Polarization Sensitive Terahertz Bolometer

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Abstract: We present a novel uncooled terahertz bolometric sensor based on plasmonic absorbers and phase-changing transducer beams. The device facilitates simultaneous sensing of incident radiation intensity and polarization by utilizing polarization-dependent plasmonic field enhancement. © 2022 The Author(s)

1. Introduction

The terahertz (THz) electromagnetic spectrum has spurred significant research interest in recent years. Development of simple, uncooled, highly sensitive, and fast THz sensors is crucial in advancing the overall scientific and technological growth in this regime. Due to the wide potential applications of THz, a lot of studies have been carried out in recent years focusing on modulators, generators, and reconfigurable surfaces. THz sensors at ultra-low temperature [1,2] can benefit from high sensitivity. On the other hand, uncooled THz bolometers [3] can enable simpler, more affordable and portable sensing, communication, and imaging. The plasmonic enhancement of absorption combined with sensors that utilizes phase changing materials, such as VO_2, biased at the transition temperature offer orders of magnitude enhancement in sensitivity at IR wavelengths [4,5], and has potential to improve sensitivity of THz bolometric sensors.

In this work, we report a polarization-sensitive THz bolometric detection device and technique. A promising bolometer design entails efficient absorber, high temperature-coefficient of resistance (TCR) material, and excellent thermal management to capture small variations in incident radiation. Here, we utilize metal-insulator-metal plasmonic absorber [4,5] in conjunction with a transducer micro/nano beam of high-TCR phase-changing material such as vanadium dioxide (VO_2) biased at transition temperature to efficiently convert THz electromagnetic radiation to electronic signals. In the presence of radiation incidence, readout signal across transducer beam changes due to thermally induced resistivity variation in proportion to the incident radiation intensity. The plasmonic absorber enables increased sensitivity, selectivity, scalability, and pixel-density by utilizing efficient sub-wavelength metallic patches. The integration of the patterned high-TCR micro/nano beams [4,5] in a quad unit cell absorber as depicted in Fig. 1(a) can lead to the efficient detection of THz radiation strength as well as its polarization by leveraging polarization-sensitive field enhancement. The use of micro/nano transducer beams enables higher readout resistance variation and sensitivity due to increased length to cross-sectional ratio [4,5]. Biasing the phase-changing beams near their transition temperature additionally ensures the device operation near highest-TCR. We show over 95% absorption at ~2 THz by the absorber with square gold patches of 40 µm. Polarization-dependent localized field enhancement and subsequent temperature rise is observed. Along with THz radiation detection, the knowledge of its polarization can often be essential for interpreting the results and measurements particularly in THz spectroscopy and imaging [6,7]. Our proposed device is thus designed to sense the THz radiation intensity as well as the polarization without any additional external components, birefringent system, or complicated setups.

2. Design

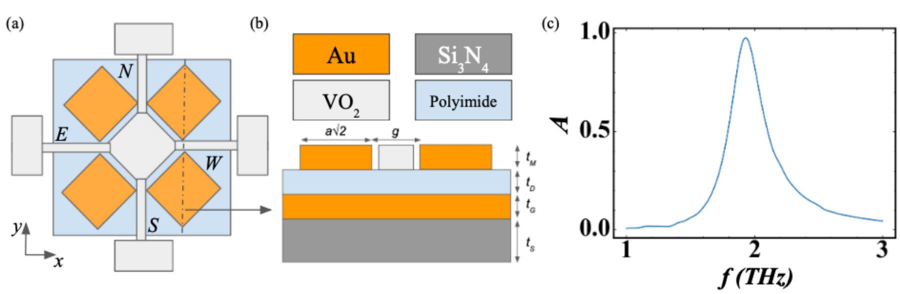

Fig. 1. (a) Schematic (not to scale) of proposed THz bolometric sensor. The four gold (Au) patches construct the MIM absorber. The transducer has four arms connecting one central pad or node to four terminal pads for individual detection. The four arms of transducers are named (N, W, S, and E) for future references, (b) cross-sectional view (not to scale) and material selection for the default design. In our default design, the film thicknesses are chosen as t_M = 0.5 µm, t_D = 4 µm, t_G = 1 µm, t_S = 0.3 µm, and the side of square patches, a = 40 µm, gap, g = 2 µm, (c) calculated absorptance profile showing resonant absorption at ~2 THz achieved by the default design of the absorber.

The proposed THz sensor consists of a metal-insulator-metal (MIM) absorber designed to selectively absorb narrow band radiation around 2 THz. One such bolometric pixel is shown in Fig. 1(a). The design can be modified to absorb radiation at other THz frequency ranges by choosing appropriate materials or by tuning the design parameters such as geometry and dimension (patch length, thickness, etc.). Broadband or multiband absorbers can also be implemented by engineering the patch absorber shapes. The cross-sectional characteristics, dimensions as well as material selections are shown in Fig. 1(b). The achieved absorption profile obtained by finite-element method calculation is shown in Fig. 1(c). Appropriate frequency-dependent material properties are used for gold [8], polyimide [9], and VO_2 [10]. A resonant absorption by the MIM absorber with over 95% efficiency is observed to take place at a frequency of ~2 THz. We design the bolometer pixel (for example, choice of materials and thickness in Fig. 1(b)) to achieve optimized thermal management and ensure maximum temperature build-up on radiation absorption as a key to high sensitivity.

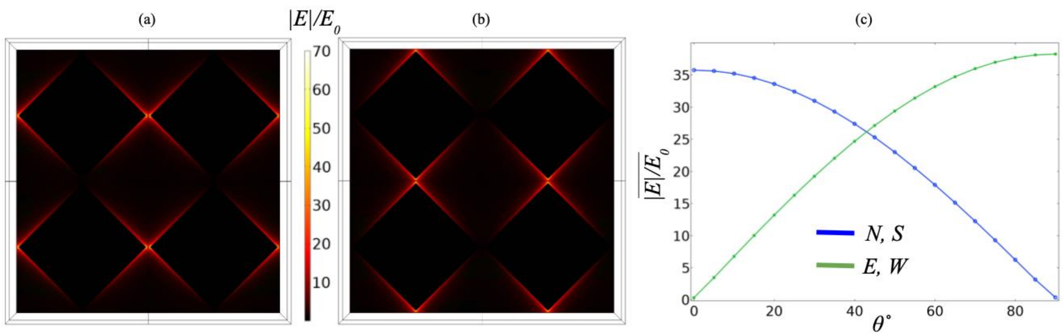

Fig. 2. (a) Field distribution for E_x (same axis as Fig. 1), showing field enhancement at horizontal tips of the square patches (b) field distribution for E_y showing field enhancement at the vertical tips (c) calculated average field enhancement along the gap between tips with respect to polarization angle (x-axis, θ=0° and y-axis, θ=90°) at the horizontal (blue - transducer beam arm location N and S as in Fig. 1(a)) and at the vertical (green - transducer beam arm location E and W as in Fig. 1(a)) tips of the top layer patches.

With the proposed implementation of plasmonic absorber cells and transducer beams, polarization of the incident radiation can be determined without additional components or complexity in the system. The transient heating due to incident radiation is localized at specific patch gaps based on polarization and can lead to different thermal energy development at different transducer arms. The field distributions for E_x and E_y polarizations are shown in Fig. 2(a) and (b). We acknowledge that, at steady state, the temperature rise due to radiation absorption and localized field will be distributed across the entire pixel. However, the transient localized field and temperature rise will contribute to specific arms readout signals. Hence, a transient probe can enable the polarization detection of the incident radiation. As observed from Fig. 2(a), E_x polarization causes transient local heating near arms N and S. Arms E and W do not experience the local heat buildup. Only when the temperature gets distributed across the entire pixel by means of conduction, arm E and W will reflect the temperature induced resistivity change. This transient duration depends on the thermal time constant of the pixel which in turn depends on material properties like heat capacity and thermal conductivity. For such bolometric designs, thermal time constants reported are usually in the order of a few μs [4].

In summary, we present a novel bolometric sensor and technique to detect radiation along with its polarization at ~2 THz frequency by incorporating polarization-sensitive plasmonic absorber and integration of transducer beams. Further detailed thermal and thermo-optical details of the proposed device will also be presented.

3. References

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