Influence of intrinsic electronic properties on light transmission through subwavelength holes on gold and MgB_2 thin films

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We show how intrinsic material properties modify light transmission through subwavelength hole arrays on thin metallic films in the THz regime. We compare the temperature-dependent transmittance of Au films and MgB_2 films. The experimental data are consistent with analytical calculations and are attributed to the temperature change of the conductivity of both films. The transmission versus conductivity is interpreted within the open resonator model when taking the skin depth into consideration. We also show that the efficiency of this temperature control depends on the ratio of the transmission peak frequency to the superconducting energy gap in MgB_2 films.

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I. INTRODUCTION

Light transmission through subwavelength holes on metallic films works beyond the traditional diffraction limit when light excites evanescent surface waves on the film.[1] This so-called extraordinary optical transmission (EOT) can play an important role in miniaturizing optoelectronic devices.[2] The frequency and intensity of the EOT peaks depend on how evanescent surface waves are excited by the incident light, which is determined by the geometry of the holes, as well as the intrinsic properties of the metal and surrounding dielectrics.[3] Although geometric factors of the excitation have been extensively investigated, the influence of the intrinsic properties of the metal remains to be explored. Especially in the THz regime, metals are routinely treated as perfect electromagnetic conductors, completely overlooking their specific material properties. Differences of the EOT between good and poor conductors have been reported by comparing samples with the same structure but made from different materials.[4–6] However, this comparison can be easily affected by the variation of both film thickness and hole diameter in different samples. We overcome such difficulties by investigating the temperature-dependent EOT, taking advantage of a nearly continuous variation of material properties through a fine control of the temperature. Besides that, we compare MgB_2 (a low-temperature superconductor) with Au (a noble metal), whose complex conductivities change with temperature differently. By investigating the similarities and differences of the evolutions of the EOT peaks on these two films, we demonstrate *the influence of intrinsic material properties on EOT in the THz regime*.

An outcome of this study, for future possible applications of subwavelength optics, is that *the EOT on metallic films can be tuned effectively by just varying the temperature*. Previously, temperature control of EOT was realized either by changing the properties of dielectric surroundings[7] or by using thin films made of doped semiconductors.[8] Here we report a ∼30% increase in the maximum transmittance of a gold film when the temperature decreases from 300 to 5 K, which is attributed to the change of the properties of gold with temperature. References 9 and 10 observe EOT on thin films of $YBa_2Cu_3O_7$, a high-temperature superconductor. Here we use MgB_2, a low-temperature superconductor, whose low-temperature properties are described more accurately by using BCS theory. We observe that both the intensity and the shape of the EOT peaks change when MgB_2 enters the superconducting phase. Through a comparison of EOT peaks at different frequencies, we explore how the interplay between superconductivity and EOT depends on both the temperature and the frequency.

II. SAMPLE PREPARATION AND MEASUREMENT

We grew *c*-axis-oriented MgB_2 films,[11] and also Au films, on MgO substrates. Wedged [111] MgO substrates were used to avoid the interference of light between the front and back surfaces of each substrate. The *c*-axis oriented MgB_2 films were grown by the hybrid physical-chemical vapor deposition technique. The Au film was grown by magnetron sputtering. Both the MgB_2 and Au films were 50 nm thick, which was checked by measuring their cross-section thickness under a scanning electron microscope. Ultraviolet lithography and reactive ionic etching were used for patterning the arrays of holes. The superconducting transition of the fabricated MgB_2 film occurred at 37.6 K, with a transition width of 0.3 K [Fig. 1(b)]. Meanwhile, our gold films showed the typical behavior of a normal metal in the entire temperature range. Each pattern was a square array of circular holes, with a total effective area of 10×10 mm^2.

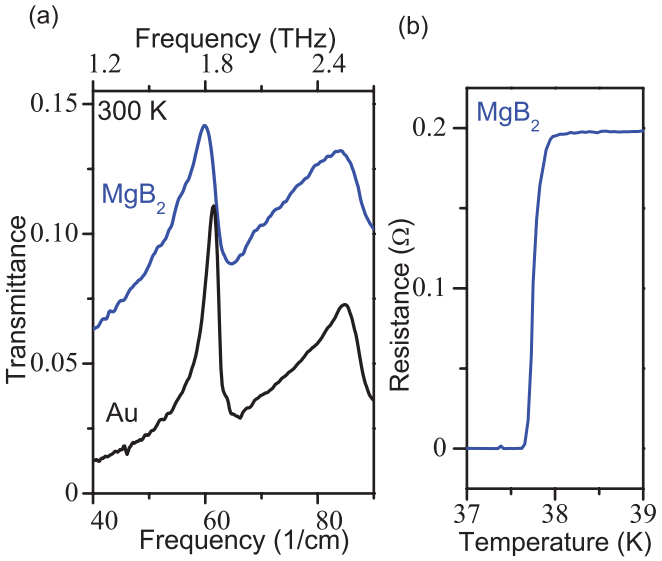

FIG. 1. (Color online) Experimental results for a MgB_2 film and a Au film with arrays of subwavelength holes. (a) Transmission spectra for both films at 300 K. (b) Resistance vs temperature for the MgB_2 film.

Samples and a bare MgO substrate were put into an optical cryostat. Temperature was varied from 300 to 5 K. The transmittance spectra of the samples and the substrate were taken in a Fourier-transformed infrared spectrometer (ABB Bomem DA8). The light had a normal incidence, with its beam diameter limited, by a diaphragm, to 5 mm. The transmittance of the samples was obtained by subtracting the spectra of the substrate from the spectra of the samples.

III. RESULTS AND DISCUSSION

Figure 1(a) shows the transmittance of a MgB film and a gold film at 300 K. The lattice constant of the hole array of both samples is 50 μm and the hole diameter is 25 μm. Transmission peaks at approximately 60 cm^{-1} (or 1.8 THz) and 85 cm^{-1} (or 2.5 THz) are observed in both samples. These are the EOT peaks because their corresponding wavelengths are far larger than the hole diameter[12] and can be assigned to the (1,0) and (1,1) modes of the metal-MgO interface, respectively.[13]

Light transmission spectra at 300 K show the combined effects of the geometry of the array of holes, as well as the intrinsic properties of the metallic and dielectric materials. Indeed, *varying the temperature highlights the effect of the material properties*. Figure 2 shows how the spectra around 60 cm^{-1} change when decreasing the temperature. The spectral peak of the Au film becomes narrower and shows a small blue shift, and the peak intensity increases smoothly [Figs. 2(a) and 2(d)]. Such a trend continues down to the lowest measured temperature of 5 K. For the MgB_2 film, the spectra show similar behaviors as those of the Au film in the normal state [Fig. 2(c)]. However, in the superconducting state, the spectra exhibit qualitatively different behaviors from the normal state. In the superconducting state [Fig. 2(b)], the peak becomes slightly *broader* (instead of *narrower*) and shows a very slight *red* shift, instead of the *blue* shift observed before, as the temperature is

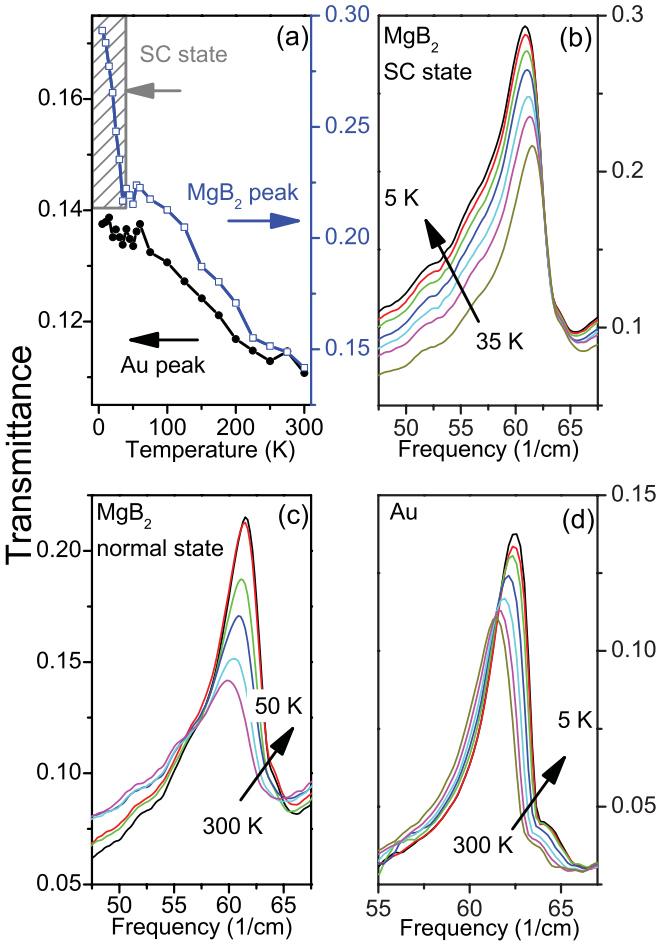

FIG. 2. (Color online) Experimental spectra of MgB_2 and Au around 60 cm^{-1} at different temperatures. (a) The maxima of the transmittance at different temperatures. The hatched area shows the superconducting (SC) regime of the MgB_2 film. (b) Transmittance spectra of the MgB_2 film in the SC state. Temperatures change from 5 to 35 K, with a step of 5 K. (c) Representative spectra of the MgB_2 film in the normal state. Temperatures change from 50 to 300 K, with a step of 50 K. (d) Representative spectra of the Au film. Temperatures are 5 K, and also from 50 to 300 K with a step of 50 K.

decreased. Moreover, the spectra show a Fano line shape[14] with the high-frequency side of the peak being nearly independent of the temperature and the low-frequency side becoming broader at low temperatures, resulting in a very slight increase of the asymmetry of the Fano line shape. This very small increase in the asymmetry could be the result of the increase in the available low-lying quasiparticle states, which act as the continuum channel of the Fano resonance. The maximum transmittance increases with decreasing temperature in the entire temperature range, with a much faster increase rate in the superconducting state than in the normal state [Fig. 2(a)]. For both MgB_2 and Au films, the effect of changing temperature is much more pronounced on the peak intensity than on the peak frequency. Because the EOT peak frequency and intensity correspond to the eigenmode and magnitude of evanescent surface waves, respectively, we conclude that the eigenmodes of evanescent surface waves are slightly modified,

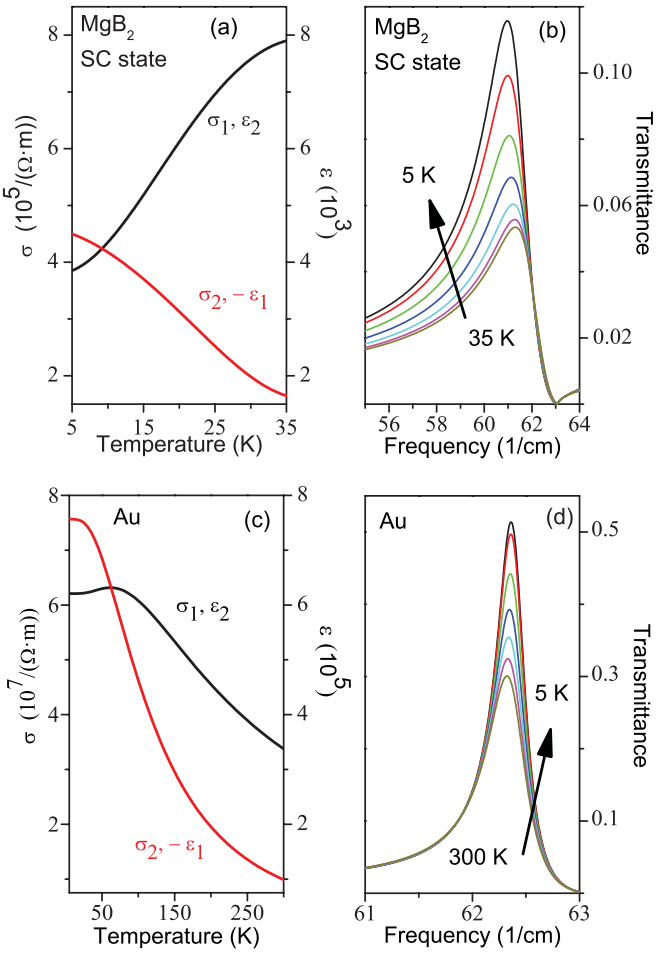

FIG. 3. (Color online) Analytically calculated results of the conductivity σ, the relative permittivity ϵ, and transmittance spectra around 60 cm^{-1}. (a) The conductivity σ and the relative permittivity ϵ of MgB_2 at 60 cm^{-1}, when MgB_2 is in the superconducting (SC) state. (b) Transmittance of the SC MgB_2 film. Temperatures change from 5 to 35 K, with a step of 5 K. (c) The conductivity σ and the relative permittivity ϵ of Au at 60 cm^{-1}. (d) Transmittance of the Au film with temperatures at 5 K, and also from 50 to 300 K with a step of 50 K.

while their amplitudes increase significantly with decreasing temperature.

The spectral line shape and their temperature dependence shown above can be described through the change of the complex conductivity σ (equal to $\sigma_1 + i\sigma_2$) of MgB_2 and Au. Because MgB_2 is a conventional BCS superconductor, its complex conductivity in the superconducting state can be calculated using BCS theory.[15,16] The obtained temperature-dependent values of σ_{MgB_2} at 60 cm^{-1} are shown in Fig. 3(a). In the superconducting state, with decreasing temperature, σ_1 decreases while σ_2 increases, which reflects the opening of the superconducting gap and the depletion of thermally excited quasiparticles when the temperature decreases. Meanwhile, we calculate σ_{Au} using an extended Drude model,[17] and the calculated values at 60 cm^{-1} are shown in Fig. 3(c). For Au, in contrast to MgB_2 in the superconducting state, both σ_1 and σ_2 increase with decreasing temperature, due to the increase in electron relaxation time coming from the suppression of electron-phonon scattering at low temperatures. The complex relative permittivity ϵ (equal to $\epsilon_1 + i\epsilon_2$) of both materials is also shown in Figs. 3(a) and 3(c), which is obtained through the equation $\epsilon = i\sigma/(\epsilon_0\omega)$, where ϵ_0 is the permittivity of free space and ω is the angular frequency. We stress there are *no adjustable parameters* in the above calculations (see Tables I and II). The transmission spectra at different temperatures are then obtained by analytically solving Maxwell's equations[18] using the obtained σ_{MgB_2} and σ_{Au}, with representative spectra shown in Figs. 3(b) and 3(d). The film thickness and lattice constant are experimental values. Square holes are adopted in the model,[18] with its side length as 5 μm. The area of the holes in the calculation is smaller than the experimental value, which may be due to the difference in the cutoff wavelength and the electromagnetic field distribution between square holes (in the calculations) and circular holes (in the experiments). The temperature-dependent features, such as the spectral line shape and intensity, of the EOT peaks on both films are reproduced (Figs. 2 and 3).

Here we use relatively thin films, so the light may transmit through the unperforated part of the film. We note that several previous reports on light transmission through artificial structures on superconducting thin films did not consider this direct transmission. The transmittance of a plain superconducting film changes significantly with temperature in the frequency range below and near the superconducting energy gap. The temperature-dependent characteristics of this direct transmission can mix up with those of the EOT. This can be a serious problem when the film thickness is less than the skin depth. Without considering and excluding the possibility of direct transmission, investigations on the optical properties of superconducting films with artificial structures are prone to error. In our work, the possible influence of the direct transmission on the EOT has been excluded because (1) the high-frequency and the low-frequency sides of the spectra show different temperature dependencies [Fig. 2(b)] and (2) these temperature-dependent characteristics are reproduced by the analytical solution [Fig. 3(b)] where the direct transmission is assumed to be zero in amplitude. So we conclude that the variation in spectra reveals the change of light transmission due to EOT, which originates from the temperature dependence of the intrinsic properties of MgB_2 and Au.

We notice that the EOT peaks in MgB_2 and Au films are significantly higher at low temperatures, with their σ_1 changing in opposite directions with decreasing temperature (Fig. 3). This is quite different from reports on either doped semiconductor films in THz or metal films at higher frequencies,[3] where an increase in σ_1 generally corresponds to a decrease in EOT intensity. This is because films have $\sigma_1 \ll \sigma_2$ for either doped semiconductors in the THz regime or noble metals in the visible and near-infrared regimes. So σ_1 can be safely treated as a small perturbation in the theoretical analysis, which describes the dissipation of evanescent surface waves and relates with the EOT peak width and strength. In our experiment, both MgB_2 and Au films have $\sigma_1 \approx \sigma_2$. So both σ_1 and σ_2 have to be treated together to describe the THz EOT of perforated metallic films. To achieve this, we incorporate σ_1 and σ_2 into the parameters of the skin depth δ, which describes the depth the electromagnetic field penetrates

into metallic films. In the THz regime, where metals have $\sigma_1, \sigma_2 \gg 0$,

$$\delta = c[\omega \mathrm{Im}\sqrt{i\sigma/(\epsilon_0\omega)}]^{-1}, \quad (1)$$

where c is the speed of light in vacuum.[19] Although σ_{MgB_2} and σ_{Au} have different temperature dependencies, both δ_{MgB_2} and δ_{Au} decrease monotonously, as both materials become better electromagnetic conductors with decreasing temperature.

Holes on the films form an array of open resonators, where evanescent surface waves resonate with incident and transmitted light.[20] The total quality factor of these resonators includes a term Q_{dis}, which describes the dissipation of evanescent surface waves in these resonators. For a closed resonator with highly conductive boundaries,

$$Q_{dis} = G/\delta, \quad (2)$$

where G is a geometric factor describing the shape of the cavity.[19] Because the electromagnetic field is highly confined inside subwavelength holes in the THz regime,[21] open and closed resonators should have a similar Q_{dis}. Because both δ_{MgB_2} and δ_{Au} decrease with decreasing temperature, Q_{dis} increases for both films at low temperatures. This explains why at low temperatures the intensity of the EOT increases for both MgB_2 and Au films.

This qualitative insight also explains another apparent discrepancy between our experiments and calculations on metal films at higher frequencies.[3] In our experiments, the EOT peaks for both MgB_2 and Au films increase in intensity when these materials approach the prefect-conductor limit. However, the EOT intensity in noble metal films can be higher than that in perfect-conducting films in the visible and near-infrared regime, which is attributed to the finite value of the skin depth in real metals.[3] This is because, in the visible and near-infrared regime, the hole diameter is usually only slightly larger than δ. So a change in δ will result in a significant enlargement of the effective hole diameter and thus influence the geometric factor G in Ref. 3. However, in our experiments G is nearly constant. This can be seen as follows: $\delta \approx 370$ and 40 nm for the superconducting MgB_2 and Au in our experiments, respectively. Thus, our hole diameter is several orders of magnitude larger than our δ, so the change in δ does not significantly influence the effective hole size and results in a nearly constant G. Thus, in our case, the change in EOT intensity is only a reflection of the change of δ.

Evanescent surface waves on superconducting MgB_2 films have very low dissipation, because Cooper pairs have a pure inductive response to the driven optical field at a finite frequency below the superconducting energy gap.[22–24] Since photons with energy larger than the superconducting energy gap can break Cooper pairs, the effect of the superconducting transition on the EOT is expected to be much weaker when the frequency goes up. To examine this, we investigated three EOT peaks with different frequencies (Fig. 4). Two of the peaks (A and C) are from the MgB_2 sample discussed above, and another peak (B) is from another MgB_2 sample with a different periodicity of the hole array. Details regarding the sample pattern and temperature-dependent spectra are available in Figs. 5 and 6

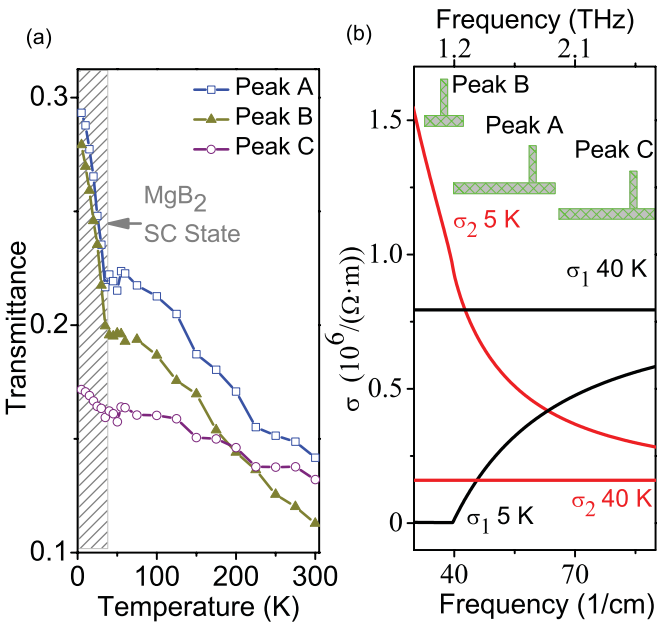

FIG. 4. (Color online) Transmittance and conductivity of three EOT peaks on two MgB_2 films. (a) Experimental result of the maxima of the transmittance of three EOT peaks. The hatched area shows the SC regime of the MgB_2 films. (b) Results of calculations for the real σ_1 and imaginary σ_2 parts of the conductivity σ of MgB_2 at 5 K (in the SC state) and 40 K (in the normal state). The horizontal bars at the top show the approximate spans of the three peaks. Vertical bars show the frequencies of the maximum transmittance.

in Appendix B. MgB_2 has two superconducting energy gaps and the lower one (equal to $2\Delta_\pi \sim 43$ cm^{-1}) dominates its optical properties.[25] These three EOT peaks correspond to the regime: slightly lower (B), slightly higher (A), and much higher (C) than $2\Delta_\pi$. It is clear from Fig. 4(a) that a phase transition is clearly revealed in the temperature-dependent transmittance maxima only for peaks with energy slightly lower and slightly higher than $2\Delta_\pi$. The phase transition can still be identified from the line-shape change of the spectra (see Fig. 5 in Appendix B), but the change of the transmittance maximum is much weaker for the peak (C) with energy much higher than $2\Delta_\pi$. Figure 4(b) shows the calculated conductivity of MgB_2 at 5 K (in the superconducting state) and 40 K (in the normal state) based on the Mattis-Bardeen model.[15] The difference between the conductivity at two temperatures diminishes for higher frequencies; indeed, in the visible or near-infrared regime, this difference should be very small. We also investigated EOT peaks in the mid-infrared regime (see Fig. 7 in Appendix B), but there the superconducting transition cannot be identified in our spectra.

IV. CONCLUSION

In conclusion, we show that light transmission through subwavelength hole arrays on metallic thin films can be controlled by modifying the intrinsic electronic properties of the films. The real part of the conductivity alone cannot describe the strength and width of the EOT peaks in the THz regime. The temperature dependence of the EOT peaks

is understood within the open resonator model, where both the real and the imaginary parts of the conductivity are taken into consideration. As we have shown, the effect of the superconducting transition on the EOT depends on the ratio of the superconducting energy gap to the frequency of the EOT. Besides the *temperature control* used here, the superconducting energy gap can be easily tuned with a magnetic field or an electric current, providing additional interesting ways to control the EOT of superconducting films (see Appendix C for more detailed discussion).

ACKNOWLEDGMENTS

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APPENDIX A: PARAMETERS USED IN CALCULATION

TABLE I. Parameters used to calculate the conductivity of MgB_2 in Fig. 3(a).

MgB_2 parameters	Value	Source
Plasmon frequency of the normal state, ω_{pl}	1.5 eV	Ref. 16
Scattering rate of the normal state, τ^{-1}	37 meV	Ref. 16
Superconducting energy gap, $2\Delta_0$	5 meV	Ref. 16
Transition temperature, T_c	37.6 K	Our experiment

TABLE II. Parameters used to calculate the conductivity of Au in Fig. 3(c).

Au parameters	Value	Source
Permittivity at 60 cm^{-1} at 300 K, ϵ	$-9.87 \times 10^4 + i3.37 \times 10^5$	Ref. 26
Fermi-surface average of scattering probability, Γ	0.55	Ref. 17
Thermal linear expansion coefficient, γ	$14.2 \times 10^{-6} K^{-1}$	Ref. 17
Fractional Umklapp scattering, Δ	0.77	Ref. 17
Debye temperature, θ_D	185 K	Ref. 17
Fermi energy, E_F	5.51 eV	Ref. 17
Poisson's number, μ	0.42	Ref. 17

APPENDIX B: SUPPLEMENTARY FIGURES

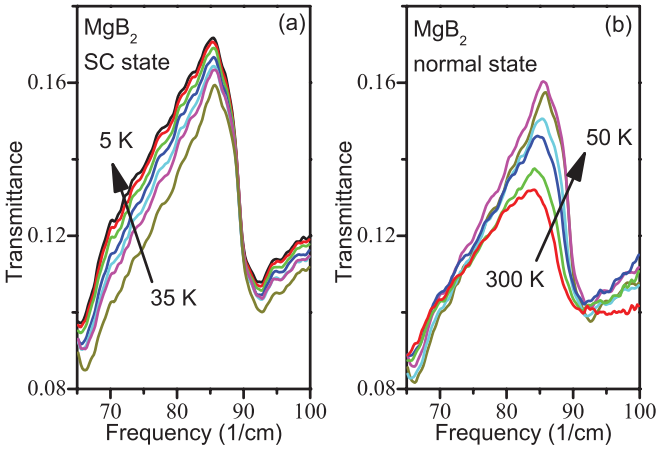

FIG. 5. (Color online) Experimental transmittance around an EOT peak of the MgB_2 film. The film thickness is 50 nm. The array of holes has a lattice constant of 50 μm and a hole diameter of 25 μm. (a) Transmission spectra when MgB_2 is in the SC state. Temperatures change from 5 to 35 K, with a step of 5 K. (b) Representative spectra when MgB_2 is in the normal state. Temperatures change from 50 to 300 K, with a step of 50 K.

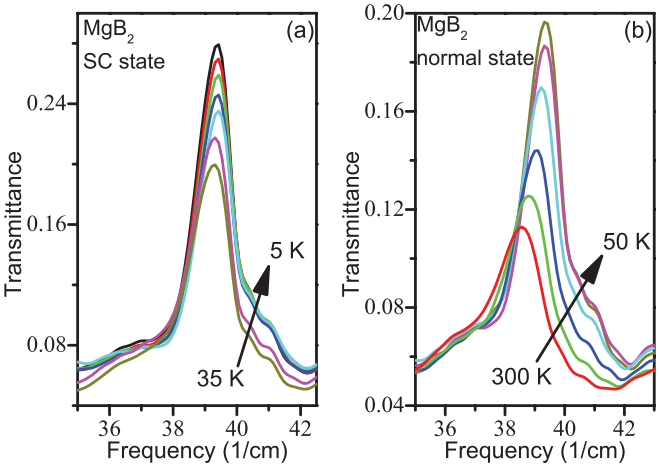

FIG. 6. (Color online) Experimental transmittance spectra around an EOT peak on a MgB_2 film. The film thickness is 50 nm. The array of holes has a lattice constant of 80 μm and a hole diameter of 40 μm. (a) Spectra when MgB_2 is in the SC state. Temperatures change from 5 to 35 K, with a step of 5 K. (b) Representative spectra when MgB_2 is in the normal state. Temperatures change from 50 to 300 K, with a step of 50 K.

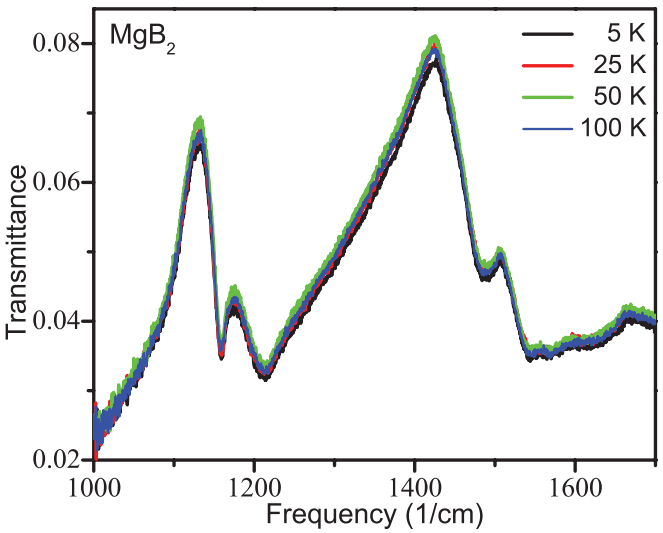

FIG. 7. (Color online) Experimental transmittance spectra around several EOT peaks on a MgB_2 film in the mid-infrared regime. The film thickness is 50 nm. The array of holes has a lattice constant of 6 μm and a hole diameter of 3 μm. Representative spectra are shown here, with temperatures at 5, 25, 50, and 100 K. These are nearly overlapping.

APPENDIX C: MODULATION OF THE EOT OF SUPERCONDUCTING FILMS BY USING ELECTRIC AND MAGNETIC FIELDS

Both static electric and magnetic fields are able to decrease the superconducting energy gap and even turn the superconducting state into a normal state when these fields are strong enough. This property can be used to modulate the intensity of the EOT of superconducting films.

As an example, we now discuss the EOT peak at 60 cm^{-1} (peak A in the main text). As shown in Figs. 2 and 4, the transmittance of this peak is 0.293 at 5 K, when MgB_2 is in the superconducting state. A strong enough electric or magnetic field is able to destroy the superconductivity of MgB_2. As a reasonable extrapolation of the data in Fig. 2, the transmittance will now decrease to a level close to that at 50 K in Fig. 2. So the maximum relative modulation amplitude at 5 K is approximately

$$\frac{\mathrm{T(5\ K,\ SC\ state)} - \mathrm{T(50\ K,\ normal\ state)}}{\mathrm{T(50\ K,\ normal\ state)}} \approx 35\%,$$

where T is the transmittance.

Sufficiently strong magnetic or electric fields are usually required to completely destroy the superconductivity of MgB_2 at low temperatures. As a type-II superconductor, the upper critical magnetic field of MgB_2 thin films is above 20 T at 5 K.[11] The zero-field critical current density is of the order of $10^{11}\mathrm{A/m^2}$ at 5 K.[11] It is possible to achieve an effective modulation at lower field strength when the magnetic field and electric field are used together, because a moderate magnetic field reduces the critical current density by orders of magnitude.[27]

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[1] T. W. Ebbesen, H. J. Lezec, H. F. Ghaemi, T. Thio, and P. A. Wolff, Nature (London) **391**, 667 (1998).
[2] E. Ozbay, Science **311**, 189 (2006).
[3] F. J. Garcia-Vidal, L. Martin-Moreno, T. W. Ebbesen, and L. Kuipers, Rev. Mod. Phys. **82**, 729 (2010).
[4] S. G. Rodrigo, F. J. Garcia-Vidal, and L. Martin-Moreno, Phys. Rev. B **77**, 075401 (2008).
[5] F. Przybilla, A. Degiron, J. Y. Laluet, C. Genet, and T. W. Ebbesen, J. Opt. A **8**, 458 (2006).
[6] A. K. Azad, Y. Zhao, W. Zhang, and M. He, Opt. Lett. **31**, 2637 (2006).
[7] T. H. Isaac, W. L. Barnes, and E. Hendry, Phys. Rev. B **80**, 115423 (2009).
[8] J. G. Rivas, P. H. Bolivar, and H. Kurz, Opt. Lett. **29**, 1680 (2004).
[9] A. Tsiatmas, A. R. Buckingham, V. A. Fedotov, S. Wang, Y. Chen, P. A. J. de Groot, and N. I. Zheludev, Appl. Phys. Lett. **97**, 111106 (2010).
[10] Z. Tian, R. Singh, J. Han, J. Gu, Q. Xing, J. Wu, and W. Zhang, Opt. Lett. **35**, 3586 (2010).
[11] X. Zeng *et al.*, Nat. Mater. **1**, 35 (2002).
[12] F. J. G. de Abajo, Rev. Mod. Phys. **79**, 1267 (2007).
[13] H. F. Ghaemi, T. Thio, D. E. Grupp, T. W. Ebbesen, and H. J. Lezec, Phys. Rev. B **58**, 6779 (1998).
[14] C. Genet, M. van Exter, and J. P. Woerdman, Opt. Commun. **225**, 331 (2003).
[15] D. C. Mattis and J. Bardeen, Phys. Rev. **111**, 412 (1958).
[16] R. A. Kaindl, M. A. Carnahan, J. Orenstein, D. S. Chemla, H. M. Christen, H. Y. Zhai, M. Paranthaman, and D. H. Lowndes, Phys. Rev. Lett. **88**, 027003 (2001).
[17] S. K. Ozdemir and G. Turhan-Sayan, J. Lightwave Technol. **21**, 805 (2003).
[18] C. P. Huang, Q. J. Wang, and Y. Y. Zhu, Phys. Rev. B **75**, 245421 (2007).
[19] J. D. Jackson, *Classical Electrodynamics* (Wiley, New York, 1998).
[20] K. Y. Bliokh, Y. P. Bliokh, V. Freilikher, S. Savel'ev, and F. Nori, Rev. Mod. Phys. **80**, 1201 (2008).
[21] J. B. Pendry, L. Martin-Moreno, and F. J. Garcia-Vidal, Science **305**, 847 (2004).
[22] A. L. Rakhmanov, V. A. Yampol'skii, J. A. Fan, F. Capasso, and F. Nori, Phys. Rev. B **81**, 075101 (2010).
[23] M. Ortolani *et al.*, Phys. Rev. B **77**, 100507 (2008).
[24] S. Savel'ev, V. A. Yampol'skii, A. L. Rakhmanov, and F. Nori, Rep. Prog. Phys. **73**, 026501 (2010).
[25] A. B. Kuzmenko, Physica C **456**, 63 (2007).
[26] M. A. Ordal, L. L. Long, R. J. Bell, S. E. Bell, R. R. Bell, R. W. Alexander Jr., and C. A. Ward, Appl. Opt. **22**, 1099 (1983).
[27] X. H. Zeng *et al.*, Appl. Phys. Lett. **82**, 2097 (2003).