Electrically Switchable Infrared Nanophotonic Devices with VO_2

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Overview

We experimentally demonstrate thermally and electronically tunable nanophotonic devices utilizing metal-insulator phase transitions in VO_2. We show that VO_2 resonators support switching between dielectric and plasmonic resonances, and that by placing Germanium resonators on VO_2 we can achieve a broadband, continuous electronic tuning on reflection, transmission, and absorption resonances.

Introduction

In strongly correlated materials electron-electron interactions lead to emergent properties such as metal-insulator phase transitions. When heat or strong electric fields are applied to such materials, their electronic and optical properties undergo dramatic shifts that are unprecedented in conventional materials. Vanadium dioxide, VO_2, is a Mott insulator at low temperatures that gradually transitions into a metal at high temperatures [1]. Through FTIR reflectivity (Fig. 1a) measurements, we characterize the optical constants of the thin film across the phase transition. By fitting a Drude-Lorentz model to the reflection spectra, we extract the real and imaginary parts of the optical permittivity (Fig. 1bc) across the insulator-metal transition and demonstrate a continuous shift from insulating ($Re[\varepsilon] > 0$) to metallic ($Re[\varepsilon] < 0$) behavior. We then show, through simulation and experiment, how to construct thermally tunable optical antennas [2] and electronically tunable Fabry-Perot cavities, with VO_2 and hybrid Ge-VO_2 resonators.

VO_2 Based Nanophotonic Devices

Utilizing a temperature-driven phase transition in VO_2, we demonstrate large shifts in the multipolar resonant behavior as resonators switch between plasmonic and dielectric regimes. In contrast to previous work on VO_2 optical elements, these metamaterial resonators support switching between dielectric Mie resonances and plasmonic resonances. We fabricate and experimentally characterize VO_2 wire arrays and disk arrays. We find that VO_2 wire arrays (Fig. 2) exhibit a dielectric resonance at low temperatures, a suppressed scattering response at intermediate temperatures, and a plasmonic resonance at high temperatures. The VO_2 disk arrays on the other hand, upon heating exhibit enhanced scattering at intermediate temperatures, as well as a narrowed phase transition. These findings are applicable in the design of wavelength-selective and wavelength-tunable infrared detectors, as well as novel thermal management systems.

Hybrid Ge-VO_2 Nanophotonic Devices

We next investigate the case of a hybrid dielectric-VO_2 architecture consisting of an un-doped Ge Fabry–Pérot cavity on a VO_2 film. We experimentally demonstrate broadband, continuous tuning of the reflection, transmission, and absorption resonances across the MIT. With proper design, switching the VO_2 film across the MIT causes the reflectance spectrum to invert (Fig. 3a). That is, the reflection maxima and minima invert across the MIT. We experimentally characterize the amplitude and phase at the nodes and anti-nodes as the VO2 undergoes a MIT. At the nodes, the amplitude remains constant, while the phase exhibits continuous tunability shift. In contrast, at the anti-nodes the amplitude is continuously tunable while the phase remains constant. We conclude with a temporal characterization of the device (Fig. 3b). We monitor the infrared FTIR reflectivity as a 60 µs electronic pulse is applied and demonstrate electrically driven thermal switching with a modulation rate of approximately 3 kHz. In terms of switching energy per unit area, our device is superior to other free-space nanophotonic devices by a wide margin.

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[2] Butakov, *et al.*, *ACS Photonics*, 5, p. 371-377, (2017).

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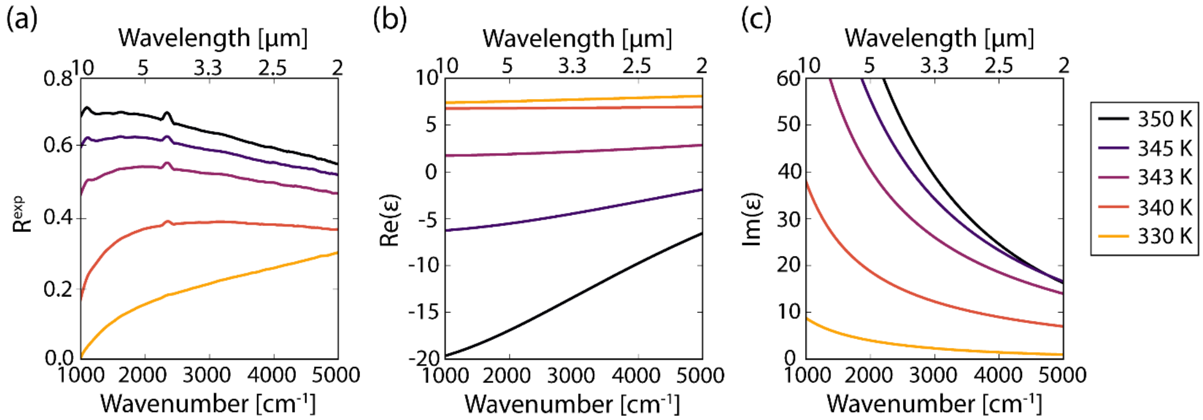

Fig. 1. The **(a)** mid-infrared reflectivity, **(b)** real part of the VO_2 optical permittivity, and **(c)** corresponding imaginary part of the VO_2 optical permittivity, of a 100 nm thick VO_2 film on a sapphire substrate.

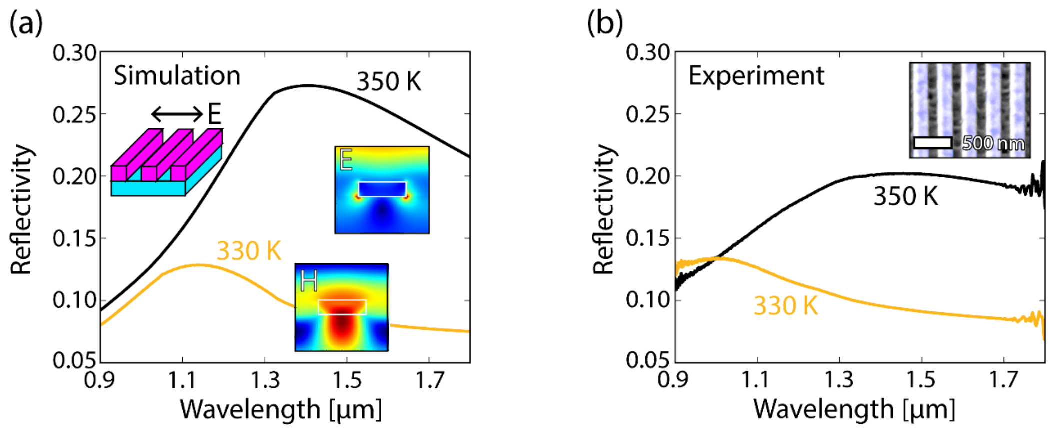

Fig. 2. **(a)** Simulated reflectivity of a VO_2 wire array under TE-polarized illumination. Insets corresponding to the magnetic- and electric-field profiles at the insulating and metallic resonances respectively. **(b)** Experimentally measured reflectivity of the corresponding VO_2 wire array. Inset is an SEM of the fabricated structure.

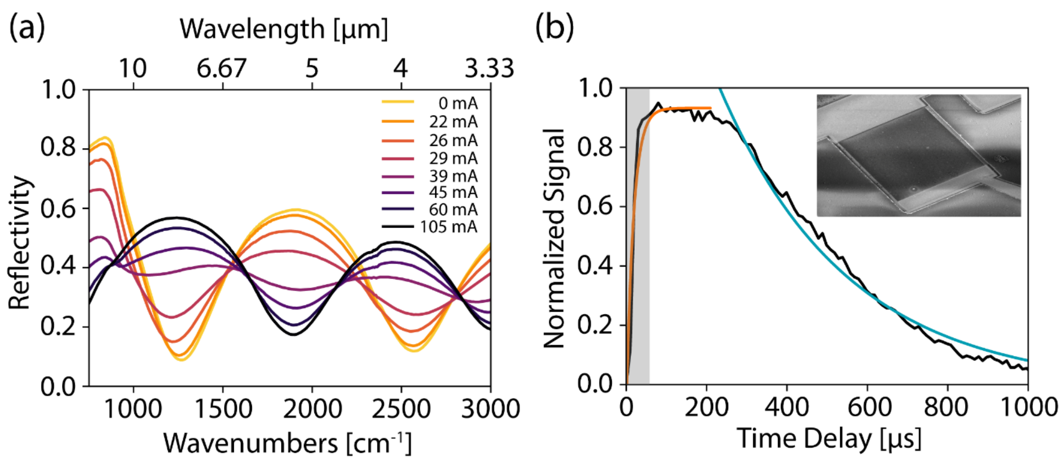

Fig. 3. (a) Experimentally-measured FTIR reflectivity of a Ge-VO2 Fabry-Perot cavity as the applied DC current is varied. **(b)** Experimentally measured, normalized, transient reflectivity at the anti-node. The shaded region corresponds to the time over a which a 26 V, 60 μs square pulse is applied. The colored lines correspond to fitted exponential curves. The inset shows an SEM of the corresponding device.