[Invited] Phase-change material (PCM) based actively tunable filters for both terrestrial and spaceborne platforms

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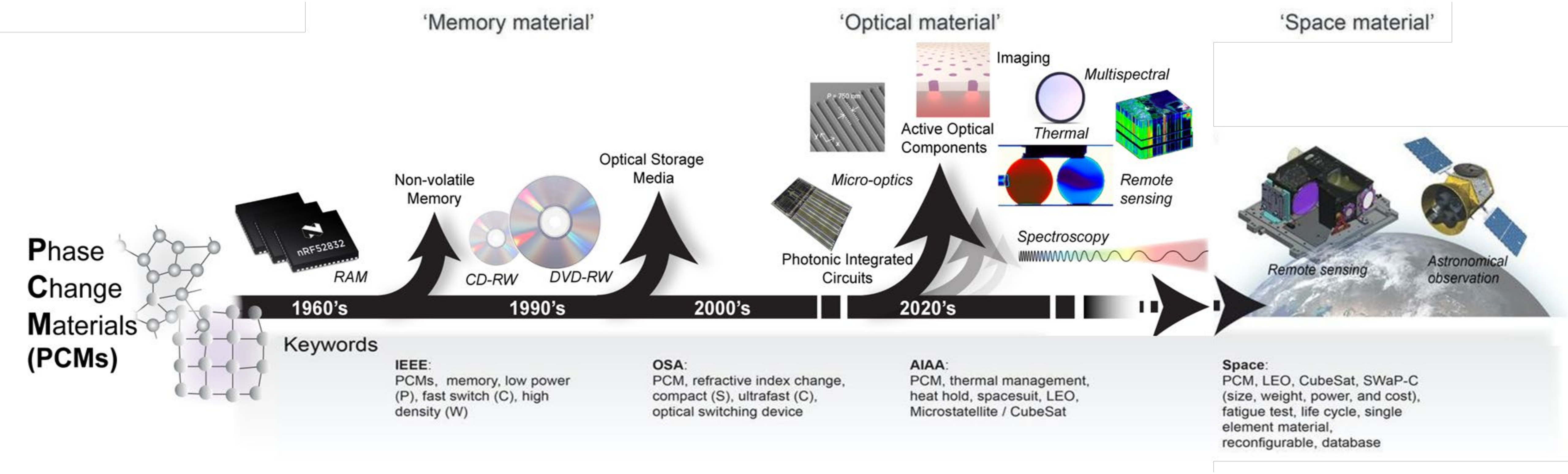
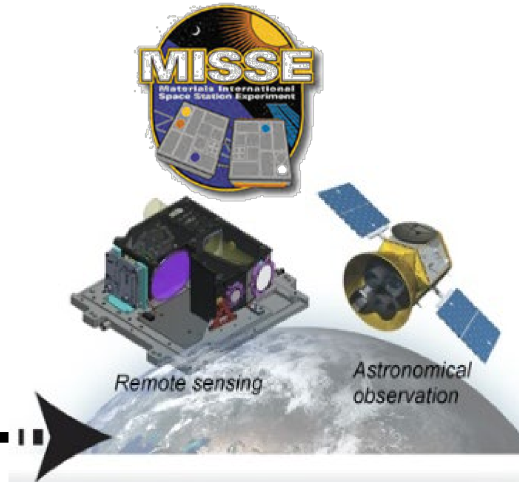
January 25th, 2022

Phase Change Material Research Trends



Team

- R&D: NASA Langley Research Center (LaRC), MIT, BAH, University of Nevada (Reno), and University of Cambridge (UK)
- Development & Testing (D&T): NASA LaRC and MIT
- New application: U. of Cambridge
- MISSE mission with MIT & University of Washington (Prof. Arka Majumdar)
- Mission Support NASA LaRC: DIAL (science mission), SAGE-IV, SCIFLI (space program)



1966
PCM for optical storage media

2017
P-ACTIVE starts at NASA Langley Research Center

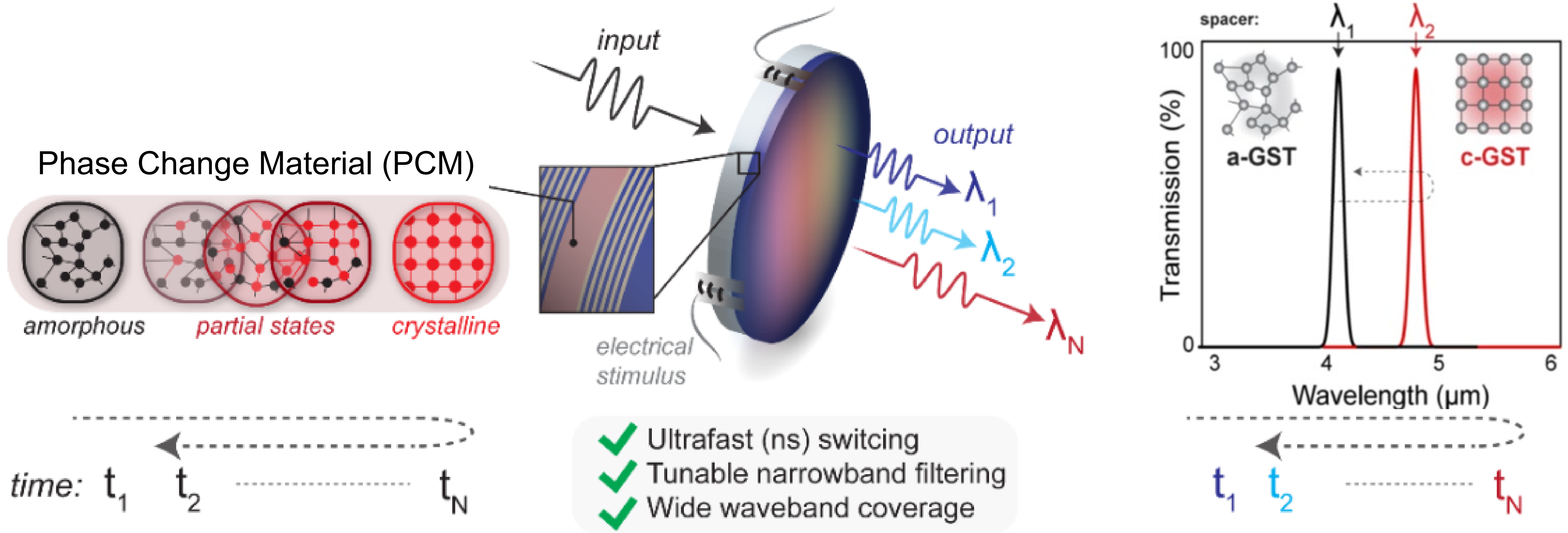
2019
R&D team
Mission support team
New application collaborator

2020

2021
MISSE -Space application team

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

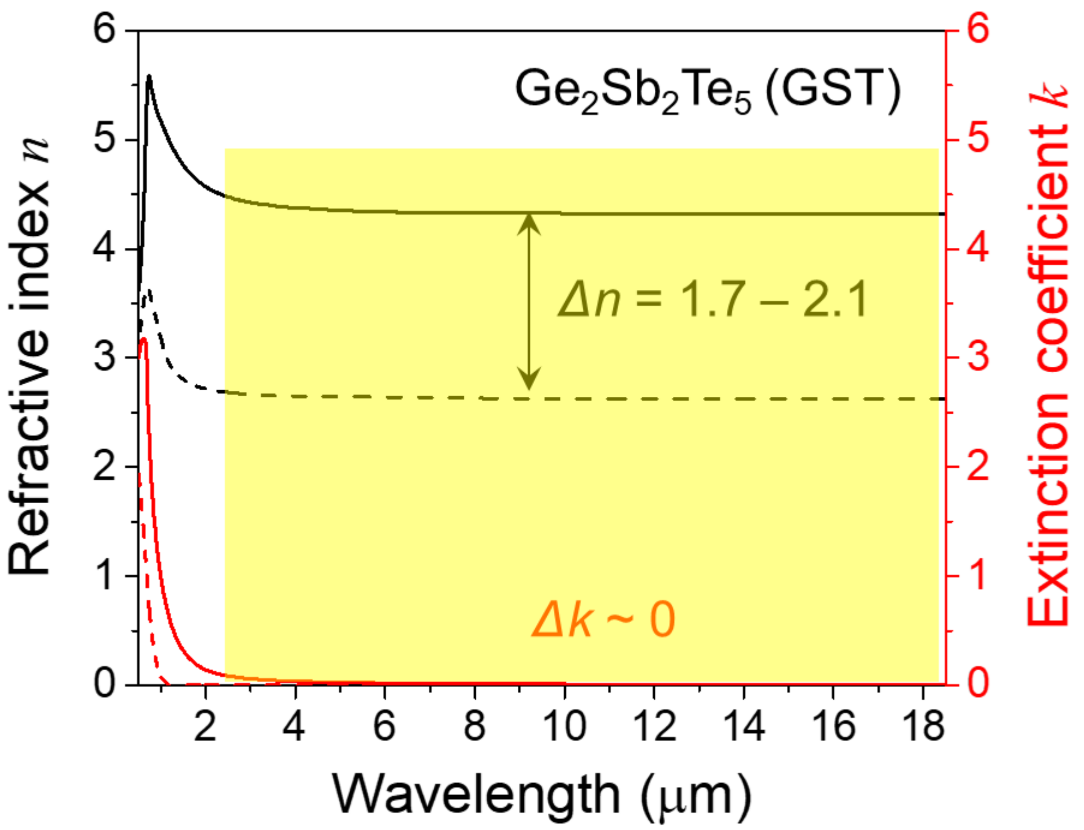
PCM-based Actively Tunable Filter (P-ACTIVE)

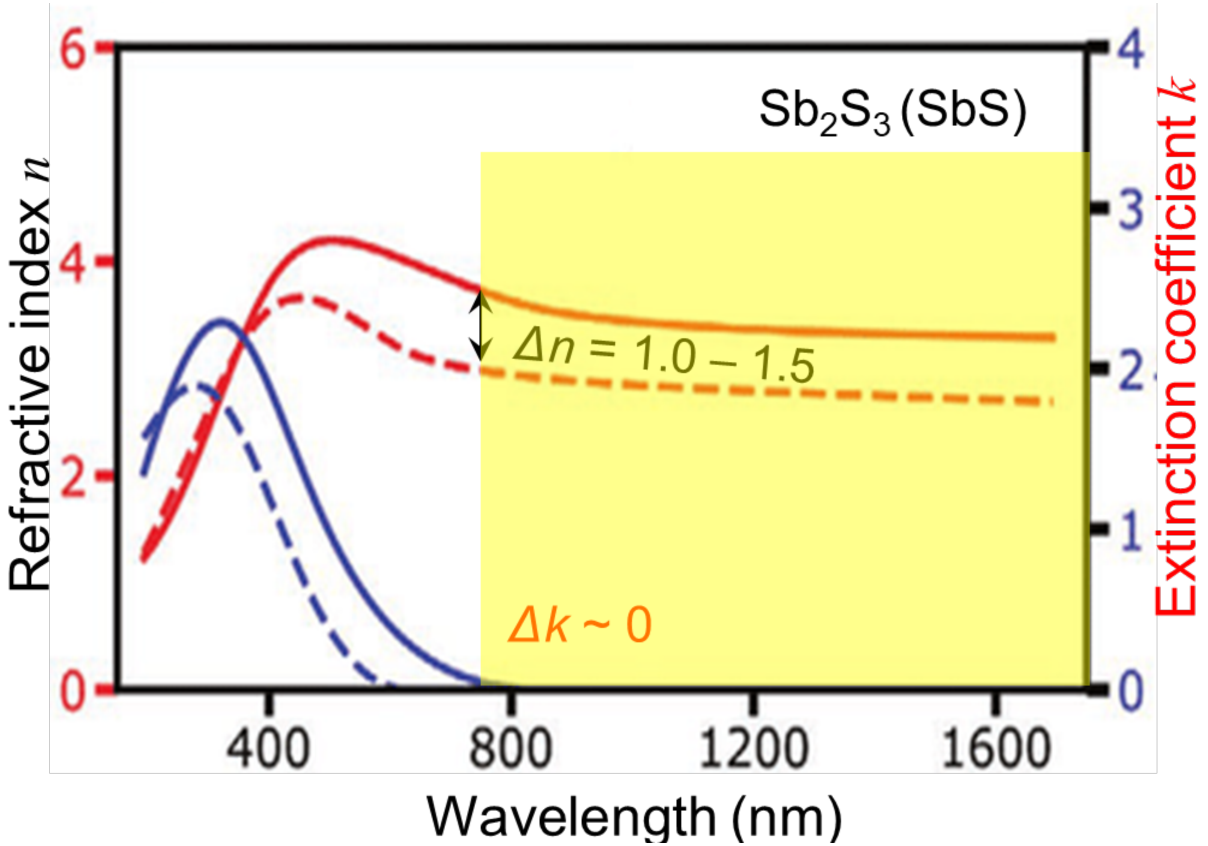


- Ultrafast (ns) switcing
- Tunable narrowband filtering
- Wide waveband coverage

Amorphous-to-crystalline phase transition provides wavelength modulation arising from large index change

- ✓ **In 1966, PCMs (i.e., $Ge_2Sb_2Te_5$ / GST) were developed for re-writable, non-volatile memory applications**
- ✓ Memory recording between amorphous (0) and crystalline (1) phase transitions
- ✓ Reversible, linear, non-volatile phase transition
- ✓ PCMs exhibit an ultrafast refractive index modulation across the infrared
- ✓ **From 2014, large refractive index contrast utilization in photonic devices** (*Nature, 511, 206-211 (2014)*)

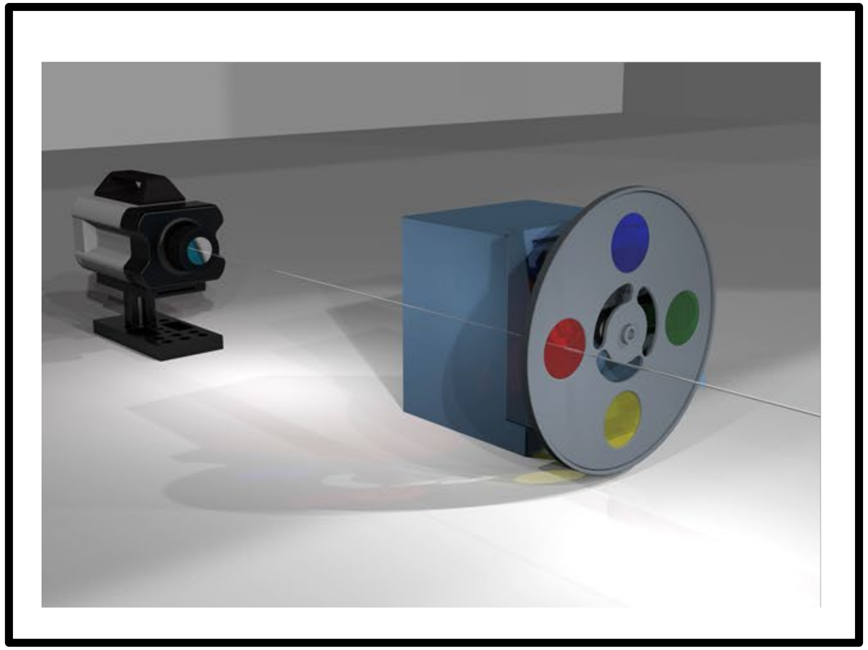




P-ACTIVE – Dramatic Improvement in Performance

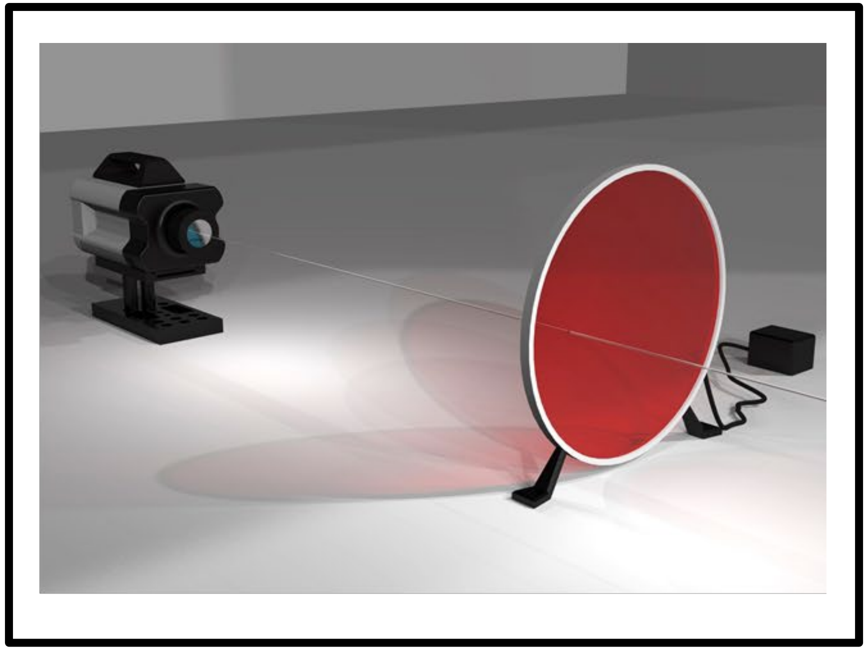
State of the Art:

- ✓ 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
- ✓ 0.8kg (weight), 725cm^3 (volume), 15W to power motor



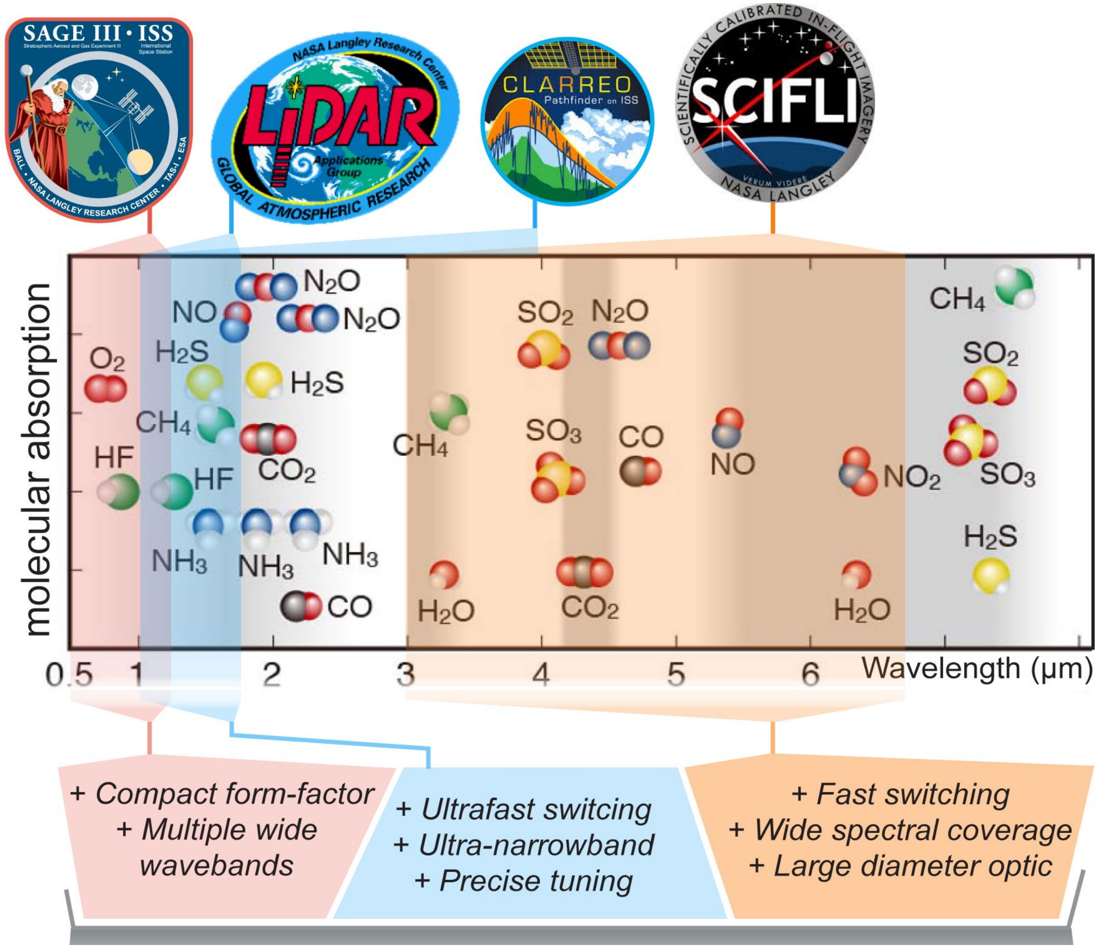
P-ACTIVE:

- ✓ 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

1~10μm waveband, 'spectral fingerprint' for many chemical species



Chemical/Gas sensing – LIDAR Science mission

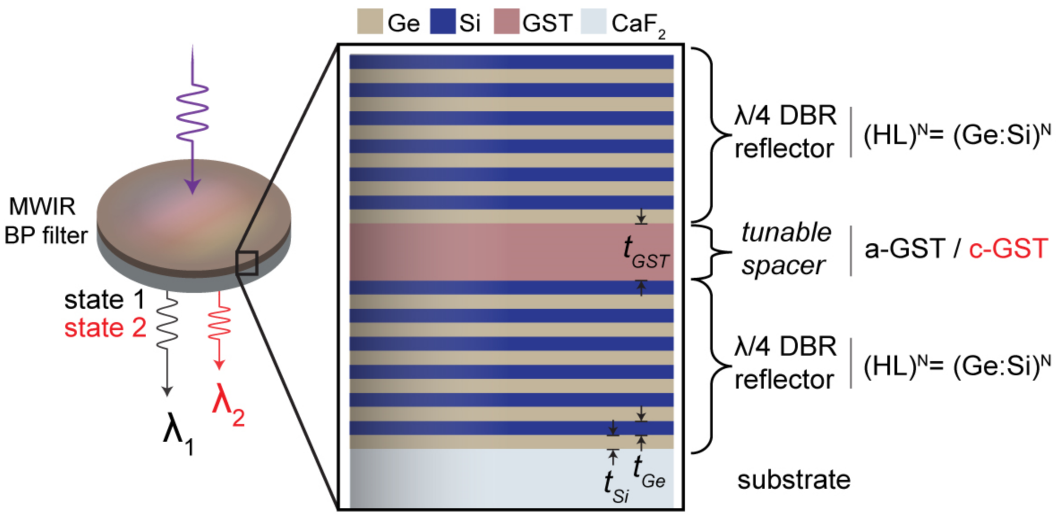
- Rapid profiling of targeted observables, greenhouse gases (NO_2, CO_2, CO, SO_2), ozone, water vapor
- DIAL (Differential Absorption Lidar) **on/off switch**: Capability to measure H_2O vapor & CH_4 profiles for deeper understanding of clouds responding to warming climate from greenhouse gases
- SAGE III / IV mission **multi-spectral filter** wheel

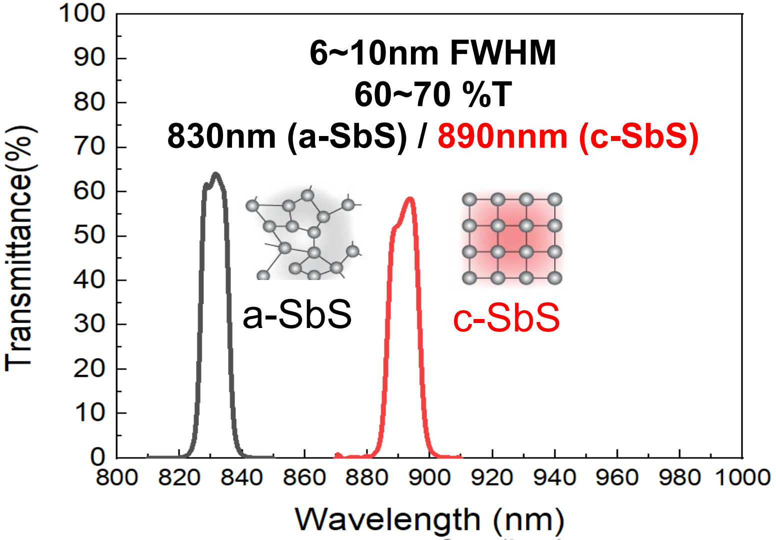
Thermal imaging – SLS Space mission

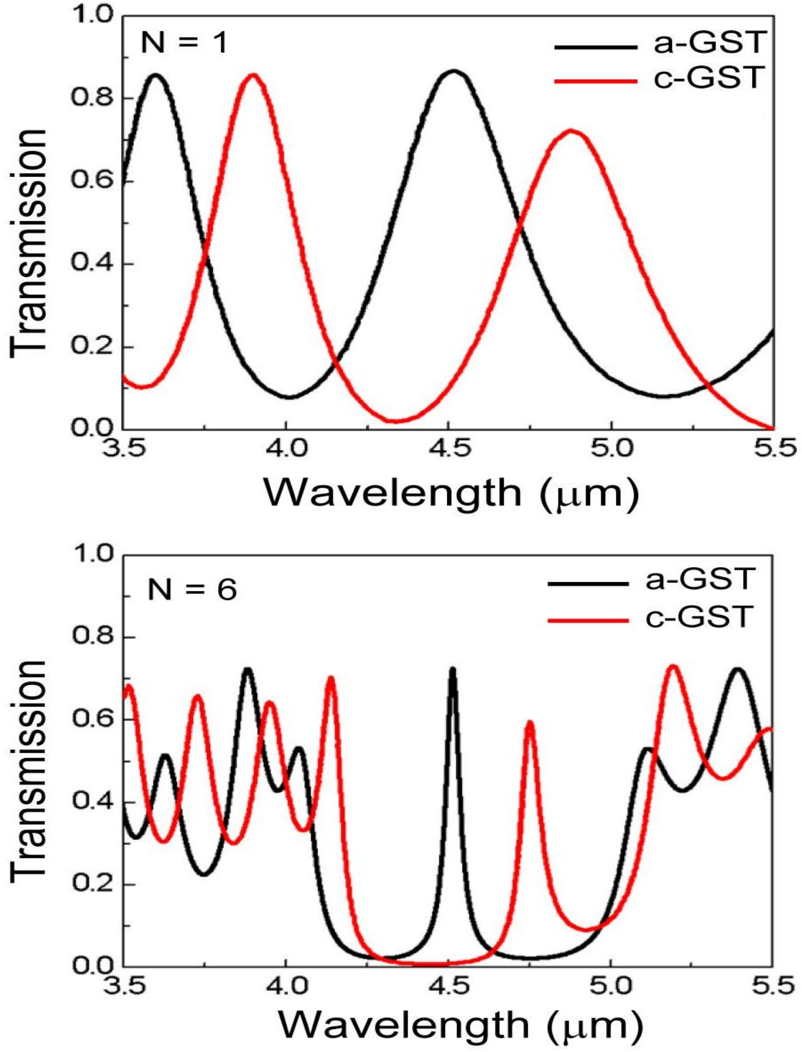
- Dynamic targets (e.g., turbulent plumes, volcano gases)
- SCIFLI project **multi-spectral filter** wheel: H_2O & CO_2/CO rocket plume emission

Prototype 1: Fabry-Perot Bandpass Filter with PCM cavity

center wavelength (λ_1 or λ_2) shift depending GST or Sb_2S_3 crystallinity (refractive index)

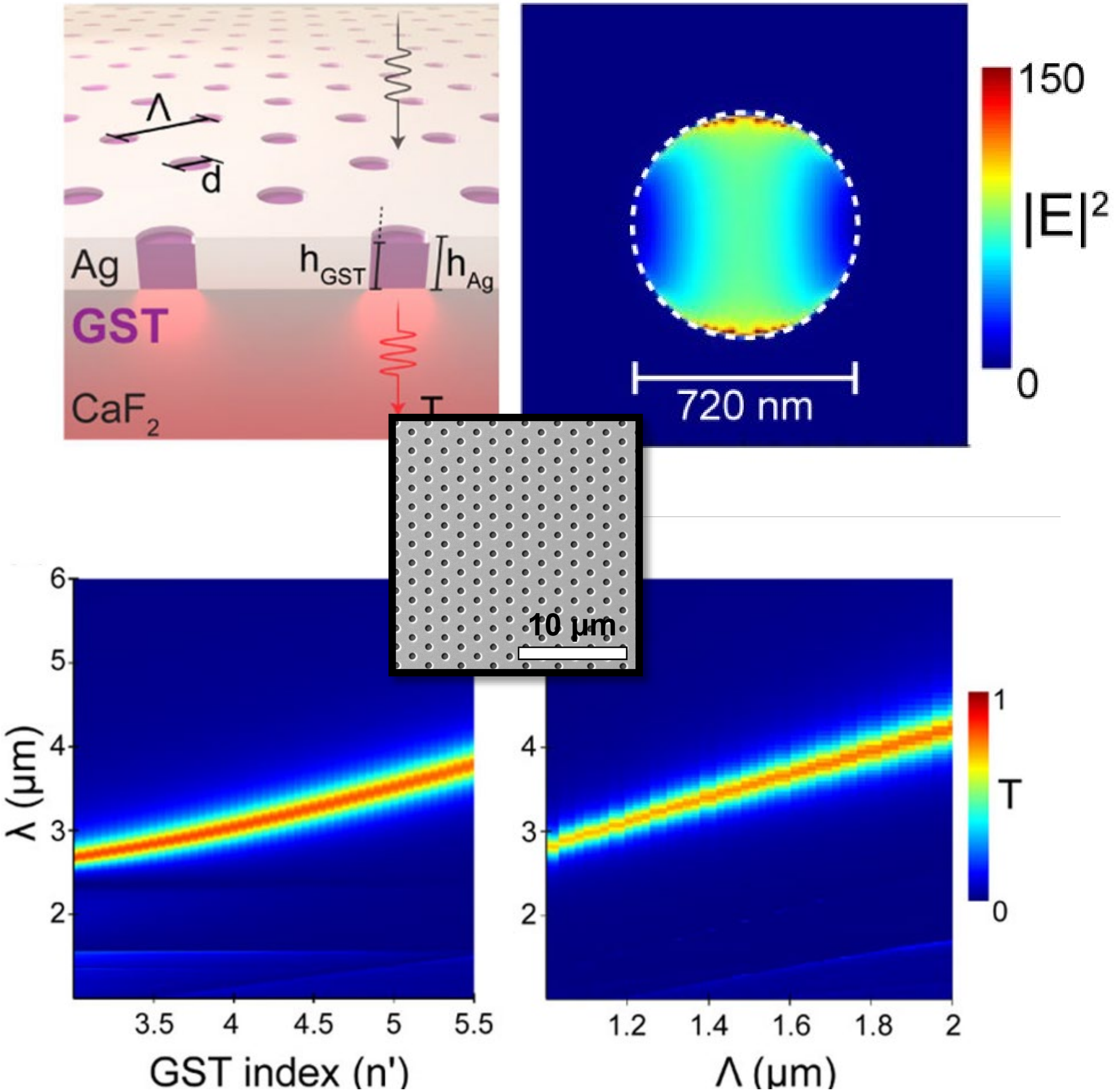






C. Williams. et al., Optics Express 28(7), 10583, 2020

Prototype 2: Metasurface filter with embedded GST



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

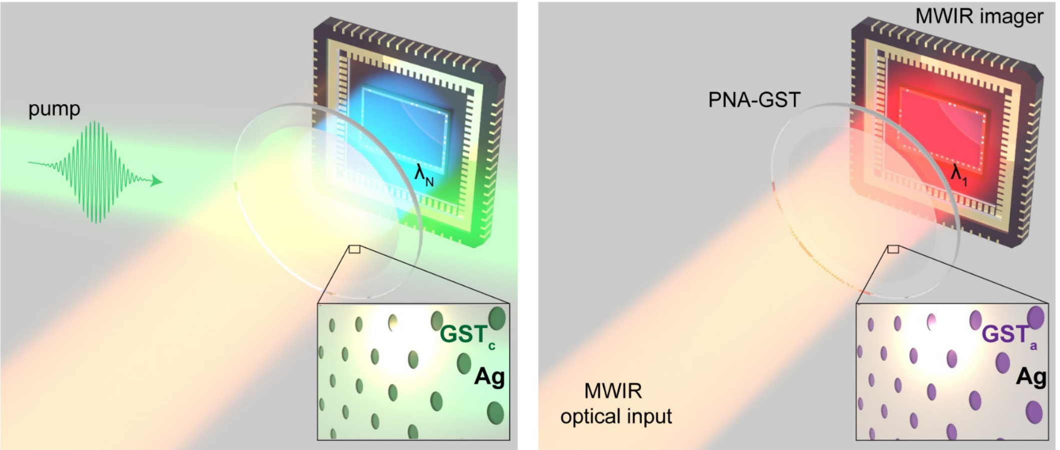
- We utilized a Plasmonic Nanohole Array (PNA) metasurface filter
- Integration **of $Ge_2Sb_2Te_5$ (GST) with PNA**
- Transmission response dependent on hole index. **Holes filled with GST (tunable)**

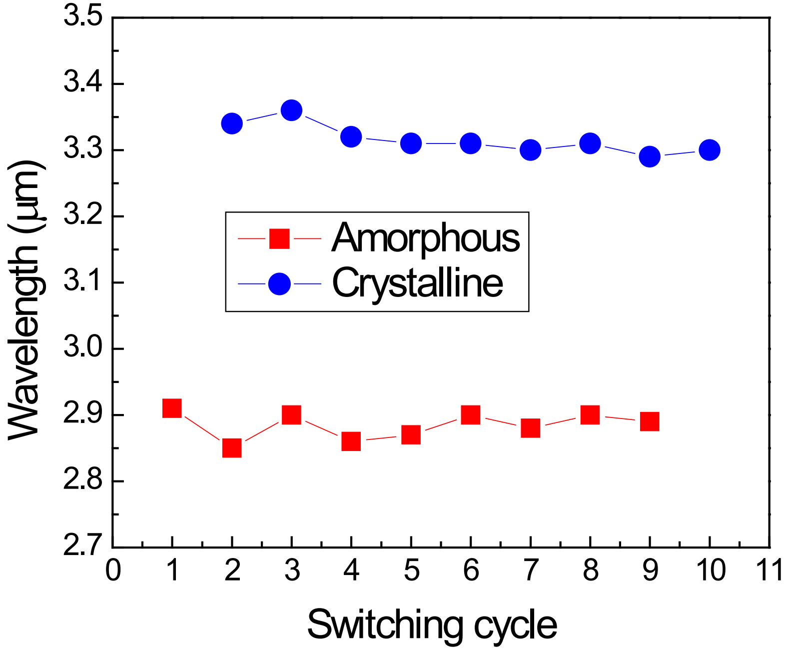
- **GST filled nanohole arrays associated resonance at particular WL in metal film**
  → transmission mode filtering

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

Metasurface GST filter shows ultrafast bi-modal wavelength switching in the MWIR

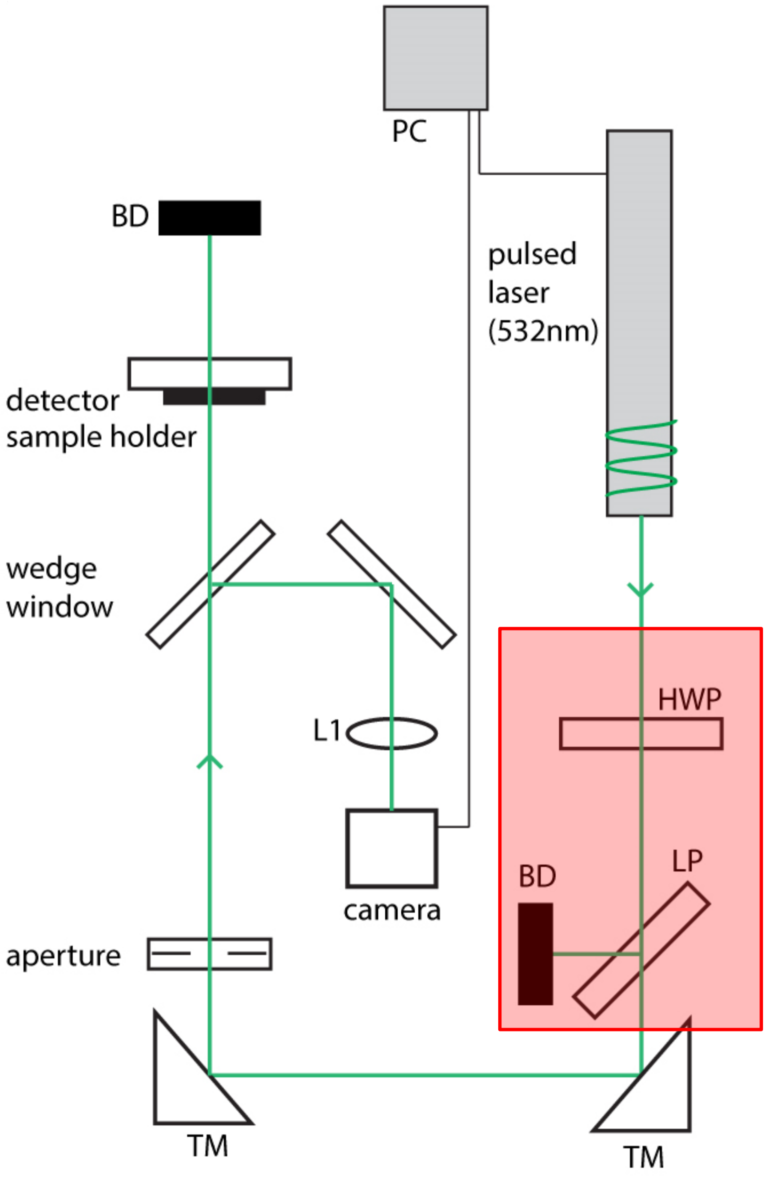
- ✓ 1-inch diameter size filter
- ✓ > 75 %T
- ✓ < 74 nm bandwidth
- ✓ 2.9 µm ~ 3.4 µm spectral tuning
- ✓ **Perfect reflection at the off-resonance**
- ✓ ~ ns tuning speed
- ✓ Multiple switching cycles
- ✓ No settling time required
- ✓ **Polarization insensitive**

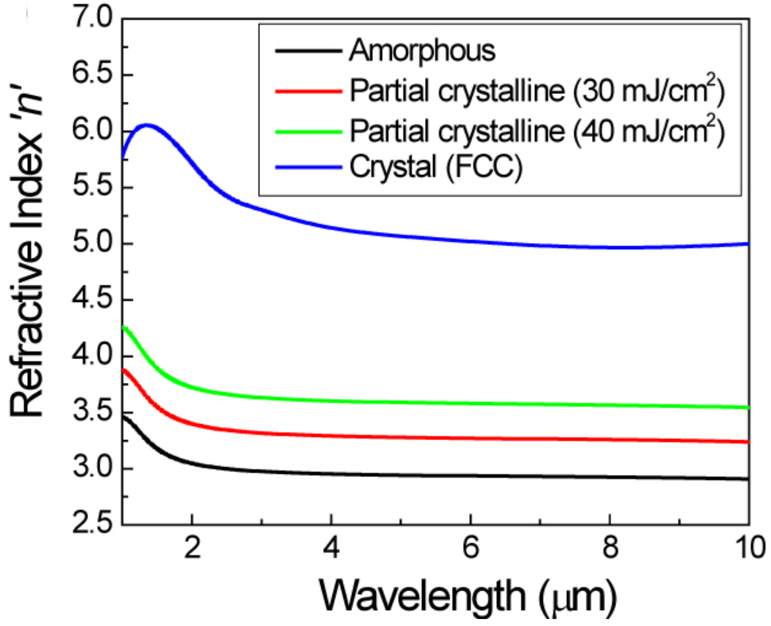


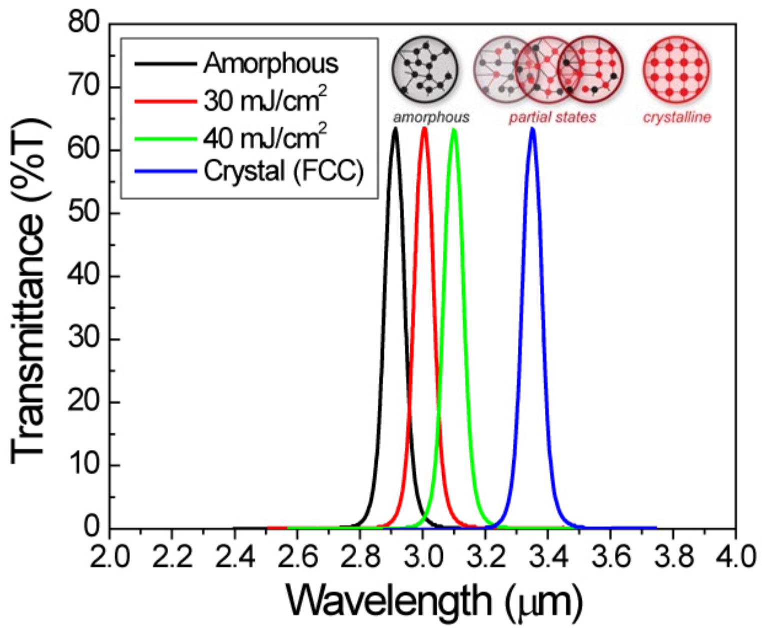


M. Julian et al., Optica, 7(7), 746-754, 2020

Pulsed-laser switching setup enables rapid center wavelength tuning



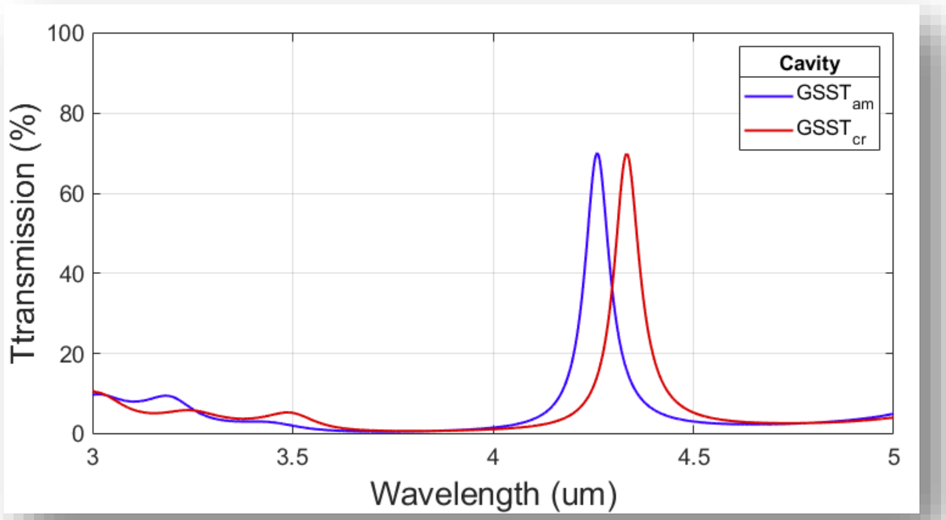




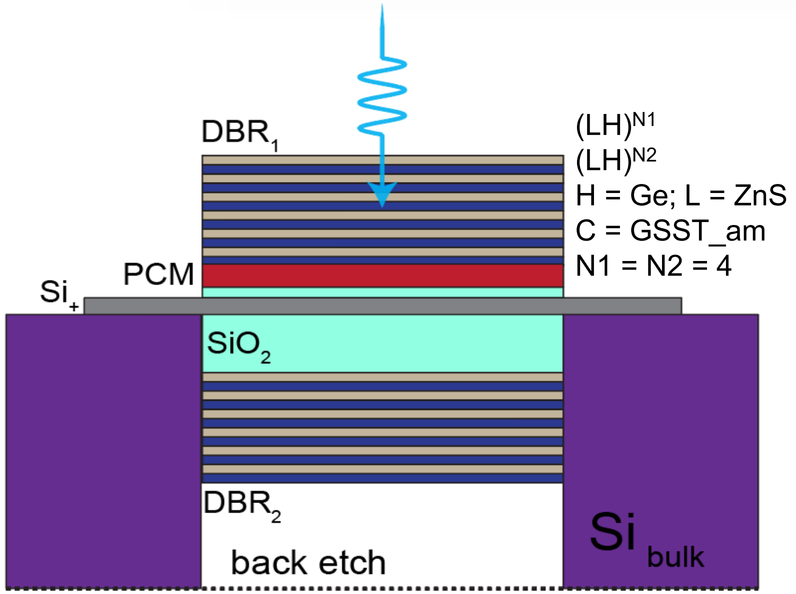
- GST-PCM is generally considered to be a 2-bit material ('0' / '1'), either amorphous (2.9μm) or crystalline state (3.4μm).
- Partial crystallizations of GST-PCM experimental demonstrations

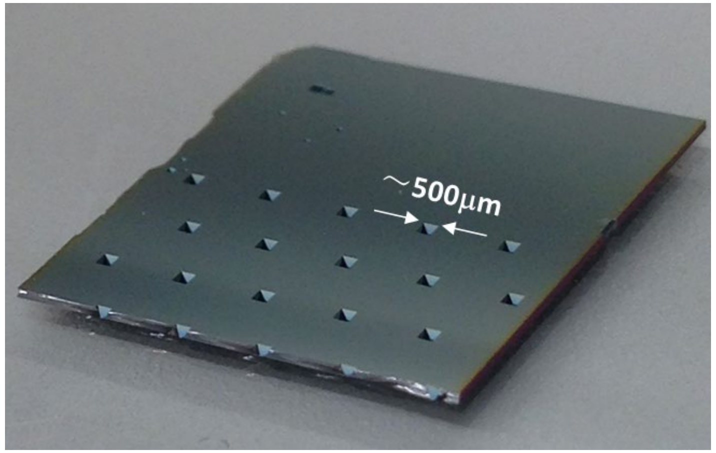
M. Julian et al., *Optica*, 7(7), 746-754, 2020

Electrically-tunable P-ACTIVE fabrication

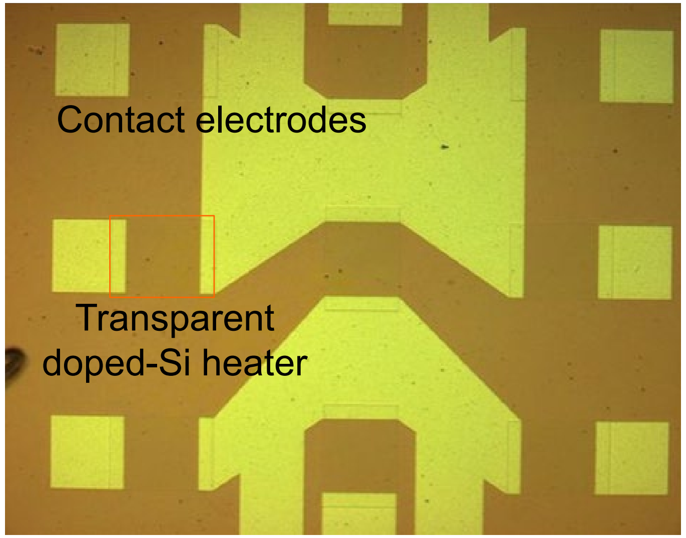


- As a proof-of-concept electrically-tunable device, a Fabry-Perot (FP) filter was designed
- Filter geometry is integrated with MIT's doped-Si heater wafers
- Bulk Si wafer is backside-etched to reduce thermal sinking
- FP mirrors are deposited on either side of doped-Si 3x3 heater layer





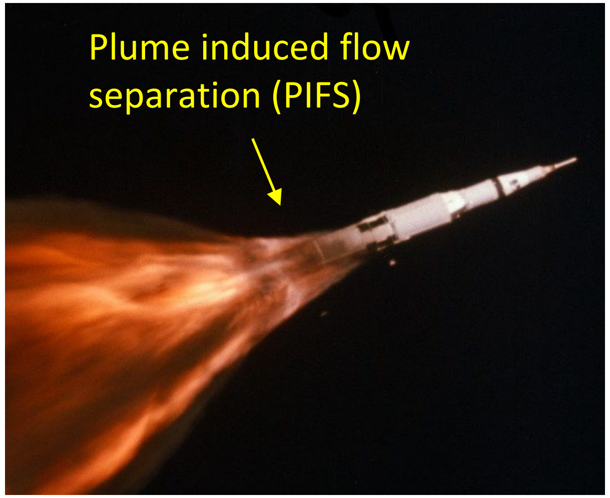
Initial results of backside-etched Si substrate



P-ACTIVE opens new opportunity ….

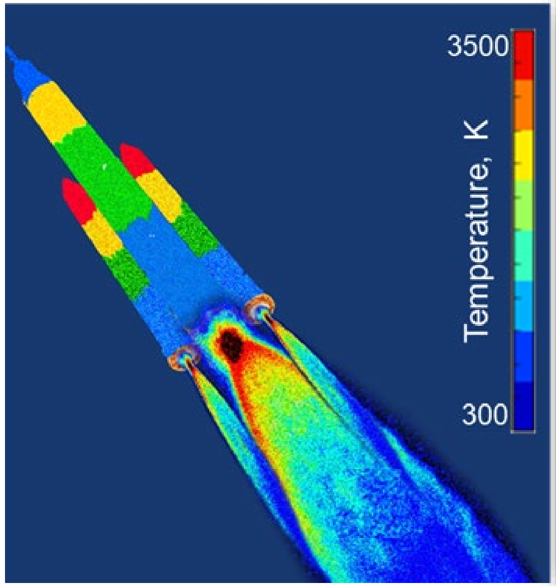
NASA Scientifically Calibrated In-Flight Imagery

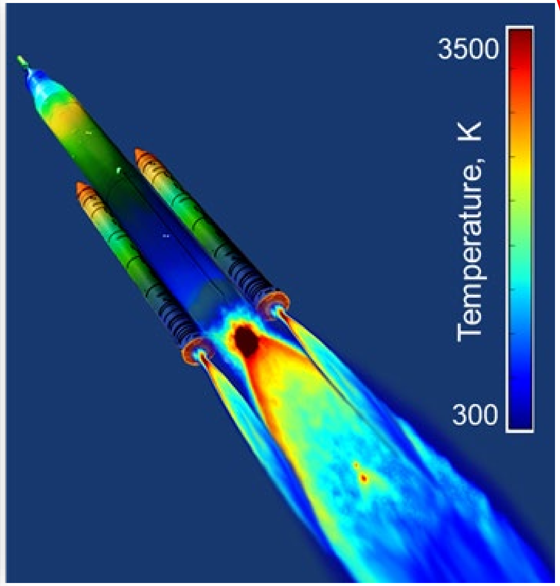
Apollo Saturn V



Kerosene + LOX
- Plume in VIS spectrum
- No temperature data

Artemis-1 Program





Hydrogen + LOX = H2O
- 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

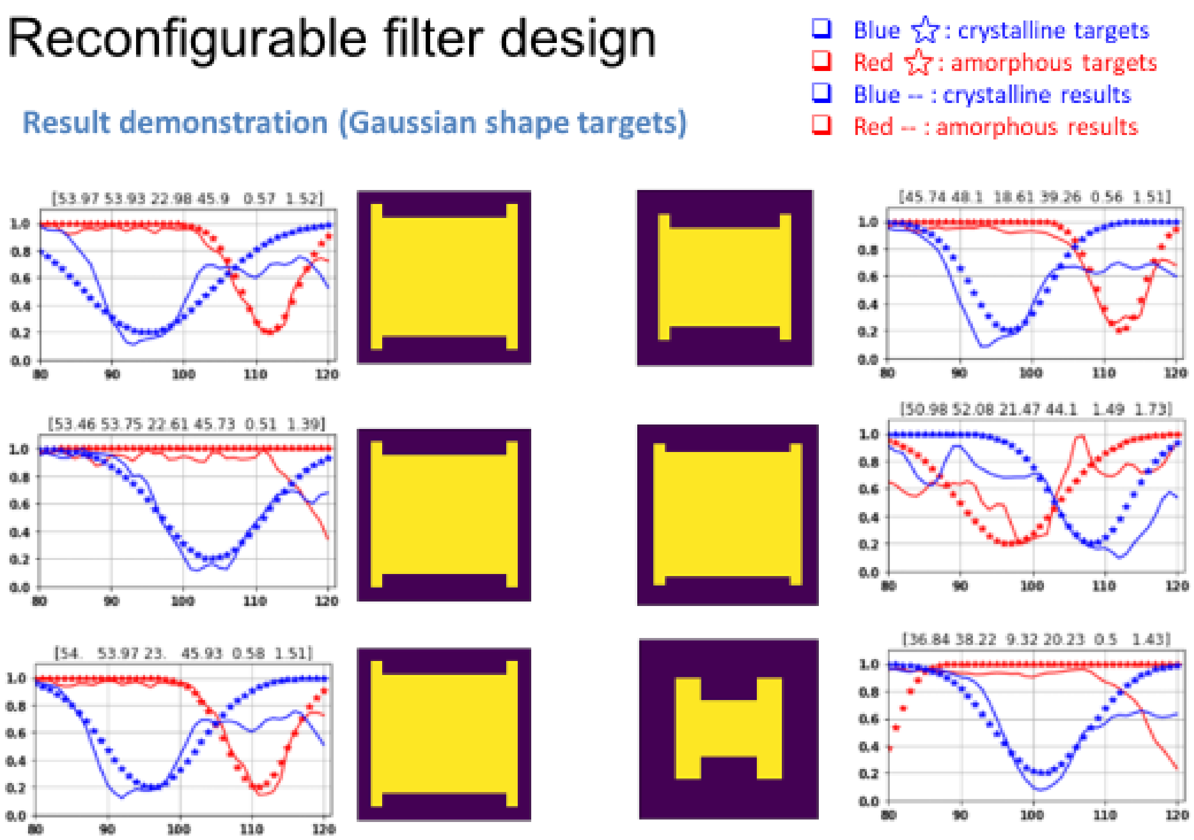
Need: Reliable and adaptable MWIR filter for increased temperature accuracy from the current high speed (MHz), narrow band filter wheel – for next-generation active thermal imaging monitoring for future missions.

Credit: scifli.larc.nasa.gov

Neural Network (NN)-designed MWIR metasurface filter by MIT

Canonical example specs chosen to demonstrate flexibility for SCIFLI missions

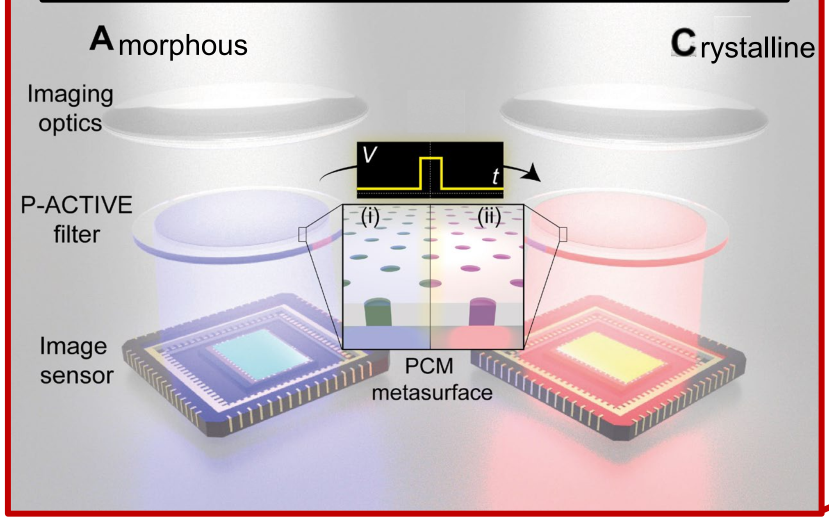
Input Parameters	
Performance Metric	**Spec Range**
Center wavelength	2 µm < λ < 5 µm
Tunable Range	>1 µm
Transmission FWHM	35 nm < FWHM < 100 nm
Peak Transmittance	>70%
Out-of-band rejection	> OD 3
PCM material	GST or GSST



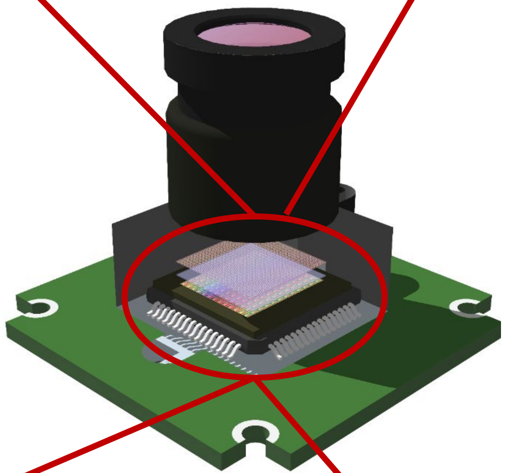
We are pursuing parallel fabrication of metasurface and FP heater structures on Si-heater substrates

Neural Network (NN)-designed metasurface filter for SCIFLI

I-SSPI system concept

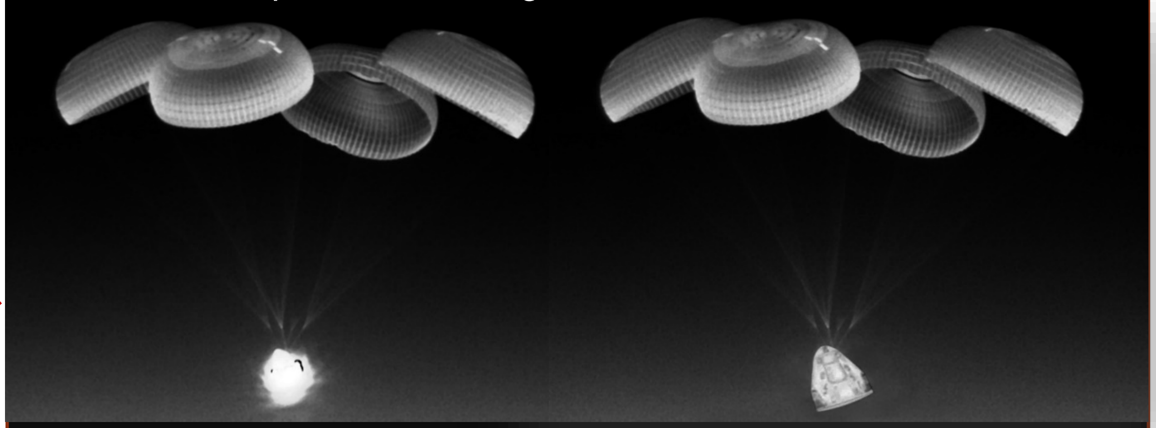


Integrated Single-optic SPectroscopic Imager (I-SSPI) for Increased Measurement Resolution (eliminate the emissivity uncertainty problematic and expand the dynamic range of image) in a Reduced SWaP Form-factor



Gimbal on NASA WB-57 (filter wheel installed)

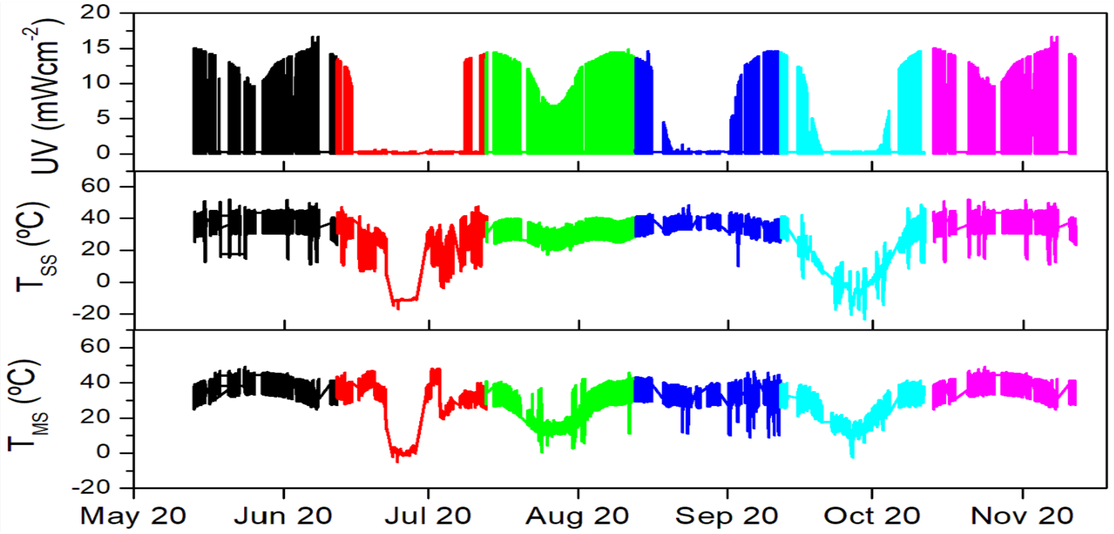
SpaceX Crew Dragon capsule nighttime splashdown image—on November 8, 2021.



Credit: NASA

NASA MISSE Program

- MISSE - Materials International Space Station Experiment
- Purpose is to determine the effects on the specimens due to the space environment
- All specimens returned to Earth for analysis
- P-ACTIVE launched through the MISSE-14 platform (Wake and Zenith)
- Wake Direction - Facing away from the direction of ISS travel, no AO and moderate solar exposure (Lunar surface demo)
- Zenith Direction - Facing away from Earth, grazing AO and highest solar exposure (LEO demo)
- Qualitative Analysis: High-resolution photographs of specimens about once a month to detect changes as a function of time
- MISSE environment flight data also provide (i.e., temperature, Ultraviolet (UV) radiation)



June 2021 July 2021 August 2021

P-ACTIVE through the MISSE-14

Launch
02.20.2021

Unpack / unsealing
04.08.2021

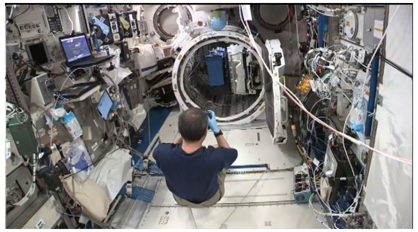
Deployment on orbit
04.25.2021

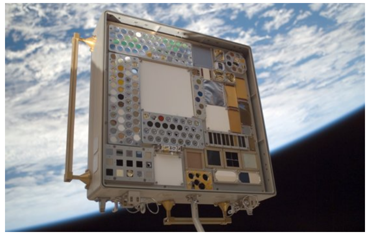
Exposure & monitoring start 06.21.2021

Removal from on orbit facility 12.27.2021

Return
01.25.2022*

- **Preparation samples for wake and zenith)**
- **Preflight characterization**





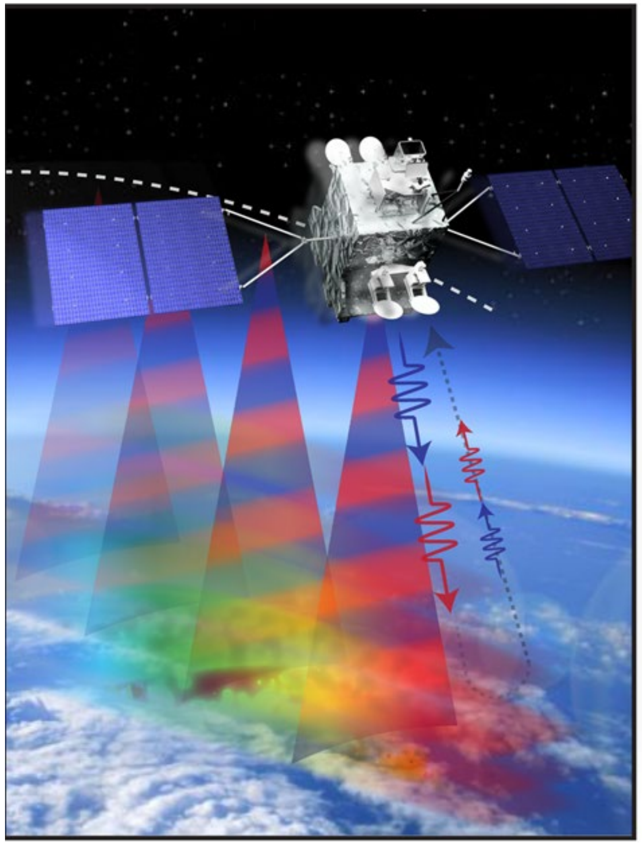
- **Retrieval**
- **Post flight characterization (optical and physical properties)**

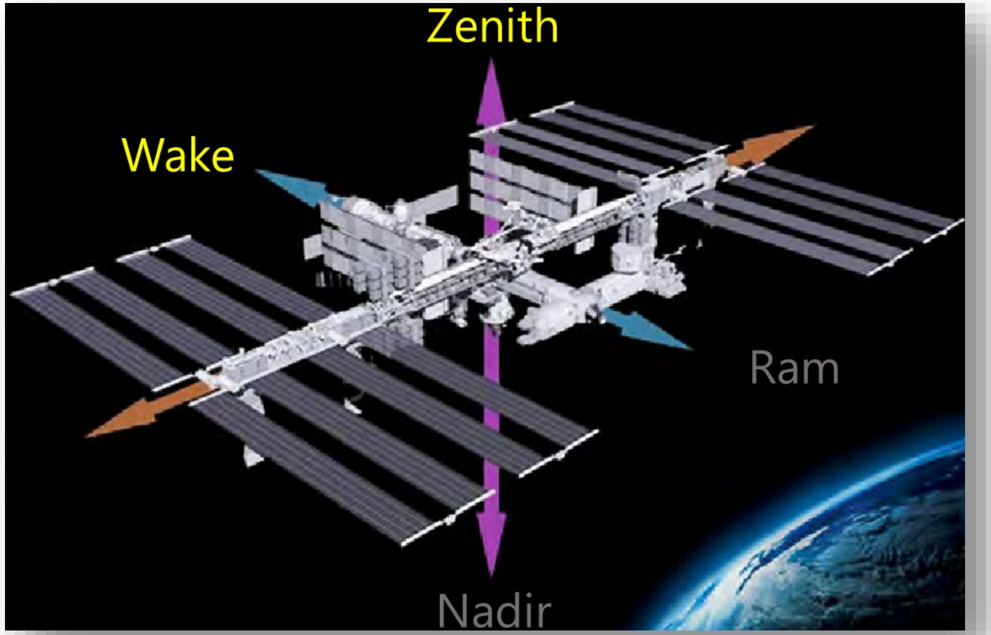
MISSE-14 opens new opportunity ….

Space PCM & Neural Network-based Filter Design

intelligently pairs user-/mission-defined performance metrics

Spaceborne LIDAR for Chemical / Gas sensing





μ-Spectrometer for Lunar & Mars exploration

[1] J. Phys. Photonics, DOI:10.1088/2515-7647, 2021
[2] https://www.nist.gov/system/files/documents/tpo/SangChoi.pdf

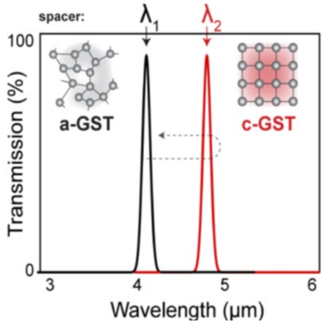
Expected Impacts of PCM alloys Beyond the P-ACTIVE…

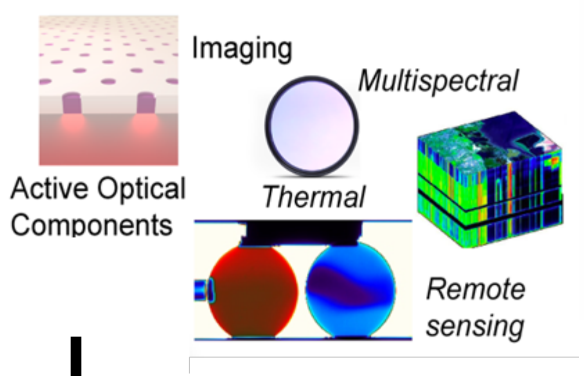
Application of PCM-based active metasurfaces

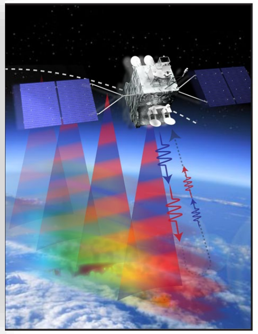
Application	Switching contrast (relevant metrics listed)	Optical efficiency	Endurance (cycling lifetime)	Speed	Power consumption
Optical signal modulation	Extinction ratio		$> 10^{15}$	> 1 GHz	
Spatial light modulation	Cross-talk		10^{10}	0.1-1 kHz	
Beam steering (LIDAR)	Cross-talk		10^{13}	100 kHz	
Tunable filter	Tuning range		10^3	1 kHz	
Adaptive optics	Phase correction coverage		$> 10^9$	> 0.1 kHz	
Lens autofocus	Focal length tuning range		10^4 - 10^7	0.1 kHz	
Zoom lens	Zoom ratio & cross-talk		10^3 - 10^6	1 Hz	
Holographic display	Color gamut		10^6 - 10^9	0.1 kHz	
Reflective display (electronic paper)	Color gamut		$> 10^6$	> 1 Hz	Must be nonvolatile
Dynamic projection display	Color gamut		$> 10^9$	0.1 kHz	
Optical limiter	Extinction ratio		1 - 10	> 1 GHz	
Adaptive thermal camouflage	Emissivity tuning range		10^4 - 10^9	1 kHz	

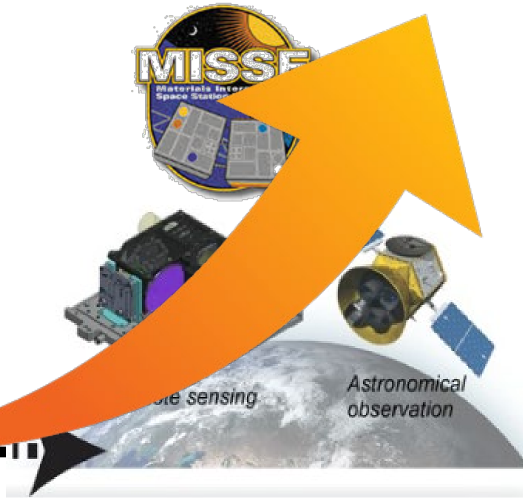
"Design for quality: reconfigurable flat optics based on active metasurfaces", Nanophotonics, 9(11), 3505-3534 (2020).

Beyond January 25th, 2022









1966
PCM
Non-volatile, reconfigurable, fast-switching, high degree of space radiation tolerance

2018
P-ACTIVE at LaRC
Success on P-ACTIVE fabrication & demonstration

2019 ~ 2021
NASA mission-specific scenario development
Key scientific component to extract maximum information from active tuning

February 2021
MISSE-14 mission
P-ACTIVE and PCM alloys expose at ISS for 6-months

February 2022
Return to the facility at NASA for the post flight testing

P-ACTIVE in space

Based on Lessons Learned from MISSE-14