Switchable Terahertz Metamaterials: Using the Insulator-Metal Transition of Vanadium Dioxide to Activate Metamaterial Properties

Fei Yan[1], Edward P. J. Parrott[1], Georges Humbert[2], Aurelian Crunteanu[2], and Emma Pickwell-MacPherson[1*]

[1]Department of Electronic Engineering, The Chinese University of Hong Kong, Shatin, Hong Kong

[2]XLIM UMR 7252, CNRS/University of Limoges, 123 av. Albert Thomas, 87060, Limoges, France

***Abstract*—Terahertz (THz) metamaterials have recently attracted much interest due to their ability to tune propagation properties using sub-wavelength structures. In this paper we demonstrate the first metamaterial device developed by patterning a vanadium dioxide (VO_2) wire-grid structure onto a c-sapphire substrate. Temperature and polarization dependent THz time-domain spectroscopy transmission measurements are taken to evaluate the device performance as a function of the metamaterial parameters. The transmission variance with polarization is enhanced by increasing the filling factor of the wire-grid structure.**

I. Introduction and Background

Terahertz (THz) wave technology has many important applications in areas such as non-destructive sensing, material characterization, biomedical imaging and high-speed communication. This in turn drives an increasing need for passive and active THz optical components such as modulators, switches, and filters. Metamaterial inspired devices are one potential solution to realize these components as the structure of the metamaterial can be tuned to produce a desired property. Several groups have studied the use of metal gratings [1] to manipulate the polarization of terahertz waves. However, active devices for THz wave polarization modulation are very limited. “Active” metamaterial devices have been proposed that employ metallic structures such as split ring resonators atop tunable substrates [2]. Such devices can alter the frequency and intensity of optical absorption features but the metamaterial property itself cannot be switched off. An ability such as this may be realized by developing a metamaterial structure using a compound that can be switched from a metallic to a non-metallic state.

Vanadium dioxide (VO_2) experiences an ultrafast insulator-to-metal (IM) phase transition at ~ 340 K. Based on this unique material property, active THz modulators and filters have been demonstrated using VO_2 by means of temperature control [3]. In this paper, we report a THz metamaterial employing 200 nm thick VO_2 wire-grids with micrometer period and width on top of c-sapphire substrate. Such a design allows us to activate the metamaterial properties from a completely passive state to a state displaying polarization sensitive transmission as the temperature passes through the IM phase transition.

II. Experimental Results and Discussion

The VO_2 wire-grids were fabricated by photolithography and etching technique of the 200 nm thick (d) VO_2 thin films that fabricated by pulsed laser deposition (PLD) method (see Fig. 1) on c-sapphire substrates. The details can be found in previous works [4]. Figs. 2 (a) and (b) show the optical images of the VO_2 wire-grids. The period (P) of both VO_2 wire-grids is 10 μm, and the width (W) is about 1 and 2 μm, respectively, with the filling factor of 10% and 20%, respectively.

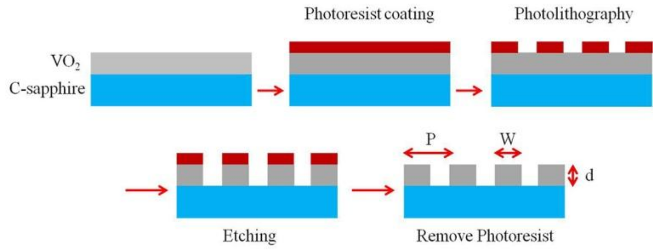

Fig. 1 Schematic diagram of the fabrication process for VO_2 wire-grids on c-sapphire substrates.

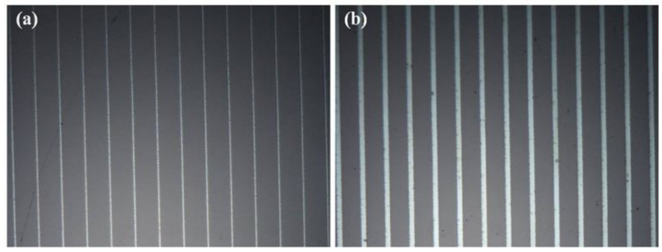

Fig. 2 Optical images of (a) 10/1μm, and (b) 10/2μm VO_2 wire-grid.

The temperature and polarization dependency of the terahertz transmission of 200 nm thick VO_2 wire grids with 10/1 and 10/2 μm (period/width) grating patterns deposited on c-sapphire substrates were measured using our free-space terahertz system. Fig. 3 shows the temperature dependent normalized amplitude transmission for 0.6 THz frequency waves polarized at an angle of 0° and 90° to the VO_2 wire-gird direction. The normalized amplitude transmission of the 90° oriented wave (open triangles and squares) remains ~ 100% for both VO_2 wire-grid gratings when the temperature increases from 60 to 80 °C ($t_{90°/80°C}$). In contrast, the normalized amplitude transmission of the 0° oriented wave (solid triangles and squares) decreases from ~ 100% to ~ 74% and ~ 37% ($t_{0°/80°C}$) for the 10/1 μm and 10/2 μm wire-grid grating, respectively. This corresponds to the transition from the insulating VO_2 phase to the conducting VO_2 phase [5]. As we can see, the polarization modulation depth (MD_p) (Eq. 1)

$$MD_p = \frac{t_{90°/80°C} - t_{0°/80°C}}{t_{90°/80°C}} \quad (1)$$

of VO_2 wire-grid at 80 °C is improved from ~ 26% to ~ 63% when the filling factor is increased from 10% to 20% due to the stronger absorption of the THz waves by the wider VO_2 wires. However, there is still a higher transmission for THz waves oriented at an angle of 0° to the metallic VO_2 wire-gird direction than the metal wire-grid structures [6, 7]. The reason is that the conductivity of metallic VO_2 is much lower than that of metals [8], and the THz waves polarized parallel to the metallic VO_2 wires are not completely reflected or absorbed. Therefore, the performance of this type of THz wave polarization modulator can also be improved through increasing the conductivity of metallic VO_2 wires by optimizing the fabrication process.

III. CONCLUSIONS

These VO_2 wire-grids with micrometer scale period and width are to our knowledge the first broadband metamaterials developed using only VO_2 and have potential applications in active THz polarization modulators. By increasing the filling factor from 10% to 20%, the polarization modulation depth is improved from 26% to 63%. The performance can be further improved by optimizing the material quality and structural parameters.

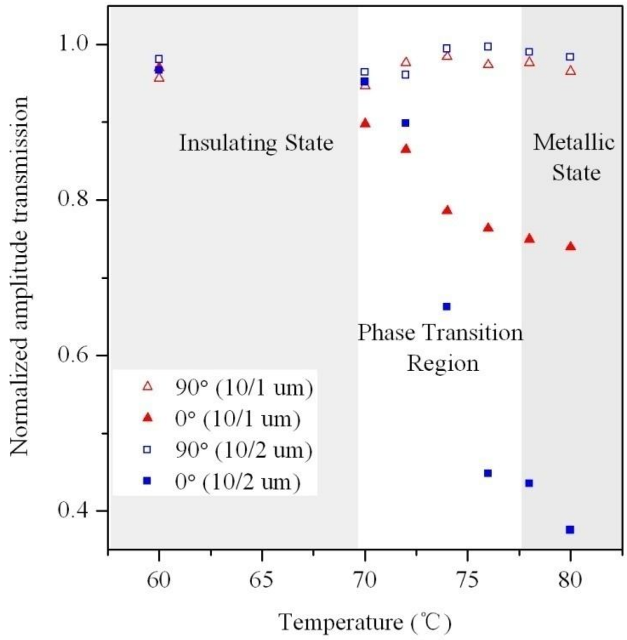

Fig. 3 Temperature dependent normalized amplitude transmission for 0.6 THz frequency waves oriented at an angle of 0° and 90° to the wire-grid direction for (a) 10/1 um, and (b) 10/2 um VO_2 wire-grid.

ACKNOWLEDGMENT

This work was partially supported by the Research Grants Council of Hong Kong (415313), the CUHK Direct Grant (4055001) and The Hong Kong Innovation and Technology Scheme (ITS/198/12).

REFERENCES

[1]. F. Yan, C. Yu, H. Park, E. P. J. Parrott and E. Pickwell-MacPherson, "Advances in polarizer technology for terahertz frequency applications," *Journal of Infrared, Millimeter, and Terahertz Waves*, vol. 34 (9), pp. 489-499, 2013.

[2]. H. T. Chen, W. J. Padilla, J. M. Zide, A. C. Gossard, A. J. Taylor and R. D. Averitt, "Active terahertz metamaterial devices," *Nature*, vol. 444 (7119), pp. 597-600, 2006.

[3]. Y. Zhu, S. Vegesna, Y. Zhao, V. Kuryatkov, M. Holtz, Z. Fan, M. Saed and A. A. Bernussi, "Tunable dual-band terahertz metamaterial bandpass filters," *Optics letters*, vol. 38 (14), pp. 2382-2384, 2013.

[4]. F. Dumas-Bouchiat, C. Champeaux, A. Catherinot, A. Crunteanu and P. Blondy, "rf-microwave switches based on reversible semiconductor-metal transition of VO_2 thin films synthesized by pulsed-laser deposition," *Applied Physics Letters*, vol. 91 (22), pp. 223505/1-3, 2007.

[5]. P. U. Jepsen, B. M. Fischer, A. Thoman, H. Helm, J. Suh, R. Lopez and R. Haglund Jr, "Metal-insulator phase transition in a VO_2 thin film observed with terahertz spectroscopy," *Physical Review B*, vol. 74 (20), pp. 205103/1-9, 2006.

[6]. Z. Huang, H. Park, E. P. J. Parrott, H. P. Chan and E. Pickwell-MacPherson, "Robust thin-film wire-grid THz polarizer fabricated via a low-cost approach," *IEEE Photonics Technology Letters*, vol. 25 (1), pp. 81-84, 2013.

[7]. Z. Huang, E. P. J. Parrott, H. Park, H. P. Chan and E. Pickwell-MacPherson, "High extinction ratio and low transmission loss thin-film terahertz polarizer with a tunable bilayer metal wire-grid structure," *Optics letters*, vol. 39 (4), pp. 793-796, 2014.

[8]. Y. Zhu, Y. Zhao, M. Holtz, Z. Fan and A. A. Bernussi, "Effect of substrate orientation on terahertz optical transmission through VO_2 thin films and application to functional antireflection coatings," *JOSA B*, vol. 29 (9), pp. 2373-2378, 2012.