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Elecrtrically Reconfigurable Infrared III-V Phased Array Metasurfaces

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14. ABSTRACT
Metasurfaces are ultrathin flat surfaces decorated with sub-wavelength nanostructures that can induce abrupt changes in the phase, amplitude, and polarization of a light beam. Demonstrations of metasurface beam shapers, flat lenses, waveplates, and holograms reveal the great promise to replace conventional bulk optical components with flat surfaces. Introducing tunability and re-configurability to metasurfaces is probably the holy grail of research in the field, and would lead to new classes of programmable optical and optoelectronics components. We report accomplishments made toward the goal of designing, fabricating and demonstrating reconfigurable metasurfaces based on electrically-controlled III-V device heterostructures and various thermo-optic based metasurfaces.

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Principal Investigator: **Jon A. Schuller**

Grantee Institution: **UC Santa Barbara**

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1. Introduction and Central Objective

Metasurfaces are ultrathin flat surfaces decorated with sub-wavelength nanostructures that can induce abrupt changes in the phase, amplitude, and polarization of a light beam [1]. Demonstrations of metasurface beam shapers, flat lenses, waveplates, and holograms reveal the great promise to replace conventional bulk optical components with flat surfaces. Introducing tunability and re-configurability to metasurfaces is probably the holy grail of research in the field, and would lead to new classes of programmable optical and optoelectronics components. The central goal of this program is to design, fabricate and demonstrate electrically reconfigurable metasurfaces based on III-V device heterostructures.

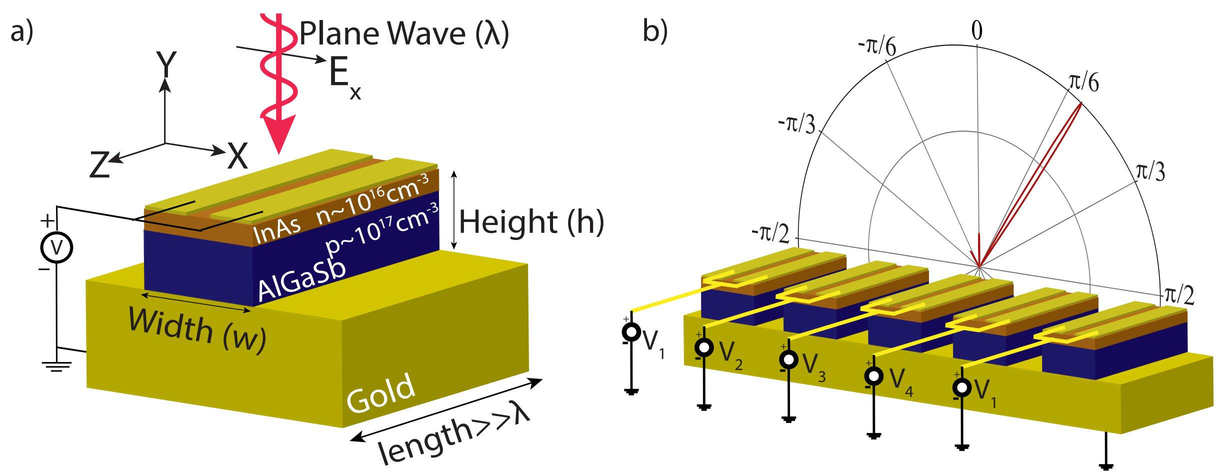

Figure 1 a) An individual metasurface element, or "metaatom", comprises a 1-D rectangular structure of subwavelength dimensions sitting atop a conducting back plane. The electromagnetic intensity is concentrated near the top center of the resonator, within an undoped InAs layer. A AlGaSb/InAs device heterostructure is used to accumulate electrons in the InAs layer under forward bias. Combined device and electromagnetics simulations demonstrate a nearly 2π phase shift of incident 12 micron radiation with less than 1V applied bias. **b)** In a metasurface array, different voltages are applied across an assembly of identical resonators, producing a spatially varying phase profile. The programmable phase profile can be used to e.g. steer an incident beam. In this example, the output beam direction can be steered continuously over a wide angular range and reconfigured at electronic timescales (e.g. GHz frequencies).

2. Proposed Approach

Our originally proposed and primary approach to create phase tunable antennas and metamaterials is based on free carrier refraction in III-V semiconductors. Materials such as InAs and InSb, etc. are nearly lossless at sub-bandgap infrared frequencies and have relatively large infrared permittivities (~ 16). Subwavelength spherical and microdisc resonators made from these materials exhibit multipolar resonances that can be used to construct highly efficient metamaterials and metasurfaces. As free carriers are introduced, the permittivity of the materials gets smaller, eventually becoming negative once the semiconductor has enough carriers to behave like a metal. Due to the very light electrons in this material, modulating the electron density between approximately $10^{17} – 3*10^{18}$ cm^{-3} is sufficient to generate order-unity refractive index modulation. In turn, this "ultrawide" index modulation enables up to 2π phase shifts in subwavelength resonator elements [2].

A schematic of our proposed reconfigurable metasurface is shown in Figure 1. The basic building block is a 1-D semiconductor resonator that employs a novel heterojunction design (Fig. 1a). Applying a bias across the device causes electrons to accumulate in an InAs layer. With less than 0.5V of applied bias, a carrier concentration of ~ 10^{18} electrons per cm^3 accumulates in the InAs layer. This high carrier density causes an extraordinarily large refractive index shift (Δn≈2) enabling a continuous tuning of the reflection phase between 0 and 2π. By changing the bias across an array (Fig. 1b), a phase profile is imparted on the surface. An incident plane wave is redirected into a high quality diffraction lobe. By changing the voltage profile, this diffraction lobe can be continuously and dynamically steered between ±90 degrees at GHz frequencies.

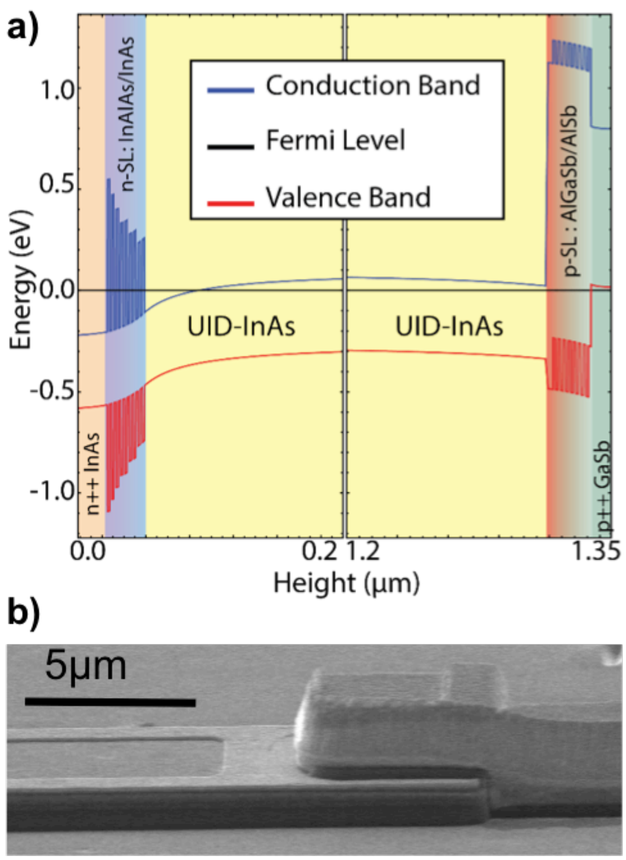

Figure 2 a) Energy level diagram of the metasurface heterojunction resonator. Under forward bias electron accumulate in the central undoped InAs layer. **b)** SEM of the fabricated device. A large contact pad is seen on the right, and connects to a split-gap gold electrode. The resonator is subwavelength in with but 100s of μms long (extending to the left).

3. Results of Originally Proposed Approach

Over the course of this project we overcame numerous MBE growth challenges and successfully demonstrated an electrically tunable heterojunction metaresonator (collaboration with Vannevar Bush Faculty Fellow Chris Palmsrom). Achieving high quality highly-doped ($n>10^{19}$ cm^{-3}) III-V backplanes has proven the greatest obstacle. We started working with InSb films, where we could only achieve plasma frequencies (i.e. ENZ point) well below 1000 cm^{-1} while maintaining good film quality. Efforts to push carrier densities higher led to poor optical quality due to excessive defects.

For this reason we switched to an InAs-based heterostructure design. Our highly reflecting backplane comprises si-doped InAs at a concentration of $5*10^{19}$ cm^{-3}. A much higher (1250 cm^{-1}) plasma frequency is achieved, enabling excellent reflectivity at our frequencies

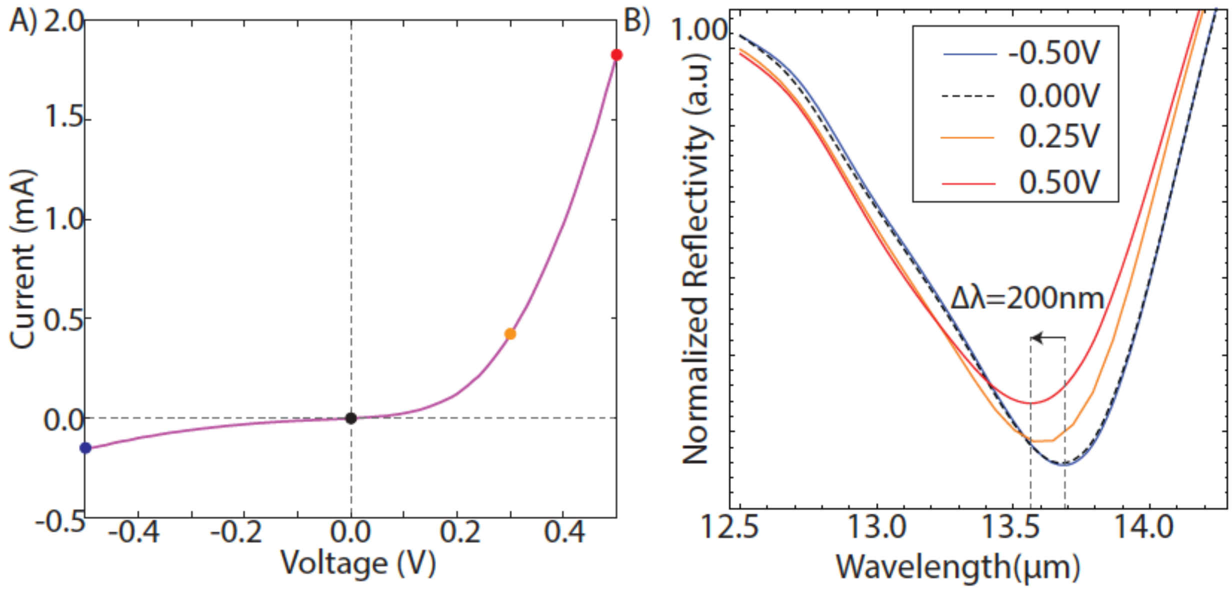

Figure 3 a) I-V curve of a heterojunction metaresonator, showing nice diode behavior. **b)** Normalized reflectivity curves taken at different applied voltages. At 0 V (black) a scattering resonance leads to a reflectivity dip at 13.7 µm. Under -0.5 V reverse bias (blue) no carriers accumulate and no shift in the resonance is observed. Under forward bias, free carriers accumulate leading to an increasing blue-shift shown at 0.25 V (yellow) and 0.5 V (red). The observed spectral shifts imply a π phase shift in resonator arrays.

of interest. We designed and grew a new MBE device stack incorporating a more sophisticated superlattice design to alleviate strain while providing superior electron and hole blocking layers (Figure 2a). After film growth, heterojunction metaresonators were fabricated with a six-step process. An SEM of a single heterojunction resonator is shown in Figure 2b. A large contact pad is seen at the right edge, which spreads out via a thinner Au electrode with a split gap window, designed to minimize electromagnetic losses.

An I-V curve of the heterojunction metaresonator is shown in Figure 3a. The device shows excellent diode behavior. Four different voltages are marked in the plot with different color symbols. Experimental reflectivities for the single metaresonator at each voltage are shown in Figure 3b. With no applied bias (black) the resonator exhibits a scattering resonance at 13.7 µm wavelength. Under reverse bias (blue) no carrier accumulation is expected and, as expected, there is no shift in the resonance wavelength. As the device is forward-biased the resonance red-shifts due to carrier accumulation. At 0.5 V of forward bias the resonance red-shifts by ~ 0.2 µm. These spectral shifts imply an expected π phase shift in metasurface arrays.

These results are a crucial validation of the novel device and electromagnetics concepts underlying our proposed electrically reconfigurable metasurfaces. A manuscript describing these results was published in ACS Photonics in the final year of the project [3]. Unfortunately, growth defects originating from the highly doped InAs back electrode prevented growth and fabrication of any metasurface arrays, preventing direct phase measurements or demonstrations of reconfigurable array functionality. Ultimately, the defect density was sufficiently high that any array of more than a few resonators was inevitably shorted. Moving forward, we redesigned our heterojunction resonators to work in an InP platform where we replaced highly doped “metallic” back electrodes instead with DBR based reflector/electrode combinations. This follow-up project builds off a collaboration with the Klamkin group—supported by this grant—to investigate reconfigurable infrared properties of gate-tunable Indium Silicon Oxide metasurfaces [4].

4. Complementary Approaches and Associated Results

The central theme of this proposal is to investigate and exploit large-magnitude tunable infrared properties. We complemented our approach based on electrically driven heterojunctions with investigations of large-magnitude tuning approaches based on *thermo-optic* phenomena:

4.a. Ultrawide Thermal Free-Carrier Tuning of InSb Meta-atoms

The temperature-dependent electron density of intrinsic InSb (i-InSb) was inferred from optical modeling of reflection spectra and compared to theory (Fig. 4a). Increasing temperature leads to increased electron density and a *reduction* in the refractive index. While this behavior was expected, the temperature dependent response of highly doped InSb (n-InSb) was quite surprising. In this case increasing temperature leads to an increase in the electron mass (Fig. 4b) and an associated *increase* in the refractive index. Both effects are more than an order of magnitude larger than conventional thermo-optic effects, in which free electrons play no role. Subsequently we demonstrated more than linewidth tuning of meta-atom resonators using these effects. These results suggest new avenues for highly tunable and reconfigurable mid-infrared optical antennas, ENZ materials, and metasurfaces. This work was published in Nature Communications [5].

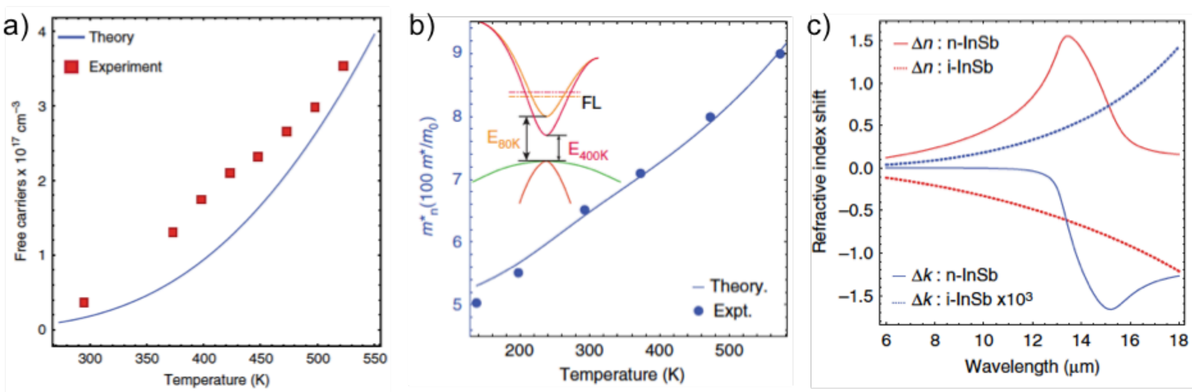

Figure 4 a) By increasing temperature from 300-550K we can vary the intrinsic InSb carrier concentration within our range of interest. **b)** Applying the same temperature change to highly doped InSb results in a changing electron mass. **c)** The temperature dependent electron density of i-InSb leads to order-unity *increases* in refractive index. Both effects are more than an order of magnitude larger than traditional thermo-optic effects.

4.b. Ultrawide Thermo-optic Tuning of PbTe Meta-atoms

In the conventional thermo-optic effect, a temperature-dependent change in a semiconductor's bandgap produces an associated change in the refractive index at sub-bandgap frequencies. Recently, we demonstrated thermo-optic tuning of a PbTe spherical Mie resonator by more than one linewidth with less than 10K change in temperature (Fig. 5). These striking results arise from i) the very high refractive index (n~6) of PbTe, ii) the anomalously large thermo-optic properties of PbTe, particularly at cryogenic temperatures and iii) the ability to sustain very high-Q high order "hexapole" Mie resonances in PbTe meta-atoms.

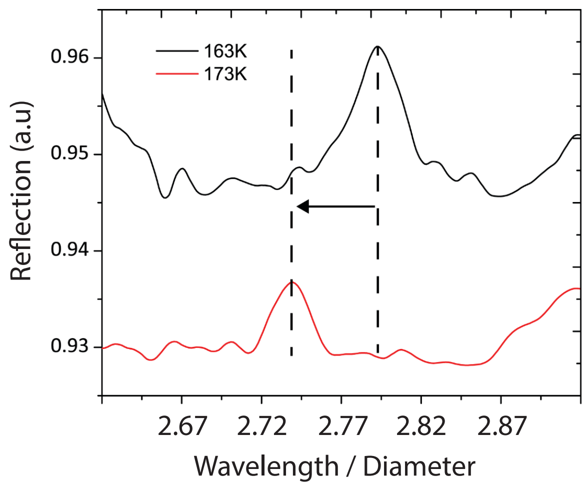

Figure 5 (experiment). A subwavelength spherical PbTe particle exhibits a high-Q Mie resonance that can be thermally ($\Delta T=10$ K) shifted by more than one linewidth despite the small change in refractive index ($\Delta n \sim 0.01$)

Tuning by one linewidth is the essential metric for achieving reconfigurable metasurfaces. Thus, we can use the effects demonstrated in Figure 3 to create reconfigurable metasurface based filters, optics, and phased arrays. These concepts are described in detail in Nano Letters [6], which delineates a promising path towards reconfigurable infrared metasurfaces based on PbTe thermo-optics. While stemming from AFOSR-funded efforts, it is important to note that this is currently an *additional* side project that is not described or outlined in the original grant. We are actively looking for new funding to establish this as a larger, fully funded research effort.

4.c. Thermo-optic Tunable Metalens

Building off our previous work on thermo-optic metasresonators, we completed an investigation answering a simple question: How do spatially-uniform thermo-optic refractive index shifts affect the performance of metasurface components. Using electromagnetics simulation we designed a novel InAs-based infrared metalens and showed that uniform index shifts change the wavelength of maximal focusing efficiency (Figure 6). These results demonstrate a new approach for fine-tuning metasurface performance via thermo-optic effects and were published in Physical Review Applied [7].

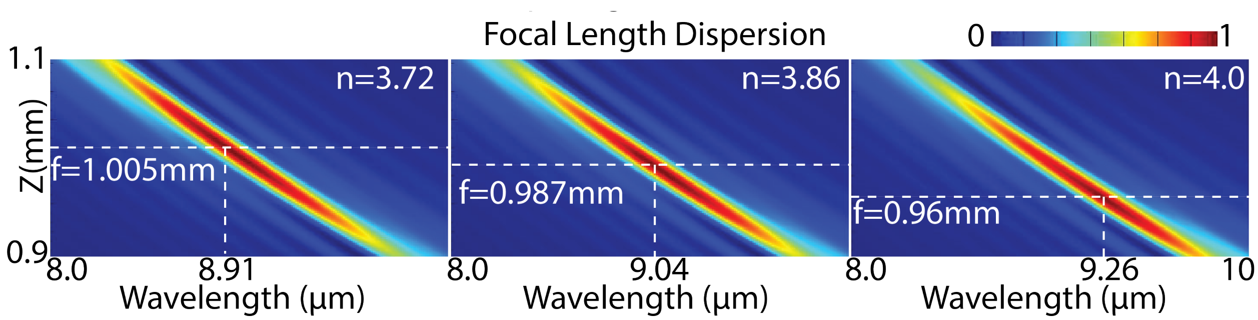

Figure 6. An InSb metasurface lens exhibits typical chromatic aberrations in numerical simulations. The focal length (Z) and focusing efficiency (scale) vary with wavelength. Uniformly shifting the index of the metasurfaces changes the wavelength of optimal focusing efficiency—here from 8.91 μm (left) to 9.26 μm (right)

4.d. Thermo-optically Tunable Metafilters

Using the knowledge derived from investigations of widely tunable meta resonators, we showed how one can construct thermo-optically tunable metafilters. A metafilters comprising arrays of Silicon disks were fabricated and show a reflection peak associated with the excitation of an Electric Dipole resonance mode. With ~ 400 K temperature change we can shift the resonance by approximately one linewidth, resulting in approx. 13dB amplitude modulation (Fig. 7). These results were published in the journal Nanophotonics [8].

4.e. Widely Tunable Photonics with VO_2 Metal-Insulator Transitions

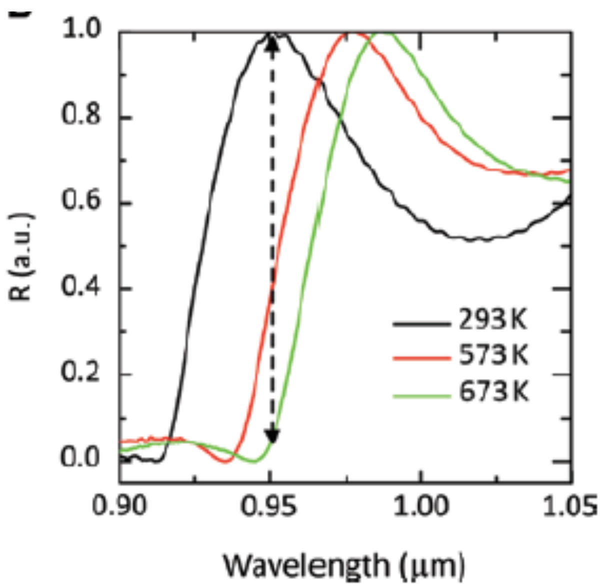

Figure 7 Experimental demonstration of a thermo-optically tunable metafilter based on Si disk arrays.

Leveraging our interest in thermo-optic metasurfaces and the associated lab infrastructure we investigated the use of VO_2 metal-insulator transitions as the basis for reconfigurable photonics. In our first foray into this topic, we constructed VO2 metaresonators and experimentally demonstrated switching between high-index magnetic dipole resonances in the insulating state and negative-permittivity plasmonic electric dipole resonances in the metallic state (Figure 8a). This work was published in ACS Photonics [9].

Following this work we experimentally a demonstrated an electrically tunable infrared Fabry-Perot cavity that exploits *continuous* tuning of VO_2 optical properties as the material *smoothly* transitions between metallic and insulating states. This result is illustrated in Figure 8b. The device comprises a thick, lightly-doped Ge film sitting atop a VO_2 back plane. Broadband Fabry-Perot resonances are seen across the infrared. Current is run through the Ge film, heating the underlying VO_2 film and driving it across the metal-insulator transition. The Fabry-Perot resonances in the fully insulating (yellow; 0 mA) and fully metallic (purple; 105 mA) are inverted due to a π phase shift in the reflectivity at the Ge/VO_2 interface. We can reach any *intermediate* value of the reflectivity by driving the film *partially* through the metal-insulator transition, demonstrating the mesoscopic, inhomogeneous nature of the metal-insulator transition in thin films. These results demonstrate a new and promising class of continuously reconfigurable infrared photonic device. The work was published in ACS Photonics, and also contains time resolved and phase-sensitive analysis of the reconfigurable device [10].

All VO_2 work is done in collaboration with Vannevar Bush Faculty Fellow Ivan Schuller (the PI's father).

4.f. Widely Tunable Optical Properties of Cd_3As_2

In addition to the materials described above, we investigated the possibilties of using Cd_3As_2 as a material platform for widely tunable thermo-optics. This entailed basic studies of the temperature dependent refractive index, determined via procedures originally developed for the project described in section 4.a. A manuscript detailing these results was published in Advanced Optical Materials [11]. All Cd_3As_2 work was done in collaboration with Vannevar Bush Faculty Fellow Susanne Stemmer.

5. Potential Impact

This program will address the Air Force's goal to develop more efficient electromagnetic beam-steering technologies with lower size, weight, and power (SWAP). More broadly, tunable and reconfigurable metasurfaces have the potential to unlock a plethora of new applications in programmable optics and optoelectronics.

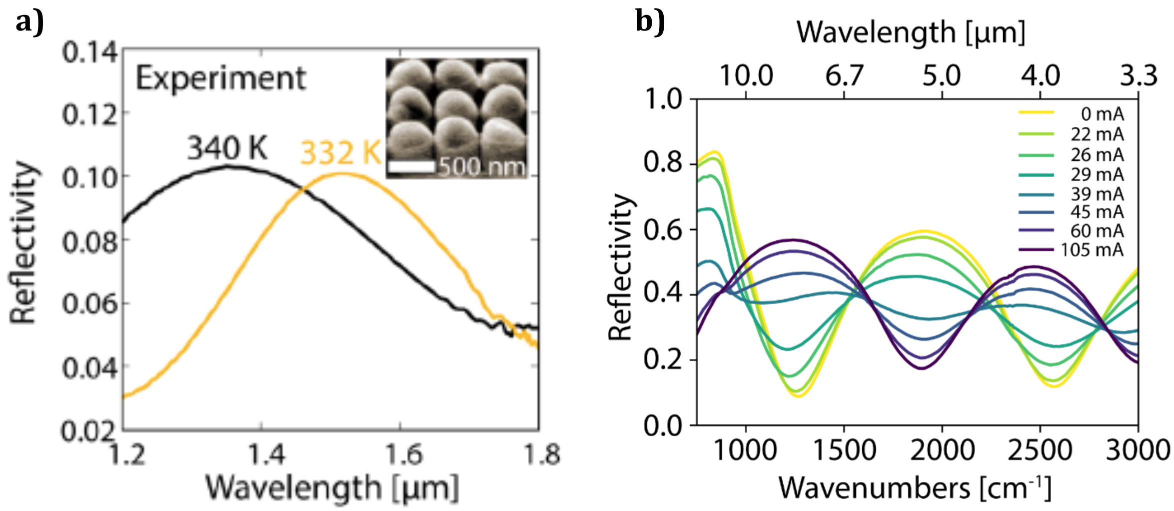

Figure 8 a) An array of VO_2 metaresonators switch between high-index magnetic dipole resonances in the insulating state (yellow) and negative-permittivity electric dipole plasmonic resonances in the metallic state (black). **b)** A thick Ge film sitting atop a VO_2 ground plane forms an electrically reconfigurable Fabry-Perot resonator. Driving a current through the Ge film causes the device to heat, driving the VO_2 metal-insulator transition. Across the transition the Fabry-Perot resonances invert due to a π phase shift in reflectivity. The reflectivity is *continuously* variable between these extremes owing to inhomogeneous intermediate states.

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