Low Loss and tunable Superconducting Terahertz Metamaterial

B. B. Jin, J. B. Wu, C. H. Zhang, H. Dai, Z. M. Ji J. Chen and P. H. Wu
Research Institute of Superconductor Electronics (RISE), School of Electronic Science and Engineering,
Nanjing University
Nanjing 210093, China

***Abstract*-Superconducting terahertz (THz) metamaterial (MM) made from niobium (Nb) and niobium nitride (NbN) have been investigated using THz spectroscopies. The quality factor of the resonance modes can be remarkably increased when the working temperature is below the superconducting transition temperature, indicating that the use of superconducting material is a possible way to achieve low loss performance of THz MM. In addition, the tuning of superconducting THz MM by a magnetic field, and the temperature are also demonstrated.**

I. Introduction

Metamaterial (MM) is an arrangement of artificial structure elements to achieve advantageous and unusual electromagnetic properties, which cannot be realized with nature material[1]. These properties make it possible to manipulate the propagation of electromagnetic waves, giving rising to a variety of applications such as planar superlens and invisible cloaks at microwave band as well as functional devices at terahertz (THz) [2-6].

Metallic resonant structures on dielectric substrates are commonly used in MMs [7]. As such kind of structure is used in THz, Two disadvantages appear in realizing the unusual electromagnetic properties mentioned above. The first one is the large loss. Such structure has a relative low loss at microwaves, and allows us to demonstrate experimentally the extraordinary properties of the MMs. However, as the frequency gets to THz regime, the ohmic losses become prominent and the desired functions may not be implemented by using the current MM designs. The second one is tuning ability. The stability of metals makes it almost hard for the resonance tuning. The tunable metamaterials should be with active devices. In microwave, many commercial active microwave devices can be used. However, it is difficult in THz. So, an important task is to solve these two problems.

Recently, metallic THz MM operating at cryogenic temperature and superconducting THz MM based on yttrium-barium-copper oxide (YBCO) film are proposed for this purpose [8, 9]. In the former case, simulations show that the quality factor of the MM can be increased by 40% when the normal metal is kept at 1 K. In the latter case, i.e. superconducting THz MM made from YBCO film, although experimentally the loss does decrease as the temperature decreases, the surface resistance R_s of YBCO film at 0.1 THz and 77 K is comparable to that of the normal metal, implying that YBCO film may not be a very good candidate for superconducting THz MMs [10].

Here, THz MM made from superconducting Nb and NbN films were studied. We successfully demonstrate experimentally that the quality factor of the MM can be increased when the Nb and NbN film is in the superconducting state. Especially, for NbN THz MM, the quality factor is higher than that of the normal metal by at least one order. Besides, the tuning of superconducting MMs by a magnetic field is realized at THz in this paper, while in earlier days this tuning possibility was demonstrated only at microwave frequencies [11-12]. The frequency can also be tuned by ambient temperature for MM made from NbN films. Thus we have provided another method to control THz wave propagation apart from the existing electric and optical methods [4,13].

II. Experimental results

Two kinds of sample were studied. The first one is a square array of double-split-ring-resonators (double SRR) as shown in Fig. 1 [7, 15]. In fact a double-split-ring-resonator consists of two concentric split rings, the outer one and the inner one. The outer one measures 120 μm × 120 μm, while the inner one 80 μm × 80 μm. The widths of the both rings, the spacing between them, and the splits on them are all 10 μm. In the array the distances between neighboring double-split-ring-resonators are 20 μm, making each cell of the sizes 140 μm ×140 μm. The transmission property of this MM is

Fig.1 The microscopic image of the sample array

simulated by the commercially available code. In the simulation, the superconducting thin film is assumed to be a normal metal with a conductivity of 5×10^7 S/m. The wave propagates perpendicular to the plane of SRR, with the ac electric field parallel to the gap. Three resonance dips below 0.5 THz are obtained at 0.13 THz, 0.24 THz and 0.41 THz, respectively.

We measured the transmission properties using continuous-wave THz spectroscopy, and the necessary DC magnetic field, H_{dc}, can be provided by a superconducting split-coil magnet [16]. At 6 K and 0.13 THz, the unloaded quality factor is 86.5, in contrast, at 26 K, i.e., in the normal state, this value becomes 6.2, which is at least one order lower than the one at 6 K. This result demonstrates that low loss can be achieved as the Nb film is in the superconducting state. The physical reason is clear because superconducting Nb film has lower surface resistance than that in the normal state. In addition to the low loss properties, DC magnetic field tuning of superconducting MM can be implemented. As the magnetic field increases from 0 to 0.7 Tesla, the resonance frequency around 0.13 THz decreases with the increasing field. The total change is about 3 GHz. The reason is that penetration depth is field dependent [17]. It increases with the applied DC magnetic field, leading to the increase of the kinetic inductance.

We also demonstrate another kind of THz metamaterial made from NbN film, as shown in Fig.2 [18]. The films typically have a 15.8 K critical temperature (T_c) and are deposited on a 500 μm-thick MgO substrate (<100> orientation) using RF magnetron sputtering. Photolithograph and reactive ion etching are applied to pattern the film surface into periodical electric-LC (ELC) resonator structure. At 8 K, the resonance frequency is about 0.6 THz. We measured very high unloaded quality factor above 150, about 2 times as much as the value from Nb THz MM. In addition, close to T_c, there is a large blueshift for resonance frequency. We also measure the transmission spectra at different temperature up to 20 K in the normal state.

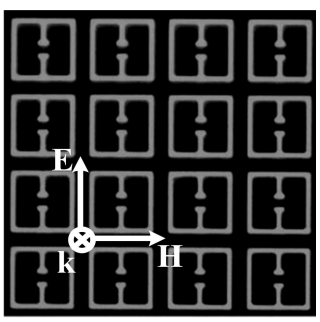

Fig.2 The schematic diagram of ELC unit cell.

The previous far-infrared measurements demonstrate the electrodynamics of the ultra-thin *NbN* film can be described in the framework of the BCS theory. Hence, we can calculate the conductivity σ(ω) of the *NbN* thin films from impurity scattering in the Born limit [19]. With this calculation, we can simulate the THz spectra. A good agreement can be obtained between the theory and the experiments.

ACKNOWLEDGMENT

This work is supported by the MOST 973 project (No.2007CB310404, No.2011CBA00107) of China, the National Natural Science Foundation (No. 61071009) and the Program for New Century Excellent Talents in University (NCET-07-0414).

REFERENCES

[1] M. Lapine and S. Tretyakov, " Contemporary notes on metamaterials, *IET Microw. Antennas Propa.* 1, 2007, pp. 3-11.

[2] A. Grbic and G. V. Eleftheriads, "Overcoming the diffraction limit with a planar left-handed transmission-line lens," *Phys. Rev. Lett.* **92**, 2004, 117403

[3] D. Schuring, J. J. Mock, B. J. Justice, S. A. Cummer, J. B. Pendry, A. F. Starr, D. R. Smith, "Metamaterial Electromagnetic cloak at microwave frequencies," *Science* **314**, 2006, pp977-980.

[4] H. –T. Chen, W. J. Padilla, J. M. O. Zide, A. C. Gossard, A. J. Taylor, and R. D. Averitt, " Active terahertz metamaterial devices, " *Nature* 444, 2006, pp.597-600.

[5] Yu Yuan, Christopher Bingham, Talmage Tyler, Sabarni Palit, Thomas H. Hand, Willie J. Padilla, David R. Smith, Nan Marie Jokerst, and Steven A. Cummer, " Dual-band planar electric metamaterial in the terahertz regime, " *Opt. Express* 16, 2008, pp.9746-9752.

[6] N. H. Shen, Maria Kafesaki, Thomas Koschny, Lei Zhang, Eleftherios N. Economou, and Costa M. Soukoulis, " Broadband blueshift tunable metamaterials and dual-band switches, " *Phys. Rev. B* 79, 2009, R161102.

[7] J. B. Pendry, A. Holden, D. D. Robbins, and W. Stewart, "Magnetism from Conductors and Enhanced Nonlinear Phenomena," *IEEE Trans. Microwave Theory Tech.* 47, 1999, pp.2075-2084.

[8] R. Singh, Z. Tian, J. Han, C. Rockstuhl, J. Gu and W. Zhang, "Cryogenic temperatures as a path toward high-Q terahertz metamaterials," Appl. Phys. Lett. 96, 071114 (2010)

[9] J. Gu, R. Singh, Z. Tian, W. Cao, Q. Xing, J. Han and W. Zhang , "Superconductor terahertz metamaterial," arXiv:1003.5169 (2010)

[10] I. Wilke, M. Khazan, C. T. Rieck, P. Kuzel, T. Kaiser, C. Jaekel and H. Kurz, "Terahertz surface resistance of high temperature superconducting thin films," J. Appl. Phys. 87, 2984-2988 (2000)

[11] M. Ricci, N. Orloff, and S. M. Anlage, "Superconducting metamaterials," Appl. Phys. Lett. 87, 034102 (2005)

[12] M. C. Ricci, H. Xu, R. Prozorov, A. P. Zhuravel, A.V. Ustinov and S. M. Anlage, "Tunability of Superconducting Metamaterials," *IEEE Trans. Appl. Supercond.* 17, 2007, pp.918-921

[13] W. J. Padilla, A. J. Taylor, C. Highstrete, M. Lee and R. D. Averitt, "Electrically resonant terahertz metamaterials: Theoretical and experimental investigations," *Phys. Rev. Lett.* 96, 2006, 107401

[14] H. T. Chen, J. F. O'Hara, A. K. Azad, A. J. Taylor, R. D. Averitt, D. B. Shrekenhamer and W. J. Padilla, "Experimental demonstration of frequency-agile terahertz metamaterials," *Nat. Photonics* 2, 2008, pp.295-298.

[15] A. K. Azad, J. Dai and W. Zhang, "Transmission properties of terahertz pulses through subwavelength double split-ring resonators," Opt. Lett. 31, 634-636 (2006)

[16] A. V. Pronin,, M. Dressel, A. Pimenov, A. Loidl, I. V. Roshchin and L. H. Greene, "Direct observation of the superconducting energy gap developing in the conductivity spectra of niobium," Phys. Rev. B 57, 14416-14421 (1998)

[17] W. Coffey and J. R. Clem, "Unified theory of effects of vortex pinning and flux creep upon the rf surface impedance of type-II superconductors," Phys. Rev. Lett. **67**, 386-389 (1991)

[18] N. Katsarakis, T. Koschny, M. Kafesaki, E. N. Economou, C. M. Soukoulis, "Electric coupling to the magnetic resonance of split ring resonators," *Appl. Phys. Lett.* **84**, 2004, pp.2943-2945.

[19] L. Kang, L. Kang, B. B. Jin, X. Y. Liu, X. Q. Jia, J. Chen, Z. M. Ji, W. W. Xu, P. H. Wu, S. B. Mi, A. Pimenov, Y. J. Wu, and B. G. Wang, " Suppression of superconductivity in epitaxial NbN ultrathin films" J. Appl. Phys. 109, 2011, 033908