APPLIED PHYSICS LETTERS **97**, 111106 (2010)

# Superconducting plasmonics and extraordinary transmission

A. Tsiatmas,[1] A. R. Buckingham,[1,2] V. A. Fedotov,[1] S. Wang,[3] Y. Chen,[4]
P. A. J. de Groot,[2] and N. I. Zheludev[1,a)]
[1]*Optoelectronics Research Centre and Centre for Photonic Metamaterials, University of Southampton, Highfield, Southampton SO17 1BJ, United Kingdom*
[2]*School of Physics and Astronomy and Centre for Photonic Metamaterials, University of Southampton, Southampton SO17 1BJ, United Kingdom*
[3]*Shangai Institute of Technical Physics, Chinese Academy of Sciences, Shanghai 200083, People's Republic of China*
[4]*Micro and Nanotechnology Centre, Rutherford Appleton Laboratory, Didcot, Oxon OX11 0QX, United Kingdom*

(Received 26 June 2010; accepted 18 August 2010; published online 14 September 2010)

Negative dielectric constant and dominant kinetic resistance make superconductors intriguing plasmonic media. Here we report on the first study of one of the most important and disputed manifestations of plasmonics, the effect of extraordinary transmission through an array of subwavelength holes, using a perforated film of high-temperature superconductor. We show that in the millimetric wave part of the spectrum exceptionally strong extraordinary transmission exists in the ideal conductor state, improves in the plasmonic regime of a superconductor, and diminishes in a highly lossy metal. © *2010 American Institute of Physics*. [doi:10.1063/1.3489091]

The effect of extraordinary transmission can be regarded as one of the most important and widely discussed phenomena in the area of plasmonics. It was observed as sharp peaks in transmission spectra of arrays of subwavelength holes made in thin metal films.[1] The transmission efficiency at those maxima exceeded multifold the predictions allowed by the pioneering theoretical work of Bethe,[2] who found a drop in the intensity transmitted through a single hole of radius $r$ in a thin perfect conductor screen as $(r/\lambda)^4$ for wavelength $\lambda \gg r$. The phenomenon was seen in periodic[3] and quasiperiodic[4–6] arrays of holes in plasmonic metals[7,8] and in perfect conductors[9] that cannot support surface plasmons. These observations have stimulated a broad discussion on the role of dynamical diffraction, surface plasmons, and other evanescent waves and their interaction with Bragg peaks in the reciprocal space of the array in the effect.[10,11] In this paper, we report on the study of extraordinary transmission in a superconducting film electromagnetic properties of which can be switched from that of a lossy metal to a plasmonic metal and ideal conductor at will, by varying the temperature. We show that extraordinary transmission exists in the ideal conductor state, improves in the plasmonic metal, and diminishes in a highly lossy metal.

Superconductors are plasmonic media. Indeed, according to the definition of Yablonovitch and co-workers,[12] the plasmonic regime is characterized by the dominance of kinetic resistance over Ohmic and inductive resistances. In the microwave to millimeter parts of the spectrum in structured superconductors at zero temperature, Ohmic resistance is negligible and kinetic resistance only competes with inductive resistance, becoming dominant when structural features are smaller than a few microns. From the other prospective, the plasmonic regime shall be important in superconductors, in particular close to the critical temperature, as they are media with inheritably negative real dielectric coefficient. For instance, within the popular two-fluid model,[13] electrodynamics of a superconductor at nonzero temperature is dominated by the existence of two noninteracting currents; the current of purely inertial motion of Cooper pairs of superconducting electrons, known as supercurrent, and the current of normal electrons encountering scattering processes. Here the Drude model[14] can be used to obtain the relative dielectric constant for a frequency well-below the superconductor's gap frequency $2\Delta/\hbar$, where $\hbar$ is Planck's constant, as follows:

$$\epsilon = \epsilon' + i\epsilon'' = 1 - \frac{\omega_s^2}{\omega^2} - \frac{\omega_n^2\tau^2}{\omega^2\tau^2 + 1} + i\frac{\omega_n^2\tau}{\omega(\omega^2\tau^2 + 1)}. \qquad (1)$$

In the above equation the second term represents the contribution of the nondissipating supercurrent with plasma frequency $\omega_s = \sqrt{N_s e^2/m\epsilon_0} = c/\lambda_L$, where $\lambda_L$ is the London penetration depth for the magnetic field, $N_s$ is the density of superconducting electrons, $m$ is the effective mass of the electrons, and $\epsilon_0$ is the permittivity of free space. The third and the fourth terms account for the normal electron plasma $\omega_n = \sqrt{N_n e^2/m\epsilon_0}$ with $N_n$ the density of normal electrons, and the relaxation time $\tau$. According to the two-fluid model, at zero temperature all free electrons are in superconducting state and thus $N_n = 0$. This corresponds to a perfect conductor. On the contrary, at the critical temperature $T_c$ and above no superconducting electrons exist, thus $N_s = 0$. This corresponds to a lossy metallic behavior. The balance between densities of the superconducting and normal electrons is often described by the empirical Gorter–Casimir relation $N_s = N[1 - (T/T_c)^4]$, where $N$ is the temperature-independent total density of free carriers, while $N_n = N - N_s$.

The coexistence of normal and superconducting plasmas determines the plasmonic properties which are most pronounced close and below $T_c$. Figure 1(a) shows the characteristic behavior of the density of superconducting carriers and the dielectric constant of the two-fluid Drude superconductor. The real part of $\epsilon$ is negative, while the imaginary part and thus losses are higher at temperatures just below $T_c$. However, the superconducting film will support weakly de-

---

[a] Electronic mail: niz@orc.soton.ac.uk.

0003-6951/2010/97(11)/111106/3/$30.00

© 2010 American Institute of Physics

**Author complimentary copy. Redistribution subject to AIP license or copyright, see http://apl.aip.org/apl/copyright.jsp**

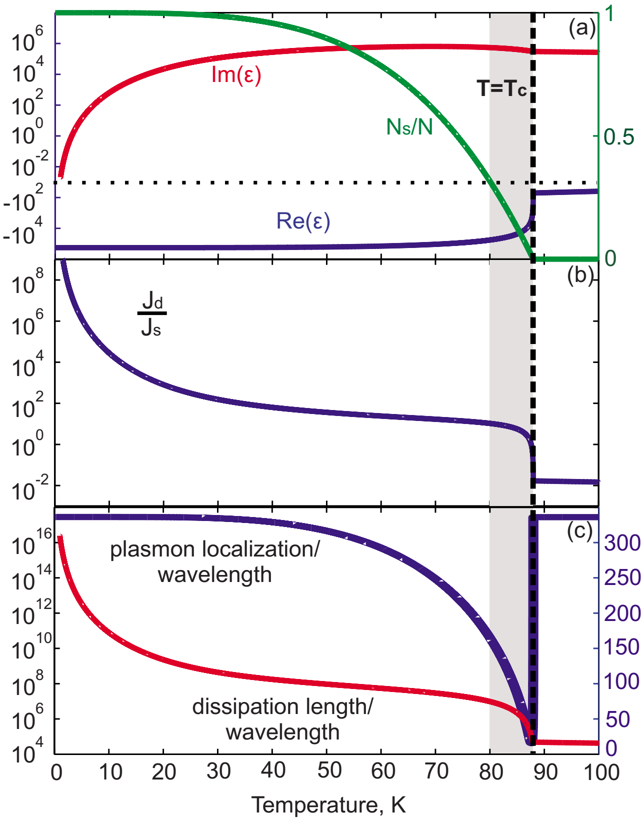

FIG. 1. (Color online) (a) Real and Imaginary part of dielectric permittivity for YBCO at 75 GHz. Fraction density of superconducting electrons is also shown. (b) Ratio of displacement current over conduction current of YBCO for the same parameters. (c) Normalized value of surface plasmon wave propagation length and wave localization in air over the wavelength. Gray area visualizes the possible plasmonic regime.

caying plasmon waves even at temperatures close to the critical temperature immediately below $T_c$ [Fig. 1(b)]. Furthermore, Fig. 1(c) shows the surface wave dissipation length in terms of plasmon wavelength: close to $T_c$, the attenuation constant is at least two orders of magnitude smaller than the propagation constant even in the millimeter-wave frequency band. With further reduction in temperature the surface plasmons will exhibit poor confinement to the surface. It is well known that a perfect conductor does not support surface plasmon modes. More sophisticated theories like the BCS theory,[15] especially for low temperature superconductors, and the Ginzburg–Landau theory[16] provide a more accurate account of their dielectric properties. However, the negative value of the real part of the dielectric coefficient and the ability to support surface waves at frequencies around the critical temperature remain key features of these models.

Here we report the first experimental observation of extraordinary transmission in a perforated superconducting film. Our experiments were performed in the millimeter-wave spectral range using a network analyzer equipped with two linearly polarized horn antennas. The superconductive sample was placed in a closed-cycle liquid-helium cryostat, as shown in the inset of Fig. 2. The superconducting film was 300 nm thick and consisted of high-temperature superconductor $YBa_2Cu_3O_{7-\delta}$ (YBCO) deposited on a low-loss 1 mm thick sapphire substrate, via an intermediate $CeO_2$ buffer layer of 40 nm. It was perforated by etching an array of holes with diameters of 954 $\mu$m and a period of 2.727 mm (see inset of Fig. 3), which rendered the structure nondiffracting at free space frequencies below 110 GHz. The sample was 30 mm in diameter and contained 81 holes. Transmission of the perforated cuprate film was measured for normal incidence at temperatures above and below its critical temperature $T_c = 88$ K in a frequency range of 75–110 GHz.

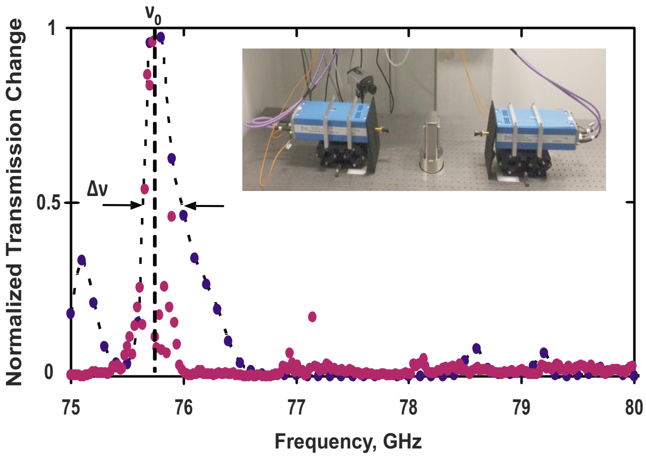

FIG. 2. (Color online) Experimental data (dots) vs simulation results (dashed line with dots) at temperature of 50 K, brought to the same scale for comparison reasons. Inset shows a part of the experimental setup with cryostat head in the middle and millimetric wave heads equipped with small horn antennas on both sides. Radiation screens and absorbers are removed for presentation purposes.

Figure 3 shows sharp peaks of extraordinary transmission at frequencies between 75 and 80 GHz measured at three different temperatures; above, just below and well below $T_c$, at 100, 60, and 10 K correspondingly. With increasing temperature the spectral position of peaks shifts toward higher frequencies, while peak amplitude dramatically increases at $T_c$. Transmission reaches its maximum at about 10 K below the critical temperature and decreases slowly toward lower temperatures (Fig. 4). We argue that the transmission dependence on temperature is directly reflected on the conductive properties of the material: transmission is low at high temperatures when the material can be described as lossy metal, is maximum at temperatures when the plasmonic regime is supported, and then drops a little while remaining high when the material can be considered a perfect conductor. This is because the origin of extraordinary optical transmission lies in the collective interaction among holes, where the flux of electromagnetic energy through a given hole depends on both the incident field acting on it and the field induced by the distant holes. For the low-temperature

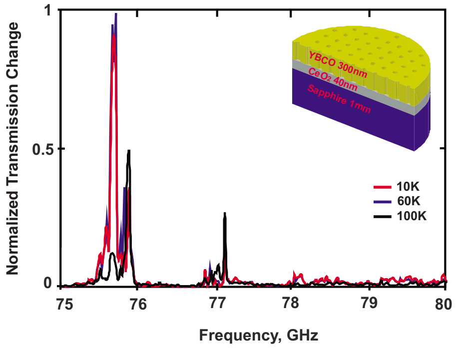

FIG. 3. (Color online) Experimental spectra of transmission change relative to transmission values at 300 K at three different temperatures. Inset shows a cross section of the sample's structure.

Author complimentary copy. Redistribution subject to AIP license or copyright, see http://apl.aip.org/apl/copyright.jsp

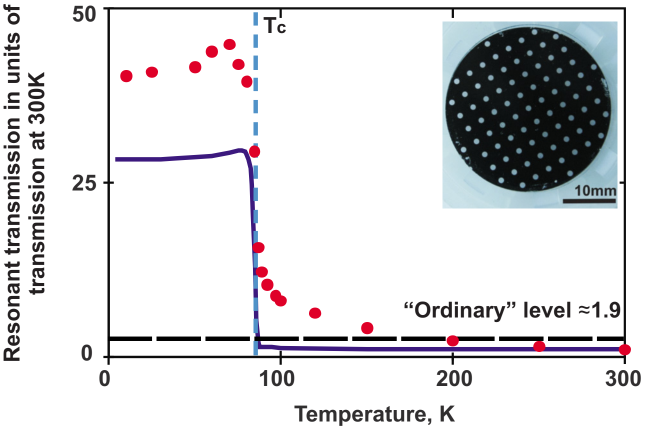

FIG. 4. (Color online) Change in amplitude of the extraordinary transmission peak at 75.7 GHz as a function of the sample's temperature. Red circles correspond to experimental data, while blue curve shows simulation results accordingly to the two-fluid model. Horizontal line presents the ordinary level of transmission calculated according to Bethe. Inset shows a photograph of the sample.

perfect conductor state, when surface plasmons are strongly delocalized, interactions between the holes are mediated by scattered fields propagating as spherical waves $\sim\exp(ikR)/R$. Under normal incidence, this gives rise to intense narrow transmission peaks, where the wave vector $k$ is close to one of the reciprocal lattice vectors of the array. As the temperature increases approaching $T_c$, the localization of the surface plasmons significantly improves and the interhole interaction acquires an additional, long-range contribution $\sim\exp(ik_{SP}R)/\sqrt{R}$, where $k_{SP}$ is the surface plasmon wave vector.[17] As a result, one also obtains narrow transmission peaks but now the strength is higher than in the low-temperature limit due to the smoother interhole interaction decay with $R$. This can qualitatively explain the rise in peak intensity for temperatures just below $T_c$, as seen in Fig. 4. Finally, the long-range interaction between holes is suppressed when the material becomes a lossy metal above $T_c$, giving rise to the inhibition of the effect. Therefore, our experiment provides the direct experimental evidence that the extraordinary transmission effect does not require surface plasmons to exist but the effect is facilitated further in the plasmonic regime.

In order to illustrate this argument, we have modeled transmission of the superconductive sample using the two-fluid model to describe the sample's dielectric properties. We characterized the sample by its surface resistance and reactance values, based on the formula for the characteristic impedance of the material:[18] $Z_s=\sqrt{\mu_0/\epsilon\epsilon_0}$ which then were used in three-dimensional Maxwell calculations of transmission. We assumed $T_c=88$ K while the value of $N=1.255\times10^{27}$ $\mathrm{m}^{-3}$ and data for $\tau$ that decreases with temperature from $9.276\times10^{-12}$ s at 10 K to $1.047\times10^{-14}$ s at 300 K were derived from published experimental data.[19,20] According to Ref. 21 for sapphire we used $\epsilon=10.31+0.0008(T-50)+i0.0004$. In spite of simplicity the model accurately predicts the main trend of spectral and temperature dependencies of transmission of the hole array in superconducting film. Such good corroboration between the experiment and prediction of the simple two-fluid model is particularly significant in the view of the known anisotropic nature of cuprate superconductors allowing for various types of plasmonic excitations.[22] It indicates that surface impedance approach may be efficiently used for describing superconducting metamaterial structures in high-$T_c$ superconductors such as recently reported split-ring arrays supporting Fano modes of excitation.[23]

In summary, we have observed an exceptionally strong manifestation of the extraordinary transmission effect through an array of holes in a film of a high-$T_c$ superconductor at millimeter wave frequencies. At about 75 GHz transmission resonance with quality factor acceding 250 has been seen. This shall be compared with a typical quality factor of 10 seen in the optical regime of extraordinary transmission. Transmission of the array exceeds the "ordinary" level of transmission by a factor of 20 at the resonance. The effect of extraordinary transmission disappears above the critical temperature of the superconductor, and peaks at about 10 K below, while remaining strong at low temperatures. The main features of the effect can be explained within the two fluid Drude model of electromagnetic response of the superconducting film.

The authors acknowledge fruitful discussions with García de Abajo on the mechanisms of extraordinary transmission and support of the Engineering and Physical Sciences Research Council (U.K.) and the Royal Society.

[1] T. W. Ebbesen, H. J. Lezec, H. F. Ghaemi, T. Thio, and P. A. Wolff, Nature (London) **391**, 667 (1998).
[2] H. A. Bethe, Phys. Rev. **66**, 163 (1944).
[3] L. Martín-Moreno, F. J. García-Vidal, H. J. Lezec, K. M. Pellerin, T. Thio, J. B. Pendry, and T. W. Ebbesen, Phys. Rev. Lett. **86**, 1114 (2001).
[4] M. Sun, J. Tian, Z.-Y. Li, B.-Y. Cheng, D.-Z. Zhang, A.-Z. Jin, and H.-F. Yang, Chin. Phys. Lett. **23**, 486 (2006).
[5] F. Przybilla, C. Genet, and T. W. Ebbesen, Appl. Phys. Lett. **89**, 121115 (2006).
[6] N. Papasimakis, V. A. Fedotov, A. S. Schwanecke, F. J. García de Abajo, and N. I. Zheludev, Appl. Phys. Lett. **91**, 081503 (2007).
[7] H. F. Ghaemi, T. Thio, D. E. Grupp, T. W. Ebbesen, and H. J. Lezec, Phys. Rev. B **58**, 6779 (1998).
[8] M. M. J. Treacy, Appl. Phys. Lett. **75**, 606 (1999).
[9] H. E. Went, A. P. Hibbins, J. R. Sambles, C. R. Lawrence, and A. P. Crick, Appl. Phys. Lett. **77**, 2789 (2000).
[10] F. J. García de Abajo, R. Gomez-Medina, and J. J. Saenz, Phys. Rev. E **72**, 016608 (2005).
[11] S. Riikonen, I. Romero, and F. J. García de Abajo, Phys. Rev. B **71**, 235104 (2005).
[12] M. Staffaroni, J. Conway, S. Vedantam, J. Tang, and E. Yablonovitch, arXiv:1006.3126v1 (unpublished).
[13] C. J. Gorter and H. B. G. Casimir, Phys. Z. **35**, 963 (1934).
[14] A. H. Majedi, IEEE Trans. Appl. Supercond. **19**, 907 (2009).
[15] J. Bardeen, L. N. Cooper, and J. R. Schrieffer, Phys. Rev. **108**, 1175 (1957).
[16] V. L. Ginzburg and L. D. Landau, Zh. Eksp. Teor. Fiz. **20**, 1064 (1950).
[17] F. J. García de Abajo, Rev. Mod. Phys. **79**, 1267 (2007).
[18] T. Van Duzer and C. W. Turner, *Principles of Superconductive Devices and Circuits* (Edward Arnold, London, 1981).
[19] F. Gao, J. W. Kruse, C. E. Platt, M. Feng, and M. V. Klein, Appl. Phys. Lett. **63**, 2274 (1993).
[20] Experimental data from the sample manufacturer THEVA, available at www.theva.com.
[21] J. Krupka, K. Derzakowski, M. Tobar, J. Hartnett, and R. G. Geyer, Meas. Sci. Technol. **10**, 387 (1999).
[22] S. Savel'ev, V. Yampol'skii, and F. Nori, Phys. Rev. Lett. **95**, 187002 (2005).
[23] V. A. Fedotov, A. Tsiatmas, J. H. Shi, R. Buckingham, P. de Groot, Y. Chen, S. Wang, and N. I. Zheludev, Opt. Express **18**, 9015 (2010).

Author complimentary copy. Redistribution subject to AIP license or copyright, see http://apl.aip.org/apl/copyright.jsp