Nonlinear response of superconducting NbN thin film and NbN metamaterial induced by intense terahertz pulses

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Abstract. We present the nonlinear response of superconducting niobium nitride (NbN) thin film and NbN metamaterial with different thicknesses under intense terahertz pulses. For NbN thin film, nonlinearity emerges and superconductivity is suppressed with increasing incident terahertz electric field, and the suppression extent weakens as the film thickness increases from 15 to 50 nm. As the variation in intense terahertz fields alters the intrinsic conductivity in NbN, a consequent remarkable amplitude modulation in NbN metamaterial is observed due to the strong nonlinearity. Absorbed photo density in either NbN film or NbN metamaterial is estimated and used to understand the mechanism of nonlinear response. With a thicker NbN film element of 200 nm, the resonance...
of the metamaterial shows similar nonlinear modulation accompanied by a lower loss and a higher quality factor compared with a thinner NbN film element of 50 nm, which demonstrates the innovative implementation of strongly enhanced nonlinearity with thick superconducting film elements and the potential for novel applications using nonlinear metamaterial.

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1. Introduction

The nonlinear response of materials is an essential and challenging task in the microwave to optical spectral range [1–10], especially in the terahertz (THz) regime because of the lack of intense terahertz sources. The recent development of a high-field terahertz source brings new opportunities to induce nonlinear effects in conventional matter, such as semiconductors [11], quantum wells [12], ferroelectrics [13] and metal oxides [14]. Studies on the nonlinear response in superconductors under an intense terahertz field not only help clarify the physical mechanism of superconductors, but are also important for potential applications. For instance, in La$_{1.84}$Sr$_{0.16}$CuO$_4$, the strong terahertz field alters the coupling between the two layers, thereby switching between two-dimensional and three-dimensional superconducting behavior [15]; in niobium nitride (NbN), the dynamics of the nonequilibrium BCS state were studied [16]. Meanwhile, we reported the nonlinear effects of superconducting YBa$_2$Cu$_3$O$_{7-δ}$ (YBCO) film [17], NbN film [18] and NbN metamaterial [19], which can be modulated by the intense terahertz field and serve as an ultrafast switch. Actually, a metamaterial is arguably an excellent environment for nonlinearity because it allows the light to be tightly confined over a subwavelength scale and thereby the high field intensity permits a greater sensitivity to small changes in the material [11, 14, 20]. Superconducting NbN metamaterials not only provide high conductivity but are also extremely sensitive to intense terahertz pulses for fast tunable devices compared with metal metamaterials, which contribute very little to tunability [21–23]. On the other hand, for superconductors, the transmission is too low and the reflection is too high in the terahertz regime due to the high superconductivity, especially in NbN thin film [24, 25], which makes it difficult to measure the NbN film with traditional transmitted terahertz time-domain spectroscopy (TDS), even for a thickness of tens of nm. Although the intense terahertz pulses can suppress the conductivity and thereby increase the transmission and decrease the reflection of NbN film to a certain extent, the propagated or penetrated terahertz field cannot induce a significant nonlinear response in deeper areas even for a film with a thickness of tens of nm. Here, we present the nonlinear response of superconducting NbN thin film with various thicknesses ranging from 15 to 50 nm, and the nonlinear dramatic modulation of superconducting 50 and 200 nm thick NbN metamaterial under intense terahertz
pulses. It is well known that thickness is an important parameter, as the reflection, absorption and surface impedance of superconducting films, and metamaterial resonance strongly depend on the thickness [22, 26, 27]. Hence, it is worth studying the thickness-dependent nonlinear response.

2. Experimental

NbN thin film was deposited on 1 mm thick MgO substrate (10 × 10 mm) using RF magnetron sputtering to fabricate three samples of different thickness: 15, 30 and 50 nm. The transition temperature $T_c$ of these three films was 14.5, 15.4 and 15.4 K, respectively. For the NbN metamaterial, which is a planar array of superconducting NbN split ring resonators (SRRs) periodically printed on the same 1 mm thick MgO substrate, other steps of standard photolithography and reactive ion etching (RIE) were taken to pattern the SRR structures from 50 nm thick ($T_c = 15.4$ K) and 200 nm thick NbN film ($T_c = 15.4$ K). Figure 1(c) shows the schematic of a single SRR unit cell, where $g = t = 5 \, \mu m$, $w = 10 \, \mu m$, $a = 50 \, \mu m$ and the period $p = 60 \, \mu m$.

For nonlinear measurements, high-field terahertz transmission experiments were performed. Figures 1(a) and (b) show the experimental diagram for measuring the superconducting NbN thin film and NbN metamaterial, respectively. The intense single-cycle terahertz pulse was generated by optical rectification in a single-domain lithium niobate (LiNbO$_3$) crystal using tilted-pulse-front excitation [28, 29]. The generated terahertz spectrum was located below the BCS energy gap region of the NbN film ($\Delta(0) \sim 1.2$ THz) as shown in figure 1(d). The experimental setup was similar to one previously used [19]. Briefly, it consists of a 100 fs Ti:sapphire regenerative amplifier (Spitfire®, Spectra-Physics) operating at 800 nm with a repetition rate of 1 kHz and a conventional terahertz detection system based on an electro-optic sampling technique in a ZnTe crystal. The terahertz beam was focused onto the cryogenically cooled samples at temperatures from 4.2 to 300 K. Using a pyroelectric detector (SPI-A-62, Spectrum Detector Inc.), the peak terahertz electric field applied to the samples was estimated to be around $E_0 = 30$ kV cm$^{-1}$. The incident terahertz field strength $E_{in}$ could be quickly varied from about 1 to 30 kV cm$^{-1}$ by using a pair of terahertz wire grids driven by an electric motor.

3. Results and discussion

First, the nonlinear response of superconducting NbN thin films with various thicknesses was studied under intense terahertz pulses. The complex transmission is obtained by

$$\tilde{t}(\omega) = \tilde{E}_{\text{sam}}(\omega)/\tilde{E}_{\text{ref}}(\omega),$$

where $\tilde{E}_{\text{sam}}(\omega)$ and $\tilde{E}_{\text{ref}}(\omega)$ are the Fourier-transformed transmitted electric fields of the sample and the reference (bare MgO substrate), respectively. The complex conductivity $\sigma(\omega) = \sigma_1(\omega) - j\sigma_2(\omega)$ can then be easily extracted from the complex transmission [30, 31]. Figures 2(a)–(c) show the extracted complex conductivity of the NbN thin films having thickness $d = 15, 30$ and 50 nm, respectively, for various incident terahertz electric fields $E_{in}$ at 4.2 K. At a low incident field strength $E_{in} = E_0/16$, all three NbN thin films show a strong superconducting state, which is almost the same as that measured by conventional low electric field THz-TDS [24]. As the incident terahertz field $E_{in}$ increases, the real conductivity $\sigma_1(\omega)$ gradually increases and the imaginary conductivity $\sigma_2(\omega)$ decreases simultaneously. This behavior was observed in all three samples. For thin NbN film, such as the 15 nm thick NbN film sample, the $\sigma_2(\omega)$ is suppressed and decreases remarkably when the incident terahertz field is
gradually increased from $E_0/16$ to $E_0$. However, for the thicker NbN film, i.e. the 30 and 50 nm thick samples, a weaker decrease in $\sigma_2(\omega)$ is exhibited. Here, we can clearly see that there is almost no prominent drop in $\sigma_2(\omega)$ with low incident terahertz electric fields $E_{in}$ from $E_0/16$ to $E_0/2$ for 50 nm thick NbN film. The increase in $\sigma_1(\omega)$ and decrease in $\sigma_2(\omega)$, respectively, starts immediately and gradually for the 15 nm thick NbN film with $E_{in}$ from $E_0/16$ to $E_0$. However, as the film thickness increases, the terahertz field shows a weaker impact on the suppression of NbN superconductivity. The obvious increase in $\sigma_1(\omega)$ and decrease in $\sigma_2(\omega)$ starts from around $E_0/4$ for the 30 nm thick NbN film, and at around $E_0/3$ for the 50 nm thick NbN film. There seems to be a certain transition value or threshold of the incident terahertz electric field that can induce obvious nonlinear effects in the superconducting NbN film. It is known that the penetration depth of NbN is more than 200 nm at 4.2 K [17]. Thus, for very thin NbN film, i.e.
Figure 2. Measured complex conductivity of superconducting NbN thin films with thicknesses of 15 nm (a), 30 nm (b) and 50 nm (c), respectively.

15 nm, it can be assumed that the penetrated intense terahertz field is almost evenly distributed in the film; in this case, the nonlinear response is evidently induced in the whole film. However, as the film thickness increases, the internal terahertz field is no longer evenly distributed and it becomes increasingly weaker in the deeper area of the film. Consequently, the thick NbN film can be considered as two shunted parts: the strongly induced top layer and the weakly or noninduced deep layer. Therefore, the overall observed nonlinear response in thick NbN film exhibits a weaker effect.

In the case of superconducting thin film, the transmission and reflection coefficients can be expressed as the following equations [17, 31]:

\[
\tilde{t}(\omega) = \frac{1 + n_{\text{sub}}}{1 + n_{\text{sub}} + Z_0\sigma(\omega)d},
\]

(1)

\[
\tilde{r}(\omega) = \frac{1 - n_{\text{sub}} - Z_0\sigma(\omega)d}{1 + n_{\text{sub}} + Z_0\sigma(\omega)d},
\]

(2)
where \( Z_0 \) is the impedance in vacuum, \( n_{\text{sub}} \) is the refractive index of the substrate and \( d \) is the thickness of the film. It is obvious that as the thickness \( d \) increases, the amplitude transmission decreases and the reflection increases, i.e. \( d = 200 \) nm, the transmittance is reduced to less than 0.2\%, and the reflectance reaches the order of 99.5\%, which makes it almost impossible to measure, or induce and evaluate the nonlinear response even under an intense terahertz field. In this case, very few of the incident terahertz fields can propagate and penetrate the film, and may induce a nonlinear response only in the surface or top layer: the deeper part of the film is still in a superconducting state, and thus an obvious nonlinear response cannot be observed in such thick NbN film.

In order to induce and evaluate an obvious nonlinear response, a metamaterial is selected as it allows the light to be tightly confined over a subwavelength scale and thereby has greater sensitivity to small changes in the material induced by high field intensity, especially for thicker superconducting metamaterial with lower ohmic losses, as the lower loss is one of the key issues in the development of metamaterial \([32–35]\). Briefly, the selected superconducting metamaterial can be equivalent to an RLC circuit \([19, 26, 32, 35]\), where the resonant transmission amplitude \( |\tilde{t}(\omega)| = |(1 + n_{\text{sub}})/(1 + n_{\text{sub}} + Z_0/R)| \) strongly depends on the effective resistance \( R \) (proportional to the ohmic losses of the film), and the resonance frequency depends on the effective capacitance \( C \) and total inductance \( L \), i.e. \( \omega_{0} = (LC)^{-1/2} \). Here, the total inductance \( L \) includes the geometric inductance \( L_g \) and the kinetic inductance \( L_k \) in the superconducting state as \( L = L_g + L_k \). The effective surface impedance of a superconducting film with a thickness of \( d \) can be expressed as \([19, 26, 35]\)

\[
Z_{s,\text{eff}}(\omega) = R_{s,\text{eff}} + jX_{s,\text{eff}} = \sqrt{\frac{j\omega\mu_0}{\sigma(\omega)}} \coth(d\sqrt{\frac{j\omega\mu_0\sigma(\omega)}}),
\]

where \( R_{s,\text{eff}} \) and \( X_{s,\text{eff}} = \omega L_k \) are the effective surface resistance and reactance, respectively, and \( \mu_0 \) is the magnetic susceptibility in vacuum. Consequently, \( R_{s,\text{eff}} \) and \( X_{s,\text{eff}} \) decrease as the film thickness increases; thus, a lower loss and high quality factor resonator can be obtained by increasing the film thickness \([26]\).

Here, we employed the intense terahertz field to induce a nonlinear response in a 200 nm thick NbN metamaterial, and another previously reported 50 nm thick NbN metamaterial was also made for comparison \([19]\). A sharp inductor–capacitor (LC) resonance is excited when the incident terahertz field polarization is perpendicular to the SRR gap. Figure 3 shows the measured amplitude transmission \( |\tilde{t}(\omega)| = |\tilde{E}_{\text{sam}}(\omega)/\tilde{E}_{\text{ref}}(\omega)| \) for the 200 nm thick (figure 3(a)) and 50 nm thick (figure 3(b)) NbN metamaterials with various incident terahertz fields at 4.2 K. The transmission shows a sharp resonance dip with \( E_{in} = E_0/16 \), and remarkable modulation of transmission without a prominent resonance frequency shift with increasing \( E_{in} \) from \( E_0/16 \) to \( E_0 \) was observed in both of these metamaterial samples, which is attributed to the nonlinearity of the lumped superconducting NbN elements. However, the transmission dip approaches −35 dB at around 0.6 THz for the 200 nm thick sample, while the transmission dip is −20 dB for 50 nm thick NbN with \( E_{in} = E_0/16 \). Such a thicker superconducting metamaterial not only allows simple and fast switching between a low and high transmission state by varying the incident terahertz field, but also provides lower ohmic loss \([26]\) and sharper resonance \([22, 27]\), and thus is an excellent choice for developing a high quality factor, which is the present goal of a metamaterial \([26, 33, 35]\). The unloaded quality factor of the demonstrated superconducting NbN metamaterial reached as high as 178 (200 nm thick sample) from 35 (50 nm thick sample), indicating low ohmic loss. To achieve a high loaded quality factor (here, around 3
Figure 3. Measured amplitude transmission spectra of NbN metamaterial with NbN thicknesses of 200 nm (a) and 50 nm (b).

Figure 4. Surface electric field distribution of 50 nm thick NbN metamaterial from the numerical simulation at a resonance frequency of 0.45 THz with various incident terahertz electric fields of $E_{in} = E_0/16$, $E_0/4$ and $E_0$, respectively.

because of the large coupling loss that manifests itself in such a structure), it is essential to optimize the structure design, for example, a recently developed high-quality sharp THz metamaterial [36–38] can obtain a quality factor of as much as 227.

To understand the nature and field-dependent resonance of the NbN metamaterial, commercial software CST Microwave Studio was used to numerically simulate the spectral response for the 50 nm thick NbN metamaterial using the measured field-dependent complex conductivity (figure 2(c)). The simulation showed good agreement with the experimental data and further confirms that the modulation of transmission is essentially associated with the changes in intrinsic conductivity of the NbN film due to the nonlinearity [19]. Here, figure 4 shows the distribution of electric field by the CST simulation at resonance frequency with various incident terahertz fields of $E_{in} = E_0/16$, $E_0/4$ and $E_0$, respectively. The color map indicates the relative local electric field amplitude. It reveals that when the incident terahertz field polarization is perpendicular to the gap, it drives the circulating surface currents in the inductive loops, which results in a strong charge accumulation at the capacitive split gap with $E_{in} = E_0/16$; however, as $E_{in}$ increases, the suppression of superconductivity affects the current,
Figure 5. Absorbed photo density as a function of incident terahertz electric field for the measured superconducting NbN films (with thicknesses of 15, 30 and 50 nm) and simulated NbN metamaterial (with a thickness of 50 nm).

a clear drop in the charge accumulation of the electric field appears around the capacitive split gap, and there is almost no prominent accumulation of charge around the capacitive split gap with $E_{in} = E_0$.

So far, we have observed an obvious nonlinear response in both the NbN film of 15–50 nm thickness and the NbN metamaterial of 50–200 nm thickness under intense terahertz fields. In order to understand and elucidate the underlying mechanism, the absorbed photo density is taken to characterize the nonlinear response (figure 5). The incident intense terahertz field can accelerate the pair electrons in superconductors despite the lower photo energy spectrum compared to the energy gap ($\Delta(0) = 1.2$ THz [17–19]) of NbN film, thus increasing the current, and thereby suppressing the superconductivity. It is expected that when the absorbed photo density exceeds a critical value, an obvious nonlinear response would appear. According to equations (1) and (2), absorption of the NbN film can be achieved

$$A = 1 - |\tilde{t}(\omega)|^2 - |\tilde{r}(\omega)|^2$$

by using the measured complex conductivity of the three NbN film samples in figures 1(a)–(c). By using the incident terahertz field $E_{in}$ and peak photo energy of the terahertz spectrum $hf \sim 2$ meV, where $h$ is the Planck constant, the absorbed photo density can be estimated to be

$$A_{PD} = \frac{E_{in}^2 A \tau}{2Z_0 df h f}.$$  \hspace{1cm} (4)

Here, $\tau$ is the terahertz pulse duration that is estimated to be about 1 ps. The equation reveals that the absorbed photo density is proportional to the square of the incident terahertz field, proportional to absorption of samples, and inversely proportional to the film thickness and peak photo energy of the terahertz spectrum. Thus, the absorbed photo density of the NbN films can easily be estimated based on the above equation. Figure 5 shows the absorbed photo density as a function of the incident terahertz field for NbN films having thicknesses of $d = 15, 30$
and 50 nm, respectively. The curves reveal a significant rise in the absorbed photo density with increasing incident field $E_{in}$ for those three NbN film samples. Note the measured complex conductivity in figure 2; the obvious nonlinear response and suppression of superconductivity in NbN films appear in the case of absorbed photo density higher than the order of $\sim 10^{17} \text{ cm}^{-3}$. Similar estimation was also taken for 50 nm thick NbN metamaterial at a resonance frequency of 0.45 THz. In this case, the transmission and reflection value from the numerical simulation was utilized for estimating the absorption $A$. The obtained field-dependent absorbed photo density curve for the 50 nm thick NbN metamaterial is also shown in figure 4, which further confirms that the significant nonlinear response is essentially associated with an absorbed photo density higher than the order of $\sim 10^{17} \text{ cm}^{-3}$, which results in distinct nonlinearity in the conductivity of NbN elements. Consequently, the absorbed quasiparticles accelerate the pair electrons, and as the photo density increases, the current increases. When the absorbed photo density exceeds a critical value, the break-up of Cooper pairs and suppression of superconductivity emerge. Thus, simple and fast control of superconductivity can be achieved using light.

4. Conclusions

We characterized the nonlinearity of superconducting NbN thin films with thicknesses from 15 to 50 nm, and proposed a superconducting NbN metamaterial that provides highly efficient ultrafast modulation switched by light for nonlinear low-loss metamaterial in the terahertz regime. As the lumped NbN film thickness increases from 50 to 200 nm, the simple and fast switchable function remains similar; this is attributed to the intrinsic nonlinearity of the lumped superconducting NbN elements. As the film thickness decreases and the incident terahertz field increases, the absorbed photo density in the NbN films rises, thereby resulting in a stronger nonlinearity in the superconductivity. The estimated absorbed photo density for either the NbN thin film or the NbN metamaterial serves to clarify the nature of the nonlinearity of superconductors. With thicker lumped NbN film, the metamaterial exhibits a sharper resonance and a higher quality factor, which offers an efficient approach to the design and implementation of high-performance terahertz devices.

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References

[1] Zharov A A, Shadrivov I V and Kivshar Y S 2003 Nonlinear properties of left-handed metamaterials Phys. Rev. Lett. 91 037401
[2] Fang A, Koschny T, Wegener M and Soukoulis C M 2009 Self-consistent calculation of metamaterials with gain Phys. Rev. B 79 241104

New Journal of Physics 15 (2013) 055017 (http://www.njp.org/)
[3] Klein M W, Wegener M, Feth N and Linden S 2007 Experiments on second- and third-harmonic generation from magnetic metamaterials *Opt. Express* **15** 5238–47

[4] Sipe J E and Boyd R W 1992 Nonlinear susceptibility of composite optical materials in the Maxwell Garnett model *Phys. Rev. A* **46** 1614–29

[5] Fischer G L, Boyd R W, Gehr R J, Jenekh S A, Osaheni J A, Sipe J E and Weller-Brophy L A 1995 Enhanced nonlinear optical response from composite materials *Phys. Rev. Lett.* **74** 1871–4

[6] Shalaev V M and Sarychev A K 1998 Nonlinear optics of random metal-dielectric films *Phys. Rev. B* **57** 13265–88

[7] Husu H, Siikanen R, Makitalo J, Lehtolahti J, Laukkanen J, Kuittinen M and Kauranen M 2012 Metamaterials with tailored nonlinear optical response *Nano Lett.* **12** 673–7

[8] Tang S W, Cho D J, Xu H, Wu W, Shen Y R and Zhou L 2011 Nonlinear responses in optical metamaterials: theory and experiment *Opt. Express* **19** 18283–93

[9] Rosanov N N, Vysotina N V, Shatsev A N, Desyatnikov A S and Kivshar Y S 2012 Knotted solitons in nonlinear magnetic metamaterials *Phys. Rev. Lett.* **108** 133902

[10] Liu H, Li G X, Li K F, Chen S M, Zhu S N, Chan C T and Cheah K W 2011 Linear and nonlinear Fano resonance on two-dimensional magnetic metamaterials *Phys. Rev. B* **84** 235437

[11] Fan K, Hwang H Y, Liu M, Strikwerda A C, Sternbach A, Zhang J, Zhao X, Zhang X, Nelson K A and Averitt R D 2012 Nonlinear terahertz metamaterials via field-enhanced carrier dynamics in GaAs arXiv:1208.1538

[12] Hirori H, Nagai M and Tanaka K 2010 Excitonic interactions with intense terahertz pulses in ZnSe/ZnMgSSe multiple quantum wells *Phys. Rev. B* **81** 081305

[13] Katayama I, Aoki H, Takeda J, Shimosato H, Ashida M, Kinjo R, Kawayama I, Tonouchi M, Nagai M and Tanaka K 2012 Ferroelectric soft mode in a SrTiO$_3$ thin film impulsively driven to the anharmonic regime using intense picosecond terahertz pulses *Phys. Rev. Lett.* **108** 097401

[14] Liu M K *et al* 2012 Terahertz-field-induced insulator-to-metal transition in vanadium dioxide metamaterial *Nature* **487** 345–8

[15] Dienst A, Hoffmann M C, Fausti D, Petersen J C, Pyon S, Takayama T, Takagi H and Cavalleri A 2011 Bi-directional ultrafast electric-field gating of interlayer charge transport in a cuprate superconductor *Nature Photon.* **5** 485–8

[16] Glossner A, Zhang C H, Kikuta S, Kawayama I, Murakami H, Muller P and Tonouchi M 2012 Cooper pair breakup in YBa$_2$Cu$_3$O$_{7-\delta}$ under strong terahertz fields arXiv:1205.1684

[17] Matsunaga R and Shimano R 2012 Nonequilibrium BCS state dynamics induced by intense terahertz pulses in a superconducting NbN film *Phys. Rev. Lett.* **109** 187002

[18] Zhang C H, Jin B B, Glossner A, Kang L, Chen J, Kawayama I, Murakami H, Muller P, Wu P H and Tonouchi M 2012 Pair-breaking in superconducting NbN films induced by intense THz field *J. Infrared Millim. Terahz Waves* **33** 1071–5

[19] Zhang C H, Jin B B, Han J G, Kawayama I, Murakami H, Kang L, Chen J, Wu P H and Tonouchi M 2013 Terahertz nonlinear superconducting metamaterial *Appl. Phys. Lett.* **102** 081121

[20] Savinov V, Fedotov V A, Anlage S M, Groot P A J and Zheludev N I 2012 Modulating sub-THz radiation with current in superconducting metamaterial *Phys. Rev. Lett.* **109** 243904

[21] Singh R, Azad A K, O’Hara J F, Taylor A J and Zhang W L 2008 Effect of metal permittivity on resonant properties of terahertz metamaterials *Opt. Lett.* **33** 1506–8

[22] Singh R, Smirnova E, Taylor A J, O’Hara J F and Zhang W L 2008 Optically thin terahertz metamaterials *Opt. Express* **16** 6537–43

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

[24] Sindler M, Tesař A, Kolacek J, Skřebek L and Simsa Z 2010 Far-infrared transmission of a superconducting NbN film *Phys. Rev. B* **81** 184529
[25] Beck M, Klammer M, Lang S, Leiderer P, Kabanov V V, Goltsman G N and Demsar J 2011 Energy-gap dynamics of superconducting NbN thin films studied by time-resolved terahertz spectroscopy Phys. Rev. Lett. 107 177007

[26] Chen H T, Yang H, Singh R, OHara J F, Azad A K, Trugman S A, Jia Q X and Taylor A J 2010 Tuning the resonance in high-temperature superconducting terahertz metamaterials Phys. Rev. Lett. 105 247402

[27] Singh R, Xiong J, Azad A K, Yang H, Trugman S A, Jia Q X, Taylor A J and Chen H T 2012 Optical tuning and ultrafast dynamics of high-temperature superconducting terahertz metamaterials Nanophotonics 1 117–23

[28] Hebling J, Yeh K L, Hoffmann M C, Bartal B and Nelson K A 2008 Generation of high-power terahertz pulses by tilted-pulse-front excitation and their application possibilities J. Opt. Soc. Am. B 25 B6–19

[29] Hirori H, Doi A, Blanchard F and Tanaka K 2011 Single-cycle terahertz pulses with amplitudes exceeding 1 MV/cm generated by optical rectification in LiNbO3 Appl. Phys. Lett. 98 091106

[30] Wu R X and Qian M 1997 A simplified power transmission method used for measuring the complex conductivity of superconducting thin films Rev. Sci. Instrum. 68 155–8

[31] Brorson S D, Buhleier R, White J O, Trofimov I E, Habermeier H U and Kuhl J 1994 Kinetic inductance and penetration depth of thin superconducting films measured by THz-pulse spectroscopy Phys. Rev. B 49 6185–7

[32] Schurig D, Mock J J and Smith D R 2006 Electric-field-coupled resonators for negative permittivity metamaterials Appl. Phys. Lett. 88 041109

[33] Zheludev N I and Kivshar Y S 2012 From metamaterials to metadevices Nature Mater. 11 917–24

[34] Gu J Q, Singh R, Tian Z, Cao W, Xing Q R, He M X, Zhang J W, Han J G, Chen H T and Zhang W L 2010 Terahertz superconductor metamaterial Appl. Phys. Lett. 97 071102

[35] Zhang C H, Wu J B, Jin B B, Ji Z M, Kang L, Xu W W, Chen J, Tonouchi M and Wu P W 2012 Low-loss terahertz metamaterial from superconducting niobium nitride films Opt. Express 20 42–7

[36] Singh R, Al-Naib I A I, Koch M and Zhang W L 2011 Sharp Fano resonances in THz metamaterials Opt. Express 19 6312–9

[37] Cao W, Singh R, Al-Naib I A I, He M X, Taylor A J and Zhang W L 2011 Low-loss ultra-high-Q dark mode plasmonic Fano metamaterials Opt. Lett. 37 3366–8

[38] Singh R, Al-Naib I A I, Yang Y P, Chowdhury D R, Cao W, Rockstuhl C, Ozaki T, Morandotti R and Zhang W L 2011 Observing metamaterial induced transparency in individual Fano resonators with broken symmetry Appl. Phys. Lett. 99 201107