P-ACTIVE (PCM-based actively tunable filter) project at NASA

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SPIE Defense + Commercial Sensing

Co-authors

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Thermal modeling /fabrication characterization/ applications

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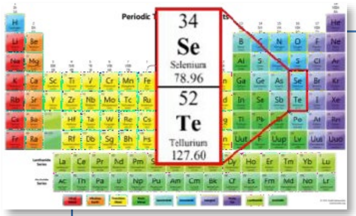
BAH

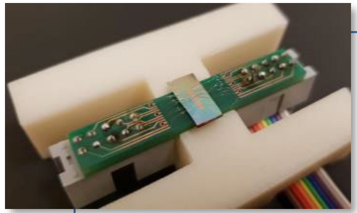
- Dr. Matthew Julian

Bio / medical applications

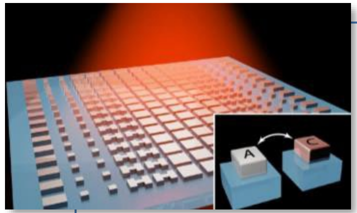
Outline



Phase change material (PCM) & P-ACTIVE



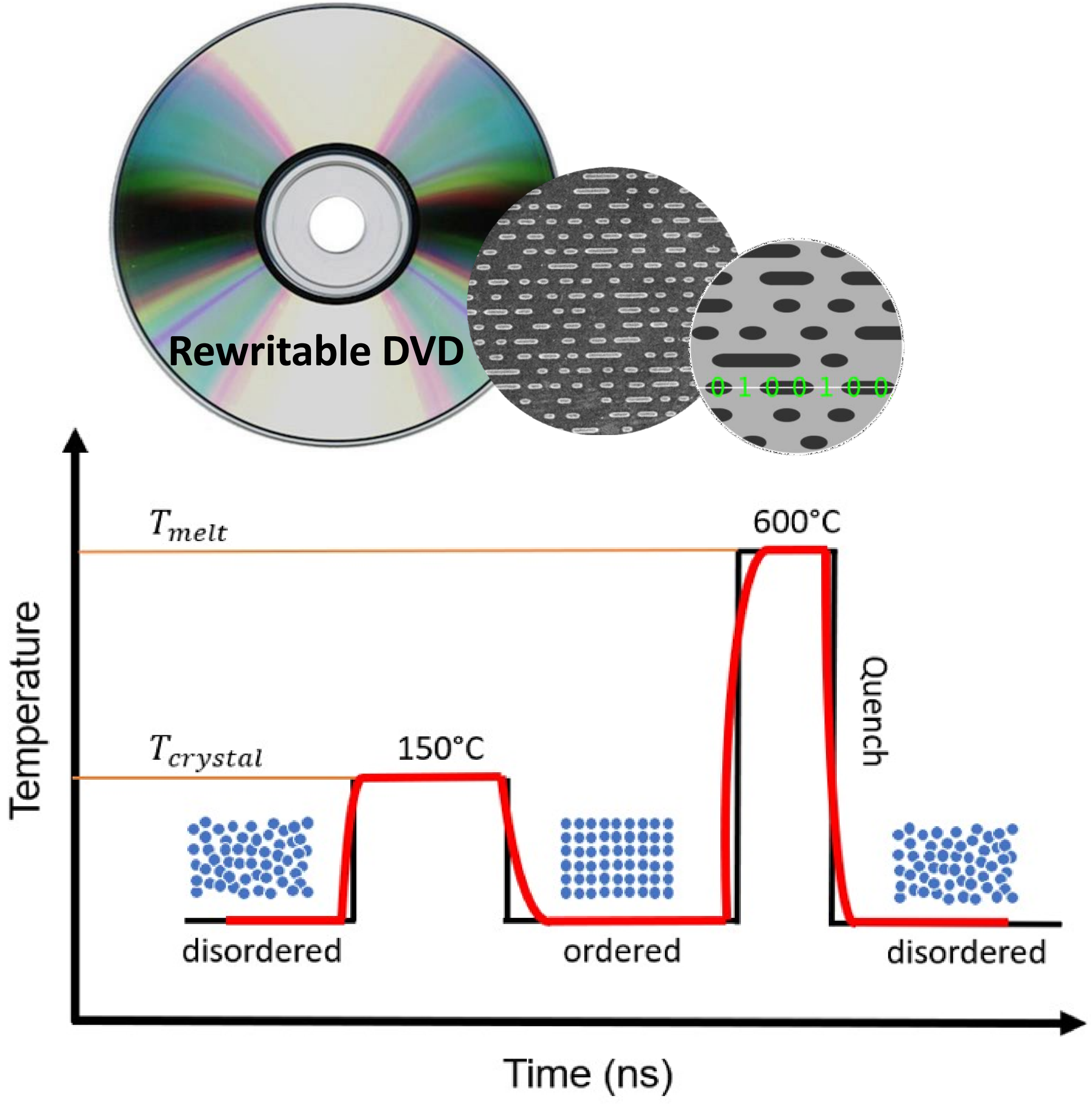
Electrical switching of P-ACTIVE

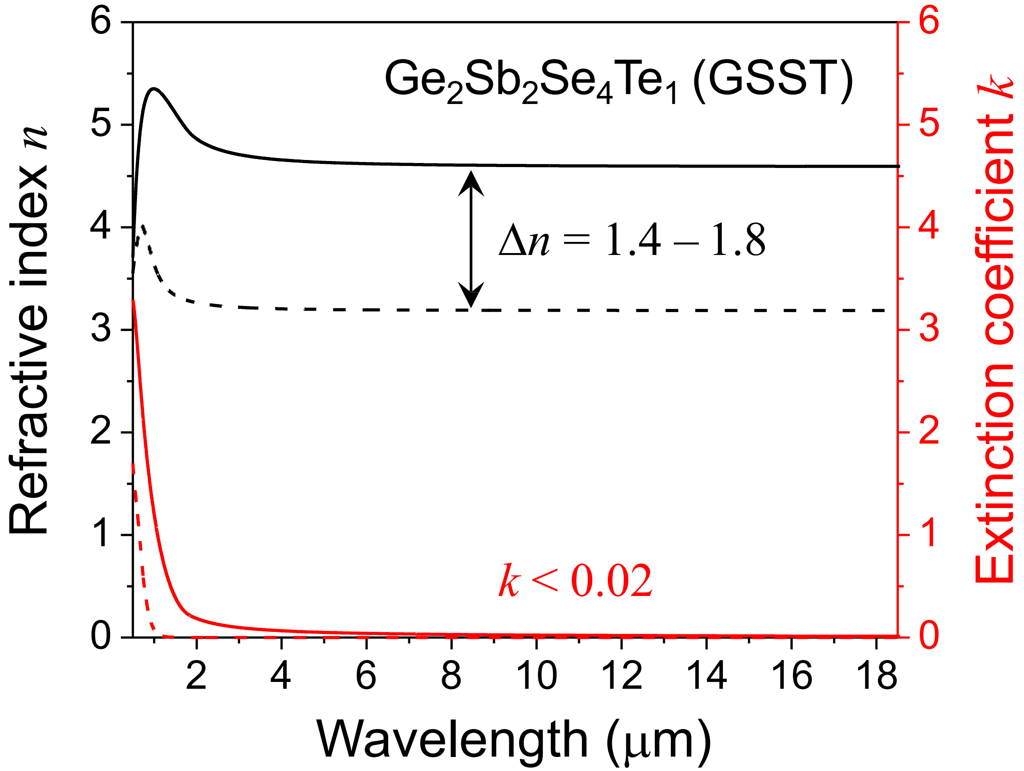


Path forward to Defense + Commercial Sensing

Future of P-ACTIVE

Phase change materials has long history (since 1966)





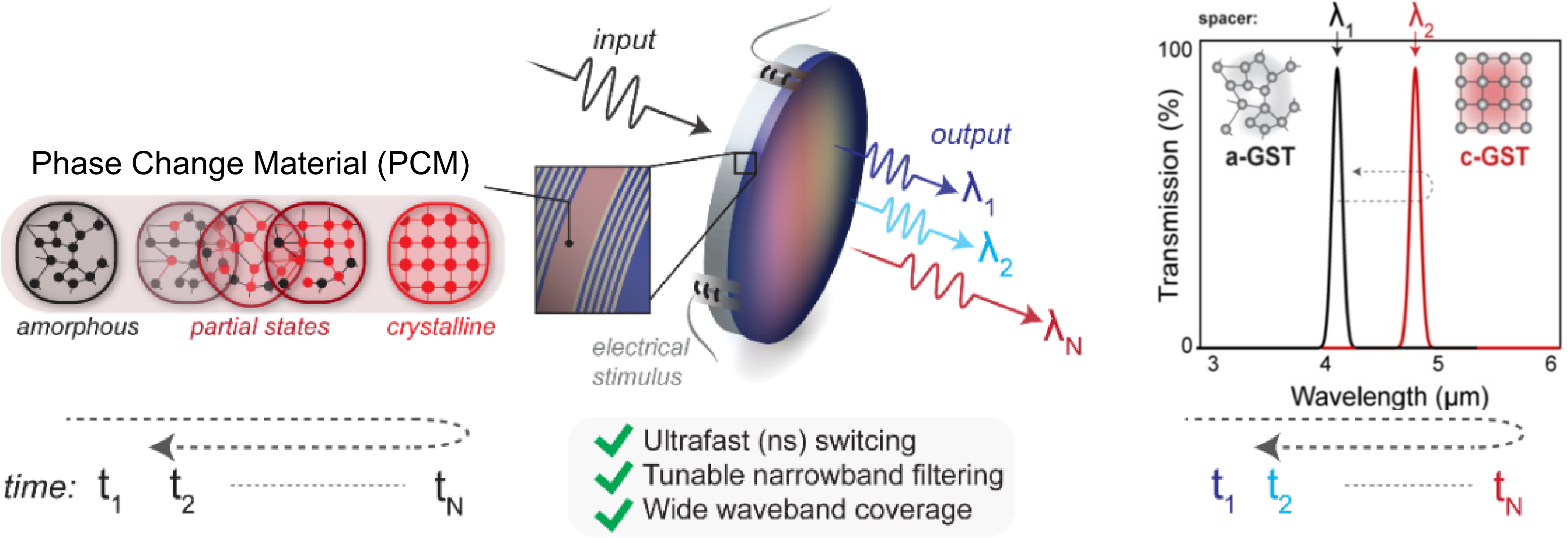
✓ Index change: Δn = 1.4 – 1.8

✓ Loss: k < 0.02

Opt. Lett. **43**, 94 (2018);
Nat. Commun. **10**, 4279 (2019);
J. Of Physics: Photonics **3.2** (2021) 024008

Exploiting the extraordinary refractive index contract in PCMs has opened the door to unprecedented functionalities in photonic components

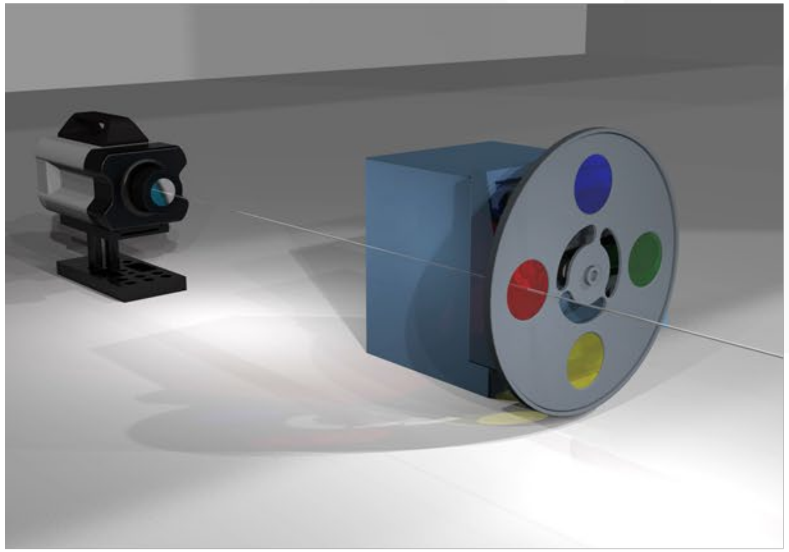
PCM-based Actively Tunable Filter (P-ACTIVE)



P-ACTIVE

State of the Art:

- ✓ Filter wheels comprised of several static filters physically rotate to switch spectral passband
- ✓ Has moving parts, large mass, slow response time (ms), and provides limited spectral resolution
- ✓ 800g (weight), 725cm^3 (volume), 15W to power motor

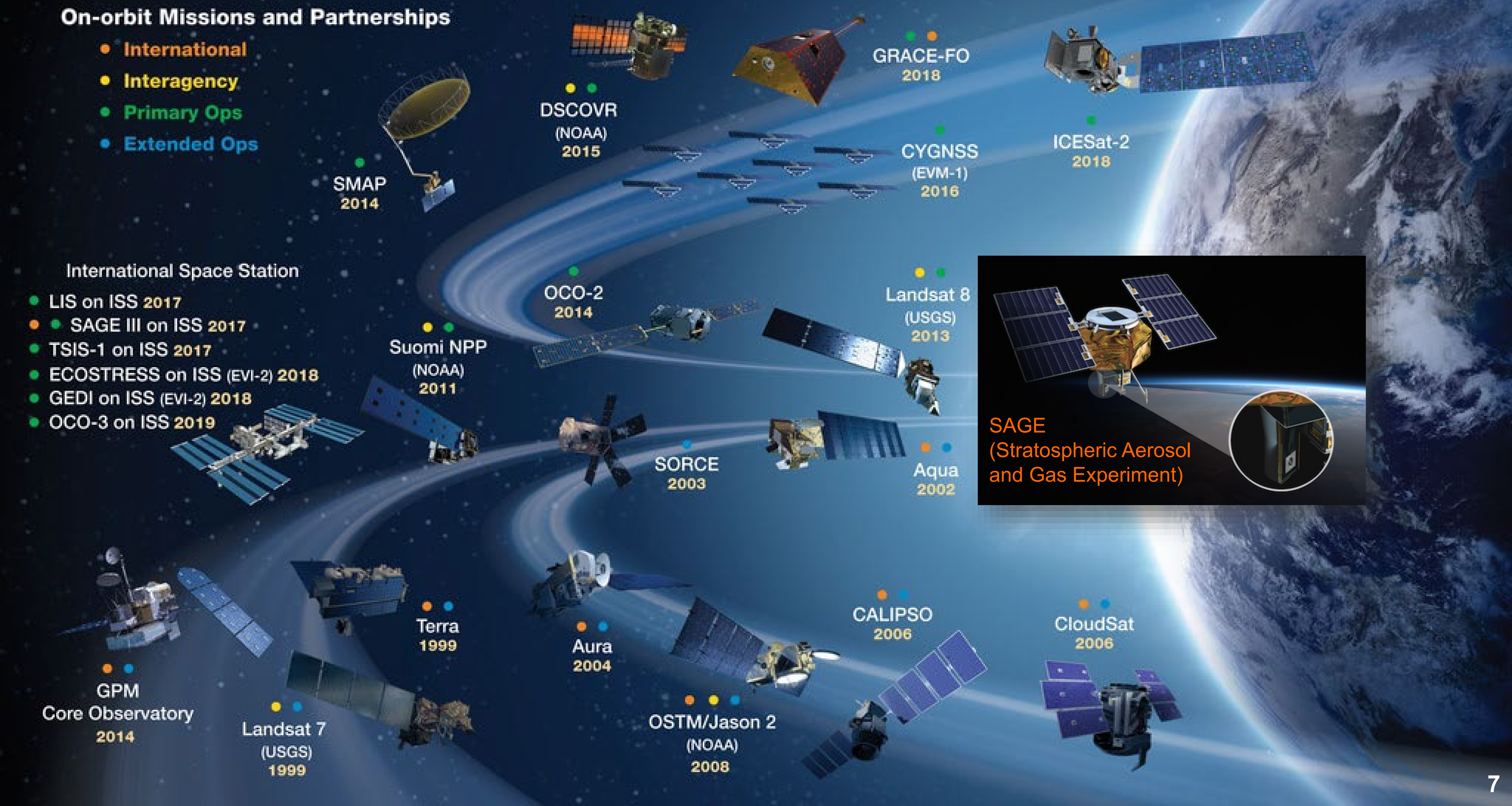


P-ACTIVE:

- ✓ Increased spectral and temporal resolutions
  - ✓ GHz (ns) switching speed (10^{6}x improvement!)
  - ✓ Continuously-tunable passband
- ✓ Single-component, non-volatile, broad tunability
- ✓ 10g (weight), 0.253cm^3 (volume), ~mW average power to tune filter

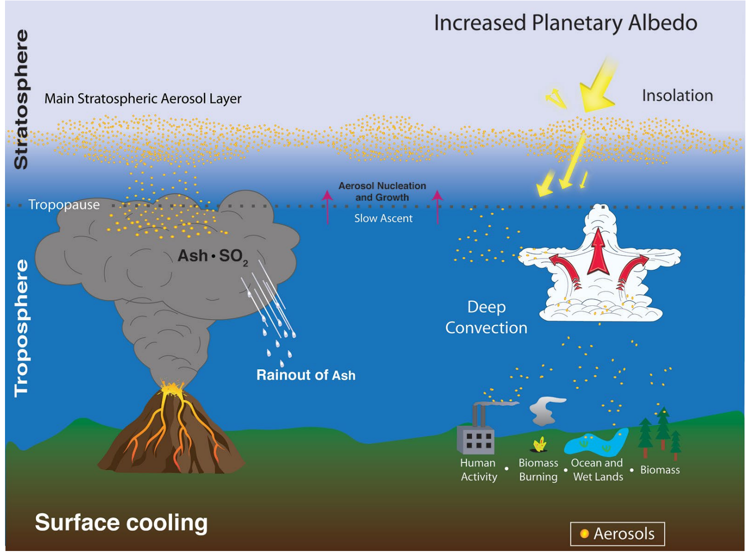
P-ACTIVE can offer a flexible platform that can meet arbitrary mission requirements and provide more science information

NASA Earth Missions

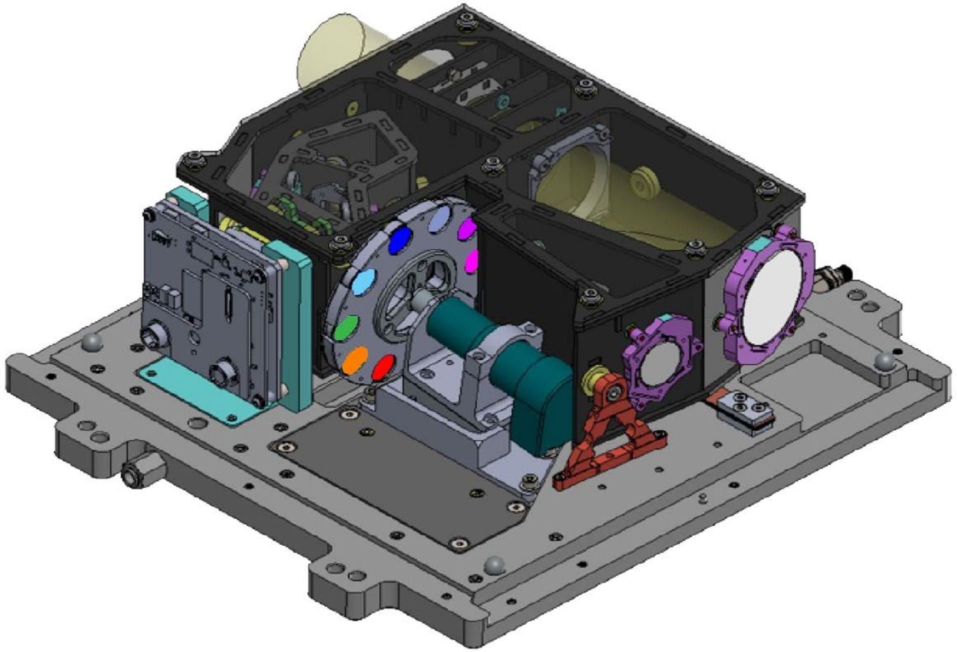


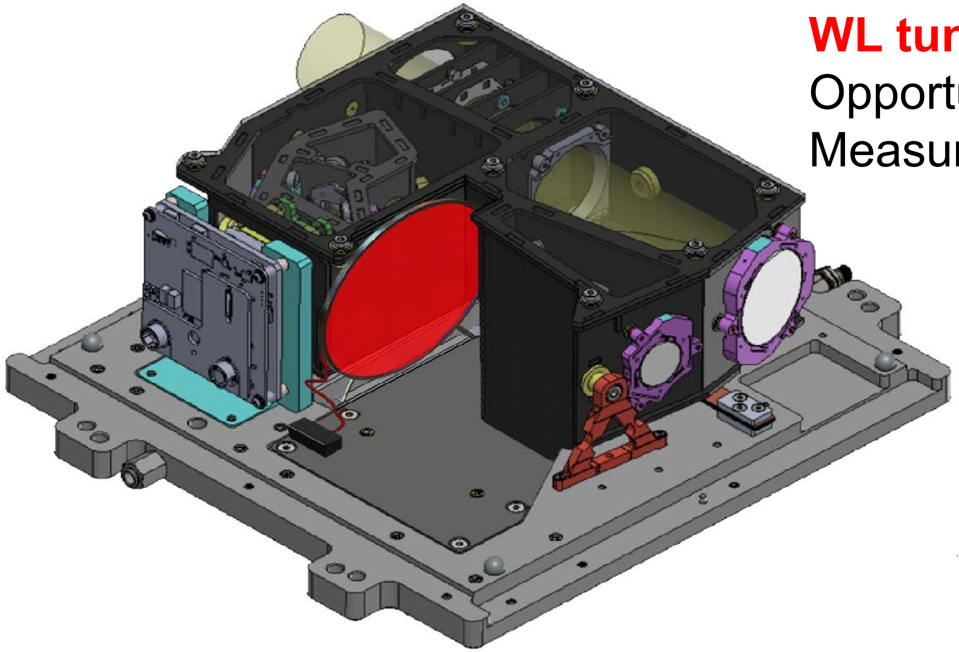
NASA SAGE mission

https://www.nasa.gov/sage3-iss



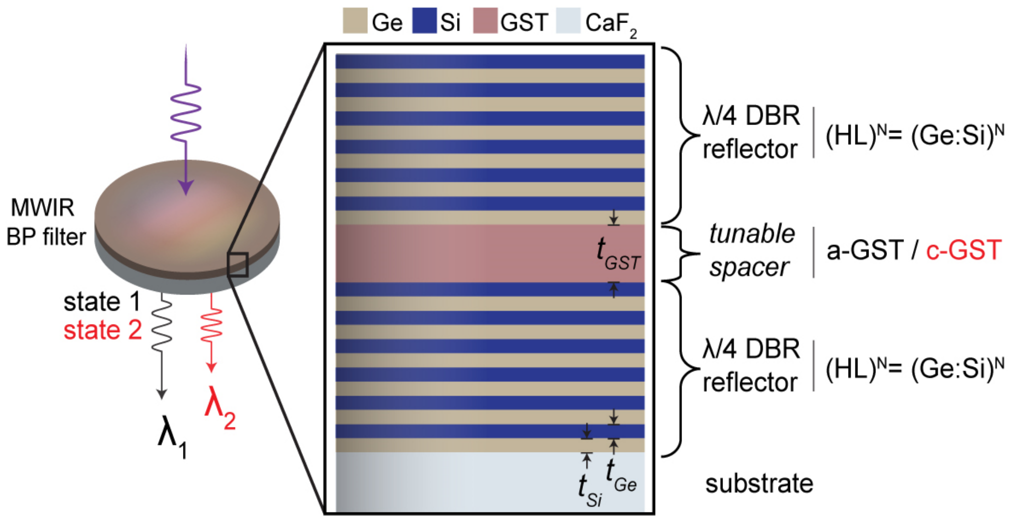
I. SAGE precisely measuring the constituents that influence the balance of our atmosphere
II. SAGE-IV was developed at 1/10th the cost of SAGE-III
III. 6U Cubesats and Smallsats open opportunities for Rideshare launches
IV. **SWaP + No moving part + More WL tunability** = More Opportunity = More Measurements

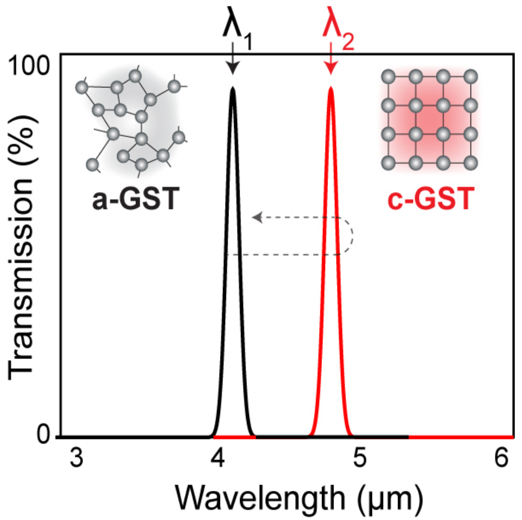


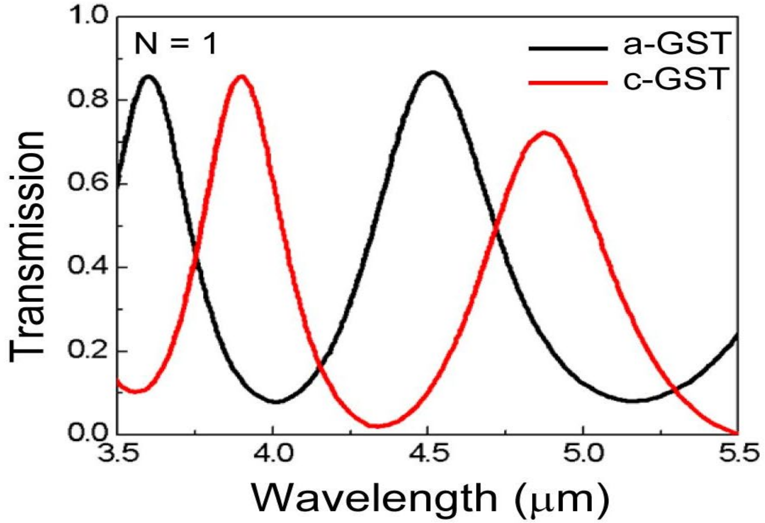


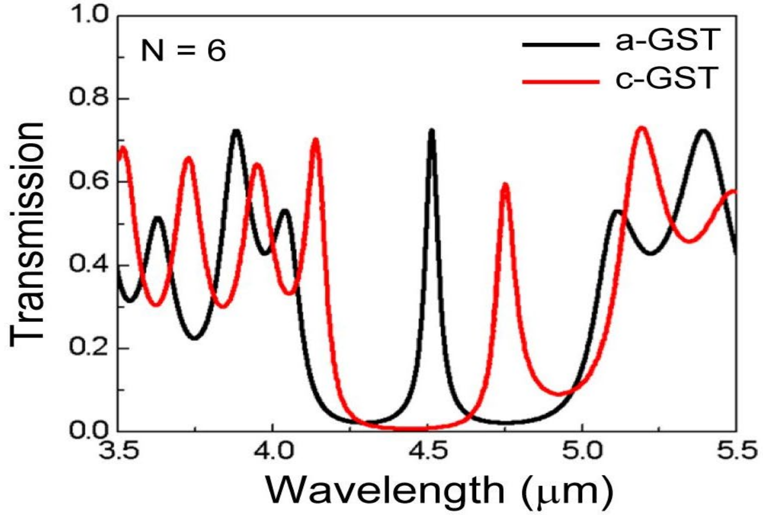
Prototype 1: Fabry-Perot Bandpass Filter with $Ge_2Sb_2Te_5$ cavity

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



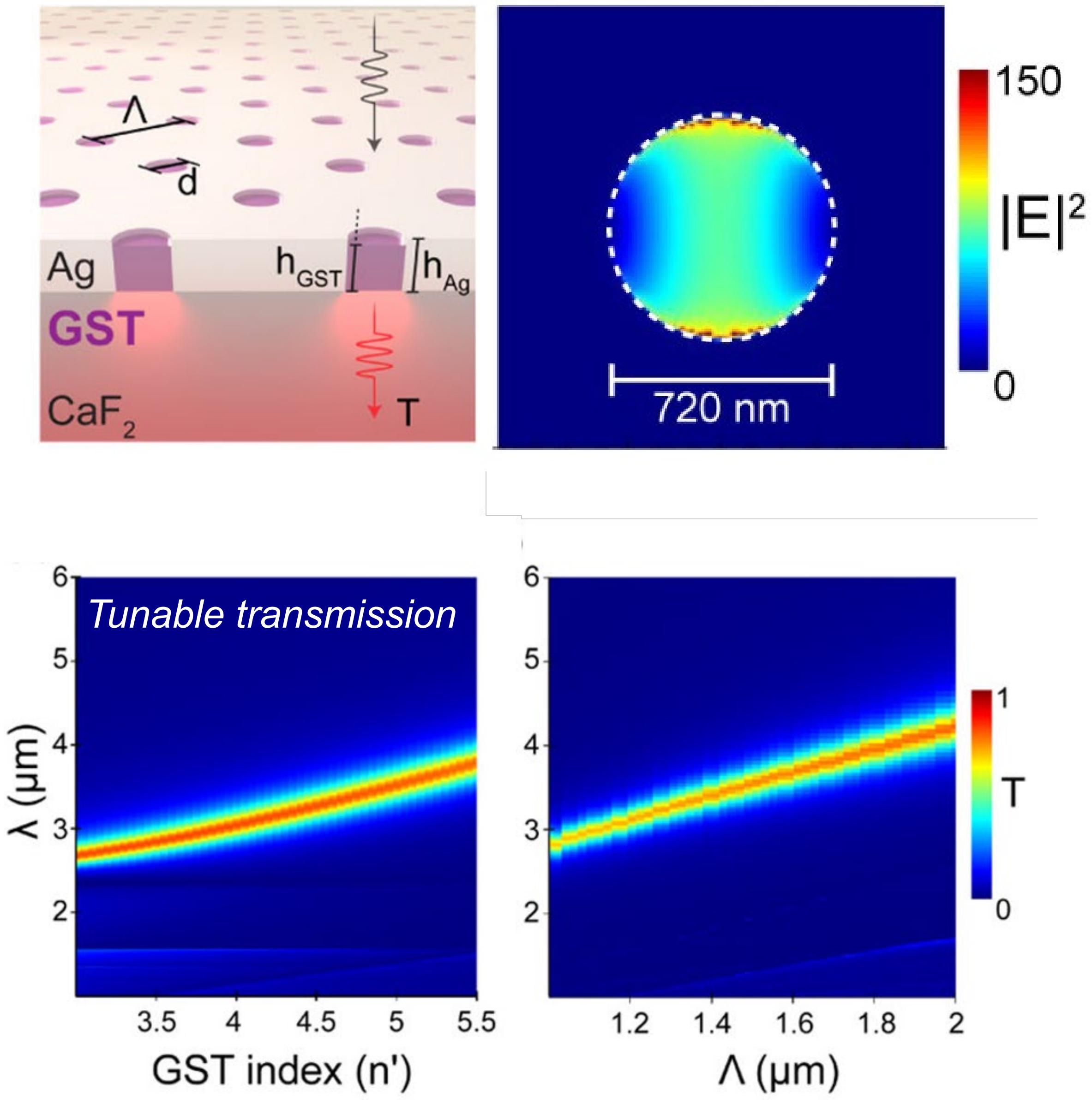






C. Williams. et al, Optics Express 28(7), 10583, 2020

Prototype 2: Metasurface filter with embedded GST



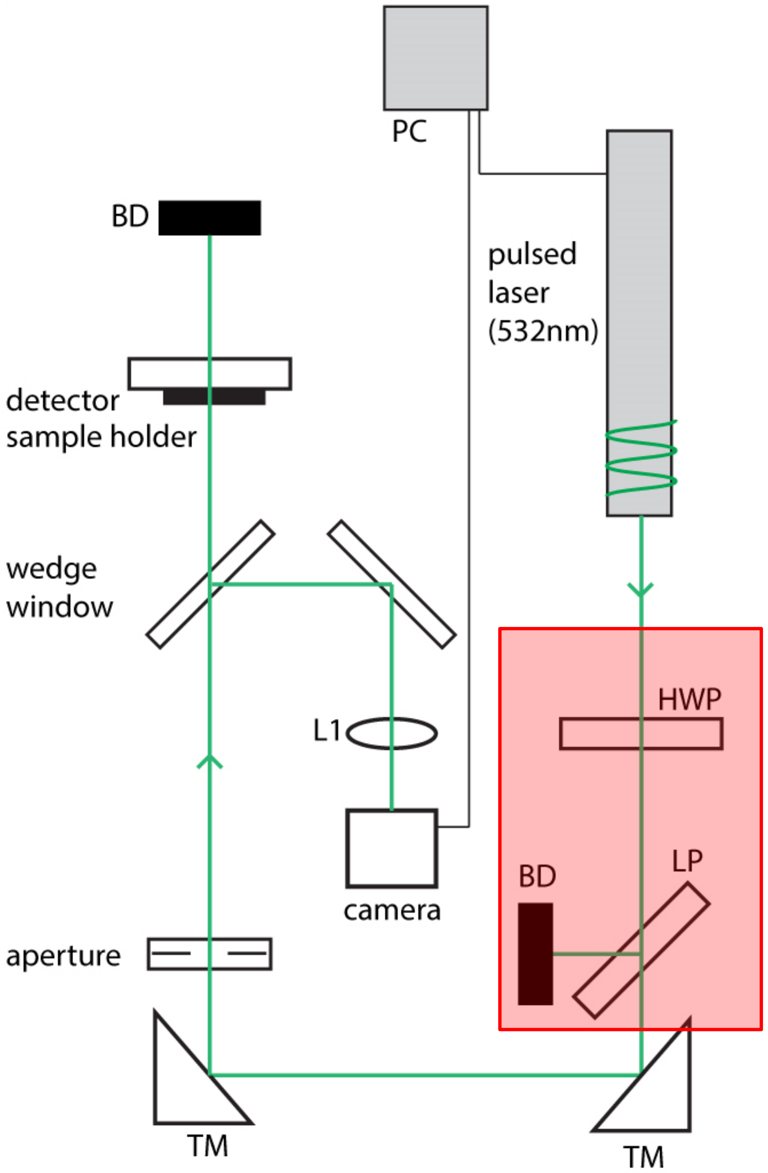
- Metasurfaces are sub-wavelength arrays which can be designed to strongly interact with the light

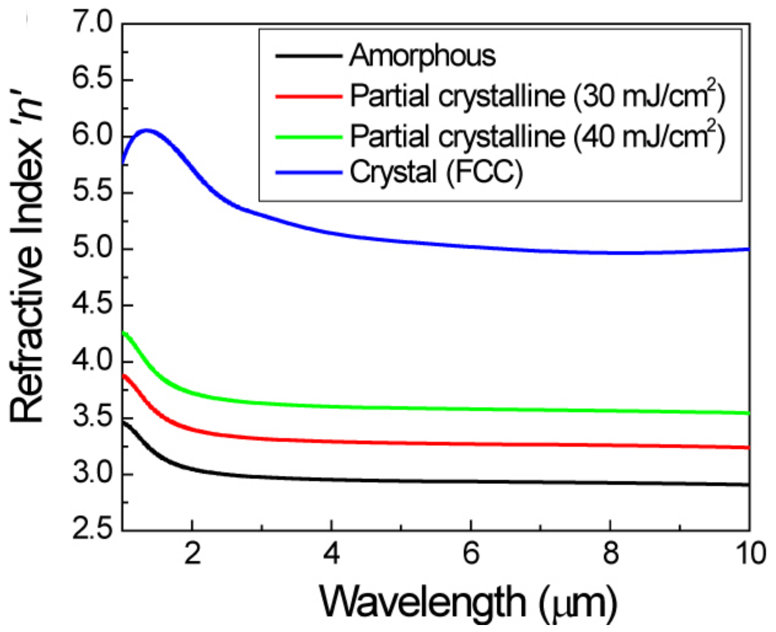
- We utilized a Plasmonic Nanohole Array (PNA) metasurface filter
- Integration of $Ge_2Sb_2Te_5$ (GST) with PNA
- Transmission response dependent on hole index. Holes filled with GST (tunable)

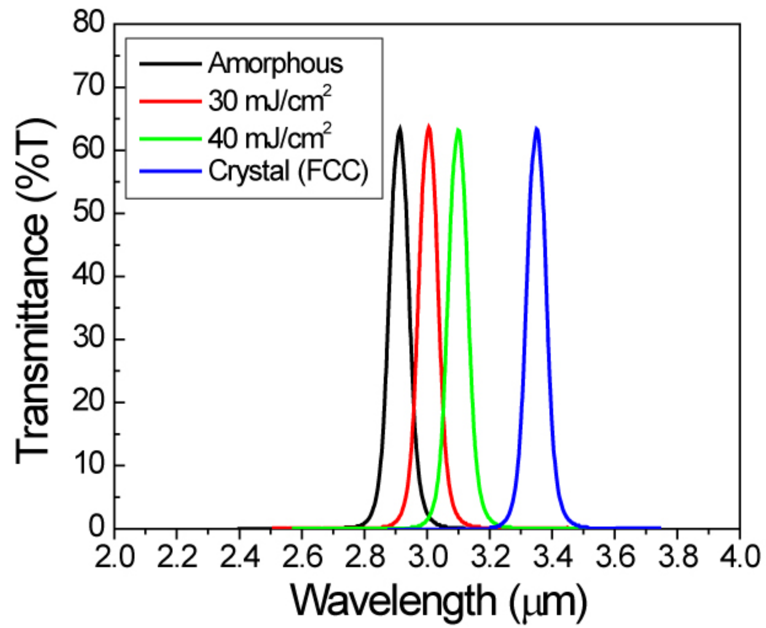
- **GST filled nanohole arrays associated resonance at particular WL in metal film → transmission mode filtering**

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

Pulsed-laser switching setup enables rapid center wavelength tuning

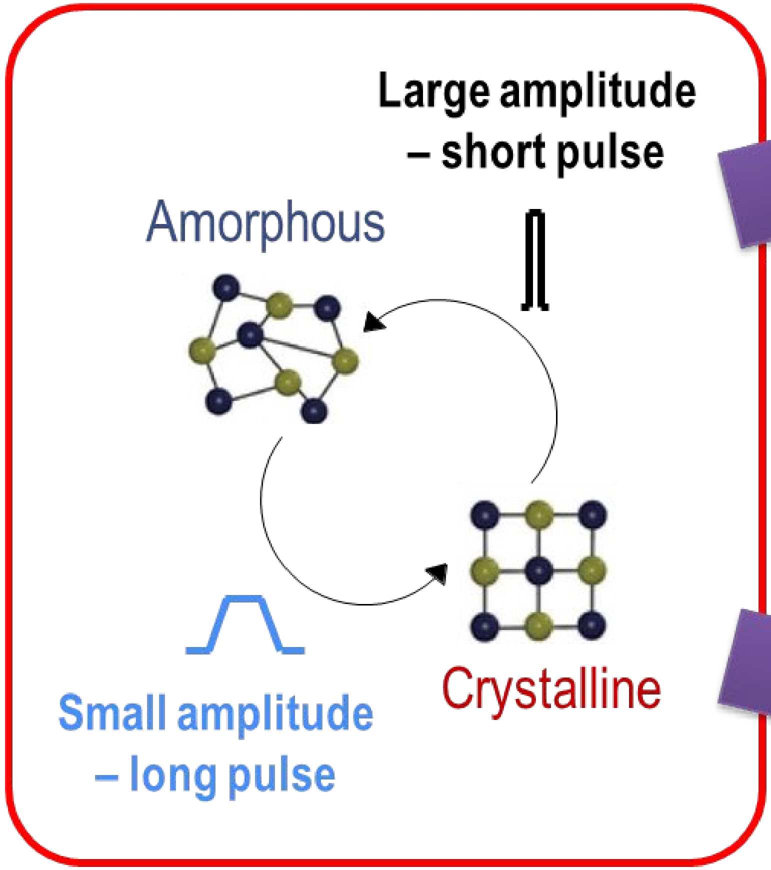


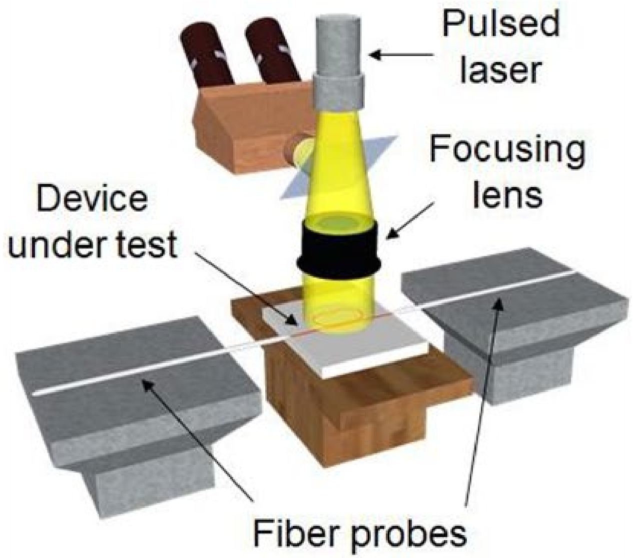




- GST-PCM is generally considered to be a 2-bit material ('0' / '1'), either amorphous (2.9μm) or crystalline state (3.4μm).
- Partial crystallizations of GST-PCM experimental demonstrations

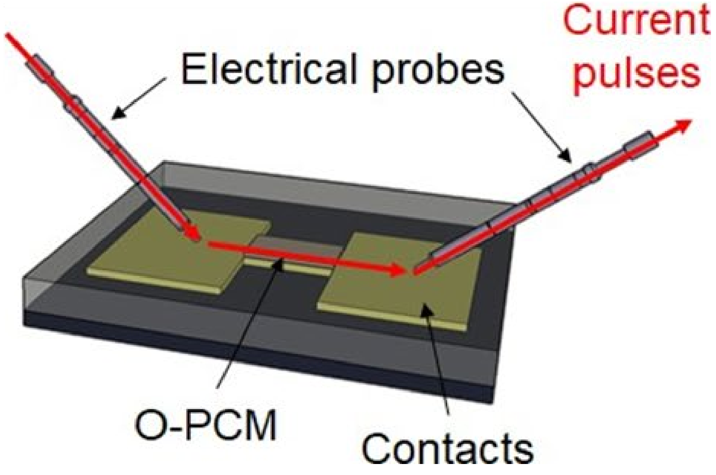
Optical and electrical switching of PCMs





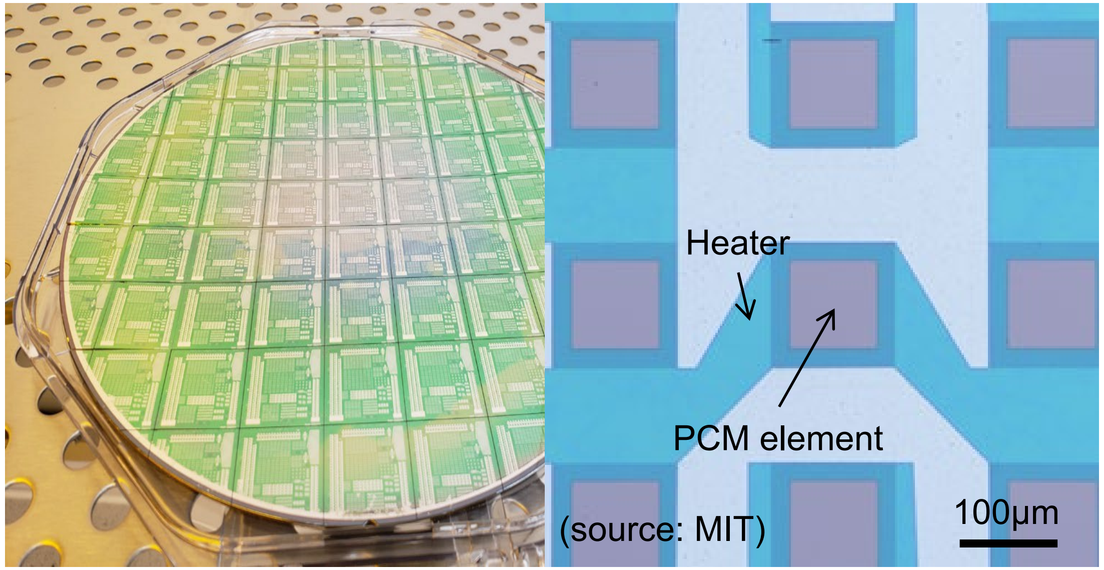
Optical (laser) switching

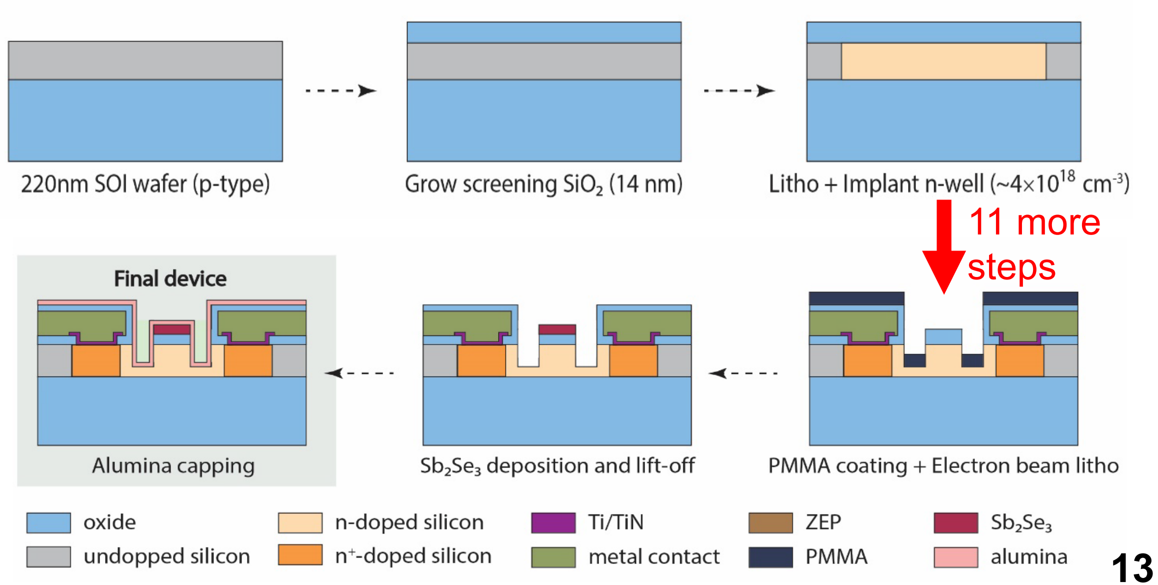
Electro-thermal switching



Electrode heater array is the core of the technology

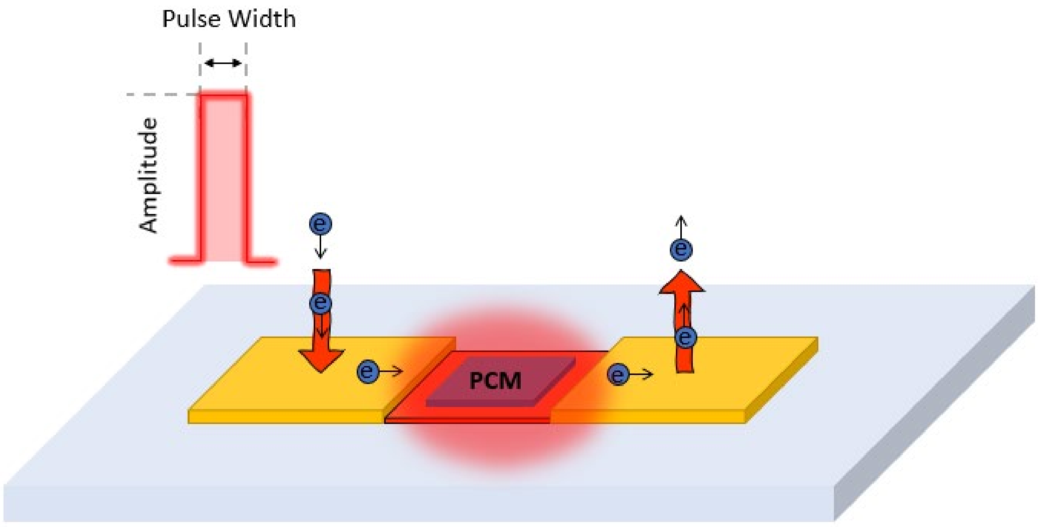
- A universal reconfigurable meta-optics/photonics array integrating phase change materials (PCM)
- Programmable 2-D high-density matrix for element-level arbitrary optical property manipulation
- Array of elements containing silicon heaters with PCMs and integrated diode selectors and cross-bar electrical connections
- Scalable, CMOS-compatible manufacturing

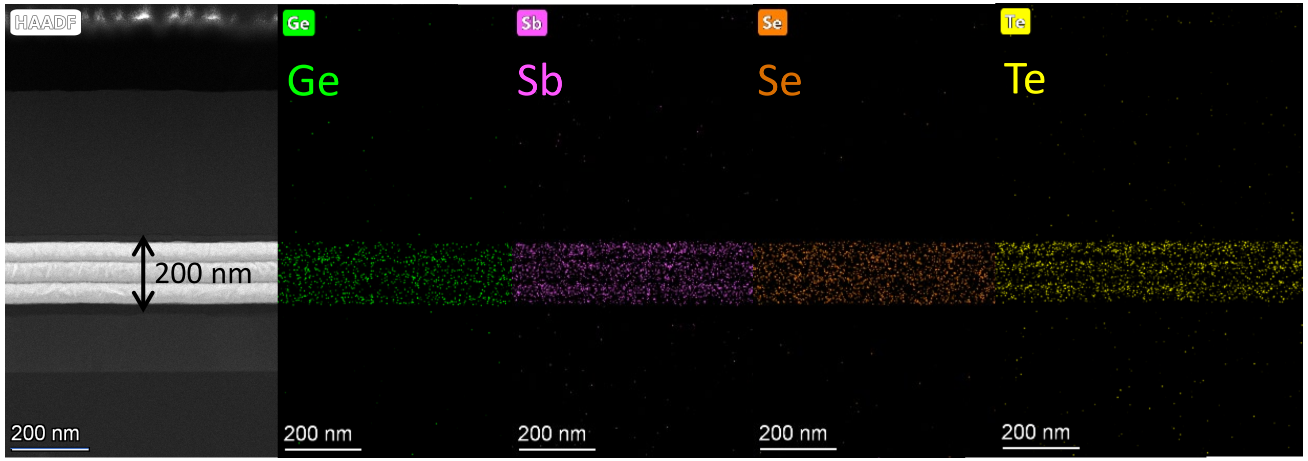




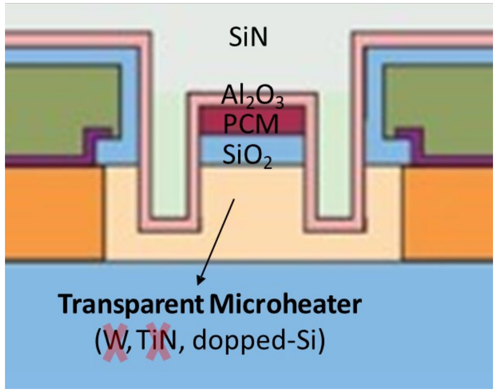
C. Popescu. et al, SPIE Proc. https://doi.org/10.1117/12.2657208 (2023)

Switching PCM via electrical pulses



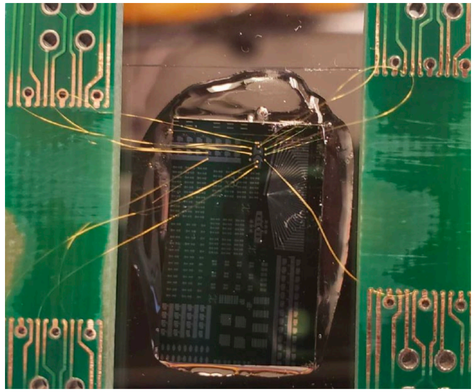


Device Architecture



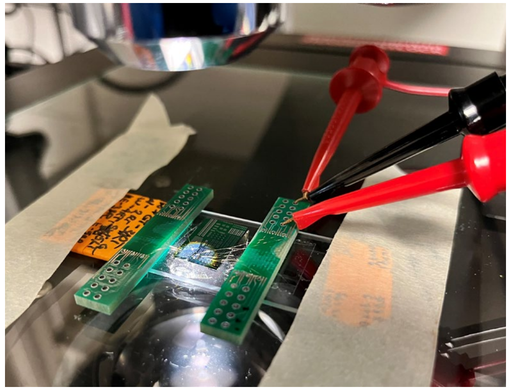
Electrode design change and different encapsulation employed

Fabrication



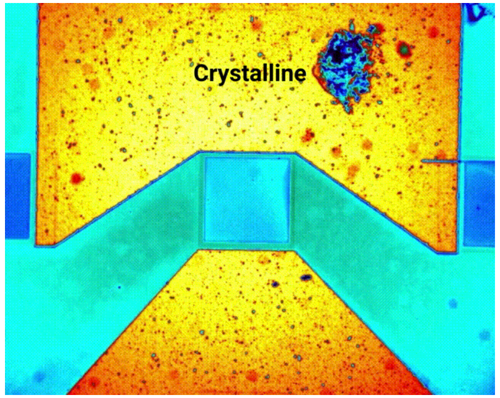
Prototype with (transparent) electrode heater

Measurement



Polished sample for transmittance testing

Evaluation

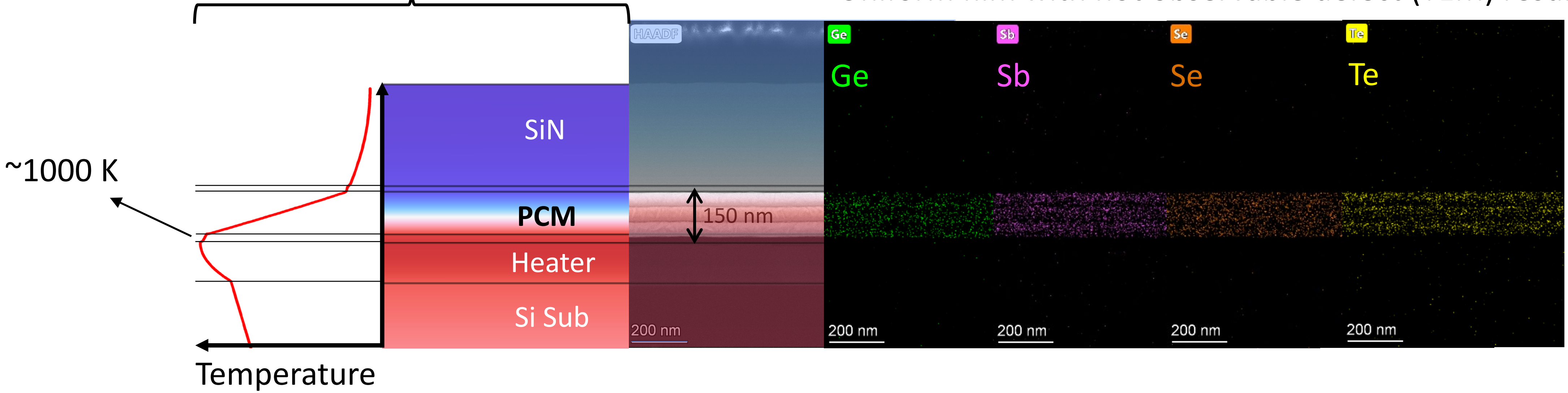


> 35,000 switching cycles demonstrated

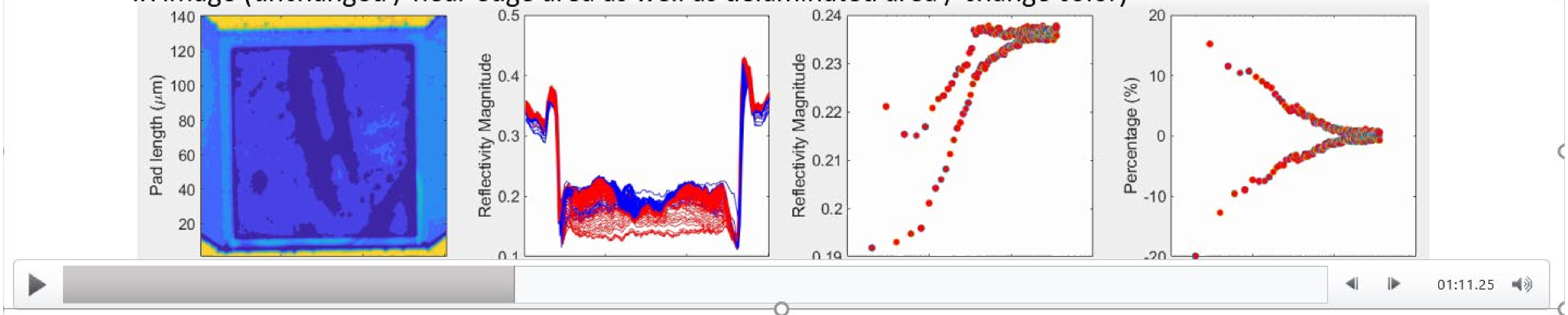
Durability and source of failure (periodically sent A and C pulses)

COMSOL Simulation

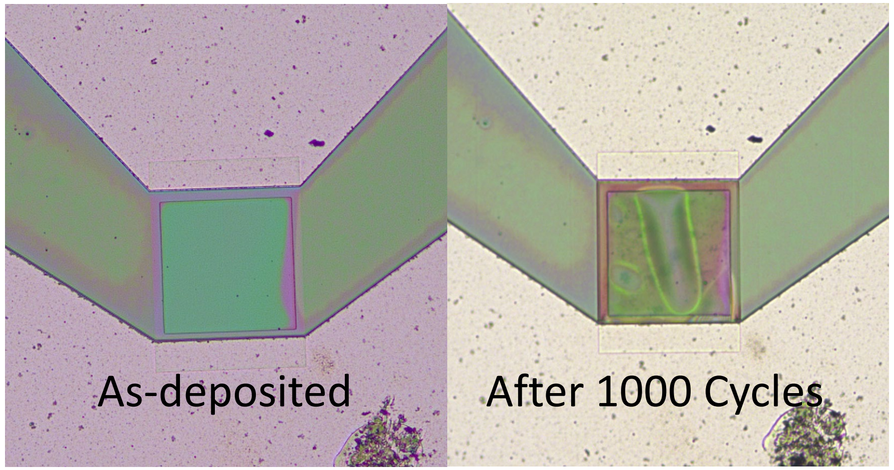
Uniform film with not observable defect (TEM) result



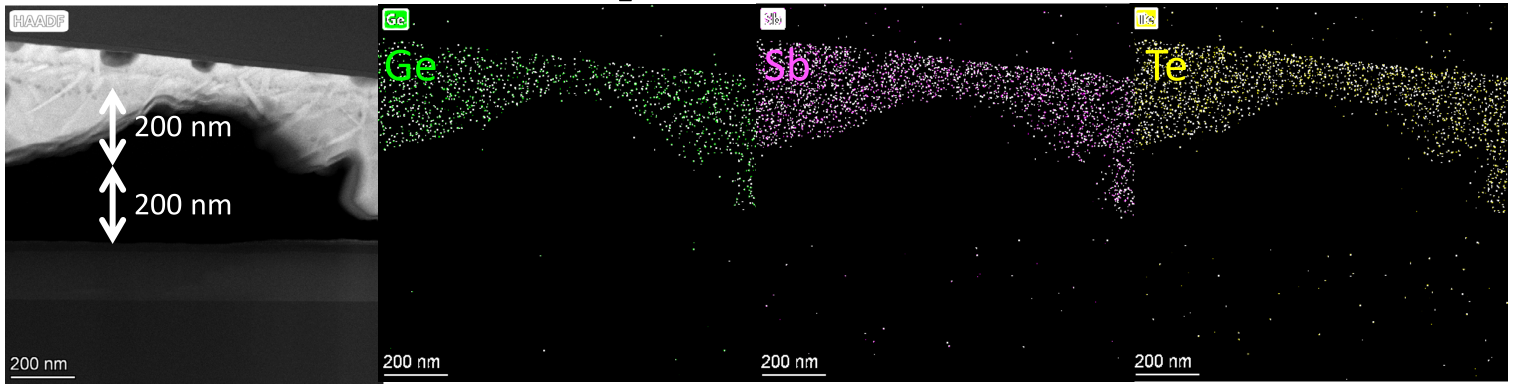
IR image (unchanged / near edge area as well as delaminated area / change color)

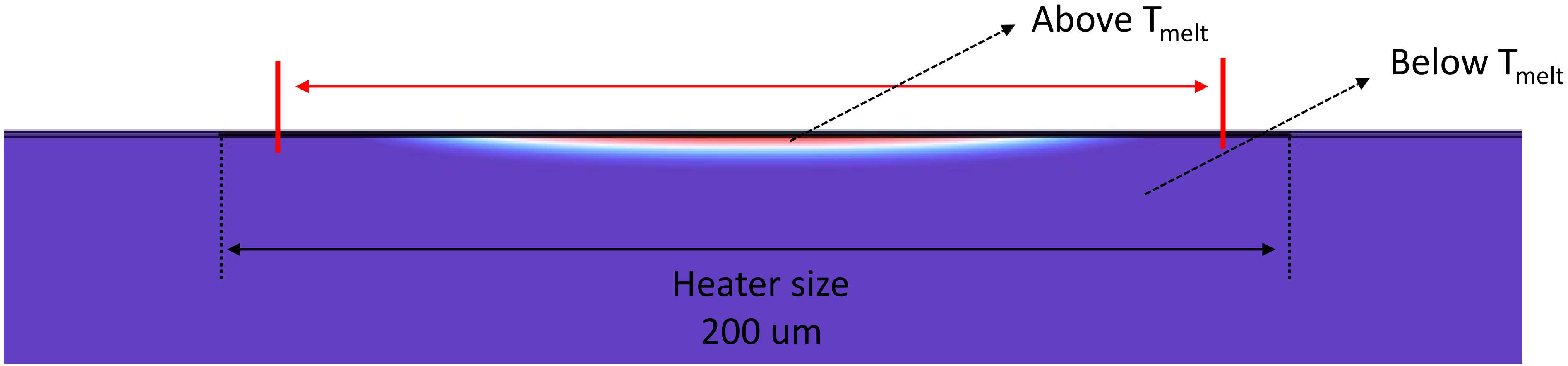


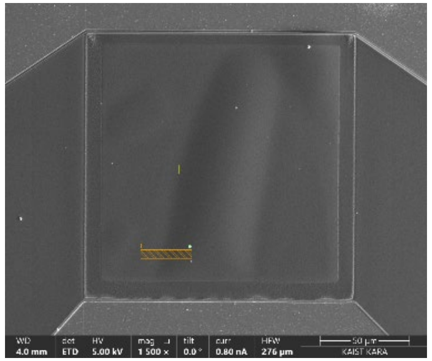
Durability and source of failure

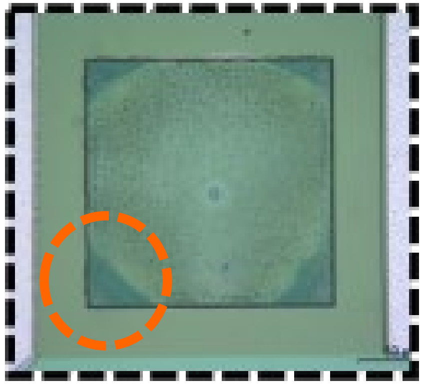


Delamination between SiO_2 and PCM interface (max. up to 1000 K)







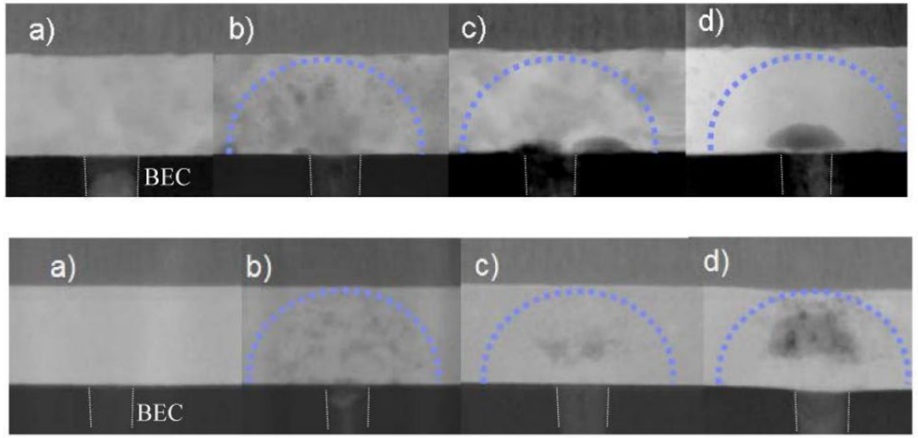


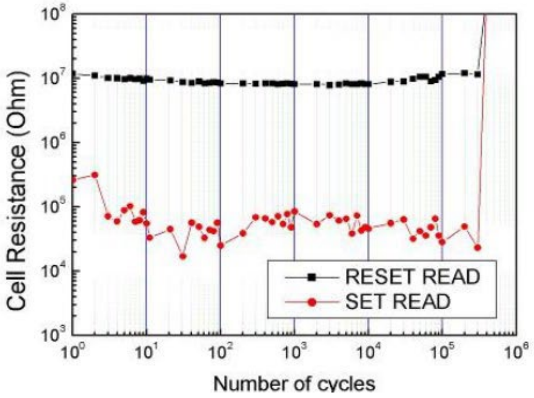
Three major reasons…and more!

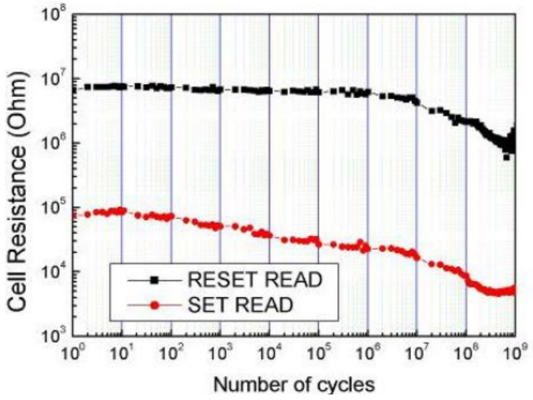
- PCM is not bonded well to the SiO_2 layer
- Non-uniform stoichiometry of GSST (Ge-rich area closer to the heater side), uniformity on crystallinity
- Lateral heat distribution profile (COMSOL simulation), sharp temperature gradient near the edges of the heater

Endurance of PCMs

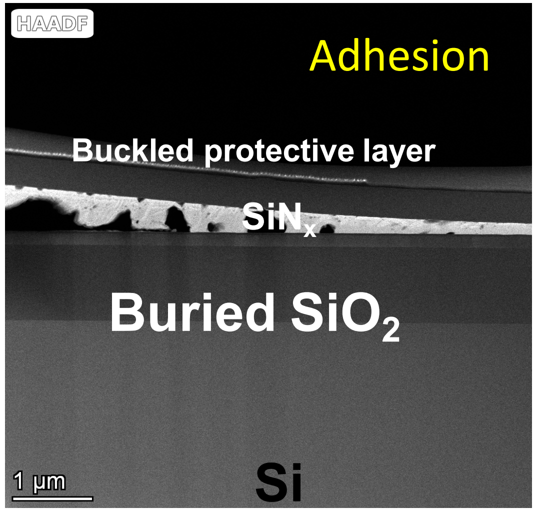
- Electrical phase change memory – resistance

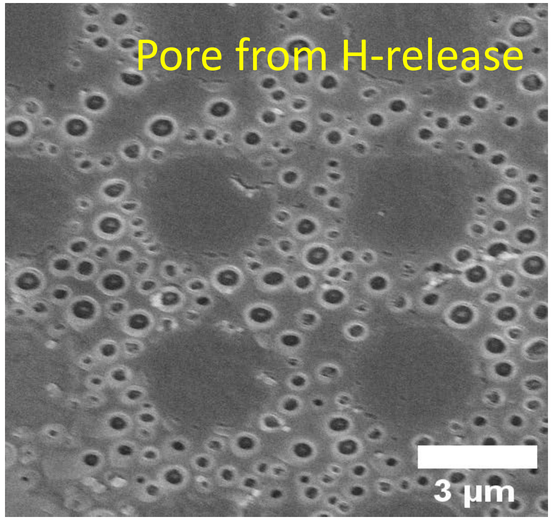


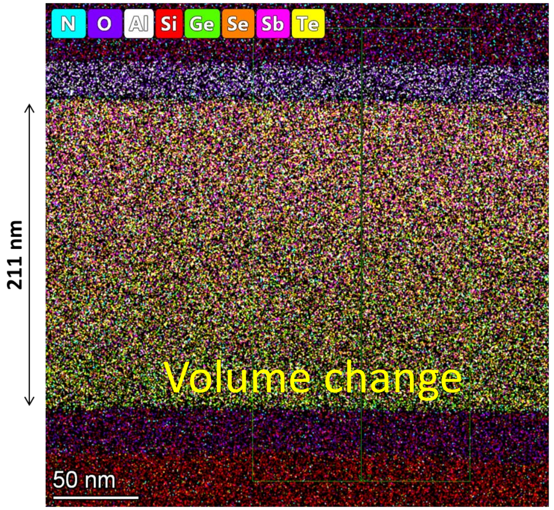


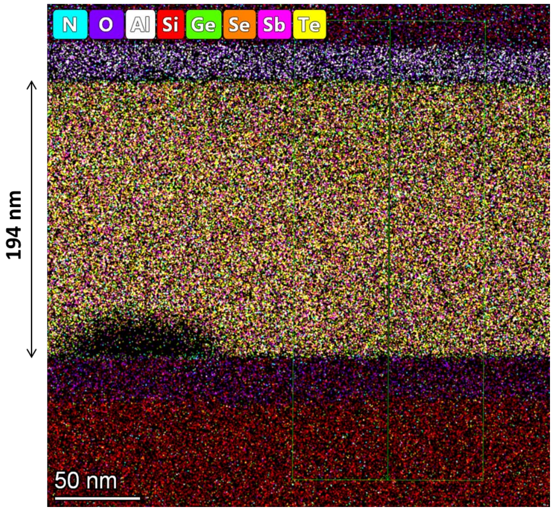


- Optical phase change device- transmission/reflection



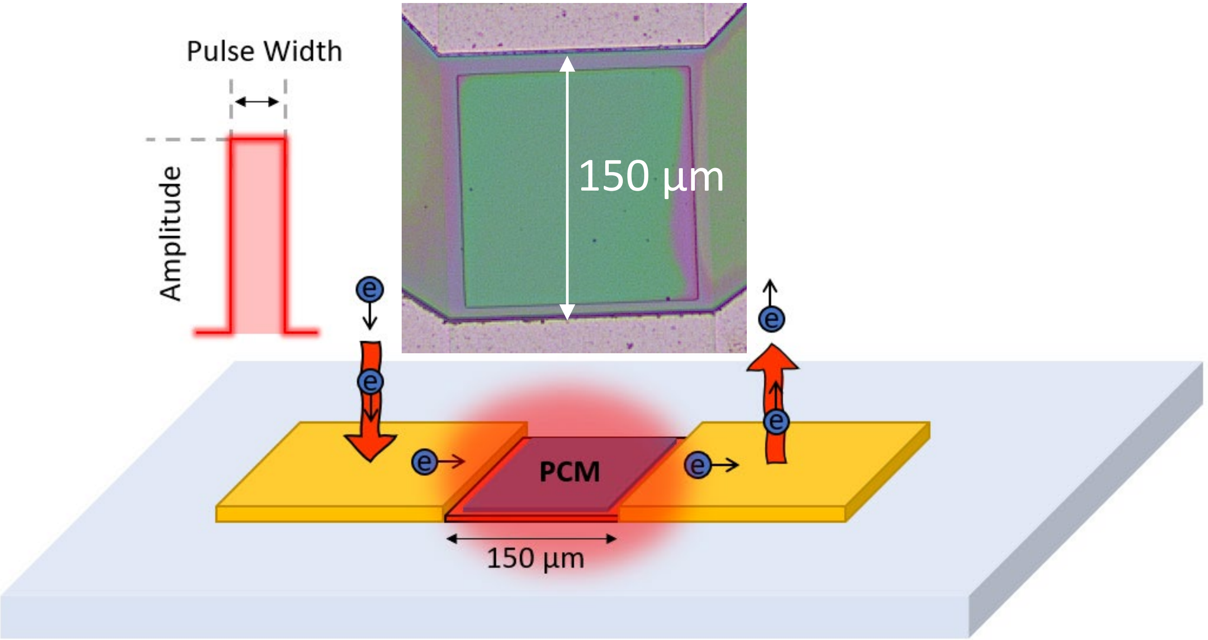


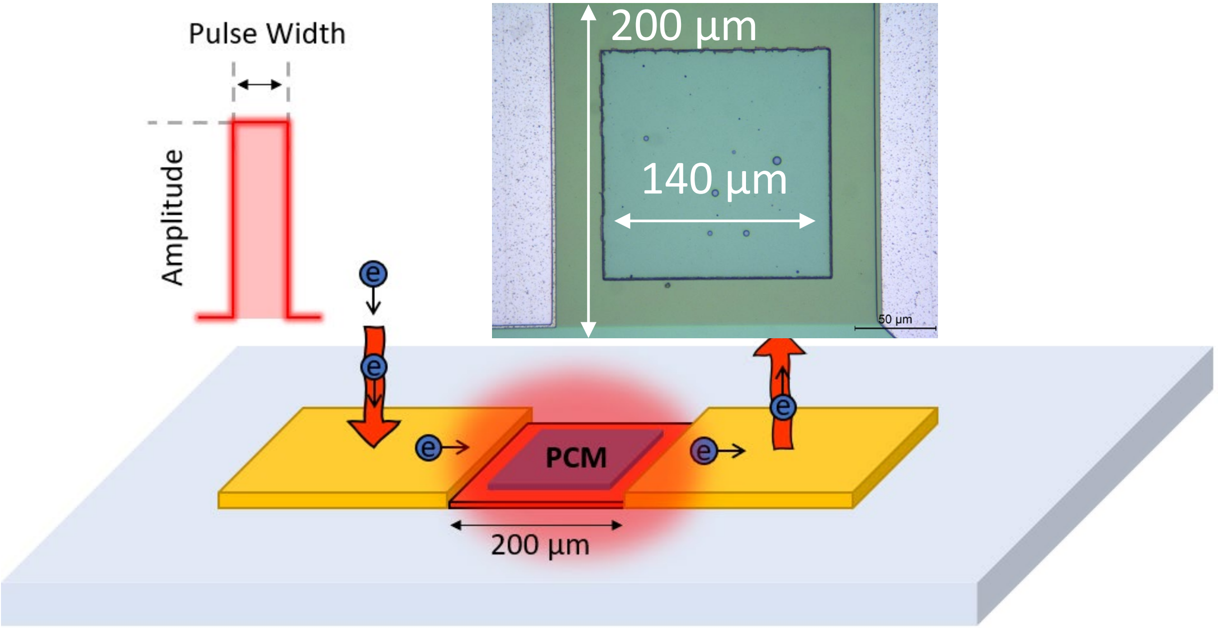


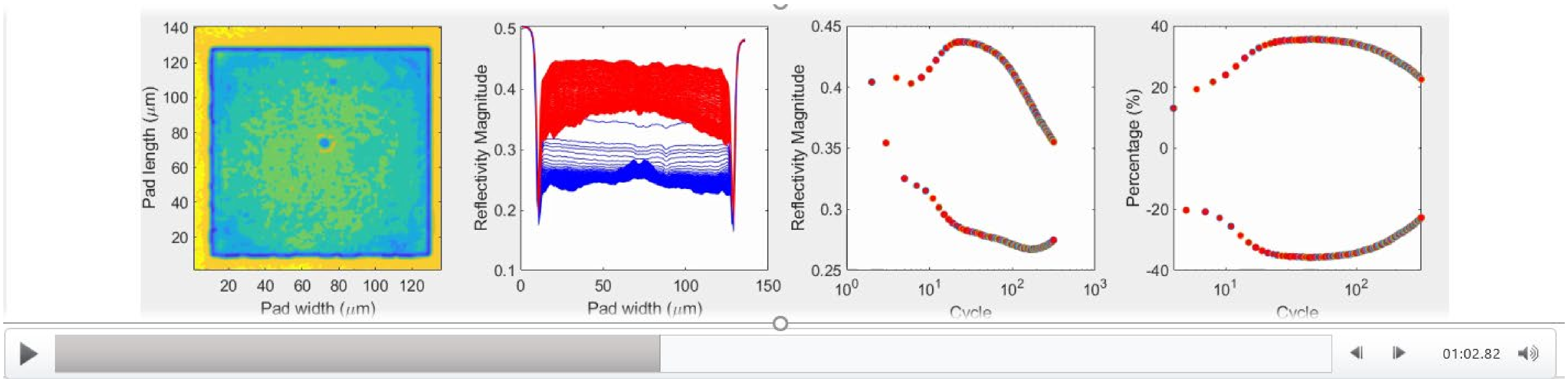


✓ Chen et al. *IEEE Int. Memory Workshop.* (2009)
✓ C. Popescu. et al, SPIE Proc. https://doi.org/10.1117/12.2657208 (2023)

Improving the device endurance



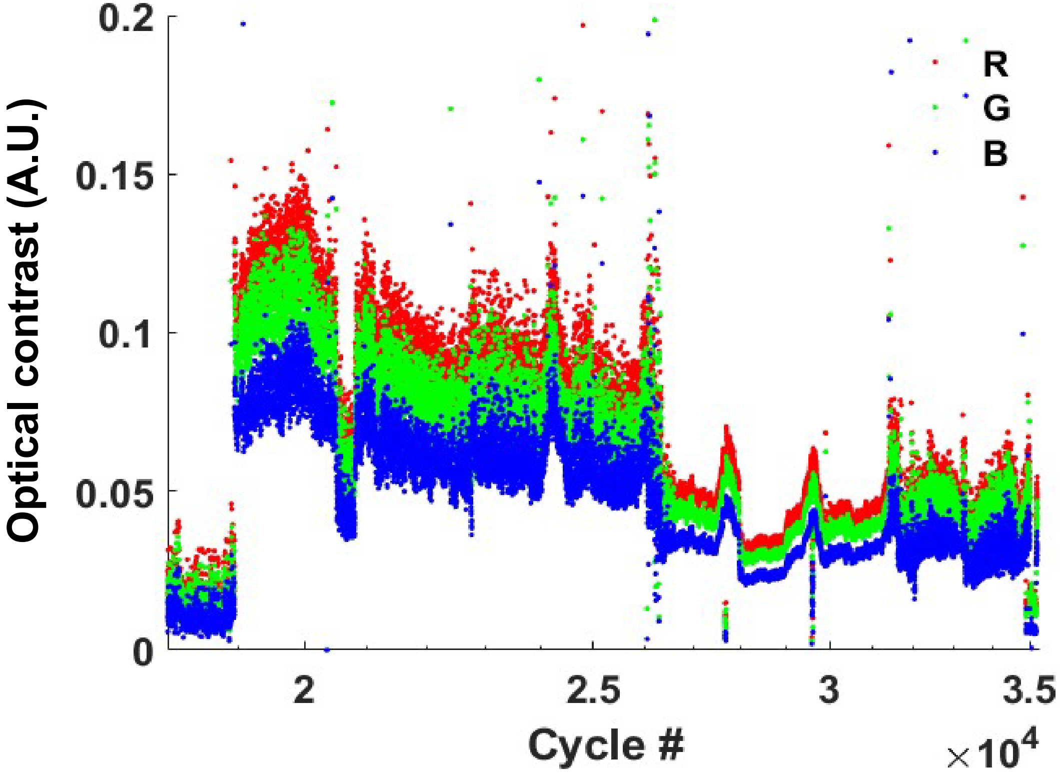




Endurance improvement in large-volume optical PCM switching

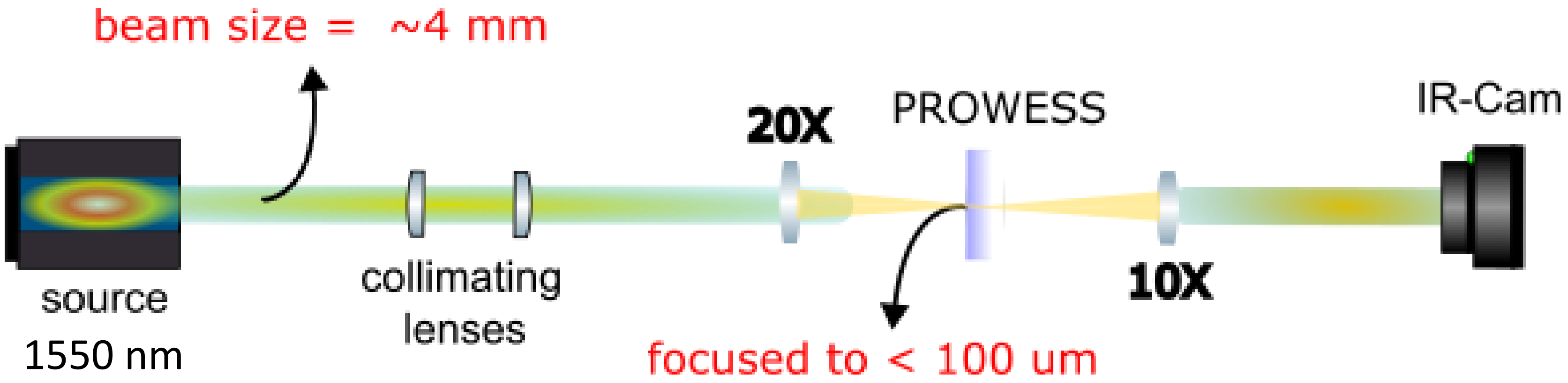
PCM switching volume: ~ 4,000 μm^3

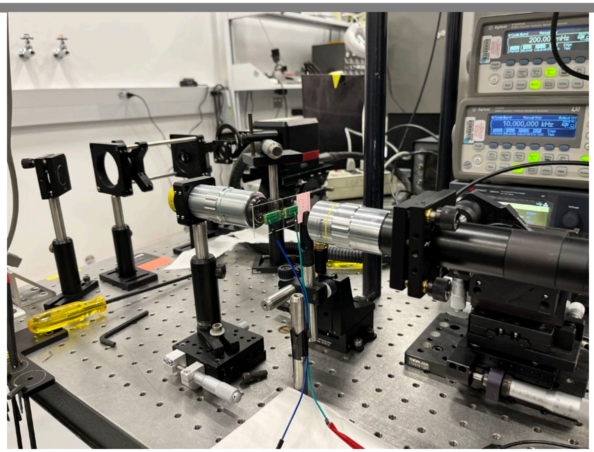
100 million times larger than that in PCMemories!



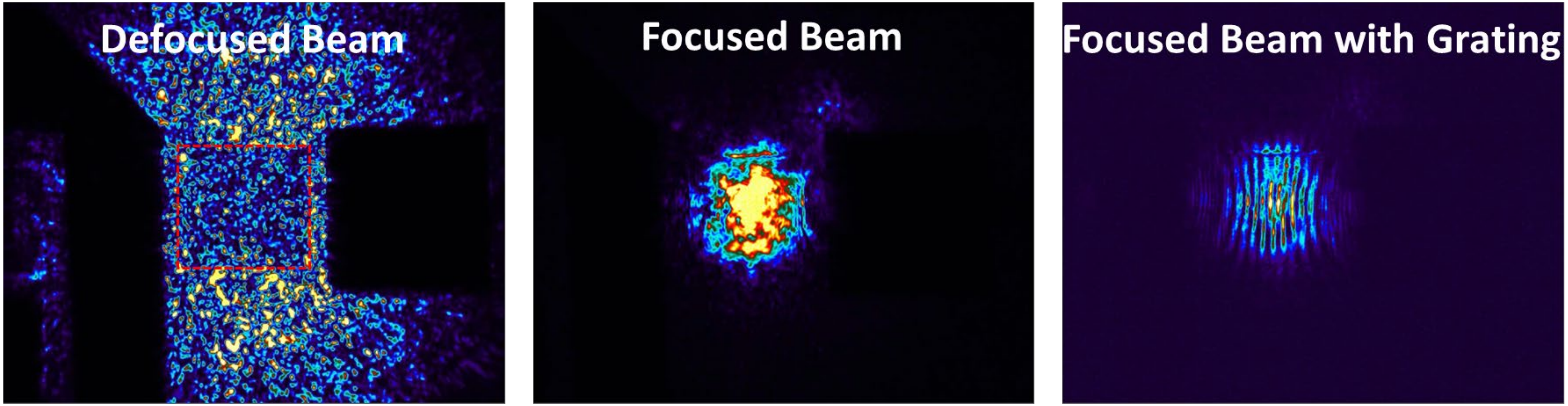
> 35,000 switching cycles demonstrated

Light manipulation – No surface functionality

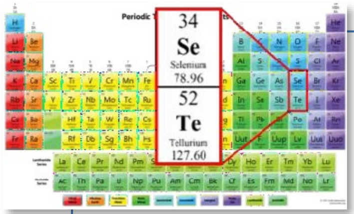




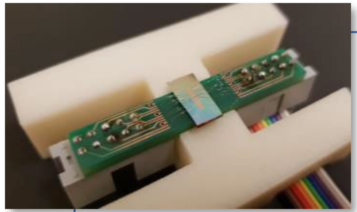
Investigate how the PCM behave across phase transition when a monochromatic 1550nm beam is focused on the PCM pixels



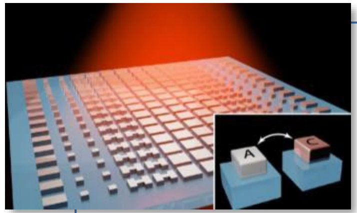
Outline



Phase change material (PCM) & P-ACTIVE



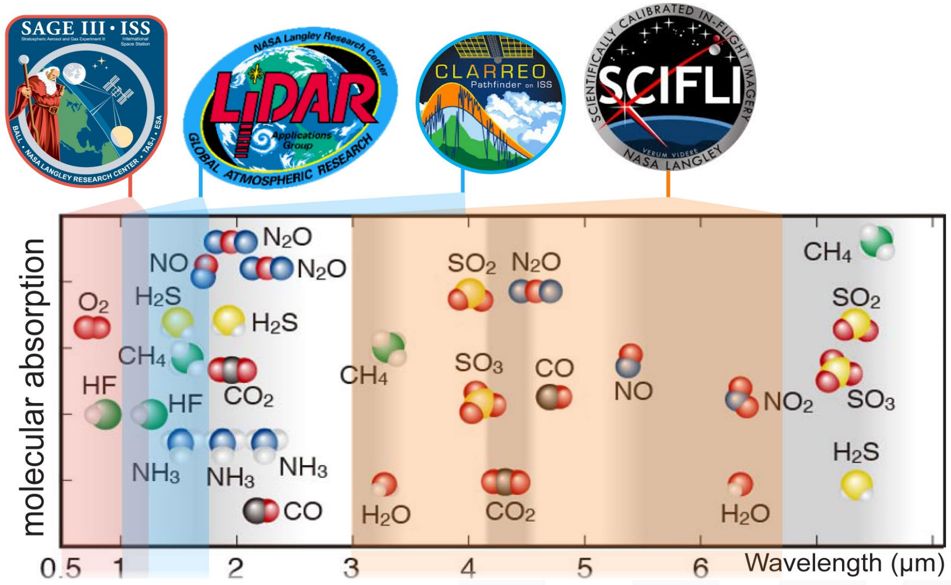
Electrical switching of P-ACTIVE



Path forward to Defense + Commercial Sensing

Future of P-ACTIVE

1-10 µm waveband, "Spectral Fingerprint"



- **Chemical/Gas sensing** – LIDAR Science mission
  - Rapid profiling of targeted observables, greenhouse gases (NO_2, CO_2, CO, SO_2), ozone, water vapor
  - DIAL (Differential Absorption Lidar) **on/off switch**: Capability to measure H_2O vapor & CH_4 profiles for deeper understanding of clouds responding to warming climate from greenhouse gases
  - SAGE III / IV mission **multispectral filter** wheel
  - (future) SAGE-IR in space (SmallSat-based)

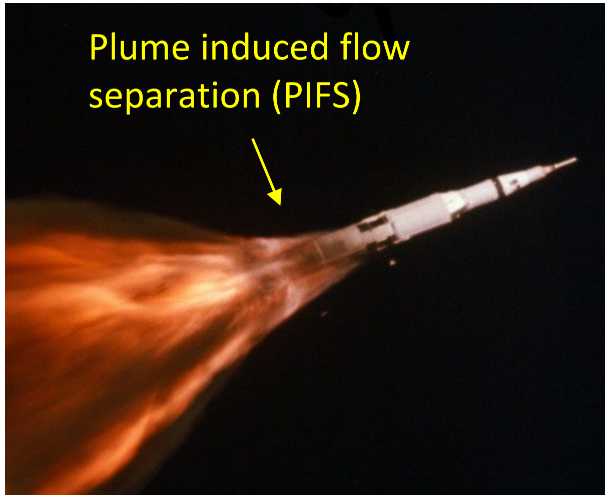
- **Thermal imaging** – SLS Space mission
  - Dynamic targets (e.g., turbulent plumes, volcano gases)
  - SCIFLI project **multispectral filter** wheel: H_2O & CO_2/CO rocket plume emission
  - Thermal Imaging Diagnostic for Satellite Thrusters

National Aeronautics and Space Administration

22

NASA Scientifically Calibrated In-Flight Imagery

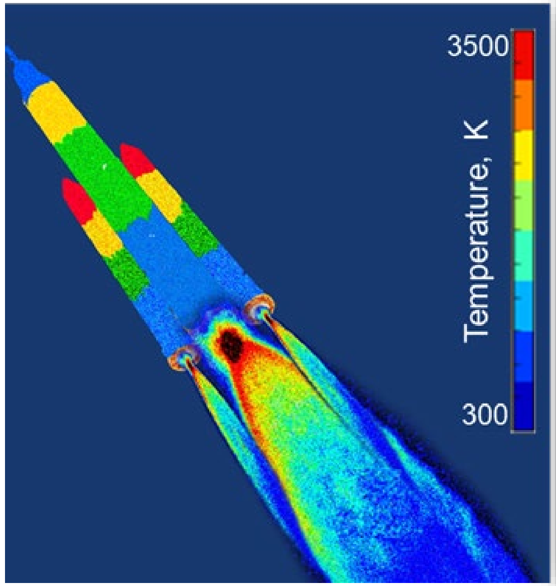
Apollo Saturn V

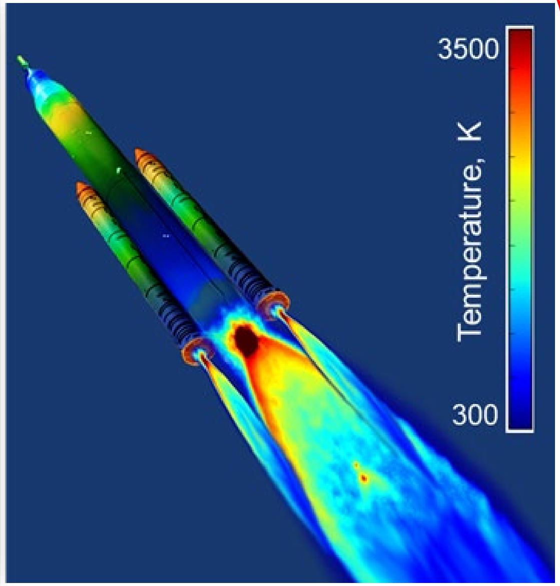


Kerosene + LOX

- Plume in VIS spectrum
- No temperature data

Artemis-1 Program





Hydrogen + LOX = H_2O

- Plume in MWIR spectrum
- Temperature retrieval possible

Goal: Obtain high quality thermal imagery data of the SLS base heat region and PIFS during ascent to validate / reduce required TPS mass for future flights – increased payload

Need: Reliable and adaptable MWIR filter for increased temperature accuracy from the current high speed (MHz), narrow band filter wheel – for next-generation active thermal imaging monitoring for future missions.

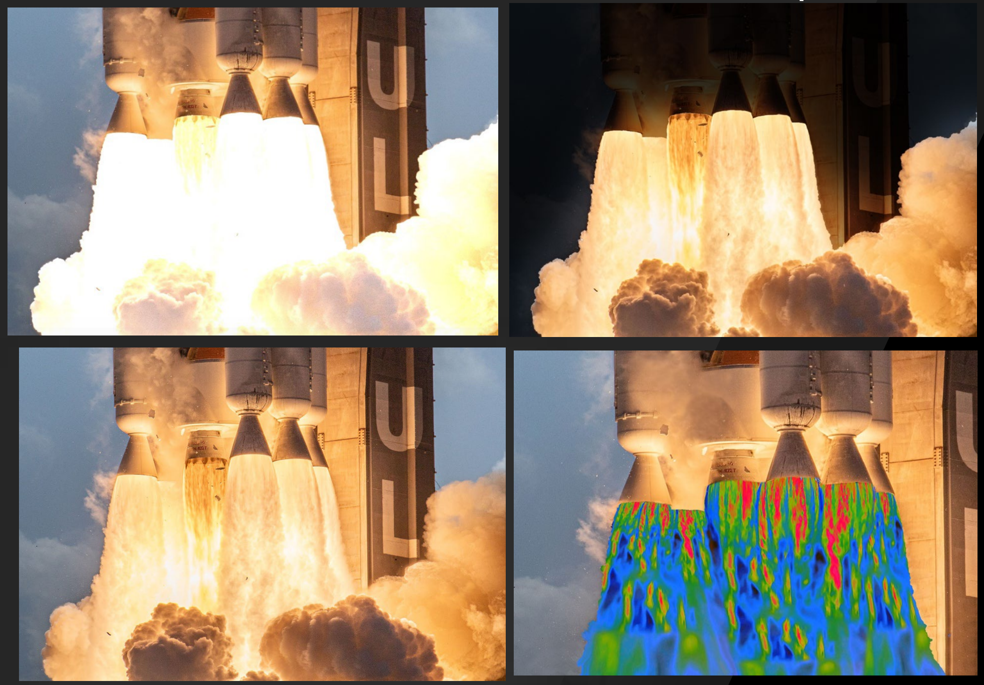
Credit: scifli.larc.nasa.gov

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

Extra information
Temporal
Spectral resolution

Accuracy improvement
Independent emissivity

Image detail improvement
Dynamic range improvement

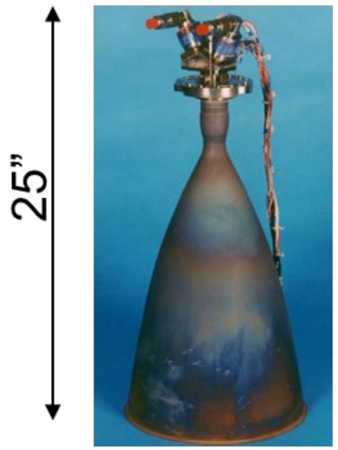


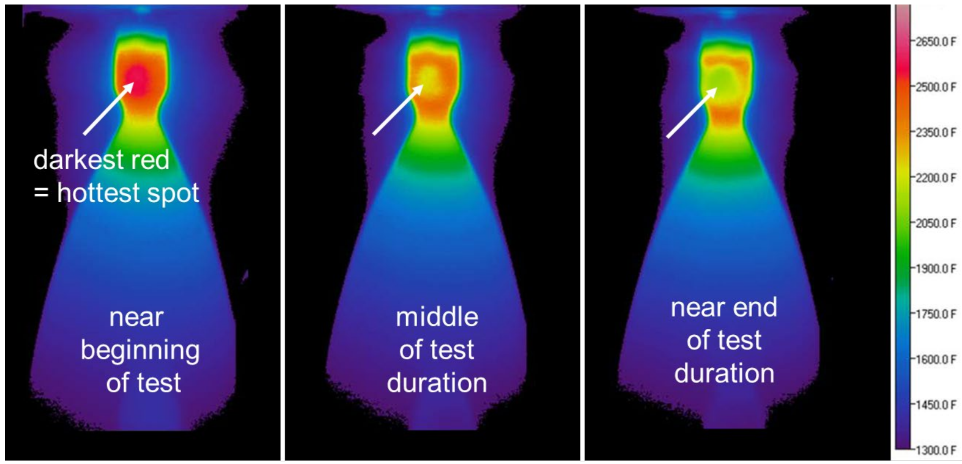
New aircraft opportunity
Smaller space
SWaP-C benefits

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

Thermal Imaging Diagnostic for Satellite Thrusters

- Satellite-sized thrusters are “small” relative to launch vehicles and historically have had very limited diagnostics during ground hot-fire test
- Current temperature data:
  - *Maximum temperature with time which is related to material life*
    - In many engines max temperature is obtained by a 2-color pyrometer aimed at the throat (which assumes that is the hottest spot – which may not be true)
    - Engine manufacturers started using IR cameras, but still only used the 2-D image to obtain the maximum value with time (with assumed emissivity value)
  - *Flange temperature measured by thermocouples*
    - Closest location to the chamber that uses a thermocouple
- Anomalies pointed out that we need to know “where” the hot-spot is located
  - *Movement / change of the hot-spot is early sign of trouble*
  - *Asymmetry / localized heating is also an indication of trouble*
- IR camera data are impaired by emissivity changes
  - *Don’t know absolute temp or even relative if local changes in emissivity occur*





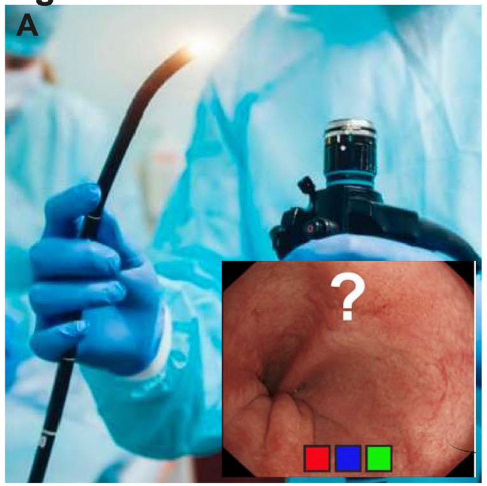
Steven J. Schneider et al., NASA TM 105348 (1991)

Multispectral Imaging Sensor for Biological Molecules

1. White-light endoscopy (WLE) is indispensable for minimally invasive medical diagnostics and therapeutics. Identifying abnormal tissue during an imaging procedure is incredibly difficult even for specialists.
2. Incorporating these measurements (contrast mechanisms), while maintaining existing thigh resolution imaging capability, into the increasingly tiny image sensor technology used in SOA chip-on-tip endoscopes presents a substantial technology challenge.
3. Time-gated P-ACTIVE with broadband SWIR sensor, filter has two center wavelengths, ns tuning speed required for in-situ all-optical diagnostics

NOW → **NEXT** → **FUTURE**

Fig. 1



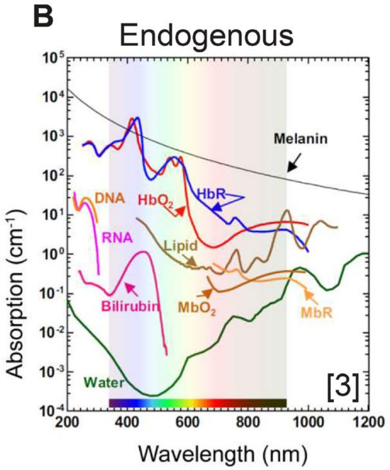
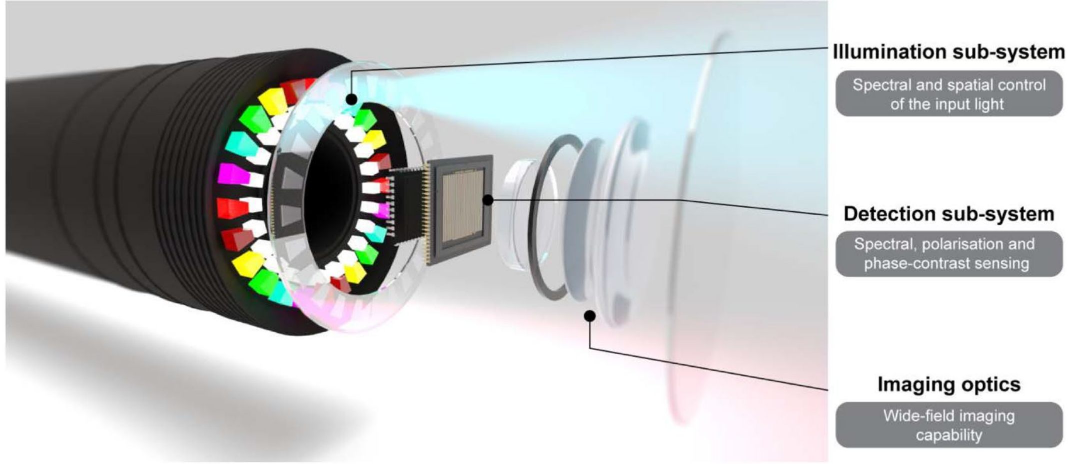


Fig. 2

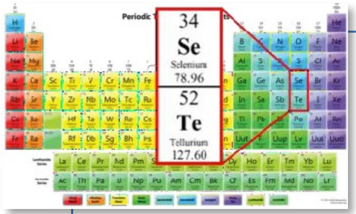
Credit: Olympus

Fig. 3

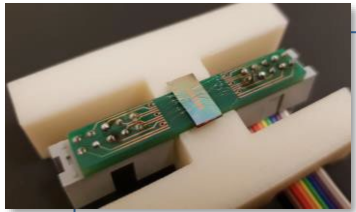


C.Williams, C.Hooper, G.S.D. Gordon, M.Julian, H.J.Kim, S.E.Bohndiek, "Nanostructured optical devices for miniaturized multi-functional imaging", UK Metamaterials Network Conference (2022)

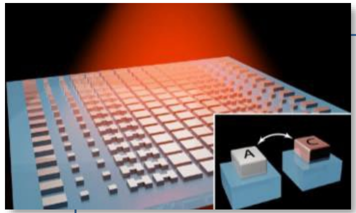
Summary



With its low optical loss, large index change and switching volume, PCM is an ideal material for active metasurfaces



PCM-based actively tunable filter (P-ACTIVE) was demonstrated for the first time for NASA science and space missions scenario



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

Future of P-ACTIVE & PCM-based photonics

PCM in ISS through MISSE-14 test campaign

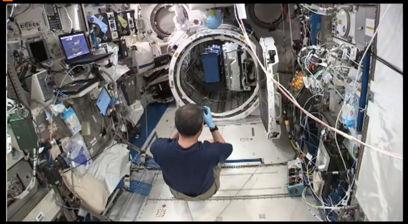
- MISSE - Materials International Space Station Experiment – materials and devices exposed to the space environment (LEO, space below an altitude of 2,000 km), atomic oxygen, -120 °C to 120 °C temperature extremes, hard vacuum, UV radiation, charged-particle radiation.

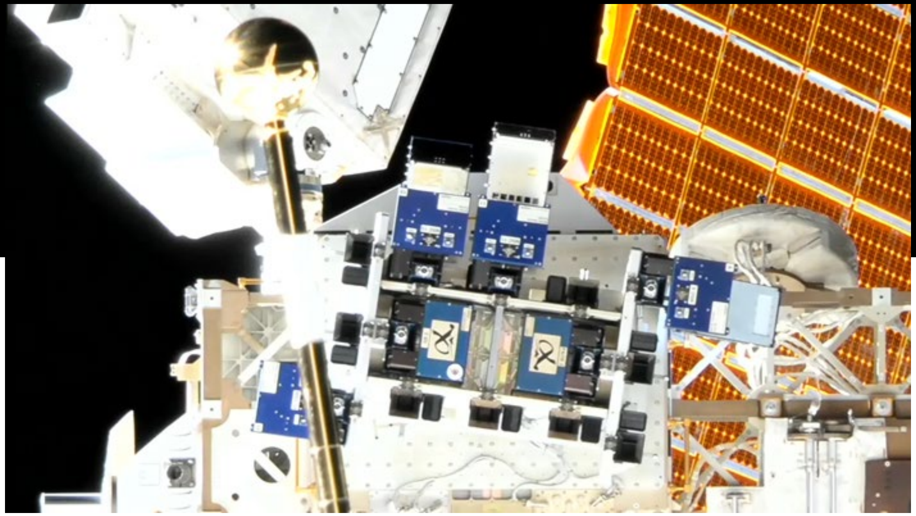
Launch 02/20/2021	Unpack / unsealing 04/08/2021	Deployment on orbit 04/25/2021	Return 01/25/2022

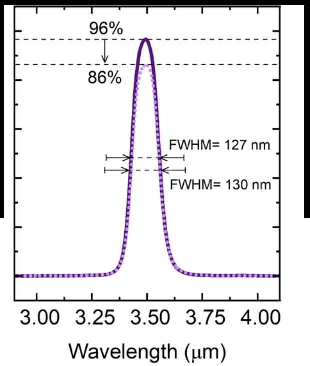
- Preparation
- Preflight characterization

Exposure & monitoring 06/21/2021-12/6/2021
(148 days 21 hours 11 minutes)

- Retrieval
- Post flight characterization



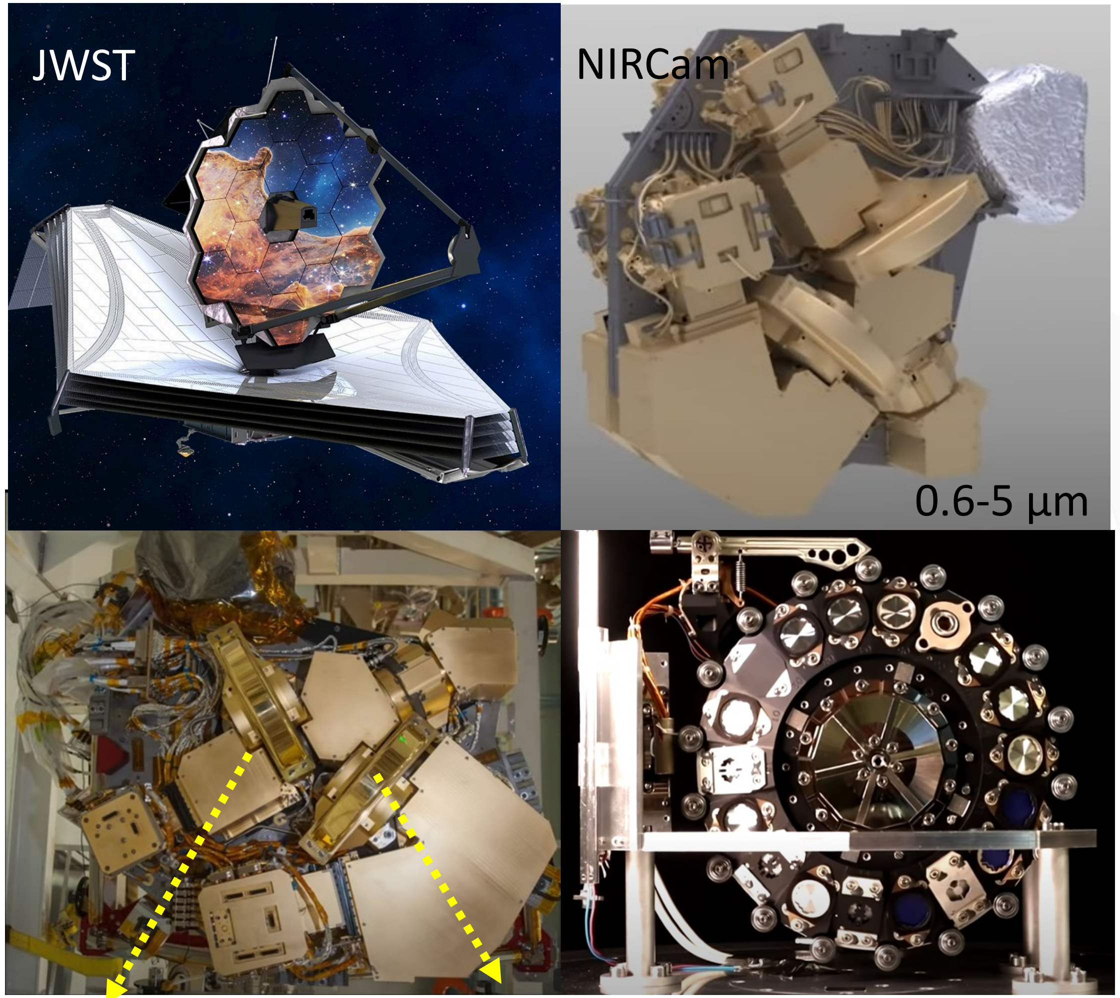




H. J. Kim et al, Nature Materials (under review, 2023)

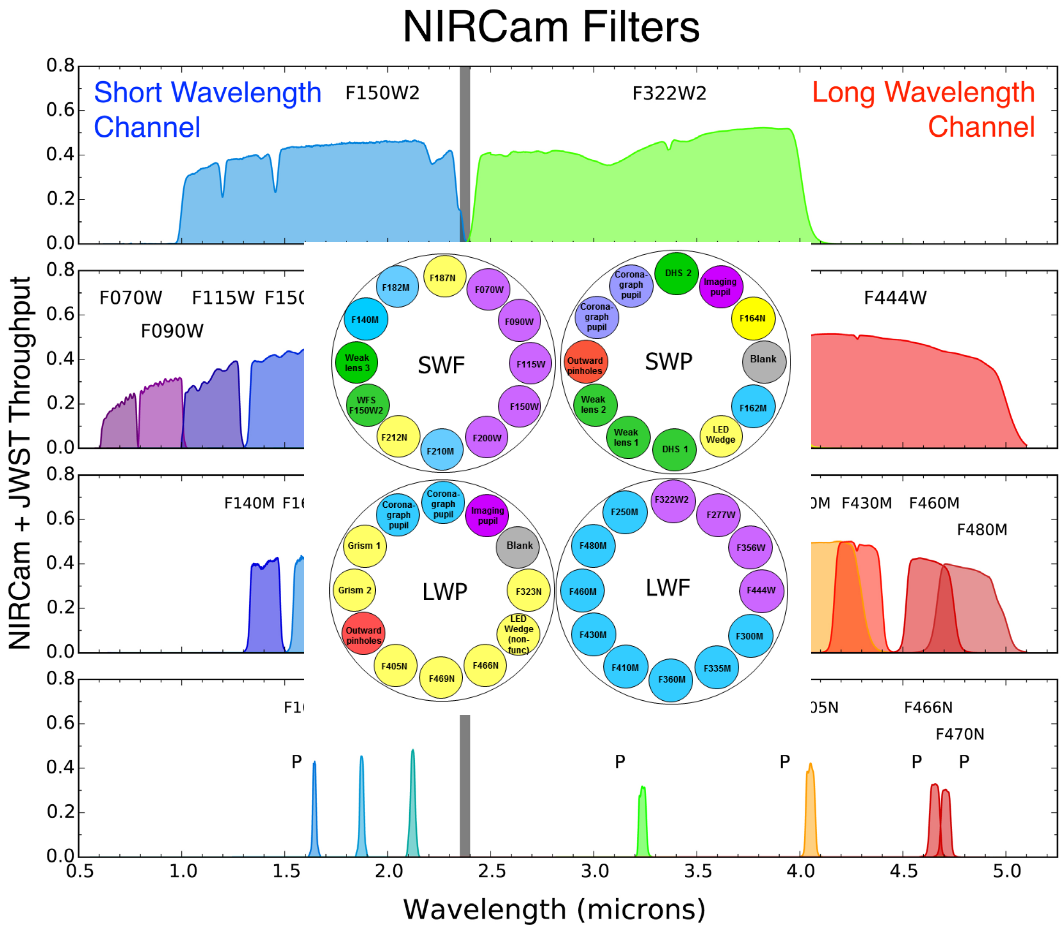
P-ACTIVE for Space Explorations

https://www.youtube.com/watch?v=MzWfUKOyvdY



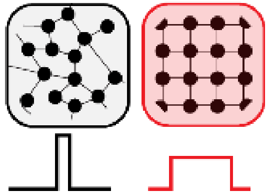
Long Wavelength Filter Wheel

Short Wavelength Filter Wheel



Future of reshaping light using PCM metasurfaces

a
Materials Property → **b** **Technology / Subsystem** → **c** **Applications**



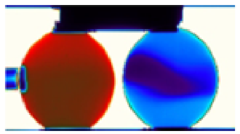
Refractive Index
Δn, Δk
Resitivity
$\Delta \rho$

Joule heating

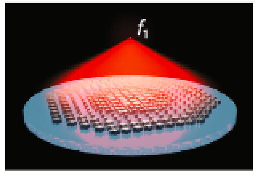
Optical pulse
Electrical stimuli

I/O

Tunable optical filters
- Smart coatings
- Switchable color pixels

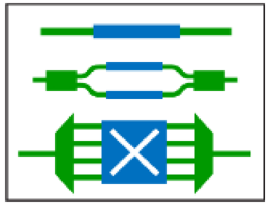


Active metaoptics
- Beam steering
- Flat tunable lenses



Switchable Fibre-optics

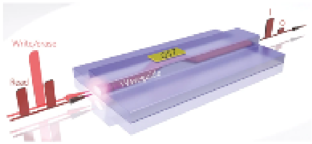
Photonic integrated circuits
- Optical phase modulator
- Optical ampltiude modulator



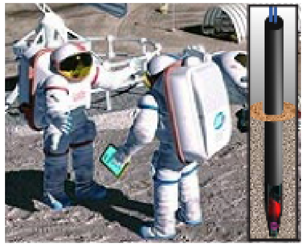
Miniaturized spectrometers

Multifunctional biosensors

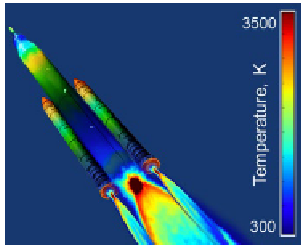
Nonvolatile memory
- Reconfigurable data elements



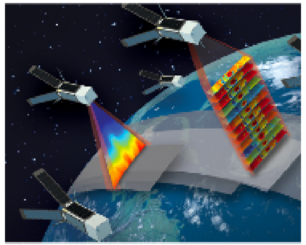
Local Optical Diagnostics
- Lab-on-a-Chip
- Astronaut Health Monitoring
- Optical gyroscopes
- Thermal control / visualization



Remote sensing
- LIDAR
- Wide-waveband thermal imaging
- Combustion diagnostics
- Hyperspectral imaging
- Miniaturized optical assemblies



Optical Communications
- High speed free-space & datacomms
- Inter- and intra-satellite links



Displays and panel coatings

Photonic Computing
- Low power data storage
- Quantum & neuromorphic circuits

- *T. Gu et al, Nature Photonics, https:// doi.org/10.1038/s41566-022-01099-4 (2023)*
- ***Dr. Tian Gu talk about "Dynamic light shaping using active optical metasurfaces" May 2nd (3:30 pm ~ 4:00 pm / Osceola 4)***