MEMS AND METAMATERIAL-BASED TERAHERTZ DETECTOR

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ABSTRACT

We have designed, fabricated and characterized metamaterials-based far-infrared detector. The detector design, which combines metamaterials (MMs) and MEMS, is frequency selective. The enhanced absorption on the cantilever pixels from split-ring resonators (SRRs) leads to a mechanical deflection which is directly detected with a He-Ne beam. As a demonstration of our first-generation devices, we have fabricated and tested detectors at 95 GHz and 693 GHz with noise equivalent powers (NEP) of 10^{-8} W/Hz^{1/2} and single-pixel responsivity as high as 16,500 V/W in a room-temperature and pressure environment.

INTRODUCTION

In the past decades, artificial materials consisting of arrayed subwavelength metallic inclusions have been drawn much attention since their exotic electromagnetic (EM) properties not readily occurring in nature, such as negative index [1-2] and invisible cloaking [3-5]. The scale invariant nature of Maxwell's equations allows tailoring metamaterial elements for a specific EM response at virtually any desired frequency. This is particularly an advantage in the terahertz (THz) spectrum where novel optical devices can impact applications such as chemical sensing and noninvasive real-time imaging [6].

Though progress in THz detector sensitivity over the past quarter century has been impressive, it is mostly accredited to improvements in thermometer sensitivity. Inefficient absorption of THz radiation – which yields a low heat-induced temperature variation – remains the performance bottleneck. Furthermore, most THz microbolometers show broadband response, which can be undesirable for applications such as spectroscopic detection of materials with unique THz responses [7, 8]. Here we present a THz detector based on metamaterial resonators. These metamaterials show high absorption, and their sub wavelength nature enables their use as a focal plane array (FPA) to image near the diffraction limit. Furthermore, their narrow band resonance is a salient feature for spectrally selective detection applications. Consequently, metamaterials hold great promise for facilitating the development of a "versatile" THz detector which can a) strongly absorb THz radiation; b) operate at room temperature with decent responsivity and sensitivity; c) be scaled up to function as a multi-pixel array for imaging applications; d) operate selectively at any frequency in the THz regime; and e) be lightweight and low cost.

Here we report on the development of an uncooled metamaterials enhanced THz radiation detector with optical read-out. Through the incorporation of SRRs, a strong resonant response is obtained that can be optimized for specific design frequencies.

DESIGN

The cantilever-based THz detector employs thermally sensitive bimaterial elements as shown in Figure 1a. The detector pixels are comprised of three basic components: 1) a THz wave absorber consisting of a single gold (Au) SRR patterned on a silicon nitride (SiN_x) thin film serving as the supporting pad; 2) bimaterial cantilever actuation legs composed of layers of SiN_x and Au which

have a large coefficient of thermal expansion (CTE) mismatch; 3) an optically reflective surface for visible light readout of the thermal deflection of the cantilevers due to the absorption of THz radiation. On resonance, the incident THz radiation drives a current in the metallic SRR resulting in ohmic heating. The primary heat flow path is through the supporting bimaterial actuation legs. Due to the CTE mismatch between Au and SiN_x, the temperature change of the legs results in mechanical deflection of the cantilever which is sensed by optical interrogation of the reflector pad. Figure 1b shows the simulation result of the absorption is over 40% on resonance (639 GHz), as opposed to nearly nothing with the bare SiN_x pad.

Figure 1: Metamaterial enhanced terahertz detector using optical readout. (a) Schematic of the device showing the metamaterial cantilever array, an individual pixel, and reflective optical read-out. (b) Simulated absorption of the device with (black line) and without (red line) SRR. (Inset) Simulated temperature profile due to the enhanced absorption.

FABRICATION

Two detectors have been designed with operating frequency at 95 GHz and 693 GHz. The dimensions of these two detectors are listed in Figure 2a. Both detectors are fabrication using MEMS technology in a four-step process (Figure 2b). First, a SiN_x layer

(500 nm) is deposited on a silicon substrate. The Cr/Au layer (10nm/200 nm) defining the SRR absorbers, readout reflector, and cantilever legs is then fabricated using standard lithography and liftoff processes. Next, the SiN_x layer is patterned using lithography and RIE etching to define the MM supporting membrane as well as the cantilever legs. Finally, the structures are released through backside KOH etching of the underlying silicon substrate. Figure 2c and 2d show the fabricated and released single pixel of detectors operating at 95 GHz and 693 GHz respectively.

Figure 2: (a) Dimensions of the metamaterial enhanced detectors resonant at 95 GHz and 693 GHz, respectively. (b) Fabrication process. (b)&(c) SEM images of released unit cell of 95-GHz and 693-GHz devices.

CHARACTERIZATION

Figure 3 shows the schematic of experiment setup for device characterization. The THz photoresponse is detected by using a position sensitive photodetector (PSD) to measure the change in location of a reflected beam off of the optical pad of a pixel caused by the deflection of the cantilever. An electronically modulated frequency tripled YIG oscillator was used as the microwave source for the 95 GHz detector experiments. The THz source used for the 693 GHz measurements was an optically chopped CO₂ pumped far-infrared laser operating on a formic acid line. A 780 nm laser diode was focused onto the reflecting pad of the cantilever through a focusing objective and the back reflection was aligned to the PSD. The photoresponse was measured using a lock-in amplifier monitoring the output voltage of the PSD. For time-response measurements the signal was captured on an oscilloscope in place of

Figure 3: Schematic of the device showing the metamaterial cantilever array, an individual pixel, and reflective optical read-out.

the lock-in. While our fabrication naturally produces an array of cantilever pixels, in our experiment we only characterized the response of single pixels.

All measurements reported in this work were taken at room temperature and pressure. First, we consider the response of the 95 GHz detector. The spectral characteristics of the array were first verified using THz-TDS, as shown in Figure 4 (left top of inset). The dip in the transmission is associated with absorption (and reflection) of the SRRs. The resonance is centered at 95 GHz with a full-width at half max of 20 GHz. The photoresponse of the detector was characterized for both polarizations of the incident microwave radiation by stepping the operating frequency of the source over its full range from 60 GHz to 120 GHz. As shown in Figure 4, a strong resonant peak was observed at 95 GHz for the polarization having the electric field perpendicular to the SRR gap which drives the LC resonance. The photoresponse was significantly weaker for the orthogonal polarization with the electric field parallel to the gap. In

Figure 4: Response of the 95 GHz detector as a function of frequency of the incident radiation at two polarizations. (Inset, left top) Transmission spectra of the detector characterized using THz-TDS with polarization of the electric field normal to the gap ($E_{\perp}$). (Inset, left bottom) Zoom-in view of the detector response with the polarization of the THz electric field parallel to the SRR gap ($E_{\parallel}$). The response is two orders of magnitude smaller than the response with the polarization of the THz electric field perpendicular to the SRR gap ($E_{\perp}$).

this case, the incident radiation does not couple to the resonance, which is the expected response for this particular SRR design. After verifying the resonant response of the detector, the source was set to 95 GHz and the response of individual pixels were characterized as a function of incident power by attenuating the source with a voltage controlled attenuator. As shown in Figure 5, a nearly linear response of the detector was observed and follows the incident power reasonably well. A signal-to-noise ratio (SNR) of $\sim 1,200$ was obtained by measuring the peak signal (~ 380 mV) of the detector at the full incident power of 10 mW with a spot size of 1 cm in diameter and noise floor of ~ 0.3 mV with no incident radiation. A responsivity of $16,500$ V/W with a minimum NEP of 1×10^{-8} W/ $\sqrt{\text{Hz}}$ was obtained when considering the measurement bandwidth of the lock-in amplifier and the detector area. The temporal response of the detector, which is important for real-time imaging applications, was determined by monitoring the output signal of the PSD on an oscilloscope. The inset to Figure 5 shows the response at 5 Hz and 25 Hz showing that the response at 25 Hz is still about 70% of the 5 Hz response. The sweep of modulation frequency in Figure 6 shows that the maximum operation frequency of the detector before signal roll off began was 15 Hz indicating a time constant of ~ 10 ms. As shown in Figure 6, the output of photoresponse at 50 Hz is about half of that at 5 Hz.

Figure 5: Photoresponse of the 95 GHz device as a function of incident power. (Inset) Oscilloscope observed temporal response of the 95 GHz at 5 Hz (blue) and 25 Hz (red), respectively.

The 693 GHz detector pixels were characterized with a similar setup using a far-infrared laser (FIRL) in place of the multiplier source. The resonant response of the 693 GHz detector was again pre-determined using THz-TDS as shown in the inset to Figure 7a. Both the polarization and the power of the FIRL source were controlled using a wire-grid polarizer pair. The FIRL beam was then focused using an off-axis parabolic mirror. The focused beam spot was measured using a pyrocam III beam imager in order to determine the peak intensity of the focused light as well as the beam diameter. A responsivity of $6,800$ V/W with a minimum NEP of 2.96×10^{-8} W/ $\sqrt{\text{Hz}}$ was experimentally obtained when considering the power incident on the single pixel. The temporal response (inset Figure 7a showing data at 8 Hz and 15 Hz) of the 693 GHz detector shows a somewhat faster roll-off response in comparison to the 95 GHz pixel. While the readout approach utilized could be significantly improved, we performed beam profiling measurements with the 693 GHz pixels in order to demonstrate the

utility of our detectors, even at this stage, for THz beam diagnostics. In Figure 7b, we show beam measurements taken using a single pixel while the beam was steered along both axes. To capture the beam along the y-axis, the focusing paraboloid was simply translated. In a similar way, the x-axis data was captured by rotating the focusing optic. The result was a Gaussian profile similar to that measured with the commercial beam imager. While this is by no means an ideal technique for characterizing the beam, it demonstrates that these relatively simple detector elements can immediately find lab applications should an appropriate multi-pixel readout scheme be implemented.

Figure 6: Modulation frequency dependent of photoresponse for detector of 95 GHz.

DISCUSSION AND CONCLUSIONS

It is worth mentioning that the performance of the metamaterial resonant detectors could be significantly improved based on the fact that our characterization was conducted at room temperature and pressure. The 95 GHz and 693 GHz pixels have similar noise which mainly comes from the optical readout system. The noise could be further reduced by using a more stable read-out laser, a higher sensitivity PSD, and further reducing the environmental vibration. Alternative signal addressing methods such as capacitive or resistive readouts could also be implemented. Significant improvements in the thermal engineering should also improve the NEP. Preliminary estimates suggest a reduction of the NEP to 10^{-10} W/ $\sqrt{\text{Hz}}$ (and perhaps lower) is possible with additional engineering effort. In its present form using the experimental setup described in this paper and sub-wavelength pixels, the minimum power detectable in a diffraction limited spot is approximately $1 \mu\text{W}$. Our metamaterial cantilever detectors are naturally fabricated in array form and are therefore suitable for real-time 2D imaging by simultaneously measuring the deflection of all of the pixels using, for example, a visible CCD/CMOS camera to obtain an intensity map for parallel pixel readout [9, 10]. Furthermore, it is possible to combine multiple SRRs with different resonant frequencies into a super pixel, thus enabling frequency-sensitive THz imaging /spectroscopy with a “multicolor” THz illumination source. The optimal design of THz focal plane imaging detector will also need to consider pixel size for particular imaging needs such as speed and sensitivity. For example, the MM unit cells are typically $\lambda/5 \sim \lambda/10$ in size. One may desire to have multiple MM SRRs constructed on a sensing pixel element that is matched to the optics of the overall system for optimum response [11].

Figure 7: Photoresponse of the 693 GHz pixel. (a) Response of the detector as a function of incident power. (Inset, left) Oscilloscope observed temporal responses of the 95 GHz at 8 Hz (blue) and 10 Hz (red), respectively. (Inset, right) THz-TDS characterized transmission spectrum of the detector showing a resonance at ~693 GHz. (b) Image of the incident THz beam profile using the metamaterial enhanced THz detector.

In summary, we have developed metamaterial enhanced resonant detectors with a simple fabrication process for active THz sensing and detection applications. While we demonstrated detection at 95 GHz and 693 GHz, in principle this approach can be applied to other unconventional wavelengths where nature does not provide us with appropriate material resonances amenable to integration with thermal detection platforms. The implementation of low cost thin film THz absorbers could enable rapid progress in extending the many benefits of uncooled thermal imaging devices to the THz portion of the spectrum.

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