Cryogenic temperature measurement of THz meta-resonance in symmetric metamaterial superlattice

J. H. Woo[1], E. S. Kim[1], Boyoung Kang[1], E. Y. Choi[1], Hyun-Hee Lee[1], J. Kim[1], Y. U. Lee[1], Tae Y. Hong[2], Jae H. Kim[2], and J. W. Wu[1]

[1]Department of Physics & Quantum Metamaterials Research Center, Ewha Womans University
120-750, Seoul, South Korea
Fax: + 82–2-32772326; email: cellis07@ewhain.net
[2]Department of Physics, Yonsei University
120-749, Seoul, South Korea
Fax: + 82–2-3921592; email: jaehkim@phya.yonsei.ac.kr

Abstract

We investigated a change in the Q-factor of THz meta-resonance as a function of temperature in a symmetric metamaterial superlattice composed by double-split ring resonators (DSRR). THz time-domain spectroscopy is carried out to measure the transmission spectra. From the FDTD simulation we found that counter-flowing current densities among the nearest neighboring metaparticles cancel each other, resulting in the excitation of a trapped mode in meta-resonance. Thus at low temperatures, we could analyze the impact factor for determining the Q-factor of the trapped mode compared with open-mode meta-resonance where radiative damping is still dominant.

1. Introduction

In metamaterials, it is possible to control the near-field interaction by changing their structural design, allowing for a control of Fano resonance characteristics such as the resonance frequency, and the quality factor [1]. It is well known that the asymmetric meta-particle in a symmetric array could excite a high Q-factor trapped mode. When an electromagnetic wave incident to asymmetric meta-particle an asymmetric current flow takes place in the meta-particle and the counter-flowing currents cancel each other by coherent coupling [2]. Also, it was reported that a metamaterial superlattice composed of symmetric double split ring resonators (DSRR) in an asymmetric array can excite a trapped mode by our group [3]. In this case, cancelation of counter-flowing currents among the nearest neighboring meta-particles give rise of trapped mode. But still there exists remnant dissipation owing to the presence of Joule loss of metallic resonator [4][5]. In this paper, we propose a symmetric metamaterial superlattice composed of symmetric DSRRs in a symmetric array to excite trapped mode. Also we demonstrate an increase in the quality factor by changing temperature from room temperature (300K) to cryogenic temperature (4K) using liquid helium.

2. Fabrication & Experiment

Double-split ring resonator (DSRR) is a highly symmetric structure possessing two orthogonal symmetry axes. It has the symmetric gap openings of 20° arc between ±10° and between ±170°. Our metamaterial is a superlattice structure of the DSRR metaparticle with the gap orientation alternating along ±22.5° respect to the x axis (Fig. 1(a)). And this alignment makes this superlattice structure as a mirror-symmetric structure with respect to the x-z and y-z planes. To fabricate metamaterial superlattice structure, a standard photolithography and lift-off process were employed. P-doped silicon wafer was used as substrate, and after photolithography process Au with thickness of 200nm was deposited on top of 10nm thick titanium which is an adhesion layer. Time-domain terahertz transmission measurements were carried out with a TeraView TPS Spectra 3000 Spectrometer at a resolution of 1.0cm^{-1} in vacuum. The time-domain pulse duration is about 2 ps, leading to the accessible spectral range of

0.1-3 THz (3-100cm^{-1}). And by using temperature controllable cryostat, liquid helium was introduced to vacuum chamber near the metamaterial superlattice permitting a low temperature measurement to investigate the changes in transmission spectra as a function of temperature.

3. Results

In Fig. 1(b), the time-domain THz pulse at different temperature of the metamaterial superlattice is shown. The silicon substrate experiences a huge change at low temperatures, so the position of time-domain THz pulse of sample has been changed [6]. In Fig. 1(c), THz transmission spectra of the metamaterial superlattice are shown for different polarization directions of the incident wave. Because of their symmetric structure, the transmission spectrum has almost the same shape when polarization angle of incident light is at 30°, 150° and at 60°, 120°. A notable feature is the appearance of a high Q resonance at 1.2THz (40cm^{-1}), which is called "trapped mode". From an FDTD simulation we figure out that trapped mode is induced by counter-flowing current densities among the nearest neighboring metaparticles. And by cancelation of these counter-flowing current densities, radiative damping is reduced resulting in high Q resonance. In Fig. 1(d), absorbance spectra of the metamaterial superlattice which is obtained from tranmission spectra are shown at different temperatures. At the liquid helium temperature it was possible to reduce Drude damping which comes from the Joule loss of metallic resonator, leading to an additional increase of the quality factor of the trapped mode.

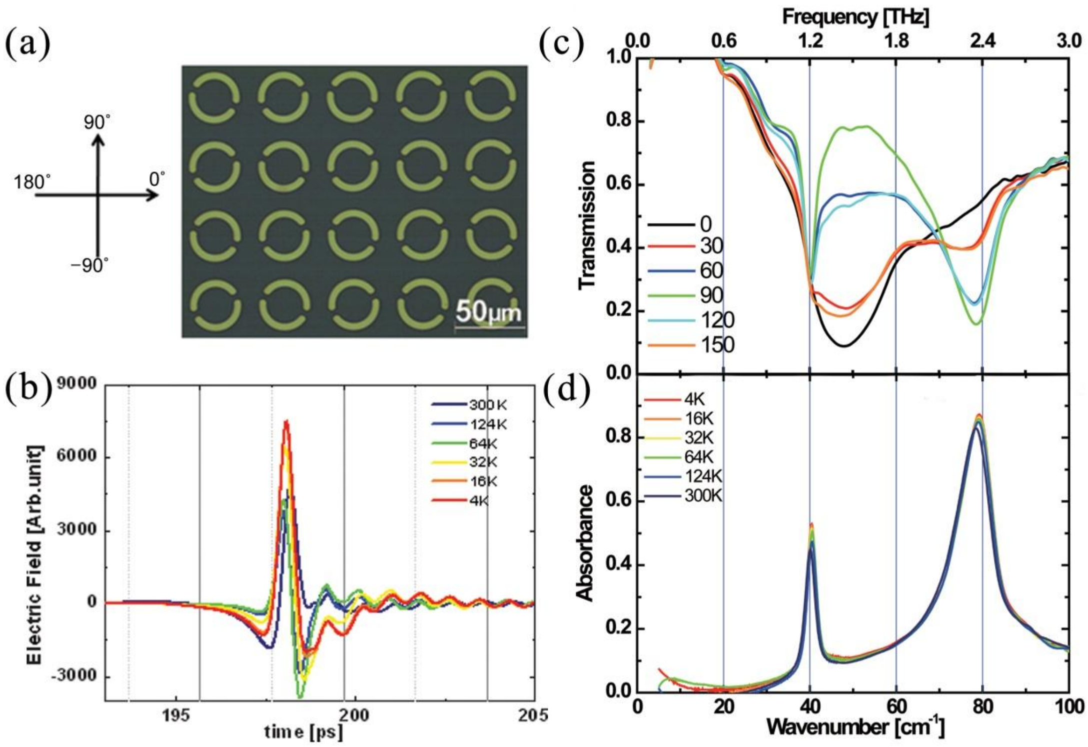

Fig 1: (a) Microscope picture of metamaterial superlattice structure and polarization angle of E-field. (b) Time-domain THz pulse of metamaterial depending on temperature. (c) Transmission spectra at different polarization angle. (d) Absorbance obtained from transmission spectra at different temperature.

From the Lorentzian resonance fitting of THz transmission spectra at each temperature, we obtain the Q-factor of trapped mode and open mode (Fig. 2). At liquid helium temperature, a 16% increase of Q factor of trapped mode is observed compared with room temperature. Also, for open mode 7% increase of Q factor is observed. With the Mathiessen's rule of the conducting electron mobility and assuming a linear dependence of the phonon scattering on the absolute temperature T, the least-squared fit of the measured damping is carried out. And supported by these results the impact factor for determining the Q-factor of the trapped mode is discussed compared with open mode [7].

ISBN 978-952-67611-0-7

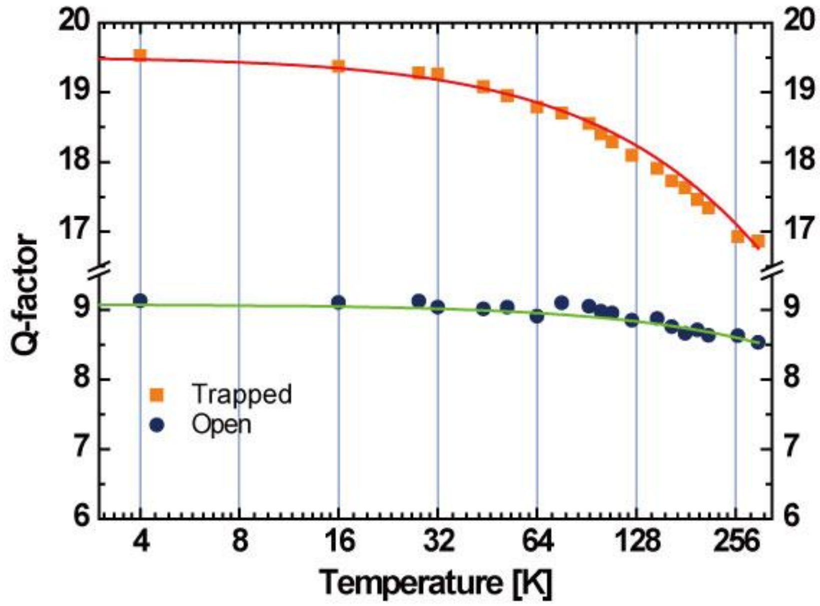

Fig. 2: Temperature dependence of the Q-factor of trapped and open-mode. The solid curve is fit to the experimental data

4. Conclusion

We demonstrated the excitation of trapped mode resonance in metamaterial superlattice structure without the presence of asymmetry. From the Finite-difference-time-domain simulation we found that cancelation of counter-flowing current densities among the nearest-neighboring meta-particles is responsible for the trapped mode excitation. The temperature dependence of meta-resonance in the symmetric metamaterial superlattice is investigated by a THz time-domain-spectroscopy measurement at the cryogenic temperature. A 16% increase of Q factor for trapped mode and 7% increase of Q factor for open mode are observed compared with room temperature.

References

[1] A. Christ, Y. Ekinci, H. H. Solak, N. A. Gippius, S. G. Tikhodeev, and O. J. F. Martin, Controlling the Fano interference in a plasmonic lattice, *Physical Review B,* vol. 76, p. 201405(R) , 2007.

[2] V. A. Fedotov, M. Rose, S. L. Prosvirnin, N. Papasimakis, and N. I. Zheludev, Sharp trapped-mode resonances in planar metamaterials with a broken structural symmetry, *Physical Review Letters*, vol. 99, p. 147401, 2007.

[3] Boyoung Kang, E. Choi, Hyun-Hee Lee, E.S. Kim, J. H. Woo, J. Kim, Tae Y. Hong, Jae H. Kim, and J.W. Wu, Polarization angle control of coherent coupling in metamaterial superlattice for closed mode excitation, *Optics Express*, vol. 18, p. 11552, 2010.

[4] V.A. Fedotov, A. Tsiatmas, J. H. Shi, R. Buckingham, P. de Groot, Y. Chen, S. Wang, and N.I. Zheludev, Temperature control of Fano resonances and transmission in superconducting metamaterials, *Optics Express*, vol. 18, p. 9015, 2010.

[5] Ranjan Singh, Zhen Tian, Jiaguang Han, Carsten Rockstuhl, Jianqiang Gu, and Weili Zhang, Cryogenic temperatures as a path toward high-Q terahertz metamaterials, *Applied Physics Letters*, vol. 96, p. 071114 2010.

[6] S. Nashima, O. Morikawa, K. Takata, and M. Hangyo, Temperature dependence of optical and electronic properties of moderately doped silicon at terahertz frequencies, *Journal of Applied Physics*, vol. 90, p. 837, 2001.

[7] J. H. Woo, E. S. Kim,1 E. Choi, Boyoung Kang, Hyun-Hee Lee, J. Kim, Y. U. Lee, Tae Y. Hong, Jae H. Kim, and J. W. Wu, Cryogenic temperature measurement of THz meta-resonance in symmetric metamaterial superlattice, *Optics Express*, vol. 19, p. 4384, 2011.

