

Non-volatile reconfigurable metasurface for free-space phase-only modulation

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Abstract: We demonstrated a nonvolatile electrically reconfigurable metasurface based on low-loss phase-change materials Sb_2Se_3 with phase-only ($\sim 0.25\pi$) modulation in the free-space. The tunable metasurface is robust against reversible switching over 1,000 times.

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Free-space modulation of light has been an enabling technology behind image projection, optical communications, holography, and more recently in light detection and ranging and virtual or augmented reality. Traditional means of modulating free-space light is through spatial light modulators (SLMs) based on liquid crystals (LCs) and microelectromechanical systems (MEMS) which are bulky, require high driving voltage, suffer from phase fluctuations, and support only volatile operation. Recent progress in meta-optics has circumvented some of the limitations by integrating active materials with metasurfaces to realize compact and fast free-space light modulation [1,2]. However, nonvolatile phase-only control, a highly desirable feature of free-space light tuning, is still missing. Here, we demonstrate nonvolatile, electrically tunable, phase-only modulation of free-space wavefront in transmission mode based on low-loss phase change materials (PCMs) Sb_2Se_3 . The strong phase modulation of $\sim 0.25\pi$ is enabled by coupling ultra-thin PCMs to a high- Q diatomic metasurface. The metasurface is robust against reversible switching over 1,000 times. This work represents a crucial step towards a truly “set-and-forget” transmissive phase-only SLM.

Sb_2Se_3 undergoes a refractive index contrast of ~ 0.7 and exhibits zero loss [3] near 1550nm upon phase transition, which stipulates a $\sim 1.1\mu\text{m}$ PCM thickness to obtain π phase shift. Although this is significantly thinner than LC used in commercial SLMs, it still poses a severe challenge in reversible switching the PCMs as PCMs need to be melt-quenched to be amorphized and such a large thickness prevents the critical cooling rate to be reached. Motivated by the use of microring resonators to increase the modulation in integrated photonics [4], a high- Q planar resonator can also be used to enhance the phase-modulation of free-space light by thin film PCMs, while allowing thinner device layer compared to Fabry-Perot cavities. Here we harnessed the high Q resonance in a diatomic metasurface [5] (Fig. 1a and 1c) to realize a phase modulation of $\sim 0.25\pi$ with near zero additional loss introduced by PCMs. In order to dynamically control the diatomic metasurface, we heavily dope the SOI into microheaters [6] that is used to switch the Sb_2Se_3 cladded on top (Fig. 1a). The Phosphorus doped (doping concentration $\sim 10^{20}\text{cm}^{-3}$) SOI is then etched into diatomic gratings before uniformly cladded with 20nm Sb_2Se_3 , followed by 40nm atomic-layer-deposited (ALD) Al_2O_3 encapsulation. The cross-section of the metasurface is shown in Fig. 1c. Current is injected into the highly doped silicon gratings via electrical pulses that causes joule heating, which in turn switches the PCMs. A two-objective transmission setup (Fig. 1b) is used to probe the reversible switching of Sb_2Se_3 -loaded diatomic metasurface. Fig. 1d shows the optical micrograph of a $30\mu\text{m}$ aperture metasurface pixel on a chip that has been wire bonded to the PCB.

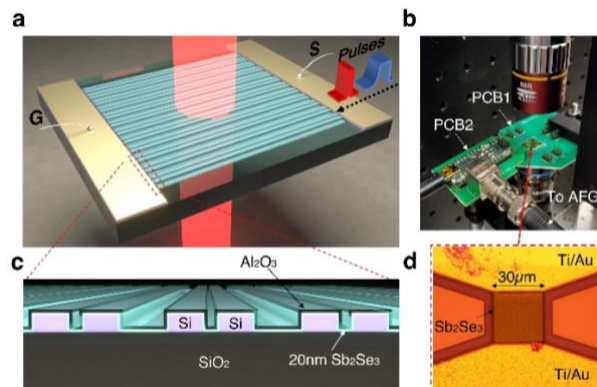


Figure 1: A nonvolatile electrically reconfigurable metasurface based on Sb_2Se_3 . (a) Schematic of the transmissive tunable diatomic metasurface based on Sb_2Se_3 . S (G), signal (ground) electrode. (b) The optical setup for probing the metasurface in transmission along with the devices under test wire bonded to a customized PCB. AFG is arbitrary function generator. (c) The schematic of the tunable metasurface cross section. (d) Optical micrograph of a single metasurface pixel on the chip under test.

Reversible tuning of the diatomic resonance is shown in Fig. 2a (simulation) and 2b (experiment). The spectra of three consecutive switching cycles are plotted in Fig. 2b and the shaded regions indicate standard deviations between the cycles. The small standard deviation reveals excellent cycle to cycle reproducibility. The experimentally extracted spectral shift ($\Delta\lambda \sim 1.2\text{nm}$) matches very well with the simulation ($\Delta\lambda \sim 1.3\text{nm}$). By matching the simulation with the measured spectral shift, we extract a maximum phase shift of $\sim 0.25\pi$ from only 20nm Sb_2Se_3 near the 1518nm resonance (Fig. 2a). To further show that this is indeed a phase-only modulation, we fit the Fano line shape to the resonances of aSb_2Se_3 and cSb_2Se_3 averaged over five consecutive cycles. The extracted Q factor only decreases from 312 to 271 upon crystallization, representing only 13% reduction, which shows that minimal loss is introduced by the phase transition. Finally, we show that the tunable metasurface is robust against switching over 1,000 times without degradation in the contrast, as shown in Fig. 2d.

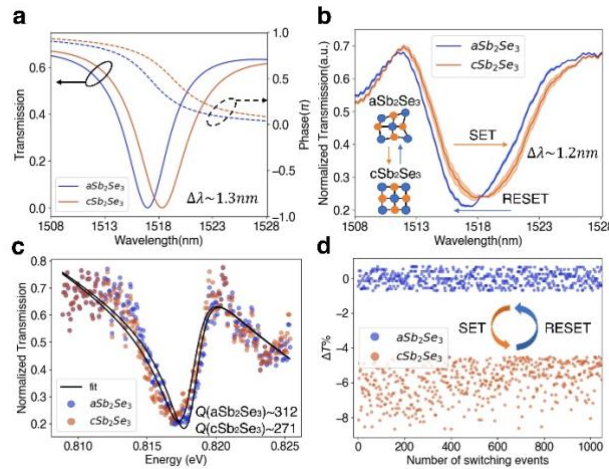


Figure 2: Reversible switching of the diatomic metasurface and nonvolatile phase-only modulation. (a) Simulated spectral and phase shift caused by 20nm Sb_2Se_3 . $\Delta\lambda$ is the wavelength shift of the resonance dip. (b) Measured reversible switching of the diatomic resonance. The switching conditions are 3.6V, 50 μs pulse width, 30 μs trailing edge for SET and 11.6V, 1 μs pulse width, 8ns trailing edge for RESET. (c) Fitting of the measured resonance averaged over five consecutive cycles by Fano equation. The Q factors of aSb_2Se_3 and cSb_2Se_3 are extracted to be 312 and 271 respectively. (d) Cyclability of the tunable metasurface for 1,000 switching events.

We have reported an electrically tunable, transmissive metasurface that can modulate optical phase in a non-volatile fashion. The strong phase-only modulation ($\sim 0.25\pi$) is enabled by the coupling of low-loss phase-change materials Sb_2Se_3 to the high- Q diatomic metasurfaces, resulting in minimal reduction in the Q factor (312 to 291) upon switching. The metasurface is robust against switching of free-space light for over 1,000 times without degradation in the performance. This work represents a crucial step towards a ‘set-and-forget’ transmissive SLMs for applications from AR/VR to light detection and ranging.

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References:

1. S.-Q. Li, X. Xu, R. Maruthiyodan Veetil, V. Valuckas, R. Paniagua-Domínguez, and A. I. Kuznetsov, "Phase-only transmissive spatial light modulator based on tunable dielectric metasurface," *Science* **364**, 1087–1090 (2019).
2. J. Park, B. G. Jeong, S. I. Kim, D. Lee, J. Kim, C. Shin, C. B. Lee, T. Otsuka, J. Kyoung, S. Kim, K.-Y. Yang, Y.-Y. Park, J. Lee, I. Hwang, J. Jang, S. H. Song, M. L. Brongersma, K. Ha, S.-W. Hwang, H. Choo, and B. L. Choi, "All-solid-state spatial light modulator with independent phase and amplitude control for three-dimensional LiDAR applications," *Nat. Nanotechnol.* **16**, 69–76 (2021).
3. Z. Fang, R. Chen, J. Zheng, A. I. Khan, K. M. Neilson, S. J. Geiger, D. M. Callahan, M. G. Moebius, A. Saxena, M. E. Chen, C. Rios, J. Hu, E. Pop, and A. Majumdar, "Ultra-low-energy programmable non-volatile silicon photonics based on phase-change materials with graphene heaters," *Nat. Nanotechnol.* 1–7 (2022).
4. Z. Fang, J. Zheng, A. Saxena, J. Whitehead, Y. Chen, and A. Majumdar, "Non-Volatile Reconfigurable Integrated Photonics Enabled by Broadband Low-Loss Phase Change Material," *Advanced Optical Materials* **9**, 2002049 (2021).
5. B. Zeng, A. Majumdar, and F. Wang, "Tunable dark modes in one-dimensional ‘diatomic’ dielectric gratings," *Opt. Express*, OE **23**, 12478–12487 (2015).
6. J. Zheng, Z. Fang, C. Wu, S. Zhu, P. Xu, J. K. Doyle, S. Deshmukh, E. Pop, S. Dunham, M. Li, and A. Majumdar, "Nonvolatile Electrically Reconfigurable Integrated Photonic Switch Enabled by a Silicon PIN Diode Heater," *Advanced Materials* **32**, 2001218 (2020).