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# Split-ring resonators imaged by THz s-SNOM

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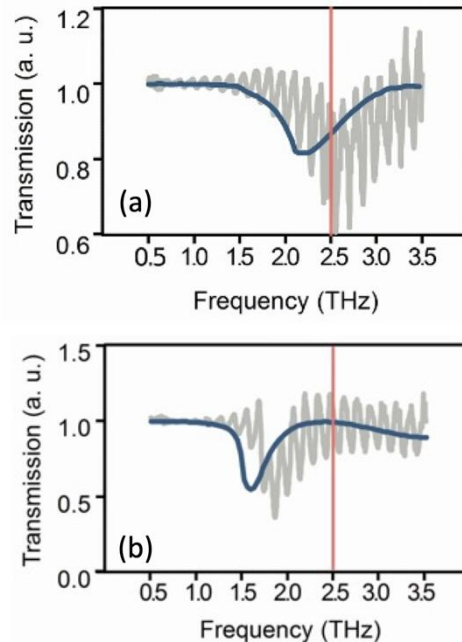
**Abstract**—Split-ring resonators (SRRs) are one of the most common building blocks to design metamaterials operating over a large range of frequencies in the electromagnetic spectrum. Here we acquire s-SNOM images with high signal-to-noise ratio on SRRs by scattering-type scanning near-field optical microscopy (s-SNOM) in the terahertz (THz) domain. By mapping the electric field distribution with subwavelength spatial resolution, we observe clear spatial asymmetries within a single SRR. These effects are more pronounced for the SRRs designed to resonate at the frequency of the probing laser (2.52 THz), compared to the SRRs that do not support a resonant mode at this frequency. This asymmetrical distribution is attributed to combined far-field and near-field multiplication effects, which depend on the position of the probing tip on the micro-resonator.

## I. INTRODUCTION

Metamaterials are geometrically scalable, and their response to light can be tailored to a large range of frequencies. Among various designs, metamaterials composed of split ring resonators (SRRs) represent well known building blocks to design metamaterials [1]. In general, SRRs consist of metallic structures with sub-wavelength dimensions, which can strongly confine electromagnetic radiation in small volumes at subwavelength scales. Owing to the long wavelength in the terahertz (THz) range, it is even more crucial to achieve subwavelength confinement in order to enhance light-matter interaction and probe fundamental local excitations of molecules and solids [2]. Although metasurfaces composed by arrays of THz photonic micro-resonators can be routinely studied by THz time-domain spectroscopy (THz-TDS) in the far-field (FF) [3,4], up to now the diffraction limit prevents characterization of a single micro-resonator at the local scale. In this work, we study single SRRs using scattering-type scanning near-field optical microscopy (s-SNOM). Reaching a sub-wavelength lateral resolution with s-SNOM in the THz range with high signal-to-noise ratio remains challenging [5, 6]. This is mainly because conventional atomic force microscopy (AFM) tips are typically 15-20  $\mu\text{m}$  long, much smaller than wavelengths in the THz range, which leads to low antenna effect due to the large mismatch between tip length and THz wavelength. Using long AFM probes, we circumvent this limitation and we demonstrate sub-wavelength mapping of the electric field distribution of the excited photonic mode in a single SRR. Such tailored probes are key to reach high-signal-to-noise ratio by increasing the scattering efficiency of the near-field (NF) signal to the FF.

## II. RESULTS

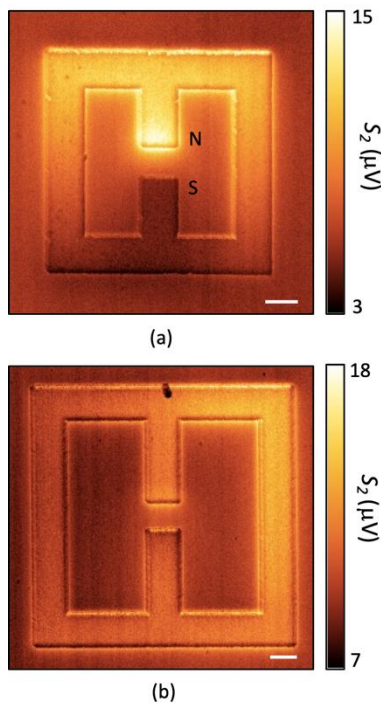
Two sets of SRRs were designed through finite-difference time-domain (FDTD) calculations (Lumerical FDTD) with two different lengths ( $l$ ) and same gap ( $g$ ) width. For the SRR



**Fig. 1.** Measured (grey) and computed (blue) THz-TDS transmission spectra of SRR metasurfaces. The metasurface composed by arrays of SRR13 couples to 2.5 THz (a), while the metasurface with SRR17 (b) does not. Red lines indicate the laser emission frequency (2.5 THz).

with  $l = 13 \mu\text{m}$  (hereafter SRR13), a resonant mode is expected to be excited by radiation at 2.52 THz, which is the emission frequency of the CO<sub>2</sub> laser-pumped methanol THz gas laser (FIRL-100, Edinburgh Instruments Ltd.) used in our s-SNOM experiments. The SRR with  $l = 17 \mu\text{m}$  (SRR17) should not support any resonant mode at this frequency. Metasurfaces composed by SRRs arrays and single SRR elements were fabricated on high-resistivity silicon substrates following standard lithography process. These metasurfaces were characterized by THz time-domain spectroscopy – THz-TDS (TeraSmart, Menlo Systems GmbH) to verify the excitation of resonant modes at 2.52 THz. Single SRR elements were characterized by s-SNOM imaging using a neasNOM microscope (Neaspec GmbH), which consists of an asymmetric Michelson interferometer and an AFM operating in tapping mode (intermittent contact) [7,8]. The incident p-polarized THz laser beam was focused on the apex of the AFM probe and sample surface by a parabolic mirror, which also collected the scattered light. Light scattered from the AFM probe, containing the NF information, was combined with the reference beam and finally detected by a pulse-tube-cooled InSb hot electron bolometer (QMC Instruments Ltd.). To acquire images with a high signal-to-noise ratio, we improved the NF to FF scattering efficiency by using elongated Pt coated Si tip, with a length of  $L = 70 \mu\text{m}$  and a

mechanical resonance frequency  $\Omega \sim 280$  kHz (Lprobe model, Vmicro SAS) [5,9-11]. The optical signals ( $S_n$ ) were demodulated at higher harmonics of the cantilever oscillation frequency  $n\Omega$  to suppress the background scattering contribution. Fig. 1 shows the measured and computed (FDTD) transmission spectra of the studied metasurfaces. The substrate was considered infinitely thick, and therefore Fabry-Perot interference effects, present in the measured transmission spectra, are not considered in the simulation. A resonance close to 2.52 THz is observed for the metasurface designed with the tuned SRR13 (Fig. 1a), while it appears at lower frequency ( $\sim 1.5$  THz) for the metasurface with the detuned SRR17 (Fig. 1b). These results confirm that the designed single SRRs will present different coupling to the laser radiation at 2.52 THz. We therefore expect that s-SNOM imaging will be able to map the photonic mode in single SRR13, while strong optical contrasts are not expected for SRR17.



**Fig. 2.** s-SNOM images of single SRR13 (a) and SRR17 (b). The optical signal  $S_2$  was obtained by demodulating the recorded signal at the second harmonic of the cantilever frequency ( $n = 2$ ). The scale bars correspond to 2

Fig. 2 presents the acquired s-SNOM images of both single SRR structures, showing high signal-to-noise ratio and fine details with subwavelength spatial resolution. The optical signal  $S_2$  was obtained by demodulating the recorded signal at the second harmonic  $n = 2$ . In these images we can indeed see that the  $S_2$  signal is enhanced in one of the arms of the SRR13 (indicated as arm N in Fig. 2a), close to the gap, when compared to the surrounding Si substrate. On the other hand, in the case of the detuned SRR17, the optical contrast is mainly related to the local dielectric properties of the materials probed by the tip, although some asymmetry is still present. We interpret these results as an interplay of the local interaction between the tip and the resonating structure, together with a spatial multiplication of the NF and FF

contributions, which are dependent on the position of the probing tip [10-12]. The proposed scenario was further investigated by FDTD numerical simulations taking into account the influence of the probing tip [12], and we found an excellent agreement. Moreover, shape-dependent contrasts in THz s-SNOM have already been reported in the literature [13].

In summary, in this work we investigated tuned and detuned SRRs by THz s-SNOM with high spatial resolution and signal-to-noise ratio. The mapped electric field distribution exhibited an asymmetry in the case of a tuned SRR, which is related to the complex interaction between the probing tip and the resonating SRR, with an interplay of NF and FF contributions, and to the experimental configuration (light illumination / collection). The FDTD simulations provided a theoretical framework to interpret the experimental results. This study opens perspectives towards a better understanding of tip-resonator interactions. The detailed analysis and interpretation of subwavelength imaging of electric field distribution in single metallic micro-resonators by THz s-SNOM, an important issue in the metamaterials domain, remains a challenging task. Different micro-resonator structures should be addressed in the future.

#### REFERENCES

- [1] H.-T. Chen, W. J. Padilla, J. M. O. Zide *et al.*, "Active terahertz metamaterial devices," *Nature*, vol. 44, pp. 597-600, Nov., 2006.
- [2] A. J. Huber, F. Keilmann, J. Wittborn *et al.*, "Terahertz Near-Field Nanoscopy of Mobile Carriers in Single Semiconductor Nanodevices," *Nano Lett.*, vol. 8, no. 11, pp. 3766-3770, 2008.
- [3] K. Meng, S. J. Park, A. D. Burnett *et al.*, "Increasing the sensitivity of terahertz split ring resonator metamaterials for dielectric sensing by localized substrate etching," *Opt. Express*, vol. 27, no. 16, pp. 23164, 2019.
- [4] R. Peretti, S. Mityukovskiy, K. Froberger *et al.*, "THz-TDS time-trace analysis for the extraction of material and metamaterial parameters," *IEEE Trans. Terahertz Sci. Technol.*, vol. 9, no. 2, pp. 136-149, March, 2018.
- [5] B. Walter, E. Mairiaux, D. Vignaud *et al.*, "Terahertz near-field imaging using batch-fabricated cantilevers with 70  $\mu\text{m}$  long tips," *44th International Conference on Infrared, Millimeter, and Terahertz Waves*, pp. 1-2, Paris, France, Sept. 1- 6, 2019.
- [6] C. Maissen, S. Chen, E. Nikulina *et al.*, "Probes for Ultrasensitive THz Nanoscopy," *ACS Photonics*, vol. 6, no. 5, pp. 1279-1288, May, 2019.
- [7] N. Ocelic, A. Huber and R. Hillenbrand, "Pseudoheterodyne detection for background-free near-field spectroscopy," *Appl. Phys. Lett.*, vol. 89, pp. 101124, Sep., 2006.
- [8] X. Chen, D. Hu, R. Mescall *et al.*, "Modern scattering-type scanning near-field optical microscopy for advanced material research," *Adv. Mater.*, vol. 31, pp. 1804774, 2019.
- [9] T. Hannotte, L. Thomas, B. Walter *et al.*, "s-SNOM imaging of a THz photonic mode," *45th International Conference on Infrared, Millimeter, and Terahertz Waves*, pp. 1-2, Buffalo, NY, USA, Nov. 8-13, 2020.
- [10] T. Hannotte, L. Thomas, C. Nascimento Santos *et al.*, "Consequences of antenna effects on s-snom imaging of a photonic mode", *CLEO: Science and Innovations*, p.p. SW2K.5, San Jose, United States of America, 2021.
- [11] C. N. Santos, L. Thomas, T. Hannotte *et al.*, "THz s-SNOM Imaging Of Logarithmic Spiral Antennas," *46th International Conference on Infrared, Millimeter, and Terahertz Waves*, Chengdu, China, Aug. 29 – Sep. 3, 2021.
- [12] L. Thomas, T. Hannotte, C. N. Santos *et al.*, "Imaging of THz photonic Modes by Scattering Scanning Near-field Optical Microscopy", [hal-03608482](https://doi.org/10.1021/acsami.2c03608), *ACS Appl. Mater. Interfaces*, 2022. (accepted)
- [13] A. Pizzuto, X. Chen, H. Hu *et al.*, "Anomalous contrast in broadband THz near-field imaging of gold microstructures," *Opt. Express*, vol. 29, no. 10, pp. 15190, 2021.