Hybrid metamaterial based structures for the development of a THz spatial light modulator

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***Abstract*—We investigate new classes of artificial materials exhibiting unconventional properties in order to build novel devices operating in the Terahertz regime. The design, fabrication and electromagnetic characterization of tunable metamaterials with unit cells based on Split Ring Resonators are presented. By incorporation of a nematic liquid crystal in the structure, we observe a frequency shift in the resonant response over 10% in bandwidth and more than 10 dB change in the signal absorption. We discuss how such a hybrid structure can be exploited for the development of a THz spatial light modulator.**

Keywords—THz Technology, Metamaterial, Liquid Crystal, Spatial Light Modulator, Split Ring Resonators

I. INTRODUCTION

In the last few years, a significant focus on the Terahertz (THz) science and technology has been observed among the scientific community all over the world. As a result of this large interest, an increasing number of devices and systems are continuously being developed in this field for a large number of different applications, namely imaging for non destructive evaluation [1], chemical and biological sensing [2, 3], material characterization [4], as well as homeland security [5].

There are however several restrictions to the full use of this attractive frequency band because the THz range is not so easily generated by natural materials. Compared to the well-established infrared and microwave neighbouring regions, the "THz gap" deserves specific approaches to be investigated and exploited. One of the most fruitful strategies comprehends the employment of artificially structured electromagnetic materials, named metamaterials [6], typically comprised of periodic arrays of sub-wavelength metallic structures acting as unit cells ("metamolecules") within or on a dielectric or semiconducting substrate.

This novel material, with an appropriate design such as Split Ring Resonators (SRRs) [7], can be used for the development of innovative devices operating in this frequency region. A number of prominent potential applications can be realized with the proper exploitation of the ability to dynamically control the material properties or tune them in real time, through either direct external tuning or nonlinear response.

The tunability of metamaterial-based devices for Terahertz applications can be achieved using different tuning mechanisms, by modifying the geometry of metamolecules array or by altering the electromagnetic near-field interaction between adjacent unit cells. To the first class belong reconfigurable metadevices making use, for example, of micro electro-mechanical systems [8], in the second class are hybrid structures based on the Schottky effect [9], or exploiting phase change media like vanadium dioxide [10], superconductors [11], or liquid crystals (LC) [12].

In this work, we focus our efforts on the investigation of this last mechanism, through the incorporation of a nematic liquid crystal as the tuning element. The basic idea is to use the birefringence properties of the LC, whose molecule orientation can be magnetically or electrically controlled, to modify the overall capacity of the device and therefore change its inherently resonant response.

II. METAMATERIAL DESIGN

The basic metamaterial structure is based on an array having Split Ring Resonators (SRRs) as unit cells. We create different capacitors over the ring gaps and use a nematic liquid crystal to change the overall permittivity and achieve the dynamic frequency modulation.

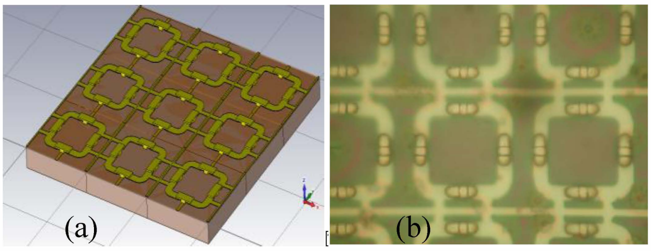

Fig. 1: (a) 3D layout of the metamaterial array based on SRR unit cells with connection wires; (b) optical image of the realised structure.

To this aim, a suspended metallic cap is designed over the planar array in order to have cantilevers that overlap each side of the ring gaps, where the infiltration of the LC takes place.

In Fig. 1(a) the 3D layout of the full metamaterial structure is presented. Fig. 1(b) shows a picture of the structure we realised, using the procedure detailed in the Section III. From the optical image, the presence of 4 metallic caps over each SSR is clearly shown. The unit cell size is 40 × 40 μm^2, whereas the split ring resonator width is 5 μm.

III. Sample Fabrication

The array of SRRs is fabricated by UV photolithography using the Al technology. The first Al layer consists of the array of SRRs designed as shown in Fig. 1 (a). An effective array area of 3 x 3 mm^2 is created. A 200 nm thick first Al layer was deposited on 1 x 1 cm^2 Si substrate by dc sputtering magnetron technique and then patterned by a lift-off process. The suspended metallic cap is fabricated using sacrificial photo resist layer used as a support for the structure. A further 600 nm thick Al layer is deposited on the sacrificial layer and then patterned.

Fig. 2 shows the SEM magnified picture (~ 10^3 X) of an element suspended on the Al based SRR array, in correspondence of the "horizontal" gap of length 7 μm between the two ends of the split ring, which acts as capacitive coupling in the base layer. The distance between the base and the cap layers, that is the "vertical" gap, is about 0.4 μm.

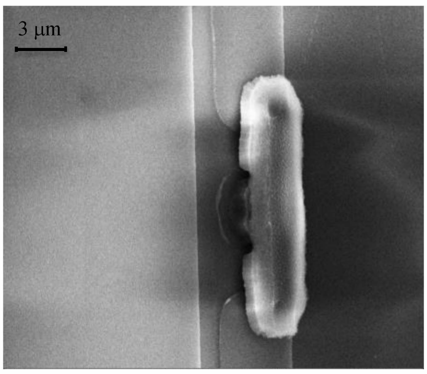

Fig. 2: SEM picture showing details of the vertical gap realised between the base and the cap layer.

IV. THz Characterization

THz measurements have been carried out on both the Al base layer structure (SSR array) and the full hybrid structure (the "quasi-3D" mematerial with LC) using a conventional Time Domain Spectrometer based on 20fs, 4nJ, Ti:Al_2O_3 laser operating in the free space, a photoconductive antennas for the signal generation and a 2mm thick ZnTe crystal for electro-optic detection.

The frequency dependent transmittance and reflectance at normal incidence have been measured from 0.5 to 2.5 THz. Linearly polarized light is used with the THz electric field perpendicular to the capacitive gap. The THz beam is focused at the sample surface with a spot of size slightly smaller than the area covered by the metamaterial sample (~ 10 mm^2). All measurements have been performed in a controlled environment, using a box purged with dry nitrogen.

At first, we measured the transmission properties of the SRR based layer only and of the complete metamaterial without LC. Then, we infiltrated the LC and measured the transmission of both hybrid structures. As expected, the resonance frequency for the SRR base layer (at 1.5 THz, not shown) is higher than the value for the full hybrid structure because of the absence of the vertical capacitive gaps, which reduces the overall effective capacitance of the metamaterial-based device.

For the experimental test, we choose as liquid crystal an isothiocyanate based mixture having low absorption coefficient α and high birefringence Δn ($\Delta n = n_{||} - n_{\perp}$, where $n_{||}$ and $n_{\perp}$ are the extraordinary and ordinary refractive indices respectively) in the THz region. At 1.5 THz and room temperature, this LC has α values in the range 10 ÷ 50 cm^{-1} and Δn as high as 0.3 [13].

Fig. 3 shows the results of the e.m. full-wave calculations compared with the experimental results for both the base layer and the complete (quasi-3D) structure. In the simulation, we assume that the liquid crystal is fully isotropic with a value of the refractive index $n_{iso} = [(n_{||}^2 + 2n_{\perp}^2)/3]^{1/2} = 1.65$.

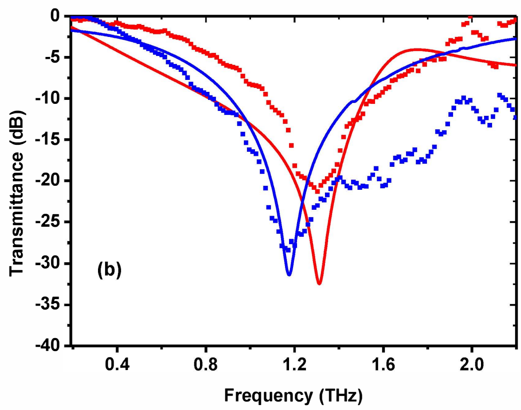

Fig. 3: The transmittance response to the THz radiation. Experimental data (dotted lines) are compared with simulation results (continuous lines) for the full (quasi-3D) structure, with and without LC infiltration (blue and red curves respectively).

A very good agreement between simulations and measurements is observed. Indeed, due to the LC infiltration, a red frequency shift of 0.16 THz, corresponding to a frequency shift of over 10% in bandwidth, and signal modulation depth up to 20 dB at the central frequency, is observed.

V. Conclusions

A planar metamaterial structure for modulation of the THz radiation based on LC polarisation has been designed, and its electromagnetic response has been numerically simulated. The device has been fabricated using Al technology and preliminarily characterized in the frequency range 0.5 – 2.5 THz using a Time Domain Spectrometer. The transmission experimental response shows a pronounced dip at around 1.5 THz for the SRR base layer only, which decreases to 1.2 THz incorporating an additional cap layer with vertical gaps in the complete structure. By infiltrating a liquid crystal mixture with a high birefringence, we observe a further frequency red shift of 0.16 THz and more than 10 dB change in signal absorption. This is mostly due to the presence of the vertical capacitive gaps, which increase the effective capacitance of the structure and therefore its capability to change the response by locally modifying the electromagnetic field interaction inside each metamolecule. Besides that, since the energy absorption is mostly confined around the SSR gaps, the coupling between adjacent unit cell is almost negligible, providing the quasi-3D metamaterial with a superior spatial selectivity. These peculiar characteristics indicate that this hybrid structure might well lend itself as a basic element for a THz spatial light modulator [14]. Tunability tests of the complete metamaterial-LC structure using an external electric field to polarize the liquid crystal are in progress.

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