4.07 All-Dielectric Phase-Change Nanoantennae and Metasurfaces in Mid-IR

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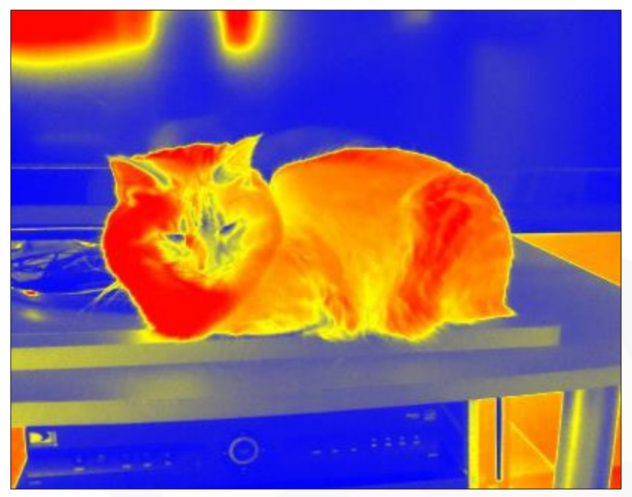
Problem: mid-IR optical elements are bulky, non-tunable, and limited in functionality

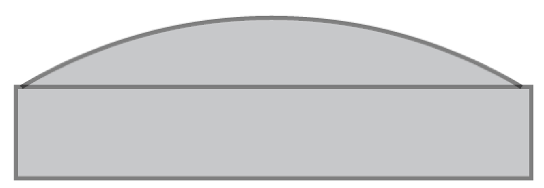
Mid-infrared spectral band is vastly utilized by numerous military, biomedical and industrial applications, including thermal imaging, biochemical sensing, and free-space communication.



Cat's glowing in the dark registered by a mid-IR camera.

typical Ge lens for mid-IR imaging

- bulky
- non-tunable
- expensive



Can we build a better lens?

Our approach: metasurface-based designs & novel phase-change materials

Huygens' principle

wavefront is a superposition of wavelets emanating from secondary sources (antennae).

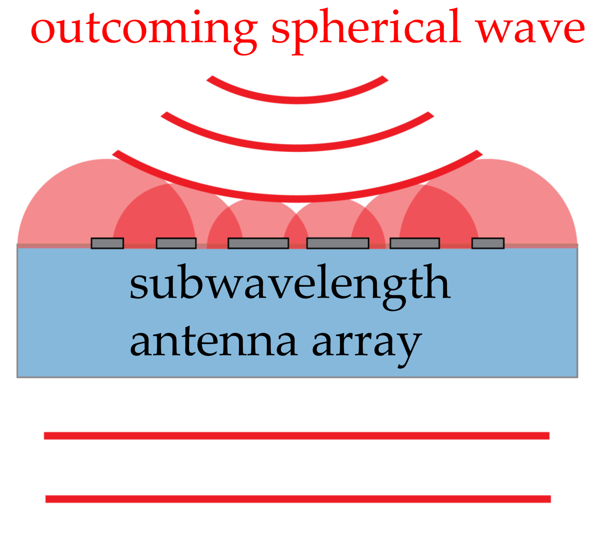


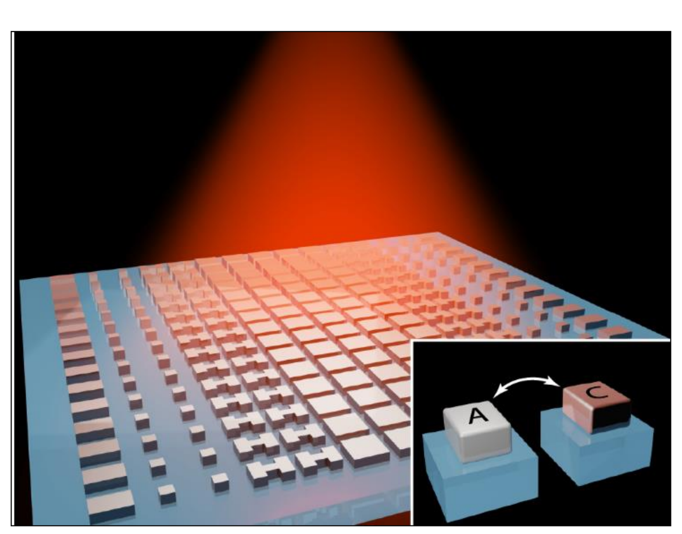
Illustration of Huygens' principle

Metasurface advantages

- ultra-thin (<1µm for mid-IR applications)
- custom tailorable (constituent antenna engineering)
- flat interface (suitable for planar technology)
- relatively easy to fabricate (typically single lithographic step)

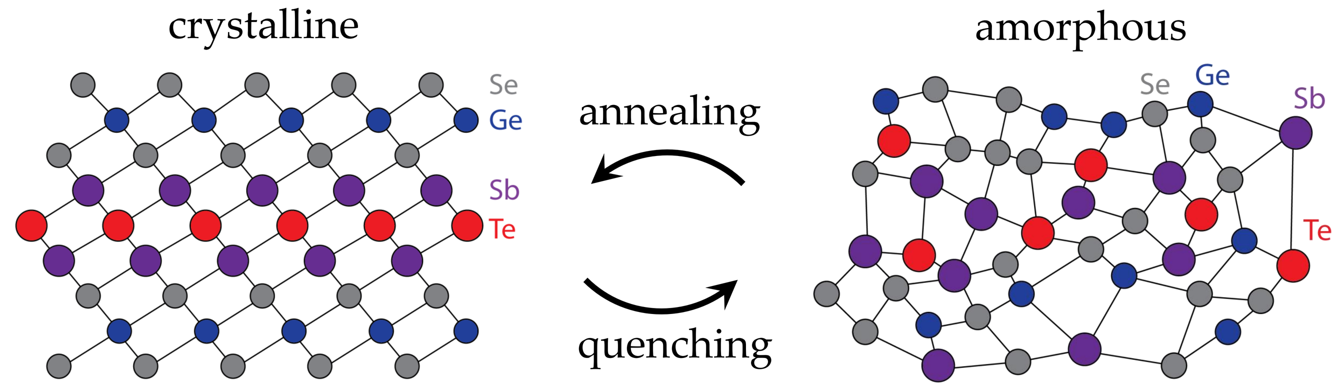
All-dielectric metasurface based on phase-change materials

- high transmission efficiency due to low absorption losses
- operation principles based on Mie scattering (resonator size ~ $\lambda_0/2n$)
- resonators support various multipole modes (e.g. electric and magnetic dipoles); their interference may drive unique phenomena, such as unidirectional scattering
- material phase switching (i.e. change in refractive index) enables tunable and switchable metasurface operation



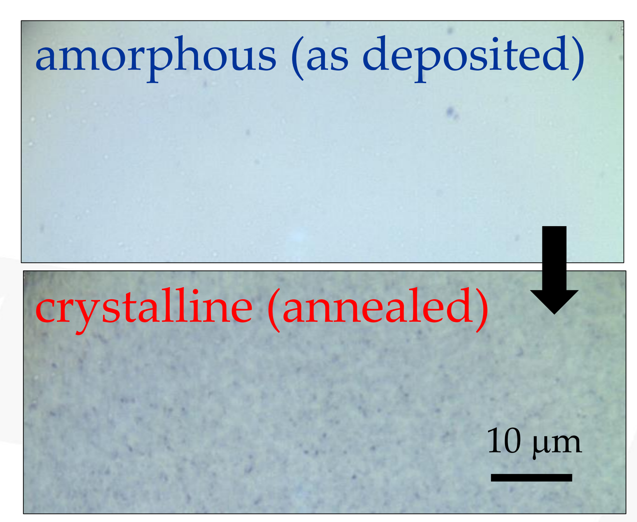
Artistic depiction of a phase-change meta-lens; "A" and "C" stand for amorphous and crystalline phases, respectively.

Ge-Sb-Se-Te (GSST) transparent phase-change material in mid-IR

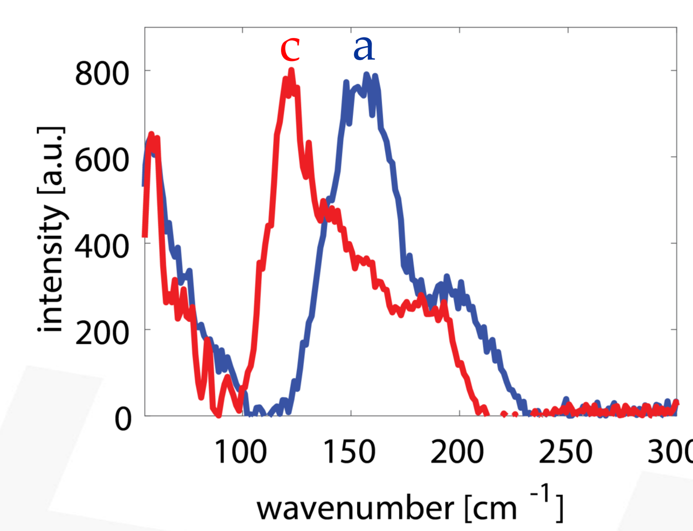


Simplified schematic of GSST atomic structure

$Ge_2Sb_2Se_4Te_1$ is a newly developed glass-type material capable to switch between crystalline and amorphous phases. The transition can happen rapidly (< 10ns) and in principle 10^6 reversible cycles may be achieved.



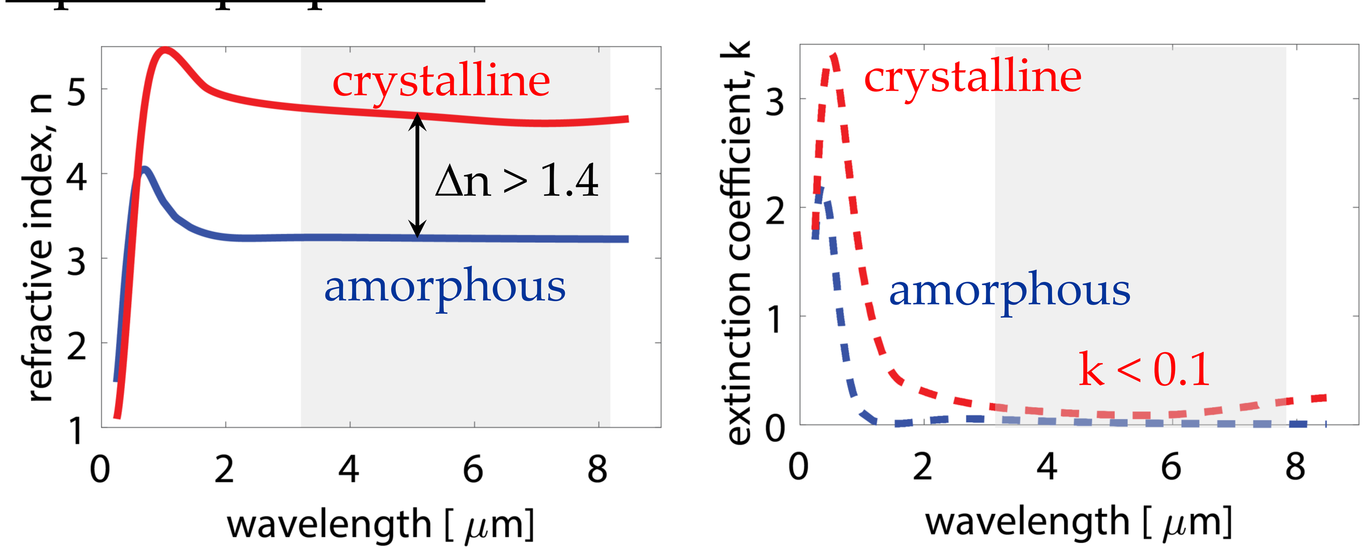
Optical microscope image



Raman scattering spectra

The phase transition is observed both visually and from Raman spectra.

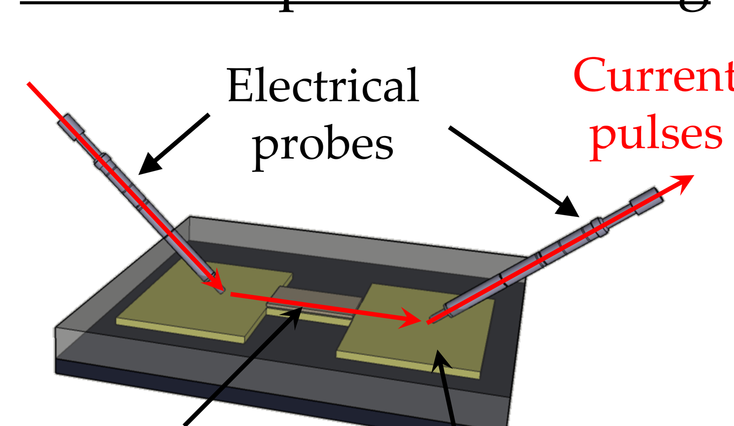
Optical properties



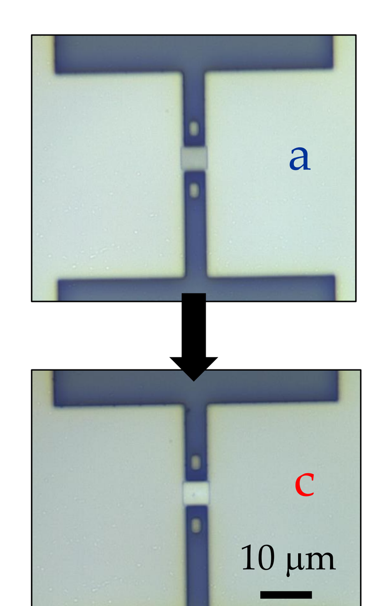
Ellipsometry measurements

In mid-IR (shaded area) GSST possesses unique optical properties, such as high absolute refractive indices (n_A ~ 3.2, n_C ~ 4.6), drastic change in refractive index (Δn > 1.4), and acceptable losses (k_A ~ 0.02, k_C ~ 0.1).

Electrical phase-switching



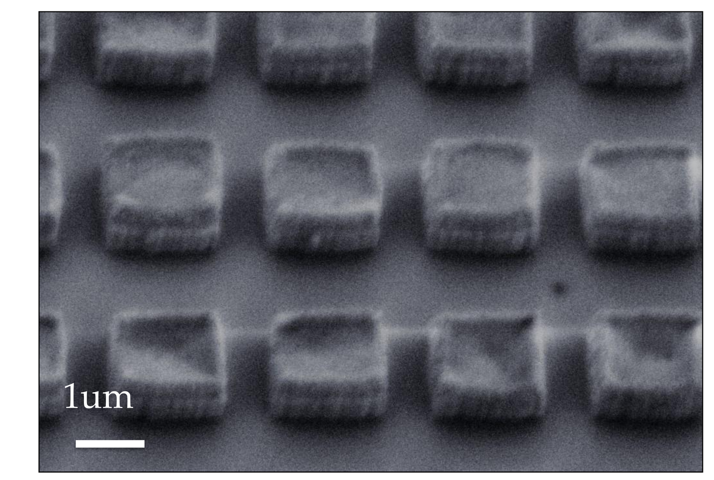
Sketch of experimental layout for performing electrical switching



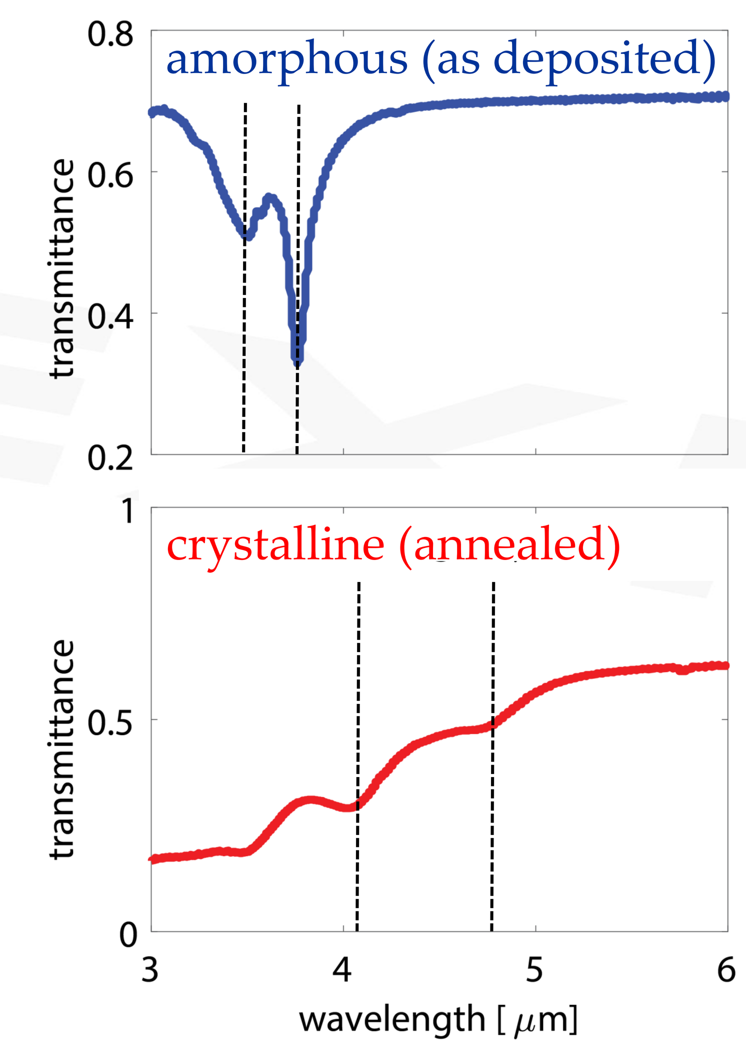
Optical microscope image

GSST all-dielectric nanoantennae: fundamental building blocks for meta-optical devices

Experimental realization



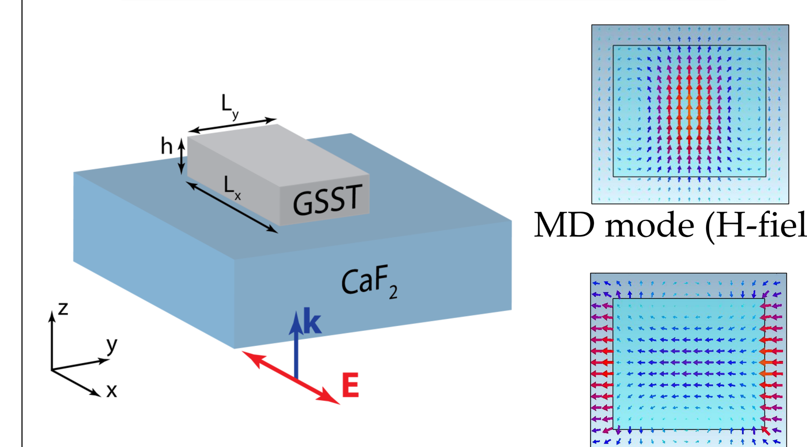
SEM scan demonstrates $Ge_2Sb_2Se_4Te_1$ antenna array fabricated using electron beam lithography and CHF_3:CF_4 dry etching.



FTIR transmission spectra

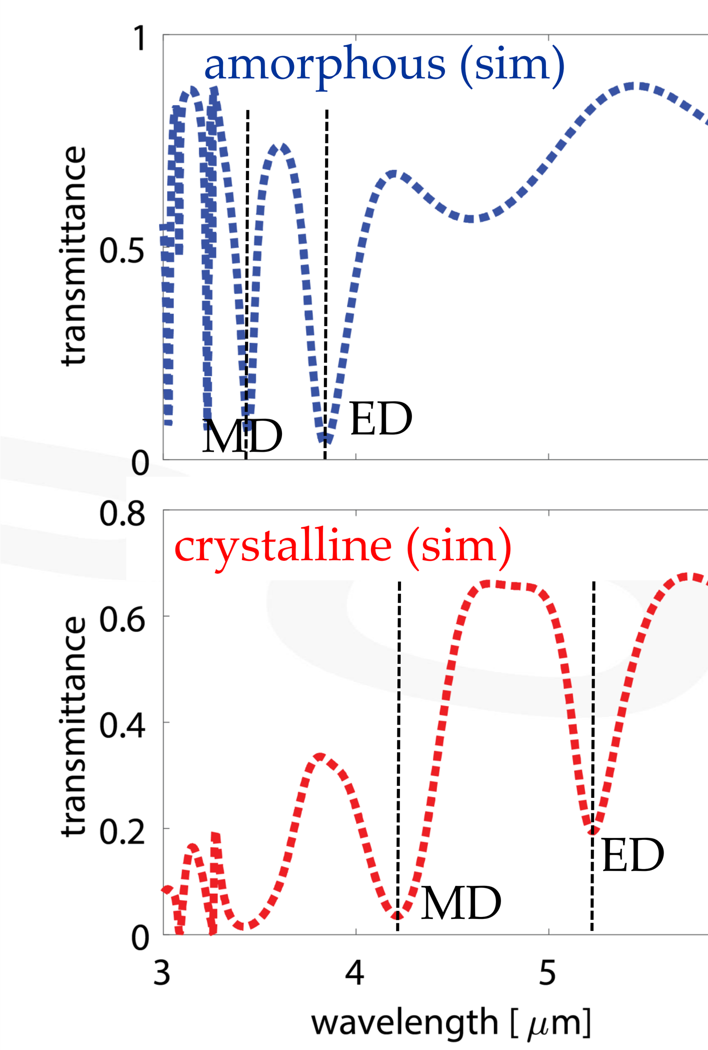
The fabricated GSST antennae give resonant responses in the desired mid-IR range. Amorphous-to-crystalline transition red-shifts the position of the resonances.

Numerical simulations



Layout of simulated resonator

Simulated antenna dimensions: L_x = 1.8µm, L_y = 1.55µm, h = 0.5µm. The antenna is expected to support both electric (ED) and magnetic dipole (MD) resonances.



Full-wave simulation spectra

Simulation results agree reasonably well with the experimental spectra (on the left side). Further studies showed that the discrepancies originate from variations in stoichiometry and incomplete phase transitions in antennae.

Impact

Developed novel phase-change material suitable for constructing transparent, switchable, and ultra-thin optical elements in mid-infrared.

References

[1] S. Kruk and Yu. Kivshar, ACS Photonics, 4, 2638 (2017)
[2] H. Zheng et al., arXiv:1707.00760 (2017)

Acknowledgements

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