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# Large omnidirectional reflection range using combination of periodic and Fibonacci quasiperiodic structures

S. KUMAR SINGH*, K. B. THAPA, S. P. OJHA
*Department of Applied Physics, Institute of Technology, Banaras Hindu University, Varanasi-221005, India*

We show numerically that the omnidirectional reflection range of a dielectric multilayer structure can be enlarged by combining a Fibonacci quasiperiodic structure and a periodic structure. Our Fibonacci quasiperiodic structure has two regions of high reflection, but only one region exhibits omnidirectional reflection. Periodic structure has one omnidirectional reflection region. The resultant structure exhibits a large omnidirectional reflection band covering not only omnidirectional reflection region but also non-omnidirectional reflection region of the Fibonacci structure. Reflection bands of the two constituent photonic crystals should overlap each other at all incidence angles to form the heterostructure with large omnidirectional photonic band gap.

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*Keywords:* Omnidirectional reflection, Multilayer structure, Fibonacci quasi-periodic structure, Photonic heterostructure

## 1. Introduction

Since the initial work of Yablonovitch [1] and John [2], Photonic crystals have attracted a lot of attention. A considerable amount of work have been done with its wide range of applications such as filters [3], waveguides [4], switches [5], photonic crystal fibers [6] etc. Absolute photonic band gap is manifested by 3D photonic crystals in which propagation of light is prohibited for all angle of incidence and all polarizations. This means that the light with a frequency lying inside the gap of the photonic crystal will be totally reflected irrespective of incident angle & polarization. Then they behave as omnidirectional reflectors. Only recently it has been observed that besides 2D and 3D photonic crystals one dimensional photonic crystal can also exhibit the property of omni-directional reflection. Quasiperiodicity has attracted much interest after the discovery of quasi-crystalline structure in 1984. In recent years, besides periodic structures, quasi-periodic structures have also been studied as photonic crystals. Fibonacci sequence is most studied and well known quasi-periodic structure. Fibonacci structures have also been studied for omni-directional reflection [7,8,9].

Large frequency range of omnidirectional reflection are required in some applications e.g. mirror or substrate for antenna. It is not easy to get the photonic crystal with the desired omnidirectional photonic band gap. Many methods like defect in photonic crystal, disordered photonic crystal etc. have been used for getting the broad photonic band gap [10]. Combination of two or more photonic crystals has been used as an efficient method to get as enlarged omni PBG [11,12]. This paper gives the numerical calculations of reflection characteristics of multilayer films composed of periodic and quasi-periodic Fibonacci dielectric materials. We will show that the combination of periodic and Fibonacci structures gives us an enlarged omnidirectional reflection range.

## 2. Theory

Fibonacci sequences are multilayer structures consisting of two different materials. Two layers are labeled as *H* and *L* where *H* denotes the material with higher refractive index and *L* denotes the material with lower refractive index. A one dimensional quasi periodic Fibonacci sequence is generated by the recursive relation, $S_{j+1} = \{S_{j-1}, S_j\}, \quad j \geq 1$, where $S_j$ is the $j^{th}$ generation of the Fibonacci structure. Here $S_0 = H$ and $S_1 = L$. In this sequence we have, $S_0 = H$, $S_1 = L$, $S_2 = HL$, $S_3 = LHL$, $S_4 = HLLHL$ etc. Using Maxwell's boundary conditions that the tangential components of electric and magnetic fields must be continuous at the interface between arbitrary two layers and simplifying, the characteristic matrix for TE (s) and TM (p) waves have the form [13,14]

$$M = \begin{bmatrix} \cos\beta & -\frac{i}{q}\sin\beta \\ -iq\sin\beta & \cos q \end{bmatrix}$$

where for TE wave $q = n\cos\theta$, and for TM wave $q = \cos\theta / n$. $\beta = 2\pi nd\cos\theta/\lambda$, $\theta$ is the angle of incident. Thus the transfer matrices are $M_0=M_H$, , $M_1=M_L$ , $M_2=M_HM_L$ , $M_3=M_LM_HM_L$ and $M_4=M_HM_LM_LM_HM_L$ for $S_0$ , $S_1$ , $S_2$ , $S_3$ and $S_4$ respectively. Considering the structure consisting of *N* layers of quasi-periodic Fibonacci structure $S_j$ and *N'* layers of periodic structure $S_2$ the total characteristic matrix is given by

$$M = (M_j)^N (M_2)^{N'} = \begin{bmatrix} M_{11} & M_{12} \\ M_{21} & M_{22} \end{bmatrix}$$

The reflection coefficient is given by

$$r = \frac{(M_{11} + q_t M_{12})q_i - (M_{21} + q_t M_{22})}{(M_{11} + q_t M_{12})q_i + (M_{21} + q_t M_{22})}$$

where $q_{i,t} = n_{i,t} \cos\theta_{i,t}$ for TE wave and $q_{i,t} = \cos\theta_{i,t} / n_{i,t}$ for TM wave, where i and t represent incident medium and substrate respectively. The reflectivity is given by $R = |r|^2$.

## 3. Results and discussion

In the numerical calculations, materials used are $SiO_2$ and Si with refractive indices 1.5 and 3.7 respectively at the wavelength of 700 nm. The structure is supposed be on a substrate of glass with refractive index 1.5. The thicknesses are taken according to the quarter wave arrangement. Therefore $d_H = \frac{\lambda_0}{4n_H} = 47.3\,\text{nm}$ and $d_L = \frac{\lambda_0}{4n_L} = 116.7\,\text{nm}$. Fibonacci structure $S_4$ having 4 periods and periodic structure $S_2$ having 10 periods are investigated. Here all the regions are assumed to be linear, homogeneous and non-absorbing. The omnidirectional photonic band gap for both TE and TM polarization is defined by the upper photonic band gap edge at $90^O$ incident angle and the lower photonic band gap edge at normal incidence. The omnidirectional photonic band gap for TM polarization lies completely within omnidirectional photonic band gap of TE polarization. Therefore complete omnidirectional photonic band gap is the omnidirectional photonic band gap of TM polarization.

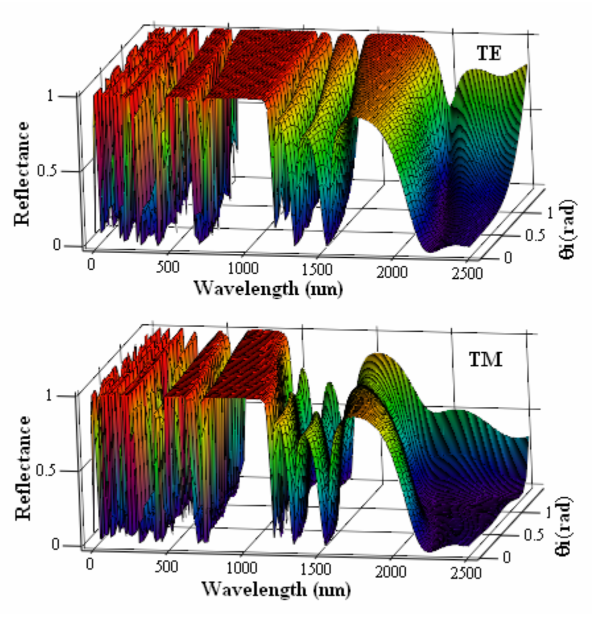


*Fig. 1. Reflectance spectra of Fibonacci quasi-periodic structure.*

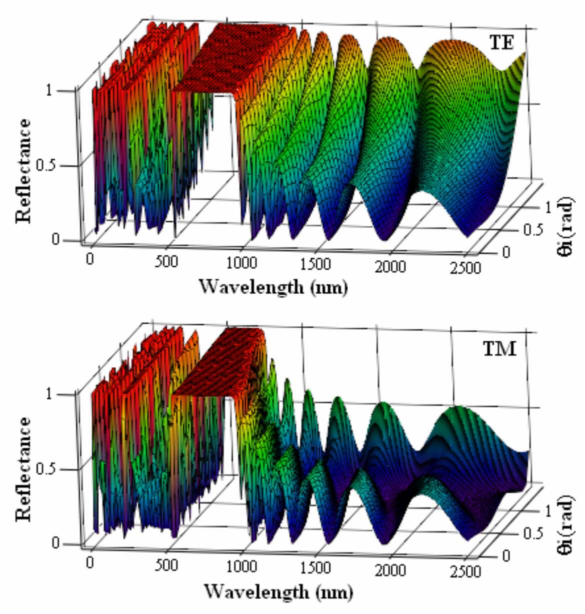


*Fig. 2. Reflectance spectra of periodic structure.*

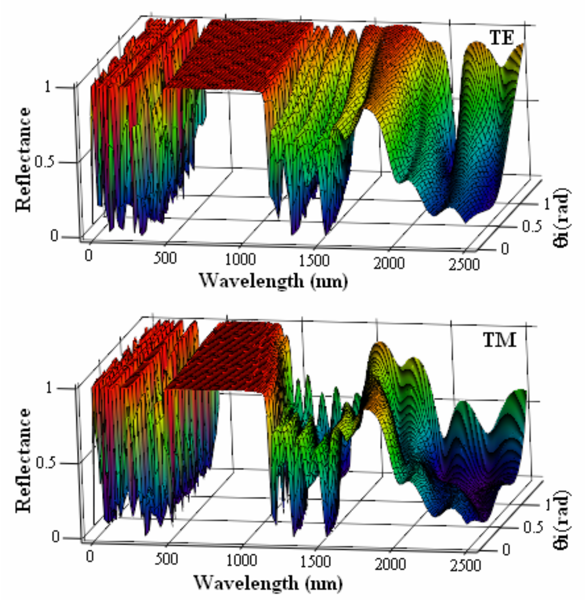


*Fig. 3. Reflectance spectra of combination of Fibonacci quasi-periodic structure and periodic structure.*

Fig. 1 shows the reflectance spectra of Fibonacci photonic crystal. Omnidirectional photonic band gap for TE polarization is displayed in the wavelength range from 754.8 nm – 1107.4 nm. Omnidirectional photonic band gap for TM polarization ranges from 754.8 nm – 914.2 nm. Therefore omnidirectional photonic band gap for any polarization of this Fibonacci structure spans from 754.8 nm – 914.2 nm. The reflectance spectra of periodic structure have been shown in Fig. 2. We see from this figure that omnidirectional photonic band gap for TE polarization has its range from 545.8 nm – 930.9 nm. For TM polarization omnidirectional photonic band gap ranges from 545.8 nm – 761.8 nm. Hence omni PBG for any polarization for this periodic structure is 545.8 nm – 761.8

nm. Comparing the reflectance spectra of the two structures we see that for the same number of layers, 20, the omnidirectional photonic band gap is large for the periodic structure as compared to quasi-periodic structure. The reflectance spectra of the third photonic structure which is the combination of Fibonacci quasiperiodic and periodic structures (Fig. 3) show that omnidirectional photonic band gap for TE polarization ranges from 499.5 nm – 1104.4 nm. For TM polarization this range is from 499.5 nm- 914.2 nm. Therefore omnidirectional photonic band gap for any polarization has its range from 499.5 nm – 914.2 nm for the combined structure. Comparing the reflectance spectra of the three structures we can say that the combined structure has a large omnidirectional reflection range, lager than the sum of the omnidirectional reflection ranges of Fibonacci quasiperiodic structure and periodic structure. Figs. 4, 5, and 6 show the conventional photonic band diagrams for the three considered structures. We see from Fig. 4 that Fibonacci structure has two high reflection bands. But it is clear from the figure that the band at the lower wavelength side does not exhibit an omnidirectional reflection band but the other band at higher wavelength side has an omnidirectional band gap. The periodic structure has only one high reflection band as shown in Fig. 5 and this band also represents an omnidirectional band gap. Surprisingly, the two bands for Fibonacci structure are on the both sides of the band of the periodic structure. Photonic band diagram for the combined structure is shown in Fig. 6. It has only one high reflection band which is very large as compared to Fibonacci and periodic structures. A large omnidirectional band gap is also obtained, which encroaches the region of non-omnidirectional high reflection band in the Fibonacci structure. Thus the two reflection bands formed by the Fibonacci structure are compensated by the reflection band of the periodic structure.

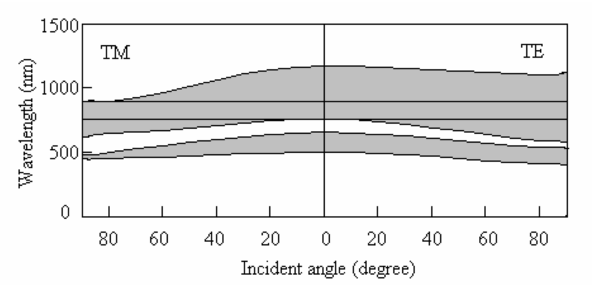


*Fig. 4. Photonic band structure Fibonacci quasi-periodic structure.*

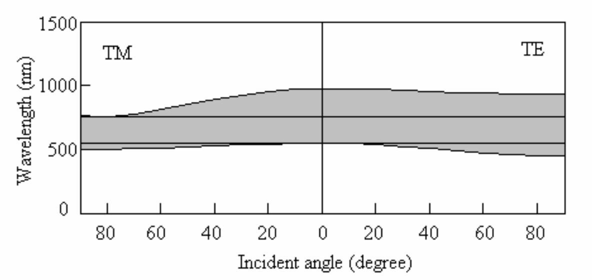


*Fig. 5. Photonic band structure of periodic structure.*


*Fig. 6. Photonic band structure of combination of Fibonacci quasi-periodic and periodic structures.*

## 4. Conclusion

It was proposed a structure which is combination of a Fibonacci quasi-periodic structure and a periodic structure. The combined structure has a large omnidirectional reflection range. The condition is that the stop bands of two sub structures should be adjacent to each other at all incident angles.

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*Corresponding author: sks_m2002@yahoo.co.in