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Metasurface-enabled Pyroelectric Detection of 140 GHz Radiation with Strong Polarization Discrimination

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***Abstract* – Despite the potential of the millimeter- and submillimeter-wave region for fundamental science and industrial applications, its technology is well behind microwaves and optics in terms of performance and cost. We propose to improve a millimeter-wave technology by engineering cost effective solutions from neighboring spectral regions. Specifically, a pyroelectric infrared sensor is transformed into a polarization-selective millimeter-wave detector of 140 GHz radiation by integrating to it a metasurface absorber, which is 136 times as thin as the operating wavelength λ and has the overall dimensions near λ. It is demonstrated that, due to the small thickness and hence the thermal capacity of the absorber, the novel detector keeps high values of the response speed and sensitivity to polarized mm-wave radiation changed insignificantly against the regime of IR detection.**

I. INTRODUCTION

Engineering the microscopic structure of artificial materials and surfaces to manipulate macroscopically electromagnetic waves is a powerful idea championed by the metamaterial community [1], [2]. After great deal of effort on its fundamentals, this philosophy has triggered the interest to develop technology, especially at radiofrequency and microwaves where fabrication is less stringent than at higher frequencies. In addition, the focus has been reoriented toward metasurfaces, the two-dimensional equivalent of metamaterials, given their easier manufacture and integration [3].

At the top end of microwaves, the so-called millimeter-wave regime, low-cost devices are hardly found commercially [4] given the difficulty to find suitable inexpensive materials and to fabricate with micrometer precision centimeter size samples. A possible solution that we propose to overcome this problem is to extend the range of infrared devices with the help of metasurfaces.

To illustrate our approach, an off-the-shelf pyroelectric infrared detector insensitive to millimeter-wave radiation is converted into a highly selective 140 GHz (millimeter-wave) polarization dependent detector by simply covering the top electrode with an ultrathin metasurface-based absorber [5]. A remarkable finding from the tested prototypes is that the detector keeps its high performance at millimeter waves despite the fact the absorbing area is restricted to the original package size having $\lambda \times \lambda$ dimensions. We conclude that this is a consequence of the strong metasurface-ground plane capacitive coupling inherent for the deep-subwavelength-thinness regime.

II. ABSORBER: DESIGN CRITERIA AND RESULTS

In pyroelectric sensors, a temporary voltage signal is generated by a pyroelectric film as a result of a its temperature change due to radiation absorption. To maximize the absorption of millimeter waves, we designed an ultrathin three-layer absorber composed of a metasurface on top of a grounded dielectric slab. Several types of metasurfaces are considered, but our analysis distinguished a simple array of rectangular patches to attain the required performance and polarization discrimination. In particular, the advantage of the "patch array" absorber

is found in a large fractional amount of the incoming mm-wave energy absorbed in the ground plane (up to 50%) that is favorable for the pyroelectric detection as it allows the heat to be transferred more rapidly to the pyroelectric film when the absorber is attached to it through the ground plane. In addition, our analytical and numerical studies show that high metal conductivity and low dielectric loss are crucial to minimize the thickness of the absorber and its operational bandwidth that is important for implementing highly sensitive spectrally-selective thermal sensors. Bearing in mind the material properties needed, the low-absorbing polypropylene polymer is chosen for the dielectric spacer [6], whose metallization is done via sputtering of aluminum.

Following the initial study, a 15 μm thick polypropylene-based metasurface absorber operating at 140 GHz is fabricated via photolithography. The optimal in-plane *x*- and *y*-lattice constants for the array of rectangular patches are found to be 384 and 822 μm, respectively, whereas the size of the patches is 281 μm × 690 μm. The 50 mm (~23λ) diameter sample is measured using a continuous wave quasi-optical backward wave oscillator spectrometer in a Michelson configuration for both *x*- and *y*-polarizations. The results are shown in Fig. 1(a). The absorptivity peak is evaluated to be over 96% for *y*-polarization at the fractional absorption bandwidth of ~5%, while the mean absorptivity for *x*-polarization is only 0.8%. This represents a polarization discrimination of 21 dB.

III. Pyroelectric Millimeter-Wave Detector

Next, the developed metasurface-based absorber is integrated with a commercial pyroelectric sensor MG33 [7]. Due to the package limitations, the metasurface absorber final dimensions are restricted to λ × λ approximately. The spectral response of the integrated detector agrees well with the isolated absorber. A polarization discrimination over 18 dB is achieved at the design frequency of 140 GHz, see Fig. 1(b).

The voltage responsivity of the detector measured at 23 Hz modulation frequency is evaluated as 56 kV/W, while the noise equivalent power is estimated to be 2.0×10^{-9} W/Hz$^{1/2}$. These values are very similar to those of the infrared detector thereby demonstrating the good performance of the proposed pyroelectric millimeter-wave detector.

The time response of the detector is also analyzed. The response time is estimated as 2.3 ms. This is almost half the response time of the original infrared MG33 detector. We conclude that the integration of the metasurface absorber increases the thermal conductance between the detector and its surroundings that inevitably decreases the time response according to the inverse proportionality law: $\tau \sim 1/G$ [8]. Our thermophysical modelling shows that such an increase is attributed mainly to the heat transfer along the ground plane layer of the metasurface absorber.

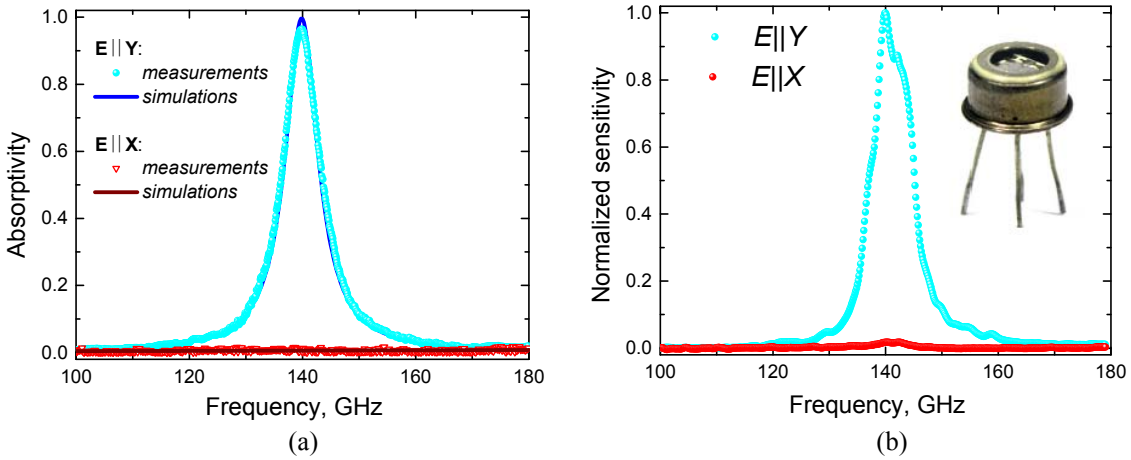


Fig. 1. (a) Simulated and experimentally measured spectral performance of the Ø50 mm metasurface absorber made of a rectangular patch array and a 15-μm-thick grounded polypropylene slab (normal illumination). (b) Normalized spectral sensitivity of the pyroelectric detector MG33 integrated with the metasurface absorber .

IV. Conclusion

In this work, we experimentally demonstrated a possibility of transforming a conventional pyroelectric infrared detector to a highly frequency- and polarization-selective millimeter-wave detector by simply attaching a metasurface absorber (with wavelength-to-thickness ratio of 136.4) to the top electrode of the original sensor. The detector operates at 140 GHz over a fractional bandwidth of ~5% and has a polarization discrimination of 18 dB. The proposed approach holds promise for creating low-cost pyro-detectors applicable to spectro-polarimetric measurements across the millimeter- and submillimeter-wave spectrum.

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References

[1] R. Marqués, F. Martín, and M. Sorolla, *Metamaterials With Negative Parameters: Theory, Design, Microwave Applications*. Hoboken, NJ: Wiley, 2008.
[2] L. Solymar and E. Shamonina, Waves in Metamaterials. New York: Oxford Univ. Press, 2009.
[3] S.A. Kuznetsov, M.A. Astafev, M. Beruete, and M. Navarro-Cía, "Planar Holographic Metasurfaces for Terahertz Focusing," *Sci. Rep.*, vol. 5, no. 7738, pp. 1-8, 2015.
[4] G. Carpintero, E. Garcia-Munoz, H. Hartnagel, S. Preu, and A. Raisanen, *Semiconductor TeraHertz Technology: Devices and Systems at Room Temperature Operation*, Chichester, West Sussex: Wiley-IEEE Press, 2015.
[5] S. A. Kuznetsov, A. G. Paulish, M. Navarro-Cía, and A. V. Arzhannikov, "Selective pyroelectric detection of millimetre waves using ultra-thin metasurface absorbers," *Sci. Rep.*, vol. 6, no. 21079, pp. 1-11, 2016.
[6] M. Navarro-Cía *et al.*, "A Route for Bulk Millimeter Wave and Terahertz Metamaterial Design," *IEEE J. Quant. Electr.*, vol. 47, pp. 375–385, 2011.
[7] "Vostok" Discrete pyroelectric sensor MG33, Available: http://www.vostok.nsk.su/files/pdf/MG33.pdf
[8] A. Rogalski, *Infrared Detectors*, 2nd ed., Boca Raton, FL: CRC Press, 2010.