THz characterization of a metamaterial-based Spatial Light Modulator

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Abstract: The aim of this work is to investigate new classes of artificial materials exhibiting unconventional properties in order to build novel devices operating in the Terahertz regime. We focus on the design, fabrication and characterization of tunable metamaterials with unit cells based on Split Ring Resonators. 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

1. 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. Among the others 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 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, amongst others: liquid crystal (LC) [8], micro electro-mechanical systems [9], Schottky effect [10] and superconductivity [11].
Presently, we are focusing our efforts on the investigation of the first mechanism, through the incorporation of a nematic liquid crystal as 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.

2. Sample fabrication

The basic metamaterial structure is based on an array having Split Ring Resonators 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. 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.

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978-1-4799-4818-5/14/$31.00 ©2014 IEEE

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 x3 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 (Fig. 1(b)) was fabricated using sacrificial photo resist layer used as a support for the structure. A further 600 nm thick Al layer was deposited on the sacrificial layer and then patterned.
Fig. 1 (c) shows the SEM magnified picture of an element suspended on the Al based SRR array.

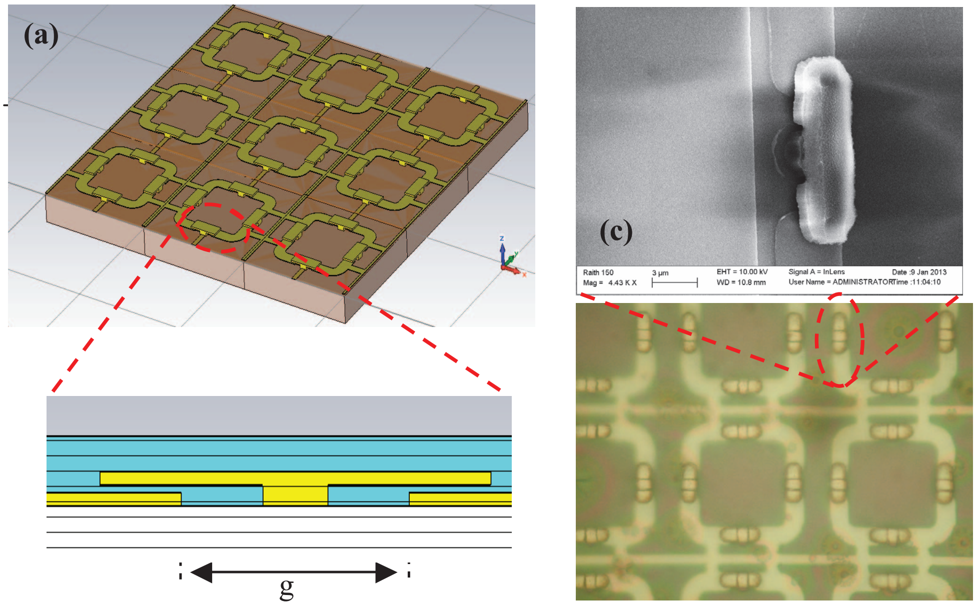

Figure 1. (a) 3D layout of the metamaterial array based on SRR unit cells with connection wires; (b) SEM and (c) optical image of the realised structure (g = 7 µm).

3. THz characterization

THz measurements have been carried out on the Al base layer structure (SSR array) 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 was characterized from 0.5 to 2.5 THz. Linearly polarized light was used with the THz electric field perpendicular to the capacitive gap. The THz beam was focused at the sample surface to 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.
An electromagnetic resonance is observed in the spectrum at around 1.5 THz. No other resonances are observed up to 2.5 THz (Fig. 2 (a)). The same setup was used to characterize the complete structure with suspended metallic caps.
At first, we measured the transmission of the complete structure without LC. Then, we infiltrated the LC and measured the transmission of the whole hybrid structure.
For the test, we choose as liquid crystal an isothiocyanate based mixture having low absorption coefficient α and high birefringence Δn ($\Delta n = n_{\parallel} - n_{\perp}$, where $n_{\parallel}$ 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 [12]. Indeed, due to the LC infiltration, a red frequency shift of 160 GHz and signal modulation depth up to 20 dB at the central frequency is observed.
Fig. 2 (b) 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 assumed that the liquid crstal was fully isotropic with a value of the refractive index $n_{iso} = [(n_{\parallel}^2 + 2n_{\perp}^2)/3]^{1/2} = 1.65$ [12]. A very good agreement between simulations and measurements is observed. The resonance frequency for the base layer 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.

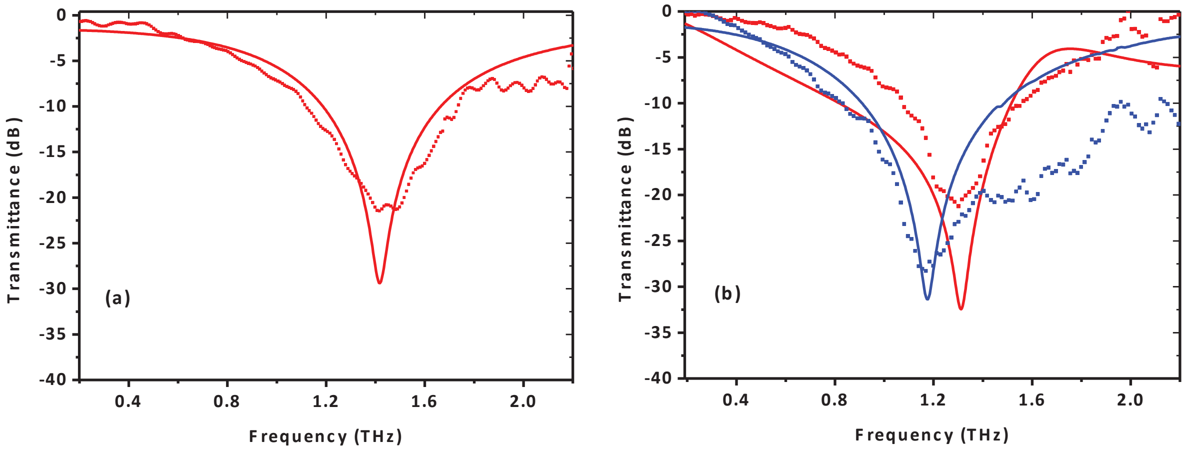

Figure 2. The transmittance S_{21} response to the THz radiation. Experimental data (dotted lines) are compared with simulation results (continuous lines) for (a) the base layer structure only and (b) the full structure, with and without LC infiltration (blue and red curves respectively).

4. Conclusion

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 Spectroscopy technique. The transmission experimental response shows a pronounced dip at around 1.5 THz for the base layer structure and 1.2 THz for the complete structure, By incorporating a liquid crystal mixture with a high birefringence, we observed a frequency red shift of 160 GHz, corresponding to a frequency shift of over 10% in bandwidth. This results in more than 10 dB change in signal absorption, indicating that this hybrid structure might well lend itself as a basic element for a THz spatial light modulator [13]. Tunability tests of the complete metamaterial-LC structure using an external electric field to polarize the liquid crystal are in progress.

References

[1] B. B. Hu and M. C. Nuss, “Imaging with terahertz waves,” *Opt. Lett.,* vol. 20 (1995), pp. 1716-1718
[2] R. H. Jacobsen, D. M. Mittleman, M. C. Nuss, “Chemical recognition of gases and gas mixtures with terahertz waves,” *Opt. Lett.,* vol. 21 (1996), pp. 2011-2013
[3] T. W. Crowe, T. Globus, D. L. Woolard, J. L. Hesler, “Terahertz sources and detectors and their application to biological sensing”, *Phil. Trans. R. Soc. London A* , vol. 362 (2004), pp. 365-377
[4] B. Ferguson and X.-C. Zhang, “Materials for terahertz science and technology”, *Nature Materials*, vol. 1 (2002), pp. 26-33
[5] D. Zimdars, “Fiber-pigtailed terahertz time domain spectroscopy instrumentation for package inspection and security imaging,” *Proc. SPIE,* vol. 5070 (2003), pp. 108-116
[6] D. R. Smith, W. J. Padilla, D. C. Vier, S. C. Nemat-Nasser, S. Schultz, “Composite medium with simultaneously negative permeability and permittivity”, *Phys. Rev. Lett*., vol. 84 (2000), pp. 4184-4187
[7] J. B. Pendry, A. J. Holden, D. J. Robbins, W. J. Stewart, “Magnetism from conductors and enhanced nonlinear phenomena”, *IEEE Trans. Microwave Theory Tech.*, vol. 47 (1999), pp. 2075-2084
[8] D. H. Werner, D.-H. Kwon, I.-C. Khoo, A. V. Kildishev, V. M. Shalaev, “Liquid crystal clad near-infrared metamaterials with tunable negative-zero-positive refractive indices”, *Optics Express*, vol. 15 (2007), pp. 3342–3347
[9] T. Hand, S. Cummer, “Characterization of tunable metamaterial elements using MEMS switches”, *IEEE Antennas Wirel. Propag. Lett.,* vol. 6 (2007), pp. 401-404
[10] H.-T. Chen, W. J. Padilla, J. M. O. Zide, A. C. Gossard, A. J. Taylor, R. D. Averitt, “Active terahertz metamaterial devices”, *Nature*, vol. 444 (2006), pp. 597-600
[11] V. Savinov, V. A. Fedotov, S. M. Anlage, P. A. J. de Groot, N. I. Zheludev, “Modulating sub-THz radiation with current in superconducting metamaterial”, *Phys. Rev. Lett.*, vol. 109 (2012), pp. 243904/1-243904-5
[12] O. Trushkevych, H. Xu, T. Lu, J. A. Zeitler, R. Rungsawang, F. Gölden, N. Collings, W. A. Crossland, "Broad spectrum measurement of the birefringence of an isothiocyanate based liquid crystal," *Appl. Opt*., vol. 49 (2010), pp. 5212-5216
[13] W. L. Chan, H. T. Chen, A. J. Taylor, I. Brener, M. J. Cich, D. M. Mittleman, “A spatial light modulator for terahertz beams”, *Appl. Phys. Lett.*, vol. 94 (2009), pp. 213511-213513