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OMNIDIRECTIONAL REFLECTION EXTENSION IN A ONE-DIMENSIONAL SUPERCONDUCTING-DIELECTRIC BINARY GRADED PHOTONIC CRYSTAL WITH GRADED GEOMETRIC LAYERS THICKNESSES

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Abstract—The omnidirectional reflection characteristics of one-dimensional (1D) superconducting-dielectric binary graded photonic crystals (PhCs) are studied by using transfer matrix method. The influences of thickness changing rate, numbers of periods, incident angles are analyzed. And the omnidirectional photonic band gaps are extended markedly in the 1D thickness-graded superconducting-dielectric PhC.

1. INTRODUCTION

The study of light transmission through photonic crystals (PhCs) has been attracting increasing attention in the last years [1]. Photonic crystals are structures that show a periodic variation of the refractive index on a length scale comparable to the wavelength of light. Photonic crystals exist in nature or can be fabricated using a wide range of techniques, with the dielectric periodicity in one, two and three dimensions [2–4].

The one-dimensional (1D) PhCs have attracted special attention since they are easier to fabricate. Recently, it has been theoretically and experimentally demonstrated that an omnidirectional Bragg reflector can be realized using one dimensional (1D) photonic crystals. The Bragg reflector plays an important role in modern photonics because of its wide use in controllable switching, tunable polarizer, narrow-band filters, solid-state lasers, etc. [5–8].

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The width of the omnidirectional band gaps (OBGs) plays an important role in the applications of 1D PhCs omnidirectional reflectors. Some methods to enlarge the frequency range of OBGs of 1D binary PhCs have been proposed, such as increasing the contrast of dielectric functions between the PhC composites [9], using a chirped PhC [10] or photonic heterostructure [11], or introducing the disorder into the periodic structures [12, 13], etc.. In recent years, 1D ternary PhCs consisting of superconductor and dielectric materials are also put forward to obtain the extended OBGs [14–16]. In addition to increasing the OBGs, the superconductor-based PhCs has tunable advantages through variations of temperature or magnetic field [17].

In this paper, the omnidirectional reflection for a graded 1D superconducting-dielectric binary PhCs as a function of the thickness changing rate for both superconductor and dielectric layers is theoretically investigated. The omnidirectional band structure is studied through the frequency-dependent transmittance spectrum calculated by using the transfer matrix method (TMM). The OBGs enhancement with the different thickness changing rate of superconductor and dielectric layers, and the different numbers of periods will be numerically elucidated.

2. THEORY

The periodic structure consisting of alternate superconductor and dielectric layer with graded thicknesses is depicted in Figure 1.

$$\Lambda\left(m\right)=d\left(m\right)=d_1\left(m\right)+d_2\left(m\right)\quad\left(m=1,2,3,\ldots,N\right)$$

With $\Lambda(m)$ defined as the lattice thickness of the mth period, and N is the number of periods. $d_1(m)$ and $d_2(m)$ represent the thicknesses of the mth superconducting and dielectric layers, respectively.

The periodic structure is placed on a glass substrate with thickness d_3 shown as the rightmost layer in the figure. The refractive indices of the dielectric layer and substrate are denoted by n_2 and n_3, respectively. The complex index of refraction for the superconducting material can be formulated as $n_1=\sqrt{\varepsilon_{r1}}=n_R+in_I$, with the imaginary part n_I defined to be the extinction coefficient. The relative permittivity ε_{r1} can be obtained on the basis of the two-fluid model as [18]

$$\varepsilon_{r1}=1-\frac{\omega_{th}^2}{\omega^2}=1-\frac{1}{\omega^2\mu_0\varepsilon_0\lambda_L^2}\tag{1}$$

where ω_{th} is the threshold frequency of the bulk superconductor and

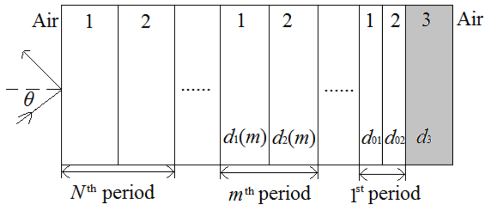

Figure 1. An N-period graded superconductor-dielectric periodic multilayer structure, in which layer 1 is the superconductor, layer 2 is the dielectric, and layer 3 is the glass substrate. The wave is incident in free space of region 0, and the region behind the substrate is also free space.

λ_L the temperature-dependent penetration depth given by

$$\lambda_L = \frac{\lambda_0}{\sqrt{1-(T/T_c)^4}} \tag{2}$$

λ_0 is the penetration depth at $T = 0\,\mathrm{K}$ and T_c the critical temperature of the superconductor.

In obtaining the refractive index in Eq. (1), we have neglected the contribution of the normal fluid because we are interested in a lossless superconductor. The behaviors of a lossless superconductor are well described in [19].

For an electromagnetic wave incident obliquely on the most left boundary of air/layer 1 at an angle of incidence θ as shown in Figure 1, the reflectance $R = |r|^2$ can be calculated by using the transfer matrix method [20] and the reflection coefficient r is expressed as

$$r = \frac{M_{21}}{M_{11}} \tag{3}$$

where M_{11} and M_{21} are the matrix elements of the total transfer matrix M given by

$$M = \begin{pmatrix} M_{11} & M_{12} \\ M_{21} & M_{22} \end{pmatrix} = D_0^{-1} M_{\Lambda(m)}^N D_3 P_3 D_3^{-1} D_0 \tag{4}$$

and $M_{\Lambda(m)}$ is the transfer matrix of mth period,

$$M_{\Lambda(m)} = D_1 P_1 D_1^{-1} D_2 P_2 D_2^{-1} \tag{5}$$

The propagation matrix P in Eq. (5) of the individual layer is

$$P_\ell = \begin{pmatrix} e^{i\phi_\ell} & 0 \\ 0 & -e^{i\phi_\ell} \end{pmatrix} \tag{6}$$

where

$$\phi_\ell = k_{\ell z} d_\ell = \frac{2\pi d_\ell}{\lambda} n_\ell \cos\theta_\ell \quad (\ell = 1, 2, 3) \tag{7}$$

Also the dynamical matrix in each layer is defined by

$$D_\ell = \begin{cases} \begin{pmatrix} 1 & 1 \\ n_\ell \cos\theta_\ell & -n_\ell \cos\theta_\ell \end{pmatrix} & \text{(TE polarization)} \\ \begin{pmatrix} \cos\theta_\ell & \cos\theta_\ell \\ n_\ell & -n_\ell \end{pmatrix} & \text{(TM polarization)} \end{cases} \tag{8}$$

And θ_ℓ is the ray angle of the ℓth layer, where $\ell = 0$, 1, 2, and 3. For $\ell = 0$, θ_0 indicates the incident angle. The ray angle in layers 1 and 2 can be calculated by Snell's law of refraction, i.e.,

$$n_0 \sin\theta_0 = n_1 \sin\theta_1 = n_2 \sin\theta_2 = n_3 \sin\theta_3 \tag{9}$$

The matrix of each single-period incorporating the refractive indices and the thicknesses as well as the ray angles of the two constituent layers plays a dominant role in the calculation of the reflectance spectrum for a Bragg reflector.

3. NUMERICAL RESULTS AND DISCUSSION

For numerical simulation, referring to Figure 1, conventional superconductor niobium (Nb) with $T_c = 9.2\,\mathrm{K}$ and $\lambda_0 = 83.4\,\mathrm{nm}$ is taken as layer 1. The SiO_2 with relative permittivity $\varepsilon_{r2} = 10$ and glass with $\varepsilon_{r3} = 2.25$ are taken for the dielectric layer 2 and substrate, respectively. The graded thicknesses of the corresponding layers are set to be

$$d_1(m) = d_{01} + (m-1)\Delta d_1, \quad d_2(m) = d_{02} + (m-1)\Delta d_2 \quad (m = 1, 2, 3, \ldots, N)$$

where $d_1(m)$ and $d_2(m)$ represent the thicknesses of the mth superconducting and dielectric layers, respectively. d_{01} and d_{02}, Δd_1 and Δd_2 denote thicknesses of superconductor layer and dielectric layer of rightmost single-period, thickness changing rate of superconductor layer and dielectric layer, respectively. N is the number of periods. The thickness of glass is $d_3 = 1\,\mathrm{mm}$, and operating temperature $T_c = 4.2\,\mathrm{K}$ are adopted for simulation.

3.1. The Relationship between Wavelength and Reflectivity under Different Changing Rate of Thickness

Figure 2 shows the reflectance spectrum of the binary graded superconducting-dielectric Bragg reflector) in Figure 1 at periods numbers of $N = 10$ and $d_{01} = d_{02} = 50\,\mathrm{nm}$, normal incidence,

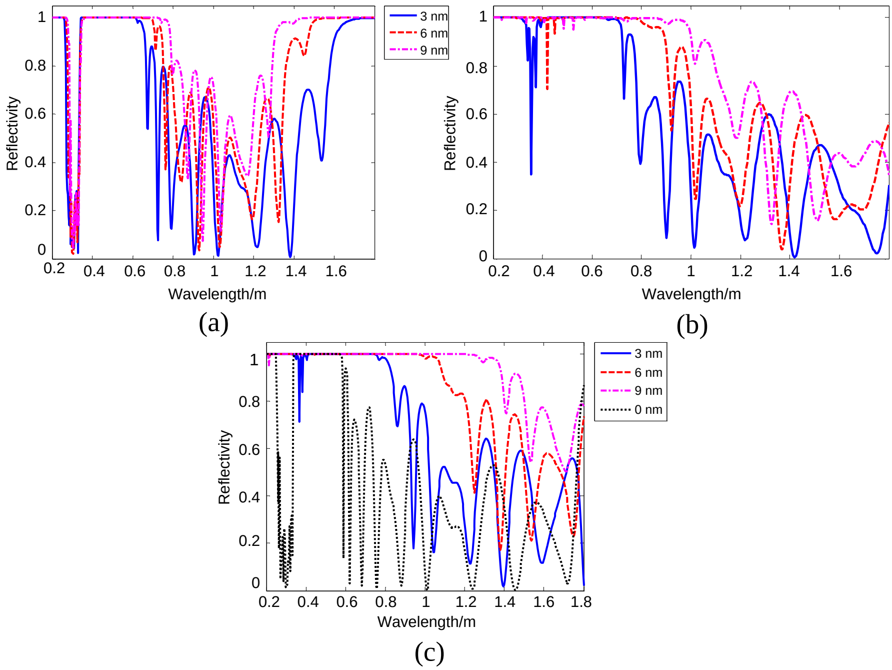

Figure 2. The calculated wavelength-dependent reflectance at distinct thickness changing rate. Here the periods numbers of $N = 10$ and the normal incidence of $\theta = 0°$ are used. (a) SiO_2 fixed thickness $d_2 = d_{02} = 50\,\text{nm}$, and Nb initial thickness $d_{01} = 50\,\text{nm}$ with thickness changing rate $\Delta d_1 = 3$, 6, 9 nm respectively. (b) Nb fixed thickness $d_1 = d_{01} = 50\,\text{nm}$, and SiO_2 initial thickness $d_{02} = 50\,\text{nm}$ with thickness changing rate $\Delta d_2 = 3$, 6, 9 nm respectively. (c) SiO_2 and Nb with initial thickness $d_{01} = d_{02} = 50\,\text{nm}$ and same thickness changing rate $\Delta d = \Delta d_1 = \Delta d_2 = 3$, 6, 9, respectively.

and different thickness changing rate. According to the results of the Figure 2(a), the high reflectivity range (HRR) is expanded with redshift to longer wavelength within visible light range, as thickness of graded superconductor layer of Bragg reflector is increased. The HRR is shifted under condition of superconductor fixed thickness $d_1 = d_{01} = 50\,\text{nm}$ and graded dielectric thickness $d_{02} = 50\,\text{nm}$ with thickness changing rate Δd_2 (as shown in Figure 2(b)). Comparing Figure 2(c) with Figure 2(a) and Figure 2(b), the HRR is expended while thicknesses of superconductor layer and dielectric layer are increasing synchronously. It is seen that the reflector with $\Delta d = \Delta d_1 = \Delta d_2 = 0\,\text{nm}$ exists reflectance bandwidth of 234 nm because its left and right band edges are 340 nm and 574 nm. When the thicknesses changing rate $\Delta d = \Delta d_1 = \Delta d_2$ are increased from 3 nm to 9 nm, the reflectance bandwidths are apparently enlarged. And the bandwidth is increased up to 1023 nm from ultraviolet 221 nm to infrared 1244 nm while $\Delta d = \Delta d_1 = \Delta d_2$ is 9 nm. The tunable HRR is obtained by through changing the thickness changing rate of superconductor layer, changing the thickness changing rate of dielectric layer, or simultaneous changing the thickness changing rate of superconductor and dielectric.

3.2. The Influence of Periods to the Reflectivity under Fixed Changing Rate of Thickness

Figure 3 shows the reflectance spectrum of the binary graded superconducting-dielectric Bragg reflector in Figure 1 at $d_{01} = d_{02} =$ 50 nm, normal incidence, and different periods numbers. It is seen that the HRR is expanded as wide as numbers of periods are increased.

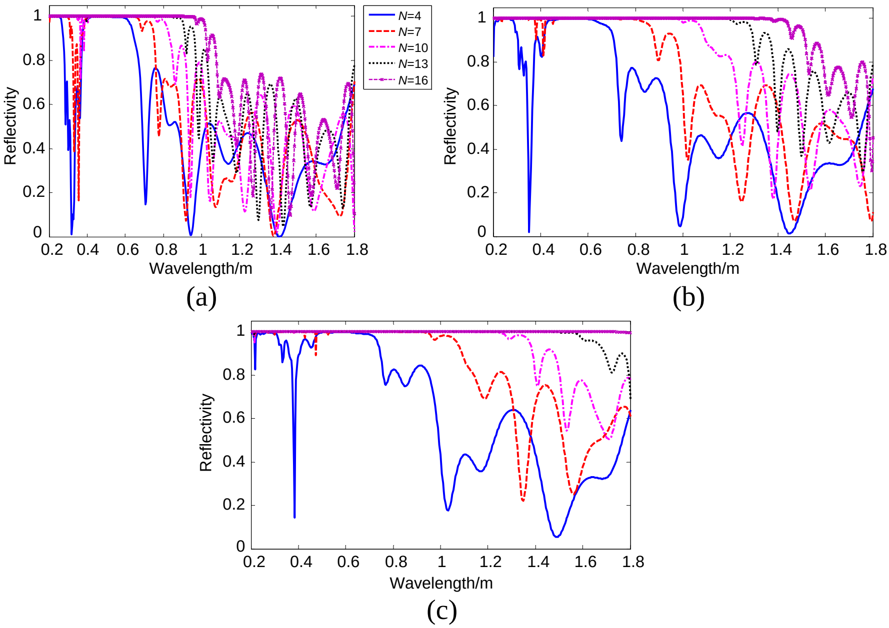

Figure 3. The calculated wavelength-dependent reflectance at different numbers of periods $N = 4$, 7, 10, 13 and 16, respectively. The same thicknesses rate of superconductor and dielectric layers is used, and the normal incidence is $\theta = 0°$. (a) For $\Delta d = \Delta d_1 = \Delta d_2 = 3$ nm. (b) For $\Delta d = \Delta d_1 = \Delta d_2 = 6$ nm. (c) $\Delta d = \Delta d_1 = \Delta d_2 = 9$ nm.

3.3. The Reflectivity Changes with Different Incident Angle

In Figure 4, the reflectance response at four different angles of incidence at $\Delta d = \Delta d_1 = \Delta d_2 = 9\,\text{nm}$ are shown. The reflectance bandwidth for the TE wave (as shown in Figure 4(a)) is obviously enlarged when the angle of incidence increases, as compared to the reflectance bandwidth of normal incidence. As for the TM wave (in Figure 4(b)), reflectance bandwidth is obvious enlarged at incident angle of 88°, however, the high reflectance range of TM wave no obvious increase at incident angels of 30° and 60°.

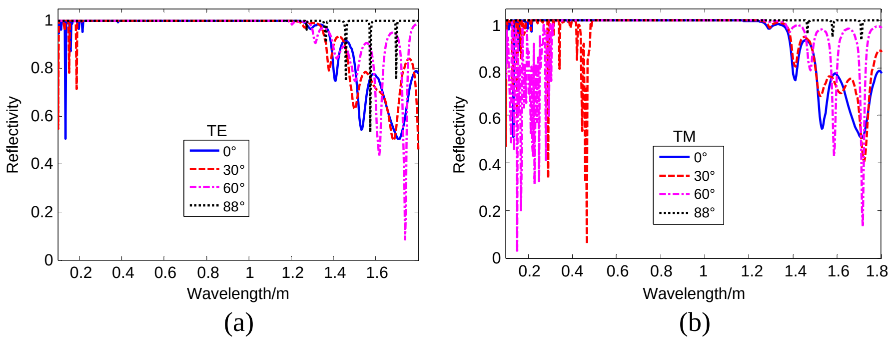

Figure 4. The calculated wavelength-dependent reflectance at four distinct incident angels of 0°, 30°, 60° and 88°. Here the thickness change rates of $\Delta d = \Delta d_1 = \Delta d_2 = 9\,\text{nm}$ is used. (a) For TE wave. (b) For TM wave.

3.4. Comparing between Graded Superconductor-dielectric 1D PhC and Conventional Superconductor-dielectric 1D PhC

The reflectance characteristics of graded superconductor-dielectric 1D PhC with graded thickness and conventional superconductor-dielectric 1D PhC with fixed thickness are compared by using transfer matrix method, and the wavelength-dependent reflectivity is shown in Figure 5. For the graded superconductor-dielectric 1D PhC, the same final thickness of 10th period of superconductor and dielectric is 131 nm when initial thickness of $d_{01} = d_{02} = 50\,\text{nm}$, thickness variety rate of $\Delta d_1 = \Delta d_2 = 9\,\text{nm}$ and total periods of $N = 10$ are used. From the results of the Figure 5, the HRR of graded superconductor-dielectric 1D PhC with graded thickness is wider than conventional superconductor-dielectric. The possible reasons of ultra-wide reflectance bandwidth of graded superconductor-dielectric 1D PhC that are inference of light and specificity of superconductor material.

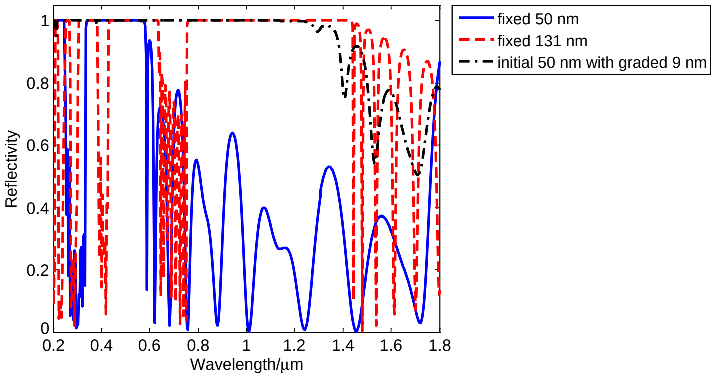

Figure 5. Reflectance spectrums of graded thickness and fixed thickness 1D PhCs.

4. CONCLUSIONS

The photonic omnidirectional reflectance band in the visible and near infrared regions for a binary graded superconductor-dielectric reflective mirror has been studied numerically by using TMM. It has been shown that the tunable reflectance spectrum is obtained by thickness changing rate of one or two kinds of superconductor layer and dielectric layer of graded superconductor-dielectric 1D PhCs. The graded superconductor-dielectric 1D PhCs have superior feature in the enhancement of the high reflectance range compared to the regular binary superconducting-dielectric PhCs with fixed lattice constant. In the normal incidence, the HRR can be significantly enlarged at increasing of thickness changing rate of superconductor, simultaneous increasing of thickness changing rate of superconductor and dielectric, increasing numbers of periods. In the oblique incidence, the existing omnidirectional band is obviously enlarged when the angle of incidence increases, as compared to the reflectance bandwidth of normal incidence. For the TE mode, reflectance bandwidth is obvious enlarged with increasing of incident angle.

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