

Dynamically Tunable, Vanadium Dioxide Huygens Source Metasurfaces

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Abstract: We design and simulate dynamically tunable metasurfaces comprised of vanadium dioxide Huygens source nanoantennas. Simulations demonstrate metasurfaces capable of transmittance, reflectance, and absorbance modulation of >85%, with experimental realization in progress.

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1. Introduction

We seek here to demonstrate the viability of metasurfaces capable of dynamically-variable optical wavefront control using phase change media coupled with abrupt phase discontinuities on a subwavelength scale. We envision a class of materials where light from the UV to the IR can have its amplitude modulated spatially across a surface with low-loss and high speed (see Fig. 1d). Tunable metasurfaces have been demonstrated in plasmonic [1] and dielectric [2] systems, but an optimal method is far from decided, with most systems demonstrating high losses, shallow modulation depth, or slow tuning speeds. We present here the design and simulation of all-dielectric metasurfaces capable of deep modulation of transmitted and reflected amplitude, as well as absorbance.

2. Huygens Source Metasurfaces

Huygens source, all-dielectric metasurfaces are particularly well suited for tunability. Huygens source nanoantennas are characterized by spectrally overlapping electric and magnetic dipole resonances. Variation of antenna diameter about the central resonance results in modulation of transmitted phase. 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 (Figs. 1a, 1b, 1c), a necessary foundation for phase-gradient metasurfaces. An important characteristic of these systems is a high degree of inter-antenna coupling. Sensitivity of nanoantenna performance to neighboring elements requires special techniques to mitigate this nearest-neighbors effect.

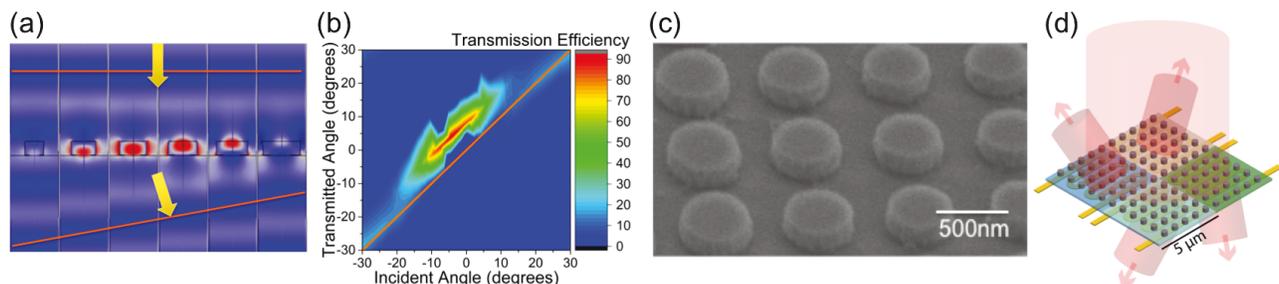


Fig. 1. (a) Computational model: discrete nanoantenna elements impose abrupt phase discontinuities on a subwavelength scale, shaping the transmitted wavefront. (b) Modeled results of a metasurface, comprised of nanoantenna elements such as those depicted in (a), demonstrating anomalous refraction as described by the generalized Snell's law; orange line depicts path of light in absence of metasurface. (c) SEM image of Si nanoantenna elements. (d) Conceptual diagram of spatially-addressed tunable metasurface

The high sensitivity of this system, due both to inter-antenna coupling and the resonant nature of each element, makes Huygens source metasurfaces ideal for tunability. These metasurfaces are highly sensitive to changes in antenna shape, size, spacing, and the optical properties of both the nanoantennas themselves and the surrounding medium. We have investigated these various possibilities and found that transmission/reflection modulation of >80% can be obtained by variation of 5%-15% of any single array parameter. This could include, for instance, mechanical stretching resulting in greater spacing between antenna elements, direct variation of antenna size/shape through the use of piezoelectric materials, or variation of refractive index using liquid crystals, electro-optic, or photoelastic materials. Here we have chosen to focus on modulation of the optical properties of nanoantennas,

avoiding mechanical complexities and utilizing an optical material with high refractive index that is tunable with minimal stimulus: vanadium dioxide.

3. Vanadium Dioxide and Deeply Tunable Metasurfaces

Vanadium dioxide has long been of interest as an optical material. It undergoes an insulator-metal transition close to room temperature, across which conductivity can change as much as five orders of magnitude. The refractive index also undergoes a large change, on the order of $\Delta n=1$ [3]. Usefully, this transition may be controlled by temperature, external electric field, or irradiance of an absorbed wavelength, and the transition can be switched back and forth at speeds sufficient for communications. Furthermore, of specific interest for tunable optics, continuous intermediate states exist with optical and electrical properties varying roughly linearly within the range of the transition. Experimental verification of modeled results is currently underway, with VO_2 grown at Tulane using pulsed laser deposition (PLD) (see Fig. 2g). We have designed a collection of Huygens source metasurfaces, using vanadium dioxide as the nanoantenna material, that demonstrate $>85\%$ modulation of amplitude across the first $<10\%$ of the insulator-metal transition, both in transmitting and reflecting configurations (Figs. 2a, 2b, 2c, 2d, 2e, 2f).

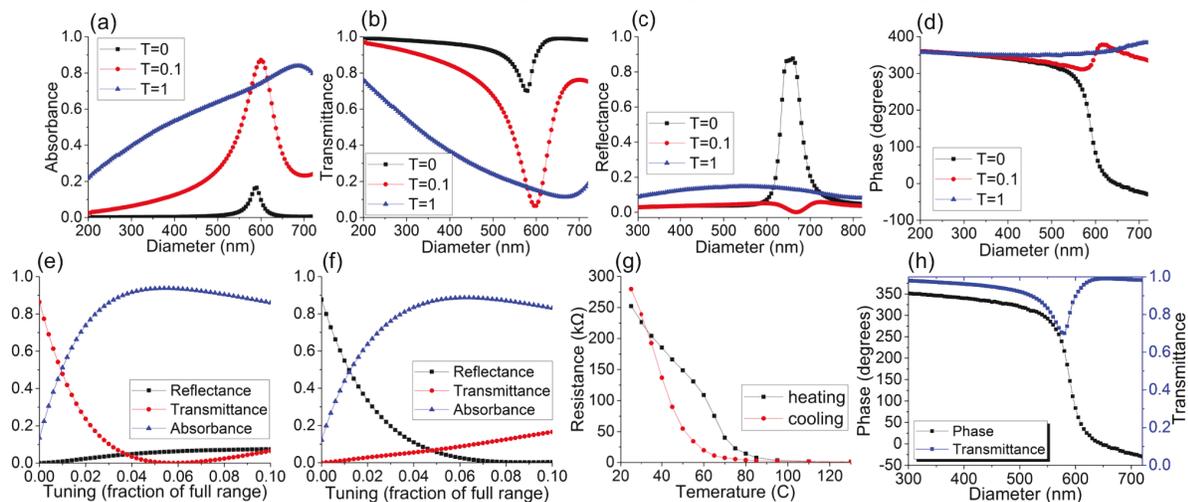


Fig. 2. (a-c) Two sets of VO_2 antenna elements on a fused silica substrate are modeled vs. antenna x-diameter, having been designed for high transmissivity (a, b) and high reflectivity (c) for 1550nm incident light. Shown here are the absorbance, transmittance, and reflectance of those antenna arrays for the insulating ($T=0$), conductive ($T=1$), and intermediate ($T=0.1$, or 10% of tunable range) states. Notable are three distinct regimes: the first dominated by the intended design of the dielectric metasurface, the second by resonant-enhanced absorption, and the third by area-coverage of the conducting VO_2 . (d) Phase response of nanoantenna elements from transmissive array at $T=0, 0.1, 1$, and (h) at $T=0$ plotted with transmittance. At $T=0$, full 2π phase range is accessible with high transmittance. (e, f) Homogeneous (single antenna diameter) transmitting (e) and reflecting (f) arrays are modeled with continuous tuning over the first 10% of the accessible range. Continuous amplitude modulation greater than 85% is achieved for both. (g) Preliminary electrical characterization of PLD-grown VO_2 film; hysteresis loop can be seen.

It is possible to design a set of antennas, in the insulating state, spanning the full 2π phase shift range with high transmittance (Fig. 2h). This allows the design of phase-gradient metasurfaces for numerous applications that can be ‘switched off’ by tuning towards the conducting state. Modulation of transmitted phase was also modeled, showing continuous tunable variation of $\sim 160^\circ$ over the first 10% of the accessible range, though with increased absorption. Ongoing design and synthesis work seeks a tunable material with similarly variable refractive index with reduced increase in conductivity. This effort is expected to lead to several types of useful optical devices, including switchable phase-gradient surfaces, amplitude and absorbance modulating devices, highly sensitive detectors and sensors, reconfigurable optics, orbital angular momentum modulators, and more.

4. Conclusions

We have designed and modeled dynamically tunable, Huygens source metasurfaces capable of continuous amplitude modulation $>85\%$, utilizing the insulator-metal transition of vanadium dioxide. This tunability is easily accessible, occurring over just 10% of the tunable range of the material.

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5. References

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