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Active Modulation of Optical Leaky Wave Antenna by Vanadium Dioxide Corrugations

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ABSTRACT

Active tunability of optical leaky wave antenna is highly desired to enable greater control on light-matter interaction, sensing, and communication. Phase-changing materials can be integrated in optical antennas to enable such tunability. Among the phase-changing materials, vanadium dioxide (VO_2) is the most useful as it shows the semiconductor to metal transition (68°C) very close to the room temperature. The phase transition in VO_2 can be commonly induced by optical pulses or electrical joule heating. VO_2 exhibits significant temperature-dependent electrical and optical coefficients even outside of the transition temperature making it suitable for both - fine and coarse tuning of the properties of optical devices depending on the temperature bias. In this work, we study optical leaky wave antenna consisting of a silicon nitride waveguide with periodic VO_2 nanowire perturbations. We present the numerical analysis of different arrangements of the periodic perturbations. The antenna operates by the coupling between the evanescent mode of the waveguide and the nanowires. We show that, by selective joule heating of individual nanowires we can tune the optical property of corrugations and enable wider tuning range and higher degree of control on the radiated beam. We also include a comparative study to show tunability and performance of the antenna with different phase-changing materials like vanadium pentoxide (V_2O_5) and germanium-antimony-tellurium (GST). We show that, around the phase transition temperature of VO_2, the directive gain of the antenna can be modulated by up to 25 dB and the radiation peak position can be tuned by up to 2.5°.

Keywords: leaky-wave, antenna, phase-changing material, VO_2, vanadium dioxide, tunable, active

1. INTRODUCTION

Phase-changing materials have huge potential of being integrated in optical devices[1,2] to enable active tunability. Of them, Vanadium Dioxide (VO_2) is particularly interesting owing to its low (68°C) semiconductor-to-metal transition temperature. The most common way to induce the phase transition in VO_2 is by optical pulses or electrical joule-heating. Even outside of the transition temperature, VO_2 exhibits significant temperature-dependent electrical and optical coefficients making it suitable for fine tuning the behavior of optical devices.

In this work, we study optical leaky wave antenna (OLWA) consisting of dielectric waveguide with VO_2 and other suitable phase-changing materials (PCM) to actively tune the radiation property of the antenna. We have earlier investigated the coupling and interaction between periodic nanostructures and dielectric waveguides.[3–5] The potential to integrate PCM materials adds another dimension and can springboard many new functionalities and applications. To demonstrate the concept PCM based OLWA, we design an antenna that operates by the coupling between the evanescent or the fundamental guided mode of the waveguide with the periodic VO_2 nanowires that act as a periodic perturbation medium. The position of the wires determines whether the coupling takes place with the guided mode (nanowires buried in the waveguide) or the evanescent mode (nanowires above the waveguide or placed at a gap from the waveguide). We show the directive gain of the antenna can be modulated by up to 10 dB (25 dB in a resonator) when the phase change occurs. We also show the radiation

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peak can be tuned by up to 2.5° for a different set of design parameters. The OLWA, by design and choice of process and materials, can be made fully integrate-able and compatible with other integrated components like lasers,[6] light-emitters[7] and low-loss waveguides.[8]

2. ANTENNA DESIGN

The proposed antenna structure is illustrated in Fig. 1(a). To demonstrate the functionality, we assume the waveguide core to be made of silicon nitride (Si_3N_4) with 250 nm thickness and the cladding is silicon dioxide (SiO_2). VO_2 nanowires are added periodically along the waveguide. We study two cases - one with the VO_2 nanowires buried in the waveguide, and other with the VO_2 nanowires above the waveguide, in which we also study the effect of gap variation on the radiated power. We also vary the width (w_{NW}) and thickness (t_{NW}) of the nanowires to find the optimized radiation properties.

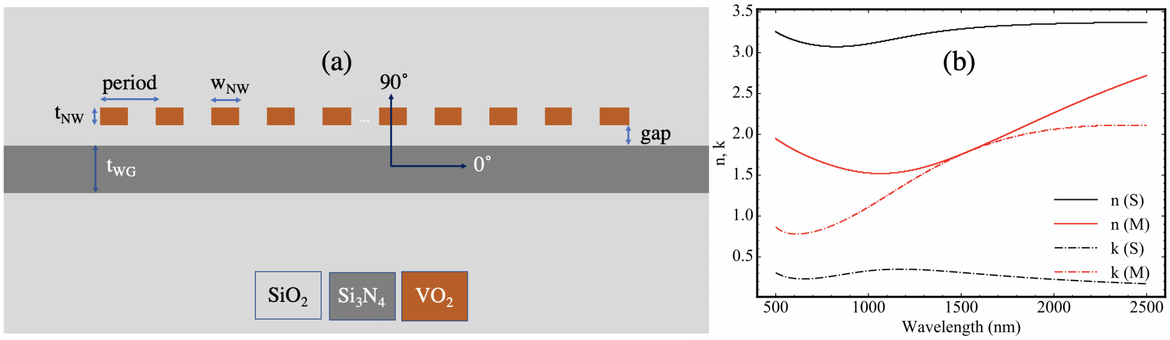


Figure 1. (a) Proposed design, (b) Complex refractive index of VO_2 (semiconductor (S) and metal(M))

We use the complex refractive index of semiconductor and metal VO_2 at 1550 nm free-space wavelength to analyze our proposed design. Fig. 1(b) shows the complex refractive index of semiconductor and metal VO_2 as obtained from.[9] For semiconductor VO_2, we consider n = 3.3 and k = 0.3, and for metallic VO_2, we consider n = 1.8 and k = 3.3.[9,10]

In our design, the coupling between the waveguided mode and the VO_2 nanowires leads to efficient and almost vertical radiation. To achieve the near-vertical radiation at 1550 nm wavelength, we optimize the period of the nanowires to 1020 nm in order to obtain maximum out-of-plane coupling.[11] By changing the gap between waveguide and the nanowires, we can control the evanescent interaction between waveguide and nanowires, thus the level of the radiated output power.

3. RESULTS

To evaluate the extent of thermally induced modulation, we report the directive gain or directivity of the antenna for two extreme states - semiconductor VO_2 and metal VO_2. We define the gain as the gain with respect to an isotropic radiator, G (dBi) $= 10log\,\frac{4\pi E^2 R^2}{2\eta P_{in}}$, where, P_{in} is the input power, η is the wave impedance of radiating far-field medium, E is the electric field at radius R. Between the two extreme states the material will coexist in metallic and semiconducting states depending on the transition width and temperature. The optical and electrical parameters will thus vary according to the temperature level.[9]

$$\varepsilon_{VO_2}(T) = f(T)\varepsilon_S + (1 - f(T))\varepsilon_M \quad \text{where} \quad f(T) = \frac{1}{exp(\frac{T-T_t}{WT_t}) + 1} \tag{1}$$

Here, ε_{VO_2} is the permittivity of the transitioning VO_2, ε_S and ε_M are the permittivity of semiconductor and metal VO_2, respectively, $f(T)$ is a function that determines the transitioning property of VO_2 which contains partial metallic and semiconducting properties, T_t is the transition temperature, T is the current temperature, and W dictates the transition width.

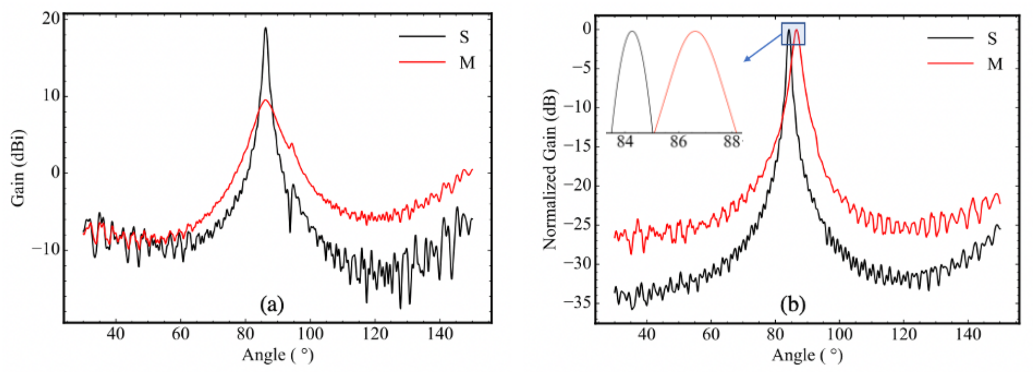


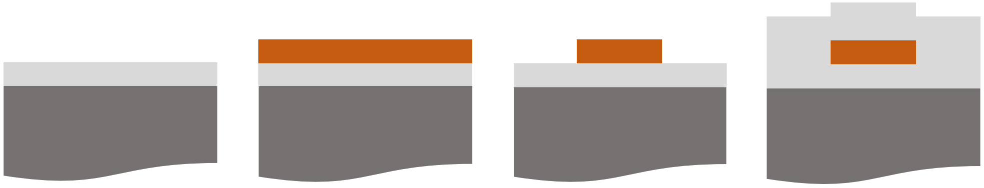
Figure 2. (a) Gain modulation, (b) angle modulation; S = semiconductor VO_2, M = metal VO_2

From Fig. 2(a), we observe slightly over 10 dB gain reduction from semiconductor to metal state of VO_2. This is achieved for w_{NW} of 260 nm (about 25% duty cycle), t_{NW} of 150 nm, and the nanowires on top of the waveguide. Fig. 2(b) shows the change in the angle of radiation peak from semiconductor (84.2°) to metal (86.7°) phase, inset shows the zoomed peaks. This is observed for a 102 nm wide and 80 nm thick nanowires which gives about 10% duty cycle. We observe that the duty cycle and corrugation thickness directly impact the amount of coupling and how the coupling happens, thus allowing us to modulate antenna gain as well as angle for the two cases. In the former case the directivity of the antenna decreases significantly from semiconductor to metal phase of VO_2. In the latter case, the sharpness of radiation is better preserved while the angle of radiation peak is modulated. Our results indicate significant multidimensional active tunability using phase-changing materials in optical antenna. Further optimization can be done to achieve desired operation and radiation control for specific application.

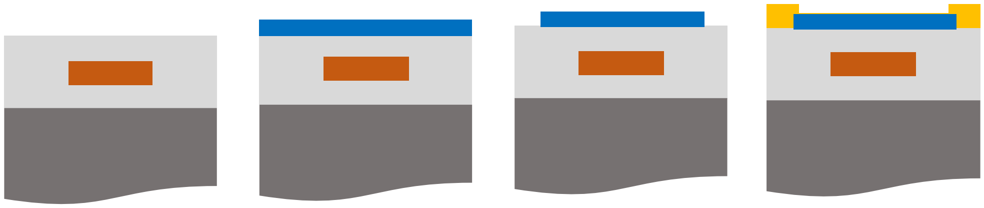
In summary, we demonstrate the gain and angle modulation capability of optical leaky wave antenna when incorporated with VO_2 phase-changing material. This active tunability has promising applications in controlled light-matter interaction, optical sensing and communication.

4. FABRICATION STEPS

The fabrication steps for the proposed OLWA with phase-changing perturbations are shown in Fig. 3. The first step of the fabrication process is to grow a thermal oxide layer on a standard silicon wafer. Then low pressure chemical vapor deposition (LPCVD) of silicon nitride layer is carried out. The nitride waveguide width is 1 um. Therefore, photolithography can be used to pattern the waveguide structure. After patterning the waveguide, silicon dioxide layer is deposited using plasma-enhanced chemical vapor deposition (PECVD). The waveguide pattern creates a bump in the deposited silica layer. The extra protrusion oxide can be etched out by calculated dry etching or chemical mechanical polishing to create a flat surface for the subsequent PCM deposition and patterning the periodic perturbations. The patterning needs to be done using electron beam lithography or stepper method depending on the duty of the PCM perturbations as the features are below the diffraction limit. After the perturbations are patterned, gold film is deposited that acts as the electrical contacts for the PCM perturbations to provide external current to heat up and cause the desired phase change for modulating the radiation properties. Further oxide deposition can be done to make silica the host material on the top side of radiation. The preparation of stoichiometric VO_2 thin films are challenging because other vanadium oxides such as V_2O_3, V_3O_5, V_2O_5, and V_3O_7 have stable structure at the growing conditions of VO_2. Precise control of deposition parameters[12,13] like Ar/O_2 partial pressure, flow rate, substrate temperature, etc. is needed to obtain a proper chemical composition. Two of the most common ways of depositing VO_2 films are - pulsed laser deposition[1,14,15] and sputtering.[16–24] GST can also be fabricated using thermal evaporation,[25] atomic layer deposition,[26] pulsed laser deposition,[27] and sputtering[28–30] method. To make periodic antenna elements, the PCMs can be dry-etched.[31–33] The external current through the PCM corrugations needs to be provided by some metallic contacts. Gold or ITO can be used in this regard, and they can be deposited by sputtering



(a) Thermal oxidation (b) LPCVD nitride (c) Waveguide patterning (d) PECVD oxide



(e) Etching oxide (f) Perturbation film deposition (g) Etching perturbation (h) Contact Lift-off

Si SiO_2 Si_3N_4 VO2 or GST Au

Figure 3. Fabrication steps, starting from a standard silicon wafer.

or evaporation technique followed by a lift-off. The top radiation side can be covered by silica as the radiation leakage medium.

5. CONCLUSION

Phase-changing materials can be incorporated with optical devices to achieve active modulation and tunability. In this work, we study the integration of VO_2 nanowires as the periodic perturbations of optical leaky wave antenna. We consider different arrangements of these perturbations for numerically analyzing the radiation property of the antenna. We show that, by selectively heating the nanowires, we can achieve wide tuning range and greater control on the radiated beam. In addition, we investigate other common phase-changing materials like V_2O_5 and GST. We report up to 10 dB (25 dB in a resonator) of directive gain modulation and up to 2.5° of peak position tuning.

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