American Journal of Electronics & Communication

Sohom Chakraborty et. al., American Journal of Electronics & Communication, Vol. II (2), 19-22

A high temperature optical filter using Si/Si_3N_4 one dimensional photonic crystal for GaSb thermophotovoltaic applications

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Abstract— **Photonic crystals (PhCs) can control the light flow in certain directions and it can be used for different applications. Specific type of 1D PhC can be used in Thermophotovoltaic systems (TPVs), where PhC can act as an optical filter and can enhance the efficiency of the TPV system. In this work, GaSb is used as a semiconductor convertor in TPV system. The 1D PhC (Si/Si_3N_4) optical filter reflects the photons whose wavelengths lie in the photonic bandgap range while transmits the photons which lie in its passband range. The reflected photons go back to the radiator for recycling and the transmitted photons go to the GaSb semiconductor convertor. Use of Si_3N_4 has been proposed due to its excellent thermal shock absorbing capability and high temperature applications. In this study, the thicknesses of Si layers and Si_3N_4 layers are considered as 145 nm and 200 nm respectively. The designed PhC optical filter has a stopband in the range 1788 nm to 2233 nm which corresponds to the bandgap of GaSb. The designed filter has a passband in the range of 991 nm to 1788 nm which makes it transmit the above bandgap photons to GaSb. The passband also makes it suitable for use in other optical communication applications.**

Keywords*— *Photonic crystals, Thermophotovoltaic systems, Multilayered structure

I. Introduction

Photonic crystals present an excellent way to control the flow of light as they possess the potential to create photonic band gaps [1]. The periodic potential in a semiconductor crystal is replaced by periodic dielectric function.[1] Due to the periodic array of dielectric materials photonic band gaps are created in a photonic crystal [1]. Hence, photonic crystals allow only certain range frequencies to pass through and block others. This characteristic feature of a photonic crystal makes it a potential candidate for use as optical filters. Thermophotovoltaics (TPVs) convert thermal radiation from a man-made high temperature source into electricity by photovoltaic cells [2-5]. Most TPVs employ GaSb as a semiconductor convertor [3]. Since the temperature of the radiator lies in the range of 1200-1800 K, the porton of the total radiated power that lies above the band gap of GaSb is extremely low. This results in poor efficiency in the overall system [2-5]. The efficiency of a TPV is proven to have been improved by the use of an optical filter which reflects the photons which lie beyond the bandgap of the semiconductor convertor back to the radiator to recycle and the photons which lie above the bandgap of GaSb are transmitted [2,4,5]. In this paper we propose to design an optical filter using Si/Si3N4 1D photonic crystal at normal incidence. Quarter wave stack concept has been used to maximize the bandgap. [1] Although, Si/SiO2 1D photonic crystals have proven to be the most promising candidates for thermophotovoltaic application [2,4,5] use of Si_3N_4 is proposed as it is an excellent thermal shock absorber and has high temperature applications [6]. Moreover, there has been interest in Si_3N_4 as an optical coating [7]. The designed 1D crystal blocks 1788 nm to 2233 nm wavelengths which mainly involves the low energy photons which do not produce excitation in the GaSb convertor since the bandgap of GaSb is 0.7 eV which corresponds to nearly 1780 nm wavelength. These photons are reflected back to the radiator for recycling. Literature suggests that practically the radiator emits photons upto the range of 2000 nm [4,5]. Additionally, the designed photonic crystal has a passband in the range of 991 nm to 1788 nm which makes it suitable for use in optical communication at 1550 nm wavelength. The 1D photonic crystal can be used as an infrared monochromator to select a small range of wavelength from a broad spectrum of wavelength. The paper has been divided into 7 sections. Section 1 gives an introduction to the problem, section 2 and 3 develops the theoretical background, section 4 illustrates the structural parameters and justifies them, section 5 represents a block diagram of the operating system, section 6 deals with results and discussions. Section 7 concludes the paper.

II. THEORETICAL BACKGROUND

Our aim in this paper is to compute the band diagram of a 1D photonic crystal in order to understand the range of frequencies that are allowed to pass through the photonic crystal and those that are stopped by the crystal. In order to accomplish this task we take the help of plane wave expansion method. Plane wave expansion method is the most extensively studied and one of the most popular method to study the propagation of wave through a periodic dielectric structure [9]. The plane wave expansion method is used to compute the eigen frequencies of a photonic crystal and uses Maxwell's equations as a starting point since Maxwell's equations regulate the behaviour of electromagnetic waves in any media. We assume that the medium is source free and perfect dielectric material [9].

Taking all these assumptions into account, Maxwell's equations in time harmonic fields reduce as [1]:-

$$\nabla.\vec{H}(r) = 0 \qquad (1)$$

$$\nabla \times \vec{E}(r) = i\omega\mu_0\vec{H}(r) \qquad (2)$$

$$\nabla.\left(\varepsilon(r)\vec{E}(r)\right) = 0 \qquad (3)$$

$$\nabla \times \vec{H}(r) = -i\omega\varepsilon\vec{E}(r) \qquad (4)$$

where, $\vec{H}$= Magnetic field intensity

$\vec{E}$= Electric field intensity

ε=$\varepsilon_0\varepsilon_r$=absolute permittivity

ε_0=permittivity of free space

ε_r= relative permittivity

μ_0=permeability of free space

ω=eigen frequency

We make an attempt to decouple the electric and magnetic fields by solving for the electric field and magnetic field to generate the master equation in terms of magnetic field [1].

$$\nabla \times \frac{1}{\varepsilon(r)} \nabla \times \vec{H} = \frac{\omega^2}{c^2}\vec{H}(r) \qquad (5)$$

III. 1D PHOTONIC CRYSTAL

1 Dimensional Photonic Crystals have periodicity only along one specific direction. The plane wave expansion method can be extended to the 1D photonic crystal. 1D photonic crystals are the simplest of all types of photonic crystals and they are easy to manufacture [9]. Figure 1 below shows the axes which will help us to find out the direction of propagation of the waveforms.

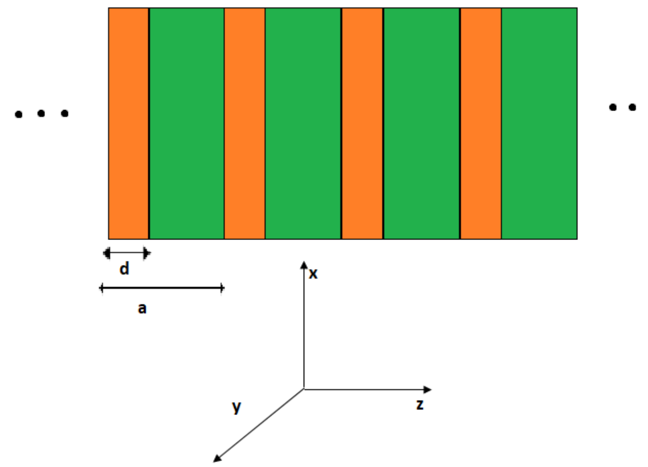

Figure 1: One-dimensional photonic crystal consisting of dielectric layers of thickness d with periodicity a.

If we consider the master equation 5 in one dimension then the equation will reduce to:

$$\frac{\partial}{\partial x}\frac{1}{\varepsilon(x)}\vec{H}(x) = \frac{\omega^2}{c^2}\vec{H}(x) \qquad (6)$$

The solution to equation 6 will help us to compute the eigen frequencies ω which will help us to plot the photonic band diagram. Now, we perform the fourier series expansion of the inverted dielectric function and the magnetic field to find the solution of the equation 6.The expansions result in the following equations [10]:

$$\frac{1}{\varepsilon(x)} = \sum_{G'' \in G} \chi(G'')\, e^{jG''x} \qquad (7)$$

$$H(x) = h_{k,n}(G)e^{j(k+G)x} \qquad (8)$$

where, $\chi(G'')$= fourier series coefficient for $\frac{1}{\varepsilon(x)}$

$h_{k,n}$= fourier series coefficient for magnetic field

k= wave vector

G= reciprocal lattice vector

Note that the representation of equation 8 is in accordance with Bloch theorem where a field vector can be represented in the form of a plane wave modulated by a periodic function whose period corresponds to the period of the dielectric material [1].

Substituting all the values from equation 7 and equation 8 equation 6 we get, the equation takes the final form [10]:

$$-\sum_{G'} \chi(G-G')\big((k+G')(k+G)\big)h_{k,n}(G') + \frac{\omega^2}{c^2}h_{k,n}(G) = 0$$

The above equation can be referred to as equation 9.

where , G=G'+G'' [10]

Equation 6 can be reduced to an N*N matrix by truncating fourier components symmetrically about zero. The set of N*N matrices will give the eigen frequencies.

IV. STRUCTURAL PARAMETERS AND CALCULATION

Our target is to set a stopband in the range where low energy photons will be reflected, hence the left stopband edge was chosen to be approximately 1780 nm. Numerically, the central wavelength was calculated to be 2000 nm. The layer thickness of Silicon and Silicon nitride was calculated using the concept of quarter wave stack because it maximizes the photonic band gap [1]. The thickness of the layers correspond to one-fourth of the central wavelength. The central wavelength and the layer thickness can be calculated as [4]:

$$\lambda_0 = \frac{1}{1 - \frac{2}{\pi}\sin^{-1}\left(\frac{n_H - n_L}{n_H + n_L}\right)}\lambda_g \quad (10)$$

$$d = \frac{\lambda_0}{4n} \quad (11)$$

where, $n_H(Si)$= 3.47 [8] and $n_L(Si_3N_4)$= 2.45 [8], λ_g (wavelength gap of GaAs)= 1780 nm, λ_0=central wavelength and d= thickness of an individual layer. Using equation 10, the central wavelength was calculated as 2000 nm. The thickness of each layer has been calculated from equation 11. The calculated thickness of Si layer (d_1) is 145 nm and the thickness of Si_3N_4 (d_2) is 200 nm.

Here Lattice constant (a) = d_1+d_2= 345 nm.

$\frac{d}{a}$ ratio has been calculated to be 0.42 where d has been considered to be the thickness of the Silicon layer.

V. BLOCK DIAGRAM

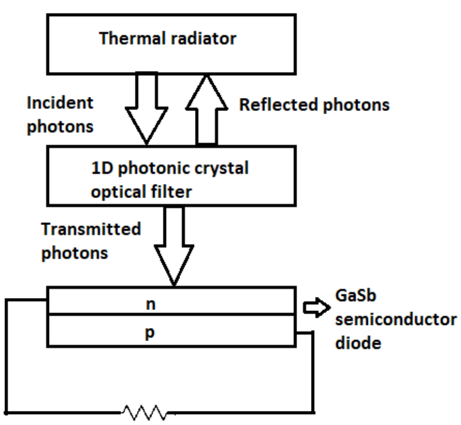

Figure 2: Schematic diagram showing the operation of the 1D photonic crystal optical filter

The above block diagram gives a basic understanding of the working of the 1D optical filter. Solar energy heats up the thermal radiator and it is the thermal radiator which releases this absorbed heat energy in the form of photons [3]. All the photons emitted from the radiator do not carry the same amount of energy. Photons having greater wavelength have lower amount of energy and photons having smaller wavelength have higher amount of energy as per the well known energy relation:

$$E = \frac{hc}{\lambda} \quad (12)$$

where, h=Planck's constant, c=speed of light, λ=wavelength of light and E= energy of radiation

When the photons are emitted from the thermal radiator on the 1D photonic crystal optical filter there are two possibilities:-

i. Photons whose energies lie in the photonic bandgap of the crystal are reflected back to the thermal radiator for re-heating the radiator. This increases the efficiency of the system.

ii. Photons whose energies lie in the passband range of the crystal are allowed to pass through the crystal to the GaSb photodiode for producing electrical excitation in it.

The photonic bandgap has been tailored in such a way so as to pass only the photons with higher energy (or lower wavelength) which can cause electrical excitation in the GaSb semiconductor diode while reflecting those which do not lie in the photonic bandgap. The photonic bandgap is a function of the material thickness and the refractive index of the 1D photonic crystal.

VI. RESULTS AND DISCUSSION

Based on the input parameters, simulation was carried out to compute the band diagram of the desired 1D photonic crystal that would serve as a high temperature optical filter owing to the presence of silicon nitride in it. The photonic diagram was computed using the plane wave expansion method [9] developed in section II and III.

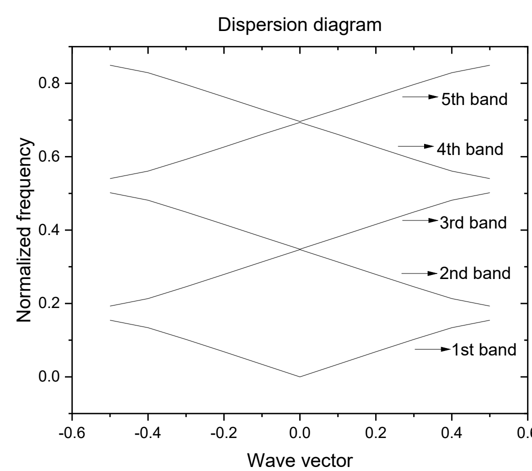

Figure 3: Dispersion diagram of the 1D photonic crystal

The above photonic band diagram shows the arrangement of different bands where the bandgaps are clearly visible between each bands at the Brillouin zones. We are utilizing the photonic bandgap between band 1 and band 2 for reflecting the photons incident on the filter. The x-axis represents the wave-vector which is normalized to $\frac{ka}{2\pi}$ and the y axis shows normalized frequency $\frac{\omega a}{2\pi c}$.

From the band diagram it was calculated that the photonic bandgap between the first and the second band is 1788 nm to 2233 nm which corresponds to the low energy photons that cannot produce electrical excitation in GaAs. The second band has a passband range of 991 nm to 1788 nm which can easily pass the high energy photons to the GaSb semiconductor converter. From the above band diagram it becomes clear that the designed 1D photonic crystal can efficiently work as a spectral filter.

VII. CONCLUSION

In this paper we have designed a 1dimensional photonic crystal filter using Si/Si_3N_4 as the constituent materials. Si_3N_4 has been introduced as an alternative since it has lot of applications at higher temperatures [6,7]. The designed photonic crystal is used as an optical filter in thermophotovoltaic systems to reflect the incident photons of lower energy back to the thermal radiator for recycling and transmit the high energy photons to a GaSb semiconductor convertor for producing electrical excitation. The filter in a way increases the efficiency of the system by not allowing all possible wavelength photons to be incident on the GaSb semiconductor convertor which cannot produce electrical excitation in it. It only allows those photons whose energies are sufficient to produce electrical excitation in the GaSb material. Introduction of Si_3N_4 adds to the reliability of the system. Simulation results show that the designed filter is a suitable candidate for use as an optical filter in thermophotovoltaic applications.

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