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DESIGN OF A TUNABLE OPTICAL FILTER BY USING A ONE-DIMENSIONAL TERNARY PHOTONIC BAND GAP MATERIAL

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Abstract—A band pass filter with a linearly periodic refractive index profile is discussed in analogy with Kroning Penney model in band theory of solids. The suggested filter is a one-dimensional ternary periodic structure and provides better control in dispersion relation as compared to a binary structure because it has two more controlling parameters relative to those of the binary one. Since three layers are involved in the formation of band gaps a much broader range of dispersion control is obtained. Both refractive index modulation and optical thickness modulation are considered. A mathematical analysis is presented to predict allowed and forbidden bands of wavelength with variation of angle of incidence. It is also possible to get desired ranges of the electromagnetic spectrum filtered with this structure by manipulating the value of the lattice parameters.

1. INTRODUCTION

The concept of photonic crystal (PC) structure was first introduced by Yablonovitch [1] and Sanjeev John [2] in their early work of 1987. A PC is an artificial material with a periodic modulation of its dielectric constant and having ranges of forbidden frequencies called photonic bandgaps (PBGs), analogous to electric bandgaps in semiconductors [3]. PCs have attracted a great deal of attention as a new optical material in recent years [1, 4–8]. Accordingly to the dimensionality of the stack, they can be classified into three main categories: one-dimensional (1-D), two-dimensional (2-D), and three-dimensional (3-D) crystals. Actually, 1-D PCs, traditionally called dielectric multilayers or superlattices, have been widely used as interference filter, high reflectors, etc before other PCs were invented [9, 10]. PCs have attracted extensive interest for their unique electromagnetic properties and potential applications in optoelectronics and optical communications [11].

PCs can shape and mould the flow of light through them, and as a result they have novel scientific and engineering applications [12] such as localization of light wave [2], the inhibition of spontaneous emission [1, 12], lasers [13–15], waveguides [16], splitters [17], fibers [18], antennas [19], optical circuits [20] and ultrafast optical switches [21].

A great deal of work has been done by technologists for the development of methods for designing multi-layer films with prescribed specifications [22–27]. Tunable optical filters have received much attention due to their potential application in fibre optic communications and other optical fields. Several configurations have been proposed, including tunable multiple electrode asymmetric directional couplers [28], tunable Mach Zehnder interferometers [29, 30], Fabry-Perot filters [31, 32], tunable waveguide arrays [33, 34], liquid crystal Fabry-Perot filters [35, 36], tunable multi grating filters [37], and acousto-optic tunable filters [38]. Another class of most popular filter is based on the phenomenon of multi-beam interference and optical waveguides [39–42].

Fabrication of optical filters in the near infrared region of the wavelength was suggested by Ojha et al. [43] in 1992. Chen et al. [44] in 1996 suggested the design of optical filters by photonic band gap air bridges and calculated the important results and some aspects of filter properties. Recently D'Orazio et al. [45] have fabricated the photonic band gap filter for wavelength division multiplexing. In another investigation Villar et al. [46] have analyzed the one-dimensional photonic band gap structures with a liquid crystal defect for the development of fiber-optic tunable wavelength filters. Banerjee et al. [27] in 2006 proposed a design of a tunable optical filter made by 1-D binary PBG material with five to six number of allowed bands. This can further be improved by using a our proposed filter design made by 1-D ternary PBG materials [47] which filters more allowed bands as compared to a filter made by 1-D binary PBG material.

In this paper we report a design of tunable optical filter by using a 1-D ternary photonic band gap material. This paper is organized as follows. In Section 2, theoretical analysis is presented which gives basic simulation equations in the transfer matrix method (TMM) for 1-D photonic bandgap structure. The advantage of using the TMM to solve the eigen value problem is that it can avoid evaluating a high order determinant and makes the calculation of wave function simpler. Results and discussion are presented in Section 3. Finally, Section 4 deals with conclusions arrived at.

2. THEORETICAL ANALYSIS [48, 49]

Consider 1-D photonic bandgap structure as a three layer homogeneous periodic dielectric film, composed of dielectric layers 1, 2, and 3 stacked alternatively along z axis. The periodic refractive index profiles of the structure is given by [27]

$$n(z) = \begin{cases} n_1, & 0 < z < d_1 \\ n_2, & d_1 < z < d_2 \\ n_3, & d_2 < z < d_3 \end{cases} \tag{1}$$

with $n(z) = n\ (z + md)$ and m is the translational factor, which takes the values of $m = 0, \pm 1, \pm 2, \pm 3, \ldots$, and $d = d_1 + d_2 + d_3$ is the period of the lattice with d_1, d_2 and d_3 being the width of the three regions having refractive indices n_1, n_2, and n_3 respectively. The z axis is the normal to the layer interface. This proposed filter is placed between semi-infinite media of refractive indices n_A and n_S. The geometry of the structure is sketched in Fig. 1.

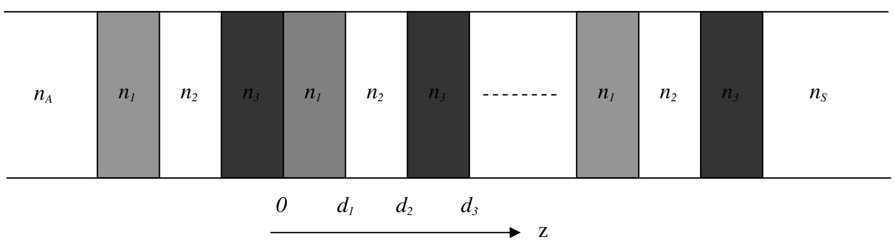

Figure 1. Depiction of a one-dimensional ternary periodic lattice.

For the TE wave, the characteristic matrix $M[d]$ of one period is given by [48]

$$M[d] = \prod_{i=1}^{k} \begin{bmatrix} \cos\gamma_i & \frac{-i}{p_i}\sin\gamma_i \\ -ip_i\sin\gamma_i & \cos\gamma_i \end{bmatrix} \equiv \begin{bmatrix} M_{11} & M_{12} \\ M_{21} & M_{22} \end{bmatrix} \tag{2}$$

where $k = 3$. (1, 2 and 3 signify the layers of refractive indices n_1, n_2 and n_3 respectively) $\gamma_i = \frac{2\pi}{\lambda_0} n_i d_i \cos\theta_i$, $p_i = n_i \cos\theta_i$, θ_i is the ray angle inside the layer of refractive index n_i, and is related to the angle of incidence θ_A by

$$\cos\theta_i = \left[1 - \frac{n_A^2 \sin^2\theta_A}{n_i^2}\right]^{1/2} \tag{3}$$

The matrix $M[d]$ in Eq. (2) is unimodular as $|M[d]| = 1$.

For an N period structure, the characteristic matrix of the medium is given by [48]

$$\begin{aligned} [M(d)]^N &= \begin{bmatrix} M_{11}U_{N-1}(a) - U_{N-2}(a) & M_{12}U_{N-1}(a) \\ M_{21}U_{N-1}(a) & M_{22}U_{N-1}(a) - U_{N-2}(a) \end{bmatrix} \\ &\equiv \begin{bmatrix} m_{11} & m_{12} \\ m_{21} & m_{22} \end{bmatrix} \end{aligned} \tag{4}$$

where

$$\begin{aligned} M_{11} &= \left(\cos\gamma_1\cos\gamma_2\cos\gamma_3 - \frac{p_2}{p_1}\sin\gamma_1\sin\gamma_2\cos\gamma_3 \right. \\ &\quad \left. -\frac{p_1}{p_2}\cos\gamma_1\sin\gamma_2\sin\gamma_3 - \sin\gamma_1\cos\gamma_2\sin\gamma_3\right), \\ M_{12} &= -i\left(\frac{1}{p_1}\sin\gamma_1\cos\gamma_2\cos\gamma_3 + \frac{1}{p_2}\cos\gamma_1\sin\gamma_2\cos\gamma_3 \right. \\ &\quad \left. +\frac{1}{p_1}\cos\gamma_1\cos\gamma_2\sin\gamma_3 - \frac{p_2}{p_1^2}\sin\gamma_1\sin\gamma_2\sin\gamma_3\right), \\ M_{21} &= -i(p_1\sin\gamma_1\cos\gamma_2\cos\gamma_3 + p_2\cos\gamma_1\sin\gamma_2\cos\gamma_3 \\ &\quad +p_1\cos\gamma_1\cos\gamma_2\sin\gamma_3 - \frac{p_1^2}{p_2}\sin\gamma_1\sin\gamma_2\sin\gamma_3), \\ M_{22} &= \left(\cos\gamma_1\cos\gamma_2\cos\gamma_3 - \frac{p_1}{p_2}\sin\gamma_1\sin\gamma_2\cos\gamma_3 \right. \\ &\quad \left. -\frac{p_2}{p_1}\cos\gamma_1\sin\gamma_2\sin\gamma_3 - \sin\gamma_1\cos\gamma_2\sin\gamma_3\right), \end{aligned}$$

For p-polarization

$$p_i = \frac{\cos\theta_i}{n_i} \tag{5}$$

U_N are the Chebyshev polynomials of the second kind

$$U_N(a) = \frac{\sin[(N+1)\cos^{-1}a]}{[1-a^2]^{1/2}} \tag{6}$$

where

$$a = \frac{1}{2}\left[M_{11} + M_{22}\right], \tag{7}$$

The optical properties of the proposed filter are essentially determined by Nth power $[M(d)]^N$ of trilayer transfer matrix $M(d)$. But behaviour of $[M(d)]^N$ is determined by eigen value of structure $M(d)$ [49]. These are determined from characteristic polynomial of $M(d)$, given by the following expression which is valid for any 2×2 matrix [49].

$$\det\left[M(d) - \lambda I\right] = \lambda^2 - Tr\left[M(d)\right]\lambda + \det\left[M(d)\right] \tag{8}$$

where I is the 2×2 identity matrix. Because $M(d)$ has unit determinant, the eigen values are the solution of the following quadratic equation

$$\lambda^2 - Tr\left[M\left(d\right)\right]\lambda + 1 = 0 \tag{9}$$

But $\frac{Tr[M(d)]}{2} = a$

So $\lambda^2 - 2a\lambda + 1 = 0$, with following solutions

$$\lambda_{\pm} = a \pm \sqrt{a^2 - 1} \tag{10}$$

The eigen values $\lambda_{\pm}$ are either both real valued or both complex valued with unit magnitude. These values will be inverse of each other i.e.,

$$\lambda_{+} = \frac{1}{\lambda_{-}}$$

or $\lambda_{+}\lambda_{-} = 1$

It can also be rewritten as

$$\left.\begin{aligned} \lambda_{+} &= e^{jKd} \\ \lambda_{-} &= e^{-jKd} \end{aligned}\right\} \tag{11}$$

The quantity K is referred to as the Bloch wave number. This proposed filter behaves very differently depending on the nature of K. The filter is primarily reflecting if K is imaginary and eigen values $\lambda_{\pm}$ are real and it is primarily transmitting if K is real and eigen values are pure phases.

Using Eqs. (10) and (11), we can obtain

$$\lambda_{+} = e^{jKd} = a + \sqrt{a^2 - 1} = a + j\sqrt{1 - a^2} \tag{12}$$

Table 1. Photonic bandgap for $[n_1 = 1.5,\ n_2 = 2.2,\ n_3 = 1.5,\ d_1 = 0.85d,\ d_2 = 0.85 \times (0.15d),\ d_3 = 0.15 \times (0.15d),\ d = 140\,\mathrm{nm}]$.

Angle of Incidence (θ_A)	Ultraviolet Region		
	Allowed Bands	Allowed Ranges (nm)	Band Width (nm)
0	1	50–58.5	8.5
	2	59.5–65	5.5
	3	66.5–72.5	6
	4	75–83	8
	5	86–96.5	10.5
	6	100.5–115.5	15
	7	121.5–144	22.5
	8	152.5–191.5	39
	9	204–287	83
$\frac{\pi}{6}$	1	50–57	7
	2	58–63	5
	3	64.5–70.5	6
	4	73–80.5	7.5
	5	83.5–93.5	10
	6	98–112	14
	7	118–139.5	21.5
	8	148.5–185.5	37
	9	198.5–278.5	80
	10	299–300	1
$\frac{\pi}{3}$	1	50–53	3
	2	54.5–58.5	4
	3	60.5–65.5	5
	4	68.5–75	6.5
	5	78.5–87	8.5
	6	92.5–104.5	12
	7	111.5–130.5	19
	8	140–173.5	33.5
	9	187.5–260	72.5
	10	282–300	18

or $a = \cos(Kd)$, or

$$K = \frac{1}{d}\left[\cos^{-1}(a)\right] \tag{13}$$

The sign of the quantity $(a^2 - 1)$ determines whether the eigen values are real or complex. The eigen values switch from real to complex equivalently, K switches from imaginary to real, when $a^2 = 1$ or $a = \pm 1$. The critical values of K are found from Eq. (13) to be

$$K = \frac{1}{d} \cos^{-1}(\pm 1) = \frac{m\pi}{d} \tag{14}$$

where m is an integer.

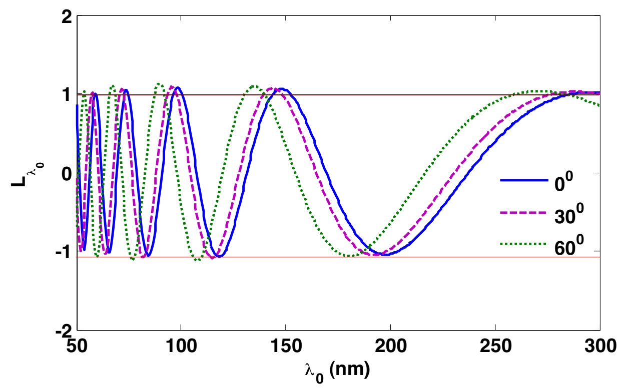

Figure 2. Variation of L_{λ_0} with λ_0 for $n_1 = 1.5$, $n_2 = 2.2$, $n_3 = 1.5$, $d_1 = 0.85d$, $d_2 = 0.85 \times (0.15d)$, $d_3 = 0.15 \times (0.15d)$ and $d = 140\,\mathrm{nm}$ at angles of incidence equal to 0°, 30°, and 60°.

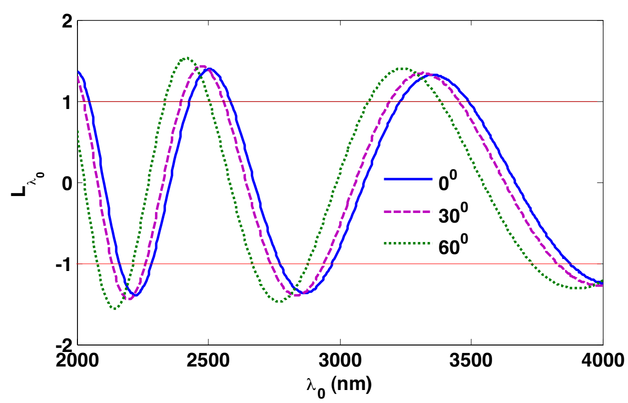

Figure 3. Variation of L_{λ_0} with λ_0 for [$n_1 = 3.6$, $n_2 = 1.52$, $n_3 = 3.6$, $d_1 = 0.85d$, $d_2 = 0.85 \times (0.15d)$, $d_3 = 0.15 \times (0.15d)$ and $d = 3000\,\mathrm{nm}$ at angles of incidence equal to 0°, 30°, and 60°.

For this proposed filter K satisfies Eq. (7)

$$\cos\beta_1\cos\beta_2\cos\beta_3-\frac{1}{2}\left(\frac{p_2}{p_1}+\frac{p_1}{p_2}\right)\sin\beta_1\sin\beta_2\cos\beta_3$$
$$-\frac{1}{2}\left(\frac{p_2}{p_3}+\frac{p_3}{p_2}\right)\cos\beta_1\sin\beta_2\sin\beta_3-\frac{1}{2}\left(\frac{p_1}{p_3}+\frac{p_3}{p_1}\right)\sin\beta_1\cos\beta_2\sin\beta_3$$
$$=\cos\left\{K\left(d_1+d_2+d_3\right)\right\} \tag{15}$$

Now abbreviating the LHS as L_{λ_0} Eq. (15) can be written as

$$L_{\lambda_0}=\cos\left(kd\right) \tag{16}$$

where the LHS (L_{λ_0}) of Eq. (15) in terms of free space wavelength (λ_0) can be written as

$$L_{\lambda_0}=\cos\left[\frac{2\pi n_1 d_1}{\lambda_0}\left(1-\frac{\sin^2\theta_A}{n_1^2}\right)^{\frac{1}{2}}\right]\cos\left[\frac{2\pi n_2 d_2}{\lambda_0}\left(1-\frac{\sin^2\theta_A}{n_2^2}\right)^{\frac{1}{2}}\right]$$
$$\cos\left[\frac{2\pi n_3 d_3}{\lambda_0}\left(1-\frac{\sin^2\theta_A}{n_3^2}\right)^{\frac{1}{2}}\right]$$
$$-\frac{1}{2}\left[\left(\frac{n_2^2\left(1-\frac{\sin^2\theta_A}{n_2^2}\right)^{\frac{1}{2}}}{n_1^2\left(1-\frac{\sin^2\theta_A}{n_1^2}\right)^{\frac{1}{2}}}+\frac{n_1^2\left(1-\frac{\sin^2\theta_A}{n_1^2}\right)^{\frac{1}{2}}}{n_2^2\left(1-\frac{\sin^2\theta_A}{n_2^2}\right)^{\frac{1}{2}}}\right)\right]$$
$$\times\left[\sin\left[\frac{2\pi n_1 d_1}{\lambda_0}\left(1-\frac{\sin^2\theta_A}{n_1^2}\right)^{\frac{1}{2}}\right]\sin\left[\frac{2\pi n_2 d_2}{\lambda_0}\left(1-\frac{\sin^2\theta_A}{n_2^2}\right)^{\frac{1}{2}}\right]\right.$$
$$\left.\cos\left[\frac{2\pi n_3 d_3}{\lambda_0}\left(1-\frac{\sin^2\theta_A}{n_3^2}\right)^{\frac{1}{2}}\right]\right]$$
$$-\frac{1}{2}\left[\left(\frac{n_3^2\left(1-\frac{\sin^2\theta_A}{n_3^2}\right)^{\frac{1}{2}}}{n_2^2\left(1-\frac{\sin^2\theta_A}{n_2^2}\right)^{\frac{1}{2}}}+\frac{n_2^2\left(1-\frac{\sin^2\theta_A}{n_2^2}\right)^{\frac{1}{2}}}{n_3^2\left(1-\frac{\sin^2\theta_A}{n_3^2}\right)^{\frac{1}{2}}}\right)\right]$$
$$\times\left[\cos\left[\frac{2\pi n_1 d_1}{\lambda_0}\left(1-\frac{\sin^2\theta_A}{n_1^2}\right)^{\frac{1}{2}}\right]\sin\left[\frac{2\pi n_2 d_2}{\lambda_0}\left(1-\frac{\sin^2\theta_A}{n_2^2}\right)^{\frac{1}{2}}\right]\right.$$

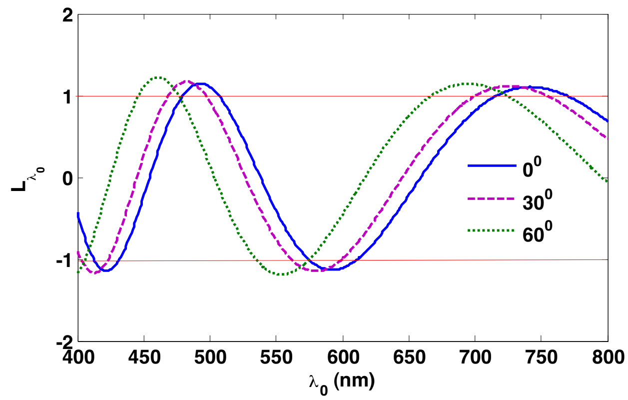

Figure 4. Variation of L_{λ_0} with λ_0 for $[n_1 = 2.6$, $n_2 = 1.52$, $n_3 = 2.6$, $d_1 = 0.85d$, $d_2 = 0.85 \times (0.15d)$, $d_3 = 0.15 \times (0.15d)$ and $d = 600\,\text{nm}$ at angles of incidence equal to $0°$, $30°$, and $60°$.

$$\sin\left[\frac{2\pi n_3 d_3}{\lambda_0}\left(1-\frac{\sin^2\theta_A}{n_3^2}\right)^{\frac{1}{2}}\right]\Bigg]$$

$$-\frac{1}{2}\left[\left(\frac{n_1^2\left(1-\frac{\sin^2\theta_A}{n_1^2}\right)^{\frac{1}{2}}}{n_3^2\left(1-\frac{\sin^2\theta_A}{n_3^2}\right)^{\frac{1}{2}}}+\frac{n_3^2\left(1-\frac{\sin^2\theta_A}{n_3^2}\right)^{\frac{1}{2}}}{n_1^2\left(1-\frac{\sin^2\theta_A}{n_1^2}\right)^{\frac{1}{2}}}\right)\right]$$

$$\times\Bigg[\sin\left[\frac{2\pi n_1 d_1}{\lambda_0}\left(1-\frac{\sin^2\theta_A}{n_1^2}\right)^{\frac{1}{2}}\right]\cos\left[\frac{2\pi n_2 d_2}{\lambda_0}\left(1-\frac{\sin^2\theta_A}{n_2^2}\right)^{\frac{1}{2}}\right]$$

$$\sin\left[\frac{2\pi n_3 d_3}{\lambda_0}\left(1-\frac{\sin^2\theta_A}{n_3^2}\right)^{\frac{1}{2}}\right]\Bigg]$$

This dispersion equation will determine the allowed and forbidden ranges of wavelengths.

3. RESULT AND DISCUSSION

For the proposed filter, investigations are carried out in ultraviolet, infrared and visible regions of electromagnetic spectrum. For ultraviolet region of investigation we have chosen the materials with refractive indices $n_1 = 1.52$, $n_2 = 2.2$ and $n_3 = 1.52$. Keeping $d_1 =$

Table 2. Photonic bandgap for [$n_1 = 3.6$, $n_2 = 1.52$, $n_3 = 3.6$, $d_1 = 0.85d$, $d_2 = 0.85 \times (0.15d)$, $d_3 = 0.15 \times (0.15d)$, $d = 3000\,\text{nm}$].

Angle of Incidence (θ_A)	**Infrared Region**		
	Allowed Bands	**Allowed Ranges (nm)**	**Band Width (nm)**
0	1	2048–2160	112
	2	2288–2428	140
	3	2588–2768	180
	4	2972–3228	256
	5	3492–3872	380
$\frac{\pi}{6}$	1	2028–2132	104
	2	2264–2396	132
	3	2560–2736	176
	4	2944–3188	244
	5	3456–3824	368
$\frac{\pi}{3}$	1	2000–2076	76
	2	2216–2332	116
	3	2504–2664	160
	4	2880–3108	228
	5	3384–3728	344

$0.85d$, $d_2 = 0.85 \times (0.15d)$ and $d_3 = 0.15 \times (0.15d)$ where $d = 140\,\text{nm}$, is the period of the structure. Investigations are also repeated for infrared and visible regions of electromagnetic spectrum by changing the period of the structure as 3000 nm and 600 nm respectively. Keeping $n_1 = 3.6$, $n_2 = 1.52$ and $n_3 = 3.6$ for infrared region and $n_1 = 2.6$, $n_2 = 1.52$ and $n_3 = 2.6$ for visible region.

Using these values in Eq. (15) L_{λ_0} is plotted against the free space wavelength (λ_0) for different values of angle of incidence (θ_A) as 0°, 30° and 60°. The curves are depicted in Fig. 2 to Fig. 4 respectively. The photonic band (in nm) obtained in this manner are shown in the Tables 1, 2 and 3. Because of the existence of the cosine function on the right-hand side of the Eq. (15), the upper and lower limiting values will obviously be $+1$ and -1 respectively. The portion of the curve lying between these limiting values will yield the allowed ranges of wavelengths and those out sides will show the forbidden ranges of transmission. From the study of these figures it is found that the width of the allowed photonic bands increases as the wavelength increases. The width of the allowed photonic bands is maximum at 0° i.e., normal incidence and as the angle of incidence increases the width decreases, for fixed values of n_1, n_2, n_3, d_1, d_2, and d_3 as shown in the Tables 1, 2 and 3 respectively. Actually these allowed bands give the different ranges of wavelengths that can be transmitted through the filter structure. The ranges of transmission depend on the values of controlling parameters n_1, n_2, n_3, d_1, d_2, and d_3. Thus by choosing suitable values of these parameters one can get the desired range of transmission (or reflection).

Table 3. Photonic bandgap for [$n_1 = 2.6$, $n_2 = 1.52$, $n_3 = 2.6$, $d_1 = 0.85d$, $d_2 = 0.85 \times (0.15d)$, $d_3 = 0.15 \times (0.15d)$, $d = 600\,\text{nm}$].

Angle of Incidence (θ_A)	**Visible Region**		
	Allowed Bands	**Allowed Ranges (nm)**	**Band Width (nm)**
0	1	400–412	12
	2	432–479.2	47.2
	3	507.2–573.6	66.4
	4	612–716	104
	5	768.8–800	31.2
$\frac{\pi}{6}$	1	400–402.4	2.4
	2	424–468	44
	3	496.8–560.8	64
	4	600–700	100
	5	754.4–800	45.6
$\frac{\pi}{3}$	1	406.4–445.6	39.2
	2	476.8–534.4	57.6
	3	576–667.2	91.2
	4	724–800	76
	5	-	-

4. CONCLUSION

In this work we have suggested the matrix formulation method for finding out dispersion relation for 1D ternary PBG structure. Using this dispersion relation we have suggested a design of an optical filter which can work for all the ranges of electromagnetic spectrum by choosing the suitable values of controlling parameters. This study can be used to develop more efficient and accurate photonic band gap material based tunable optical filter. The proposed optical filter made of 1-D ternary PBG material filters more number of allowed bands as compared to a filter made of 1-D binary PBG material and with better control in the wavelength of allowed bands to be filtered.

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REFERENCES

1. Yablonovitch, E., "Inhibited spontaneous emission in solid-state physics and electronics," *Phys. Rev. Lett.*, Vol. 58, 2059–2062, 1987.
2. John, S., "Strong localization of photons in certain disordered dielectric superlattices," *Phys. Rev. Lett.*, Vol. 58, 2486–2489, 1987.
3. Makhan, M. and S. K. Ramchurn, "Polarization-independent omnidirectional defect modes in Bragg gaps of one-dimensional photonic crystals," *J. Opt. Soc. Am. B*, Vol. 24, 3040–3047, 2007.
4. Joannopoulos, J. D., P. R. Villeneuve, and S. Fan, "Photonic crystals: Putting a new twist on light," *Nature*, Vol. 386, 143–149, 1997.
5. Zheng, Q. R., Y. Q. Fu, and N. C. Yuan, "Characteristics of planar PBG structures with a cover layer," *Journal of Electromagnetic Waves and Applications*, Vol. 20, No. 11, 1439–1453, 2006.
6. Fink, Y., J. N. Winn, S. Fan, C. Chen, and J. Michel, "A dielectric omnidirectional reflector," *Science*, Vol. 282, No. 5394, 1679–1682, 1998.

7. Rojas, J. A. M., J. Alpuente, J. PiËœneiro, and R. Sanchez, "Rigorous full vectorial analysis of electromagnetic wave propagation in 1D," *Progress In Electromagnetics Research*, PIER 63, 89–105, 2006.
8. Chigrin, D. N., A. V. Lavrinenko, D. A. Yarotsky, and S. V. Gaponenko, "Observation of total omnidirectional reflection from a one-dimensional dielectric lattice," *Appl. Phys. A*, Vol. 68, 25–28, 1999.
9. Sakoda, K., *Optical Properties of Photonic Crystals*, Springer-Verlag, Berlin, 2001.
10. Han, P. and H. Wang, "Extension of omnidirectional reflection range in one-dimensional photonic crystal with a staggered structure," *J. Opt. Soc. Am. B*, Vol. 20, No. 9, 1996–2001, 2003.
11. Ozbay, E., M. Bayindir, I. Bulu, and E. Cubukcu, "Investigation of localized coupled-cavity modes in two-dimensional photonic bandgap structures," *IEEE J. of Quantum Electronics*, Vol. 38, 837–843, 2002.
12. Boroditsky, M., R. Vrijen, T. F. Krauss, R. Coccioli, R. Bhat, and E. Yablonovitch, "Spontaneous emission extraction and Purcell enhancement from thin-film 2-D photonic crystals," *J. Lightwave Technol.*, Vol. 17, 2096–2112, 1999.
13. Painter, O., R. K. Lee, A. Scherer, A. Yariv, J. D. O'Brien, P. D. Dapkus, and I. Kim, "Two dimensional photonic bandgap defect mode laser," *Science*, Vol. 284, 1819–1821, 1999.
14. Mekis, A., M. Meier, A. Dodabalapur, R. E. Slusher, and J. D. Joannopoulos, "Lasing mechanism in two-dimensional photonic crystal lasers," *Appl. Phys. A: Materials Science and Processing*, Vol. 69, 111–114, 1999.
15. Noda, S., M. Yokoyama, M. Imada, A. Chutinan, and M. Mochizuki, "Polarization mode control of two-dimensional photonic crystal laser by unit cell structure design," *Science*, Vol. 293, 1123–1125, 2001.
16. Mekis, A., J. C. Chen, I. Kurland, S. Fan, P. R. Villeneuve, and J. D. Joannopoulos, "High transmission through sharp bends in photonic crystal waveguides," *Phys. Rev. Lett.*, Vol. 77, 3787–3790, 1996.
17. Sondergaard, T. and K. H. Dridi, "Energy flow in photonic crystal waveguides," *Phys. Rev. B*, Vol. 61, 15688–15696, 2000.
18. Knight, J. C., J. Broeng, T. A. Birks, and P. St. J. Russell, "Photonic bandgap guidance in optical fibers," *Science*, Vol. 282, 1476–1479, 1998.

19. Brown, E. R., C. D. Parker, and E. Yablonovitch, "Radiation properties of a planar antenna on a photonic-crystal substrate," *J. Opt. Soc. Amer. B*, Vol. 10, 404–407, 1993.
20. Kosaka, H., T. Kawashima, A. Tomita, M. Notomi, T. Tamamura, T. Sato, and S. Kawakamib, "Photonic crystals for micro lightwave circuits using wavelength dependent angular beam steering," *Appl. Phys. Lett.*, Vol. 74, 1370–1372, 1999.
21. Villeneuve, P. R., D. S. Abrams, S. Fan, and J. D. Joannopoulos, "Single-mode waveguide microcavity for fast optical switching," *Opt. Lett.*, Vol. 21, 2017–2019, 1996.
22. Zandi, O., Z. Atlasbaf, and K. Forooraghi, "Flat multilayer dielectric reflector antennas," *Progress In Electromagnetics Research*, PIER 72, 1–19, 2007.
23. Aissaoui, M., J. Zaghdoudi, M. Kanzari, and B. Rezig, "Optical properties of the quasi-periodic one-dimensional generalized multilayer Fibonacci structures," *Progress In Electromagnetics Research*, PIER 59, 69–83, 2006.
24. Maka, T., D. N. Chigrin, S. G. Romanov, and C. M. S. Torres, "Three dimensional photonic crystals in the visible regime," *Progress In Electromagnetics Research*, PIER 41, 307–335, 2003.
25. Wu, C.-J., "Transmission and reflection in a periodic superconductor/dielectric film multilayer structure," *Journal of Electromagnetic Waves and Applications*, Vol. 19, 1991–1996, 2005.
26. Delano, E. and R. J. Pegis, *Progress in Optics*, E. Wolf (ed.), Chap. 7, Vol. 69, North-Holland, Amsterdam, 1969.
27. Banerjee, A., S. K. Awasthi, U. Malaviya, and S. P. Ojha, "Design of a nano-layered tunable optical filter," *Journal of Modern Optics*, Vol. 53, No. 12, 1739–1752, 2006.
28. Brooks, D. and S. Ruschin, "Integrated electrooptic multielectrode tunable filter," *J. Lightwave Technol.*, Vol. 13, 1508–1513, 1995.
29. Wooten, E. L., R. L. Stone, E. W. Miles, and E. M. Bradely, "Rapidly tunable narrowband wavelength filter using LiNbO3," *J. Lightwave Technol.*, Vol. 14, 2530–2536, 1996.
30. Oda, K., N. Yakato, T. Kominato, and H. Toba, "A 16-channel frequency selection switch for optical FDM distribution systems," *IEEE J. Sel. Areas Commun.*, Vol. 8, 1132–1140, 1990.
31. Stone, J. and L. W. Stulz, "High-performance fibre Fabry-Perot filters," *Electron. Lett.*, Vol. 27, 2239–2240, 1991.
32. Born, M. and E. Wolf, "Basic properties of the electromagnetic field," *Principles of Optics*, Cambridge University Press, U.K.,

1980.

33. Zirngibl, M., C. H. Joyner, and B. Glance, "Digitally tunable channel-dropping filter/equalizer based on waveguide grating router and optical amplifier integration," *IEEE Photonics Technol. Lett.*, Vol. 6, 513–515, 1994.
34. Ishida, O., H. Takahashi, and Y. Inoue, "Digitally tunable optical filters using arrayed-waveguide grating (AWG) multiplexers and optical switches," *J. Light Wave Technol.*, Vol. 15, 321–327, 1997.
35. Sneh, A. and K. M. Johnson, "High-speed tunable liquid crystal filter for WDM networks," *J. Lightwave Technol.*, Vol. 14, 1067–1080, 1996.
36. Chen, P. L., K. C. Lin, W. C. Chuang, Y. C. Tzeng, K. Y. Lee, and W. Y. Lee, "Analysis of a liquid crystal Fabry-Perot etalon filter: A novel model," *IEEE Photonics Technol. Lett.*, Vol. 9, 467–469, 1997.
37. Fujii, Y., "High-isolation polarization-independent optical circulator coupled with single-mode fibers," *J. Lightwave Technol.*, Vol. 9, 456–460, 1991.
38. Smith, D. A., J. E. Baran, J. J. Johnson, and K. W. Cheung, "Integrated-optic acoustically tunable filters for WDM networks," *IEEE J. Sel. Areas Commun.*, Vol. 8, 1151–1159, 1990.
39. Zhao, L. P., X. Zhai, B. Wu, T. Su, W. Xue, and C.-H. Liang, "Novel design of dual-mode bandpass filter using rectangle structure," *Progress In Electromagnetics Research B*, Vol. 3, 131–141, 2008.
40. Jopson, R. M., J. Jtone, and L. W. Stulz, "Nonreciprocal transmission in a fiber Fabry-Perot resonator containing a magneto optic material," *Photonics Tech. Lett.*, Vol. 2, 702–704, 1990.
41. Morishita, K., "Optical fiber devices using dispersive materials," *IEEE J. Lightwave Technol.*, Vol. 7, 198–201, 1989.
42. Reid, D. C. J., C. M. Rogdale, I. Robbins, D. J. Robbins, J. Buus, and W. J. Stewart, "Phase-shifted Moire grating fibre resonators," *Electron. Lett.*, Vol. 26, 10–12, 1990.
43. Ojha, S. P., P. K. Chaudhary, P. Khastgir, and O. N. Singh, "Operating characteristics of an optical filter with a linearly periodic refractive index pattern in the filter material," *Jpn. J. Appl. Phys.*, Vol. 31, 281–285, 1992.
44. Chen, J. C., A. Haus, S. Fan, P. R. Villeneuve, and J. D. Joannopoulos, "Optical filters from photonic band gap air bridges," *IEEE J. Lightwave Technol.*, Vol. 14, 2575–2580, 1996.

45. D'Orazio, A., M. de Sario, V. Petruzzelli, and F. Prudenzano, "Photonic band gap filter for wavelength division multiplexer," *Opt. Exp.*, Vol. 11, No. 3, 230–239, 2003.
46. DelVillar, I., I. R. Matias, F. J. Arregui, and R. O. Claus, "Analysis of one-dimensional photonic bandgap structures with a liquid crystal defect toward development of fiber-optic tunable wavelength filters," *Opt. Exp.*, Vol. 11, No. 5, 430–436, 2003.
47. 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.
48. Born, M. and E. Wolf, "Basic properties of the electromagnetic field," *Principles of Optics*, 1–70, Cambridge University Press, U.K., 1980.
49. Orfanidis, S. J., "Multilayer film applications," *Electromagnetic Waves and Antennas*, 193–194, (www.ece.rutgers.edu/∼orfanidi/ewa).