The Design of a Switchable Infrared Hybrid Plasmonic Metasurface Absorber for Energy Harvesting Applications

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Abstract **─** A plasmonic switchable polarization-insensitive metasurface absorber is proposed. The design provides two modes of operation by employing phase-change material in semiconductor and metallic phases. In this paper, we study the switchable absorption behavior of the metasurface operating in a dual-band and single-band modes targeting the mid-infrared range suitable for energy harvesting applications such as thermophotovoltaics. The design is optimized using a global optimization technique.

Index Terms **─** energy harvesting, metasurface, plasmonic, polarization-insensitive, switchable.

I. INTRODUCTION

The interest in using metasurfaces as electromagnetic absorber dramatically increased after the realization of the first perfect metasurface absorber by Landy et al. in 2008 using a metal-insulator-metal (MIM) configuration [1]. Metasurfaces can behave as perfect absorbers because they can satisfy impedance matching with air at the resonating wavelengths [2].

Active tuning of metasurfaces using phase-change materials (PCMs) is an interesting approach to change the response of the structure without modifying the design. Vanadium dioxide (VO_2) is a PCM that experiences transition from semiconductor to metallic phase at around 68°C [3]. It was used to design tunable metasurfaces for applications such as filters, thermal switches, and temperature sensors [3].

In this work, we propose a switchable, polarization insensitive metasurface absorber for operation at single or dual modes using the phase transition property of VO2. Using the design introduced in [4], VO_2 is embedded within the gaps of a gold resonator. The structure provides dual-band absorption when operated at 30°C, and single-band absorption at 90°C. The proposed absorber operates in the mid-infrared (MIR) range, which is suitable for ambient energy harvesting applications such as thermophotovoltaics.

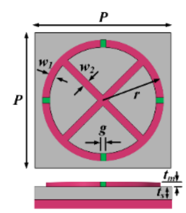

Fig. 1. Top and side views of the unit cell of the proposed absorber (t_m = 50 nm, t_s = 280 nm, P = 2780 nm, R = 1120nm, w_1 = 120 nm, w_2 = 420 nm, and g = 100 nm).

II. PROPOSED STRUCTURE

Figure 1 shows the unit cell geometry of the switchable absorber suggested in this work. A circular gold resonator of radius R and width w_1 includes four gaps each of width g, and is combined with an inner cross of width w_2. The gaps are filled with patches of VO_2 to achieve the switchable operation. A thick gold layer is placed at the bottom to suppress wave transmission. A silicon dioxide layer separates the upper and bottom gold layers to complete the MIM configuration.

A practical realization of the structure can be achieved by first depositing VO_2 based on a lithography pattern followed by overlaying of the gold resonator [5]. The gold regions touching the VO_2 patches can be used as joule heating elements to control the operating temperature [5]. To find the absorption characteristics of the structure, a normally incident transverse electromagnetic plane wave is excited upon the metasurface. The absorption A can be calculated as:

$$A = 1 - R - T, \tag{1}$$

where R and T are the reflectance and transmittance of the structure. The bottom gold layer blocks the transmission, so T can be ignored in the calculation. Full-wave simulations were carried out using finite-element

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method in COMSOL Multiphysics 5.3, with periodic boundary conditions applied over lateral sides to model periodicity *P*. The refractive index of gold was obtained from [6], while that of silicon dioxide is set to 1.5. Temperature-dependent permittivity models of VO_2 were obtained from [7].

Optimization is initialized with the values of the parameters reported in [4]. We target dual-band resonance at 6 µm and 10.6 µm suitable for ambient energy harvesting [8]. Adaptive wind-driven optimization is employed as a global optimization technique [9].

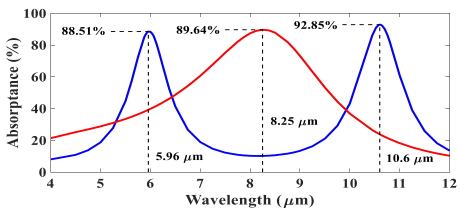

Fig. 2. Absorptance versus wavelength for the proposed metasurface at 30°C and 90°C.

III. RESULTS AND DISCUSSION

Figure 2 shows the absorption spectra of the optimized absorber at different operating temperatures. At 30°C, the absorber exhibits a dual-band absorption with absorptance values of 88.4% and 92.85% at 6 µm and 10.6 µm respectively. At 90°C, single-band absorption at 8.25 µm with absorptance of 89.64% is achieved. Switching between single and dual-band absorption modes can thus be achieved without modifying the absorber configuration.

Figure 3 shows the electric field distribution over the structure at the resonant wavelengths at 30°C. Electric field is highly confined within the semiconductor VO_2 patches at 6 µm and 10.6 µm. At 90°C, the VO_2 patches attain metallic properties, and the field confinement vanishes. New single mode resonance is obtained at 8.25 µm, where high field is concentrated at the edges due to coupling between neighboring elements of the metasurface as shown in Fig. 4.

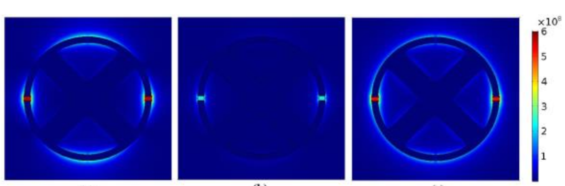

Fig. 3. Distribution of electric field at: (a) 6 µm, (b) 8.25 µm, and (c) 10.6 µm when the operating temperature is 30°C.

IV. CONCLUSION

A switchable metasurface absorber for energy harvesting in the MIR range is proposed. The symmetry of the design provides a polarization-insensitive response, and the phase transition property of VO_2 provides the switching mechanism. The dimensions of the structure are optimized using a global optimization technique.

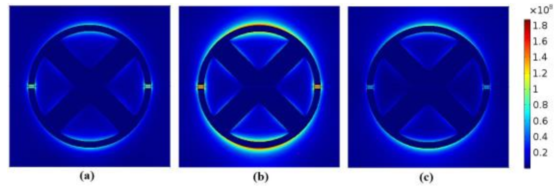

Fig. 4. Distribution of electric field at: (a) 6 µm, (b) 8.25 µm, and (c) 10.6 µm when the operating temperature is 90°C.

REFERENCES

[1] T. Lu, D. Zhang, P. Qiu, J. Lian, M. Jing, B. Yu, and J. Wen, "Ultrathin terahertz dual-band perfect metamaterial absorber using asymmetric double-split rings resonator," *Symmetry*, vol. 10, no. 7, p. 293, 2018.

[2] J. Li, F. Wang, G. Wen, Y. Huang, and W. Zhu, "Planar metamaterial for matched waveguide termination," *ACES Journal*, vol. 28, pp. 1236-43, Dec. 1, 2013.

[3] Y. Ke Y, S. Wang, G. Liu, M. Li, T. J. White, Y. Long, "Vanadium dioxide: The multistimuli responsive material and its applications," *Small*, vol. 14, no. 39, p. 1802025, Sep. 2018.

[4] A. Negm, M. Bakr, M. Howlader, S. Ali, "A Dual Band Plasmonic Metasurface Absorber for Energy Harvesting Applications," *In 2019 International Applied Computational Electromagnetics Society Symposium (ACES), IEEE*, pp. 1-2, Apr. 14, 2019.

[5] Z. Zhu, P. G. Evans, R. F. Haglund, Jr., and J. G. Valentine, "Dynamically reconfigurable metadevice employing nanostructured phase-change materials," *Nano Letters*, vol. 17, no. 8, pp. 4881-5,Aug. 9, 2017.

[6] A. D. Rakić, A. B. Djurišić, J. M. Elazar, and M. L. Majewski, "Optical properties of metallic films for vertical-cavity optoelectronic devices," *Applied Optics*, vol. 37, no. 22, pp. 5271-83, Aug. 1, 1998.

[7] H. Wang, Y. Yang, and L. Wang, "Wavelength-tunable infrared metamaterial by tailoring magnetic resonance condition with VO2 phase transition." *Journal of Applied Physics*, vol. 116, no. 12, p.123503, Sep. 28, 2014.

[8] A. Y. Elsharabasy, A. S. Negm, M. H. Bakr, and M. J. Deen, "Global optimization of rectennas for IR energy harvesting at 10.6 µm," *IEEE Journal of Photovoltaics*, vol. 9, no. 5, pp. 1232-9, July 29, 2019.

[9] J. Nagar, S. D. Campbell, D. H. Werner, Z. Bayraktar, and M. Komurcu, "The Adaptive Wind Driven Optimization and its Application in Electromagnetics," *In 2018 International Applied Computational Electromagnetics Society Symposium (ACES), IEEE*, pp. 1-2, Mar. 25, 2018.