Design and Fabrication of Vanadium Dioxide Metasurfaces for Continuous Optical Wavefront Tuning

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Abstract: We design and fabricate vanadium dioxide metasurfaces for dynamic optical amplitude, phase, and beam angle modulation. Temperature-dependent ellipsometry yields a refractive index modulation of ~1.8. Metasurface optical modulation of ~17 dB is projected with near π phase tuning.

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1. Introduction

Flat optics based on metasurfaces with the ability to bend and direct light in unconventional ways have demonstrated potential to outperform their conventional bulky counterparts. These precisely engineered, two-dimensional, sub-wavelength structures have found applications in lensing, displays, switching, and sensing applications among others.[1] Many of the current applications of metasurfaces are designed to have their optical functionality fixed at fabrication, making them useful only for static applications. However, active devices made from tunable materials like vanadium dioxide (VO_2), germanium-antimony-tellurium (GST), and antimony trisulfide (Sb_2S_3) are highly desirable, as they can enhance compact photonic device integration in dynamic displays and optical communications.[2] Vanadium dioxide is especially interesting because it undergoes a continuously reversible semiconductor to metal transition at ~68°C, making it suitable for perpetual optical modulation in photonic devices near room temperature. Vanadium, being a transition metal, has multiple oxidation states. This makes it quite challenging to obtain a stoichiometrically accurate thin film layer which is necessary for dynamic tunability near room temperature. Also, obtaining highly anisotropically etched nanoantennas presents a challenge for obtaining patterned arrays that match simulated geometries. A carefully optimized deposition and etching method is therefore necessary to take advantage of the tunable optical properties of VO_2 for efficient devices.

2. Device Design

VO_2 nanodisk arrays were designed to obtain spectrally overlapping electric and magnetic resonances at near infrared wavelengths. In a lossless system, this yields near unity transmittance at resonance; however, in low-loss systems (with non-zero loss at resonance) like VO_2, this results in amplified absorption with low continuous optical modulation (see Figures 1 A and 1B). Due to this effect, ~85% of the incident light is attenuated at the resonant wavelength (2120 nm here). However, at an off-resonance spectral location on the slope of the overlapping resonances (1830 nm), ~50% amplitude modulation is achieved (~17 dB) as shown in Figure 1C with a minimal phase modulation. Also, a higher order magnetic resonance mode is excited at 1550 nm. As the metasurface optical properties are tuned from insulating to metallic, this magnetic resonance gradually decays yielding a near π phase shift in transmission (see Figure 1D) with minimal change in transmittance. Further design is underway to utilize a phase gradient of these metasurfaces to build a tunable beam deflector. A key benefit of VO_2, relative to other phase change materials, is that these metasurfaces are continuously tunable across a range of amplitude, phase, or deflected angle, rather than only switching between discrete states.

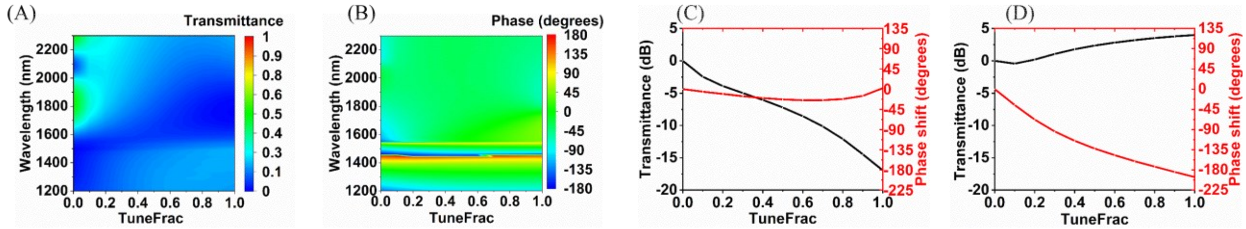

Fig. 1 (A). Amplitude and (B). Phase modulation of VO_2 metasurface across the transition from insulating to metallic optical properties at different wavelengths. TuneFrac (Tuning Fraction) is a modelling parameter defined as the fractional change in material properties of VO_2 from insulator to metal. (C). Amplitude tuning at 1830 nm showing ~17 dB with little residual phase shift. (D). Phase tuning at 1550 nm showing near π phase shift with little residual amplitude shift

3. Fabrication and Characterization

Thin films of vanadium oxide were deposited onto a quartz substrate using RF magnetron sputtering with a VO_2 sputtering target (AJA 50.0 mm diameter, 99.9% purity). The sputtering chamber was pumped down to a pressure of 1.0 µTorr before the deposition. The quartz substrate was pre-sputtered for 5 minutes before the deposition of the film. The film was deposited using an RF power of 200 W at 3.3 mTorr, yielding a deposition rate of 0.2 Å/s. The substrate-target distance was maintained at about 5 cm to achieve a higher deposition rate and reduce material waste. A VO_2 target was chosen to eliminate the need for Ar/O_2 flow rate optimization and to yield a starting oxide film close to the desired stoichiometry.[4] The sputtered films were then annealed at 500ºC in a quartz tube (1-inch diameter) in inert atmosphere at 8.4 Torr for three hours (one-hour ramp time and two hours annealing). The annealing process was necessary to ensure that films with the correct oxygen-vanadium ratio are obtained and useful for crystallization of the amorphous sputtered film. Variable angle spectroscopic ellipsometry was done on these films at different temperatures using a custom-made heating stage showing a large refractive index modulation ($\Delta n \sim 1.8$) which is a useful metric for dynamic tunability (Figures 2A and 2B). The nanostructures for dynamic tuning are then encoded on the substrate using electron beam lithography and reactive ion etching. Reactive ion etching is done in two steps. First, a silicon dioxide (SiO_2) layer is etched off using CHF_3 & Ar etch gases, leaving an SiO_2 protective layer on the metasurfaces for the next etch. Second, the vanadium dioxide layer is etched using Cl_2 & Ar etch gases. A scanning electron micrograph of the etched structures is as shown in Figure 2D, currently resulting in an amplitude modulation of ~10 dB. We continue to tune the model-fabrication feedback loop to refine our structures and improve performance.

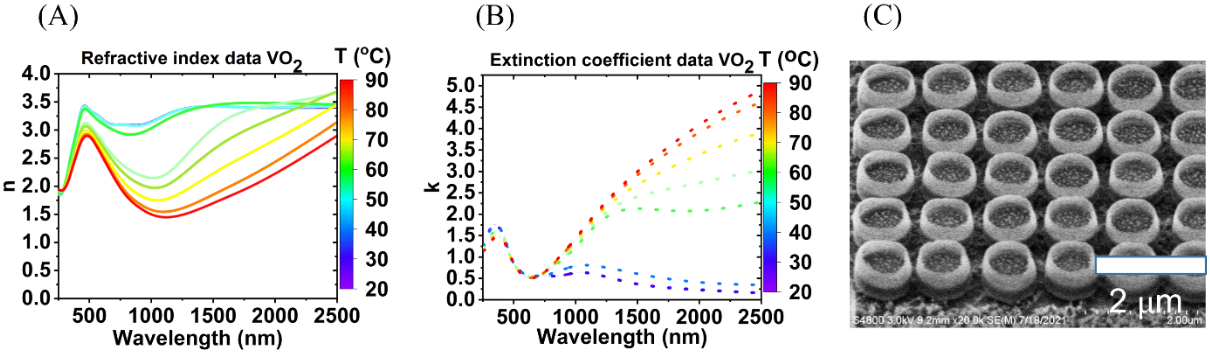

Fig. 2 (A). Temperature-dependent refractive index of VO_2 showing a refractive index modulation of ($\Delta n \sim 1.8$). (B). Temperature-dependent extinction coefficient of VO_2 (C). Scanning electron micrograph showing etched nanoantennas using Cl_2/Ar reactive ion etching process.

4. Conclusion

VO_2 thin films were successfully synthesized using novel sputtering and ex-situ annealing process. Tunable refractive index ($\Delta n \sim 1.8$) was measured using variable angle temperature-dependent spectroscopic ellipsometry. The design-fabrication device development loop is being closed to produce continuously tunable amplitude, phase, and beam angle modulators.

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