Fully-Integrated and Electronically-Controlled Millimeter-Wave Phase Modulator

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***Abstract*—We present a fully-integrated and voltage-controlled millimeter-wave phase modulator based on vanadium dioxide (VO_2). It consists of a resonant reconfigurable meta-surface fabricated on a thin VO_2 film integrated with voltage-controlled heating electrodes. By varying the applied voltage to the heating electrodes, the dielectric properties of the VO_2 layer is controlled and the resonance frequency of the meta-surface is shifted accordingly, introducing a considerable phase shift. We experimentally demonstrate the highest reported phase shift of 60º at 85 GHz through a fully integrated, voltage-controlled device platform by varying the control voltage from 0 V to 14 V.**

I. INTRODUCTION

Rapid developments in terahertz/millimeter-wave radiation sources and detectors necessitate the need for high performance passive terahertz/millimeter-wave components to enable advanced imaging and sensing systems. Metamaterials and meta-surfaces have been very promising means for developing passive terahertz components since their specifications are not limited by properties of natural material and can be engineered according to the composition of their sub-wavelength building blocks [1-9].

One of the important passive components in terahertz and millimeter-wave regime is a phase-modulator which is essential for many applications such as beam-steering for imaging and sensing. Hence, we have developed a novel phase modulator based on vanadium dioxide (VO_2), which offers extreme tunability in dielectric properties in the millimeter-wave regime. VO_2 is a correlated electron material that behaves as a semiconductor at the room temperature but it goes under insulator-to-metal transition at temperatures near 68 ºC. It has been shown that the dielectric properties of VO_2 can be controlled via thermal, electrical, and optical stimuli with a reversible process that has a hysteresis associated with it [10-12]. Using this unique characteristic, we present a fully-integrated and voltage-controlled millimeter-wave phase modulator based on a reconfigurable resonant meta-surface with cross-shape unit-cells, fabricated on a thin VO_2 film, as shown in Fig. 1.

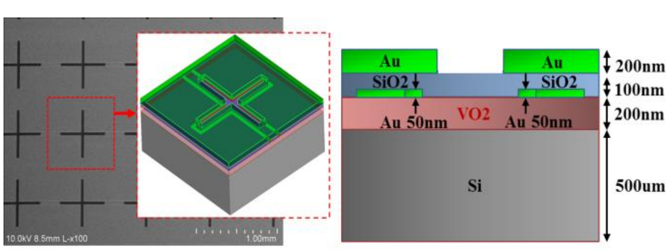

Fig. 1. Schematic diagram and microscope image of the presented phase modulator (left image) and its side view profile (right image).

Two voltage-controlled heating electrodes are incorporated in each meta-surface unit-cell buried under the cross-shape layer to control the temperature of the VO_2 layer. By varying the applied voltage to the heating electrodes, the dielectric properties of the VO_2 layer is controlled and the resonance frequency of the meta-surface is shifted, introducing a considerable phase shift near the resonance frequency.

II. RESULTS

A prototype of the presented phase modulator is fabricated and a frequency-domain interferometry setup [12] is used to extract the phase and amplitude response of the fabricated phase modulator in 75-110 GHz frequency range. Figure 2a shows the measured phase shift offered by the fabricated phase modulator as a function of frequency. It indicates phase variations of 60º-20º in the 75-110 GHz frequency range and by varying the control voltage from 0 V to 14 V. A record-high phase shift of 60º is achieved at 85 GHz by sweeping the control voltage from 0 V to 14 V, with less than 50% intensity modulation. By repeating the measurements in a reverse order (from 14 V to 0 V), a hysteresis in phase modulation is observed, which is associate with the hysteresis in VO_2 complex permittivity (Fig. 2b) [10-12].

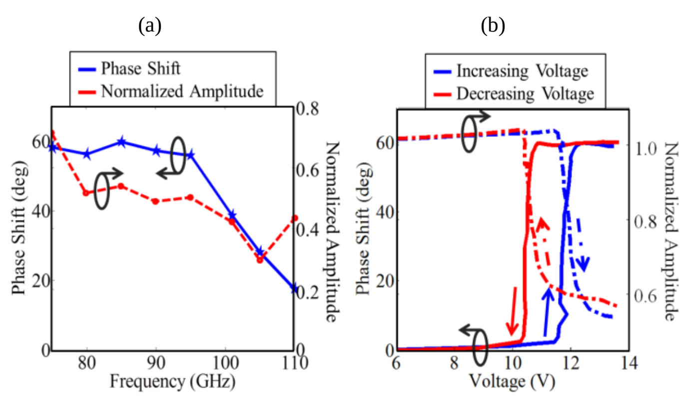

Fig. 2. (a) The measured phase modulation and intensity modulation offered by the fabricated phase modulator as a function of frequency, and (b) the observed hysteresis in the phase modulation performance at f = 85 GHz.

III. SUMMARY

In summary, we present a fully-integrated and voltage-controlled millimeter-wave phase modulator based on a VO_2 reconfigurable meta-surface. We demonstrate up to 60º of phase shift by tuning the control voltage of the modulator from 0 V to 14 V at 85 GHz. Furthermore, the tradeoff between the phase modulation and intensity modulation is analyzed and the hysteresis effect associated with the phase transition property of VO_2 is investigated.

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