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Cyprien Brulon, Baptiste Fix, Patrick Bouchon. Inkjet printed ultra-thin metasurfaces for terahertz multi-spectral imaging by thermal conversion. OPTRO 2022 : 10th International Symposium on OPTRONICS IN DEFENCE AND SECURITY., Jun 2022, Versailles, France. <hal-03838252>

HAL Id: hal-03838252

<https://hal.science/hal-03838252v1>

Submitted on 3 Nov 2022

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Inkjet printed ultra-thin metasurfaces for terahertz multi-spectral imaging by thermal conversion.

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Abstract

In this work, we discuss the fabrication of ultra-thin sub-terahertz metasurfaces consisting of split-ring resonator arrays sized for the 70 GHz range by an inkjet printing method. These metasurfaces are then coupled to an infrared camera allowing a new terahertz imaging configuration by thermal conversion. This detection technique, briefly applied to the detection of hidden objects, appears as a promising low-cost alternative for multispectral terahertz imaging.

1. Introduction

Terahertz (THz) imaging is an active field of research and find applications in many fields such as non-destructive industrial testing, security, chemical identification, medical imaging, and telecommunications [1, 2]. Most of the technological efforts have been made on bolometric or CMOS based cameras, however, their high cost and their low spectral selectivity constitute a serious obstacle for a wide range of applications. In that perspective, terahertz imaging by thermal conversion (cf Fig.1) promise to be a low-cost alternative technique to conventional terahertz detectors but still suffers from low sensitivity [3, 4]. In this work, we investigate the use of thin printed metasurfaces as a way to improve the THz to IR conversion efficiency and spectral selectivity.

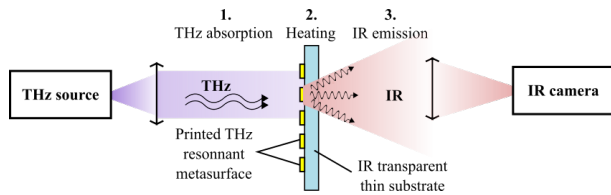


Figure 1: Schematic of the thermo-conversion terahertz imaging principle. The absorption of THz radiation by the membrane leads to a heating that can be detected with a standard infrared (IR) camera. The use of plasmonic resonators integrated into the membrane allows this heating to be located and concentrated while making the detection sensitive to wavelength and/or polarisation. It also becomes possible to significantly reduce the thickness of the converter to improve both its sensitivity and response time (typically 100 ms).

2. Printing of sub-terahertz metasurfaces

The metasurfaces of interest are periodic arrays of metallic split ring resonators (SRR) printed on a 3 μ m thick membrane of polyethylene terephthalate (PET - cf Fig. 2a).

2.1. Method of fabrication

An ultrasonically excited inkjet printing method (Microplotter II) is used to produce these metallic metasurfaces (cf Fig. 2b). This particular printing method is carried out in contact with the surface in a pencil like fashion contrary to the usual inkjet printing methods [5, 6, 7, 8]. This technique makes it possible to achieve printing resolutions of up to ten micrometres with relatively viscous inks [9]. First, a borosilicate glass capillary (GBF100-50-10, World Precision Instrument) is drawn to a tip (P-1000, Sutter Instrument). The tip is then charged with metallic ink (silver nanoparticle in solution - JS-A291 Metalon) by capillary action before being bonded with cyanoacrylate glue on a piezoelectric element. Finally, the tip is brought close to the surface until contact is made by measuring a change in the capillary resonance frequency. A mechanical arm then draws the pattern while the piezoelectric element imposes ultrasonic excitation that enables the ejection of the ink from the tip. The ink is then heated by conduction to 220° C for 30 minutes to allow the solvent to evaporate and the metallization of the silver nanoparticles.

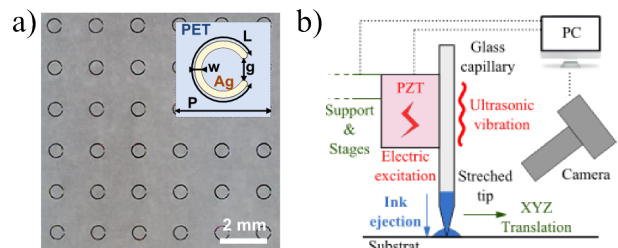


Figure 2: a) SRR array printed on a 3 μ m thick membrane of PET. Structural dimensions for the two samples under study are: $P=2000 \mu\text{m}$, $L=2050 \mu\text{m}$ (resp. $1850 \mu\text{m}$), $w=60 \mu\text{m}$, $g=70 \mu\text{m}$. b) Illustration of the printing method (Microplotter II - Sonoplot).

A conductivity of $7.910^6 \text{ S}\cdot\text{m}^{-1}$ was measured for the metallic structures by a four-terminal sensing method (SP4 Microworld). As the metal's thickness deposited by one

imprint varies between 150 and 200 nm (AFM measurement), it is necessary to drop at least 5 successive imprints to reach the skin depth for the metallic structures. It has recently been demonstrated that this manufacturing process can print structures that resonates up to 1 THz. [10, 11]

2.2. Terahertz resonance of printed metasurfaces

Geometric parameters of the SRRs gives frequency resonances in the 60-80 GHz spectral domain. The theoretical resonant behavior of such well-known resonator is fully described in literature [12, 13]. By varying the geometry of the structure (here its length L), we are able to absorb specific wavelengths (68 and 74 GHz) at one given polarization (Transverse Magnetic - TM) as shown in Fig. 3a. When a resonant magnetic flux penetrates the metal rings, it will induce rotating currents by Faraday's law which produce their own flux to oppose the incident field. In transverse magnetic (TM) polarisation, the electric field being perpendicular to the SRR gap, the electrons circulate throughout the entire ring, giving rise to a first resonant mode at around 70 GHz for the two fabricated samples. In transverse electric (TE), the electric field is parallel to the gap and the electrons circulate in half of the SRR, giving rise to a second resonant mode at around 150 GHz for the two samples. Thus, with the described setup, only the first resonant mode is visible in TM polarisation. Measures were conducted with a tunable terahertz source based on Schottky diodes (TeraSchottky, Lytid) coupled with a terahertz pyrometer (TeraPyro, Lytid) by a lock-in amplifier (SR830 Stanford Research). Simulations were performed with the electromagnetic module of the commercial software COMSOL.

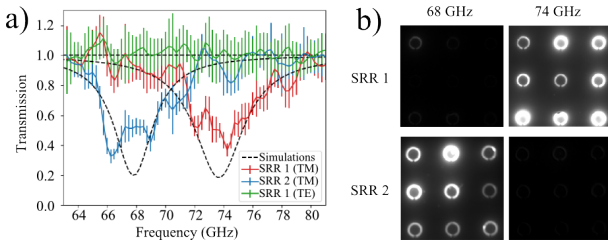


Figure 3: a) Transmission spectrum of the two arrays of SRR in TM polarization (red and blue) and TE polarization (green). b) Infrared normalised response of membranes at 68 GHz and 74 GHz for TE and TM illumination

3. Thermal conversion for multispectral terahertz detection and imaging

In order to demonstrate the efficiency of thermal conversion applied to terahertz multispectral detection, we used an IR camera (FLIR SC7600, 1.5-5 μm) to collect the IR radiation of the membranes at different wavelengths and polarizations of illumination. Fig. 3b illustrates the typical normalised infrared response for the two membranes at 68 and 74 GHz under TM illumination. We notice an important

infrared emission only at the frequency and polarization of resonance. This heating corresponds to local absorption of the THz radiation by the SRR antennas. The minimal terahertz power detectable experimentally is about $20 \mu\text{W}/\text{cm}^2$ with a 2 ms IR camera's integration time.

Finally, as a proof of concept, the membrane can be used in a hidden object detection configuration (see Figure 4). A metallic object is placed behind a 1 cm thick cardboard between the collimated terahertz source and the converter+IR camera system. For a given object position, the infrared emission of each sub-wavelength structure is integrated to indirectly access the local transmission of the terahertz wave. Using automated stages, the object can be translated to scan an area larger than the size of the printed metasurface. In the case of reflection imaging or with low source power ($<10\text{mW}$), it is necessary to use a vacuum cell to increase the heating temperature of the membrane by suppressing convective heat loss.

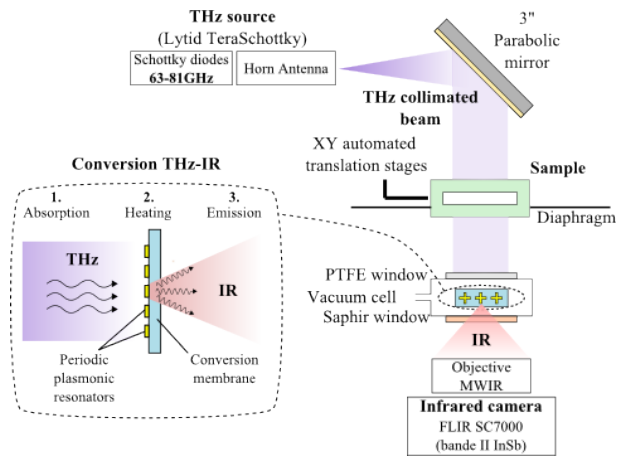


Figure 4: Schematic of the thermo-conversion terahertz imaging bench in transmission configuration.

The figure 5 shows the scan reconstruction in a transmission configuration for a triangular metal pattern -with or without an internal mask- hidden behind a 1 cm thick cardboard. The resulting terahertz imaging is then resolved to a few wavelengths. As the membrane is spectrally sensitive, this device is a first step towards the development of a multispectral low-cost terahertz camera or sensor.

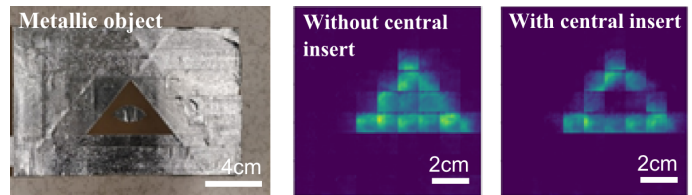


Figure 5: Terahertz imaging of a hidden metallic object using a thermo-conversion membrane resonating at a single 140GHz frequency ($\lambda=2\text{mm}$).

Further developments still remain to be done to increase the sensitivity and lower the response time of the membrane

while preserving a compromise with mechanical rigidity and thermal resistance. In this perspective, a study of the heating dynamics of the conversion membranes will be carried out. Some works of calibration must also be done to compare the performances of the detection by thermal conversion with conventional terahertz detectors (CMOS and micro-bolometer based detectors).

4. Conclusions

We have demonstrated the fabrication of ultra-thin membranes consisting of periodic arrays of resonant SRRs in the 60-80 GHz range with the aim of applying them to multispectral terahertz imaging by thermoconversion. The manufacturing method by inkjet printing appears to be low cost, reproducible (dispersion $< 5\mu m$) for flexible terahertz metasurfaces. The spectral and polarization sensitivity and the response time of these THz \rightarrow IR conversion membranes pave the way for low cost multispectral terahertz imaging.

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