Extraordinary optical properties of Fibonacci quasi-periodic 1D superconducting photonic crystals in near-zero-permittivity operation range*

WU Ji-jiang (武继江)** **and GAO Jin-xia** (高金霞)

School of Science, Shandong University of Technology, Zibo 255049, China

(Received 7 April 2013)

In near-zero-permittivity operation range, the position-dependent extraordinary optical properties of a one dimensional (1D) Fibonacci quasi-periodic superconducting photonic crystal (PC), which consists of alternating superconductor and dielectric layers, are theoretically investigated by using the transfer matrix method. Based on the calculated reflectance spectrum, it is shown that the extraordinary optical properties depend on the relative positions of the threshold wavelength and the photonic band gaps (PBGs). By suitably choosing the thickness of the superconducting or dielectric layer, a transmission narrow band filter or resonator can be designed without introducing any physical defect in this structure.

Document code: A **Article ID:** 1673-1905(2013)04-0289-4

DOI 10.1007/s11801-013-3066-7

Photonic crystals (PCs) have attracted intensive studies in recent years due to their unique electromagnetic properties and potential applications[1-3]. In the earlier stage, the PCs were mainly fabricated by using the conventional dielectrics. Nevertheless, unconventional constituents for PCs, such as magnetic materials, ferroelectric materials and negative index materials, have also been studied. In addition, the PCs containing superconductors also attracted much attention recently[4-7]. Due to the dependences of the optical properties of superconductors on temperature and magnetic field, the response of electromagnetic wave in superconducting photonic crystals (SCPCs) is tunable.

Moreover, the concept of PBG has been extended to quasiperiodic structures. Periodic multilayer structures consisting of superconducting and dielectric materials have been reported[8-13]. Recently, the optical properties of one-dimensional (1D) SCPC with Fibonacci quasiperiodic structure are also investigated[14,15].

Besides the tunable optical properties, an extraordinary optical property in near-zero-permittivity operation range for the SCPCs was found[5,6,10,11]. It is found that for the transverse magnetic (TM) wave, at wavelength near the superconducting threshold of λ_{th}, an additional high-reflectance band appears, and some reflection dips exist, which are not seen for the transverse electric (TE) wave. The extraordinary optical properties, different from the regular all-dielectric Bragg reflectors, are mainly attributed to the operation in the near-zero-permittivity range of superconductors. These dips are like the localized passbands which provide a feasible way for designing a multi-resonance multilayer Fabry-Pérot resonator without physically inserting any defect layer.

In Ref.[10], Chen et al investigated the extraordinary optical property when the threshold wavelength λ_{th} is located within the PBG. As the incident angle θ increases, the range of dips increases first up to $\theta\approx0.8$ rad, and then decreases. The positions of dips are shifted to the short wavelength. The change of the dips' range discussed here is different from the results presented in Ref.[6], because the threshold wavelength λ_{th} in Ref.[6] is located outside the PBG.

For superconducting periodic multilayer structures, the physical origin of the phenomena is attributed to the combined effect of the extremely small refractive index and the structural periodicity[6]. In this paper, we investigate the extraordinary optical properties of 1D quasiperiodic Fibonacci PC containing superconducting and dielectric materials through the transfer matrix method (TMM) in the near-zero-permittivity range. Three different conditions are considered. Our study reveals that the extraordinary optical properties can also be found in quasiperiodic multilayer structures. In addition, we demonstrate that the extraordinary optical properties depend on the relative positions of the threshold wavelength λ_{th} and the PBG.

The Fibonacci sequence is one of the well-known examples of 1D quasiperiodic structure. The two-component Fibonacci structure can be grown experimentally by juxtaposing two building blocks A and B in such a

* This work has been supported by the National Natural Science Foundation of China (No.11104165).

** E-mail: w9513110@163.com

way that the nth stage of the superlattice S_n is given interactively by the rule $S_n = S_{n-1}S_{n-2}$ for $n \geq 2$, with $S_0 =$ B and $S_1 =$ A. The first few sequences are $S_2 =$ AB, $S_3 =$ ABA, $S_4 =$ ABAAB and so on. In a Fibonacci quasiperiodic 1D SCPC, two types of layers, A and B, are considered as the superconducting material and the dielectric material, respectively. As an example, the fifth sequence S_5 is shown in Fig.1. We consider that an electromagnetic wave is incident with an angle θ from the leftmost medium which is taken to be free space with a refractive index of n_1=1. The index of refraction of the lossless dielectric is given by $n_3=\sqrt{\varepsilon_{r3}}$, where ε_{r3} is its relative permittivity.

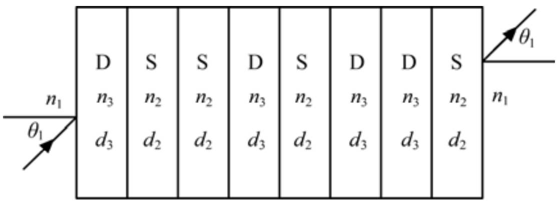


Fig.1 Schematic diagram of Fibonacci quasiperiodic 1D SCPC

The two-fluid model is adopted to describe the electromagnetic response of a superconductor without external magnetic field. With some approximations, the relative permittivity of a lossless superconductor can be expressed as[16]

$$\varepsilon_r = 1 - 1/\omega^2\mu_0\varepsilon_0\lambda_L^2 , \tag{1}$$

where the temperature-dependent penetration depth is given by

$$\lambda_L(T) = \lambda_0 \Big/ \sqrt{1-f(T)} , \tag{2}$$

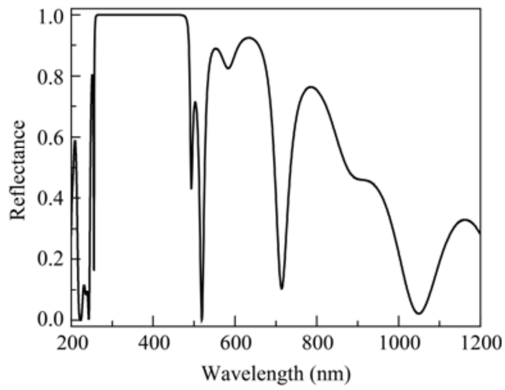
where λ_0 is the London penetration length at temperature T = 0 K, the Gorter-Casimir expression for $f(T)$ is $f(T) = (T/T_c)^4$, and T_c is the critical temperature of a superconductor. Eq.(1) gives the refractive index of a superconductor, i.e., $n_2 = \sqrt{\varepsilon_r}$, which apparently depends on the temperature and the frequency. The superconductor material is thus a dispersive medium. It also can be seen from Eq.(1) that the refractive index n_2 is equal to zero when the angular frequency is at the angular threshold frequency of ω_{th} as

$$\omega_{th} = 2\pi f_{th} = 2\pi c/\lambda_{th} = 1\Big/\sqrt{\mu_0\varepsilon_0}\lambda_L , \tag{3}$$

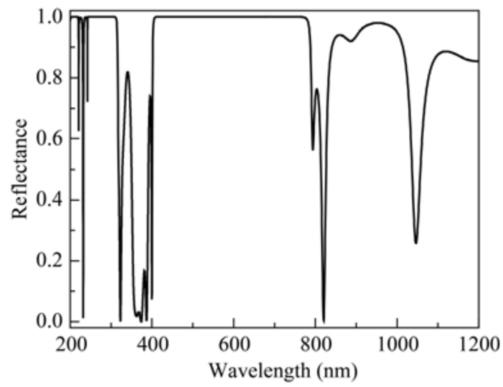
where c is the speed of light in vacuum, and f_{th} and λ_{th} are the threshold frequency and threshold wavelength, respectively.

The following material parameters of S and D, as an example, Nb and SiO_2, are taken from Ref.[6]: T_c = 9.2 K, λ_0 = 83.4 nm and ε_{r3} = 9.7. The operating temperature of T = 4.2 K is used. At this temperature, the threshold wavelength is calculated to be $\lambda_{th} = 2\pi c/\omega_{th}$ = 536 nm. The seventh sequence S_7 is adopted in our calculation. The photonic band structures of 1D SCPCs depend on the thicknesses of the constituents. Fig.2 shows the calculated reflectance spectra of Fibonacci quasiperiodic SCPCs at normal incidence of θ = 0°. At normal incidence, the TE polarization and TM polarization have the same reflectance spectrum. To investigate the dependence of position, four different combinations of d_2 and d_3 are considered.

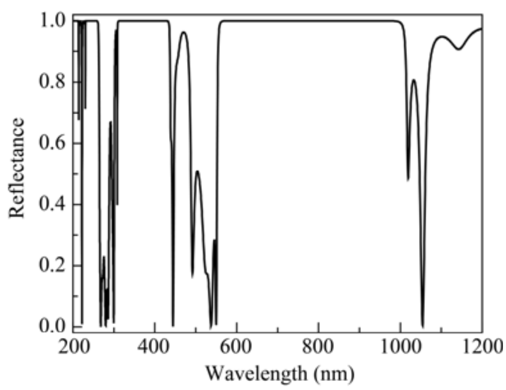
As shown in Fig.2(a), when d_2=36 nm and d_3=36 nm, there is a PBG from 265 nm to 270 nm, and the λ_{th} is located outside the PBG. For the SCPCs with periodic structure, just as discussed in Ref.[10], there is a new PBG appearing owing to the oblique incident λ_{th}. At this time, the extraordinary optical properties can not be observed near the oblique incident λ_{th}. Numerical results show that the extraordinary optical properties can also not be observed for the quasiperiodic structure SCPCs.



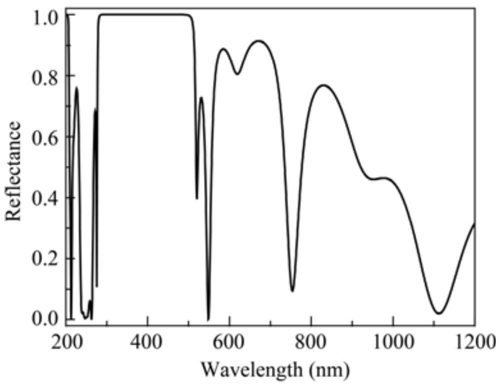
(a) d_2 = 36 nm, d_3 = 36 nm



(b) d_2 = 60 nm, d_3 = 60 nm



(c) d_2 = 60 nm, d_3 = 90 nm



(d) d_2 = 35 nm, d_3 = 40 nm

Fig.2 Calculated reflectance spectra of the quasiperiodic SCPCs with different combinations of d_2 and d_3

When d_2 = 60 nm and d_3 = 60 nm as shown in Fig.(b), the threshold wavelength λ_{th} is located within a PBG. It can be seen from Fig.2(c) that the threshold wavelength λ_{th} is located outside a PBG when d_2 = 60 nm and d_3 = 90 nm. Strictly, it is located at the left hand side of the left bandedge. In the case of d_2 = 35 nm and d_3 = 40 nm as shown in Fig.2(d), the threshold wavelength λ_{th} is located at the right hand side of the right bandedge. By comparing Fig.2(a) with Fig.2(c) and (d), we can see that the distance between the threshold wavelength λ_{th} and the bandedge in Fig.2(a) is larger than that in Fig.2(c) and (d). For the case in Fig.2(a), the extraordinary optical properties can not be observed. The extraordinary optical properties can still present in the condition of Fig.2(c) and (d), although the threshold wavelength λ_{th} is located outside a PBG.

Fig.3 shows the TM- and the TE-polarization wavelength-dependent reflectance spectra of the 1D Fibonacci quasiperiodic SCPC at different incident angles from 0° to 90°. The parameters used in our simulation are the same as those used in Fig.2(b). Just as shown in Fig.2(b), in this case, the threshold wavelength λ_{th} is located within the PBG at normal incidence. It is seen that the extraordinary optical property presented in Fig.3 for TM-polarization is similar to that reported in Ref.[10]. We can see that the range of dips increases first, and then decreases with the increase of incident angle. The positions of dips are also shifted to the short wavelength. We can also see from Fig.3, compared with TM-polarization, no extraordinary optical property is observed near the threshold wavelength for TE-polarization. Therefore, similar to the periodic structure superconducting PCs, the extraordinary optical property cannot be seen in the TE wave for Fibonacci quasiperiodic SCPCs. So in our following numerical calculation, only the TM wave is considered.

Under the condition of d_2 = 60 nm and d_3 = 90 nm, the calculated TM wave reflectance spectrum of the 1D Fibonacci quasiperiodic SCPC is shown in Fig.4. In this case, at normal incidence, the threshold wavelength λ_{th} is located at the left hand side of the left bandedge. The calculated results shown in Fig.4 are consistent with the numerical calculation in Ref.[6]. In Fig.4, we see that the range of dips decreases first and then disappears with the increase of incident angle. The positions of dips are also shifted to the short wavelength. Compared with the first condition presented in Fig.3, the shift can be neglected.

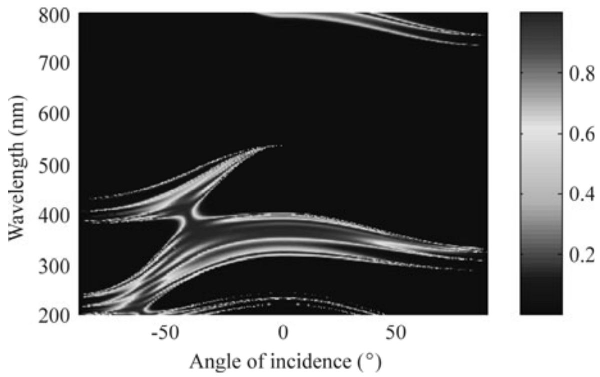


Fig.3 Calculated TM wave and TE wave reflectance spectra for the quasiperiodic SCPC under the condition of d_2 = 60 nm and d_3 = 60 nm

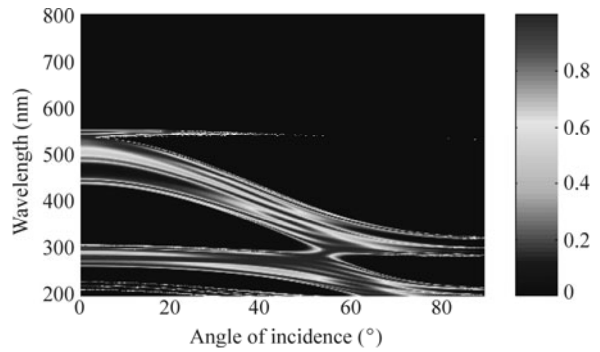


Fig.4 Calculated TM wave reflectance spectrum for the quasiperiodic SCPC under the condition of d_2 = 60 nm and d_3 = 90 nm

Finally when the thicknesses of the corresponding layers are set to be d_2 = 35 nm and d_3 = 40 nm, the calculated TM wave reflectance spectrum of the 1D Fibonacci quasiperiodic SCPC is shown in Fig.5. In this case, the threshold wavelength λ_{th} is located at the right hand side of the right bandedge at normal incidence. In Fig.5, we see that the range of dips increases first and then decreases with the increase of incident angle. The positions of dips are also shifted to the short wavelength.

By the above discussion for the three different cases, we can find out that the extraordinary optical properties depend on the relative positions of the threshold wavelength λ_{th} and the PBG. When the threshold wavelength λ_{th} is located outside the PBG, the extraordinary optical properties can not be observed. But when the threshold wavelength λ_{th} is located at the edge of the PBG, the extraordinary optical properties can also present.

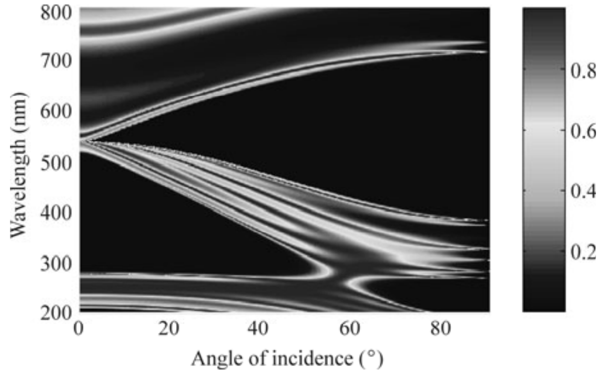


Fig.5 Calculated TM wave reflectance spectrum for the quasiperiodic SCPC under the condition of d_2 = 35 nm and d_3 = 40 nm

In summary, the position-dependent extraordinary optical properties in near-zero-permittivity operation range for a 1D Fibonacci quasiperiodic SCPC are theoretically investigated. We find that the extraordinary optical properties depend on the relative positions of the threshold wavelength λ_{th} and the PBG. However, the relative positions depend on the thicknesses of the superconductor and dielectric layer. By suitably choosing the thicknesses of the superconductor and dielectric layer, a transmission narrow band filter or resonator can be designed without introducing any physical defect. Compared with the period structure SCPCs, the device size realized by the quasiperiodic structure SCPCs will be smaller[15].

References

[1] X. D. Lu, T. Zhou, S. X. Lun and F. Chi, Journal of Optoelectronics·Laser **23**, 83 (2012). (in Chinese)

[2] X. Lu, W. H. Bi and S. Ma, Journal of Optoelectronics·Laser **23**, 21 (2012). (in Chinese)

[3] C. L. Zhao, Journal of Optoelectronics·Laser **22**, 9 (2011). (in Chinese)

[4] T. H. Pei and Y. T. Huang, J. Appl. Phys. **101**, 084502 (2007).

[5] M. S. Chen, C. J. Wu and T. J. Yang, Solid State Commun. **149**, 1888 (2009).

[6] A. H. Aly, H. T. Hsu, T. J. Yang, C. J. Wu and C. K. Hwangbo, J. Appl. Phys. **105**, 083917 (2009).

[7] S. Y. Wang, S. B. Liu and L. W. J. Li, Chin. Phys. B **19**, 084101 (2010).

[8] H. M. Lee and J. C. Wu, J. Appl. Phys. **107**, 09E149 (2010).

[9] W. H. Lin, C. J. Wu, T. J. Yang and S. J. Chang, Opt. Express **18**, 27155 (2010).

[10] M. S. Chen, C. J. Wu and T. J. Yang, Appl. Phys. A **104**, 913 (2011).

[11] H. M. Lee, J. H. Shyu, L. Horng and J. C. Wu, Appl. Opt. **50**, 3860 (2011).

[12] C. Z. Li, S. B. Liu, X. K. Kong, B. R. Bian and X. Y. Zhang, Appl. Opt. **50**, 2370 (2011).

[13] C. Z. Li, S. B. Liu, X. K. Kong, B. R. Bian and X. Y. Zhang, Acta Phys. Sin. **61**, 075203 (2012). (in Chinese)

[14] H. F. Zhang, S. B. Liu, X. K. Kong, B. R. Bian and X. Zhao, Progress In Electromagnetics Research B **40**, 415 (2012).

[15] J. J. Wu and J. X. Gao, Optik **123**, 986 (2012).

[16] K. B. Thapa, Sanjay Srivastava, Alka Vishwakarma and S. P. Ojha, Optoelectronics Letters **7**, 277 (2011).