Progress In Electromagnetics Research M, Vol. 25, 211–222, 2012

INFRARED OMNI-DIRECTIONAL MIRROR BASED ON ONE-DIMENSIONAL BIREFRINGENT-DIELECTRIC PHOTONIC CRYSTAL

M. Upadhyay[1], S. K. Awasthi[1, *], S. K. Srivastava[2], and S. P. Ojha[3]

[1]Department of Physics and Material Science and Engineering, Jaypee Institute of Information Technology, Deemed University, Noida 201304, India

[2]Department of Physics, Amity Institute of Applied Science, Amity University, Noida 201303, India

[3]Department of Physics, Shobhit University Meerut, India

Abstract—In the present communication, we have theoretically investigated and studied the reflection properties of one-dimensional birefringent-dielectric photonic crystal (1D BDPC) structure consisting alternate layers of BD material. From the analysis of the reflectance spectra it is found that 100% reflection region for both TE- and TM-mode can be enhanced significantly in comparison with 1D dielectric-dielectric photonic crystal (DDPC). In order to obtain the reflection spectra of the proposed structure we have used the transfer matrix method (TMM). The structure proposed by us, has a wider omni-directional reflection (ODR) range in comparison to conventional all dielectric photonic crystals (PCs). The width of ODR can be enlarged by considering the suitable choice of lattice parameters.

1. INTRODUCTION

In the last decades, a new frontier has emerged to control the optical properties of materials. PCs have attracted much attention as a new kind of optical materials. Photonic crystals are composite structures of a periodic arrangement of refractive index material with periodicity of the order of the wavelength. To achieve ODR, one must have total

Received 18 June 2012, Accepted 31 July 2012, Scheduled 17 August 2012

* Corresponding author: Suneet Kumar Awasthi (suneet_electronic@yahoo.com).

reflection for all incident angles and all polarization states. If for some wavelength range, a PC reflects light of any polarization incident at any angle, we say that the crystal has a complete photonic bandgap. In such a crystal, no light modes propagate if they have same wavelength within that range [1].

The omnidirectional photonic bandgap (OPBG) for TE and TM polarization is defined by the upper photonic bandgap edge at 89° incident angle and the lower photonic bandgap edge at normal incidence [2]. The OPBG for TM polarization lies completely within OPBG of TE polarization. Therefore it is the TM bandgap that determines the bandwidth of the omnidirectional reflector.

Ouchani et al. [3] reported that a multilayer dielectric reflector can have a high reflectivity over a broad range of frequencies at all incident angles if the refractive index and the thickness of the constituent dielectric layer are correctly chosen. Such a "perfect mirror" has been the subject of interest in recent years and has been designed using one-dimensional (1D) all-dielectric binary PCs (i.e., two material layers constituting a period of the lattice) [4–21]. This characteristic can be used to design unprecedented control of light and show promise for their applications in several areas, including waveguides, biophotonic sensors, nanotechnology, integrated photonic chips, spontaneous emission, photon trapping, and biomedical optics [17].

Most previous researches, have involved the use of a number of periodic and quasi-periodic structures based on alternating homogeneous isotropic layers of high and low refractive index to achieve an omnidirectional reflection. To the best of our knowledge, there have been works involving the use of an anisotropic stack to study the reflection property [22, 23]. Abdulhalim [22] was the first to report on omnidirectional reflection in birefringent periodic multilayers. This study is further analyzed by Cojocaru [23]. It has been reported that wider omnidirectional ranges can be obtained from birefringent multilayers as compared to those obtained from isotropic ones. Awasthi et al. [24] showed that the ternary BDPC gives a much larger range enhancement as compared to DDPC.

In this study, we have made an attempt to study the reflection properties of 1D BDPC, by using the TMM. The omnidirectional reflectors (ODRs) have been designed with a wide reflection range in the infrared region. In contrast to prior work by Awasthi et al. [24], the main challenge in this study is to maintain a small structure size while keeping the wide spectral band width in the range of infrared wavelengths.

2. THEORETICAL ANALYSIS

Consider the 1D BDPC with the periodic structure of $(\mathrm{BD})_N$ where B and D represent birefringent material layer and dielectric layers respectively and N is the number of periods. Let a plane wave be injected from vacuum onto the 1D BDPC at an angle θ with the z direction, as shown in Fig. 1. For the transverse electric (TE)/the transverse magnetic (TM) wave, the electric field E/the magnetic field H is along the x direction. The dielectric layers are in the x-y plane.

Optical birefringence describes the difference of a material's refractive indices with direction and with the state of polarization. Let us assume that the biaxial layer in each period has principal refractive indices n_x, n_y and n_z along the x, y and z axes respectively. We take the xyz coordinate axes to coincide with the principal dielectric axes (so that the permittivity tensor is diagonal) and the wave vector $\bar{k}$ to lie in the xz plane, the plane of incidence. The xy plane is then the interface plane [24].

We define an effective refractive index n_B [25] for the biaxial layer, such that $k = n_B k_0 = \frac{n_B \omega}{c}$ where ω is the angular frequency and c is the speed of light in free space. The parameter n_B depends on the polarization state of the fields and the direction of the wave vector as

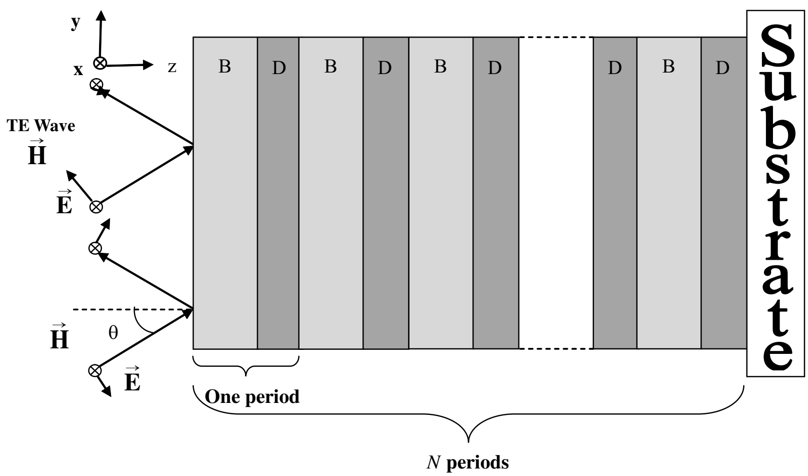


Figure 1. Depiction of a one-dimensional birefringent/dielectric periodic structure.

follows:

$$n_B = \begin{cases} \dfrac{n_x n_z}{\left[n_x^2 \sin^2\theta_1 + n_z^2 \cos^2\theta_1\right]^{\frac{1}{2}}}, & TM\text{-polarization} \\ n_y & TE\text{-polarization} \end{cases} \tag{1}$$

Here θ_1 is the ray angle inside the biaxial layer.

The characteristic matrix of the assembly of layers is given by [26]

$$M(\Lambda) = \left[\begin{pmatrix} M_{11} & M_{12} \\ M_{21} & M_{22} \end{pmatrix}\right] = \prod_{l=1}^{2} \begin{pmatrix} \cos\delta_l & -\frac{i}{q_l}\sin\delta_l \\ -iq_l \sin\delta_l & \cos\delta_l \end{pmatrix}, \tag{2}$$

where $l = 1$ and 2 signify the B and D layers of one period. The parameters δ_l and q_l represent the propagation phases or phase thicknesses and transverse refractive indices in each medium respectively.

$$\begin{aligned} M_{11} &= \cos\delta_1 \cos\delta_2 - \frac{q_2}{q_1}\sin\delta_1 \sin\delta_2, \\ M_{12} &= \frac{i}{q_2}\cos\delta_1 \sin\delta_2 + \frac{i}{q_1}\sin\delta_1 \cos\delta_2, \\ M_{21} &= iq_1 \sin\delta_1 \cos\delta_2 + iq_2 \cos\delta_1 \sin\delta_2, \\ M_{22} &= \cos\delta_1 \cos\delta_2 - \frac{q_1}{q_2}\sin\delta_1 \sin\delta_2. \\ r(\omega) &= \frac{m_{11}q_A + m_{12}q_A q_S - m_{21} - m_{22}q_A}{m_{11}q_A + m_{12}q_A q_S + m_{21} + m_{22}q_A}, \end{aligned}$$

The reflectance of the multilayer is given by [25–28].

$$R = |r|^2 = (r\, r^*)$$

For the TE-polarized wave [25], the phase thicknesses δ_1 and δ_2 in the B and D layers are given by

$$\delta_1 = \frac{2\pi}{\lambda_0} n_B d_B \cos\theta_1 = \frac{2\pi}{\lambda_0} n_y d_B \left[1 - \frac{n_A^2 \sin^2\theta_A}{n_y^2}\right]^{\frac{1}{2}}, \tag{3a}$$

$$\delta_2 = \frac{2\pi}{\lambda_0} n_2 d_D \cos\theta_2 = \frac{2\pi}{\lambda_0} n_2 d_D \left[1 - \frac{n_A^2 \sin^2\theta_A}{n_2^2}\right]^{\frac{1}{2}}, \tag{3b}$$

respectively; transverse refractive indices q_1 and q_2 of B and D layers are defined as

$$q_1 = n_B \cos\theta_1 = n_y \left[1 - \frac{n_A^2 \sin^2\theta_A}{n_y^2}\right]^{\frac{1}{2}}, \tag{4a}$$

$$q_2 = n_2 \cos\theta_2 = n_2 \left[1 - \frac{n_A^2 \sin^2\theta_A}{n_2^2}\right]^{\frac{1}{2}}, \tag{4b}$$

$$q_S = n_S \cos\theta_S = n_S \left[1 - \frac{n_A^2 \sin^2\theta_A}{n_S^2}\right]^{\frac{1}{2}}, \tag{4c}$$

and θ_A, θ_S, θ_1 and θ_2 are the ray angles in the incident medium, in the substrate, and inside the layers B and D of each period, respectively; λ_0 is the free space wavelength. The symbols n and d denote the refractive index and the thickness of the layers respectively. Here $q_A = n_A \cos\theta_A$ and the asterisk denotes the complex conjugate.

For the TM-polarized wave, the phase thicknesses δ_1 and δ_2, the transverse refractive indices q_1 and q_2 of the B and D layers are given by

$$\delta_1 = \frac{2\pi}{\lambda_0} n_B d_B \cos\theta_1 = \frac{2\pi}{\lambda_0} n_x d_B \left[1 - \frac{n_A^2 \sin^2\theta_A}{n_z^2}\right]^{\frac{1}{2}}, \tag{5a}$$

$$\delta_2 = \frac{2\pi}{\lambda_0} n_2 d_D \cos\theta_2 = \frac{2\pi}{\lambda_0} n_2 d_D \left[1 - \frac{n_A^2 \sin^2\theta_A}{n_2^2}\right]^{\frac{1}{2}}, \tag{5b}$$

$$q_1 = \frac{n_x^2}{n_B \cos\theta_1} = \frac{n_x n_z}{\left[n_z^2 - n_A^2 \sin^2\theta_A\right]^{\frac{1}{2}}}, \tag{6a}$$

$$q_2 = \frac{n_2}{\cos\theta_2} = \frac{n_2}{\left[1 - \frac{n_A^2 \sin^2\theta_A}{n_2^2}\right]^{\frac{1}{2}}}, \tag{6b}$$

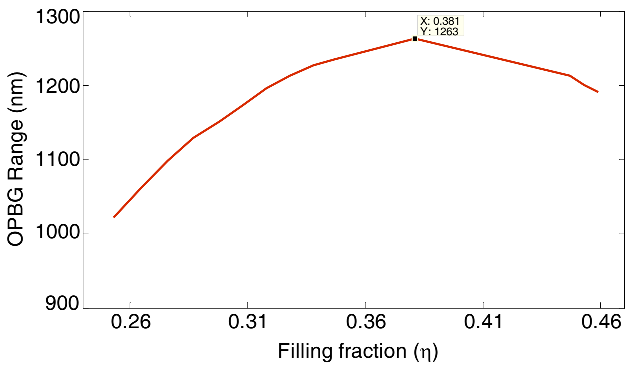


Figure 2. OPBG range versus filling fraction for BD periodic structure.

$$q_A = \frac{n_A}{\cos\theta_A}, \tag{6c}$$

$$q_S = \frac{n_S}{\cos\theta_S} = \frac{n_S}{\left[1 - \frac{n_A^2 \sin^2\theta_A}{n_S^2}\right]^{\frac{1}{2}}}. \tag{6d}$$

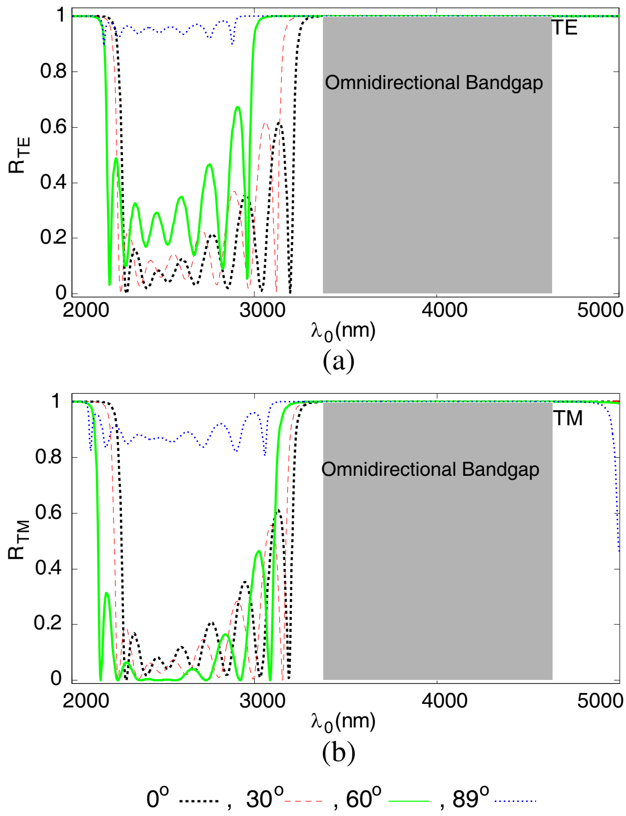


Figure 3. (a) Calculated reflectance spectra of BD 8-layer structure measured for TE polarizations at various angles of incidence (0° — black line, 30° — red line, 60° — green line, 89° — blue line). The gray area is the total OBG. (b) Calculated reflectance spectra of BD 8-layer structure measured for TM polarizations at various angles of incidence (0° — black line, 30° — red line, 60° — green line, 89° — blue line). The gray area is the total OBG.

3. RESULT AND DISCUSSION

We propose air/(BD)^8/substrate (SiO_2), where (BD)^8 means that the periodic multi-layered stack consists of eight sub-layers of birefringent and dielectric materials. In our computations, the layers of different material B and D are considered to be biaxial birefringent one, i.e., potassium titanyl phosphate (KTP) and lead sulfide (PbS) respectively. The refractive index value for PbS in infrared region of investigation is 4.35 and the principal refractive indices n_{1x}, n_{1y} and n_{1z} for the biaxial KTP layer are 1.67983, 1.68969 and 1.7538, respectively. The thickness of birefringent layer is taken as 470 nm. The refractive indices of the incident and exit media are $n_A = 1$ and $n_S = 1.52$, respectively.

For the chosen refractive index values of the two layers (B & D) taken, there is a particular value of the filling fraction $\eta \left(= \frac{d_D}{\Lambda}\right)$ which gives optimum OPBG range. Fig. 2 is a plot of the OPBG range versus filling fraction. The filling fraction corresponding to the maximum value of the OPBG range is given by $\eta_{opt} = 0.3815$ which yields a value of $d_D = 290$ nm.

Using TMM, the TE and TM reflectance spectra for an 8-layer stack were calculated. From Snell's law, $n_A \sin\theta_A = n_1 \sin\theta_1$. For ODR of both polarizations (TE and TM) to occur, it is essential that the maximum value of the refracted angle θ_1 should be less than the internal Brewster's angle $[\theta_{1B} = \tan^{-1}(n_2/n_1)]$ so that the TM mode does not couple to the Brewster window. This is done by selecting large values of n_1 and n_2 with respect to air, so as to make cone of internal

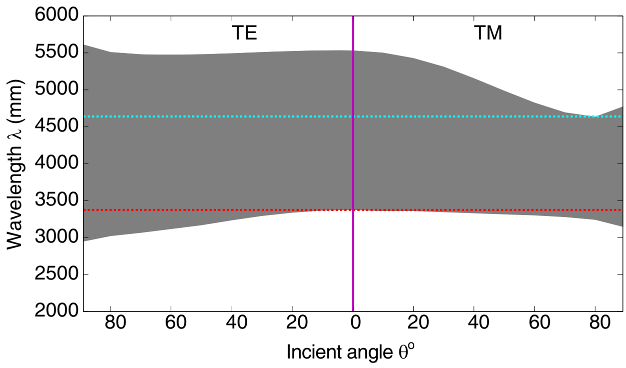
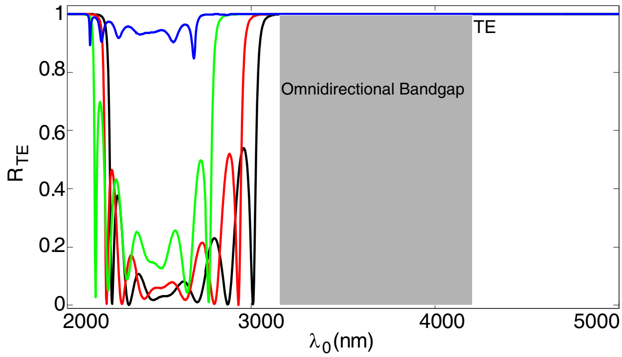


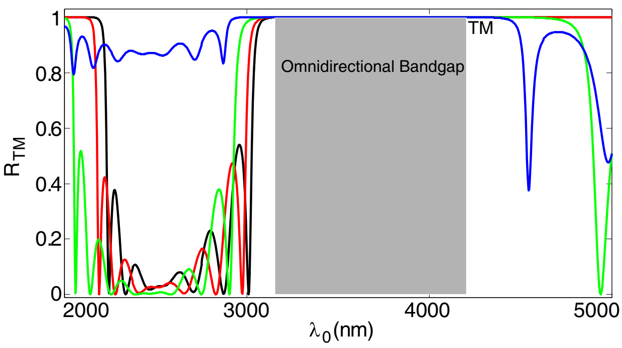
Figure 4. Photonic band structure of BD periodic structure in terms of wavelength and incident angle. The wavelength range between two dashed lines in the gray area is the total OBG.

angles then layers narrow. Also, sharper refractive index contrasts n_2/n_1) yield wider ODR [9]. The change in the spectral characteristics for the incident angles of 0°, 30°, 60°, and 89°, are shown in Figs. 3(a) and 3(b) respectively. The gray area is the total omnidirectional band gap (OBG), which was 3373 to 4636 nm, centered at a wavelength of 4004.5 nm. This area is also shown in the band structure for BDPC (Fig. 4).

Now we compare above findings of BDPC with DDPC. For this purpose, we have replaced birefringent layer of BDPC with BaF_2



(a)



(b)

Figure 5. (a) Calculated reflectance spectra of DD 8-layer structure measured for TE polarizations at various angles of incidence (0° — black line, 30° — red line, 60° — green line, 89° — blue line). The gray area is the total OBG. (b) Calculated reflectance spectra of DD 8-layer structure measured for TM polarizations at various angles of incidence (0° — black line, 30° — red line, 60° —green line, 89° — blue line). The gray area is the total OBG.

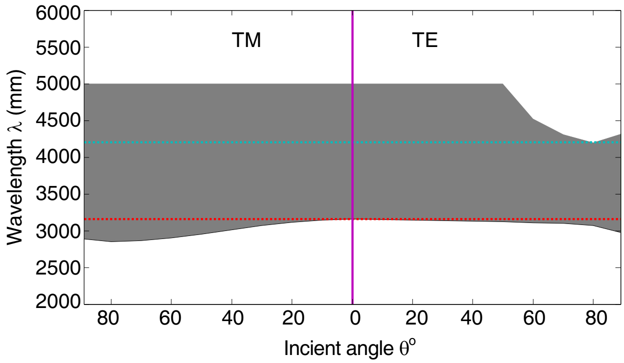


Figure 6. Photonic band structure of DD periodic structure in terms of wavelength and incident angle. The wavelength range between two dashed lines in the gray area is the total OBG.

dielectric layer of refractive index $n_1 = 1.46$. Other remaining parameters of DDPC are chosen to be same as BDPC.

Figure 5 is a plot of reflectivity spectra of DDPC at various angles of incidence, as determined by TMM. The gray area is the total OBG which was 3155 to 4202 nm centered at a wavelength of 3678.5 nm. This area is also shown in band structure of DDPC (Fig. 6). Comparison of Fig. 4 and Fig. 6 shows an increase of 216 nm in the ODR with a shift of 326 nm of the central wavelength towards higher wavelengths as compared to DDPC was observed. Although we may increase the ODR range of 1D DDPC further by increasing the number of periods of structure from eight to desired value. But this will also increase the size of structure.

4. CONCLUSION

In conclusion, we can say that the omnidirectional reflection region of 1D DDPC structure can be significantly broadened to a desired range of electromagnetic radiation by replacing one of the dielectric layers with birefringent layer. Since birefringent material layer introduces two or three more controlling parameters in obtaining the larger ODR with reduced structure size, therefore birefringent materials have a better alternative of dielectric materials for designing efficient omnidirectional reflectors (ODRs). Such type of ODRs are very small in size therefore they have potential applications not only in photonics but also in optoelectronics.

ACKNOWLEDGMENT

One of the authors, Dr. Suneet Kumar Awasthi, is thankful to Prof. Usha Malaviya for providing valuable suggestions pertaining to this work. Authors are thankful to JAYPEE UNIVERSITY NOIDA, INDIA for providing facilities required for this work.

REFERENCES

1. Joannopoulos, J. D., R. D. Meade, and J. N. Winn, *Photonic Crystals: Molding the Flow of Light*, Princeton University Press, UK, 1995.
2. Kumar, V., K. S. Singh, S. K. Singh, and S. P. Ojha, "Broadening of omni-directional reflection range in 1-d photonic crystal by using photonic quantum well structures," *Optik — International Journal for Light and Electron Optics*, 2011, http://www.sciencedirect.com/science/article/pii/S0030402611005651.
3. Ouchani, N., D. Bria, B. Djafari Rouhani, and A. Nougaoui, "A birefringent reflector from a 1D anisotropic photonic crystal," *J. Phys.: Condens. Matter.*, Vol. 21, 485401–485410, 2009.
4. Chigrin, D. N., "Omnidirectional bragg mirror," *Electromagnetic Waves Propagation in Photonic Crystals with Incomplete Photonic Band Gap*, 62–75, Thesis, University of Wuppertal, 2003.
5. Guida, G., A. de Lustrac, and A. Priou, "An introduction to photonic band gap (PBG) materials," *Progress In Electromagnetics Research*, Vol. 41, 1–20, 2003.
6. Srivastava, R., K. B. Thapa, S. Pati, and S. P. Ojha, "Omnidirection reflection in one dimensional photonic crystal," *Progress In Electromagnetics Research B*, Vol. 7, 133–143, 2008.
7. Singh, S. K., J. P. Pandey, K. B. Thapa, and S. P. Ojha, "Structural parameters in the formation of omnidirectional high reflectors," *Progress In Electromagnetics Research*, Vol. 70, 53–78, 2007.
8. Srivastava, R., S. Pati, and S. P. Ojha, "Enhancement of omnidirectional reflection in photonic crystal heterostructures," *Progress In Electromagnetics Research B*, Vol. 1, 197–208, 2008.
9. Awasthi, S. K., U. Malaviya, and S. P. Ojha, " Enhancement of omnidirectional total-reflection wavelength range by using one-dimensional ternary photonic bandgap material," *J. Opt. Soc. Am. B*, Vol. 23, 2566–2571, 2006.
10. Winn, J. N., Y. Fink, S. Fan, and J. D. Joannopoulos,

"Omnidirectional reflection from a one-dimensional photonic crystal," *Opt. Lett.*, Vol. 23, 1573–1575, 1998.
11. Chigrin, D. N., A. V. Lavrinenko, D. A. Yarotsky, and S. V. Gaponenko, "Observation of total omnidirectional from a one-dimensional dielectric lattice," *Appl. Phys. A*, Vol. 68, 25–28, 1999.
12. Srivastava, S. K. and S. P. Ojha, "Omnidirectional reflection bands in one-dimensional PC structure using fullerene films," *Progress In Electromagnetics Research*, Vol. 74, 181–194, 2007.
13. Wang, X., X. Hu, Y. Li, W. Jia, C. Xu, X. Liu, and J. Zi, "Enlargement of omnidirectional total reflection frequency range in one-dimensional photonic crystals by using heterostructures," *Appl. Phys. Lett.*, Vol. 80, 4291–4293, 2002.
14. Perez, E. X., L. F. Marsal, J. Pallares, and J. F. Borrull, "Porous silicon mirrors with enlarged omnidirectional bandgap," *J. Appl. Phys.*, Vol. 97, 064503-1–064503-5, 2005.
15. Banerjee, D, and M, Zhang, "Quarter-wave design criteria for omnidirectional structural colors," *Journal of Modern Optics*, Vol. 57, 1180–1188, 2010.
16. Wu, C.-J., Y.-C. Hsieh, and H.-T. Hsu, "Tunable photonic band gap in a doped semiconductor photonic crystal in near infrared region," *Progress In Electromagnetics Research*, Vol. 114, 271–283, 2011.
17. Kumar, N. and S. P. Ojha, "Photonic crystals as infrared broadband reflectors with different angles of incidence: A comparative study," *Progress In Electromagnetics Research*, Vol. 80, 431–445, 2008.
18. Banerjee, A., "Enhanced refractometric optical sensing by using one-dimensional ternary photonic crystals," *Progress In Electromagnetics Research*, Vol. 89, 11–22, 2009.
19. Wu, C.-J. and Z.-H. Wang, "Properties of defect modes in one-dimensional photonic crystals," *Progress In Electromagnetics Research*, Vol. 103, 169–184, 2010.
20. Awasthi, S. K., U. Malaviya, S. P. Ojha, N. K. Mishra, and B. Singh, "Design of a tunable polarizer using a one-dimensional nano sized photonic bandgap structure," *Progress In Electromagnetics Research B*, Vol. 5, 133–152, 2008.
21. Wu, C.-J., Y.-H. Chung, B.-J. Syu, and T.-J. Yang, "Band gap extension in a one-dimensional ternary metal-dielectric photonic crystal," *Progress In Electromagnetics Research*, Vol. 102, 81–93, 2010.

22. Abdulhalim, I., "Omnidirectional reflection from anisotropic periodic dielectric stack," *Opt. Commun.*, Vol. 174, 43–50, 2000.
23. Cojocaru, E., "Forbidden gaps in periodic anisotropic layered media," *Appl. Opt.*, Vol. 39, 4641–4648, 2000.
24. Awasthi, S. K., U. Malaviya, and S. P. Ojha, "Enhancement of omnidirectional high-reflection wavelength range in one-dimensional ternary periodic structures: A comparative study," *J. Nanophotonics*, Vol. 2, 023505, 2008.
25. Orfanidis, S. J., "Multilayer film applications," *Electromagnetic Waves and Antennas*, 193–194, 2008, www.ece.rutgers.edu/~orfanidi/ewa.
26. Macleod, H. A., "Basic theory," *Thin-film Optical Filters*, 32–43, Adam Hilger Ltd., Bristol, 1986.
27. Ye, Y.-H., G. Bader, and V.-V. Truong, "Low-loss one-dimensional metallodielectric photonic crystals fabricated by metallic insertions in a multilayer dielectric structure," *Appl. Phys. Lett.*, Vol. 77, 235–237, 2000, doi:10.1063/1.126935.
28. El-Kady, I., M. M. Sigalas, R. Biswas, K. M. Ho, and C. M. Soukoulis, "Metallic photonic crystals at optical wavelengths," *Phy. Rev. B*, Vol. 62, 15299–15302, 2000, doi:10.1063/1.126935.