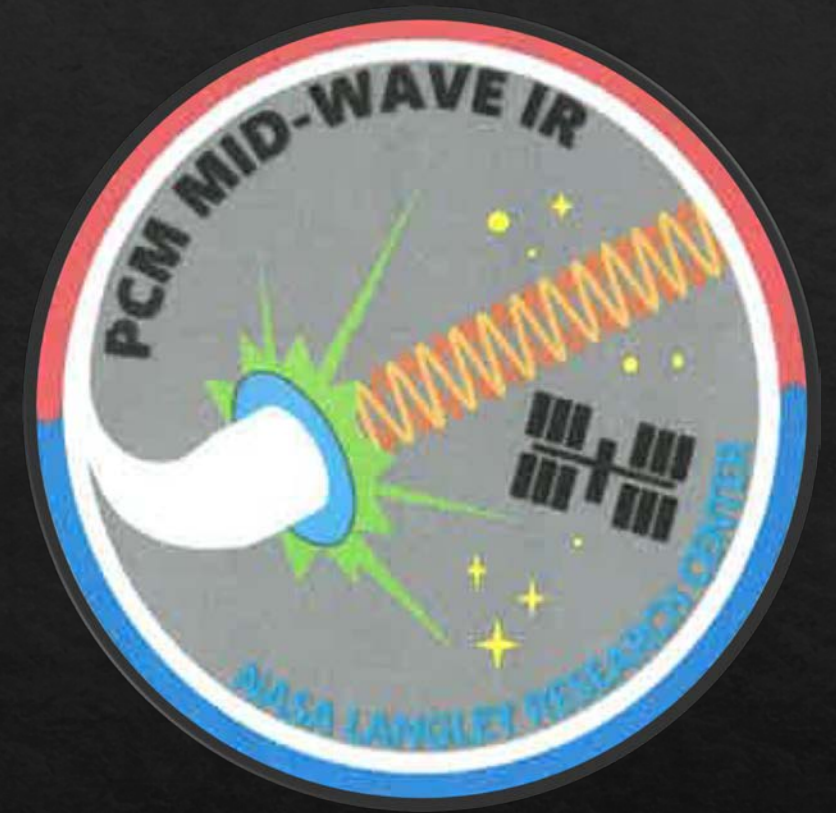


Active tunable filters based on GeSbTe phase- change materials and surface plasmon resonance

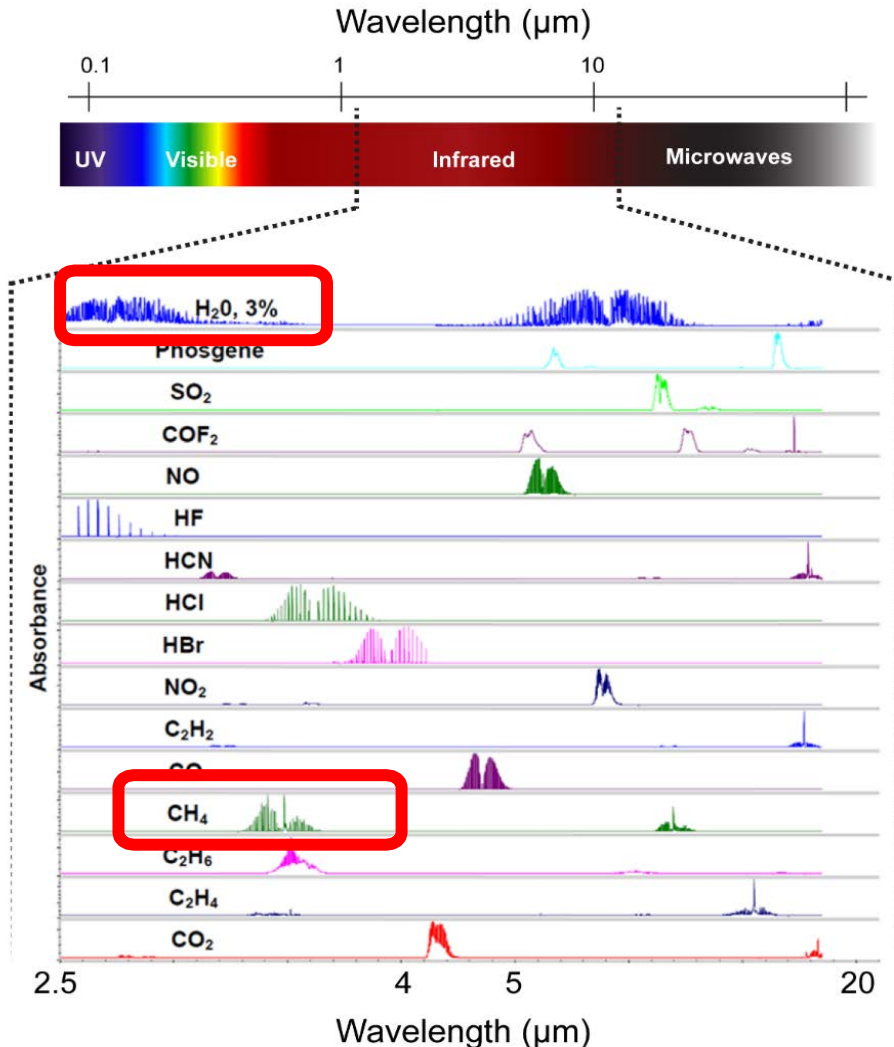


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2. NASA Langley Research Center, Hampton VA USA
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4. University of Cambridge, UK

Why Mid Wave-IR (MWIR) and Tunable Filters?

- MWIR waveband (3—10 μm): ‘**spectral fingerprint**’ for many chemical species



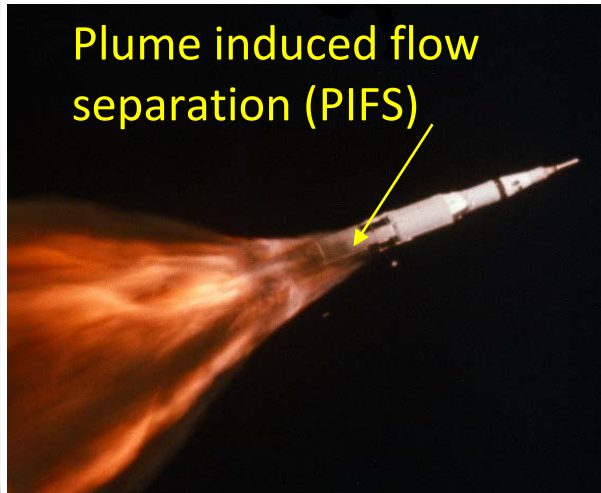
- **Chemical/Gas sensing** – LIDAR Science mission
 - Decadal Survey (2017)
 - DIAL (Differential Absorption Lidar) **on/off switch**: Capability to measure H₂O vapor & CH₄ profiles for deeper understanding of clouds responding to warming climate from greenhouse gases
 - SAGE III / IV mission **multi-spectral filter** wheel
- **Thermal imaging** – Artemis1 Space mission
 - SCIFLI project **multi-spectral filter** wheel: H₂O & CO₂/CO rocket plume emission

MWIR at LaRC: SCIFLI Project



The Scientifically Calibrated In-Flight Imagery

Apollo Saturn V



Plume induced flow separation (PIFS)

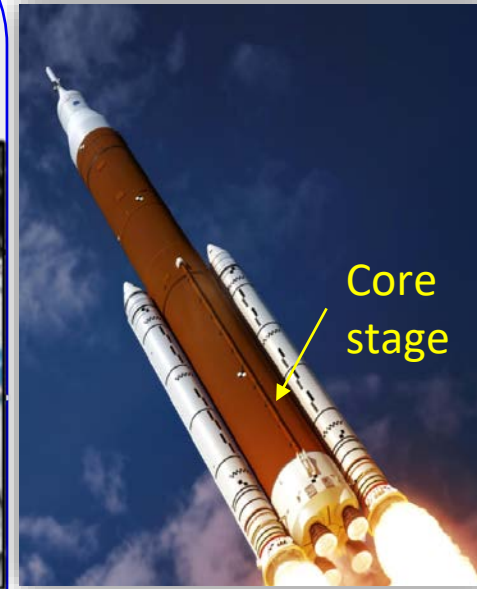
Kerosene + LOX

DYNAMITE turret on nose of NASA WB-57



Ref: scifli.larc.nasa.gov

Artemis-1 Program



Core stage

Hydrogen / Oxygen combustion + LOX



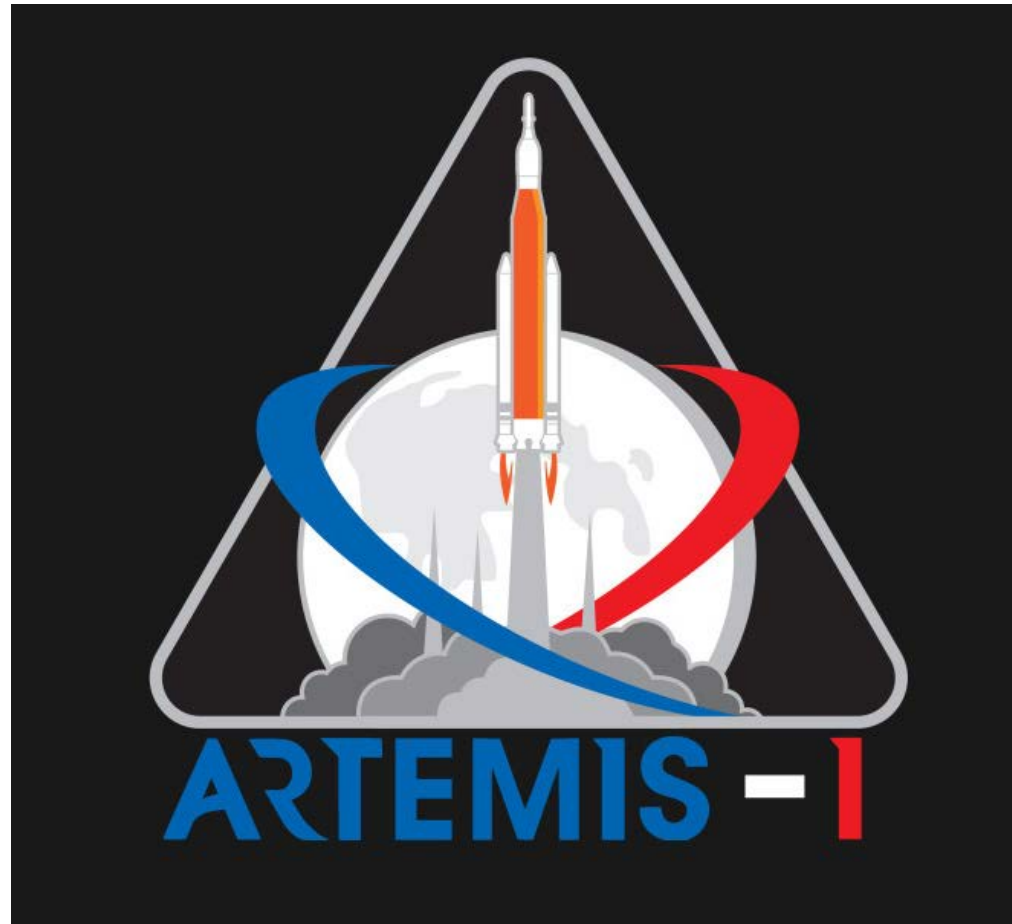
Base heat shield

1. **Temperature** measurement of the core booster stage and PIFS to reduce the engine heat shield weight
2. The core stage of rocket, a super-heavy thermal protection system to protect the engine
3. Need alternative way to replace for the **filter wheel** – for accurate temperature from high frequency (MHz), narrow band filter– for next-generation active thermal imaging monitoring for the future mission

MWIR at NASA: Artemis Program



Remote sensing characterization of capsule heat-shield performance during entry and descent upon return to Earth.

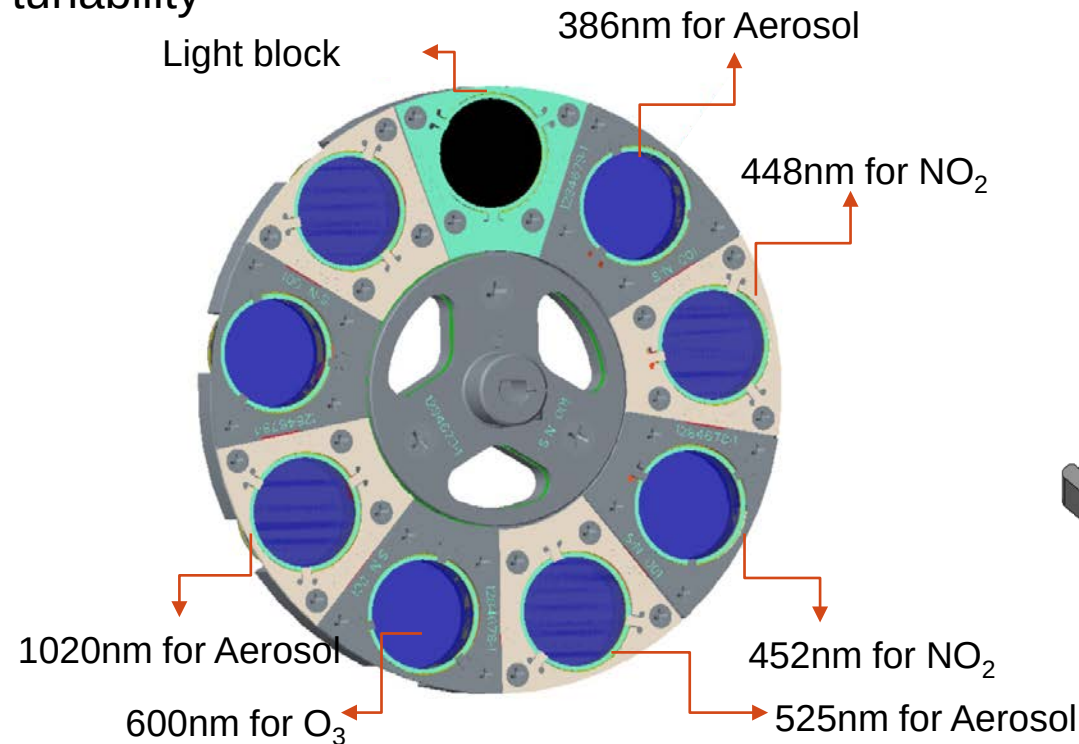


MWIR at LaRC: SAGE-III / IV Program

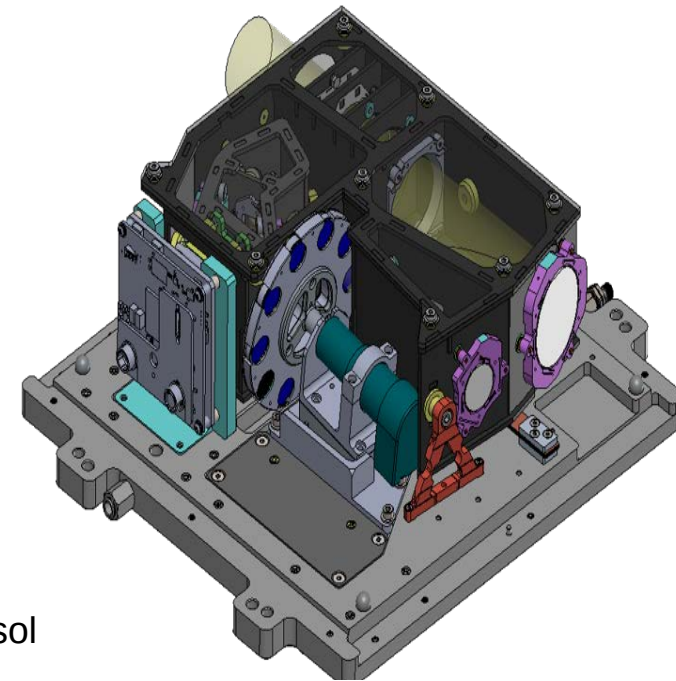
- ✓ Accurate records of stratospheric aerosols are a vital piece of the puzzle regarding climate change and are now a Designated Observable under the 2017 Decadal Survey.
- ✓ SAGE has historically been shown to be one of the best measurement systems for precision and accuracy of stratospheric ozone and aerosol retrievals.
- ✓ Filter wheel from wide wavelength tunability



SAGE III

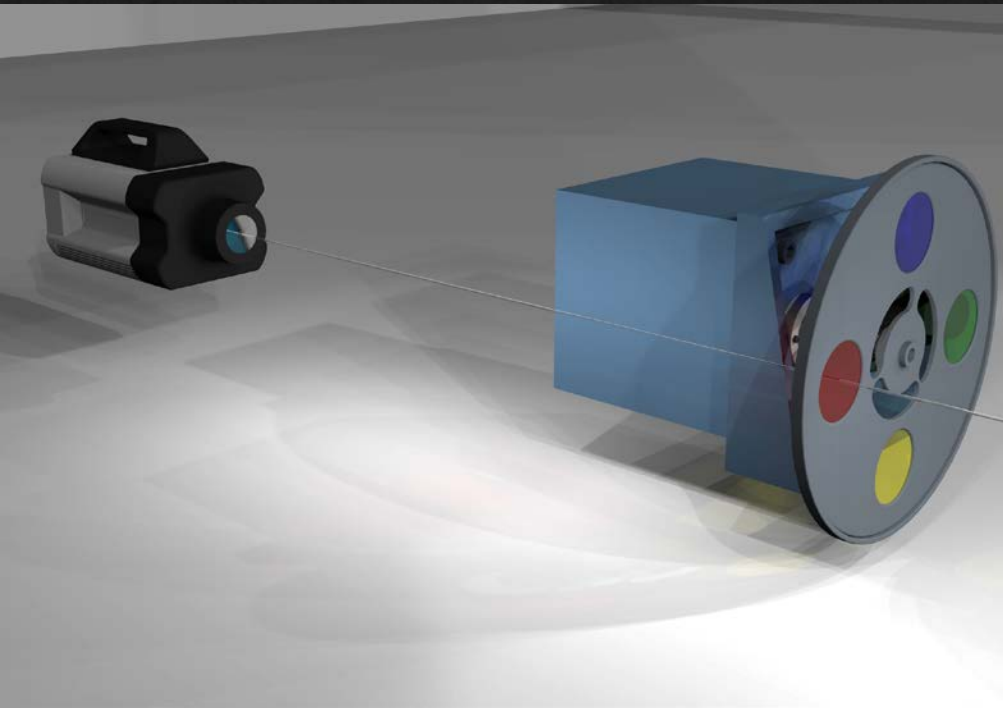


Why Not Just Build A Mini SAGE III?



SAGE IV Pathfinder (6U CubeSat)

Actively Tunable Filter



GOAL

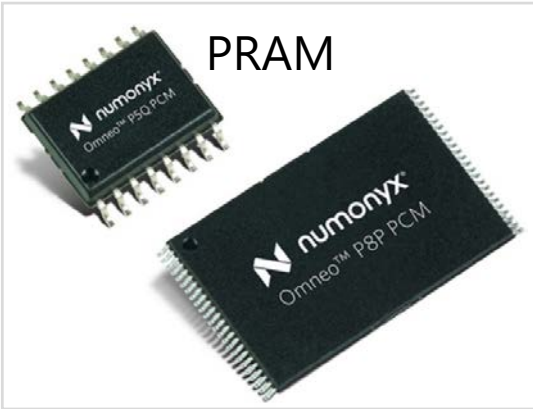
- ✓ Develop the ATFC, all solid-state and a single-component tunable filter, based on MHz (ns) switching speed Phase Change Material (PCM)
- ✓ The ATFC increases spectral, spatial, and temporal resolutions; six orders-of-magnitude faster than filter wheel.

CHALLENGE

- ✓ The filter wheel has moving parts, large mass, slow response time (ms), and provides limited spectral resolution.
- ✓ Need an Active Tunable Filter Component (ATFC), all solid-state and a single-component tunable filter which has the advantages of high spectral, spatial and temporal resolutions and Size, Weight, and Power (SWaP) merit.

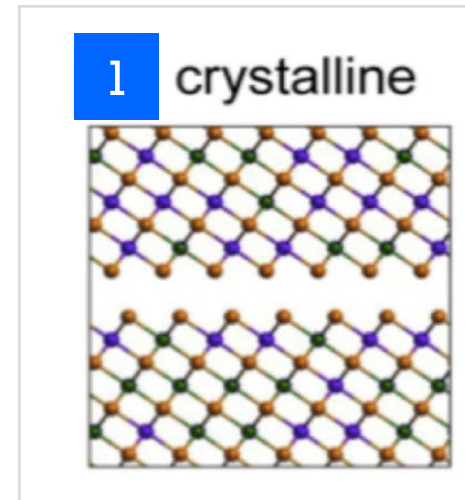
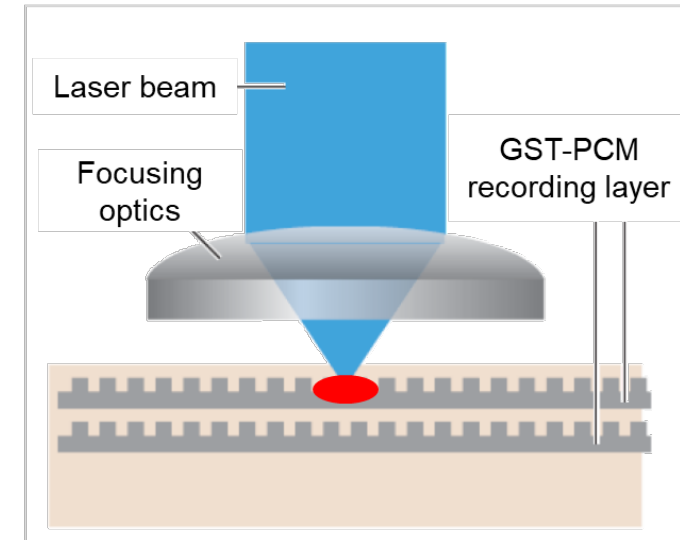
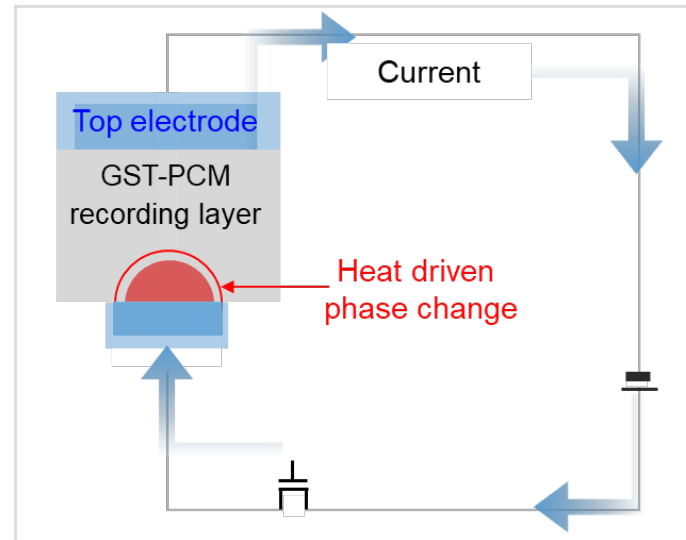
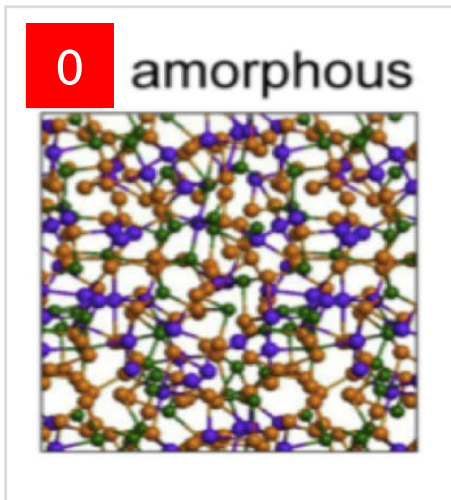


Phase Change Material (PCM) History



- ✓ In **1966**, PCM originally developed for memory material
 - ✓ The $\text{Ge}_2\text{Sb}_2\text{Te}_5$ (GST-PCM), the recording layer

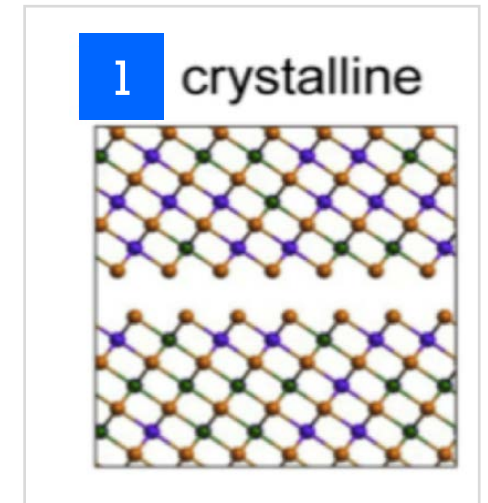
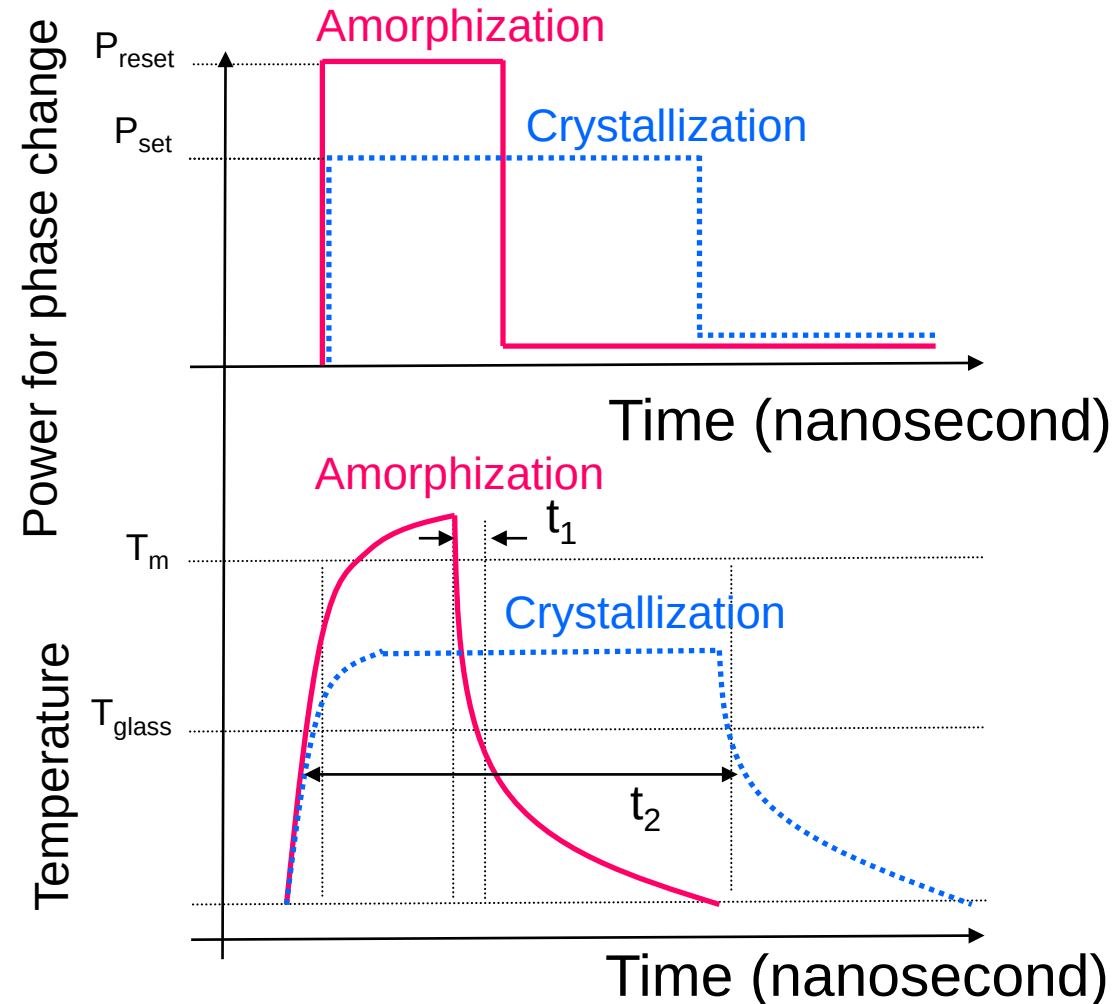
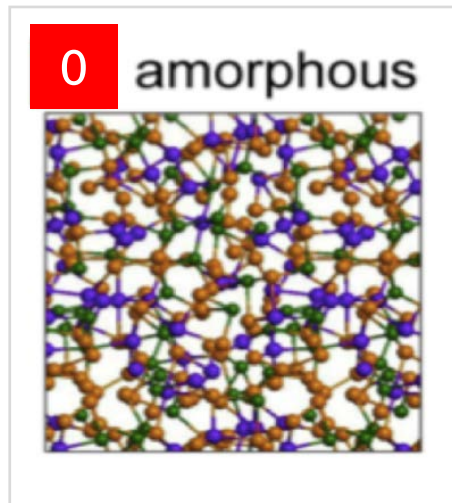
- ✓ Memory recording between amorphous (0) and crystalline (1)
- ✓ Electrically or optically induced heat for ns phase transitions
 - ✓ Reversible / linear phase transition ($>10^{15}$ cycles)



- ✓ PCM, **active material** — MHz (ns) speed (energetic movement) from one state to the other by heat

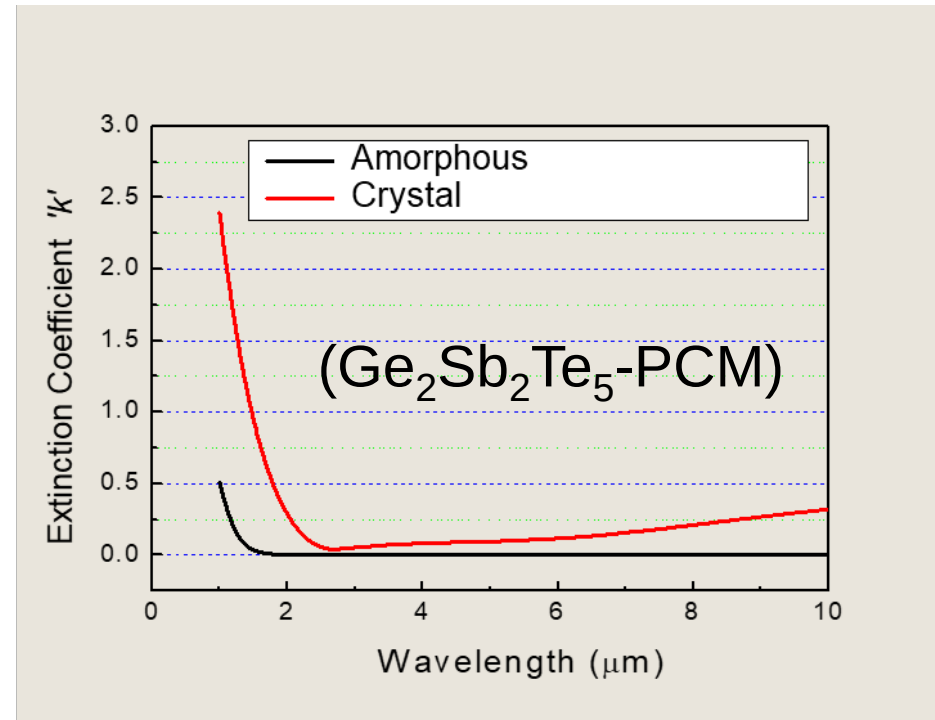
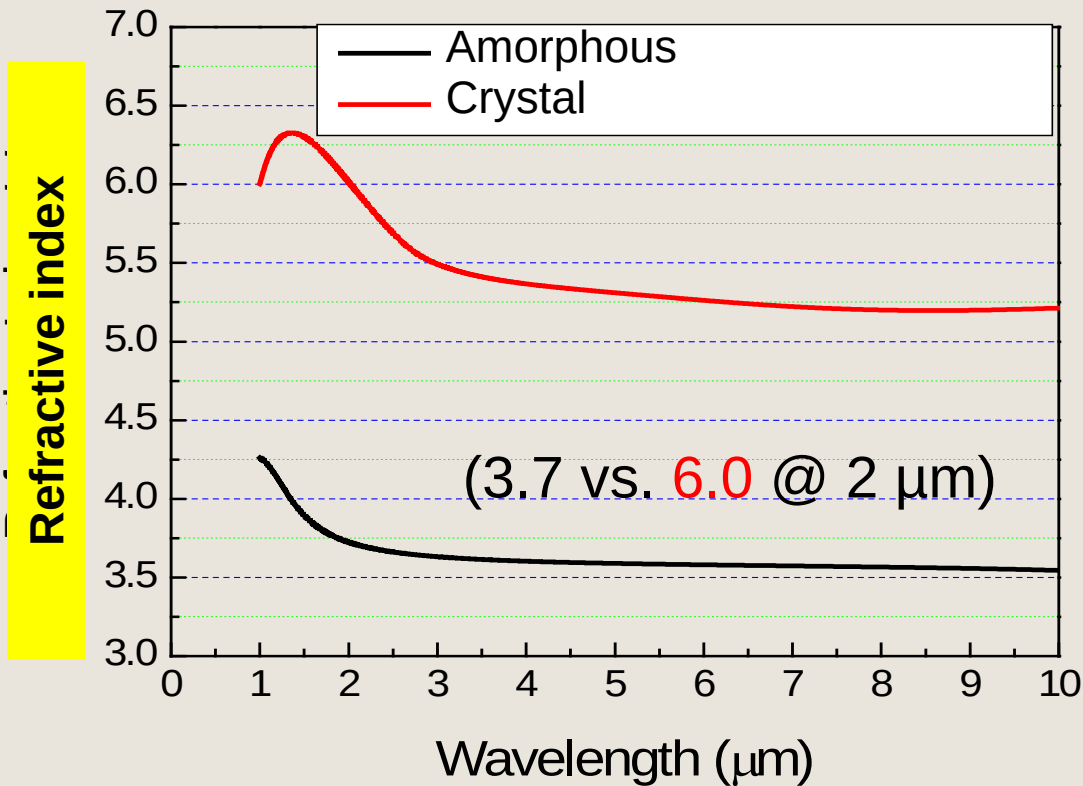
Amorphous – Crystalline Phase Change

can be triggered repeatedly by heat (electrical or laser power) in nanosecond (MHz)

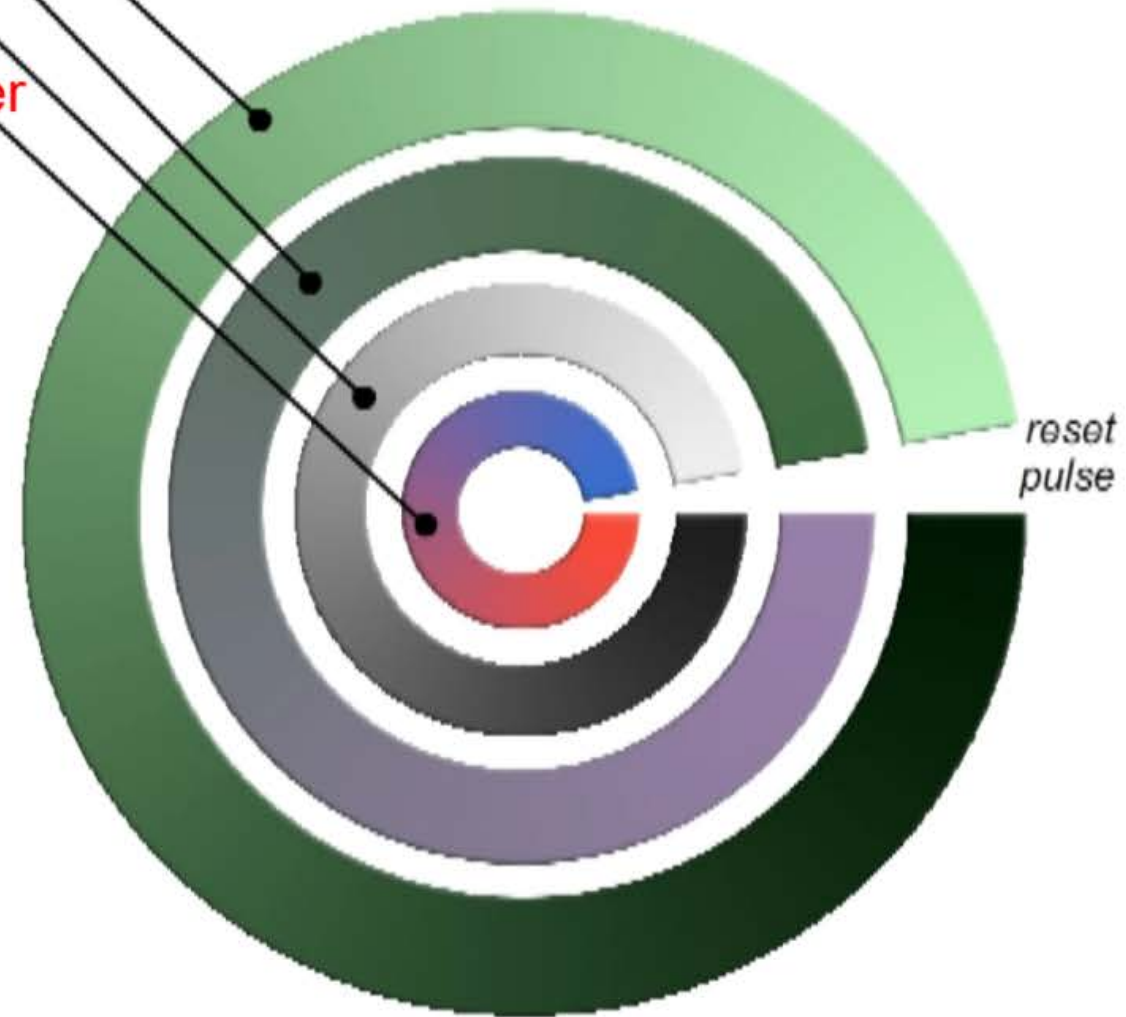
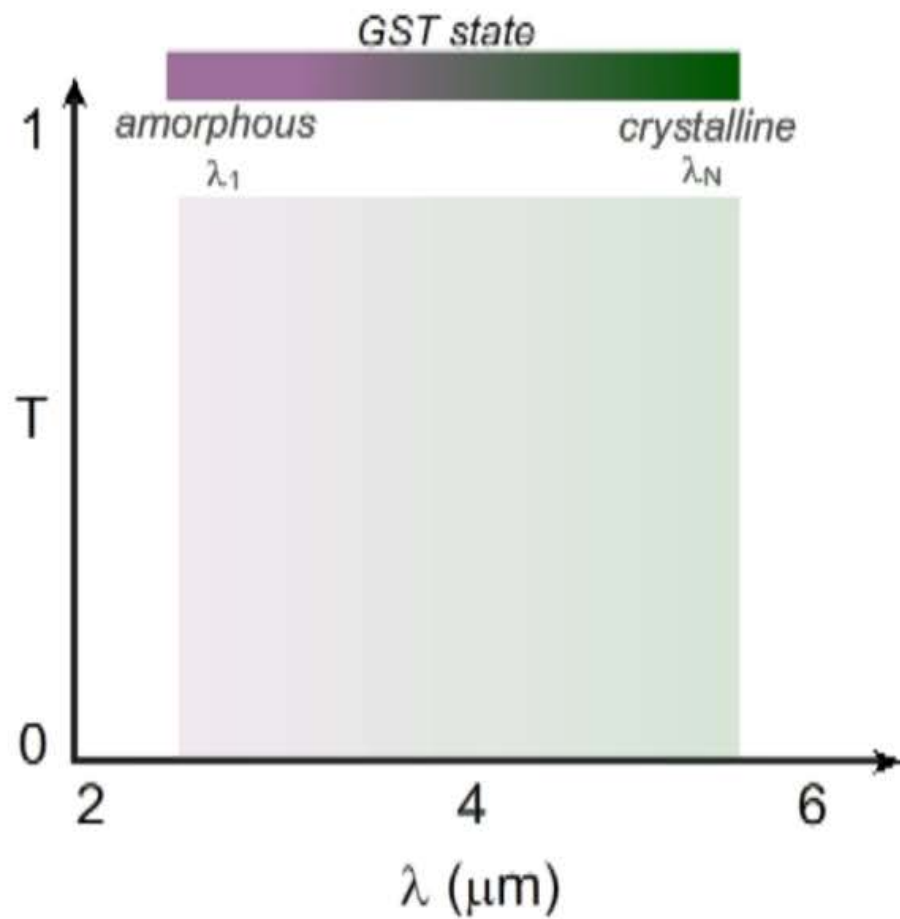
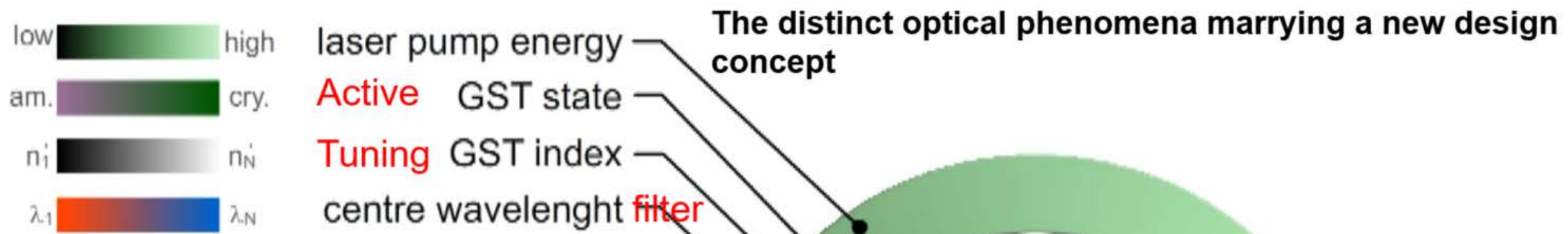


Huge Refractive Index Shift!

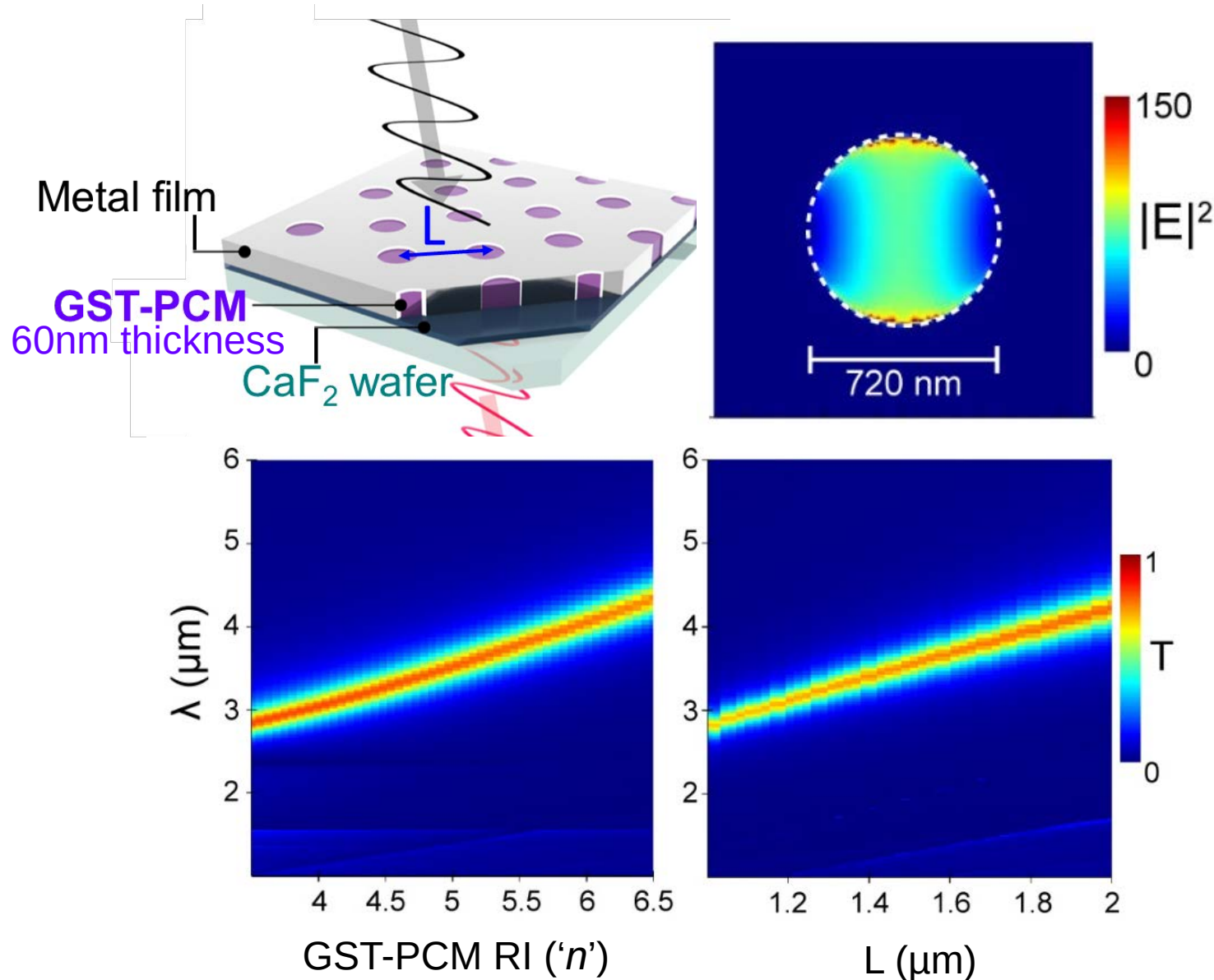
- ✓ In 2014, Large Refractive Index contrast between phases in MWIR (*Nature*, 511, 206-211)



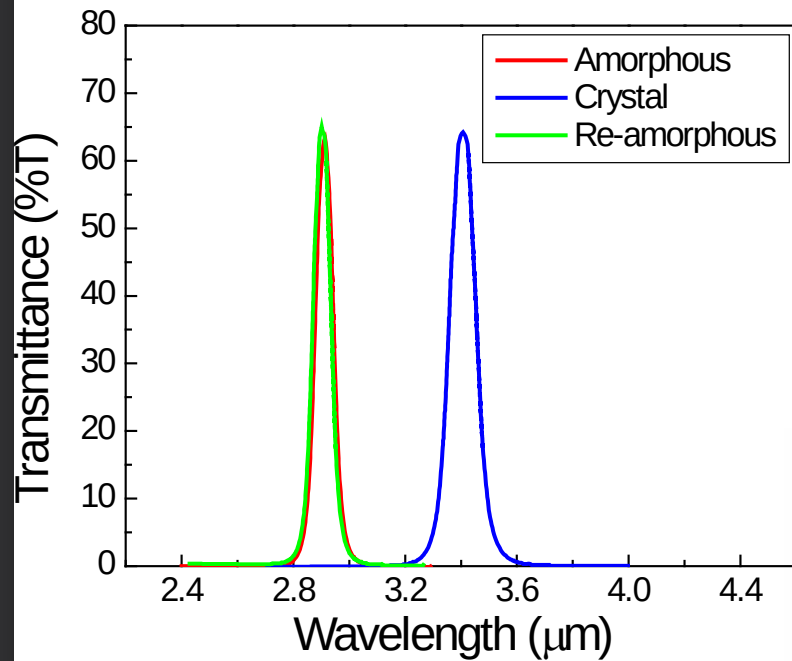
Phase change materials and extraordinary optical property are independently well-known. However, by combining their specific benefits in a single novel design, unexplored capabilities have been demonstrated.



Active Filter Configuration (PCM / PNA)



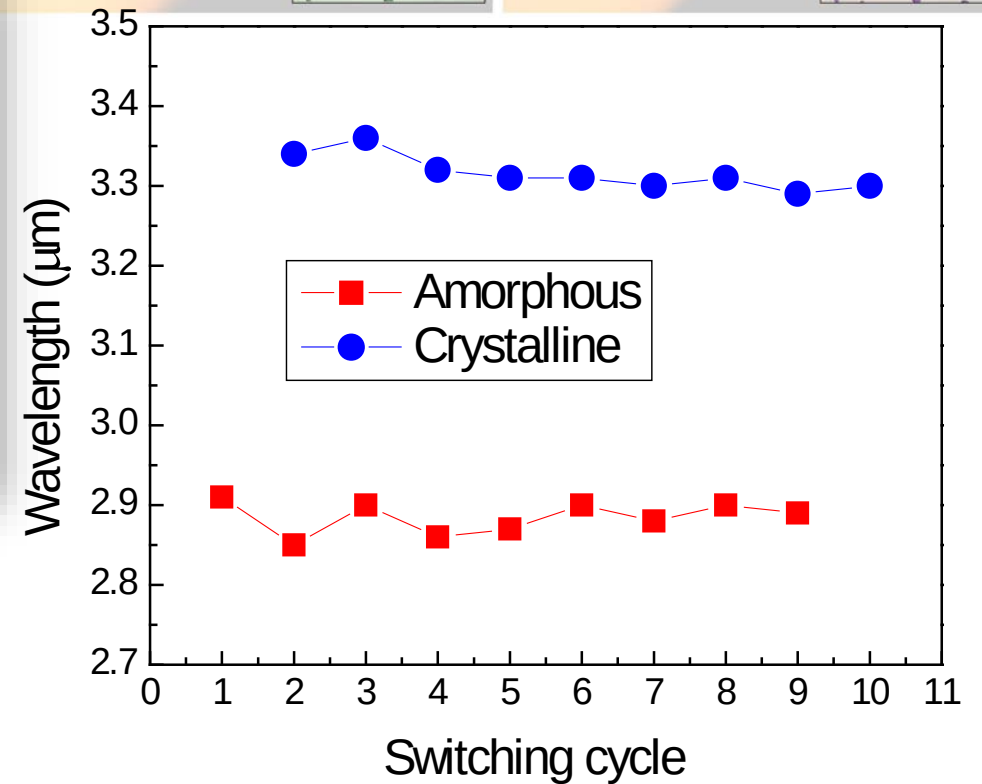
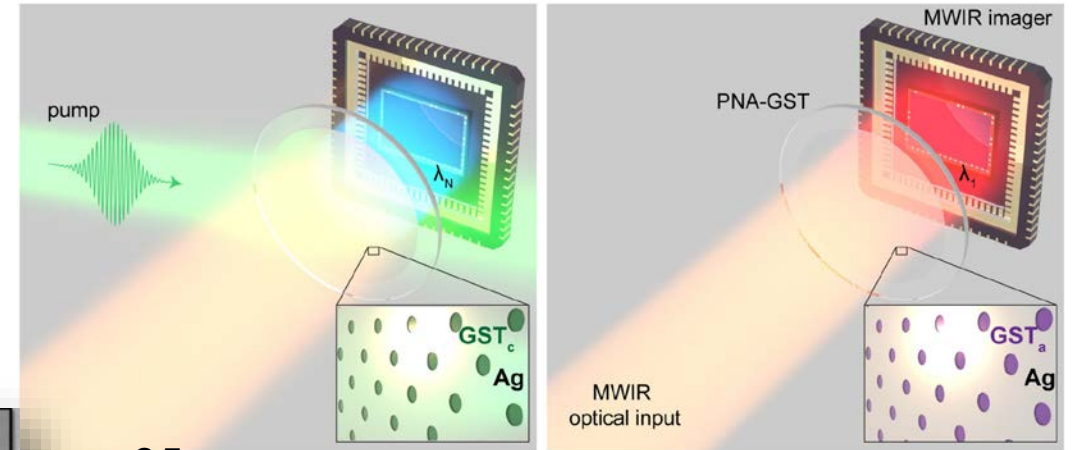
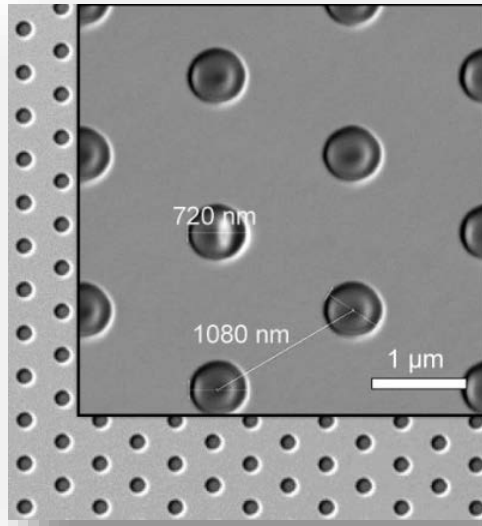
- Integration of GST-PCM with nano structured Al filter design
- **GST-PCM (active material) & Plasmonic Nanohole Array (PNA-passive device)**
- GST-PCM filled nanohole arrays associated resonance at particular WL in metal film $\rightarrow$ transmission mode filtering
- Polarization insensitive design

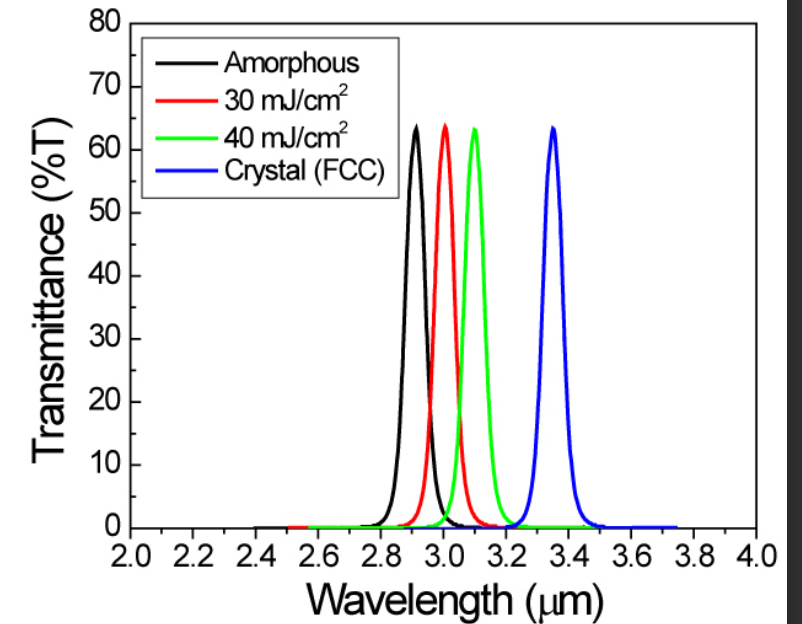
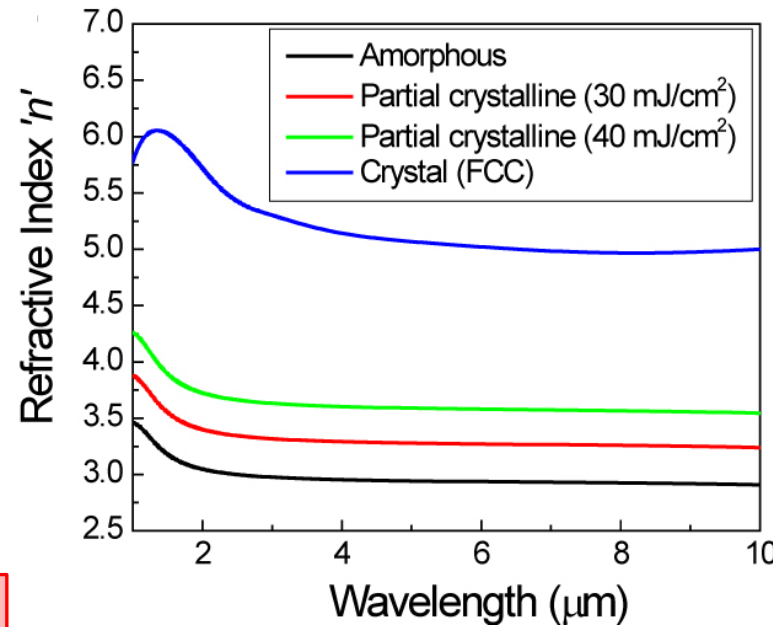
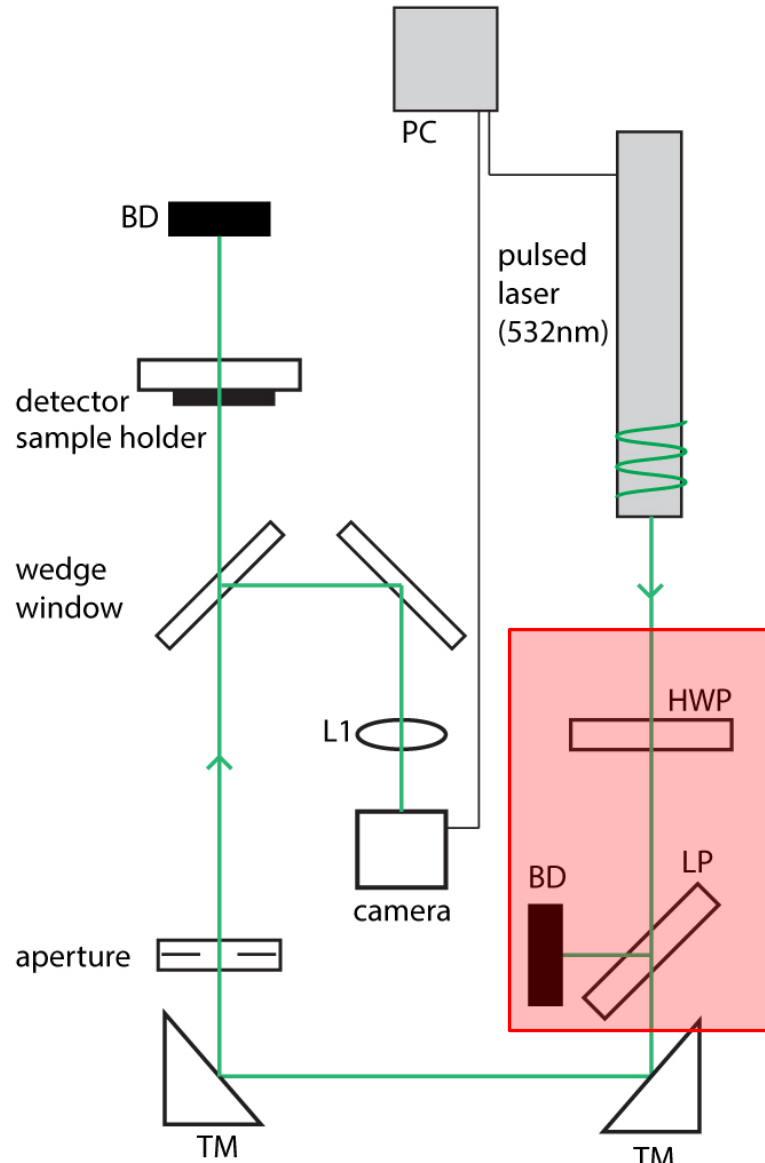


- ✓ 65%T
- ✓ 74nm bandwidth
- ✓ 2.9 μm and 3.4 μm spectral tuning
- ✓ Perfect reflection at the off-resonance

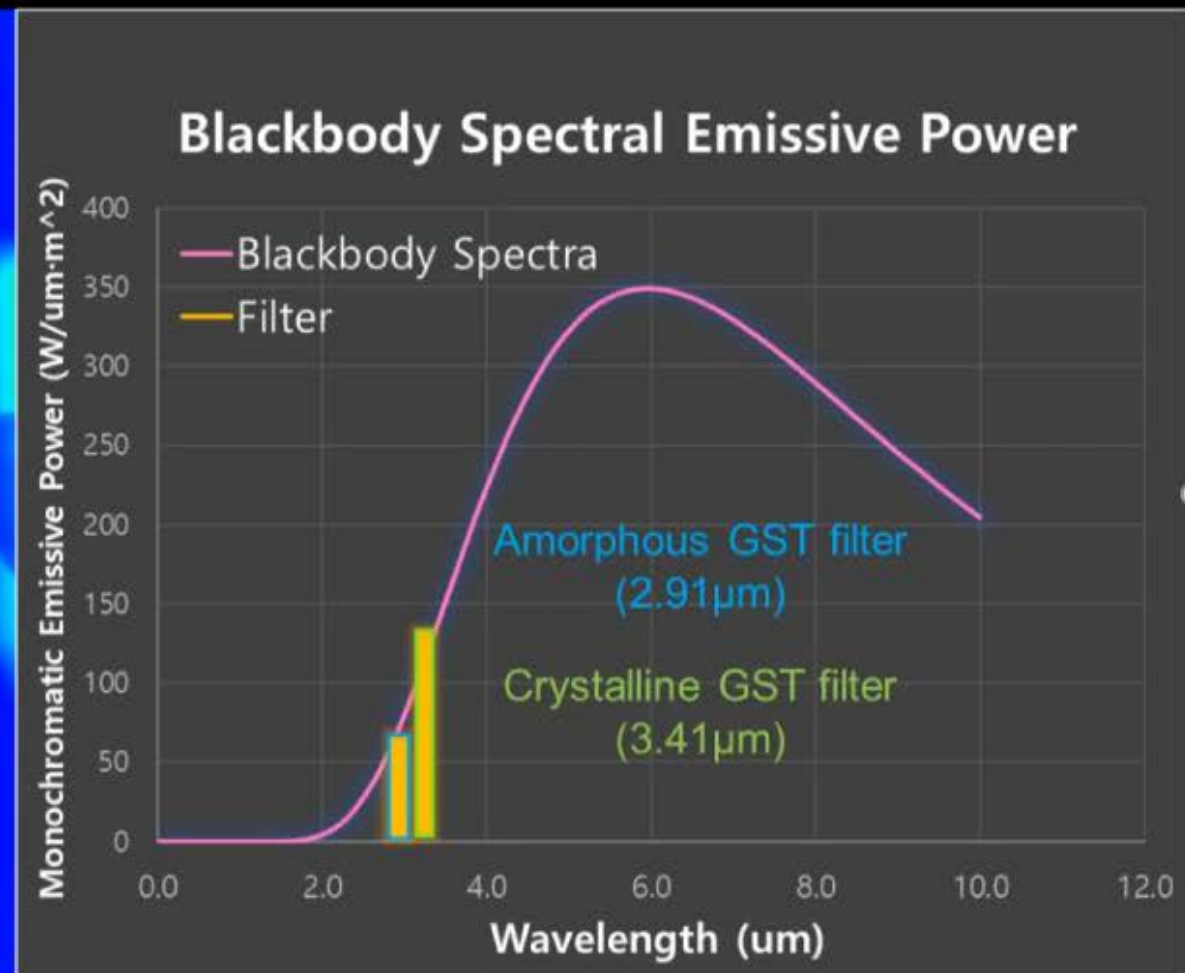
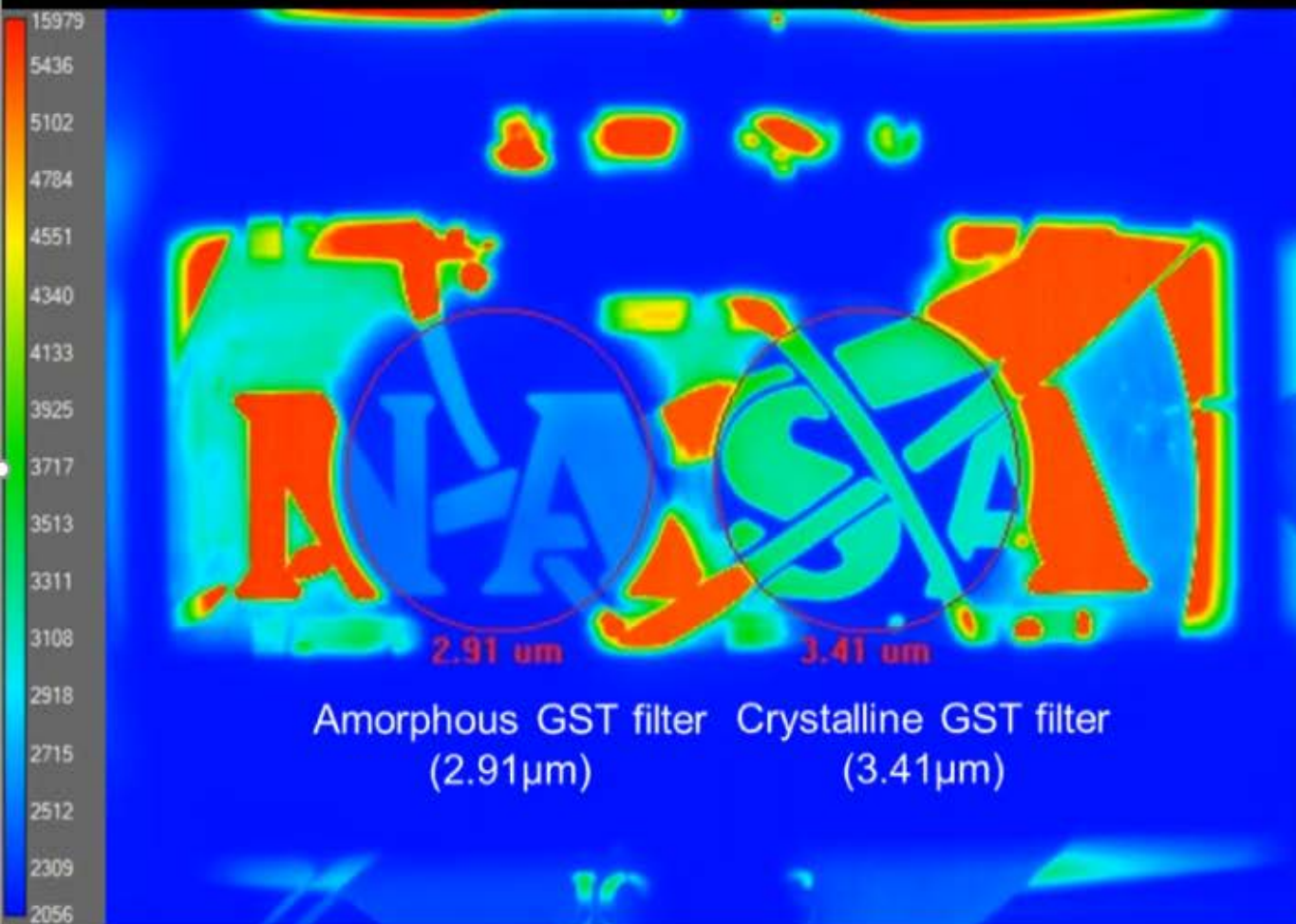
Challenge & Lesson learned

- ✓ Switching cycle surface damage
- ✓ ZnS – SiO₂ protect layer add (prevent oxidation/volatilization)

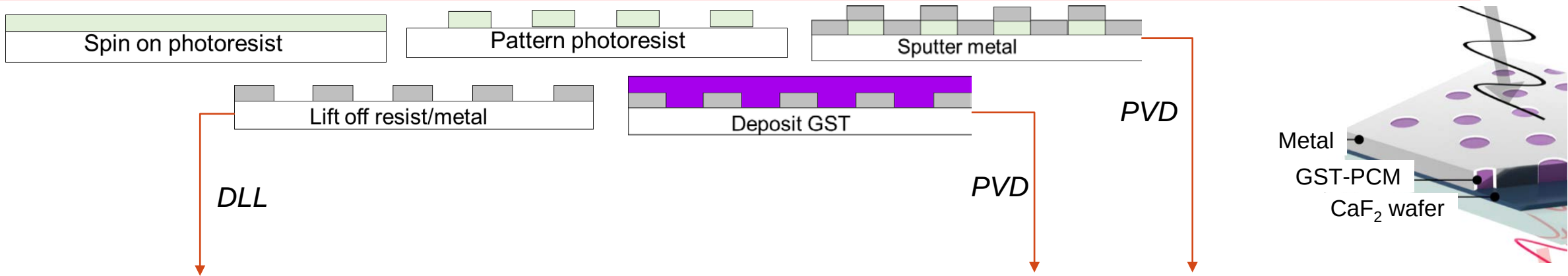




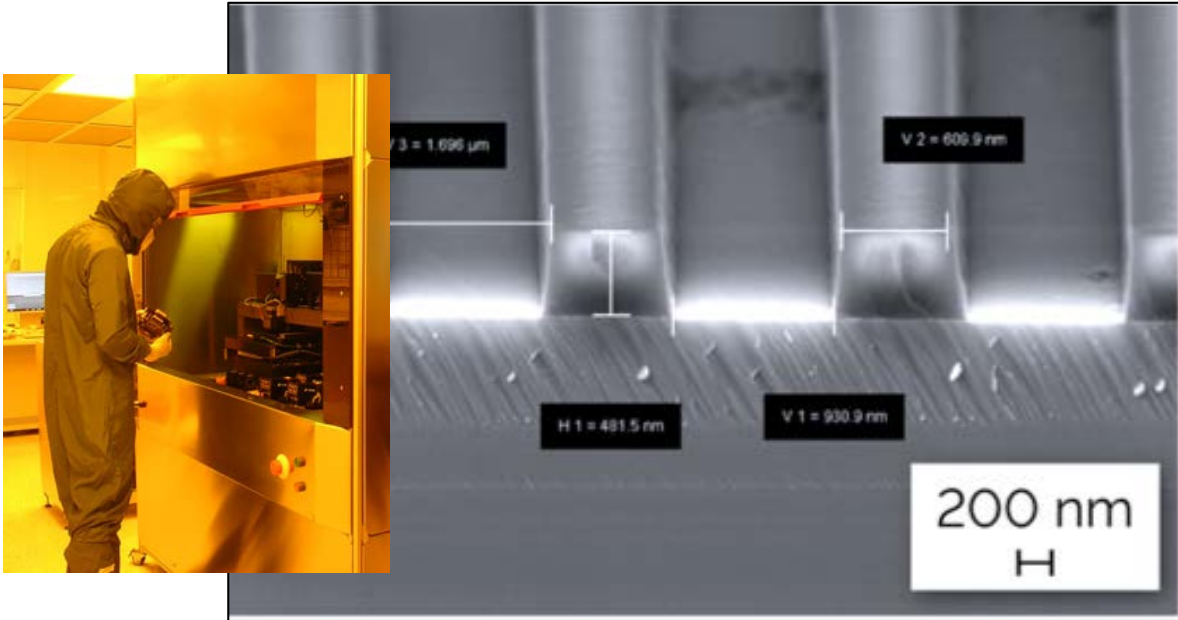
- GST-PCM is generally considered to be a 2-bit material ('0' / '1'), either amorphous or crystalline state.
- Partial crystallizations of GST-PCM experimental demonstrations by using the energy-controlled (Half Wave Plate & Polarizer) & 100 nanosecond pulsed laser



LaRC ISO5 Cleanroom for ATFC Fabrication



Device DLL (Direct Laser Lithography)
< 600nm resolution



Material PVD (Physical Vapor Deposition)
>100 layers

Process recipe			
	STEP1	STEP2	STEP3
Step Name	START	GAS ON	RF ON 50W
Run Time(H)	0	0	0
Run Time(M)	0	0	0
Run Time(S)	10	30	10
Temp(°C)	100	200	100
Throttle Valve Set	0	20	20
Rotate Speed(RPM)	0	10	10
Gun1 Shutter(1-Open)	0	1	1
MFC1(Ar-50sccm)	0	30	30
MFC2(O2-50sccm)	0	0	0
Loop Start No	0	0	
Loop Count	0	0	15

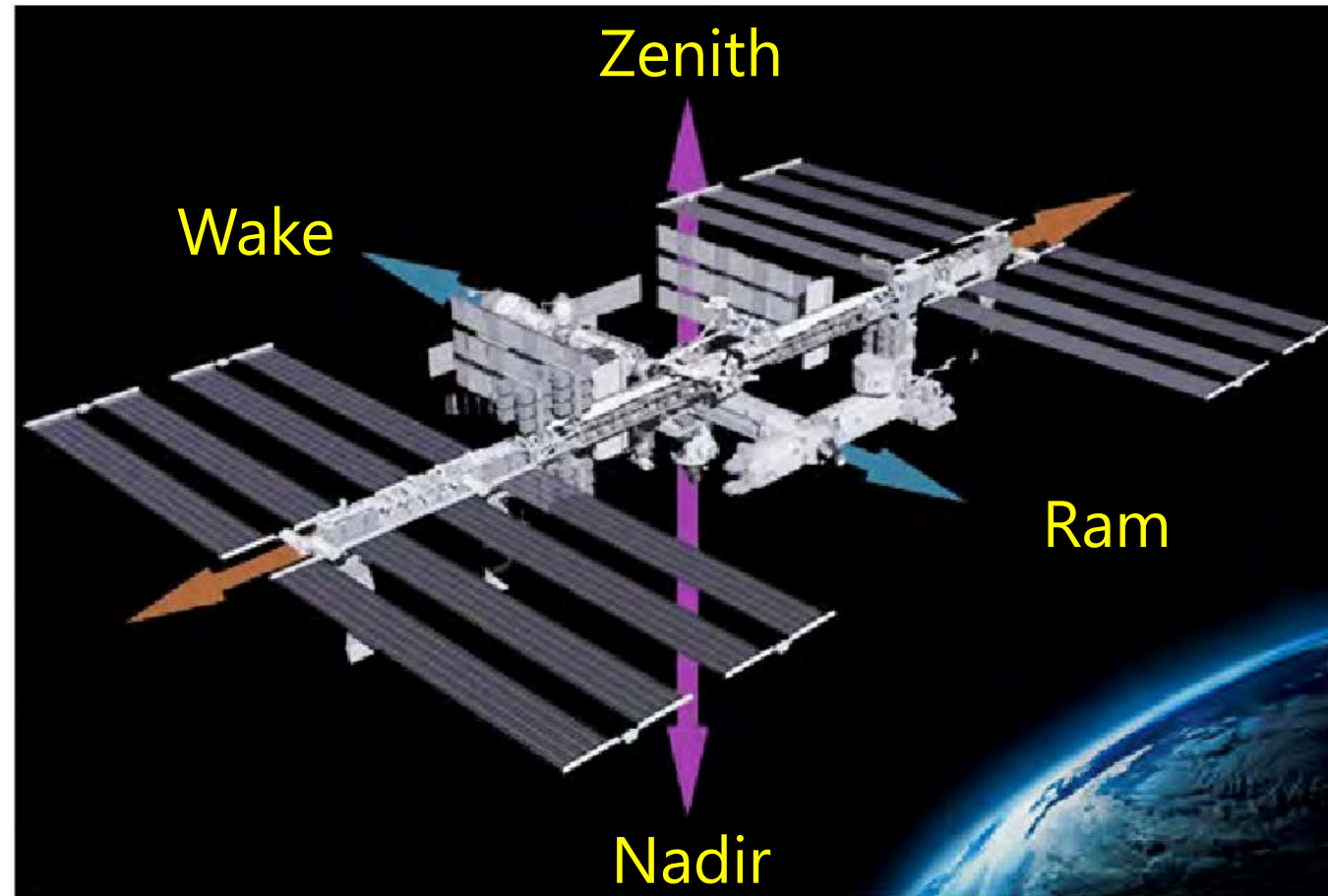
Materials International Space Station Experiment

ATFC is selected for MISSE-14 program & will flight to ISS in August 2020 for performance evaluation in LEO

Atomic oxygen

would
affect optical
properties

UV exposure under
vacuum would affect
material properties



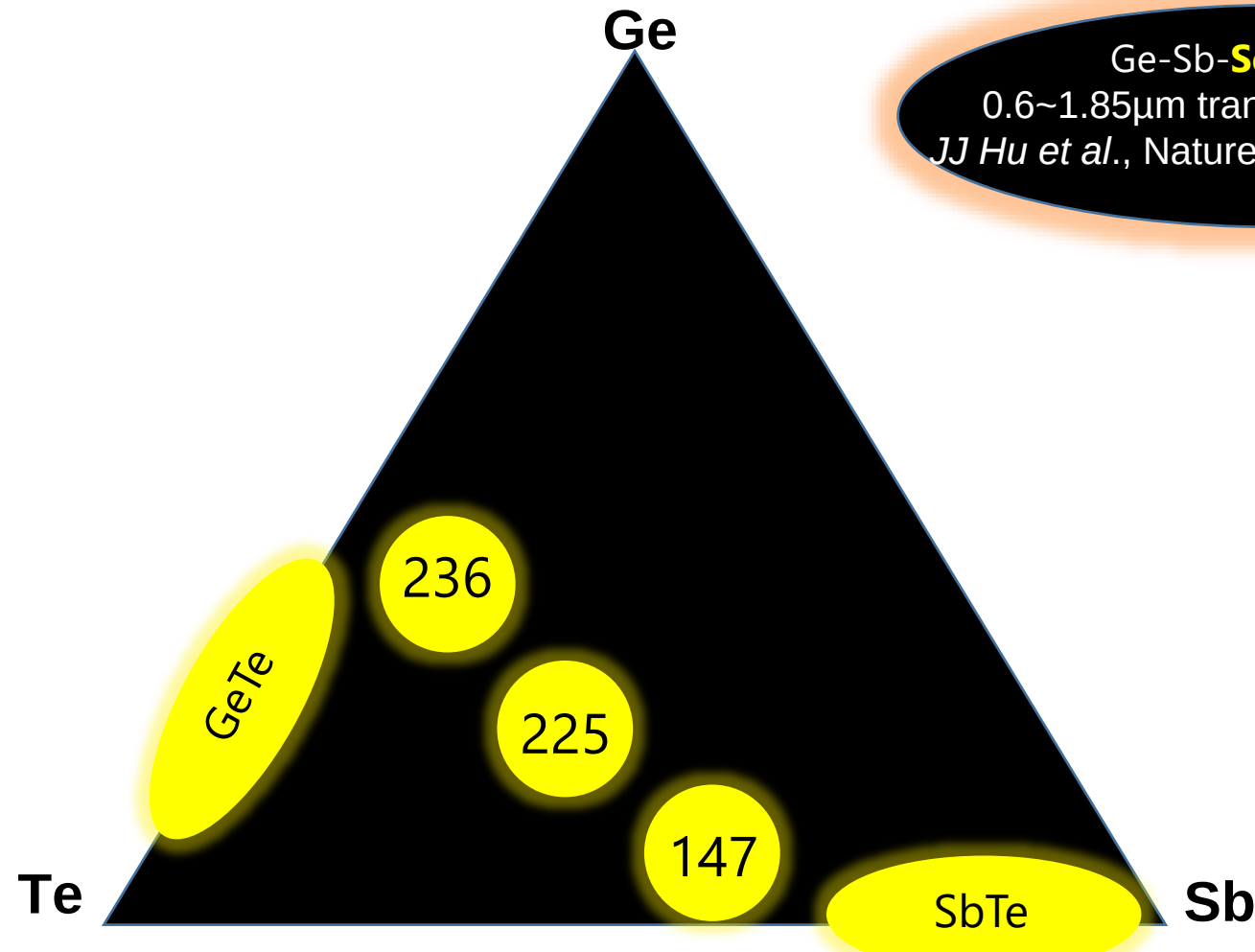
Extreme thermal cycle would affect
filter
efficiency

Solar illumination
Radiation
Contamination

ATFC expose at ISS will provide data to enable the manufacturing of long-term reliable components used on space

Toolbox - Customized Filter Design

- ✓ Select and combine various PCM alloys with device designs to create customized tunable filter
- ✓ Toolbox for specific applications with targeted wavelength bands



Ge-Sb-**Se**-Te (**GSST**)
0.6~1.85 μ m transparency, $\Delta n = 2.0$
JJ Hu et al., Nature Com, 10:4279 (2019)

Summary and Plan

- The MWIR spectrum contains a wealth of invaluable information with applications in
 - Remote sensing (H₂O / CH₄ LIDAR)
 - Thermal signatures (rocket core booster stage)
 - Astronomical imaging systems (exo-plant atmospheres)
- Phase Change Material (PCM) offers the advantages of nano-seconds switching speed, >10¹⁵ switching robustness, and scaling potential.
- PCM-based tunable filter is capable of **MHz tuning speed and reduced size, weight, and power (SWaP)**.
- We have demonstrated 1st steps in developing MWIR filter based on GST, incorporated into **PNA device**.
- **Customizable to meet specific requirement of tunability and resolution** in order to extract maximum information from the active tuning.
- The MWIR filter can improve the key scientific component metrics of associated with active tuning filter systems.