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► **To cite this version:**

Théo Hannotte, Adrien Pillet, Nouredin Osseiran, Jean-Francois Lampin, Romain Peretti. Terahertz time domain spectroscopy of a single split ring resonator coupled to an amino acid crystal. 2023 48th International Conference on Infrared, Millimeter, and Terahertz Waves (IRMMW-THz), Sep 2023, Montreal, Canada. pp.1-2, 10.1109/IRMMW-THz57677.2023.10299331 . hal-04325110

HAL Id: hal-04325110

<https://hal.science/hal-04325110>

Submitted on 5 Dec 2023

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Terahertz time domain spectroscopy of a single split ring resonator coupled to an amino acid crystal

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Abstract—Split Ring Resonators (SRRs) have been used in large arrays to interact with objects much smaller than the wavelength in the terahertz range. Using arrays of SRRs facilitates the measurements, but prevents one from extracting accurate information regarding the object properties in this frequency range. Here, we demonstrate that the experiment is possible with a single SRR. We measured the transmission spectrum of a single SRR coupled with less than 1 μ m of glutamic acid (GA) crystals, and extracted information on the 1.2THz vibration mode of GA crystals.

I. INTRODUCTION

THz spectroscopy is expected to have a valuable purpose for analyzing biological samples. Because far-field spectroscopy techniques such as THz Time Domain Spectroscopy (THz-TDS) are subject to the diffraction limit, those samples are often in the form of pressed powder pellets [1] or diluted in liquid [2]. Indeed, a THz beam with a wavelength between 0.1 and 1 mm cannot be focused on a spot smaller than about 50 μ m [3], which is two orders of magnitude larger than biological objects such as bacteria, cells, proteins or viruses [4]. The powder pellet approach has several issues. Firstly, some of the objects of interest such as viruses simply cannot be produced in quantities large enough to produce a pellet. Secondly, it has been shown that vibrational signatures of protein crystals in the THz range are often the result of delocalized vibration in the crystal structure [5], meaning that a measurement on a large quantity of crystals will be blurred by the random orientations and sizes of each crystal.

One approach to surpass the diffraction limit is to place the sample directly in the near-field of a subwavelength THz source, as the group of A. Markelz recently demonstrated [6,7,8]. However, this approach requires a complex experimental setup, which cannot be implemented in a standard THz-TDS system. Another approach is to use a secondary structure, such as a waveguide, or a resonator, to confine the energy from a propagating THz beam.

Resonant structures such as Split Ring Resonators (SRRs) can confine an electric field in a deeply subwavelength volume, and have already been used to interact with small particles like yeast cells [9]. However, such experiments are always done with a large array of SRRs on which the particles are randomly distributed. This means that each SRR is coupled to the particle in a different way, and has a different response. Therefore, measuring the array altogether only gives access to an average of many different responses, which is not suitable for quantitative measurement of the particle properties. Extracting the particle properties from a measurement on SRRs requires either to have each SRR to be identically coupled to the particles, or to perform the experiment on a single SRR.

THz-TDS measurement on a single SRR has only been documented once, on a *complementary* SRR, with silicon lenses in direct contact with the sample [10,11]. In this abstract, we

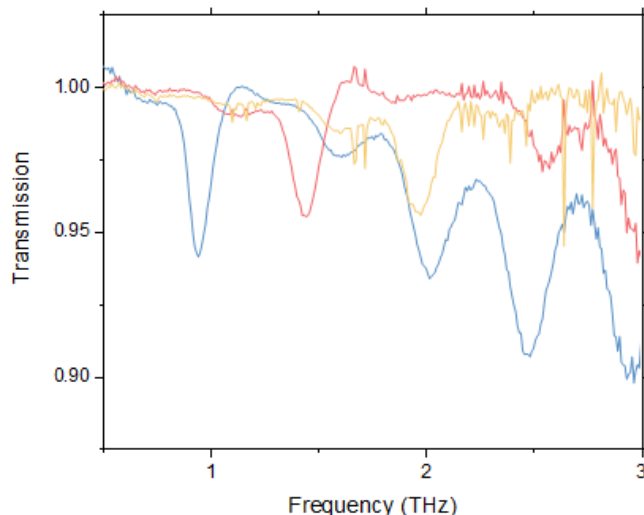


Fig. 1. Three transmission spectra measured on three different single SRRs, with resonance at 1THz, 1.5THz, and 2THz. We were able to obtain such result with resonance frequency ranging from 240GHz to 3THz.

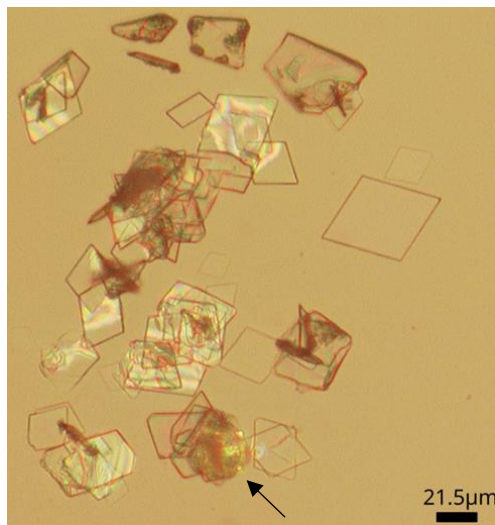


Fig. 2. Glutamic acid crystals formed after evaporation of a saturated GA solution. A SRR is slightly visible behind the crystals pile at the bottom of the picture (marked with an arrow).

demonstrate THz-TDS performed on a single SRR coupled with a glutamic acid (GA) crystal. We show how the correction of a systemic error coming from TDS systems allows us to extract the SRR signal from the large background signal.

II. RESULTS

We fabricate a set of SRRs on a quartz substrate. The SRRs are spaced at least two millimeters away from the other to allow for individual measurement.

Our experiment is done with a commercial THz-TDS system operating in transmission. The THz beam is collected from the

III. SUMMARY

We successfully demonstrated that commercial THz-TDS systems are sensitive enough to detect the weak signal from a single subwavelength SRR, even on a transparent sample with a large background signal. This allowed us to extract resonance parameters of GA from less than a microgram of material. However, there is still room for improvement regarding the coupling between the SRR and the sample material. We will reproduce the experiment with multiple SRR with different resonance frequency to better estimate the accuracy of this measurement method.

The possibility to accurately detect the signal from a single SRR opens the way to new experiments such as probing the vibration mode of single proteins, ultra-strong coupling with single biomolecules and testing the spatial range of delocalized vibration in crystals.

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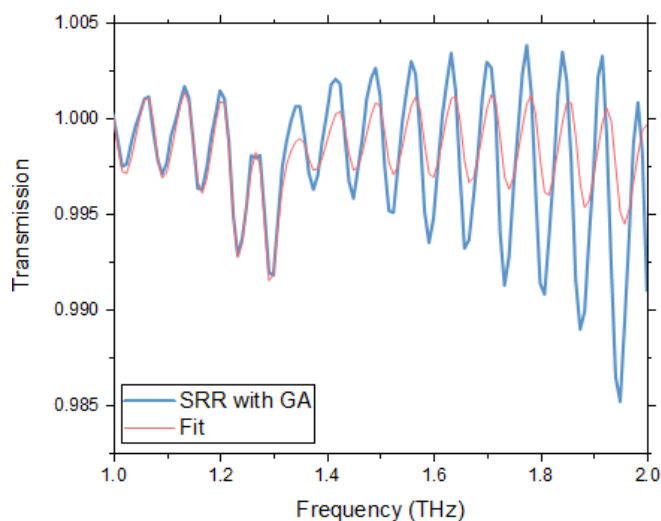


Fig. 3. Measured transmission spectrum of the SRR covered with GA crystals., and the fit using an analytical RLC model for the SRR, and a Lorentz model for the GA permittivity. The oscillations come from the Fabry-Pérot effect. The discrepancy at higher frequency is mostly due to the high absorption of GA around 2THz, not taken into account in the fit model.

emitter antenna with a parabolic mirror, and focused on the sample with a 5cm focal length TPX length resulting in a numerical aperture of 0.356. The collection of the transmitted signal is done with the same set of lens and parabolic mirror. The measured signal is an average over 10,000 acquisitions. However, the individual time traces are first corrected to account for the slight delay between each trace, which we identified as a major source of error [12,13].

The spectra, normalized with the transmission through the bare substrate, clearly show the resonance of the SRRs on a wide band of frequency (fig. 1).

Having successfully demonstrated the possibility of measuring the properties of single SRRs in THz-TDS, we put the system to the test as a measurement tool for microscopic samples placed in the gap of the SRR. We use GA as our test sample. GA is an amino acid with a strong resonance line at 1.2THz in its crystal form, with a 41GHz bandwidth. After preselecting SRRs with a resonance frequency close to 1.2THz, we couple the GA with the SRR by depositing a droplet of saturated solution of GA. After evaporation of the water, we observe GA crystals formed over the SRRs (fig. 2). The measured SRR spectrum after GA deposition is shown on figure 3. The effect of the GA resonance is not directly visible by looking at the spectrum, mostly because of the Fabry-Pérot effect, which is cannot be completely suppressed by the normalization. However, we are still able to fit the spectrum using an analytical RLC model for the SRR, and a Lorentz model for the GA permittivity (see fig.3). The Lorentz resonance frequency extracted from the fit is 1.22THz, and the bandwidth of the mode is 38GHz. Those values are remarkably close to the ones measured on a pure GA pellet, which is very encouraging for this method of measurement.