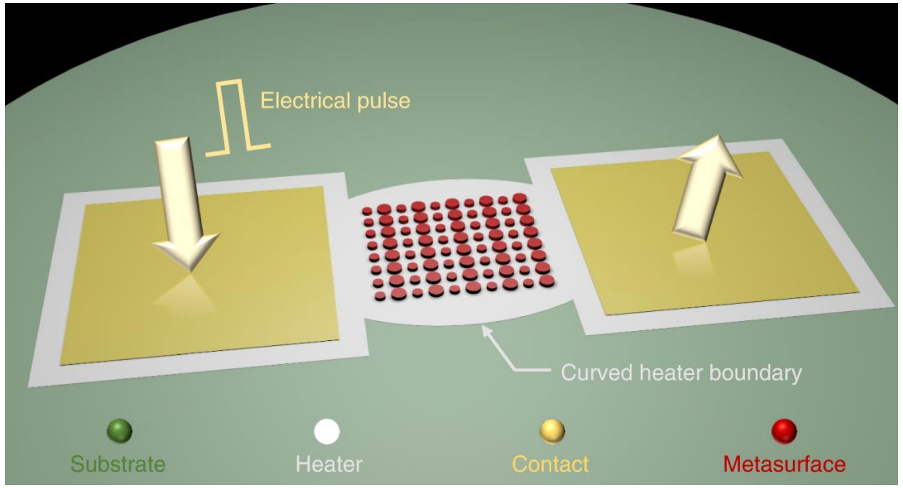
? Lifetime: 50 cycles

We showed reversible switching of a tunable metasurface and produced a record half-octave spectral shift with a large relative optical contrast exceeding 400%. By exploiting the same device architecture, we also prototyped a polarization-insensitive deflector for beam steering.

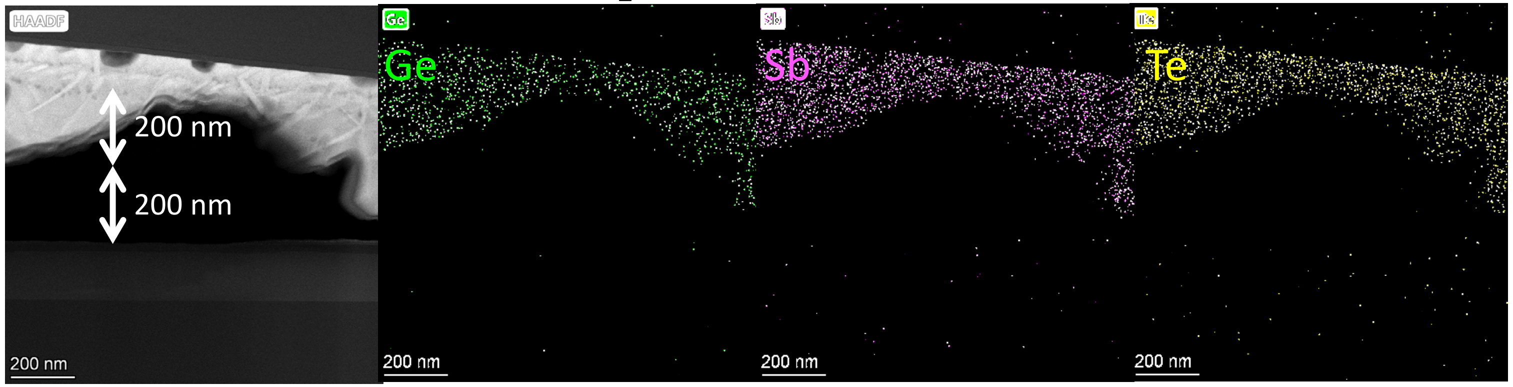
Our advances in phase-change-material meta-optics demonstrate that active metasurfaces can achieve optical quality on par with conventional precision bulk optics involving mechanical moving parts. The work points to exciting applications fully unleashing the SWaP-C benefits of active-metasurface optics. OPN

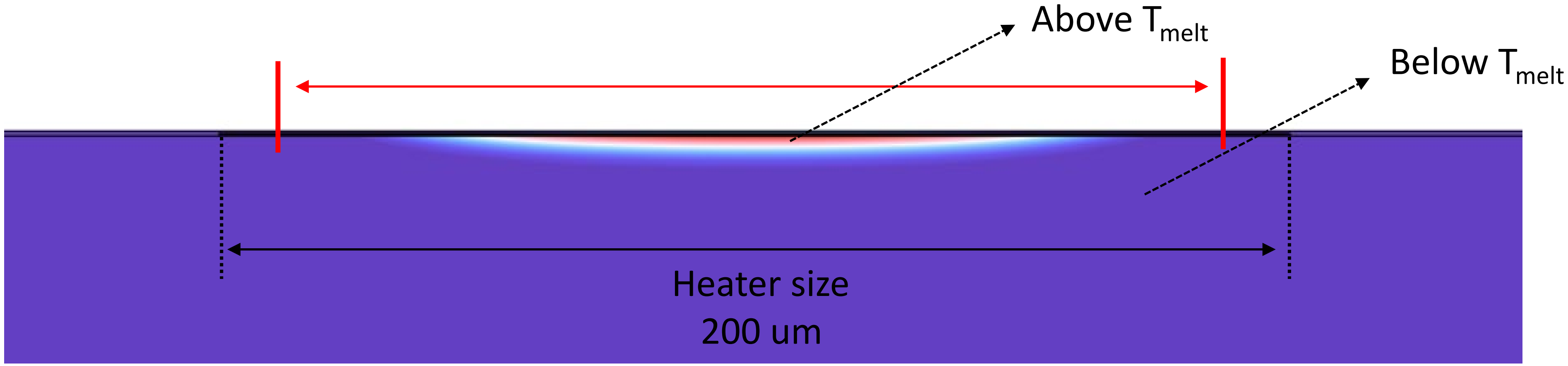
Top: Rendering of a $Ge_2Sb_2Se_4Te_1$ varifocal metalens. The focal-spot position is shifted by changing the crystallinity of the phase-change-material meta-atoms collectively. Bottom: Illustration of an on-chip, electrically switchable metasurface with beam-steering functionality, and photograph of a metasurface chip wire-bonded onto a custom-made printed circuit board.

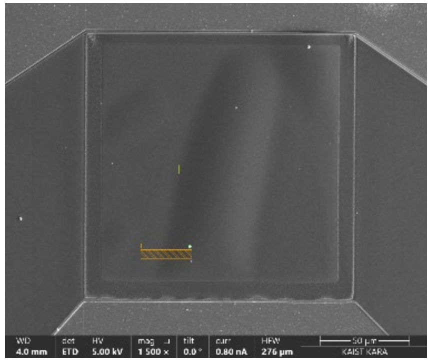
Thermal modeling to improving endurance

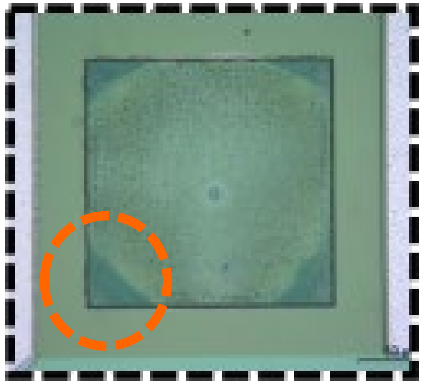


Delamination between SiO_2 and PCM interface (max. up to 1000 K)







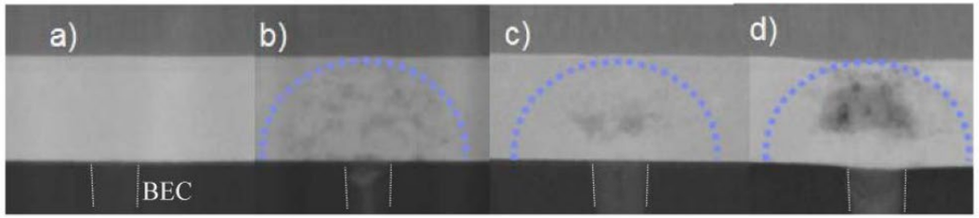


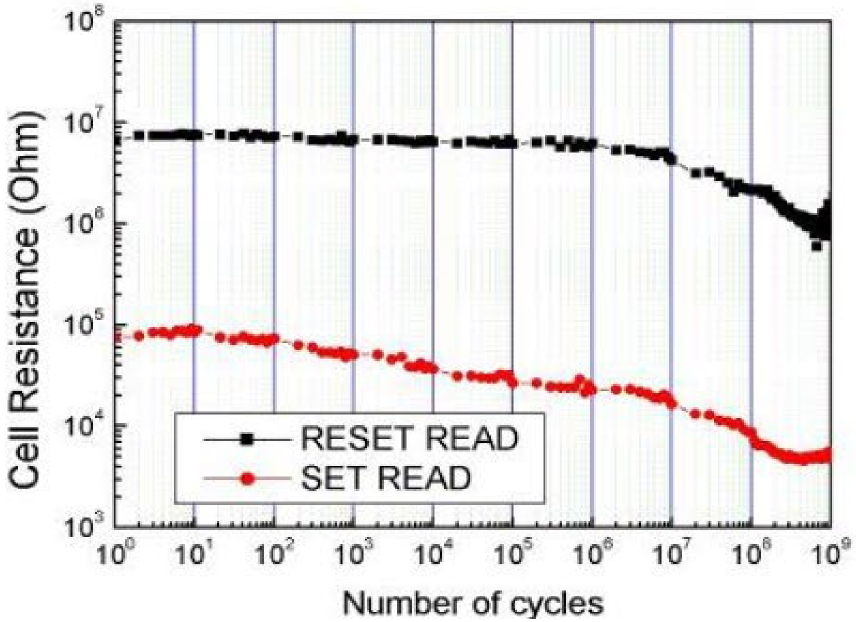
🔑 Three major reasons…and more!

- Lateral heat distribution profile - sharp temperature gradient near the edges of the heater
- Non-uniform stoichiometry of GSST - uniformity on crystallinity
- PCM is not bonded well to the SiO_2 layer – structure issue

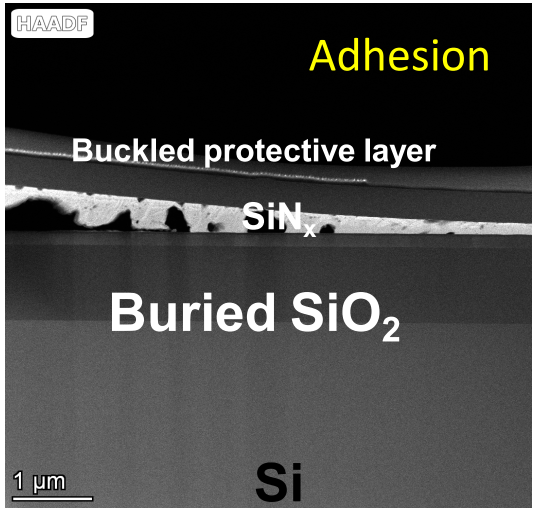
P-ACTIVE – Electrical Switching – Long Live

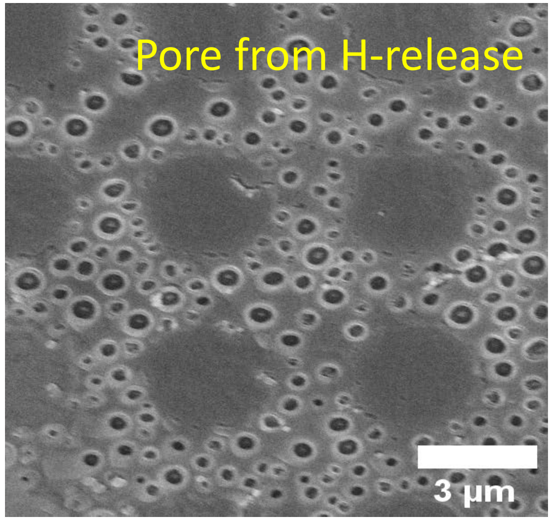
- Electrical phase change memory – resistance

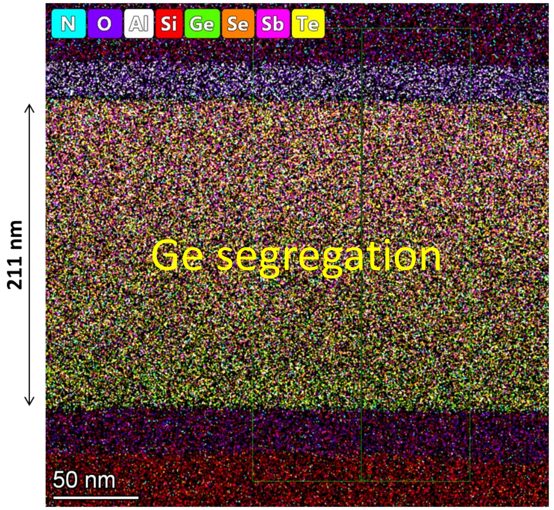


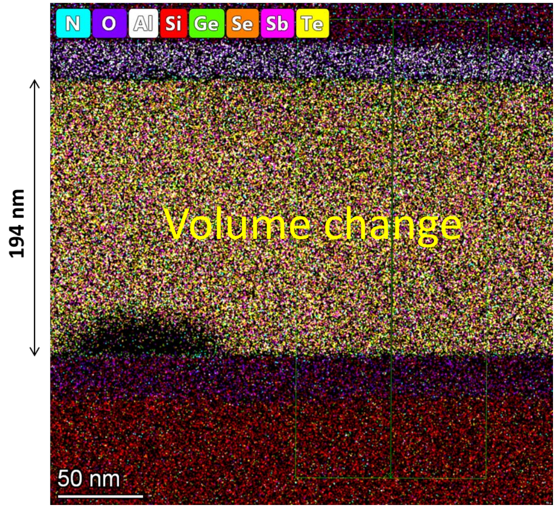


- Optical phase change device- transmission/reflection



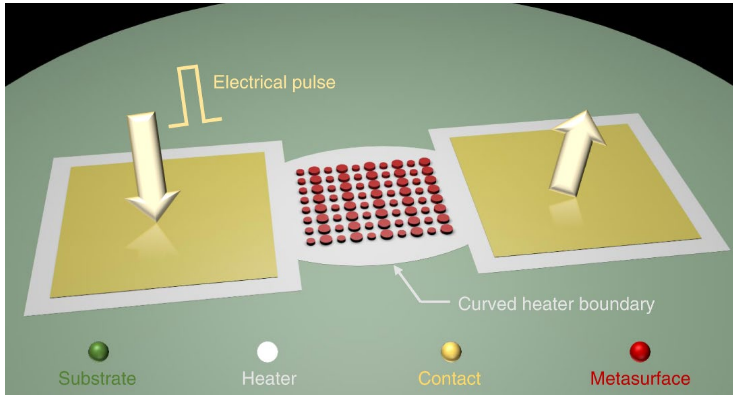


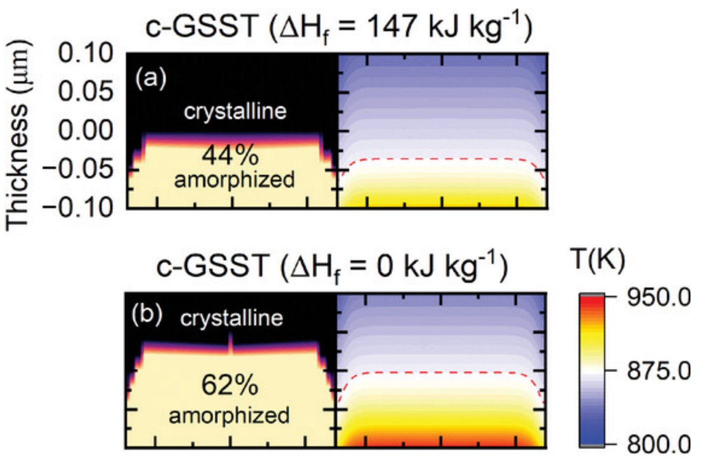




- Y. Zhang et al., Nat Commun **10**, 4279 (2019)
- J. Meng et al., Light: Science & Applications **12** (1), 189 (2023)
- C. Popescu. et al, SPIE Proc. **https://doi.org/10.1117/12.2657208** (2023)

Accurate thermal modeling of PCM devices

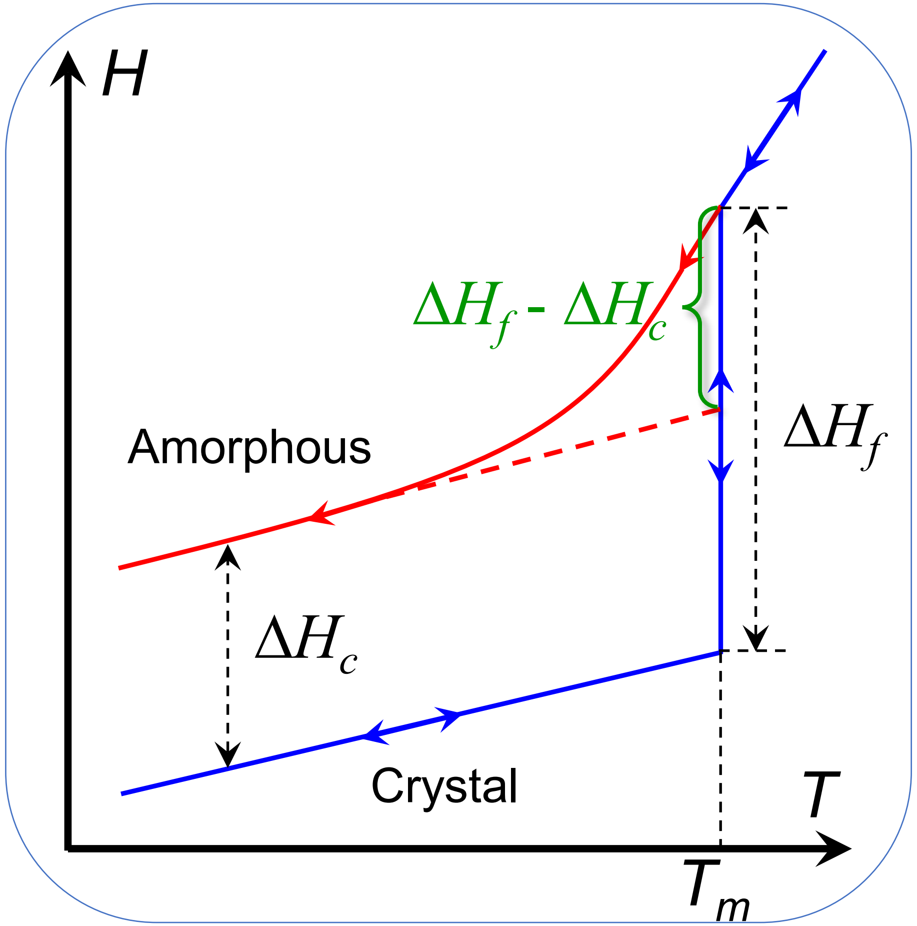




Thermal modeling is critical to device optimization and improving endurance

	Si	SiO_2	Si_3N_4	am-GSST	cry-GSST	Graphene	Al_2O_3	Au
Density [kg m^{-3}]	2329	2203	3100	5267	5267	2250	3900	19 300
Specific heat [J kg^{-1} K^{-1}]	700	740	700	275	351	420	900	129
Thermal conductivity [W m^{-1} K^{-1}]	150	1.38	20	0.2	0.4	160[90]	30	317
Relative permittivity	–	–	–	–	–	4.708	–	6.9
Electrical conductivity [S m^{-1}]	–	–	–	–	–	$1/(d \cdot R_{sh})$	–	45.6×10^6

Constants?

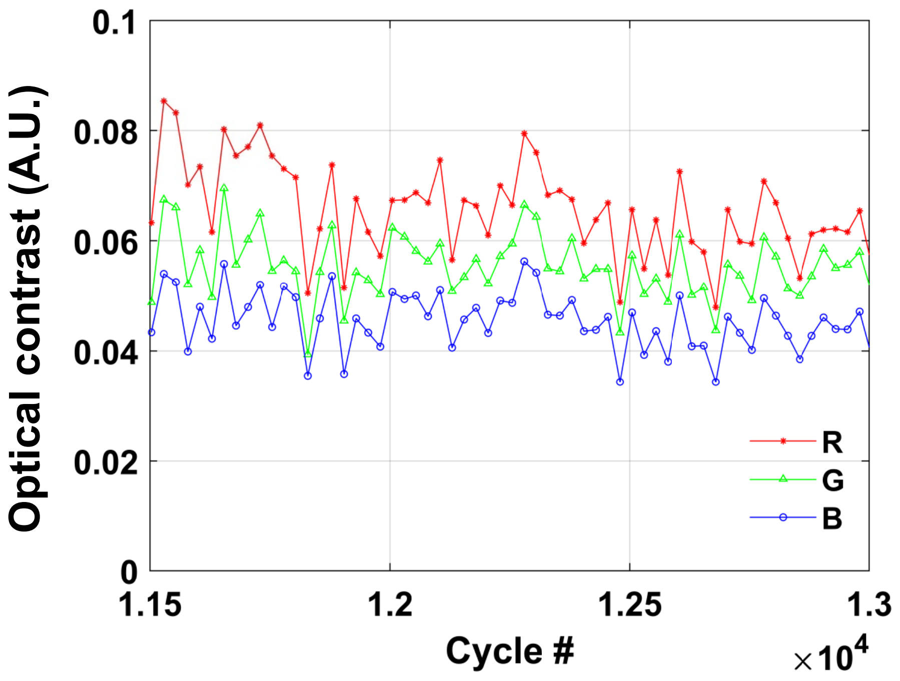


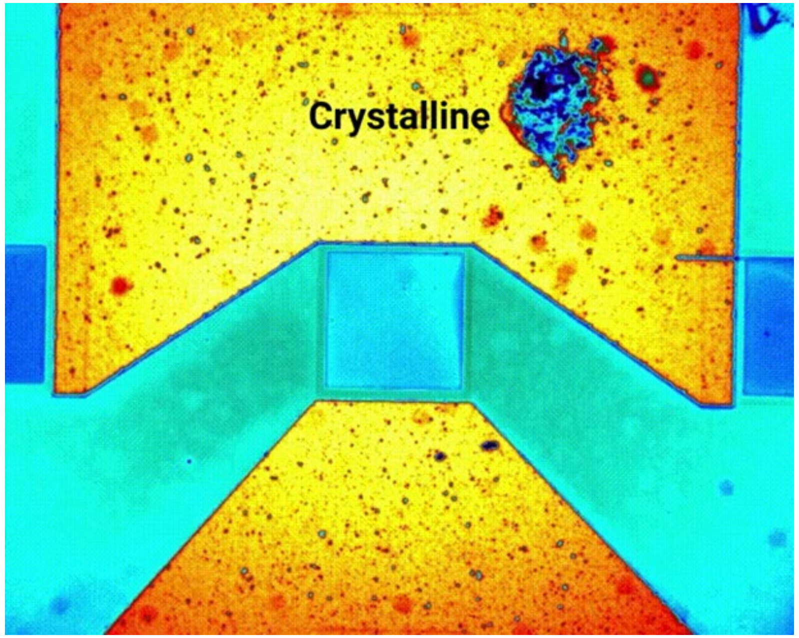
- ❑ **Fundamental behavior studying on the effect of enthalpy of melting on solidification of PCMs as part of controlling phase change kinetics** (Small, https://doi.org/10.1002/smll.202304145, 2023)
- ❑ **Scaling up phase change material-based devices**

Endurance improvement in large-volume optical PCM switching

PCM switching volume: ~ 4,000 μm^3

100 million times larger than that in PCMemories!

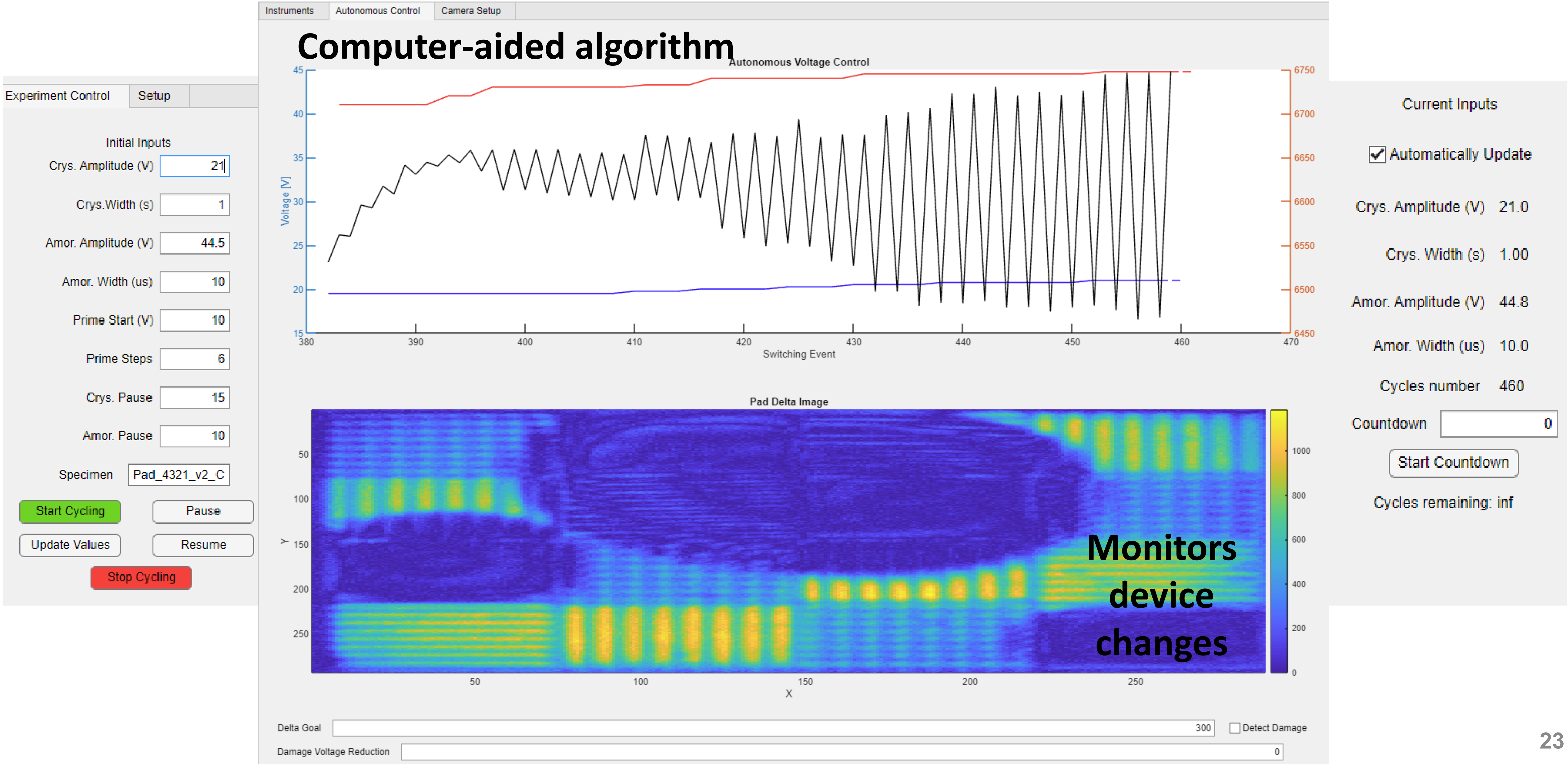




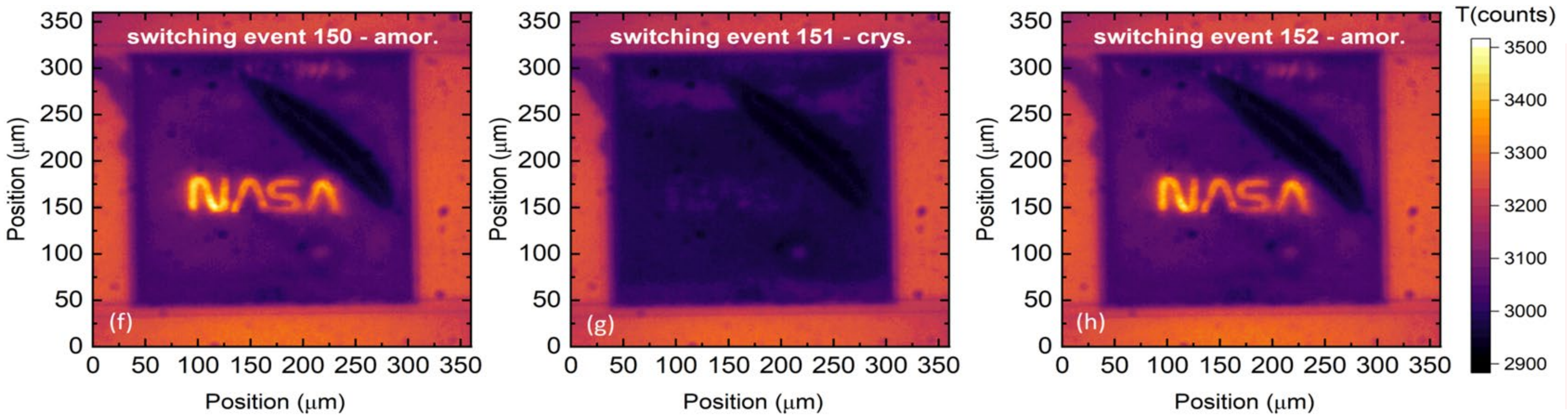
- C. Popescu. et al, Nature Comm under review (arXiv preprint arXiv:2312.10468) (2023)

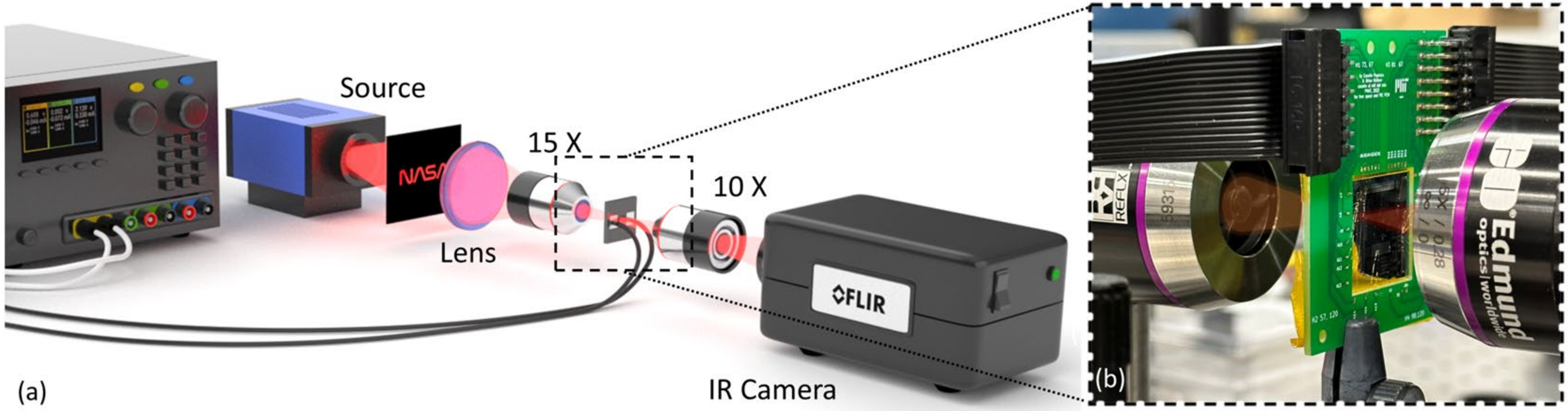
Large-area PCM switching with endurance of over 60,000 cycles

Auto Control of Switching Operations (Toward >10^5 cycles)



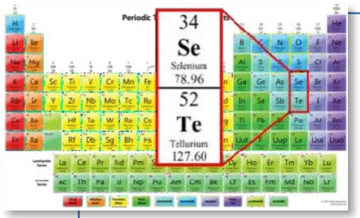
Reshaping light using a PCM-based tunable filter



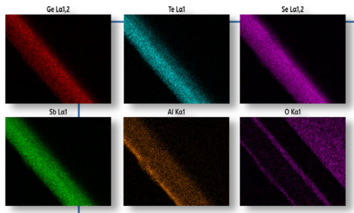


Nature Com., “Electrically reconfigurable phase-change transmissive metasurface” under review (2024)

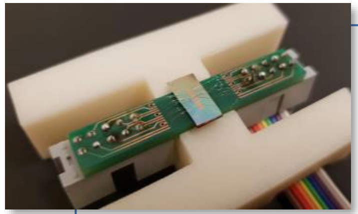
Takeaways



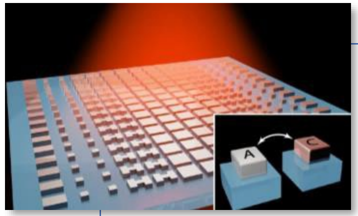
PCM is an ideal material for active / reconfigurable metasurface optics



Electrically reconfigurable PCM photonic circuits and metasurfaces have been **demonstrated** leveraging Si foundry processing



Understanding and **mitigating failure mechanisms** enable electrical switching of PCM metasurfaces over tens of thousands of cycles (and likely more)



Temperature dependence of heat capacity and thermal conductivity of PCMs must be **accounted for to enable accurate thermal modeling**

Data-based & Mission-driven Trade study

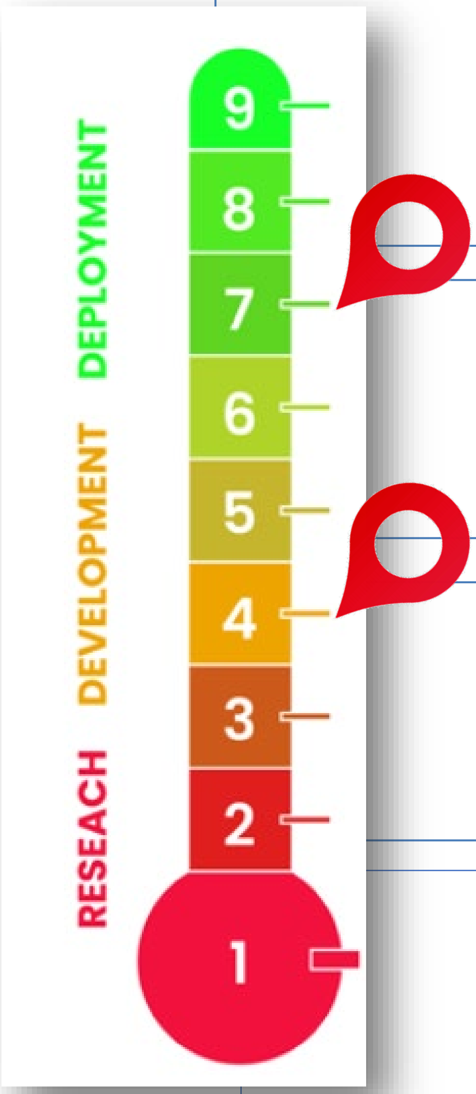
Application	Tuning scheme	Optical tuning parameter (phase/amplitude)	Optical contrast (relevant metrics)	Optical loss suppression	Endurance (cycling lifetime requirement)	Speed (bandwidth requirement)	Power consumption
Tunable filters for multispectral sensing [75–77]	Continuous	Amplitude	Extinction ratio		10^7	1 kHz	
Beam steering for LiDAR [78,79]	Continuous	Both	Full 2π phase tuning range		10^9	10 Hz	

… optical computing … zoom lens …

Application	Tuning scheme	Optical tuning parameter (phase/amplitude)	Optical contrast (relevant metrics)	Optical loss suppression	Endurance (cycling lifetime requirement)	Speed (bandwidth requirement)	Power consumption
Digital signal modulation for free-space communications [15,91,92]	Discrete	Either	Modulation contrast		10^{18}	10 GHz	
Adaptive optics [93]	Continuous	Phase	Full 2π phase tuning range		10^9	100 Hz [94]	
Nonreciprocal optics based on spatiotemporal modulation [95–97]	Discrete	Either	Isolation ratio		10^{18} h	10 GHz	
Optical limiter [98,99]	Discrete	Amplitude	Extinction ratio		10^3	> 1 GHz	Nonvolatile
Adaptive thermal camouflage [100,101]	Continuous	Amplitude	Dynamic range		10^8	10 Hz	

T. Gu et al, Nature Photonics, https:// doi.org/10.1038/s41566-022-01099-4 (2023)

Conclusions and Future Work



Proper electrical integration must be achieved for large scale optics.

- ❑ 1” diameter tunable filter for multispectral imaging for imaging spectrometer

Material lifetime and repeatability is probably the biggest challenge.

- ❑ 2.0124e7 [switches/year] for LiDAR mission (science event in LEO orbits * % of time filter is actively switching)

For non-filter applications, pixelation of the PCM device is required.

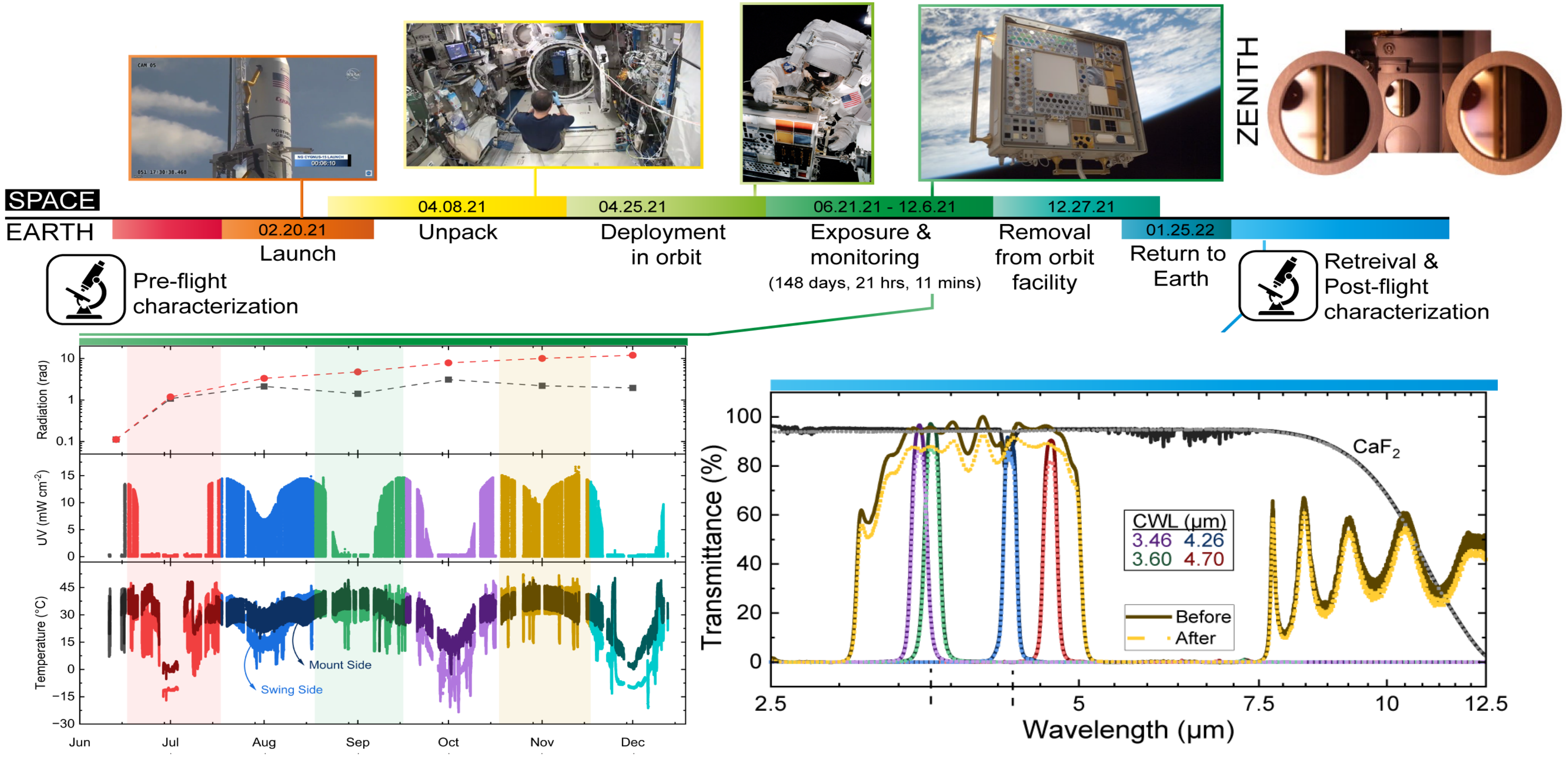
- ❑ For aberration-correction applications, need at least a few hundred x a few hundred-pixel arrays (significant integration) and good thermal isolation of the PCM between adjacent pixels is required

For applications intending to do imaging in the MWIR/LWIR, design work is required to ensure that the thermal emission from the filter does not interfere with the signal.

- ❑ Requires a better understanding of nanoscale thermal transport in these materials and in specific architectures.

H. J. Kim *et al.*, npj Microgravity perspective article (2024)

MISSE-14 Space Materials (https://spaceborne-pcms.github.io/)



H. J. Kim et al., npj Microgravity (2024)

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