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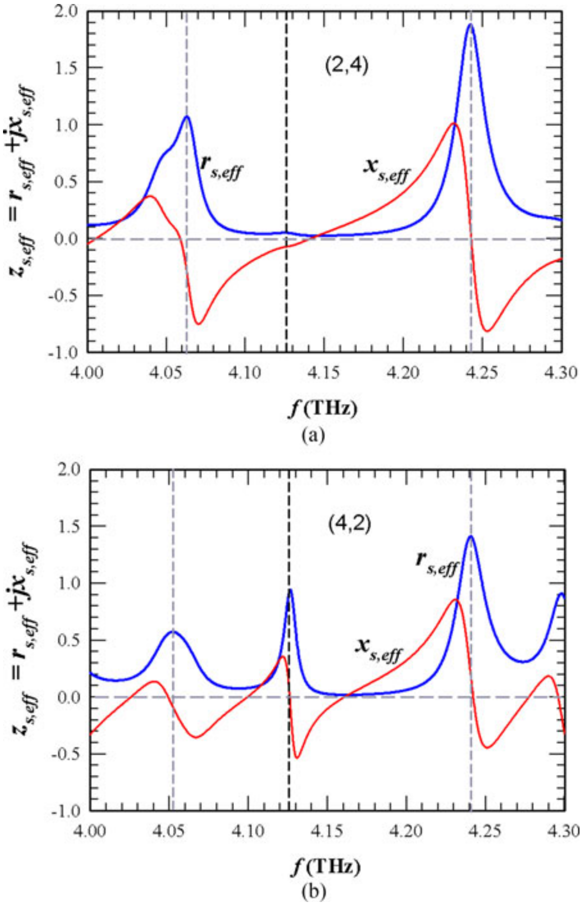

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# Analysis of Unidirectional Absorption in a Defective Superconducting Photonic Crystal

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**Abstract:** Terahertz unidirectional resonant absorption in a finite one-dimensional defective superconducting photonic crystal is theoretically investigated. We consider an asymmetric photonic crystal $(AB)^N D(BA)^M$, where A is a dielectric, B is a superconductor, D is the dielectric defect, and $N$, $M$ are the stack numbers, respectively. At $N \neq M$, it is found that the resonant absorption for the structure exhibits the unidirectional property. The unidirectional resonant absorption points increase as the difference between $N$ and $M$ increases. We also investigate the unidirectional property as a function of angle of incidence. The results show that the unidirectional absorption is nearly independent of the polarization at a given angle of incidence. The proposed structure can be used to design a polarization-independent optical device which may be technically used in superconducting photonics.

**Index Terms:** Photonic crystal, unidirectional absorption, superconductor.

## 1. Introduction

Since the pioneering works by Yablonovitch [1] and John [2], photonic crystals (PCs), artificially periodic layered structures, have attracted much attention over the past two decades. PCs are attractive because they can be used to manipulate and control the flow of light [3]. In general, in a one-dimensional PC optical properties such as reflection, transmission, and even absorption are bidirectional (or two-way) because of the symmetry in structure. Recently, unidirectional (one-way) propagation in a PC has been of much interest to the community [4]–[7]. Such property means that a certain optical phenomenon is unidirectional. Unidirectional property is of great importance in applied optical physics [8], [9]. For instance, the unidirectional PCs are known to be good candidates for achieving optical diodes which are able to transmit light in one direction and forbidden in the opposite direction. In addition to optical diodes, optical couplers and narrowband transmission or reflection filters are also possible applications. There are several methods for realizing the unidirectional phenomena. A simple way is to break the symmetry in structure. Recently, researches have investigated unidirectional properties by particularly considering PCs in the presence of the

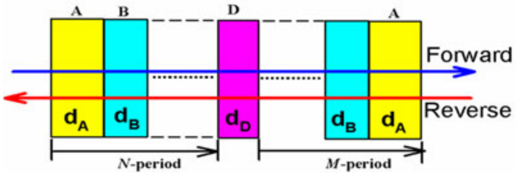


Fig. 1. The definition of forward and reverse propagations for the considered structure $(AB)^N D(BA)^M$.

magnetic field [4]–[6], [10]–[15]. This magneto-optical (MO) effect provides a convenient way to break the time-reversal symmetry, leading to related unidirectional properties.

In this paper, instead of using magnetic materials in constructing PCs, to study the unidirectional wave property, we shall consider a superconducting PC (SPC). SPCs have been of much interest to the community in recent years [16]–[20]. A superior feature for SPCs is that the metallic loss in metal-dielectric or the magnetic loss in magnetic-dielectric PC can be largely decreased and negligibly small [16]. There have been many reports on SPCs, including the basic optical physics and the applicational issues as well. The lateral shift of the transmitted light in a one-dimensional (1D) SPC was studied by Dadoenkova *et al.* [17]. Hsu and Wu investigated the anomalous transmission in an SPC containing nearly ferroelectric superconductor [18]. Using a superconducting film as a defect layer in a dielectric PC, the filtering property was reported by Liu *et al.* [19]. In addition, a superconducting photonic quantum well structure has been considered to design a filter with multiple channels [20]. Reports on the photonic band structures in SPCS are also available thus far [21]–[26].

The purpose of this paper is to study the terahertz (THz) unidirectional resonant absorption in a finite SPC containing a defect layer because the superconductor is operated within THz regime. By the way, such SPC (operated at 70-75 $\mu$m, as seen later) can also be used for the part region of far-infrared (50-1000 $\mu$m). The considered structure is denoted as $(AB)^N D(BA)^M$, where A is a dielectric, B is a superconductor, D is a dielectric defect, and N, M are stack numbers, respectively. In addition, in order to have an asymmetric structure, we assume that $N \neq M$. Referring to Fig. 1, for a given value of (N, M), say (2,4), the propagation is defined as the forward direction (the wave propagation is set to be from the left to the right). Conversely, at (4, 2) we have a reverse propagation direction because the wave propagation from the left to the right is identical to the case of (2,4) with wave propagation from the right to the left. If at a certain frequency, the difference in absorption between two directions can attain a maximum, then we say that the unidirectional phenomenon occurs. That is, the whole structure has a large absorption in one direction whereas it has a small amount of absorption in the reverse direction. We further find that the number of unidirectional resonant points will increase as the difference between N and M increases. Other related dependences of the unidirectional property will be analyzed in details. The unidirectional property will be analyzed based on the absorption response calculated by the transfer matrix method (TMM) [27].

## 2. Basic Equations

Let us consider the photonic crystal structure as $(AB)^N D(BA)^M$, in which A is a dielectric, B is a superconductor, and D is a dielectric defect. In addition, $N$ and $M$ are stack numbers of the left and right mirrors, respectively. To study the absorption property, one has first to calculate the reflectance $R$ and transmittance $T$ for the structure. $R$ and $T$ can be obtained from the TMM [27]. In the analysis that follows we shall take the temporal part as exp(j$\omega$t) for all fields. Following the TMM, the total transfer matrix $M_T$ is expressed as

$$M_T = \begin{pmatrix} M_{11} & M_{12} \\ M_{21} & M_{22} \end{pmatrix} = D_0^{-1}\left[(M_A M_B)^N M_D (M_B M_A)^M\right] D_0, \tag{1}$$

where the single layer transfer matrix is given by

$$M_q = D_q P_q D_q^{-1},\ q = A, B, \text{or } D \tag{2}$$

Here, the dynamical matrix in each region is written by

$$D_{q,TE} = \begin{pmatrix} 1 & 1 \\ n_q \cos\theta_q & -n_q \cos\theta_q \end{pmatrix}, \tag{3}$$

For the TE wave and

$$D_{q,TM} = \begin{pmatrix} \cos\theta_q & \cos\theta_q \\ n_q & -n_q \end{pmatrix}, \tag{4}$$

for the TM wave, respectively, where $q = 0$ represents the free space and $\theta_0$ is the angle of incidence. In medium $q$, the refraction of index is $n_q$ and $\theta_q$ is the ray angle related by the Snell's law of refraction. In addition, the propagation matrix is expressible as

$$P_q = \begin{pmatrix} e^{j\phi_q} & 0 \\ 0 & e^{-j\phi_q} \end{pmatrix}, \tag{5}$$

where

$$\phi_q = k_{q,x} d_q = \frac{\omega}{c} d_q n_q \cos\theta_q,\ q = A, B, D, \tag{6}$$

where $d_q$ denotes the thickness in medium $q$, $\omega$ is the angular frequency, and $c$ is the speed of light in vacuum. According to the TMM, the reflection coefficient r and the transmission coefficient t are obtained to be [27]

$$r = \frac{M_{21}}{M_{11}},\ t = \frac{1}{M_{11}}, \tag{7}$$

where $M_{11}$ and $M_{21}$ are the two matrix elements in Eq. (1). With $r$ and $t$, the reflectance and the transmittance are $R = |r|^2$ and $T = |t|^2$. Thus, the absorptance is $A = 1 - T - R$.

The refraction of index of a superconducting material is complex-valued and related to the permittivity function $\varepsilon_B$ by

$$n_B = n'_B - jn''_B = \sqrt{\varepsilon_B} \tag{8}$$

where the permittivity function is a function of the frequency and the temperature given by

$$\varepsilon_B\left(\omega, \tilde{T}\right) = -j\frac{\sigma_B\left(\omega, \tilde{T}\right)}{\omega\varepsilon_0}, \tag{9}$$

where $\tilde{T}$ is the temperature, $\varepsilon_0$ is the permittivity of free space, and the superconducting conductivity $\sigma_B(\omega, \tilde{T})$ can be obtained on the basis of the two-fluid model (TFM) together with the local London electrodynamics [28]. According to TFM, the superconducting conductivity is expressed as

$$\begin{aligned}\sigma_B\left(\omega, \tilde{T}\right) &= \sigma'_B\left(\omega, \tilde{T}\right) - j\sigma''_B\left(\omega, \tilde{T}\right) = \frac{\varepsilon_0\omega_p^2\tau}{1 + j\omega\tau}x_n - j\frac{1}{\omega\mu_0\lambda_L^2}x_s \\ &= \frac{\varepsilon_0\omega_p^2\tau}{1 + \omega^2\tau^2}x_n - j\left(\frac{\varepsilon_0\omega_p^2\tau^2\omega}{1 + \omega^2\tau^2}x_n + \frac{1}{\omega\mu_0\lambda_L^2}x_s\right)\end{aligned} \tag{10}$$

Here, the penetration length is dependent on the temperature, i.e.,

$$\lambda_L\left(\tilde{T}\right) = \frac{\lambda_0}{\sqrt{1 - \left(\tilde{T}/\tilde{T}_c\right)^4}} \tag{11}$$

where $\lambda_0$ is the penetration depth at $\tilde{T} = 0\ K$, $\omega_p = (n_t e^2/m\varepsilon_0)^{1/2}$ is the plasma frequency of the total electrons and $\tau = 1/\gamma$ is the momentum relaxation time of normal electrons, where $\gamma$ is the phenomenological damping parameter. In addition, $x_s$ and $x_n = 1 - x_s$ represent the fractions

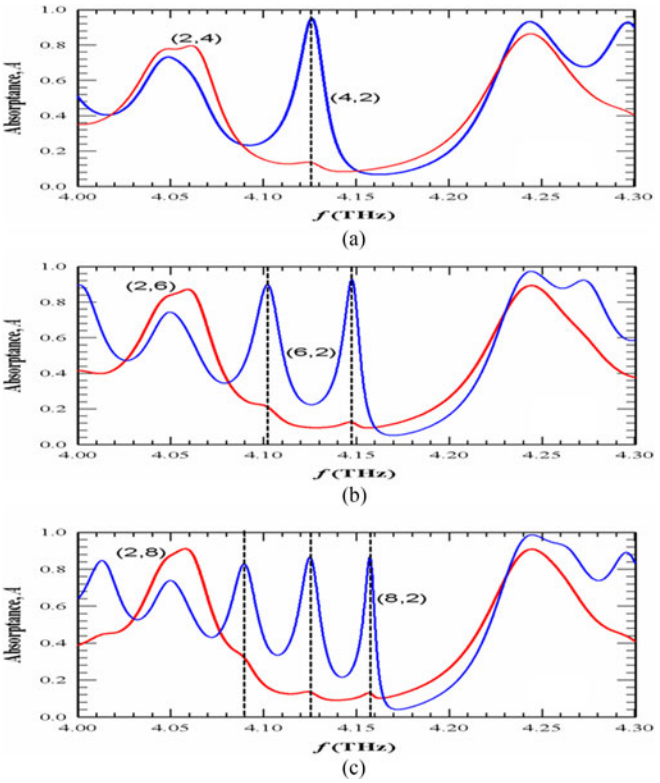


Fig. 2. The calculated absorptance at 70 K for different values of (*N,M*). It can be seen that the number of unidirectional resonant frequencies increases as the difference between *N* and *M* increases.

of the superelectrons and the normal electrons. At zero or weak magnetic field, $x_s$ is dependent only on the temperature, namely

$$x_s = 1 - \left(\tilde{T}/\tilde{T}_c\right)^4, \tag{12}$$

where $\tilde{T}_c$ is the superconducting critical temperature. It can be seen from Eq. (12) that the fraction of superelectrons decreases as the temperature increases. The role of superelectrons is that the loss in the superconducting state will be less when the number of superelectrons increases. That means the normal electrons will dominate the electron system as the temperature is close to the critical temperature. The large fraction of normal electrons will in turn lead to a large loss or dissipation in the superconductor.

## 3. Numerical Results and Discussion

Let us now start to study the unidirectional resonant absorption property for an SPC of $(AB)^N D(BA)^M$. Here, the refractive index of A is taken be to $n_A = \sqrt{\varepsilon_A} = \sqrt{15}$ and the thickness is $d_A = 150\ \mu$m. As for the superconductor layer B, we chose to use the typical high-temperature superconducting system, $YaBa_2Cu_3O_{7-x}$ (YBCO) whose material parameters are $\tilde{T}_c = 92$ K, $\lambda_0 = 200$ nm, $\omega_p = 1.7 \times 10^{15}$ rad/s, $\gamma = 1.3 \times 10^{13}$ rad/s, and the superconducting gap frequency $2\Delta/\hbar = 8$ THz [22]. In order to keep the superconductor in the superconducting state, the operating frequency is taken below the gap frequency. In addition, the thickness of superconductor is $d_B = 0.01\ \mu$m. Without loss of generality, the defect layer is taken as air with a thickness of $d_D = 10\ \mu$m. In the first part, we limit our attention to the case of normal incidence.

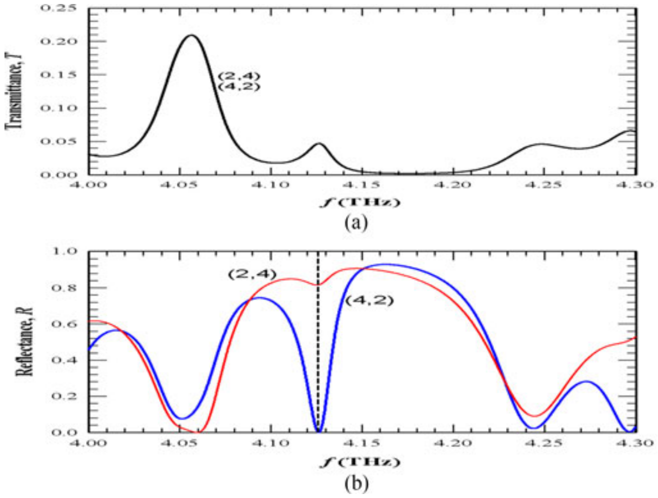


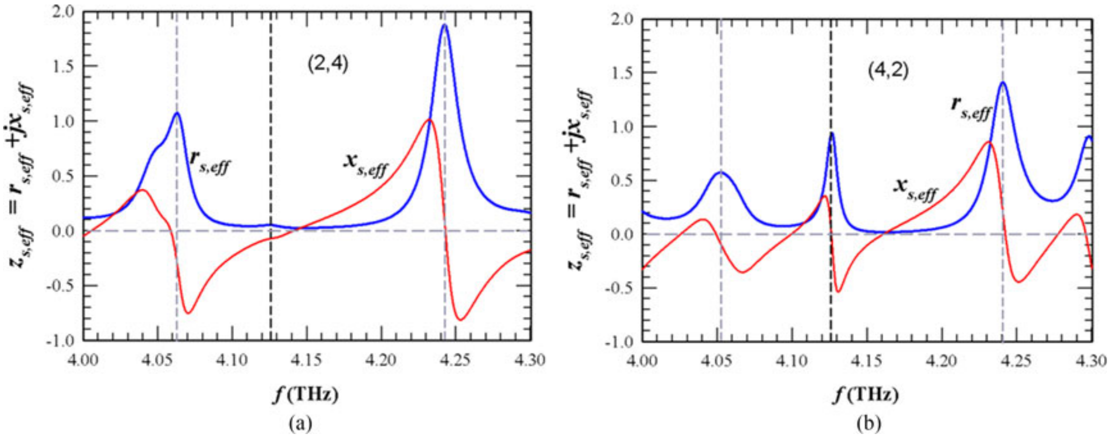
Fig. 3. The frequency responses of $T$ and $R$ at $(N, M) = (2, 4)$ and $(4, 2)$ and at 70 K. Unidirectional absorptance comes from the large difference of reflectance spectra at the resonant frequency.

In Fig. 2, we plot the frequency response of the absorptance for different values of $(N, M) = (2, 4)$, $(4, 2)$, $(2, 6)$, $(6, 2)$, $(2, 8)$ and $(8, 2)$, respectively. It is found from Fig. 2(a) that there exists an obvious unidirectional aborptance at $f = 4.126$ THz when $(N, M) = (2, 4)$ and $(4, 2)$. At this frequency, the forward ($(N, M) = (2, 4)$) absorptance is much less than that the reverse ($(N, M) = (4, 2)$), leading to the so-called unidirectional resonant absorptance. It is also seen that the number of unidirectional absorptance frequencies depends on the value of ($N$, $M$), as seen in Fig. 2(b) and (c). For (2,4), (2,6), and (2,8), the unidirectional frequencies are 1, 2, and 3, respectively, as illustrated by the vertical dashed lines. The increase in the number is caused by the ratio of layer number defined as $M/N$ (as in this case is 2, 3, 4, respectively). Physically, this increase in the number of peaks can be ascribed to the increase in the multiple reflection when the ratio is increased. Let us define $A_F$ and $A_R$ as the absorptance of forward and reverse propagation, respectively. However, the contrast of sharpness ($A_F - A_R$) of unidirectional absorption is most pronounced for (2,4) and thus in the analysis that follows we shall limit our interest in the case of $(N, M) = (2, 4)$ and $(4, 2)$ to study the unidirectional property.

In Fig. 3, we plot the frequency-dependent transmittance $T$ and reflectance $R$ at $(N, M) = (2, 4)$ and $(4, 2)$. As expected, the transmittance is bidirectional because both forward and reverse directions are the same for any multilayer structure. However, the reflectance spectrum shows a strong difference at the resonant frequency of 4.126 THz, which is the frequency of unidirectional absorptance in Fig. 2(a). To further gain the insight of the resonant frequency, in Fig. 4, we have plotted the effective surface impedance for $(N, M) = (2, 4)$ and $(4, 2)$, respectively. It is worth mentioning that the effective surface impedance is closely to the reflection coefficient for a layered structure and can be used to investigate the resonant phenomenon. The normalized (normalized to the wave impedance of free space, $Z_0 = 377\,\Omega$) effective surface impedance for a layered structure can be calculated from the reflection coefficient, namely

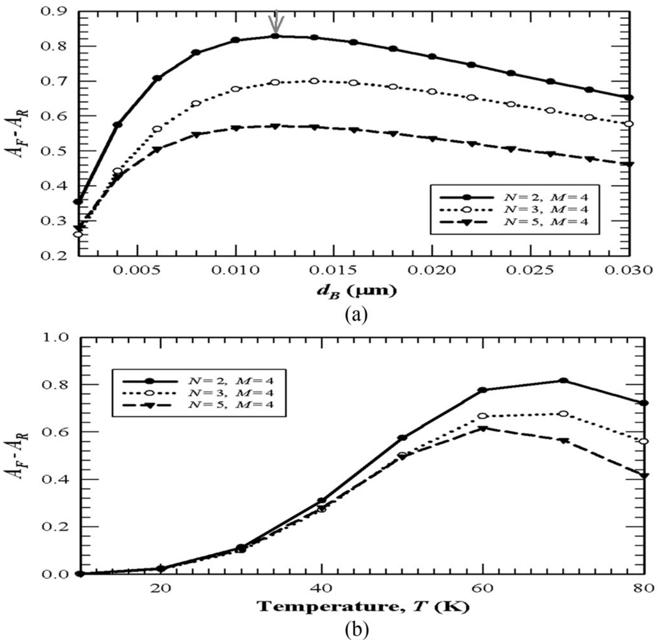
$$\frac{Z_{s,\mathrm{eff}}}{Z_0} = z_{s,\mathrm{eff}} = r_{s,\mathrm{eff}} + jx_{s,\mathrm{eff}} = \frac{1 + r}{1 - r}, \tag{13}$$

In Fig. 3(b), we see that, for the reverse direction (4,2), the reflectance coefficient, $r = 0$ at resonance frequency, leading to $r_{s,\mathrm{eff}} = 1$ and $x_{s,\mathrm{eff}} = 0$ as illustrated by the vertical dashed line in Fig. 4(b). This kind of resonance is known as the antiresonance because the surface resistance attains a maximum at resonance. However, for the forward direction (2, 4), it does not correspond to a resonant point. Thus the unidirectional absorptance occurs because one direction is at antiresonace



(a) (b)

Fig. 4. The calculated surface resistance (blue) and surface reactance (red) for forward direction (2,4) and reverse direction (4,2), respectively.



(a)

(b)

Fig. 5. The calculated difference in the resonant absorptance between the forward and reverse directions as a function of the superconductor thickness (a) and the temperature (b) at three values of (*N, M*).

while the other is at nonresonance. Physically, the antiresonance at (4, 2) means that the total energy of the incident wave is confined in the structure and no propagation is allowed. On the other hand, for the nonresonant (2, 4), the wave propagation is still allowed.

We continue to study how the layer thickness affects the resonant absorption. In Fig. 5(a), we change the thickness of superconductor layer from 0.002 $\mu$m to 0.03 $\mu$m, at $T = 70$ K for different values in $(N, M) = (2, 4)$, $(3, 4)$, and $(5, 4)$, respectively. It can be seen that there exists a unidirectional absorptance for each of the three conditions. However, there is a maximum difference in absorptance between the forward and reverse directions at (2, 4), meaning that the unidirectional property is most pronounced in this condition. The better performance at (2, 4) might be due to the large value in the ratio of layer number, i.e., $M/N = 2, 4/3$, and $4/5$ respectively. In addition, there

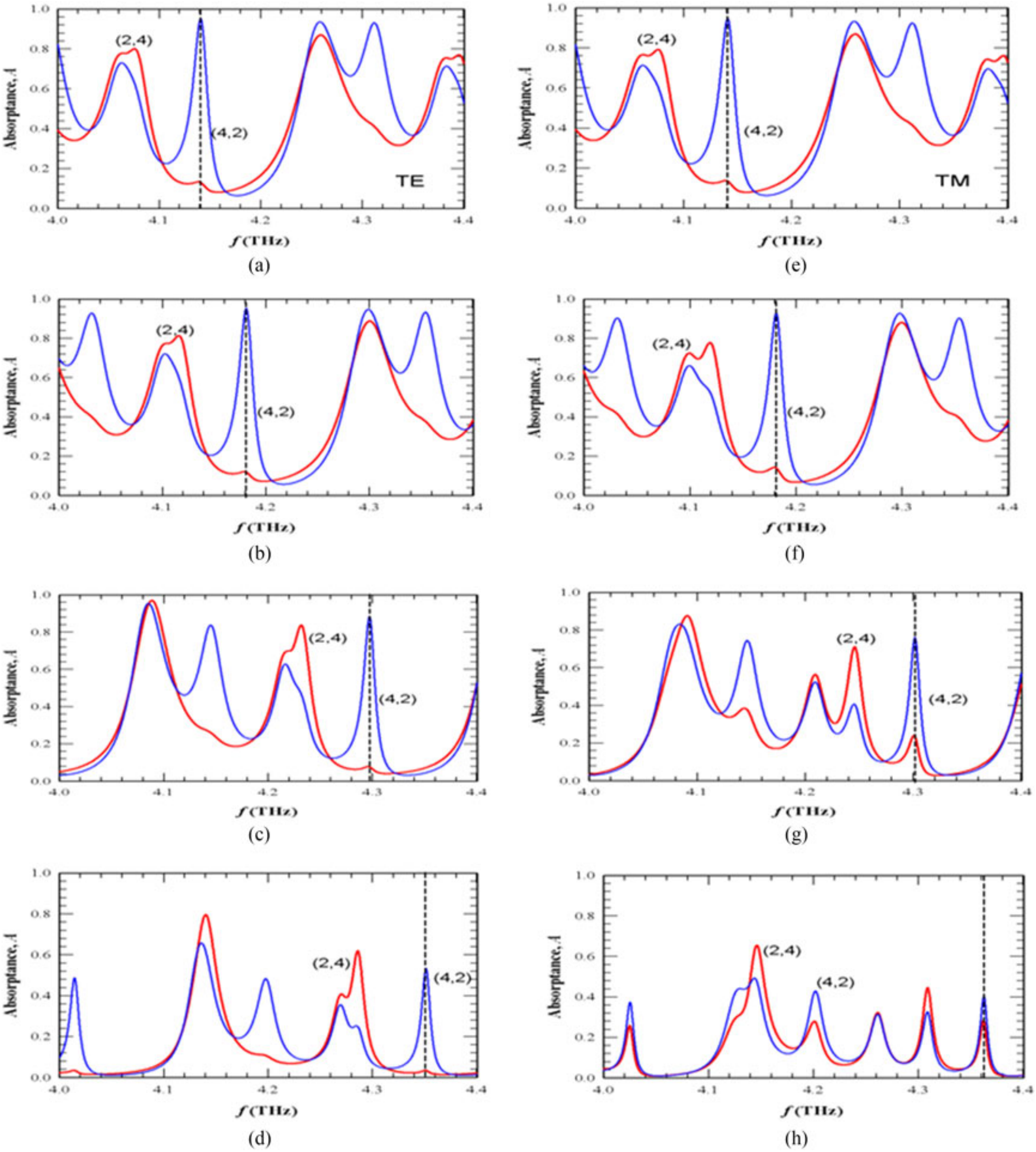


Fig. 6. The calculated absorptance spectra for TE ((a)-(d)) and TM ((e)-(h)) waves at different angles of incidence, 15°, 30°, 60°, and 80°, respectively.

is optimal thickness $d_B = 0.012\,\mu$m at which the difference attains the maximum. The existence of optimal thickness indicates that a complete standing wave is formed at this thickness. These results illustrate that the thickness plays an important role in obtaining the unidirectional property. In addition, since the superconducting permittivity function is temperature-dependent, it is thus worth investigating on how the unidirectional property is influenced by the temperature variation. In Fig. 5(b), at $d_B = 0.01\,\mu$m, we have plotted the $A_F - A_R$ as a function of temperature below $T_c$, namely, $T = 10 - 90$ K. Like in Fig. 5(b), at (2, 4), we have a maximum in the unidirectional absorptance and it also can be seen that at a temperature $T \sim 70$ K the property dominates. At temperatures below about 50 K, the variations in the three cases are small, indicating that the unidirectional absorptance can only be found at a higher temperature and 70 K can be an optimal temperature. This optimal temperature might be closely related to the optical thickness, that is, a correlation between them might exist. The reason is that the ratio of superelectrons to normal electrons that leads the change of resonance condition in the structure. At a certain layer thickness, an optical refractive index might exist that permits complete standing wave.

The above results are calculated in the case of normal incidence. We now extend our study to the oblique incidence. In Fig. 6, we plot the absorptance spectra for TE ((a)-(d)) and TM ((e)-(h)) waves, respectively. Here, we again limit in the case of $(N, M) = (2,4)$ and (4, 2), and the angle of incidence is taken 15°, 30°, 60°, and 80°, respectively. First, we show the results of the TE wave in (a)-(d). Comparing with the normal case in Fig. 2(a), we see that the unidirectional frequency is blue-shifted as the angle increases. The resonant frequencies are at 4.14, 4.182, 4.296, and 4.357 THz for angles at 15°, 30°, 60°, and 80°, respectively. By the way, at 60°, there is an additional minor unidirectional resonant frequency at 4.143 THz. The secondary peak can be ascribed to a partial standing wave formed at this angle. For the TM wave, it is of interest to note that the results in the right column are similar to those of the TE wave. The resonant frequency is also blue-shifted and nearly the same as TE wave. This indicates that the unidirectional resonant absorptance is nearly polarization-independent, showing that the energy confinement is nearly independent of the polarization. This is a special feature of one-way property in such an SPC, which can be used to achieve other polarization independent applications such as the narrowband notch reflection filter in the viewpoint of reflection spectrum.

## 4. Conclusion

We have investigated the THz unidirectional absorption property for a one-dimensional SPC of $(AB)^N D(BA)^M$. Some conclusions can be drawn. First, the number of unidirectional resonant frequencies can be increased as the difference between $N$ and $M$ increases. The resonant type is shown to be antiresonant. We also investigated the unidirectional property as a function of the superconductor layer thickness and the operating temperature. It is found that there exists an optimal thickness and a temperature to obtain a pronounced unidirectional absorptance. Finally, our results show that the unidirectional property is nearly independent of the polarization of the incident wave. The analysis suggests that, based on the use of a superconducting photonic crystal, the unidirectional property is of technical use in superconducting photonics such as a design of optically diode-like device.

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