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Reconfigurable semiconductor Mie-resonant meta-optics

Tomer Lewi[a*], Nikita A. Butakov[b], Prasad P. Iyer[b], Hayden A. Evans[d], David Higgs[b], Hamid Chorsi[b], Juan Trastoy[c,e], Javier Del Valle Granda[c], Ilya Valmianski[c], Christian Urban[c], Yoav Kalcheim[c], Paul Y. Wang[c], Ivan K. Schuller[c] and Jon A. Schuller[b]

[a]*Faculty of Engineering and Institute for Nanotechnology and Advanced Materials, Bar-Ilan University, Ramat-Gan 5290002, Israel*
[b]*Department of Electrical & Computer Engineering, University of California Santa Barbara, Santa Barbara, California 93106, United States*
[c]*Department of Physics, University of California, San Diego, La Jolla, California 92093, United States*
[d]*Materials Research Laboratory and Department of Chemistry and Biochemistry, University of California Santa Barbara, California 93106, United States*
[e] *Unité Mixte de Physique CNRS, Thales, Univ. Paris-Sud, Univ. Paris Saclay, 91767 Palaiseau, France*

Abstract

Metasurfaces allow unprecedented control of light through engineering the amplitude, phase and polarization across arrays of meta-atom resonators. Adding dynamic tunability to metasurface components would boost their potential and unlock a vast array of new application possibilities such as dynamic beam steering, LIDAR, tunable metalenses and reconfigurable meta-holograms, to name a few. We present here high-index reconfigurable meta-atoms, resonators and metasurfaces that can dynamically and continuously tune their frequency, amplitude and phase, across the near to mid-infrared spectral ranges. We highlight the importance of narrow linewidth resonances along with peak performance of tunable mechanisms for efficient and practical reconfigurable devices.

Keywords: Dielectric Mie resonators, nanoparticles, tunable metasurfaces, reconfigurable metasurfaces, phase change materials

1. INTRODUCTION

Metasurfaces are planar optical structures designed to manipulate light through arbitrary wavefront shaping [1] [2] [3] [4]. Recently, all-dielectric metasurfaces have led to tremendous progress, giving rise to several demonstrations including achromatic and broadband metalenses [5] [6] [7], axicon lenses[8], sub-diffraction focusing[9], nonlinear generation[10] [11] [12] beam deflectors[8,13] [14], wave plates and beam converters [15] [16] [17] [18], holograms[19] [20] [21], antireflection coatings[22] and magnetic mirrors[23], to name a few. However, most metasurfaces are still implemented for static operation and optimized for limited bandwidth of operation. The next frontier lies in dynamic and active control over light, which will drastically increase metasurface capabilities and potential applications.

The fundamental challenge for achieving reconfigurable operation is to obtain large and continuous modulation of optical properties within subwavelength meta-atoms and meta-molecules which are inherently low-

* *E-mail: tomer.lewi@biu.ac.il

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Q resonators[24,25]. Desirable tuning mechanisms continuously shift the resonance frequency of the metastructure with at least one linewidth of the resonance, thus allowing to maximize the modulation of both amplitude and phase. These challenges have motivated several studies exploring different approaches, designs, and materials that provide extreme tunability. Previous investigations of active tuning in dielectric metasurfaces and meta-atoms have focused on ultrafast free-carrier injection[26,27], coupling to liquid crystals[28,29], to atomic vapor[30] or to ENZ materials[31,32], phase change materials[33,34] and MEMS[35 36 37]. However, most of these approaches do not provide a viable solution for a fully reconfigurable metadevice where at each subwavelength meta-atom the phase and amplitude can be individually and continuously tuned to provide an arbitrary phase profile. Recent studies have showed that the thermo-optic effect (TOE), i.e. refractive index variation with temperature dn/dT can be used to induce large and continuous index shifts in materials having extraordinary thermal dependence[38 39 40,41]. The TOE was also recently used to actively tune Si metasurfaces, but only at a limited temperature range (273-573K)[42]. Here we study thermal tunability in several groups of high-index semiconductor resonators, over large temperature and spectral ranges. We demonstrate thermal tuning of Mie resonances due to the normal positive (TOE) (dn/dT >0) and the anomalous negative TOE (dn/dT<0) in group IV semiconductors (Si and Ge) and in the lead chalcogenide family of group IV-VI semiconductors (PbTe). We also demonstrate the tuning of high order mid-infrared (MIR) Mie resonances by several linewidths with temperature swings as small as ΔT<10K. Lastly, we discuss reconfigurable and switchable devices driven by metal-insulator transitions in vanadium-oxide (VO_2). We demonstrate independent and continuous tuning of both amplitude and phase in a single electrically controlled nanophotonic device based on Ge on VO_2.

Thermo-optic (TO) effects provide an ideal test bed for demonstrating and elucidating reconfigurable metasurface properties. TO tuning can provide large index shifts with no added losses and be integrated into electrically-controlled architectures. Thus, TO tunability forms the basis for many reconfigurable integrated photonic devices. However, the TOC of most materials is small for subwavelength applications, hence typical TO applications exploit small index changes acting over distances much larger than a wavelength to achieve useful modulation. For efficient modulation of subwavelength resonators, the maximally induced index shift Δn should tune the resonance wavelength by more than its linewidth (Δλ/FWHM>1, where Δλ is the resonance wavelength shift and FWHM is the full width at half max of the linewidth). The route for achieving this tunability is by maximizing the TOE using extraordinary materials[24,38,39-41,43,44] and/or narrowing the resonance linewidth using high-Q modes[38] such as supported by asymmetric[28] or fano-resonant[10] metasurfaces.

2. RESULTS AND DISCUSSION

This study of thermal tunability is mainly focused for the MIR spectral range which has tremendous scientific and technological interest including nanospectroscopy[45], thermal imaging[46], chemical and biological sensing[47-50], medical applications[51], laser countermeasures[52] and spectro-interferometry for astro-photonics[53-60], to name a few. Importantly, thermal tunability can be extended to the NIR and visible ranges where the performance of e.g. Si and Ge, can be improved due to the expected increase of dn/dT at shorter wavelengths.

Group IV semiconductors

In the following we first study the TO tuning capabilities of Ge – one of the most commonly used materials for dielectric metasurfaces and nanophotonics. The TOC of Ge is amongst the highest of natural materials[61] which, along with its high refractive indices and CMOS compatibility, makes it very attractive materials for reconfigurable metasurfaces. However, the typical TOC value (~5 x 10^{-4} K^{-1}) requires large temperature modulation which may cause problems if the TOC is strongly temperature dependent[38 39]. In the mid-infrared (MIR) range, for instance, working at high temperatures can generate FC densities in semiconductors that dramatically alter the optical constants due to Drude-like dispersion[62].

To investigate thermal tunability and assess its capabilities, we start by studying Ge single spherical meta-atom resonators fabricated by laser ablation[24,63]. Temperature dependent spectra of a Ge (r=850nm) meta-atom Mie resonator is illustrated in Figures 1a. The first three multipolar Mie resonances in the range 4-8μm, are observed and their thermally tuned resonance wavelength shifts are tracked (dashed lines). These multipolar resonances are labeled according to their polarization (Magnetic or Electric) and mode order (Dipole, Quadrupole). The challenge to obtain sufficient resonance tuning is observed in Figure 1a. Spectral shifts are observed for all resonances as a response to the thermal modulation of the refractive index of the resonators. However, the observed red shifts of resonances are insufficient to allow tuning by one resonance linewidth. Moreover, the expected gradual red shift of the dipole modes plateaus at elevated temperatures then followed by blue shift of resonances at high temperatures. The origin of this behavior is the chromatic dispersion and temperature dependence of the dn/dT. The reason for this peculiar behavior of the TOC can be explained when taking into account thermally generated free carriers (FCs)[62]. Neglecting all other secondary effects of temperature (such as effective mass, mobility, band structure changes etc'), the explicit form of the temperature dependent permittivity can be written as:

$$\varepsilon(T) = n(T)^2 = \varepsilon_{\infty,TO}(T) - \frac{\omega_p^2(T)}{\omega^2 + i\gamma\omega} \quad (1)$$

where the first term on the right hand side, $\varepsilon_{\infty,TO}$, is responsible for the normal TOE with no FC effects, and the second term is the free carrier contribution with the plasma frequency ω_p, the damping coefficient γ, and scattering time τ are defined as $\omega_p = \sqrt{\frac{n_i e^2}{m_c \varepsilon_0}}$ and $\frac{1}{\gamma} = \tau = \frac{\mu m_c}{e}$, n_i is the intrinsic free carrier concentration (not to be confused with the refractive index n), e is the electron charge, m_c is the conductivity effective mass, ε_0 and ε_∞ are the permittivity of free space and the high frequency permittivity, respectively, and μ is the free carrier mobility.

In Figure 1b. we track the temperature dependent resonance wavelength shifts of the MD and ED, with respect to the RT resonance wavelength, and extract the corresponding index shifts Δn. Using our model for the temperature dependent permittivity (Eq. 1), we compare experiments to calculated resonance and index shifts of the ED and MD modes.

For low and intermediate temperatures, the density of thermally generated FCs is negligible (n_i<10^{17} cm^{-3}), and thus all resonances in figure 1a red shift in response to a positive thermal gradient due to the normal positive dn/dT. At elevated temperatures (T>550K), significant amount of intrinsic FCs are generated which tends to decrease

the refractive index according to Eq. (1). Finally, at high temperature T>700K, the effect of thermal FCs dominates over the normal (positive) TO effect and leads to an anomalous negative TOC (dn/dT<0), as seen in figures 1a and 1b.

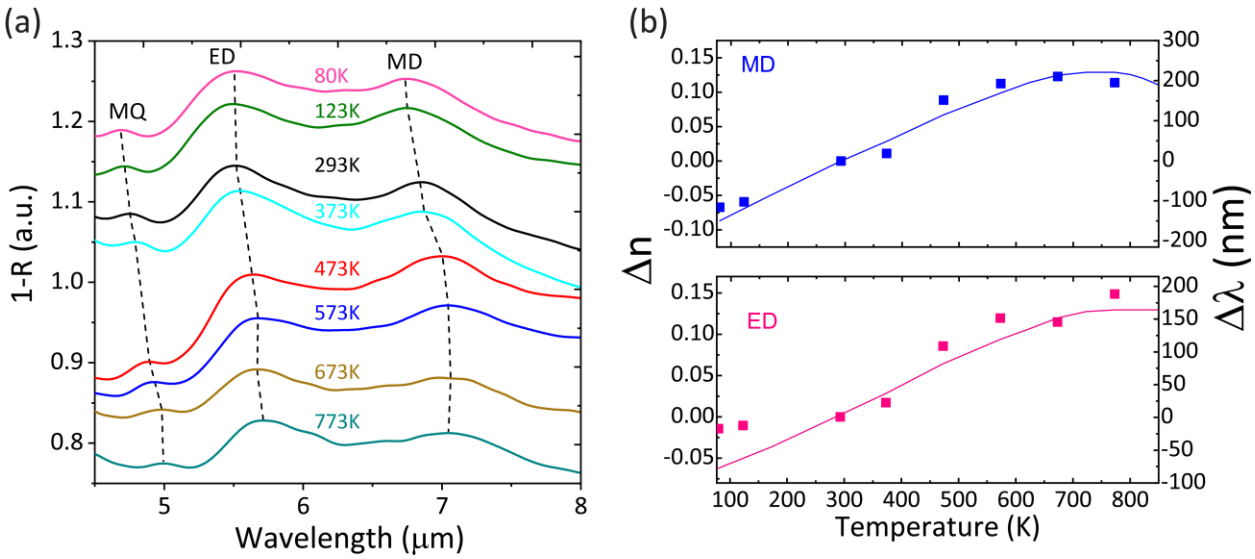

Figure 1: Thermal tuning of a r=850nm Ge spherical Mie resonator. (a) Temperature dependent spectra. The dashed lines track the thermal shifts of the MD, ED and MQ resonances, respectively (b) Thermally Induced index and wavelengths shifts

Altogether, these results show that the dispersion, the sign, and magnitude of dn/dT can be controlled with temperature in low and moderate bandgap semiconductor resonators through the generation of free carriers. This can be used to engineer the dispersion of dn/dT and for tuning of infrared meta-atoms, thermal emitters and resonators.

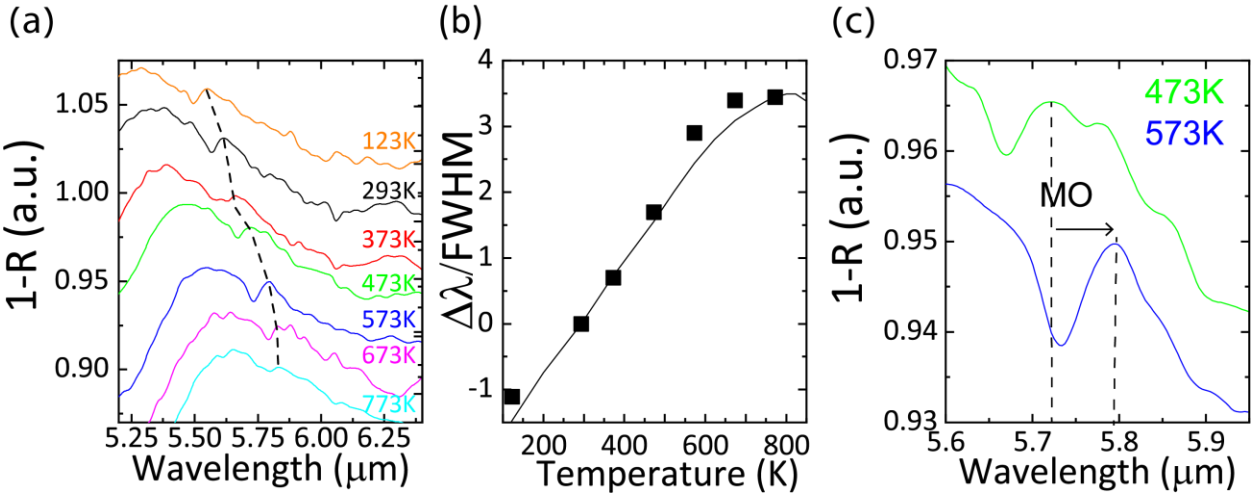

Figure 2: Thermal tuning of a high order magnetic octapole (MO) in a r=1.54μm Ge spherical resonator (a) Temperature dependent spectra in the 123-773K range (b) Temperature dependent MO shifts normalized to the resonance linewidth (c) Tuning by more than one resonance linewidth (Δλ/FWHM=1.2) with a ΔT=100K temperature gradient.

The ability to maximize the control over the phase and amplitude of incident light depends on the capability of tuning resonance wavelengths by more than one linewidth Δλ/FWHM>1. Figure 2a presents temperature dependent spectra of a high order magnetic octapole mode (MO) in the 123-773K range. Figure 2b depicts the normalized tunability (Δλ/FWHM) of this MO resonance that is tuned by ~ 4.5 normalized linewidths across the full 123-773K temperature range. This wide normalized tunability becomes possible due to an order of magnitude increase in the resonance Q-factor of Q_{MO}=88.1 compared with Q_{MD}=8.2 for the MD mode. As evident from Figure 2b, the normalized tunability exhibits a linear like dependence up to 675K, with almost one normalized linewidth per 100K. For ~ T>675K, the linear dependence breaks as free carrier effects become significant which leads to a rapid saturation of tunability with increased temperature. Figure 2c, presents the spectral shift of Δλ/FWHM=1.2 with a temperature gradient of ΔT=100K. Such tunability with a practical temperature difference of ΔT=100K, would be useful for implementing reconfigurable high-Q Ge metasurfaces.

Group IV-VI semiconductors

Although TOCs of group-IV such as Si and Ge are amongst the highest of natural materials[61], achieving the desired tunability (Δλ/FWHM>1) in Si and Ge metasurface requires large temperature gradients. Meeting the desired linewidth tunability with relaxed temperature modulation, requires materials with higher TOCs and/or narrowing the resonance linewidth. Remarkably, the lead chalcogenide family PbX (X=S, Se, Te) possesses both very large refractive indices with highest reported values of TOCs[64]. Figure 3a presents the geometric dispersion of cubic PbTe meta-atoms exhibiting size tunable high-Q resonances which arise due to the high refractive index of the material (n_{PbTe}~6). Interestingly, the sign of the TOC in PbTe is negative (dn/dT<0) due to anomalous temperature-dependent bandgap dispersion[61,65,66]. Combining the large low-temperature TOE with high-Q resonances enables complete tuning (i.e. by more than one linewidth) of resonances with significantly reduced temperature swings (ΔT). TO spectral tuning of a high order high-Q (Q~100) resonance of a d=1.76μm PbTe sphere is shown in Figure 3b. This sharp resonance can be tuned by more than one linewidth (normalized tunability=1.6) with a temperature swing as small as ΔT=10K. This exceptional tunability is enabled by the combination of the narrow linewidth and peak TOE. The observed dn/dT at 173K (-0.0134 K^{-1}) is almost an order of magnitude larger than previously reported RT TO effects[61] (dn/dT=-0.0015K^{-1}). These results clearly demonstrate the strong, negative TO effect in PbTe nanoparticles and is the largest dynamic tuning of Mie resonators reported to date[67-70]. These properties make PbTe an ideal candidate material for TO-tunable nanophotonics and metasurface resonators.

Tracking the shift of all Mie resonances across a variety of temperatures provides valuable insight into the dispersion of TOE with temperature and wavelength. An example of temperature dependent spectra of a PbTe cube of side a=1 μm on Si, is presented in Figure 4a. The temperature dependence of the MD (blue) and buried MD (red) resonance wavelengths are plotted in Figure 4b. The tunable resonances exhibit some unusual characteristics. The wavelength shifts at low temperatures (80K-293K) are much larger than the shifts above room temperature (293K-573K), as evidenced by the differences in slopes of the modes seen in Figure 4b. These results show that the largest dn/dT occurs between 80K to RT and a more thorough examination reveals a maximum in dn/dT somewhere

between 80K and 200K[38]. Although observed shifts are consistent with other measurements[65 71 72], this significant increase in TO coefficient at low temperatures has not previously been reported. Moreover, standard TO models[61], based on temperature-dependent bandgap (E_g) dispersion,[66 73] are unable to explain this effect, suggesting unknown physical mechanisms may be at play. Nevertheless, by operating at cryogenic temperatures, significant increases in TO tunability can be achieved, as demonstrated in figure 3b. Altogether these results reveal a great potential for practical TO switching with PbTe components.

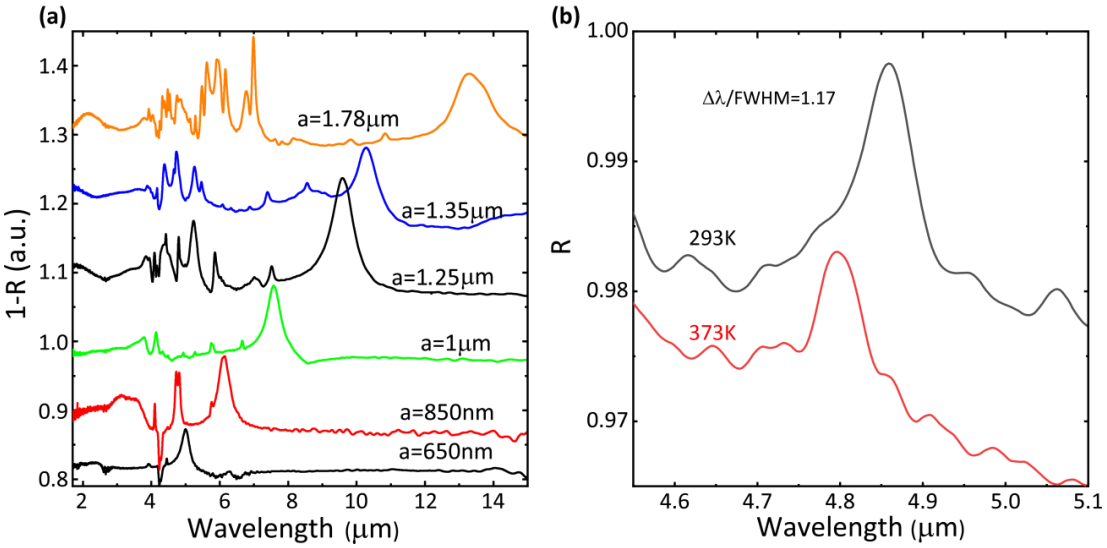

Figure 3: Tunable PbTe meta-atoms (a) Geometric dispersion in PbTe cubic resonators (b) High order resonance tuning by more than a linewidth in PbTe spherical resonators with ΔT=80K. At T=173K normalized tunability Δλ/FWHM=1.6 is achieved with ΔT=10K thanks to peak TO coefficient.

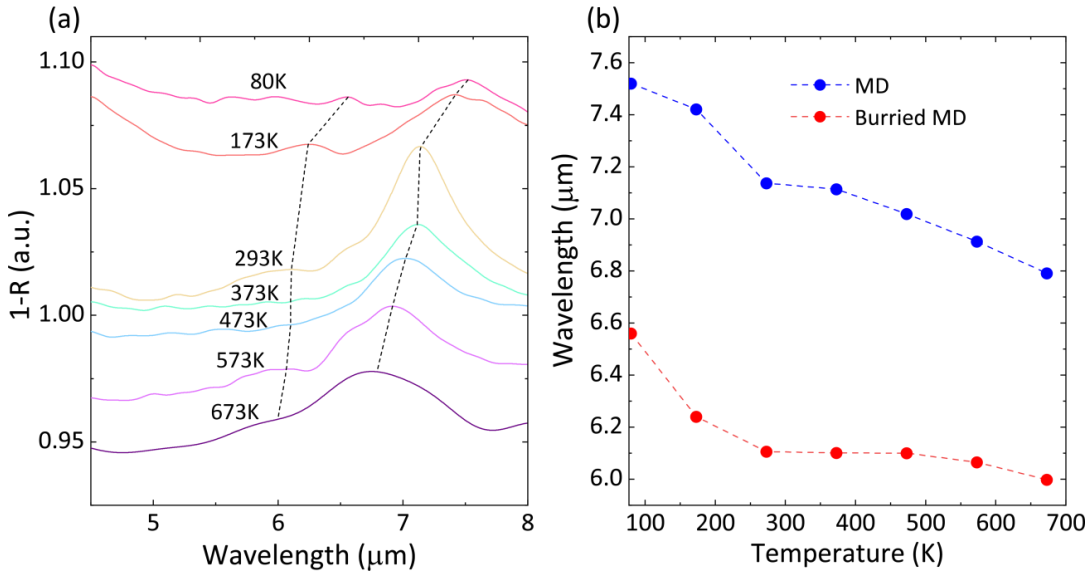

Figure 4: Dynamic tuning in PbTe cubic resonators. (a) TO induced shift between 80 K and 673K (b) Temperature dependent resonance shifts of the MD (blue) and buried MD (red) modes in a a = 1 μm PbTe cube on Si. The dashed lines are a guide to the eye. Resonance shifts exhibit the large and anomalous (dn/dT < 0) TO coefficient, and a marked increase in magnitude below room temperature.

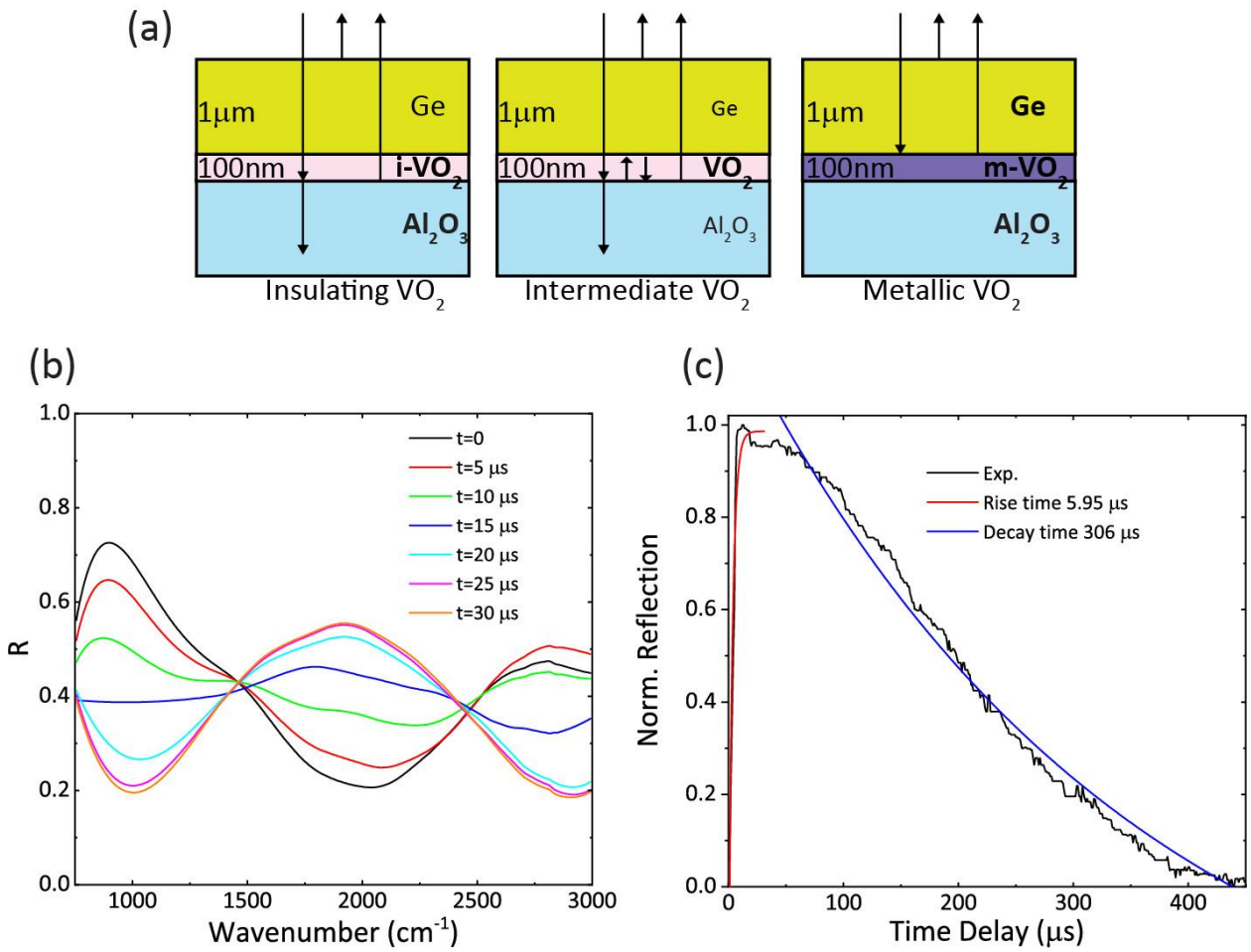

Figure 5: Electrically tunable Fabry–Pérot resonator. (a) Schematic of Ge–VO_2–Al_2O_3 device in the insulating, intermediate, and metallic states. The arrows represent the dominant reflection interfaces. (b) Experimentally measured transient reflectivity spectrum of the TFP for a 26 V, 60 μs wide square excitation pulse (c) Normalized transient reflectivity at the anti-node wavelength (λ = 10.13μm). Solid black line corresponds to the experimental raw data while the red and blue lines correspond to fitted exponential curves (red, heating; blue, cooling).

Phase transition materials

Among active materials, phase transition and phase change materials can arguably provide the largest variation in optical constants. When applying heat, electric or magnetic fields to these materials, their optical constants can undergo dramatic (and reversible) shifts. Various mechanisms have been investigated and employed to realize tunable nanophotonic and metasurface platforms. These include the transition from nematic to isotropic phases in liquid crystals[28,67], amorphous to crystalline phase change in GeSbTe (GST)[46,74,75] and metal–insulator transitions (MIT) in prototypical strongly correlated materials such as vanadium dioxide (VO_2)[63,76-80] and V_2O_3[81,82].

We have previously demonstrated that VO_2 metasurfaces support switchable dielectric-plasmonic response[63]: in the insulating phase, the metasurfaces exhibit dielectric Mie-type resonances, that are switched to plasmonic resonances in the metallic phase. In the following, we show that hybrid dielectric–VO_2 structures exhibit several novel behaviors of great interest in the development of reconfigurable optics, including independent tuning of the reflection amplitude and phase, large modulation of transmission and absorption, and electronic switching. Our device is basically a tunable Fabry–Pérot (TFP) cavity, comprised of a 1 μm thick Ge layer, atop of a 100 nm thick film of VO_2, on an R-cut sapphire substrate (Figure 5a). At the interface between a transparent material and VO_2, the reflectivity undergoes a π phase shift across the MIT. Here, reflection-phase switching of the MIT, modulates the complex reflectivity (i.e., amplitude and phase), transmission, and absorption of the simple Ge–VO_2 TFP. Unlike existing switchable VO_2 photonic devices, here the mesoscopic continuous nature of the MIT in the VO_2 thin film, is used to achieve continuous reflection modulation (Figure 5a), as well as independent control over the phase[83], a key requirement for reconfigurable high-efficiency metasurfaces.

In Figure 5b and 5c, we demonstrate an electrically controlled TPF device. The device is modulated through Joule heating by passing current directly through a 200 μm × 200 μm TFP. In the VO_2 insulating state, current passes predominantly through the lightly doped Ge layer. This enables Joule heating of the device in both metallic and insulating VO_2 states, without introducing additional lossy metals. The temporal characteristics of the device are investigated by exciting the TFP with a square voltage pulse (26 Vpp, 60 μs), and monitoring the temporal response of the device with a fast MCT detector and the FTIR in a step-scan mode. Figure 5b presents the transient reflectivity in the 900-3000cm^{-1} range, exhibiting the continuous temporal evolution of the spectrum, including the nodes and antinodes. Figure 5c traces the rise and decay time characteristics of at λ=10.13μm. Fast rise time, due to rapid Joule heating is observed, followed by a slower thermal-diffusion-limited decay. Dynamic traces exhibit an approximately 5.95 μs rise time, as determined through an exponential fit with an approximately 306 μs decay time, corresponding to estimated modulation rates on the order of 3.3 kHz. When applying even larger voltages, faster rise times can be achieved[44]. These values are an order of magnitude faster than previous large-area VO_2 optical modulators[81,82] which have rise and relaxation times of the order of few milliseconds. The decay time is likely limited by the relatively large thermal capacitance of the device and may be improved with thermally engineered metasurface structures that reduce the Ge and VO_2 volumes. Further improvements in speed can also be attained by reducing the modulation depth or by utilizing vertical contact geometries.

3. CONCLUSIONS

In summary, we studied thermal tuning performance in resonators and metasurfaces obtained from several materials systems comprising group IV, group IV-VI semiconductors and phase transition materials. Identifying the linewidth tunability (Δλ/FWHM>1) as the figure of merit for efficient tuning, we pinpoint the route to achieve such tunability by combings materials with large optical effects along with high-Q resonances. We study TO tuning in Ge

resonators and highlight their capabilities with a demonstration of tunable high-order resonances which are completely tuned ΔT=100K.

To further reduce the temperature gradients required for linewidth tunability, we investigate lead chalcogenides of group IV-VI semiconductors. We show that PbTe is an excellent candidate for infrared reconfigurable meta-optics, having both high refractive index and largest known TOC of all materials. We find that PbTe exhibits an anomalous TOE with peak performance at cryogenic temperatures, which cannot be explained with standard TOC models. Utilizing peak TOC with high-Q resonances, we demonstrate normalized tunability Δλ/FWHM=1.6 for temperature modulation as small as ΔT=10K.

Finally, we investigate tunability in hybrid dielectric–VO_2 structures and show that these structures exhibit novel properties highly desirable for reconfigurable meta-optics. We utilize the metal–insulator phase transition of VO_2 to create electrically reconfigurable, continuously tunable nanophotonic devices across a broad spectral range. The continuous modulation is enabled by driving the underlying VO_2 film across the phase transition. Electronically triggered transient reflection measurements revealed switching rates of 3.2KHz, which can be further improved with thermal management and more sophisticated designs. These findings expand the potential of active metasurfaces, that take advantage of the reconfigurable properties of hybrid semiconductor–VO_2 architectures. Altogether, this work highlights the opportunities and potential of thermally tunable semiconductor metasurfaces and can pave the way to efficient high-Q reconfigurable metadevices, which will ultimately be implemented in important applications for the infrared range.

Conflicts of interest

There are no conflicts to declare

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