Design of an Omnidirectional reflector using one dimensional ternary photonic crystal

Sanjeev Sharma, Rajendra Kumar, Kh. S. Singh, Deepti Jain

***Abstract*— In the present communication, we study omni-directional reflection in one-dimensional ternary photonic crystal (PC) based on Ge/CaF_2/GaAs multilayered structure. The theoretical analysis shows that the proposed structure works as a perfect mirror within a certain wavelength range. Reflectance characteristics of 1-D ternary photonic crystal (PC) structure have been studied. This property shows that the ODR range of structure increased when a third layer of semiconductor added in a binary photonic crystal.**

***Index Terms*— ODR, multilayer structure, Transfer matrix method (TMM).**

I. Introduction

In the last two decades, studies on photonic crystals particularly photonic band gap structures attracted lot of attention of researchers [1–3], due to their enormous potential applications in optical communications, optoelectronics and optical instrumentation. A photonic crystal (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 electronic bandgaps in semiconductors [3-7]. According 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, one dimensional photonic crystal can be used as omnidirectional totally reflecting mirrors, frequency filters, microwave antenna substrates and enclosure coatings of waveguide etc. Its applications depend on the chosen geometry and frequency regions [8-10].

The width of the OBGs plays an important role in the applications of 1DPC omnidirectional reflector. In recent years, one-dimensional ternary photonic crystals (1DTPCs) are also put forward to obtain the extended omni-directional reflection band gaps (OBGs) [11-16]. 1DTPCs are constituted by three material layers in a period of the lattice. Awasthi et al. [13] demonstrated that the wavelength range of OBGs can be enhanced to a great extent when the structure was modified by sandwiching a thin layer of ZrO_2 between every two layers of conventional one-dimensional binary photonic crystal Wu et al. [14] showed that the OBGs can be significantly enlarged in the ternary metal-dielectric PC. Xiang et al. [12] found that the zero-effective-phase bandgap will be enlarged by sandwiching the third material between the two single-negative materials. In this paper, we report a design of omnidirectional reflector filters by using a 1-D ternary photonic band gap material.

THEORY

The periodic structure consisting of alternate layers of refractive indices n_1 (first material layer), n_2 (second material layer) and n_3 (third material layer) with thicknesses d_1, d_2 and d_3 respectively is depicted in Fig. 1. Here, $d = d_1 + d_2 + d_3$ is the period of the lattice. It is assumed that the incident media is air (n_i= 1). Light is incident on the multilayer at an angle θ_i.

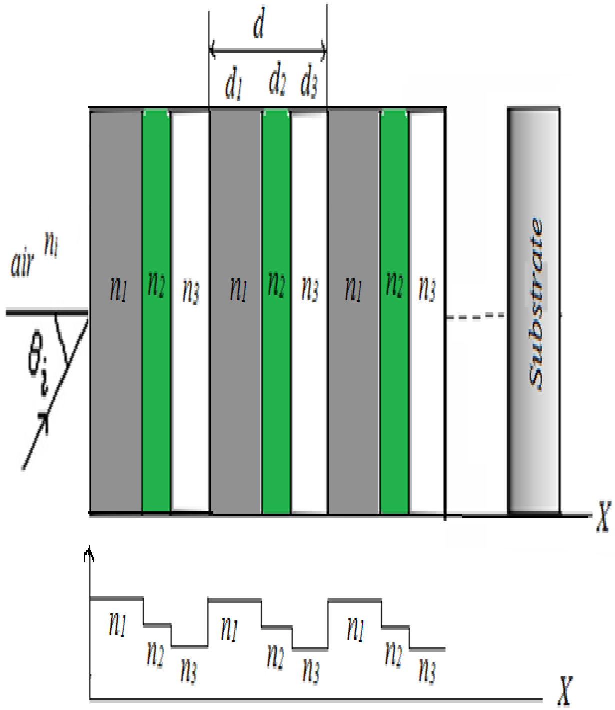

Fig. 1 One-dimensional ternary photonic crystals and refractive index profile of the structure.

For the s- wave, the characteristic matrix M[d] (17) of one period is given

Sanjeev Sharma, Department of Physics, Gurukul Kangri Vishwavidyalaya Haridwar, Uttarakhand, India, PIN-249404.
Rajendra Kumar, Department of Physics, Gurukul Kangri Vishwavidyalaya Haridwar, Uttarakhand, India, PIN-249404.
Kh. S. Singh, Department of Physics, D.J.College Baraut, Uttar Pradesh, India, PIN – 250611.
Deepti Jain, Department of Physics S.K.K.J.(P.G) college Khatauli, Muzaffarnagar, Uttar Pradesh, India, Pin-251201

$$M[d] = \prod_{i=1}^{3} \begin{bmatrix} \cos\beta_i & \frac{-i}{p_i}\sin\beta_i \\ -ip_i\sin\beta_i & \cos\beta_i \end{bmatrix} = \begin{bmatrix} M_{11} & M_{12} \\ M_{21} & M_{22} \end{bmatrix} \quad (1)$$

where, $\beta_i = \frac{2\pi}{\lambda} p_i d_i \cos\theta_i$, $p_i = n_i \cos\theta_i$, θ_i is the ray angles inside the layer of refractive index n_i and is related to the angle of incidence θ_0 by

$$\cos\theta_i = \left[1 - \frac{n_0^2 \sin^2\theta_i}{n_i^2}\right]^{\frac{1}{2}} \quad (2)$$

The matrix $M[d]$ in equation (1) is unimodular as $M[d] = 1$.
For an N-period structure, the characteristic matrix of the medium is given by,

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

$$= \begin{bmatrix} m_{11} & m_{12} \\ m_{21} & m_{22} \end{bmatrix} \quad (3)$$

where,

$$M_{11} = \left(\cos\beta_1\cos\beta_2\cos\beta_3 - \frac{p_2}{p_1}\sin\beta_1\sin\beta_2\cos\beta_3 - \frac{p_3}{p_2}\cos\beta_1\sin\beta_2\sin\beta_3 - \frac{p_3}{p_1}\sin\beta_1\cos\beta_2\sin\beta_3\right)$$

$$M_{12} = -i\left(\frac{1}{p_1}\sin\beta_1\cos\beta_2\cos\beta_3 + \frac{1}{p_2}\cos\beta_1\sin\beta_2\cos\beta_3 + \frac{p_3}{p_2}\cos\beta_1\cos\beta_2\sin\beta_3 - \frac{p_2}{p_1p_3}\sin\beta_1\sin\beta_2\sin\beta_3\right)$$

$$M_{21} = -i\left(p_1\sin\beta_1\cos\beta_2\cos\beta_3 + p_2\cos\beta_1\sin\beta_2\cos\beta_3 + p_3\cos\beta_1\cos\beta_2\sin\beta_3 - \frac{p_1p_3}{p_2}\sin\beta_1\sin\beta_2\sin\beta_3\right)$$

$$M_{22} = \left(\cos\beta_1\cos\beta_2\cos\beta_3 - \frac{p_1}{p_2}\sin\beta_1\sin\beta_2\cos\beta_3 - \frac{p_2}{p_3}\cos\beta_1\sin\beta_2\sin\beta_3 - \frac{p_1}{p_3}\sin\beta_1\cos\beta_2\sin\beta_3\right)$$

U_N is the Chebyshev polynomials of the second kind

$$U_N(a) = \frac{\sin[(N+1)\cos^{-1} a]}{[1-a^2]^{\frac{1}{2}}} \quad (4)$$

$$\text{where,} \quad a = \frac{1}{2}[M_{11} + M_{22}] \quad (5)$$

The transmission coefficient of the multilayer is given by,

$$t = \frac{2p_0}{(m_{11} + m_{12}p_0)p_0 + (m_{21} + m_{22}p_0)} \quad (6)$$

And the reflection coefficient of the multilayer is given by,

$$r(\omega) = \frac{(m_{11} + m_{12}p_0)p_0 - (m_{21} + m_{22}p_0)}{(m_{11} + m_{12}p_0)p_0 + (m_{21} + m_{22}p_0)} \quad (7)$$

and the reflectance for this structure can be written in terms of reflection coefficient as,

$$R = |r(\omega)|^2 \quad (8)$$

where, $p_0 = n_0 \cos\theta_0$.

II. RESULTS AND DISCUSSION

In this paper, we study ODR property in one-dimensional ternary PC structures consisting of alternate layers of Ge, CaF_2 and GaAs. The theoretical analysis is based on the transfer matrix method. For the optical properties of Ge, CaF_2 and GaAs the data used for the ranges of wavelengths of our interest are those of R. Newman et al. (18), I. H. Malitson et al. (19) and Piktin et al. (20) respectively. The refractive indices of Ge, CaF_2 and GaAs are 4.23, 1.42 and 3.37 respectively in the range of wavelength of our interest that is around 1550 nm. Applying transfer matrix method, we plotted reflectance of the structures with wavelength for various angles of incidence.

In this case, we have taken the thicknesses of Ge, CaF_2 and GaAs layers to be $d_1 = 1000\ nm$, $d_2 = 350\ nm$, $d_3 = 250\ nm$ and $d = d_1 + d_2 + d_3 = 1600\ nm$ .This particular combination of thicknesses of Ge, CaF_2 and GaAs layers is choose such that we may get making omni-directional reflection (ODR) range in the reflection spectra of such a structure. Fig. 2 shows the reflectivity (reflectance) of the structure for different angles of incidence, namely, 0^0, 15^0, 30^0, 45^0, 60^0, 75^0 and 85^0 for TE and TM mode respectively and the ODR range for angles of incidence from 0^0 to 85^0 is shown in shaded portion of Fig. 2.

Angle of incidence, θ (deg.)	TE (nm)	Band width (nm)	TM (nm)	Band width (nm)
0	1520-1645	125	1520-1645	125
15	1514-1641	127	1516-1640	124
30	1497-1631	134	1504-1626	122
45	1475-1617	142	1489-1605	116
60	1454-1602	148	1474-1581	107
75	1438-1592	154	1463-1561	98
85	1433-1588	155	1460-1554	94

Table 1 Photonic bandgap for Ge/CaF$_2$/GaAs materials [n_1 = 4.23, n_2 = 1.42, n_3 = 3.37, d_1 = 1000 nm, d_2 = 350 nm, d_3 = 250 nm, $d = d_1 + d_2 + d_3$ = 1600 nm, N = 12] for various incidence angle.

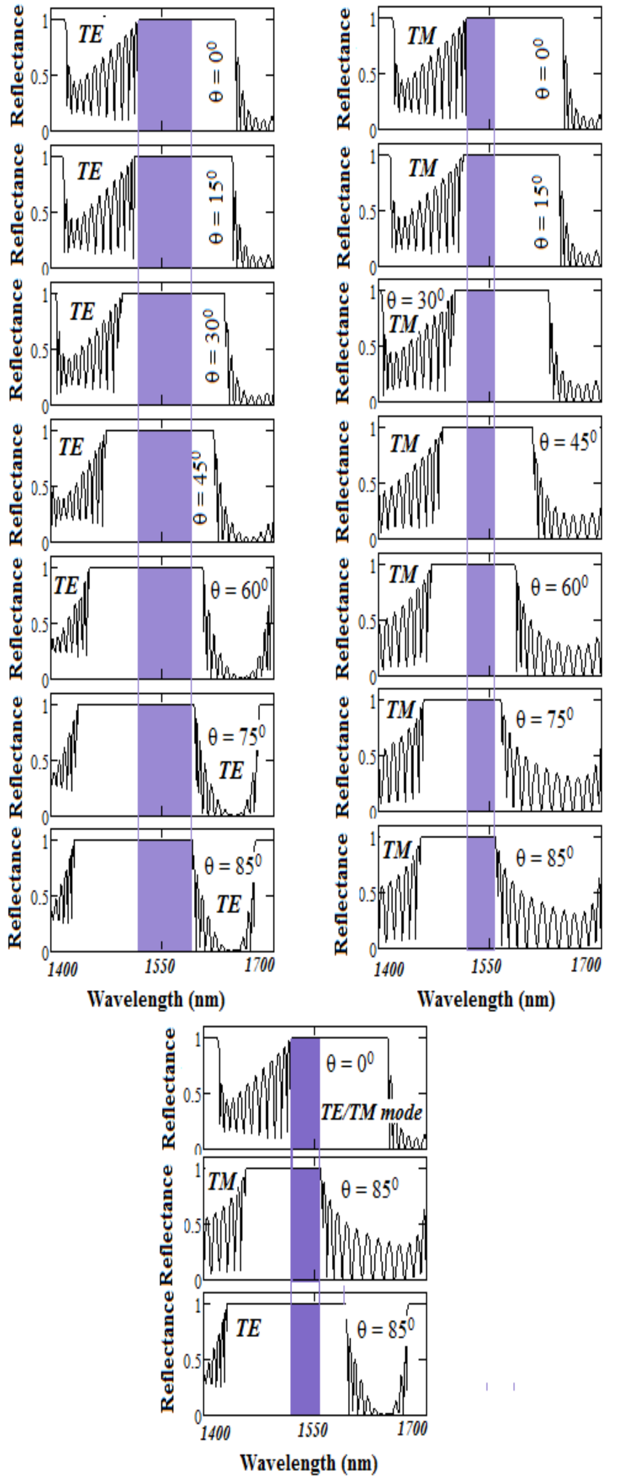

Fig. 2 Reflectance Vs wavelength of Ge/CaF$_2$/GaAs multilayer structure for TE & TM mode at different angles and omnidirectional reflection range.

From the plots of reflection spectra of **Ge/ CaF$_2$/ GaAs** for different angles of incidence, 100 percent reflection ranges for different angles of incidence are tabulated in Table 1. It is clear from Table 1 that the 100% reflectance-range for TE mode is 1520-1645 nm at normal incidence. Similarly, for angles of incidence of 15^0, 30^0, 45^0, 60^0, 75^0 and 85^0 the respective ranges of wavelength with 100% reflection are 1514-1641 nm, 1497-1631 nm; 1475-1617 nm; 1454-1602 nm, 1438-1592 nm and 1433-1588 nm for TE mode. Also the ranges of 100% reflection for TM mode are 1520-1645 nm, 1516-1640 nm; 1504-1626 nm; 1489-1605, 1474-1581, 1463-1561 nm; and 1460-1554 nm for angles of incidence at 0^0, 15^0, 30^0, 45^0, 60^0, 75^0 and 85^0 respectively. Hence the total omnidirection range of wavelength for this multilayer structure lies between 1520–1554 nm and the width of the omnidirection wavelength range is **34 nm**. In this paper, we have chosen the parameters of each of the structures such that the 1550 nm wavelength primarily used in optical communication falls in the omnidirectional reflection ranges of wavelength for all the structures. Hence, each of these multilayered one-dimensional structures can be used as an omni-directional mirror in optical communication devices.

III. CONCLUSION

We have shown theoretically that a one-dimensional ternary dielectric/semiconductor photonic crystal structure of Ge/CaF$_2$/SiO$_2$ can exhibit total omni-directional reflection of incident light. The ternary photonic crystal can be used as omnidirectional reflectors in fiber optic communication systems for the particular choices of design parameters in the third transmission window of optical fibers, which is around 1550 nm, falls in the ODR band of the structure.

ACKNOWLEDGMENT

One of the authors, Sanjeev Sharma is thankful to the Head, Department of Physics, Gurukul Kangri Vishwavidyalaya, Haridwar and Head, Department of Physics, D.J. College Baraut (UP) for their kind cooperation.

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