Active tunability of surface phonon polaritons resonances by using Vanadium Dioxide-GaAs metasurfaces at far-infrared wavelength of light

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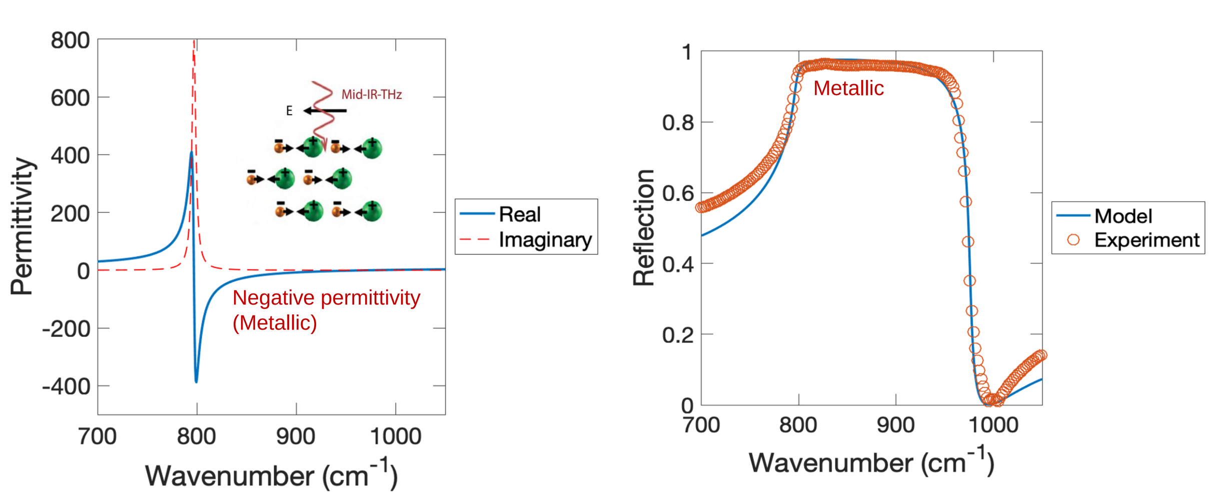
Abstract

Vanadium dioxide (VO_2) undergoes a reversible insulator-to-metal phase transition (IMT) near room temperature, providing an active tunable platform for photonics devices due to drastic change in VO_2 optical properties at IMT. A high-quality VO_2 film on a Gallium Arsenide (GaAs) substrate is significant in photonics applications for the development of electrically and thermally tunable devices operating at far-infrared (FIR) spectral range. VO_2 film on GaAs will be an attractive platform to develop phonon polaritonic metasurfaces because GaAs support phonon polaritons at its FIR Reststrahlen band (28.5 – 33 μm). In this work, we numerically demonstrate thermally tunable surface phonon polaritonic devices using VO_2 films on GaAs, working within GaAs's Reststrahlen band. The device consists of 40 nm thick gold grating (periodicity = 1100 nm, gap = 100 nm) on 100 nm thick VO_2 on GaAs substrate. The cavity resonance is observed near 30.2 μm and shows redshifts as temperature increases. Furthermore, we explore various grating periods and gaps to control the cavity resonance tuning and its dynamic redshift induced by temperature changes.

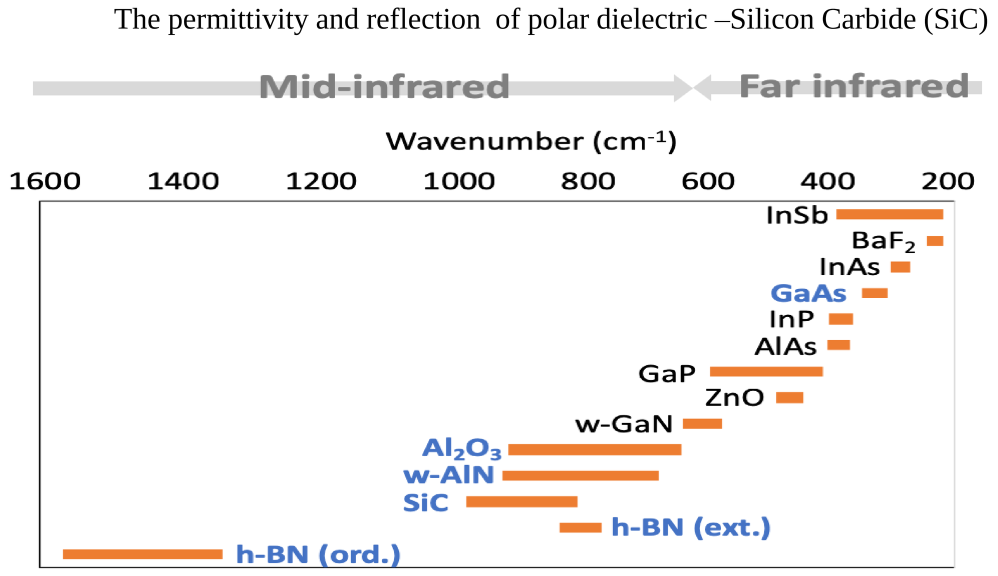
Introduction

Optical metasurfaces are two-dimensional (2D) nanostructures which form arrays of subwavelength optical elements that resonantly interact with the incident light and alter its properties, such as enhancing the amplitude, changing the polarization, and/or phase of electromagnetic wave. These metasurfaces have drawn tremendous attention in the IR/THz range due to their potential applications in data storage, biomedical sensing devices, optical switching, thermal emitters and many others. Recently, active metasurfaces, which provide dynamic control of wave propagation with multiple functionalities in a reconfigurable manner have been extensively studied. Our proposed device has dynamic tuning by using phase transition material, vanadium oxide (VO_2). Vanadium dioxide is a promising candidate as the spacer layer to make nanocavity active and reconfigurable. A demonstration of the thermally controlled phase responses of metasurfaces in far infrared region, integrated with VO_2 is expected to provide a new platform to realize reconfigurable functionality of phase transition change based tunable optical devices.

Reststrahlen Band in Polar Dielectrics : The Reststrahlen band is a wavelength region of high reflectivity and strong absorption that lies between the transverse, TO, and longitudinal, LO, optical phonon energies of a polar dielectrics.



The permittivity and reflection of polar dielectric –Silicon Carbide (SiC)



Device Design

•We adapted surface waveguide design which consists of metal-insulator-metal slab waveguide structure, but the bottom metal is replaced with metallic state of polar dielectrics. Our design is a hybrid structure, which is mixture of plasmon and phonon polaritons.

•The design and simulation of 2D polaritonic metasurfaces were done with a full-wave simulation (Finite Difference Time Domain solution, Lumerical Inc.). The top metallic surface can be used as electrode to apply voltage, heat or to detect photovoltaic signals.

•The far infrared spectrum measurement of the fabricated metasurfaces will perform by using Fourier Transform Infrared Spectrometer (FTIR, VERTEX 70v, Bruker) integrated with infrared microscope (Hyperion 2000, Bruker).The tunability and switching properties of the device will be investigated by applying external stimuli such as heat and electric voltage.

Results

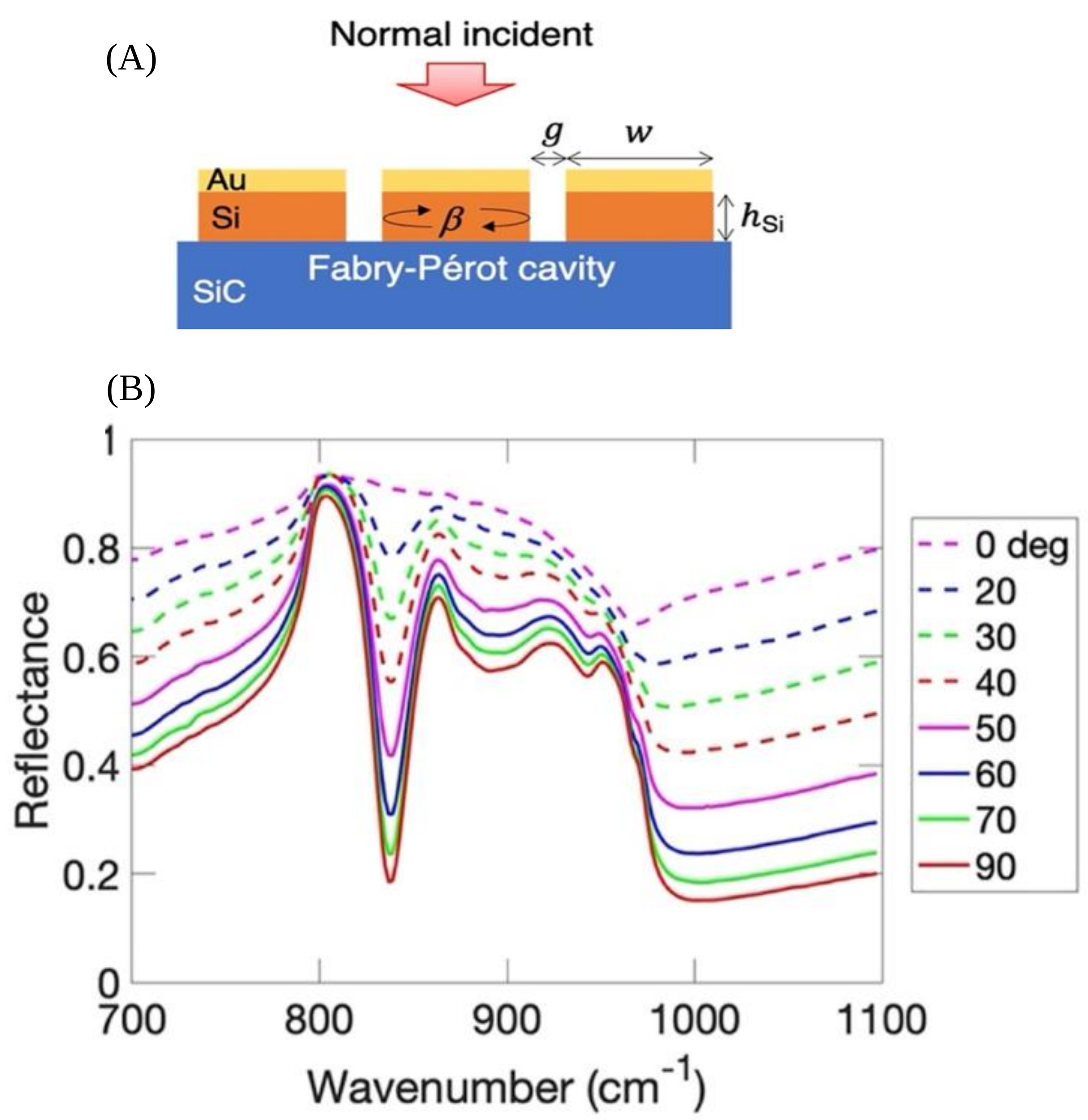


Figure 1. Passive device (A) Schematic of a thin layered metal (Au)–dielectric (Si) subwavelength-scale grating on a polar dielectric crystal (6H-SiC). When 6H-SiC has a metallic surface at the Reststrahlen band, the layered Au–Si on 6H-SiC constructs an asymmetric slab waveguide supporting a guided mode of the coupled surface plasmon polariton (SPP)–surface phonon polariton (SPhP) with a propagation constant β. Fabry–Pérot cavity array is formed by the grating structure and traps the guided mode under the light of normal incidence. (B) Measured reflectance of the device with respect to the polarization (θpol) of the mid-infrared light under normal incidence. The strong and well-defined absorption at 90◦ polarization (only $E\perp$ excites SPhPs) occurs at a frequency of 838 cm^{-1}.

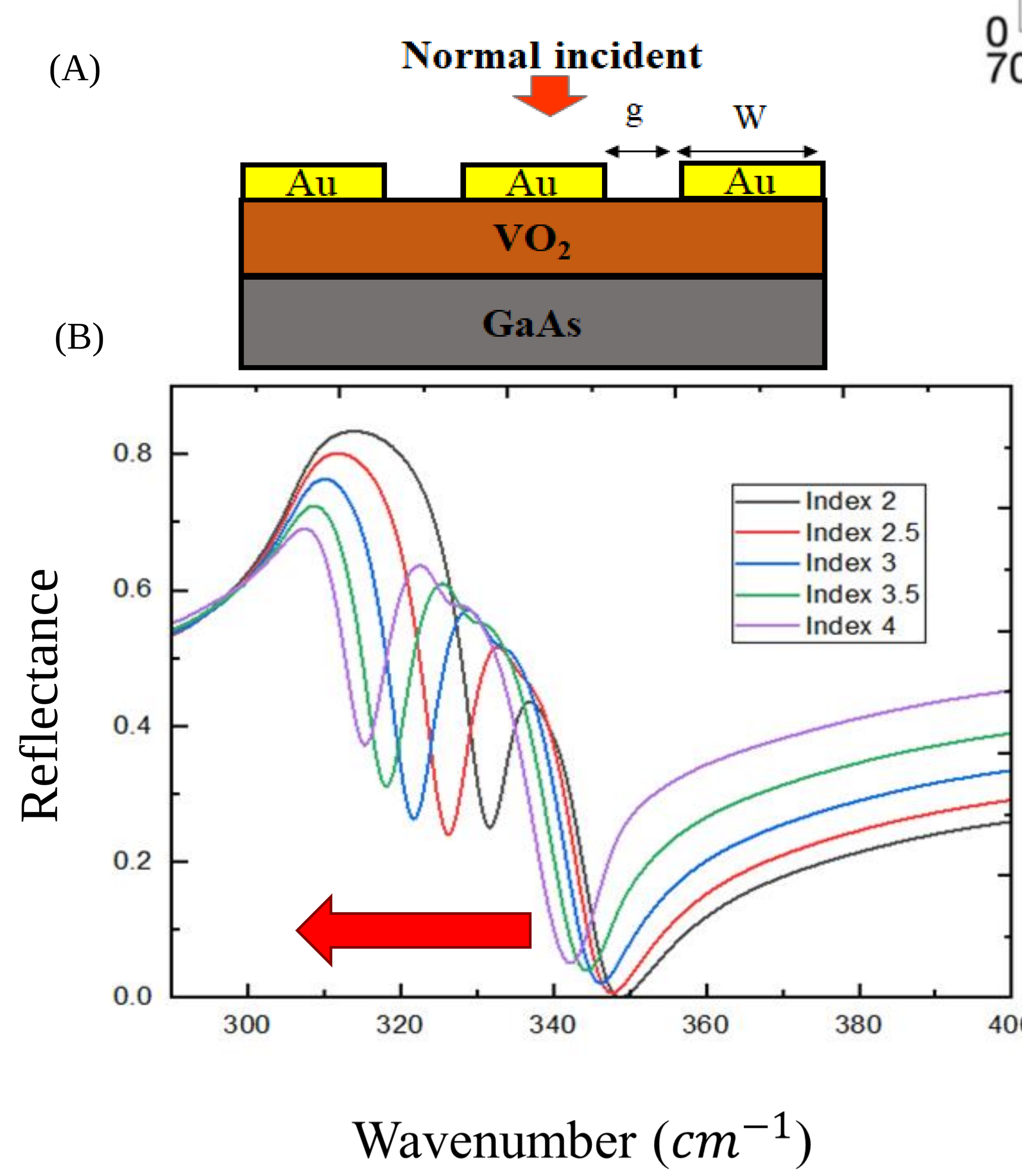


Figure 2. Active device (A) Schematic of a thin layered metal (Au)–phase transition material (VO_2) on a polar dielectric crystal (GaAs). The coupling of surface plasmon polariton (SPP)–surface phonon polariton (SPhP) supports a guided modes with a propagation constant β. Fabry–Pérot cavity array is formed by the grating structure and traps the guided mode under the light of normal incidence (B) The simulated reflectance of the Au device with parameters: width w(Au)=1000 nm, thickness (Au) =40 nm, VO_2 thickness =100 nm. Strong absorption shows at a frequency of 317.6 cm^{-1} at higher index active of the device.

Results

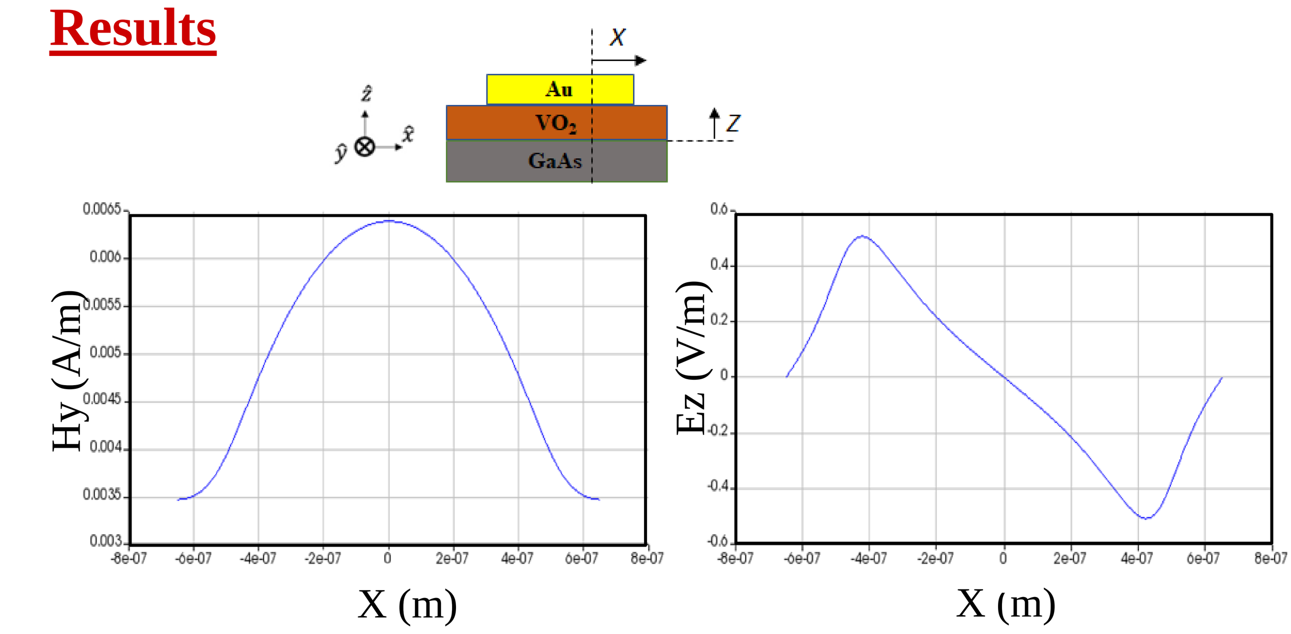


Figure 3. Simulated field profiles inside the cavity at the resonance with cavity width w =1000 nm , gap =100 nm and Index 3

Conclusion

- Active reconfigurable resonant cavity supports the propagating surface plasmon and phonon polaritons confined in a deeply sub-wavelength grating structure on phase transition material (VO_2) on polar dielectrics.
- The increase in temperature cause to change the effective index of VO_2 which results the tuning of resonance frequency.
- Enhanced far-infrared absorption observed at half-wave Fabry-Pérot cavity resonance under normal incident and resonance frequency is tuned dynamically over a range of 17 cm^{-1} with redshift.
- Our reconfigurable optical metasurfaces would be useful to control fundamental optical processes include perfect absorber, amplitude & phase modulators, and high numerical aperture nano-optic devices.

Future work

The strong coupling of infrared light and surface polarized ions provides a unique channel between photon and phonon via electric charge oscillations, which enables bidirectional energy flow between optical and thermal energy. Therefore, our optical metasurfaces based on phonon polaritons are promising candidates for thermal metasurfaces. According to Kirchhoff's law of thermal radiation stating that the absorptivity of a resonator is equal to the emissivity. We will investigate our proposed optical metasurface device as:

1: Thermal emission from metasurfaces

2:Thermal gradient optical metasurfaces

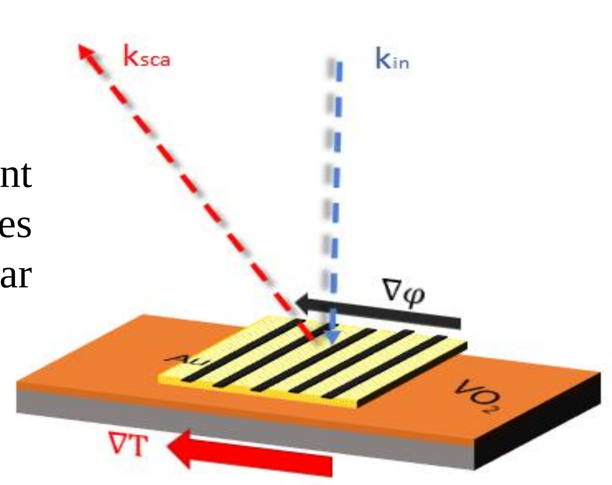


Figure 4. Schematic of thermal gradient metasurface with serval cavity modes with sample size 500 microns works at far infrared regions.

Bibliography

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