EPJ Web of Conferences 41, 09006 (2013)
DOI: 10.1051/epjconf/20134109006

Near-field terahertz imaging of a discontinuity in split ring resonator array

F. Blanchard[1,2], K. Ooi[1], T. Tanaka[1,2], A. Doi[3] and K. Tanaka[1,2,4]

[1]Institute for Integrated Cell-Material Sciences (WPI-iCeMS), Kyoto University, Kyoto, Japan
[2]CREST, Japan Science and Technology Agency, Kawaguchi, Saitama, Japan
[3]Olympus Corporation 2-3 Kuboyama-cho, Hachioji-shi, Tokyo, Japan
[4]Department of Physics Graduate School of Science, Kyoto University, Kyoto, Japan

Abstract. We investigated the spatiotemporal evolution of single cycle terahertz pulses transmitted through a split ring resonator array including a void. Using a large-field-of-view terahertz microscope, we revealed the confinement and enhancement of the defect mode.

1 Introduction

Metamaterials have attracted a lot of attention due to their unique ability to be engineered to have the desired electromagnetic properties at optical wavelengths [1]. These artificial materials have exotic properties such as negative magnetic permeability, perfect lensing, and cloaking [1]. The most common metamaterial is an array of split ring resonators (SRR), where the unit cell is small compared with the wavelength and consists of metallic rings each with a small gap [2]. In SRRs organized in a periodic fashion, the coupling between elements leads the material to behave like a photonic crystal with electromagnetic modes propagating in the array, i.e., topic related to magneto-inductive wave [3].

A lot of study has gone into making photonic crystals with a high-Q resonant mode inside the band-gap [4]. The defect mode, or cavity resonant mode, should also be present in an SRR array that has properties like those of photonic crystal. However, as yet, there has been no investigation of how the electromagnetic field distribution evolves in the presence of defects in a SRR array.

In this study, we investigated the effect of defects inside an SRR array by visualizing the electromagnetic field distributions at terahertz (THz) frequencies. The recent technique of near-field THz microscopy was used for this purpose. In particular, we recorded THz images of the electric field distribution inside the cavity and for several SRR neighbors. The field was enhanced at the resonance frequency inside the space left by one missing element. To our knowledge, this is the first electric field visualization of a defect mode in the THz region (including the defect mode in photonic crystals).

2 Experimental

We used a THz microscope, as previously reported [5]. A large probe beam at 800 nm illuminated a $LiNbO_3$ (LN) crystal used for the purpose of two-dimensional electro-optic (EO) imaging in the reflection scheme. When dealing with THz images, a very thin EO crystal is needed in order to preserve the high spatial resolution of the optical elements. This constraint enables the THz field to be collected from a sample before diffraction [5]. The losses in sensitivity caused by a thin EO crystal were compensated by a tightly focused pulse ranging from 0.1 to 2.5 THz and with a peak field of 600 kV/cm [6]. In addition, using a two-dimensional EO near-field imaging technique prevents any perturbation from an external metallic structure, e.g., the tip used for the raster scanning near-field technique. Thus, the THz field localized inside the cavity along with amplitude and phase changes induced in its neighbors can be accurately and simultaneously measured.

Figures 1-(a) and (b) show a visible image and an illustration of a metallic mask fabricated on top of a 1 μm-thick x-cut LN crystal sensor to evaluate the spatial resolution at THz frequencies. By Fourier transforming the measured temporal evolution of the electric field passing through the sample, we obtained the spatial resolution as a function of frequency. The components at 1 THz and 0.24 THz are presented in Fig. 1-(c) and (d), respectively. As shown in Fig. 1-(d), the line and space pattern is completely resolved, which confirmed that the spatial resolution was better than λ/125.

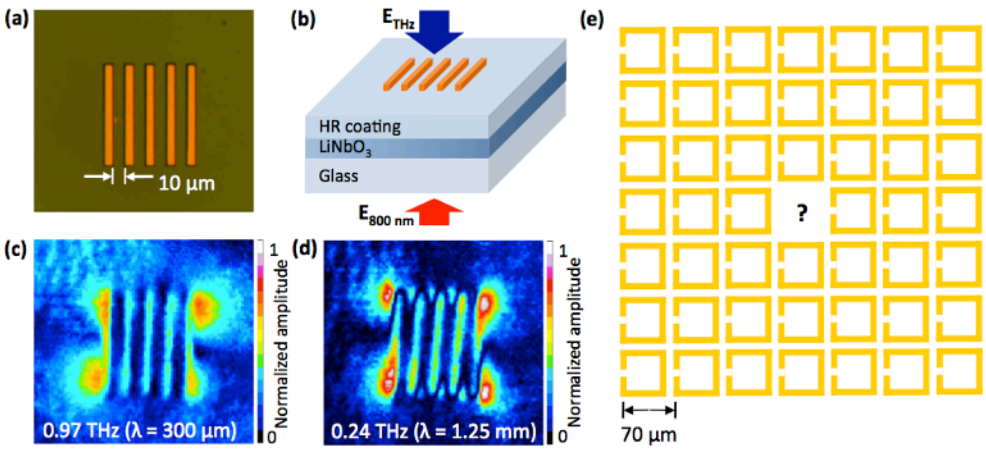

Fig. 1. (a) Visible image of a line and space metallic pattern; (b) illustration of the measurement technique.; (c) and (d) Fourier components at 1 THz and 0.24 THz of the measured temporal evolution of the electric field passing through the sample; (e) schematized array of SRRs including a void.

To explore the defect mode at THz frequencies, we fabricated an array of 23 x 23 SRRs with 70 μm lattice and removed one element in its center (Fig.1-(e)). The THz excitation polarization and the probe beam (λ_{800nm}) polarization were set parallel to each other and parallel to the gap. The sample was directly patterned on the high-reflecting-coating side of a 3 μm-thick x-cut LN crystal by using standard photolithography and lift-off techniques on a 100 nm-thick deposition of gold. A 50 μm long, 9.5 μm wide square shape and a 5 μm gap composed each SRR element inside the array.

3 Results

Figure 2 shows two aspects of the defect mode in the SRR array that relates the temporal near-field evolution of the THz pulse passing through the samples (with and without a void) and the visualization of the enhancement found inside the void. The left-hand and right-hand sides of Fig. 2-(a) show the time-domain near-field THz images of a SRR array with and without a void, respectively. Both movies (SRR arrays with and without the defect) are 300 frames long, with a 27-fs time step.

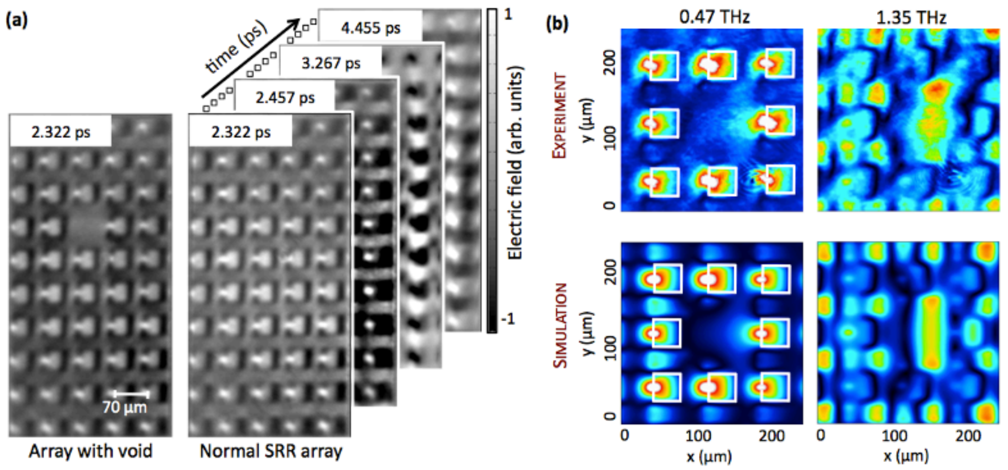

Fig. 2. (a) Near-field THz electric field distributions from SRR arrays with and without a missing element; (b) experimental and simulated Fourier transformed near-field maps at 0.47 THz and 1.35 THz.

Figure 2-(b) shows the magnitude of the Fourier transformed near-field maps at 0.47 THz and 1.35 THz, which correspond to the lowest resonant mode of the SRR array together with one cavity resonance found inside the void. To validate our measurements, we used finite domain time difference (FDTD) software that reproduced the experimental conditions. The lower part of Fig. 2-(a) represents the corresponding simulated frequencies, which perfectly match our measurements. The narrow band resonant frequencies found inside the cavity exhibited an enhancement factor of 2 and are not confined symmetrically inside the void; i.e., the strongest amplitude is not at its center. This may be due to the asymmetric shape of the unit cell itself.

4 Discussions

We conducted a near-field THz study on metamaterials where one element was removed from an array in order to elucidate the electromagnetic field distribution inside the discontinuity. Our system successfully identified the resonant frequency of the SRR array and the resonant modes created inside the void space. This work provides the first insight on defect modes in two-dimensional metamaterial arrays. A deeper analysis of the role and merits of defect modes in SSR arrays will be part of a further publication.

References

1. D. R. Smith, J. B. Pendry, and M. C. K. Wiltshire, Science **305**, 788–792 (2004)
2. J. B. Pendry, A. Holden, D. Robbins, and W. Stewart, IEEE Trans. Microwave Theor. Tech. **47** (11), 2075 (1999)
3. E. Shamonia, V. A. Kalinin, K. H. Ringhofer, and L. Solymar, J. Appl. Phys. **92**, 6252-6261 (2002)
4. Y. Akahane, T. Asano, B.-S. Song, and S. Noda, Nature **425**, 944-947 (2003)
5. F. Blanchard, A. Doi, T. Tanaka, H. Hirori, H. Tanaka, Y. Kadoya, and K. Tanaka, Opt. Express **19**, 8277-8284 (2011)
6. H. Hirori, A. Doi, F. Blanchard, and K. Tanaka, Appl. Phys. Lett. **98**, 091106 (2011)