Tunable and high quality factor Fano and toroidal dipole resonances in terahertz superconducting metamaterials

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Keywords: Fano resonance, high quality factor, slow light, superconducting devices, terahertz metamaterials, toroidal resonance

Abstract

We experimentally studied a series of terahertz (THz) metamaterials with asymmetric resonator structures made from superconducting niobium nitride or gold films. Fano and toroidal dipole resonances are excited in superconducting metamaterials and their quality factors are higher in comparison with those of gold samples. Superconducting samples possess good tuning behaviors for both Fano and toroidal dipole resonance frequencies due to the change of kinetic inductance under different temperatures. The superconducting samples also exhibit good slow light effect due to the sharp dispersion in transmission spectra. These tunable and low loss metamaterials possess great significance to the development of THz nonlinear and slow light devices.

1. Introduction

In recent years, metamaterials offer us an approach to realize a multitude of exotic electromagnetic responses by designing subwavelength structures and have many promising applications such as flat lens, holography, compressive imaging, and wireless communication [1–8]. In the terahertz (THz) band, metamaterials have been used to develop a variety of functional devices such as modulators, filters, wave plates, biosensors, etc [9–12]. Along with the rise of metamaterials, the inherent loss issue greatly limits their performance and hinders many applications. Reducing the loss of THz metamaterials will be of great benefit for elevating the performance of THz functional devices [13]. What is more, THz metamaterials with low loss can be used to strengthen the interaction of THz wave and materials and induce the nonlinear response of natural materials [14–16].

For metamaterials at microwave and THz frequencies which commonly consist of the metallic resonant structures, the loss mainly includes Ohmic loss of metal and radiation loss coming from the coupling of resonant structure with free space. A lot of attempts have been done on minimizing the loss of metamaterials. In previous work, placing the metallic elements into cryogenic environments [17] and using superconductors such as yttrium–barium–copper oxide (YBCO) [18–21], niobium (Nb) [22, 23] and niobium nitride (NbN) [24] could bring in the reduction of Ohmic loss. Compared with high-temperature superconductor such as YBCO, Nb and NbN have remarkably lower Ohmic loss below the gap frequency. On the other hand, an effective way to reduce the radiation loss is to introduce asymmetry into the resonator structure to excite Fano [25–27] and toroidal resonances [28–30] which are absent from direct interaction with free space electromagnetic wave. Accordingly, the combination of superconducting film and asymmetric resonator structures offers a reasonable solution to low loss THz metamaterials.

A specific advantage of superconducting metamaterials is the good tuning properties. It has been demonstrated the spectral response of superconducting metamaterials could be tuned under external stimuli such as the magnetic field [23], electric bias [31], optical pump [32] and temperature [20, 33, 34]. The sharp change of complex conductivity along with the phase change of superconducting film results in the change of resonance strength and frequency. In that case, the introduction of superconducting film into the metamaterials...
In this study, we chose four typical asymmetric split ring resonator (SRR) structures to fabricate NbN and gold metamaterials [30, 35]. The microscopic images and the geometric parameters of each unit cell are plotted in figure 1. They are named ASR, ASY, REC0, and REC3.5, respectively. As shown in figures 1(a) and (b), the unit cells of ASR and ASY are asymmetric SRRs with double gaps. In the case of ASR, the inner radius and outer radii are 27 and 36 μm, respectively. In figure 1(a), α and β denote the angle of the upper and lower arc segment. Correspondingly, the asymmetry parameter are defined as \( \delta = \frac{(\alpha - \beta)}{(\alpha + \beta)} \times 100\% \) [35]. For the fabricated ASR sample, \( \alpha = 170^\circ \) and \( \beta = 150^\circ \) and \( \delta = 6.25\% \). As shown in figure 1(b), the asymmetric square ring resonator is divided into top and bottom part by two 12.5 μm-long gaps, the inner and outer side lengths of the square ring are 50 and 60 μm separately. \( l_1 \) and \( l_2 \) denote the length of the top and bottom parts. The degree of asymmetry is expressed as \( \delta = \left(\frac{\left|\left(l_1 - l_2\right)\right|}{\left(l_1 + l_2\right)}\right) \times 100\% \) [25], where \( l_1 = 105 \mu m, \ l_2 = 90 \mu m \) and \( \delta = 7.6\% \). Figures 1(c) and (d) show the structures of two bonding rectangle rings with each ring split by two 1.5 μm-long gaps. Asymmetry is introduced by moving the centerline of gaps equally away from the lateral central axis of the square ring with a distance of \( d \). REC0 and REC3.5 have the same geometric structure except for \( d \). The values of \( d \) for REC0 and REC3.5 are 0 and 3.5 μm respectively. The geometric parameters are shown in the close-up of a unit cell in figure 1(d).

For the fabrication of NbN samples, firstly, the 200 nm-thick NbN film was deposited onto the 1 mm-thick MgO substrate using radio frequency magnetron sputtering. The NbN film has a superconducting critical temperature (\( T_c \)) of 15 K. The patterned structures are formed by conventional photolithography and reactive ion etching. For comparison, we fabricated the gold samples with the same geometry and substrate using the lift-off process.

We used the low temperature THz time-domain spectroscopy to characterize the NbN superconducting metamaterials. The samples were placed in a liquid helium continuous flow cryostat, and temperatures were changed from 4.5 K to 300 K. The transmitted THz pulses are at normal incidence and the electric field is oriented as plotted in figure 1. Using a blank MgO substrate as a reference, we obtained the THz transmission spectra which are the ratios of the Fourier transformed spectra of the transmitted signals through sample and reference substrate.
3. Measurement and simulation

The measured THz transmission spectra of NbN metamaterials at different temperatures are shown in figure 2. At low temperature, the asymmetric spectral lineshape appears at a lower frequency along with a symmetric resonance profile at higher frequency in each transmission spectra. These asymmetric resonances can be attributed to Fano or toroidal resonance which arises from the destructive interference of the sharp dark mode and broad bright mode. When the temperature goes up to 14 K and above, the asymmetric lineshapes almost disappear and the broad resonances at higher frequency remain. The transmission spectra of the gold samples at room temperature are also plotted in figure 2. Compared with the transmission spectra of NbN samples, their spectral responses are quite similar. However, the asymmetric resonance profiles of NbN samples at 4.5 K is significantly sharper than those of gold samples at room temperature, indicating higher Q factor resonances are excited when NbN film is in the superconducting state.

Meanwhile, we did numerical electromagnetic simulations of both superconducting and gold samples for comparison. The complex conductivity of NbN film at different temperatures was calculated using the formula of Born limit model based on BCS theory \[[36]\]. The substrate used in the simulation was MgO substrate and the permittivity was set to be 9.8. We used the time-domain solver with periodic boundaries in the x and y directions and open boundaries in the z-direction. The simulated THz transmission spectra of NbN samples and Au samples are plotted in figure 3. As illustrated in figure 3, the lineshapes of the transmission spectra of NbN samples at various temperatures and the corresponding Au samples at room temperature agree well with the experimental results. When the NbN samples transit from the normal state to the superconducting state, there is a significant drop for resonance frequency due to the surge of kinetic inductance with the appearance of superconducting carriers. With the further decrease in temperature, resonant frequency increases gradually. According to the theory of superconductivity, the penetration depth of the superconductor decrease due to the increase of the superconducting carrier concentration. Correspondingly, the kinetic inductance decreases, resulting in the gradual increase of the resonant frequency. The tuning behavior of both resonant frequency and

![Figure 2](image_url)
amplitude with temperature in the measured transmission spectra is also well reproduced by the obtained simulation results.

To understand the mechanism of resonances having asymmetrical lineshapes, we simulated the surface current distribution of four structures at these resonant frequencies and plotted them in figure 4. Figures 4(a) and (b) show the surface current distribution of ASR and ASY at asymmetric resonance frequencies, respectively. The excited current in the upper and lower arm of ring resonator is antiphase and has nearly anti-symmetric distribution. In this case, the radiation field coming from the electric and magnetic dipole is canceled, so the coupling with the free space is suppressed. As a result, the radiation loss is greatly reduced. It proves that the resonances of two asymmetric lineshapes can be attributed to Fano mode. As displayed in figures 4(c) and (d), the current circulating the two loops of the unit cell forms a toroidal dipole moment ($T_{tor}$) along the direction of the incident electric field, which is consistent with the former work [30]. It means the toroidal dipole mode is excited in both REC0 and REC3.5. For toroidal dipole resonance, similarly, the asymmetry spectral line arises from the destructive interference between radiative electric dipole and toroidal dipole mode, and the loss of radiation into the far-field zone is reduced. Therefore, the samples of REC0 and REC3.5 have low radiation loss as well. In figures 4(c) and (d), we notice that the current in the central arm of the structure is larger than the top and bottom arms when $d = 0$, whereas the current distribution on the three arms is almost equal in magnitude when $d = 3.5 \, \mu m$. The balanced current distribution of REC3.5 leads to the strong excitation of the toroidal dipole mode.

4. Discussion

From the measured and simulated transmission spectra of superconducting metamaterials, we could observe the tuning of the Fano or toroidal dipole resonance in the superconducting state. Both the resonance frequency and strength experience obvious changes with the increase of temperature for all four samples due to the temperature-dependent impedance in the superconducting state. We chose the NbN samples of ASY and REC0 for analysis. The Fano and toroidal dipole resonance frequencies and dip values as a function of temperature are obtained and plotted in figure 5. As the temperature goes up, both the Fano and toroidal dipole resonance...
Figure 4. The simulated surface current distribution at the lower resonance frequency of the asymmetric model for superconducting NbN samples of ASR (a), ASY (b), REC0 (c), and REC3.5 (d).

Figure 5. The measured resonance frequency of Fano resonance or toroidal dipole resonance and transmission dip value for NbN samples of ASY (a) and REC0 (b) as a function of temperature.
frequencies gradually red-shift, while the resonance dips gradually increase. The Fano resonance frequency for ASY gradually decreases from 0.571 THz at 4.5 K to 0.547 THz at 13 K, the frequency tuning range is 24 GHz. Similarly, the toroidal dipole resonance frequency of REC0 changes from 0.789 THz at 4.5 K to 0.745 THz at 13 K, the frequency tuning range is 44 GHz. The frequency tuning behavior, which is similar to previous reports of superconducting metamaterials [20, 33, 37], can be attributed to the increase of kinetic inductance. The dip values gradually increase with the increasing temperature and the dips finally disappear when the temperature is above 14 K. The weakening of the Fano and toroidal resonances is mainly due to the increase of Ohmic loss of NbN film.

The time domain profiles of transmitted THz pulses through both superconducting and gold samples of ASR and REC0 are plotted in figure 6. The main THz pulses passing through the sample are accompanied by oscillations lasting for a long time. The center frequencies of the trailing oscillation are corresponding to the transmission peaks of Fano and toroidal resonances in their transmission spectra. The phenomenon, which is similar to electromagnetic induced transparency metamaterials [20, 33, 37], can be attributed to the increase of kinetic inductance. The dip values gradually increase with the increasing temperature and the dips finally disappear when the temperature is above 14 K. The weakening of the Fano and toroidal resonances is mainly due to the increase of Ohmic loss of NbN film.

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The phase and group delay spectra of ASR and REC0 for NbN sample at the temperature of 4.5 K and the corresponding Au samples at room temperature are plotted in figure 7. There are obvious changes of phase around the Fano and toroidal resonances. The group delay \( t_g \) at each frequency is calculated using \( t_g = \frac{d\varphi(\omega)}{d\omega} \), where \( \omega \) is the angular frequency and \( \varphi(\omega) \) is the measured phase delay shown in figures 7(a) and (b). The group delays of both two NbN samples at 4.5 K are much higher than those of corresponding gold samples. The
maximum group delays of the NbN samples of ASR and REC0 reach 20.6 ps and 16.7 ps (denoted by the triangle dots in figure 7) while the maximum group delays of the gold samples for contrast are 12.5 ps and 6.8 ps, respectively. The results suggest that the superconducting samples have better ‘slowing light’ effects than gold samples. A similar ‘slow light’ effect is also observed in the other two kinds of samples. The slow light effect has many promising applications such as communication, high-speed optical processing, and quantum information [38].

In the following, we analyzed the Q factors of the Fano and toroidal resonances from the measured THz transmission spectra. Based on the above study, the lower frequency resonance modes are corresponding to Fano resonance for ASR and ASY and toroidal dipole resonance for REC0 and REC3.5 [30, 39]. The coupled mode theory is used to analyze asymmetric profiles of Fano resonance [40]. Based on the coupled mode theory, the asymmetric profiles of Fano resonances arise from the destructive interference of dark modes and a highly radiative mode. To obtain the Q value of Fano or toroidal dipole resonance, the asymmetric profiles of resonance were fitted with the Fano resonance formula [41]

\[
T(f) = A \left[ \frac{q + \frac{2(f - f_0)^2}{\Gamma}}{1 + \frac{2(f - f_0)^2}{\Gamma}} \right] + B,
\]

where \(q\) is Fano parameter, \(\Gamma\) is the resonance width, and \(A, B\) are constants. To simplify the fitting process, we first remove the background around the asymmetric resonance, which mainly comes from the contribution of the symmetric resonance profile at a higher frequency. Then, we use equation (1) to fit the asymmetric resonance profile. After completing the fitting process, the values of the Q factor are obtained by \(Q = f_0/\Gamma\). The Q factors of NbN samples at 4.5 K are 23.0, 21.8 and 23.4 for ASR, ASY, and REC0. In contrast, the corresponding Q factors of gold samples are 19.0, 16.6 and 15.6, which are all lower than those of NbN samples. As for REC3.5, the Q factor of the NbN sample at 5.7 K is 21.5. On the contrary, the asymmetric resonance disappeared in the measured transmission spectra of the gold sample. It can be explained by the previous theoretic studies that high
conductivity is required for conductors to excite the high Q factor resonances in structures with little asymmetry [25].

Based on the above study, we demonstrate the Q factors of Fano and toroidal resonance could be increased by introducing a superconducting NbN film. However, their Q factors are still not as high as we expect. The optimization of the structure design to reduce radiative loss is highly desired. One feasible way to obtain sharp resonance is by reducing the asymmetry degree of resonator structure as demonstrated in previous work [25, 35]. We characterized NbN metamaterials of ASR with an asymmetry degree of 1.25% (data not shown). Unfortunately, the Fano resonance is not observed in the measured transmission spectra. We also used zero-padding to extend the time-domain data for a better frequency resolution, but the sharp Fano resonance is still not found. The result is not so encouraging. In our understanding, the dark modes ideally have no radiative loss due to the absence from coupling with free space, and the Ohmic loss is negligible in the superconducting state, however, the radiative loss of bright modes and the interaction of two modes still limit the increase of Q factors. On the other hand, the search for high Q factor resonance is limited by the measurement apparatus. Restricted by the space of cryostat, the thickness of MgO substrate is 1 mm and the scanning time after the main peak of THz pulse is about 20 ps. Increase the scan time of THz TDS system will be of great help for the improvement of frequency resolution. Besides that, further study about the loss mechanism of Fano and toroidal dipole resonances and the optimization of structure design will be valuable.

5. Conclusion

In conclusion, we demonstrated THz superconducting NbN metamaterials with asymmetric structure favor the excitation of Fano and toroidal dipole resonances with high Q factor. The superconducting metamaterials exhibited good tuning properties and a better slow light effect than the gold metamaterials. Recently, it has been demonstrated superconducting film under intense THz radiation could exhibit nonlinear behavior [15, 16]. Thus, the superconducting metamaterials will contribute to the development of nonlinear THz devices with tuning ability. Our work is also useful for the strengthening of the interaction between THz wave and matter and the development of THz slow light devices.

Acknowledgments

This work was supported by National Key Research and Development Program of China (2017YFA0700202); National Nature Science Foundation of China (NSFC) (61521001, 61701219, 61731010, 61671234 and 61571217); Jiangsu Provincial Natural Science Fund (BK20170649); the Fundamental Research Funds for the Central Universities; Jiangsu Key Laboratory of Advanced Techniques for Manipulating Electromagnetic Waves.

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