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Modelling and Simulation (using MATLAB) of Silicon Carbide (SiC) based 1-Dimensional Photonic Crystal with 3 Layered Unit Cell

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Abstract

In this paper Silicon Carbide (SiC) based 1D photonic crystal with 3 layered unit cell are analyzed .The transmission characteristics of 3 layered unit cell phonic crystal have been analyzed by transfer matrix method and when someone construct a periodic structure of such kind of phonic crystal and compare their various characteristics such as stop band width , pass band width, centre band gap etc, by passing a particular light waves of its particular wavelength in nanometer range ,where one layer is always should be of SiC based semiconductor material. The purpose of such periodic structure is to compare the characteristics of various material combinations, when a light passes through every semiconductor layer, each layer has its own refractive indices due to this reason the different material combination shows different characteristics. This procedure able us to know the characteristics of a light wave when it goes through Silicon Carbide (SiC) based 1D photonic crystal with 3 layered unit cell.

Keywords: 1-Dimentional photonic crystal, Transmission coefficient, 3-layered unit cell, Light wave.

Introduction

In this paper first to know about photonic crystal the statement is like that periodic optical nanostructures that are designed to affect the motion of photons in a similar way that periodicity of a semiconductor crystal affects the motion of electrons. such photonic crystals with photonic band gap (for some frequency range, a photonic crystal prohibits the propagation of electromagnetic waves of any polarization travelling in any direction from any source, then we say that the crystal has a complete photonic band gap) preventing light from propagating in certain directions with specified frequencies In order to construct these crystals in the optical regime, suitable nanofabrication techniques have to be developed and demonstrated, including high resolution electron beam lithography and anisotropic chemically assisted ion beam etching. These periodic dielectric structures are expected to exhibit interesting properties in both fields of physics and engineering. Silicon Carbide (SiC) being an important semiconductor in the situation. The basic characteristics of Silicon Carbide (SiC) – based photonic crystals will be analyzed [2].

One Dimensional Photonic Crystal (Phc)

In a 1-D Photonic Crystal layers of different dielectric constant may be deposited or adhered together to form a band gap in a single direction .A Bragg grating is an example of this type of photonic crystal .This type of photonic crystal systems exhibits three important phenomena i) Photonic Band gap , ii)Localized mode iii) surface state ,because the index contrast is only along one direction , the band gaps and bound states are limited to that direction .By the help of this concept this characteristics analysis is being processed.[1]

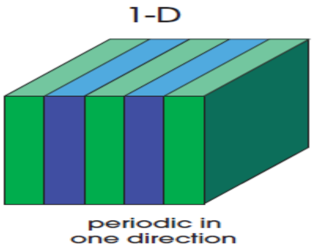

Fig (1)-1-D Photonic Crystal

Reason behind the choosing of Silicon Carbide (SiC) as a semiconductor material

SiC (wide forbidden energy gap of 2.86 eV@ 302 K) has been emerged as an attractive substrate for high power devices due to its larger band gap , higher break down strength , high thermal conductivity and high electron saturation drift velocity. Most important advantage of SiC over other wide band gap semiconductor is that SiC can be thermally oxidized to form an insulator Silicon die oxide. Although the refractive index of SiC is lower than that of a conventional semiconductor such as GaAs or Si , a wide photonic band gap , a broadband wave guide and a high quality nanocavity comparable to those of previous photonic crystals can be obtained in Silicon Carbide based photonic crystals, for above many reason in this analysis process we choose SiC.[4]

Description

In this paper photonic crystal contain 3 layers .In 3 layers photonic crystal we have to relate their thicknesses to the photonic crystal . For that particular 3-layer case the governing equation stated as

$n_1d_1=n_2d_2= n_3d_3=\lambda_0/6$………….. (1)

Where d_1, d_2, d_3 signifies the thicknesses of layers 1, 2, 3 respectively and n_1, n_2, n_3 are the refractive indices of the corresponding layers. λ_0= Free space (vacuum) wavelength, whose value is taken here as 1550 nanometer, since it is the most important wavelength for optical communication.

When an electromagnetic wave with S-polarization incidents on a unit cell of two materials a and b, the reflection and transmission coefficient can be expressed as [3]

$$\frac{A_R}{A_I} = \frac{\sqrt{\epsilon_a/\mu_a}\cos\alpha - \sqrt{\epsilon_b/\mu_b}\cos\beta}{\sqrt{\epsilon_a/\mu_a}\cos\alpha + \sqrt{\epsilon_b/\mu_b}\cos\beta} \text{.........(2)}$$

$$\frac{A_T}{A_I} = \frac{2\sqrt{\epsilon_a/\mu_a}\cos\alpha}{\sqrt{\epsilon_a/\mu_a}\cos\alpha + \sqrt{\epsilon_b/\mu_b}\cos\beta} \text{.......... (3)}$$

Where A is the complex amplitude of the electric field, α and β are angle of incidence and refraction at the interface.

Here S- polarized wave has its electric field vector confined perpendicular to the plane of incidence. Here electric field E is in the y direction, so $\tilde{E}$ = (0,A,0). Using S-polarization [equation (2) and (3)] we get the equation (4)

$$C_{m-1}e^{ik_m z_m \cos\alpha_{m-1}} = \frac{\sqrt{\epsilon_{m-1}/\mu_{m-1}}\cos\alpha_{m-1} - \sqrt{\epsilon_m/\mu_m}\cos\alpha_m}{\sqrt{\epsilon_{m-1}/\mu_{m-1}}\cos\alpha_{m-1} + \sqrt{\epsilon_m/\mu_m}\cos\alpha_m} A_{m-1} \times e^{-ik_m z_m \cos\alpha_{m-1}} + \frac{2\sqrt{\epsilon_m/\mu_m}\cos\alpha_m}{\sqrt{\epsilon_{m-1}/\mu_{m-1}}\cos\alpha_{m-1} + \sqrt{\epsilon_m/\mu_m}\cos\alpha_m} C_m \times e^{ik_m z_m \cos\alpha_m}$$

………………………(4)

And

$$A_m e^{-ik_m z_m \cos\alpha_m} = \frac{2\sqrt{\epsilon_{m-1}/\mu_{m-1}}\cos\alpha_{m-1}}{\sqrt{\epsilon_{m-1}/\mu_{m-1}}\cos\alpha_{m-1} + \sqrt{\epsilon_m/\mu_m}\cos\alpha_m} A_{m-1} \times e^{-ik_m z_m \cos\alpha_{m-1}} + \frac{\sqrt{\epsilon_m/\mu_m}\cos\alpha_m - \sqrt{\epsilon_{m-1}/\mu_{m-1}}\cos\alpha_{m-1}}{\sqrt{\epsilon_{m-1}/\mu_{m-1}}\cos\alpha_{m-1} + \sqrt{\epsilon_m/\mu_m}\cos\alpha_m} C_m \times e^{ik_m z_m \cos\alpha_m}$$

……………(5)

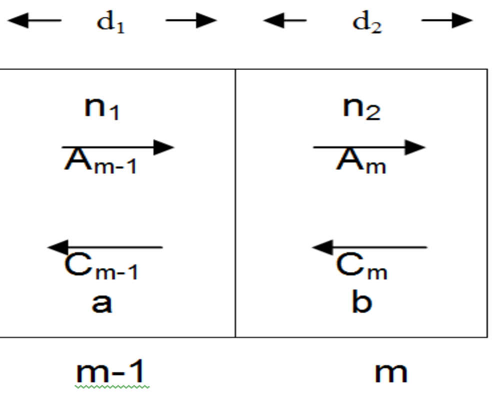

Fig-(2)- Standard 2 layered unit cell Photonic Crystal a and b indicates the two layers with refractive indices n_1 and n_2.

From the figure 2, First layer is for denser material and other one is for rarer material. d_1 and d_2 are the thickness of each layer. C_m is the amplitude in the m^{th} layer for waves and C_{m-1} is for m-1 layer that is first layer. A_m is the amplitude in the m^{th} layer for waves and A_{m-1} is the amplitude in the m-1 layer. From equation (4) & (5) it is possible to construct transfer matrix ,here cosine value is 0 for all cases (consider) and μ=1 in all cases but € value is changed for different material. Here m-1 layer signify the first layer and m is for second layer of an unit cell photonic crystal. In this particular 3-layer case the equation (4) and (5) cannot help us directly to form transfer matrix , because this two equation (4&5) is directly applicable for 1D photonic crystal containing two layer unit cell where by using this two equations we can easily form transfer matrix .So to get out from this problem we split the unit cell of three layers into unit cell of two layers each. As for example Si-SiC-SiO_2 unit cell will become a combination of Silicon-Silicon Carbide, Silicon Carbide-Silica and Silica-Silicon. Therefore we will have to apply the three layers equation for each unit cell to get the desired result.

The matrix form is like that

M=

$$\begin{bmatrix} a1 * \exp(-i.* km.* zm) & a2 * \exp(i.* km.* zm) \\ a2 * \exp(-i.* km.* zm) & a1 * \exp(i.* km.* zm) \end{bmatrix}$$

$$\begin{bmatrix} b1 * \exp(-i.* km1.* zm1) & b2 * \exp(i.* km1.* zm1) \\ b2 * \exp(-i.* km1.* zm1) & b1 * \exp(i.* km1.* zm1) \end{bmatrix}$$

Here zm = d_2 and zm1 = d_1, where d_1, d_2 stated earlier. By the help of equation (6)

$$M = \begin{pmatrix} 1/t & r_1^*/t^* \\ r_1/t & 1/t^* \end{pmatrix} \ldots\ldots\ldots\ldots\ldots (6)$$

we get the transmission coefficient value of overall matrix, and from equation (7)

$$M^N = \begin{pmatrix} 1/t_N & r_N^*/t_N^* \\ r_N/t_N & 1/t_N^* \end{pmatrix} \ldots\ldots\ldots\ldots (7)$$

we can stack the matrix by 10 times to get the overall transmission coefficient for the entire photonic crystal.

Computation of result using different parameters

Using equation (6) transmission coefficient has been computed using matlab. For computation this paper takes the following parameters.

Free space wavelength (λ_0) = 1550 nanometer (nm)
Number of unit cell (N) = 10
d_1 = Thickness of the first layer.
d_2 = Thickness of the second layer.
d_3 = Thickness of the third layer.
n_1 = Refractive index of the first layer.
n_2 = Refractive index of the second layer.
n_3 = Refractive index of the third layer.

Discussion of Results

Silicon_Silicon Carbide_Silica:

In that case of Silicon, Silicon Carbide and Silica the value of n_1 for Silicon is 3.5 and the value of n_2 for Silicon Carbide is 2.55 and the value of n_3 for Silica is 1.5, so by using equation (1) thickness of the first layer (d_1) = 1550/6*3.5 = 73.809 nm and thickness for the second layer (d_2) = 1550/6*2.55 = 101.3 nm and the thickness for the third layer (d_3) = 1550/6*1.5 = 172.22 nm.

In this three layer photonic crystal Pass band lies in between 850 nm – 1320 nm (Approx), so Pass band width is 1320 – 850 = 470 nm. After 1880 nm we find the Pass band till the range investigates 2400 nm. We also find Stop band lies in between 1320 nm to 1880 nm (Approx), where transmission coefficient value is 0. So the Stop band width is 1880 – 1320 = 560 nm. In that graph Centre band gap lie is at 1600 nm (Approx), so our wavelength shift towards the high frequency range.

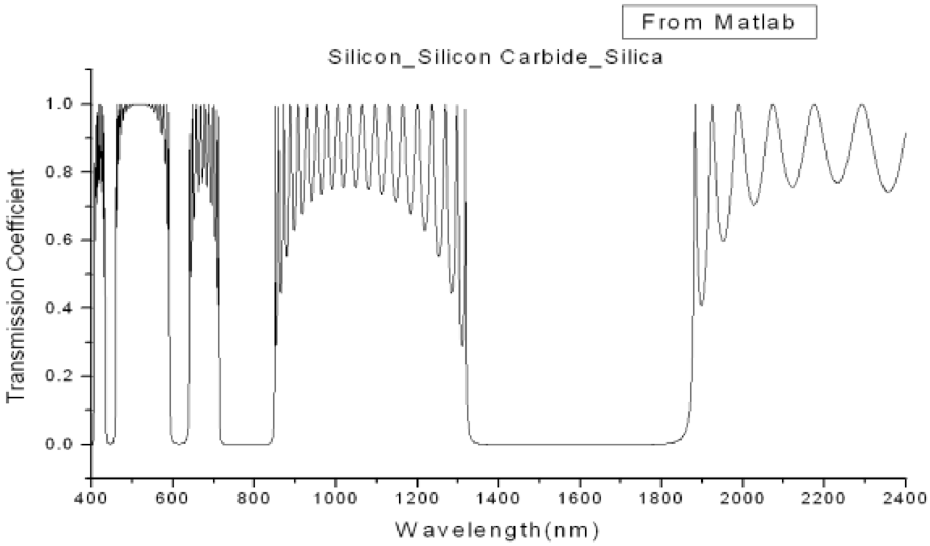

Fig3: Plot between Wavelength(nm) Vs. Trasmission Coefficient in case of Silicon_ Silicon Carbide_Silica based photonic crystal containing number of unit cells (N) = 10

Silica_Silicon_Silicon Carbide:

In that case of Silica, Silicon and Silicon Carbide the value of n_1 for Silica is 1.5 and the value of n_2 for Silicon is 3.5 and the value of n_3 for Silicon Carbide is 2.55, so by using equation (1) thickness of the first layer (d_1) = 1550/6*1.5 = 172.22 nm and thickness for the second layer (d_2) = 1550/6*3.5 = 73.809 nm and the thickness for the third layer (d_3) = 1550/6*2.55 = 101.3 nm.

Here at first the Pass band which we find is lies in between 850 nm to 1320 nm (Approx), so the Pass band width is 1320 – 850 = 470 nm. From 1880 nm we find a Pass band till the range investigates 2400 nm. Here Stop band lies in between 1320 nm to

1880 nm (Approx), so the transmission coefficient is 0. Stop band width is 560 nm. In that graph Centre band gap lie is at 1600 nm (Approx), so our wavelength shift towards the high frequency range.

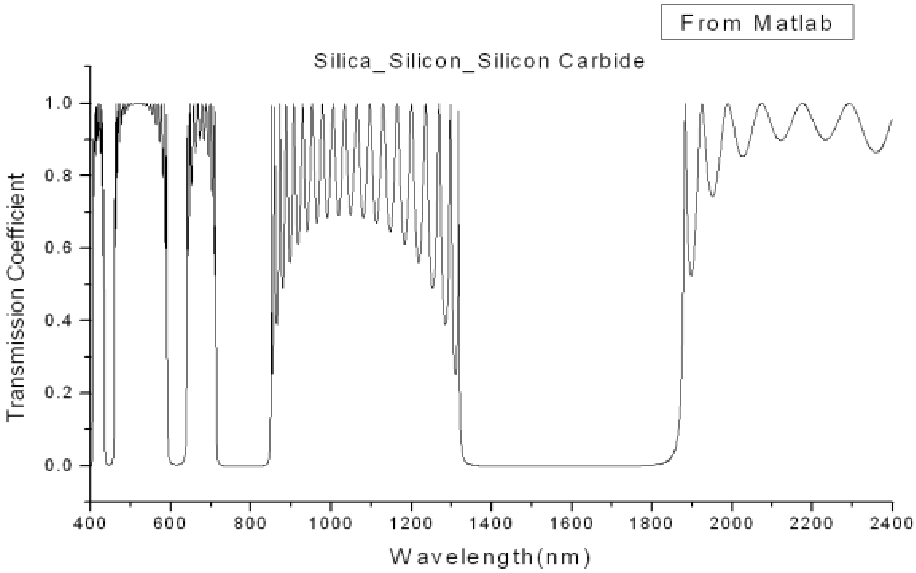

Fig4: Plot between Wavelength(nm) Vs. Trasmission Coefficient in case of Silica_ Silicon_Silicon Carbide based photonic crystal containing number of unit cells (N) = 10

Silica_Silicon Carbide_Silicon:

In that case of Silica, Silicon Carbide and Silicon the value of n_1 for Silica is 1.5 and the value of n_2 for Silicon Carbide is 2.55 and the value of n_3 for Silicon is 3.5, so by using equation (1) thickness of the first layer (d_1) = 1550/6*1.5 = 172.22 nm and thickness for the second layer (d_2) = 1550/6*2.55 = 101.3 nm and the thickness for the third layer (d_3) = 1550/6*3.5 = 73.809 nm.

In that particular graph we find that Pass band lies in between 850 nm to 1320 nm (Approx), so Pass band width is 1320 – 850 = 470 nm. From 1880 nm to investigate range 2400 nm (Approx) we find a Pass band. Here Stop band lies in between 1320 nm to 1880 nm (Approx), so transmission coefficient value is 0, so Stop band width is 1880–1320 = 560 nm. Here Centre band gap lie is at 1600 nm (Approx), so our wavelength shift towards the high frequency range.

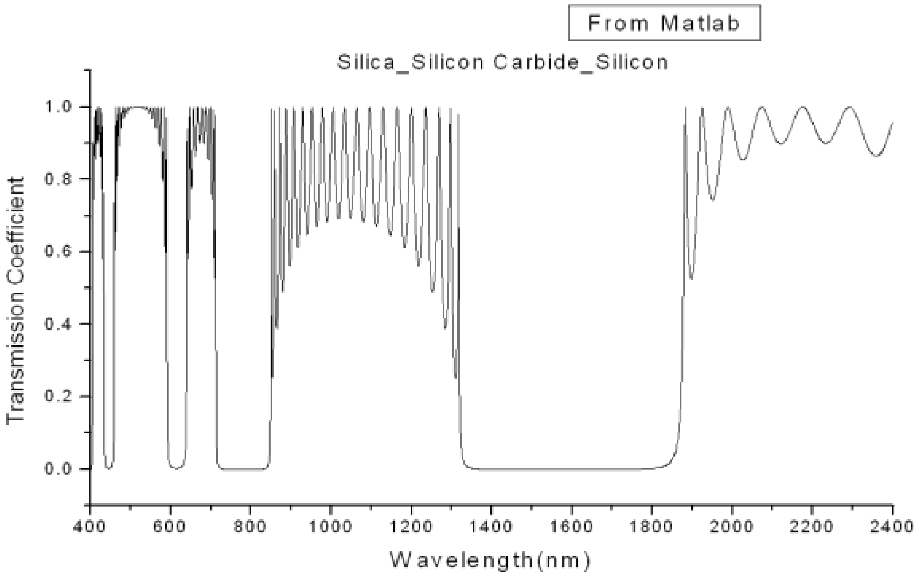

Fig5: Plot between Wavelength(nm) Vs. Trasmission Coefficient in case of Silica_ Silicon Carbide_Silicon based photonic crystal containing number of unit cells (N) = 10

Silicon_Silica_Silicon Carbide:

In that case of Silicon, Silica and Silicon Carbide the value of n_1 for Silicon is 3.5 and the value of n_2 for Silica is 1.5 and the value of n_3 for Silicon Carbide is 2.55, so by using equation (1) thickness of the first layer (d_1) = 1550/6*3.5 = 73.809 nm and thickness for the second layer (d_2) = 1550/6*1.5 = 172.22 nm and the thickness for the third layer (d_3) = 1550/6*2.55 = 101.30 nm.

In that case the Pass band lies in between 850 nm to 1320 nm (Approx), so the Pass band width is 1320 – 850 = 470 nm. From 1880 nm to investigate range 2400 nm (Approx) we find a Pass band. Here Stop band lies in between 1320 nm to 1880 nm (Approx), in that range transmission coefficient value is 0. So Stop band width is 560 nm. Here Centre band gap lie is at 1600 nm (Approx), so our wavelength shift towards the high frequency range.

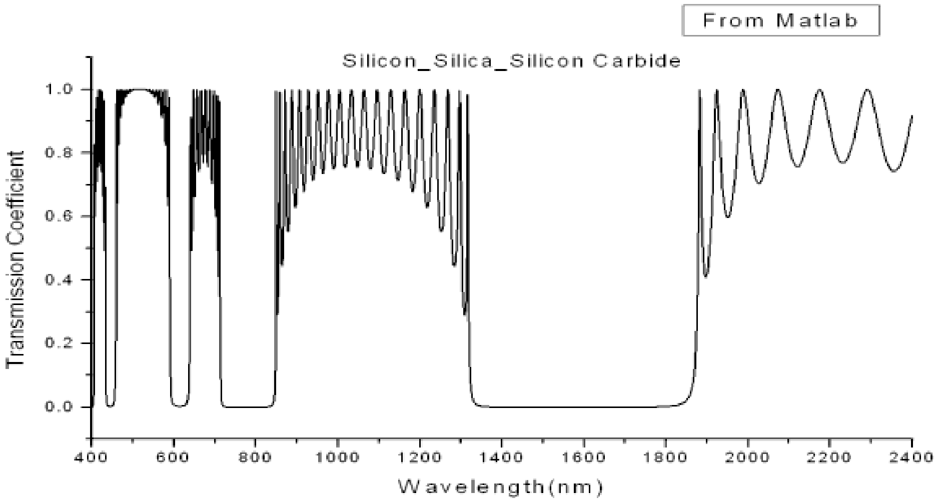

Fig6: Plot between Wavelength(nm) Vs. Trasmission Coefficient in case of Silicon_ Silica_Silicon Carbide based photonic crystal containing number of unit cells (N) = 10

Silicon Carbide_Silicon_Silica:

Here for Silicon Carbide, Silicon and Silica the value of n_1 for Silicon Carbide is 2.55 and the value of n_2 for Silicon is 3.5 and the value of n_3 for Silica is 1.5, so by using equation (1) thickness of the first layer (d_1) = 1550/6*2.55 = 101.30 nm and thickness for the second layer (d_2) = 1550/6*3.5 = 73.809 nm and the thickness for the third layer (d_3) = 1550/6*1.5 = 172.22 nm.

In that case the Pass band lies in between 850 nm to 1320 nm (Approx), so the Pass band width is 1320 – 850 = 470 nm. From 1880 nm to investigate range 2400 nm (Approx) we find a Pass band. Here Stop band lies in between 1320 nm to 1880 nm (Approx), here we find transmission coefficient is 0, Stop band width is 1880 – 1320 = 560 nm. Here Centre band gap lie is at 1600 nm (Approx), so our wavelength shift towards the high frequency range.

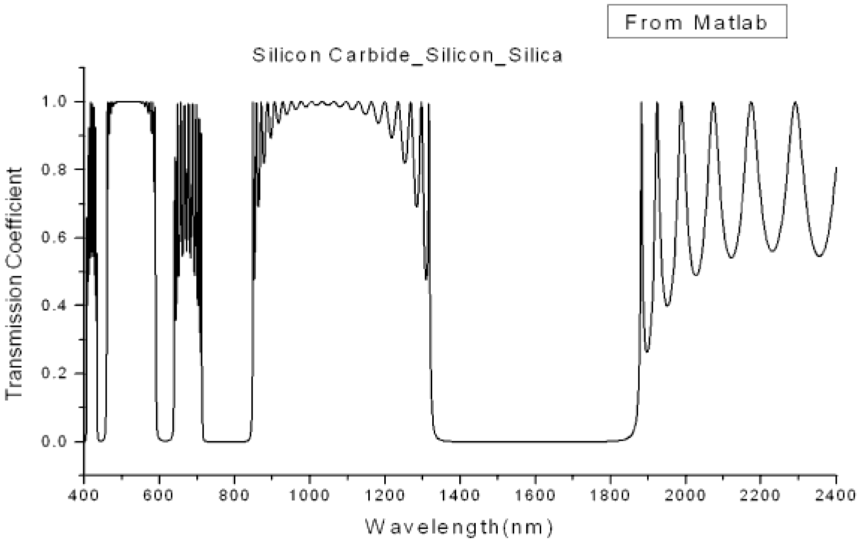

Fig7: Plot between Wavelength(nm) Vs. Trasmission Coefficient in case of Silicon Carbide_ Silicon_Silica based photonic crystal containing number of unit cells (N) = 10

Silicon Carbide_Silica_Silicon:

Here for Silicon Carbide, Silica and Silicon the value of n_1 for Silicon Carbide is 2.55 and the value of n_2 for Silica is 1.5 and the value of n_3 for Silicon is 3.5, so by using equation (1) thickness of the first layer (d_1) = 1550/6*2.55 = 101.30 nm and thickness for the second layer (d_2) = 1550/6*1.5 = 172.22 nm and the thickness for the third layer (d_3) = 1550/6*3.5 = 73.809 nm.

In that case the Pass band lies in between 850 nm to 1320 nm (Approx), so the Pass band width is 1320 – 850 = 470 nm. From 1880 nm to investigate range 2400 nm (Approx) other Pass band lies. Here Stop band lies in between 1320 nm to 1880 nm (Approx), within this range transmission coefficient value is 0. Stop band width is 560 nm. Here Centre band gap lie is at 1600 nm (Approx), so our wavelength shift towards the high frequency range.

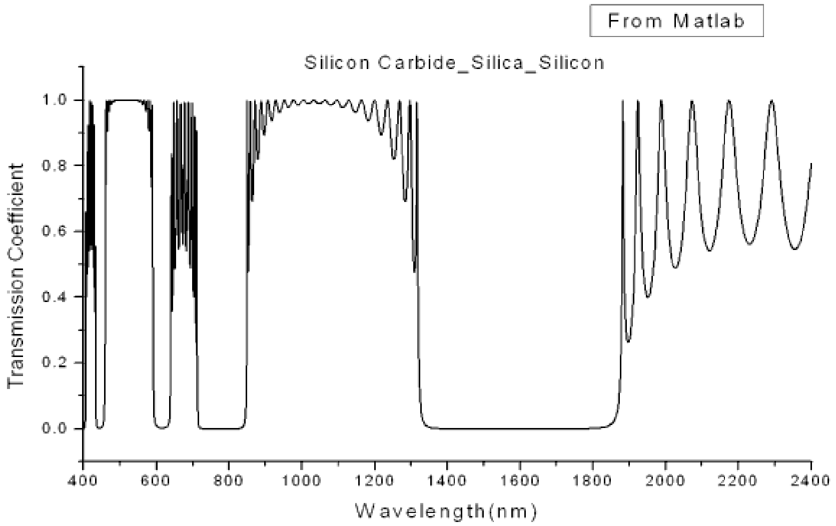

Fig8: Plot between Wavelength(nm) Vs. Trasmission Coefficient in case of Silicon Carbide_ Silica_Silicon based photonic crystal containing number of unit cells (N) = 10

Conclusion

By using each and every necessary equation regarding this Silicon Carbide based 1D photonic crystal which contain 3 layers unit cell we are now at the end of our task where several semiconductor material combination we are constructed where each layer containing their own refractive index. One thing is common in that process that Silicon Carbide is always be there in every 3-layer semiconductor material combination. After seeing all the results it has been clearly shown that whenever we are studying the semiconductor material combinations using 2- layer unit cell, there are some variations in stop band width, pass band width ,centre band gap etc in nanometer range(value wise) after light wave passing through that particular 2- layered unit cell with a wavelength of 1550nm.But in case of SiC based 1D photonic crystal with 3 layer unit cell there are no such variations in pass band width, stop band width and centre band gap value for different semiconductor material combinations, all are approximately same. So it can be concluded that when a light wave of a particular wavelength passes through a Silicon Carbide (SiC) based 1D photonic crystal with 3-layered unit cell, the characteristics of that wave remain almost same though in this paper material is varying time to time to construct different combinations. one thing must have to watch that whatever may be the combination one layer must be made of Silicon Carbide(SiC).Below table format shows clearly the values

Material	***Stop band width (nm) approx.***	***Pass band width (nm) approx.***	***Center band gap (nm) approx.***	***Deviation of wavelength w.r.t. 1550 nm.***
Silicon_Silicon Carbide_Silica	560	470	1600	50
Silica_Silicon_Silicon Carbide	560	470	1600	50
Silicon Carbide_Silica_Silicon	560	470	1600	50
Silica_Silicon Carbide_Silicon	560	470	1600	50
Silicon_Silica_Silicon Carbide	560	470	1600	50
Silicon Carbide_Silicon_Silica	560	470	1600	50

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