Dynamically Tunable, Vanadium Dioxide Huygens Source Metasurfaces

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Abstract: An active vanadium dioxide Huygens source metasurface offering >85% near-infrared transmittance modulation over the first 10% of the metal-insulator transition is demonstrated. The fabricated vanadium dioxide Huygens source nanoantennas exhibit experimental results similar to the model.

OCIS codes: (160.3918) Metamaterials; (160.4670) Optical materials; (260.5740) Resonance

1. Introduction

Metasurfaces have shown the ability to arbitrarily manipulate light propagation by modifying an incident wavefront through the imposition of abrupt phase discontinuities on a subwavelength scale. Here we seek to demonstrate the viability of metasurfaces capable of dynamically-variable optical wavefront control. Dielectric Huygens source metasurfaces comprised of nanoantenna elements supporting spectrally overlapping electric and magnetic dipole resonances have been shown to perform a variety of optical applications with high efficiency [1]. The resonant nature of the nanoantenna elements makes this system highly sensitive to changes in both geometric and material properties, making it a prime platform for dynamically tunable performance. Here we have chosen to focus on modulation of the optical properties of nanoantennas, avoiding mechanical complexities. We utilize an optical material with high refractive index that is tunable with minimal stimulus: vanadium dioxide.

Vanadium dioxide undergoes a so-called metal-to-insulator transition(MIT) when induced by external factors such as temperature, pressure, electric field, and optical excitation. In response to those stimuli, VO_2 shows drastic changes in its optical and electrical properties which makes it an excellent candidate for the tunable Huygens source metasurfaces. At the critical temperature, $T_c = 68°C$, VO_2 transforms from the low temperature monoclinic structure to a high temperature tetragonal structure, and the refractive index decreases from ~3.2 to ~2.2 [2]. With careful selection of antenna shape and spacing, a collection of antenna elements can be obtained covering a full 2π phase shift range with very high transmission efficiency (see Fig. 1(a)), indicating the viability of this system for wavefront shaping. We have computationally modeled vanadium dioxide metasurfaces (as illustrated in Fig. 1(c)), demonstrating amplitude modulation >85% with changing temperature in a transmissive configuration. These results reflect temperature tuning across only 10% of the VO_2 metal-insulator transition (see Fig. 1(b)).

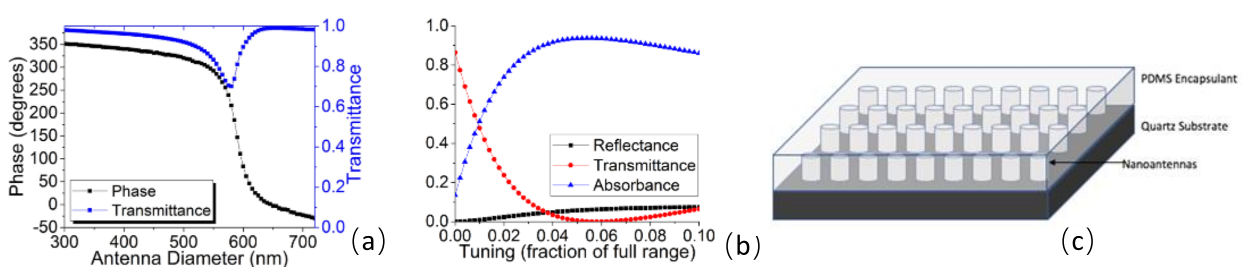

Fig. 1. (a) Phase and transmission response of nanoantenna elements in periodic array vs. antenna diameter. In insulating phase, full 2π phase range is accessible with high transmittance. (b) A periodic, transmissive nanoantenna array is modeled with continuous tuning over the first 10% of the accessible tuning range. Continuous amplitude modulation greater than 85% is achieved. (c) Schematic of VO_2 metasurface fabricated on fused quartz substrate and encapsulated by PDMS. The nanoantenna elements have diameter of 590nm and height of 262nm. The edge-to-edge distance is 340nm.

2. Material Growth and Device Fabrication

VO_2 thin film samples were grown by pulsed-laser deposition (PLD) on silica quartz substrate. The laser energy used was 115mJ per pulse, with a pulse frequency of 10 per second. The distance between the target and substrate was 4cm. Background pressure before deposition was ~10^{-6} Torr before the heater temperature was increased. Deposition was performed by ablating a V_2O_5 target, which had been sintered at 600°C in oven for 12 hours. The substrate temperature was kept at 560°C and the oxygen pressure was maintained at 10mTorr. Deposition time was 30 mins. After film growth, the heater was turned off, gas flows were stopped, and samples were cooled in vacuum. No post-deposition heat treatment was performed.

The metasurface fabrication process is as follows. After the VO_2 film growth, PMMA with thickness of ~100nm was spin-coated on top of the film. Electron-beam lithography was performed, using 3:1 IPA:MIBK developer at approximately -14°C to increase the lithographic resolution. Nearly 50nm thick gold was deposited by e-beam evaporator and PMMA was lifted-off. Then, the VO_2 film not covered by gold was etched away using a mixture of oxygen (O_2) and tetrafluoromethane (CF_4) in a reactive-ion etching system. Finally, the gold mask was removed via wet etch and the tunable VO_2 metasurface was encapsulated in PDMS. The metasurface is shown in Fig. 2(a) with the edge-to-edge distance of 300nm, the diameter of 500nm and the thickness of VO_2 material 200nm.

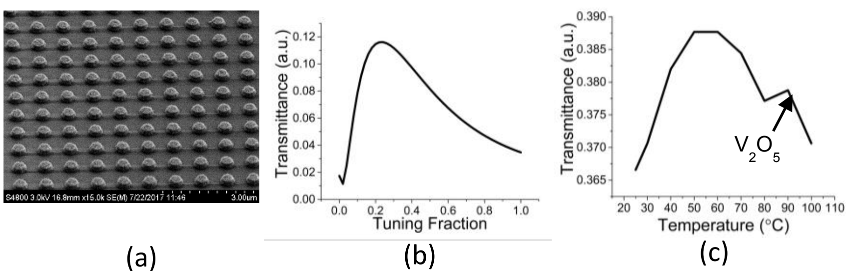

Fig. 2. (a) SEM micrograph of VO_2 metasurface fabricated on fused quartz substrate. (b) The modelled and (c) experimental results of normalized transmittance of the metasurface vs. tuning parameter, at wavelength 1250nm.

3. Metasurface Characterization

To predict the transmission modulation properties of the fabricated metasurface, finite element method simulations were implemented using the actual geometry of the fabricated structure, at a wavelength of 1250nm.The simulation result is shown in Fig. 2(b). The tuning fraction refers to the fractional shift in material properties between the insulator and metal states. As can be seen, the simulated transmission of the metasurface at tuning fraction ~0.25 is almost 10 times larger than the insulating phase (room temperature). The smaller total modulation relative to Fig. 1(b) is due to the difference in geometry between the ideal and early fabricated metasurfaces. Experimental results were obtained by measuring the power transmitted through the metasurface at various temperatures (see Fig. 2(c)). The measured transmittance has a similar performance vs. temperature/tuning to the modelled results, except at the temperature 90°C. This difference is likely caused by V_2O_5 material with critical MIT temperature 90°C, indicating that the grown film is a mixture of the two. Direct measurement of the phase shift vs. tuning parameter is assessed using an optical interferometer. Further improvement of the VO_2 thin film and metasurface quality is in progress.

4. Conclusion

Wavefront manipulation of incident light is achieved using tunable Huygens source VO_2 nanoantennas, which manipulate transmittance as a function of temperature. The modelled metasurface with carefully chosen geometric parameters shows modulation of transmittance >85% by tuning temperature over the first 10% of the metal-insulator transition. Early experimental implementations exhibit a similar performance to the model using the fabricated geometric dimensions. Improvement of the VO_2 metasurface synthesis with resultant better performance is expected in the near future.

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5. References

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