Terahertz superconducting plasmonic hole array

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We demonstrate a superconductor array of subwavelength holes with active thermal control over the resonant transmission induced by surface plasmon polaritons. The array was lithographically fabricated on a high-temperature yttrium barium copper oxide superconductor and characterized by terahertz time-domain spectroscopy. We observe a clear transition from a virtual excitation of the surface plasmon mode to a real surface plasmon mode. The highly controllable superconducting plasmonic crystals may find promising applications in the design of low-loss, large-dynamic-range amplitude modulation and surface-plasmon-based terahertz devices. © 2010 Optical Society of America

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The discovery of extraordinary transmission of light through gratings of subwavelength holes has ignited great interest in the field of surface plasmon optics (plasmonics) over the past few years from both the basic science and applied physics points of view [1–3]. Plasmonics is predicted to have a strong future in the high-technology world for the design and development of next-generation electronic and photonic chips [4]. To realize this promise, the bigger challenge is to actively control surface plasmon polaritons (SPPs). It has been demonstrated that SPP-assisted light propagation can be controlled through thermal, optical, and electrochemical means in the visible and near-IR frequency regimes [5–7]. At terahertz frequencies, semiconductors are efficient materials for active plasmonics. Thermal, electrical, magnetic, and optical switching of terahertz SPPs has been extensively demonstrated in recent years, allowing active control of the surface plasmon resonance [8–14]. The semiconductor and the metal used in fabricating plasmonic devices suffer from the limitation of higher losses. This drawback can be lifted by the use of high-transition-temperature (T_c) superconductor thin films. Cuprate superconductors are highly anisotropic and have multilayer superconducting Cu_2O planes with interlayer tunneling of copper pairs between them, which introduces the c-axis Josephson plasma resonance (JPR). The JPR usually lies in the microwave and terahertz spectral regions [15]. Recent works have predicted the existence of surface waves in the HTS films [16–20].

In this Letter, we demonstrate the existence and active thermal control of SPPs in a periodic subwavelength hole array made up of high-T_c yttrium barium copper oxide (YBCO) by using terahertz time-domain spectroscopy (THz-TDS) [21]. In the hole array, owing to c-axis Josephson plasma frequency, we observed a sharp transition between a virtual-excitation-type SPP mode and a real SPP mode accompanied with enhanced transmission amplitude modulation.

The sample is made from a commercial (THEVA, Germany) 280-nm-thick YBCO film, which typically has an 86 K T_c and 2.3 MA/cm^2 critical current density grown on a 500-μm-thick sapphire substrate. By using conventional photolithographic [22–24] exposure, we patterned a 3-μm-thick negative photoresist, NR7-3000P film into a hole shape on the YBCO film as the protective layer. The sample was then wet etched in 0.04% nitric acid to remove YBCO from other parts of the wafer that did not have the photoresist protection, forming the hole array. The remaining photoresist was then removed by use of acetone. The optical images of the hole array are illustrated in Fig. 1. The dimension of a unit hole is 65 μm × 50 μm, with a lattice constant of 100 μm.

The measurements were performed at room temperature and then gradually cooled down to 51.4 K in a helium cryo-assisted THz-TDS system. Figure 2 illustrates the measured normalized transmission response of the YBCO array under normal incidence at 297, 183, 133, 86, and 51.4 K. At 297 K, we observed two resonance modes at 0.85 and 1.16 THz with peak amplitudes of 0.69 and 0.51, respectively, which correspond to the $[\pm 1, 0]$ and $[\pm 1, \pm 1]$ modes of the surface wave. As the hole array was cooled down, both resonances gradually became prominent, with an increase in their respective peak amplitudes. Finally, at 51.4 K, a temperature well below T_c, the $[\pm 1, 0]$ resonance mode shows a clear switching effect, attaining a peak transmission value of. 0.97.

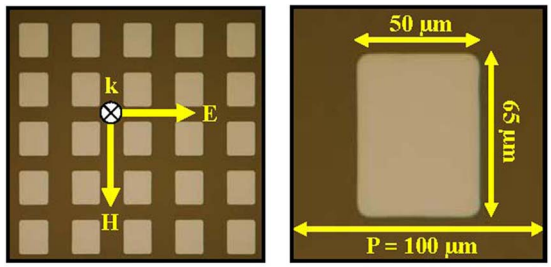

Fig. 1. (Color online) Optical images of (a) a periodic subwavelength YBCO hole array on a sapphire substrate and (b) a unit cell with geometric dimensions.

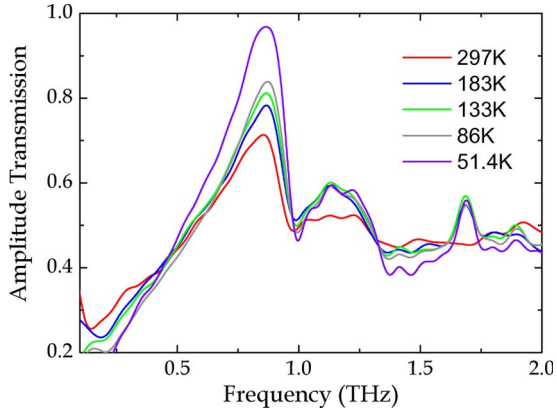

Fig. 2. (Color online) Measured amplitude transmission response of the YBCO hole array at 297, 183, 133, 86, and 51.4 K at normal incidence.

The anisotropic dielectric function of YBCO can be written as [15]

$$\varepsilon_c(\omega) = \varepsilon_\infty^c\left(1 - \frac{\omega_{pc}^2}{\omega^2} + \frac{4\pi i\sigma_c}{\varepsilon_\infty^c \omega}\right),$$
$$\varepsilon_{ab}(\omega) = \varepsilon_\infty^{ab}\left(1 - \frac{\omega_{pab}^2}{\omega^2}\right), \quad (1)$$

where ω_{pc} and ω_{pab} are the out-of-plane and in-plane plasma frequencies, respectively. The plasma frequency along the c axis is also called the Josephson plasma frequency ω_{Jp}, which usually lies in the microwave and terahertz regions. Since the critical current density J_c is known, ω_{Jp} can be evaluated using the following equation [25]:

$$\omega_{\mathrm{Jp}} = \sqrt{\frac{2eJ_c d}{\hbar\varepsilon_0\varepsilon_c}}, \quad (2)$$

where $J_c = 2.3$ MA/cm^2 is the critical current density, d is the interlayer spacing (≈ 1 nm), and $\varepsilon_c = 15$ is the dielectric constant of YBCO. Based on Eqs. (1) and (2), the estimated ω_{Jp} is 3.4 THz at T_c, and this value is consistent with that in [26]. For temperatures higher than the T_c value, the superconducting carriers will disappear and the YBCO film along the c axis can be treated as a dielectric material. The plasma frequency along the a–b plane can be measured directly from the normal incidence transmission and is found to have a value close to that in the near-IR regime. It should be noted that the structure of YBCO allows high conduction in copper planes, thus confining the conductivity to the a–b planes and giving rise to large anisotropy in the transport properties. The normal conductivity in the c axis is 1 order of magnitude lower than that in the a–b plane.

Since YBCO is a highly anisotropic material, the dispersion relation of surface polaritons can be expressed as [27]

$$k^2 = \frac{\omega^2}{c^2}\varepsilon_s\varepsilon_c\frac{\varepsilon_{ab} - \varepsilon_s}{\varepsilon_{ab}\varepsilon_c - \varepsilon_s^2}, \quad (3)$$

where ε_s is the dielectric constant of the surrounding substrate, and ε_{ab} and ε_c are the dielectric function of YBCO along the a–b plane and the c axis, respectively. This dispersion relation is consistent with that in the isotropic material if $\varepsilon_{ab} = \varepsilon_c$. For YBCO, however, $\varepsilon_{ab} \neq \varepsilon_c$, and thus two cases arise. When the temperature is lower than $T_c = 86$ K, $\varepsilon_{ab} < 0$, $\varepsilon_c < 0$, and $|\varepsilon_{ab}| \gg |\varepsilon_c|$, the dispersion relation can be simplified as $k^2 = (\omega^2/c^2) \times \varepsilon_s$. In this case, the terahertz wave can be coupled to the real SPP mode, which is similar to the case in a metallic hole array. As the temperature soars above T_c, $\varepsilon_{ab} < 0$, $\varepsilon_c > 0$, and $|\varepsilon_{ab}| \gg \varepsilon_c$, the dispersion relation again simplifies to the same expression, $k^2 = (\omega^2/c^2) \times \varepsilon_s$, but the surface mode excited here is a virtual SPP mode that occurs only for a small magnitude of wave vector. Furthermore, the virtual-excitation-type SPPs must always be driven by the associated electromagnetic wave. When the associated excitation is removed, the virtual SPP mode will disappear immediately [28]. Figure 2 clearly reveals that all the measured transmission resonances above $T_c = 86$ K are caused by the virtual excitation of SPPs and a strong enhancement at 51.4 K is mainly due to resonant excitation of a real SPP mode.

To verify our experimental results at temperatures above and well below T_c, finite-element simulations using CST Microwave Studio were carried out in which we used measured real and imaginary conductivity values for unpatterned YBCO film at 297, 183, 133, and 86 K. The conductivity at 51.4 K was taken from [29]. As shown in Fig. 3(a), owing to an increase in the ratio of the real to the imaginary dielectric constant [30,31], the peak amplitude transmission caused by the virtual-excitation-type SPP becomes larger gradually and, at a superconducting state, the transmission peak caused

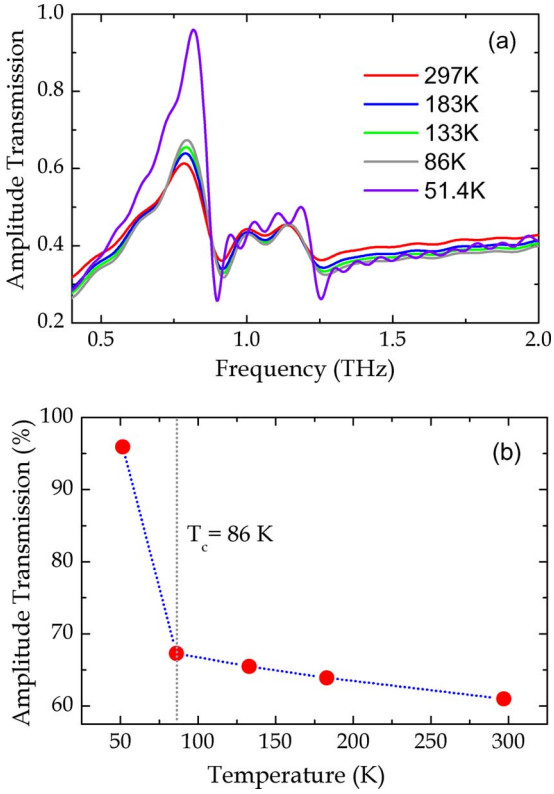

Fig. 3. (Color online) Simulated (a) terahertz amplitude transmission of the subwavelength YBCO hole array and (b) amplitude transmission peak percentage at varying temperatures. The dotted lines are to guide the eye.

by a real SPP nearly reaches 1, demonstrating extremely low loss. The dramatic change in amplitude transmission can be seen in Fig. 3(b), where the transmission at resonance suddenly increases by almost 30% owing to the formation of superconducting copper pairs below T_c. This switching behavior in the simulation matches reasonably well with our measurement. The slight difference between the simulated and the measured data can be attributed to the defects in the YBCO film and change in the superconductor film thickness while processing the hole array sample. Before the superconductor reaches T_c, the change in transmission from room temperature up to the critical temperature is only $\sim 5\%$.

In summary, an active control over terahertz resonant transmission with an amplitude modulation of 35% and sharp resonance strengthening has been achieved in a periodic subwavelength YBCO hole array by cooling it down to temperatures below T_c. Such plasmonic superconducting structures would open up promising avenues for the design and development of a low-loss large-dynamic-range amplitude modulator and temperature-controlled terahertz devices.

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