Dynamically Tunable Amplitude and Phase Modulation Using Vanadium Dioxide Huygens Metasurfaces

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Abstract: We design and fabricate continuously tunable vanadium dioxide Huygens metasurfaces for optical modulation in an all-in-one device. Simulation results show near π continuous phase modulation and ~20 dB amplitude modulation at near infrared wavelengths. Experimental verification is in progress.

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1. Introduction

Optical modulators that have high switching speeds, energy efficiency, and easy integration are highly desirable for applications in telecommunications, optical displays, optical metrology, and more [1]. Much previous research in this field has focused on amplitude-only modulation, however, in recent times there have been great efforts towards achieving amplitude and phase modulation using the same device. Many of these efforts use resonant systems where a material that is responsive to an external stimulus for tuning is included in an array of nanostructures and used as a driving tool for modulation.

Huygens source optical nanoradiators are distinct by utilizing spectrally overlapping electric and magnetic resonances. By carefully selecting the geometry, we can achieve phase tuning around the spectral resonance location of a Huygens source array of phase-change nanoantennas. These resonators are made from vanadium dioxide, which was chosen as a good candidate for achieving optical modulation because of its well-known insulator-metal transition at around 68^{o}C and its response to thermal, optical, and electrical stimuli. Due to the lossy nature of vanadium dioxide at near infrared wavelengths, Huygens VO_2 metasurfaces whose geometric design has spectrally overlapping electric and magnetic resonances results in resonance-enhanced absorption, a feature that may be utilized for amplitude modulation but must be designed around for phase modulation.

2. Modulator Design and Fabrication

2.1 Design and Modeling

Given the nature of these size- and shape-dependent resonances, six different design concepts were explored to minimize absorption at the resonant wavelengths. However, the amount of light absorbed was observed to be of the same order across widely varying designs at the spectrally overlapping resonant wavelength. Huygens sources designed as low aspect ratio nanodisks (as shown in Fig. 1a) in a periodic arrangement were chosen and geometry was optimized to be resonant at a wavelength with near zero loss in insulating phase (λ=2100nm) to achieve desirable amplitude and phase modulation at nearby wavelengths. This design was selected for its modulation properties and its relative ease of fabrication. The electric and magnetic dipole resonances spectrally overlap for selected geometric parameters as shown in the enhanced field within the resonator (Fig. 1b). In this paper, we demonstrate over 80% simulated transmittance modulation (~20dB) from insulator to metal phase at λ=1800 nm. We also show near π continuously modulated phase shift at λ=1620 nm (with relatively low change in transmittance while tuning phase), which in reflective applications would cover a full 2π phase shift, allowing full control over the wavefront of light.

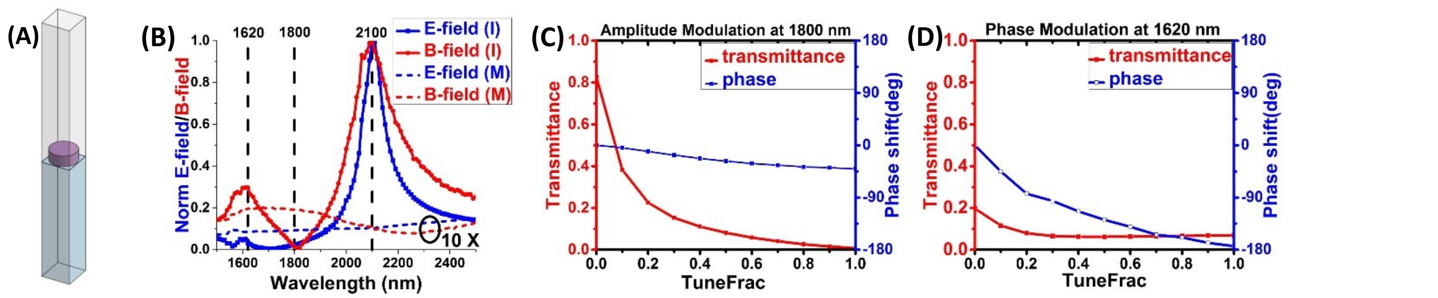

Fig. 1 (A). Schematic of periodic unit cell of designed VO_2 Huygens metasurface showing the encapsulant (PDMS), nanoantenna (VO_2), and substrate (quartz) domains (from top to bottom). (B). Normalized electric and magnetic fields confined within the nanoantenna for both insulating (I) and metal (M) VO_2 phases. Dashed vertical lines show magnetic higher order resonance at 1620 nm (phase tuning wavelength), off resonance spectral point at 1800 nm (amplitude tuning wavelength) and overlapping electric and magnetic dipole resonances at 2100 nm. (C). Amplitude modulation with minimal phase change at 1800 nm. TuneFrac (Tuning Fraction) is a modelling parameter defined as the fractional change in material properties of VO_2 from insulator (0.0) to metal (1.0). (D). Near π phase modulation with minimal transmittance change at 1620 nm.

2.2 Fabrication and Characterization

Vanadium dioxide thin films were fabricated using pulsed laser ablation, with x-ray diffraction and x-ray photoelectron spectroscopy confirmation of film quality (see Fig. 2a). Fig. 2b shows the optical properties of the film characterized using a custom made three beam Mach-Zender interferometer. This was done using a continuously referenced phase and transmittance measurement affirming that the film has the expected optical properties and phase transition as described in detail here [2]. VO_2 metasurfaces are patterned using the Raith Voyager 100 electron beam lithography tool. A thin layer of silica hard mask (note: other hard masks are being thoroughly tested) was deposited using electron beam evaporation. Reactive ion etching efforts are being optimized towards making the fabricated nanoantennas match modelled geometries. Fig. 2c shows a scanning electron micrograph of some unoptimized etch results. Once etch process is optimized, VO_2 metasurfaces will be characterized as shown in Fig. 2b.

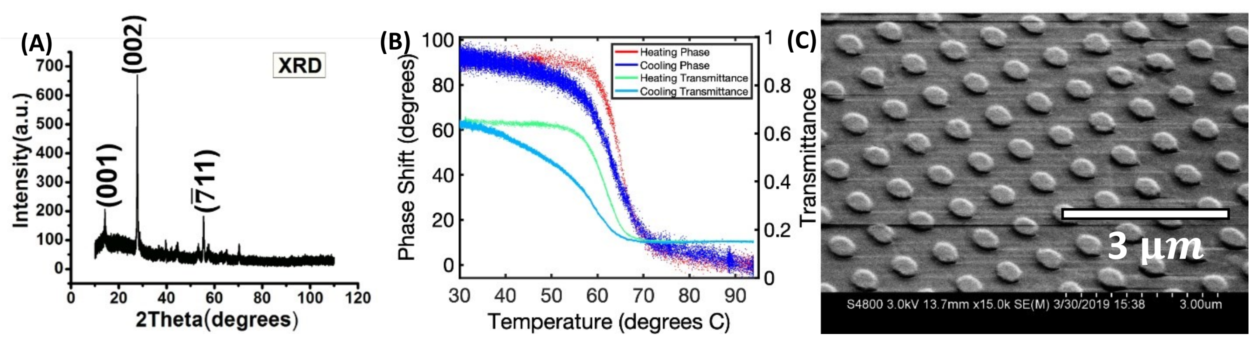

Fig. 2 (A). X-ray diffractogram of VO_2 film grown by pulsed laser ablation, showing expected monoclinic VO_2 crystal structure (B). Phase shift and transmittance measurements from a VO_2 thin film (170 nm thick) heated across the insulator-metal transition and then cooled down, with expected hysteresis [2]. (C). Scanning electron micrograph of etched VO_2 nanoantennas using Cl_2/Ar reactive ion etching process and SiO_2 hard mask.

3. Conclusion

Design and model of ~20 dB continuously tunable amplitude and near π phase modulation in a single Mie-resonant VO_2 metasurface has been achieved. Experimental verification for anisotropic etched metasurface geometries is underway. Work is in progress towards optimizing several design concepts for various tunable optics applications.

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References

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