Active plasmonic devices and optical metamaterials

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Abstract

We studied active near-infrared metamaterials based on phase transition of vanadium oxide thin films, asymmetrically coupled split-ring resonators for narrowing resonance line-widths , field effect modulation of plasmon propagation and 3D single layer, plasmonic negative-index metamaterials.

Frequency Tunable Infrared Metamaterials

We present the demonstration of frequency tunable infrared metamaterials whose basic elements are Ag/VO_2 hybrid split ring resonators (SRR). Vanadium oxide (VO_2) is a promising phase-transition material that can be used in designing active metamaterials, which undergoes a phase transition from a semiconducting monoclinic phase to a metallic rutile phase at 68 ºC. Thin films of vanadium dioxide have been grown by pulsed laser deposition on sapphire substrate. The complex refractive indices of thin films in both phases were determined by spectroscopic ellipsometry. The split ring resonator frequency response was determined using full field electromagnetic simulations for bilayer Ag-VO_2 split ring resonator (SRR) arrays with complex refractive index models for the semiconductor and metallic phases of vanadium oxide. Ag SRR arrays were patterned on 60 nm thick VO_2 film using electron-beam lithography. Using infrared spectroscopy, we have observed suppression of the resonant reflection peak at 3.2 µm by thermal actuation of VO_2 thin films. VO_2 thin films were then etched to form bi-layer Ag-VO_2 hybrid SRR arrays. Full-field electromagnetic simulations have predicted that bi-layer hybrid SRR design yields a highly tunable frequency response upon thermal actuation of the VO_2 layer. Self-aligned, hybrid Ag/VO_2 laminate structures allow us to demonstrate optical and geometrical engineering of metamaterial devices leading to resonant peak position tuning of 110 nm at near-IR wavelengths (Fig. 1).

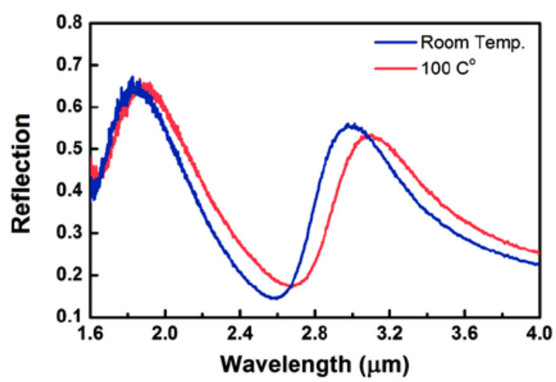

Fig. 1. Resonant peak shift of 110 nm is observed as the self-aligned Ag/VO_2 hybrid metamaterial is thermally switched above the VO_2 insulator-metal phase transition.

Asymmetric Split Ring Resonators

We studied the effect of coupled asymmetric split-ring resonators for reducing the spectral linewidth at the resonance frequency. A narrower resonant peak will increase the tuning figure of merit (FOM), the ratio of the tuning range to the full width at half maximum (FWHM) of the resonant peak. Figure 2 shows the numerical simulations of asymmetric SRRs that are coupled face-to-face with different spacings (inset of Fig. 2(b)). Simply, by breaking the structural symmetry of metamaterials we have shown narrower metamaterial resonances could be obtained. We fabricated arrays of Au SRRs on ITO coated glass substrates and experimental measurements are performed at the near-IR wavelengths using FTIR. Full-field electromagnetic simulations with Lumerical, agree well with the experimental results. Metamaterial resonances can be engineered using different coupling and hybridization mechanisms. Different geometries and coupling schemes were investigated by means of experiments and numerical simulations that show transmission resonances of different magnitudes, at wavelengths dependant on the size and degree of coupling between SRRs. We have calculated the magnetic and electric field intensities inside SRR structure that provided insights on the differences of various coupling mechanisms.

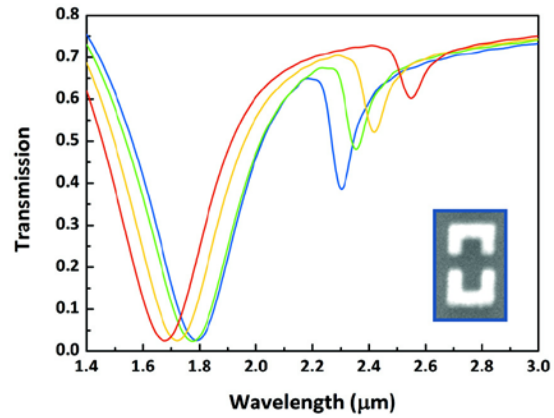

Fig. 2. Calculated transmission spectra of different face-to-face coupled SRRs with varying separation. Unit cell of a fabricated device is shown in the inset.

Three Dimensional All-Angle Negative Index Metamaterials

We expand upon recently reported work on direct observation of two-dimensional negative refraction in the visible frequency range to develop a general approach to realization of three-dimensional single-layer, all-angle, polarization-independent plasmonic metamaterials exhibiting negative refraction. The single layer negative index material is composed of an array of vertically-oriented coaxial metal-insulator-metal structures. Full wave simulations such as those shown in Fig. 3 and dispersion calculations are used to demonstrate that metal-dielectric-metal plasmonic waveguides are characterized by negative wave vectors and negative refractive indices. We also have been able to show that thin wedge-shaped metamaterial sheets composed of arrays of coaxial metal-dielectric-metal plasmonic structures exhibit negative refractive for transmitted beams projected into the far field.

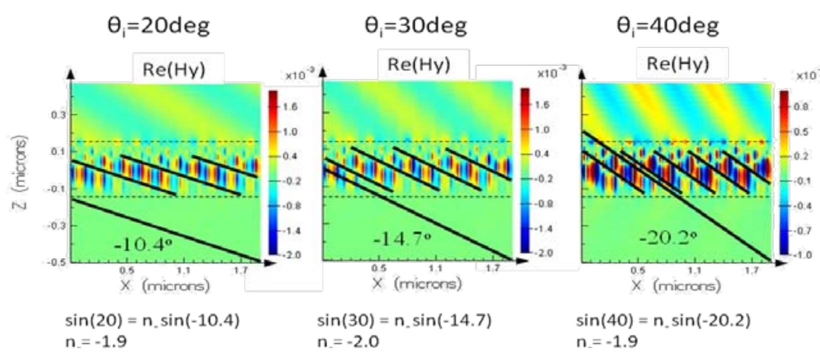

Fig. 3: Wave incidence on single-layer negative index metamaterials at several different angles.

Active Plasmonic Devices – PlasMOStor

Metal-dielectric plasmon waveguides can serve as active switching elements when the dielectric refractive index can be actively modulated. We demonstrate electro-optic refractive index modulation in metal-dielectric-metal plasmon waveguides using low-voltage electro-optic modulation of both silicon metal-oxide-semiconductor plasmonic resonators to yield a "plasMOStor" – an MOS field effect plasmonic modulator—with 11 dB on/off ratio in a footprint of a few square microns.