A UNCOOLED MULTI-BAND METAMATERIAL DETECTOR FOCAL PLANE ARRAY FOR REAL-TIME MULTI-SPECTRAL TERAHERTZ WAVE SENSING AND IMAGING

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ABSTRACT

We have designed, fabricated, and characterized an uncooled, multi-band sub-wavelength metamaterial detector focal plane array (FPA) for real-time multi-spectral terahertz (THz) wave sensing and imaging. A rise in temperature due to the resonant absorption by split ring resonators (SRRs) leads to an increase in the interconnected SRR array's resistance, which can be readily read out electrically. Based on a triple band metamaterial SRR design, using MEMS processing technology, we report a THz metamaterial detector FPA working at 2.5 THz, 3.4 THz, 4.3 THz, respectively. The experiment results show that our device has good sensitivities with acceptable spatial resolution and response time at all three frequency bands.

INTRODUCTION

THz imaging remains as a promising candidate for a variety of applications ranging from medical imaging, parcel inspection, safety scanning and drug detection [1], due to the fact that THz radiation is non-ionizing, non-hazardous to human tissues and can pass through many optically opaque materials such as clothing, cardboard, and ceramics [2]. Many progresses have been made using a variety of technologies, such as THz time domain spectroscopy (THz-TDS) imaging, quantum well-based THz imaging, Golay Cell-based THz imaging, to name a few. Each of them has relative merits and also limitations: slow read out speed, the necessity for cryogenic cooling, bulky and expensive equipment, or the challenge of scaling to large array formats. Recently, metamaterials consisting of artificially constructed electromagnetic (EM) materials with exotic EM properties have attracted considerable interest [3, 4]. An uncooled metamaterial-based FPA for single band terahertz imaging has been previously reported with an optical readout [5]. In this work, we report a multi-spectral THz metamaterial detector FPA based on multi-band sub-wavelength metamaterial resonators.

DESIGN

The multi-band sub-wavelength metamaterial-based THz imager is essentially a thermal detector which employs the thermal resistance effect of platinum due to selective THz absorption. The resistance change of interconnected SRR array is measured to detect the incident THz waves. A single pixel is composed of an array of electrically interconnected multi-band split ring resonators (10×10) located on four suspending silicon nitride cantilevers that provide good thermal isolation. On resonance, the incident THz radiation drives a current in the platinum SRR resulting in ohmic heating, which leaded to an increasement of platinum resistance. The silicon nitride cantilevers were designed to be as narrow as possible to reduce the conductive heat loss via cantilever legs and therefore improve the sensitivity, without compromising the required mechanical strength for structural integrity.

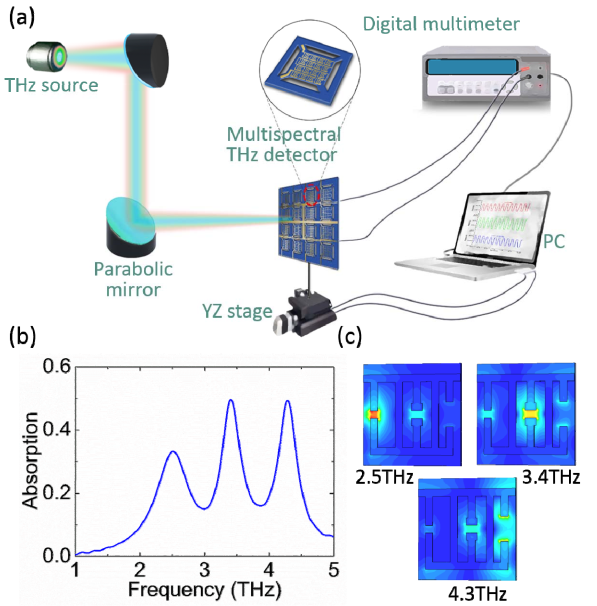

Fig 1. (a) Schematic of multi-spectral THz wave sensing using a multi-band metamaterial detector FPA. (b) Numerical simulation of the absorption of the device. (c) Simulated normal component of the electric field on resonance.

Figure 1a shows the schematic of multi-spectral THz wave sensing using a multi-band metamaterial detector FPA. The FPA has been designed to operate at the frequencies of 2.5 THz, 3.4 THz and 4.3 THz, which was determined by available THz sources and can be further tuned by simply scaling and optimizing the SRR geometries. Numerical simulations were performed using a commercial finite-difference time domain solver CST Microwave Studio ™ 2013. The simulation result of the absorption of the triple-band metamaterial was shown in Figure 1b. Three distinct absorption peaks were found at 2.5 THz, 3.4 THz and 4.3THz, respectively. Figure 1c showed the normal component of the electric field for the three absorptivity peaks on resonance. Note that as-reported triple band metamaterial detector FPA employ a hybrid SRR structure consisting of three single band SRRs. All three resonances originate from circulating currents and can be tuned independently in individual single-band resonators. For example, the 2.5 THz response is determined mainly by the left SRR, the 3.4 THz response is determined mainly by the middle electric-field-coupled (ELC) resonator and the 4.3 THz response is contributed mainly by the right SRR.

FABRICATION

The multi-spectral terahertz detector array was fabricated using a standard micromachining technology, as shown in Figure 2a. First, a low stress silicon nitride thin film with a thickness of 800 nm was deposited on a (100) silicon substrate. The Cr/Pt layer (10 nm/100 nm) defining the SRR array was then fabricated using a standard UV lithography followed by an ion beam etching process. Next, 30 nm/ 300 nm Cr/Au defining the wire was performed using a standard liftoff process. Subsequently, the silicon nitride layer was patterned using the lithography and plasma etching processes to define the SRR array supporting membrane. Finally, the structures were released through TMAH wet etching of the silicon underneath the SRR array from the front side. Figure 2b shows the SEM images of a 4×4 array for triple band THz metamaterial detector FPA which was fabricated in this manner. Each array/pixel consists of 10×10 metamaterial resonators. The geometry and dimensions of each single multi-band terahertz metamaterial resonator are shown in Fig 2c.

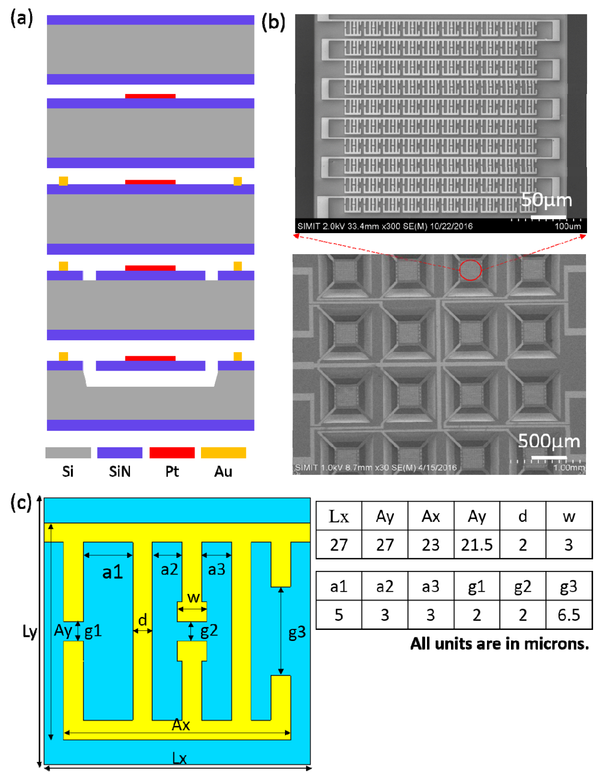

Fig2. (a) Fabrication process flow of a multi-band sub-wavelength metamaterial-based THz detector FPA. (b) SEM images of the multi-band terahertz metamaterial detector FPA. (c) Dimensions of the triple band THz metamaterial SRR resonating at 2.5 THz, 3.4 THz, and 4.3 THz.

CHARACTERICATION

Three THz quantum cascade lasers (QCLs) were used as the THz sources and the responses of the as-fabricated THz metamaterial detector FPA were characterized by measuring the resistance change of electrically interconnected split ring resonator array upon THz illumination using a digital multimeter (DMM). The detector FPA was mounted at normal incidence with the electric field perpendicular to the gap of metamaterial.

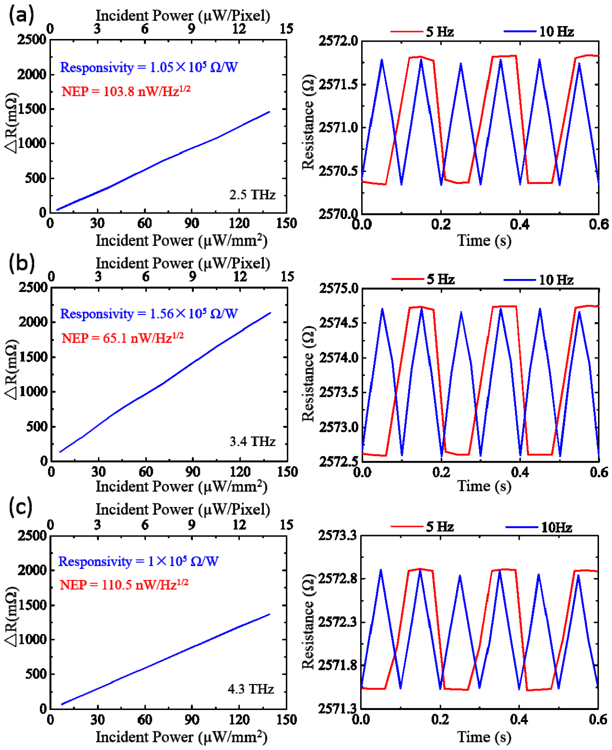

Fig3. (a)-(c) Performance characterization of an individual pixel of the THz metamaterial detector FPA as a function of the incident power of three THz QCL sources at 2.5 THz, 3.4 THz and 4.3 THz, respectively. Temporal responses were characterized at 5 Hz (red) and 10 Hz (blue), respectively.

Figure 3 shows the characterized responses of an individual pixel as a function of the incident power irradiated by THz QCL sources at 2.5 THz, 3.4 THz and 4.3 THz, respectively. The left panels showed excellent linearity of the THz detector in terms of the photo-response, thanks to the high linearity of the temperature coefficient of resistance of platinum. The responsivities for the device were measured to be 1.05×10^5 Ω/W, 1.56×10^5 Ω/W, and 1×10^5 Ω/W at 2.5 THz, 3.4 THz and 4.3 THz, respectively. The corresponding minimum noise equivalent power (NEP) were 103.8 nW/Hz$^{1/2}$, 65.1 nW/Hz$^{1/2}$ and 110.5 nW/Hz$^{1/2}$, respectively. The right panels show temporal responses of the detector FPA. The maximum operation frequency of the detector before the signal roll-off was 10 Hz with the current device. Trade-offs can be made to improve the time response (i.e., the frame rate) at the cost of sensitivities. All measurements were conducted at ambient conditions. Note that liquid helium refrigeration was needed for QCL sources but not the THz metamaterial detector FPA.

The multi-band THz detector FPA can be readily used for real-time multi-spectral THz imaging. Figure 4 shows the incident THz beam profiles of three THz QCL sources used in this work that were captured by the multi-spectral THz metamaterial detector FPA.

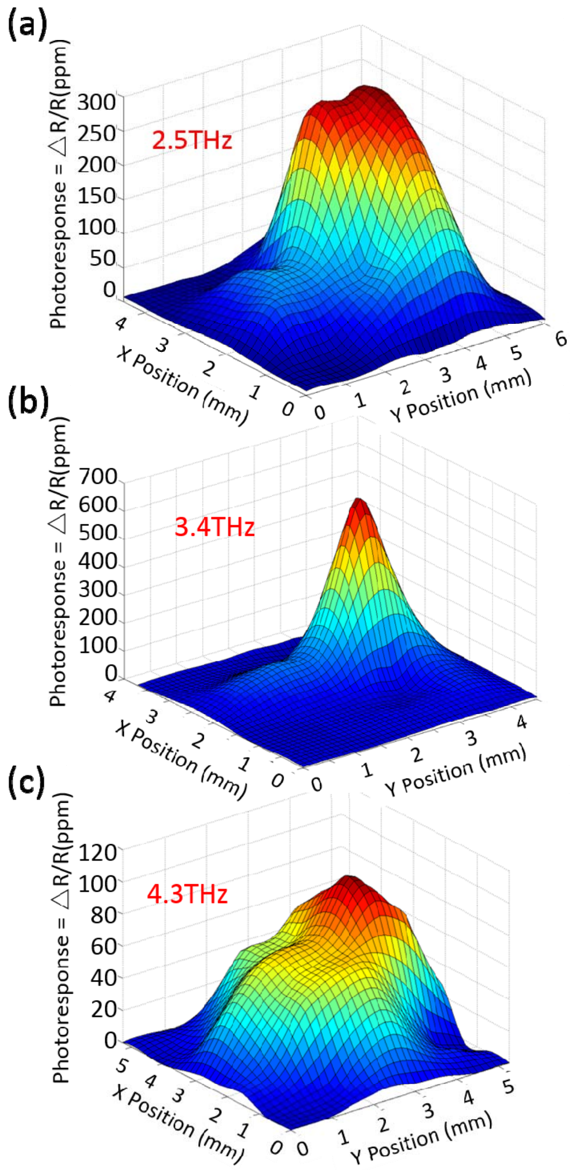

Fig4. Images of the incident THz beam profiles at 2.5 THz, 3.4 THz and 4.3 THz using a multi-band terahertz metamaterial detector FPA.

CONCLUSION

In summary, we report an uncooled, multi-band sub-wavelength metamaterial detector FPA with a simple fabrication process for multi-spectral THz imaging. The narrowband responsivity of metamaterial FPAs promises spectrally selective detection. Furthermore, metamaterials are geometrically scalable and have been demonstrated over many decades of frequency. Thus, our approach is not limited to THz frequencies and can be used over a broad electromagnetic spectrum range. The successful demonstration of this prototype holds great promise for future application, such as nondestructive testing and noninvasive medical imaging.

ACKNOWLEDGEMENTS

This work was partly supported by the National Natural Science Foundation of China (Grant No. 61574156, No. 61527818), MOST of China (Grant No.2016YFA0200800), the National Basic Research Program of China (973 Program, 2015CB755500), the International Science & Technology Cooperation Program of China (2014DFA31470).

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