Production of Intensifying Blue Light by Cherenkov Radiation Phenomena and Their Use as Power Source Applications

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Production of intensifying blue light by Cherenkov radiation phenomena and their use as power source applications

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Abstract

It is interesting to note in recent years for a large number of researchers the topic of photonic crystals (PhCs) because of their new and useful properties. In addition, there are many advantages to photonic crystals materials as a high reflectance materials as well as the high transmittance materials based on the target application. The calculations were done for Aluminum oxide and titanium oxide ($\text{Al}_2\text{O}_3/\text{TiO}_2$) composite photonic crystal in one dimension, which shows a high reflectivity ($\sim 99\%$). The chosen photonic crystal composite can be useful to reflect the Cherenkov light many times which comes out from Cherenkov radiation by using radioisotope ^{90}Sr - ^{90}Y . The output intensified light has power 1.45 μwatt and 1.45 nwatt for ^{90}Sr - ^{90}Y with the activity 1Ci and 1mCi respectively, that can be used for micro/nano-power source applications.

Keywords: blue light; Cherenkov radiation; PhCs; reflectance; Transmittance

1. Introduction

Recently photonic crystals have great importance in many applications, thanks to the periodic structure of different materials which forming a specific band gap, the optical properties like reflectivity and transmission could be improved.^[1,2] Cherenkov radiation is interesting phenomenon to

act as a detector for charged objects using light emission to measure the velocity of the beta particle and used in various applications. Cherenkov counters can be used in nuclear physics detectors and accelerators as well as in nuclear reactors, cosmic rays, particle astrophysics, biomedicine and biological molecules^[3].

Photonic crystals (PCs) feature is due to the interaction of electromagnetic waves propagations with the matter which has the contrast in refractive index. Also, the structure arranged periodically in one, two and three dimensions using artificial materials.^[4] The unique feature of PCs is photonic band gap (PBG) which appears and controls the electromagnetic waves as well as makes photon localization easy which is of great importance in the optical and photonic communities^[5]. PBGs are prohibited frequency regions that offer an efficient control on the electromagnetic waves propagation because of the destructive interference at the interfaces of the constituent materials.^[6]

Photonic crystals structure of high reflectivity and high transmittance were designed using a periodic structure of different materials. Cherenkov radiation makes several reflections by the designed PCs which lead to an increase in the intensity of the final beam. The beam is guided to a window made of materials that have a high light transmission to keep the outcome radiation passing without decreasing the intensity, and thus increase the blue light power.

We aim to fabricate a photonic crystal structure that works to reflect all the emitted Cherenkov photons and intensify the blue light produced by Cherenkov radiation phenomena, then all the intensified light passes without losing its energy through the window made from high transmittance photonic crystal which can be used for some applications.

One of these applications is to use the intensified photons as a micro/nano-watt power source.

1.1. Cherenkov radiations

Cherenkov radiations (CR) can producing if a charged particle travels within a transparent medium (liquid or solid) with a speed greater than the speed of light in the same medium^[7]. The CR can extend from ultraviolet (UV) to visible light which is their spectrum have a maximum at 420 nm^[8]. Thus, the radiation is within the detection range (with a maximum sensitivity at wavelength ~ 420 nm) of the photomultiplier tubes of a liquid scintillation counter (LSC). CR photon emission is due to the local polarization along the path of travel of the charged particle with the electromagnetic radiation emission when the polarized molecules return to their original states^[9]. The CR is propagated as a conic wavefront, Which are the radiation is emitted as a cone in the direction of particle travel^[10].

The measurement process of CR by LSC is called the Cherenkov counting technique. The energy threshold of a radionuclide for Cherenkov counting in water is 0.263 MeV^[8]. Thus, ^{90}Sr and ^{90}Y , with maximum beta energies of 0.546 MeV and 2.280 MeV, respectively, are above the threshold energy. Therefore, making the Cherenkov counting technique a convenient radionuclide testing technique. The threshold energy for Cherenkov production will change according to the medium refractive index and will be lower for media of higher index of refraction.

Some time they used^[11] employ the CR in the measurement of radioactivity and different applications, especially when CR are produced at significant levels. For the medical applications, therapeutic photon,

proton and gamma-ray beams can be obtained by measuring the intensities of Cherenkov radiations [12,13].

Cherenkov counting was carried out with 20-ml volume polyethylene plastic (1-mm wall thickness) and low-potassium borosilicate glass sample vials^[14].

2. Experimental suggestion

Bottle made from polyethylene containing water and trace amount of ⁹⁰Sr (⁹⁰Y) isotopes. β -particles travel in water with light production. Therefore, the light will incident on polyethylene of the bottle. The Cherenkov radiation is emitted in the forward direction of the Beta particles^[15].

The photonic crystal is located at polyethylene. Therefore, the medium is water and the substrate is polyethylene i.e water- photonic crystals – polymer. Using water- photonic crystals- polyethylene in the vial where the blue light emitted from Cherenkov process travels in water and incident on the PCs. One-dimensional photonic crystals materials consists of Aluminum oxide (Al_2O_3) and titanium oxide (TiO_2) with the periodicity, $N = 5$ which are used as a reflectors around the surface of the bottle in the system shown in Figure 1. These composite materials are characterized by high reflectivity for the target application. The intensify light is directed to the window made from high light transmission photonic crystal materials like Silicon dioxide SiO_2 / Silicon Nitride Si_3N_4 composite. Thus, the light is intensified and incident on top of the vial which has a high transmission PCs. Consequently, the intensified light gets out of the vial through the window.

Figure 1 Schematic diagram for intensified light production by Cherenkov Effect.

3. Theoretical Calculations

To calculate the matrixs at the interface between the proposed materials we have used the transfer matrix (TMM) which are used for studying the electromagnetic waves propagations in the current medium which was designed as a 1DPC described in Figure 2. We have used the MATLAB software to build the convenient code for our calculations and simulation, where reflectance and transmittance has been investigated with the photonic crystal design with wavelength range between 200-900 nm. The reflectance for 1DPC of $\text{Al}_2\text{O}_3/\text{TiO}_2$ composite was studied at a different incident angle (θ) of the incident light, many periods ($N = 5$) and different thickness of two materials (d_1, d_2). We assume that the Al_2O_3 refractive index is n_1 with thickness is d_1 . Also the TiO_2 refractive index is n_2 with thickness is d_2 . The transmittance for 1DPC of $\text{SiO}_2/\text{Si}_3\text{N}_4$ composite was studied at the normal incident ($\theta = 0^\circ$, $N=5$, the thickness and the refractive index of SiO_2 and Si_3N_4 are d_1, d_2, n_1 and n_2 respectively.

Figure 2 The n_1 and n_2 structures of $\text{Al}_2\text{O}_3/\text{TiO}_2$ composite in 1 DPC.

In the present analysis, we used TMM for the theoretical calculations ^[16]. The electromagnetic waves interaction with 1DPCs also treated by the characteristic matrix method where the interaction between the incident radiations and the present structure described by the following matrix:

$$M_{2 \times 2} = \begin{pmatrix} M_{11} & M_{12} \\ M_{21} & M_{22} \end{pmatrix} = D_0^{-1} (D_1 P_1 D_1^{-1} \quad D_2 P_2 D_2^{-1})^N D_s \quad (1)$$

This method treated our problem through multilayers along the x-direction and obtained using TMM.^[16] This method is based on the analysis of the electric field interactions with the structure along the specified direction in terms of the dynamical and propagating matrices for both TM and TE waves, where the dynamical (D) matrices can be written in the following form:

$$D = \begin{pmatrix} 1 & 1 \\ n \cos \theta & -n \cos \theta \end{pmatrix} \text{ for TE wave, } (2)$$

the propagation matrices (P) take the form:

$$P = \begin{pmatrix} \exp(iQ) & 0 \\ 0 & \exp(-iQ) \end{pmatrix}, \quad i = 1, 2, 3, \dots \quad (3)$$

The reflectance R and transmittance T are described by the following expression:

$$T = |t|^2 = \left| \frac{1}{M_{11}} \right|^2, \quad R = |r|^2 = \left| \frac{M_{21}}{M_{11}} \right|^2. \quad (4)$$

4. Results and Discussion

The direction θ of emitted CR obey the condition described in equation 5^[17],

$$\cos \theta = 1/n\beta \quad (5)$$

where n is the reflective index of the medium and $\beta = v/c$ is the relative phase velocity of the particle which can be calculated using equation 9.

Using equation 5 for ^{90}Sr (^{90}Y) [$\beta_{(0.546 \text{ MeV})} = 0.875$ and $\beta_{(2.284 \text{ MeV})} = 0.983$], respectively. The emitted Cherenkov radiation will be at angles $(\theta_{\max})_1 = 30.85^\circ$ and $(\theta_{\max})_2 = 40.1^\circ$ for their energies 0.546 MeV and 2.284 MeV, respectively. The possible angles of incident Cherenkov photons on the reflective materials which are designed by PCs can be calculated from the following assumption (equation 6),

$$\theta_{\text{incident}} = 90^\circ - \theta_{\max} \quad (6)$$

The values of incident angle (θ_{incident}) are about 60° and 50° for energies 0.546 MeV and 2.284 MeV, respectively. Our calculations focus to investigate the reflectance at angles 50° , 60° , 70° , 80° and 89° .

The reflectance spectra at different angles ($50^\circ - 89^\circ$) for our proposed photonic crystal structure were investigated as shown in Figure 3-7. The used parameters were refractive indices $n_1 = 1.43$ and $n_2 = 2.65$ of Aluminum oxide (Al_2O_3) and Titanium dioxide (TiO_2) respectively, the thicknesses of the layers were $d_1 = 150 \text{ nm}$ and $d_2 = 50 \text{ nm}$ for Al_2O_3 and TiO_2 respectively, and the periodicity for this composite was $N = 5$.

In Figure 3-7 we observed the calculated optical reflectance spectra for $\text{Al}_2\text{O}_3/\text{TiO}_2$ photonic crystal at different incident angles ($50^\circ - 89^\circ$) using

Cherenkov radiation. The obtained data based on the PC is calculated using TMM^[16].

At incident angle $\theta = 50^\circ$ the width of photonic band gap (PBG) is 425 - 818 nm with reflectivity of 99.88 % as shown in Figure 3, and at Figure 4 the incident angle is $\theta = 60^\circ$ in which the width of PBG becomes 375 - 780 nm with reflectivity 99.98 %.

Figure 3 Reflectance spectra at 50° incident angles of dielectric photonic crystal with $n_1 = 1.43$, $n_2 = 2.65$, $d_1 = 150$ nm, $d_2 = 50$ nm and number of periods $N = 5$.

Figure 4 Reflectance spectra at 60° incident angles of dielectric photonic crystal with $n_1 = 1.43$, $n_2 = 2.65$, $d_1 = 150$ nm, $d_2 = 50$ nm and number of periods $N = 5$.

However, there is a blue shift at $\theta = 70^\circ$ and the width of PBG is 323 - 748 nm with reflectivity 99.98% as illustrated Figure 5.

Figure 5 Reflectance spectra at 70° incident angles of dielectric photonic crystal with $n_1 = 1.43$, $n_2 = 2.65$, $d_1 = 150$ nm, $d_2 = 50$ nm and number of periods $N = 5$.

By increasing the incident angle of the electromagnetic waves at $\theta = 80^\circ$ we noted the photonic bandgap shifted to the less wavelength. As a result, the value of reflectance for $\text{Al}_2\text{O}_3 / \text{TiO}_2$ is very high and can be reached to 100% in the range of photonic bandgap 290 - 728 nm at angle $\theta = 80^\circ$ (Figure 6).

Figure 6 Reflectance spectra at 80° incident angles of dielectric photonic crystal with $n_1 = 1.43$, $n_2 = 2.65$, $d_1 = 150$ nm, $d_2 = 50$ nm and number of periods $N = 5$.

The incident angle affects the reflectance of the $\text{Al}_2\text{O}_3/\text{TiO}_2$ photonic crystal where increasing the incident angle of the electromagnetic waves causes an increasing the blue shift of the band gaps. As a result at angle $\theta = 89^\circ$ (Figure 7), the value of reflectance for $\text{Al}_2\text{O}_3 / \text{TiO}_2$ is very high and

can be reached to 100% in the range of photonic band gap from 270 - 715 nm.

Figure 7 Reflectance spectra at 89° incident angles of dielectric photonic crystal with $n_1 = 1.43$, $n_2 = 2.65$, $d_1 = 150$ nm, $d_2 = 50$ nm and number of periods $N = 5$.

Therefore, for all mentioned angles, we observed about 99% reflectivity was obtained by $\text{Al}_2\text{O}_3/\text{TiO}_2$ photonic crystal at a wide band of wavelengths 400 - 600 nm (Cherenkov photons wavelengths) for the present angles.

Due to the high reflectance of the current photonic crystals composite, the reflection of all possible photons emitted from Cherenkov radiation could be intensified at the output gate as depicted in Figure 1.

Table 1 shows the relation between incident angle of electro magnetic wave which produced from Cherenkov phenomena and shift wavelength, when the incidence angle increase photonic band gap blue shifted due to Brew-ster effect at the interface between low and high index layers.

Table 1: the wavelength values which are shifted at different incident angles

Incident angle (θ°)	Shift wave length(nm)
50°	425-818 nm
60°	375-780 nm
70°	323-748 nm
80°	290-728 nm
89°	270-715 nm

The intensified photons can pass easily through the gate made from a high transmittance photonic crystal Silicon dioxide SiO_2 / Silicon Nitride Si_3N_4 composite, which shows an excellent light transmission especially at wavelengths ranges 400 - 600 nm as shown in Figure 8.

Figure 8 Transmittance spectra for photonic crystal $\text{SiO}_2/\text{Si}_3\text{N}_4$ composite at $\theta=0$, $N=5$, $n_1=1.55$, $n_2=2.0167$, $d_1=20\text{nm}$ and $d_2=10\text{nm}$.

The used parameters for the periodic photonic structure described in Figure 9 were as following : refractive indices, $n_1 = 1.55$ and $n_2 = 2.0167$ of Silicon dioxide SiO_2 and Silicon Nitride Si_3N_4 respectively, the thicknesses of the layers were $d_1 = 20 \text{ nm}$ and $d_2 = 10 \text{ nm}$ for SiO_2 and Si_3N_4 respectively, and the periodicity for this composite was $N = 5$ and at normal incident $\theta=0^\circ$. Due to high transmittance, the intensified output beam will pass from the window side to the other side without losing its original power.

Figure 9 The n_1 and n_2 structures of $\text{SiO}_2/\text{Si}_3\text{N}_4$ composite in 1 DPC as a transmittance

4.1. Number of Cherenkov photons and power calculation

The total number of photons for each Beta $k(E)^{[13]}$ emitted can be calculated for the individual beta particle energy can be obtained using equations (7-9).

$$\beta = \sqrt{1 - \left(\frac{1}{E/511 + 1} \right)^2} \quad (7)$$

$$\frac{dk}{dx} = 2\pi\alpha \left(\frac{1}{\lambda_1} - \frac{1}{\lambda_2} \right) \left(1 - \frac{1}{n^2\beta^2} \right) \quad (8)$$

$$k(E) = \int_{E_{th}}^E \frac{dk}{dx} \frac{1}{\rho} \frac{dE}{dx} dE \quad (9)$$

Where $\beta = v/c$ and dk/dx is the number of photons per nm, α is the fine structure constant ($\alpha = 1/137$), n is the medium refractive index (water=1.333). Also, $\lambda_1 = 400$ nm and $\lambda_2 = 600$ nm are the lower and upper limit of the wavelength region for Cherenkov radiation, ρ is the

density of water (medium) which equal 1 g/cm³, dE/dx is the electron stopping power in water for the given energies ^[18,19] and E is the energy of incident beta particles.

From the calculations using the reported equations 7-9, the number of emitted photons for beta particle energies 0.546 MeV and 2.284 MeV are $k(E_1) = 18$ photons and $k(E_2) = 243$ photons, respectively.

Finally, the total number of photons emitted per second (n) from Cherenkov radiation of radioactive source ⁹⁰Sr of activity (A= 1 Ci) can be calculated using equation 10.

$$n = (k(E_1) + k(E_2)) * A \quad (10)$$

Consequently, the n-value was calculated and founded to be 9.66X10¹² photons/sec.

4.1.1 Power calculations

Equations 11 and 12 are used to calculate the total power of emitted photons from Cherenkov radiation by radioactive source ⁹⁰Sr(⁹⁰Y) of activity (A = 1 Ci).

The energy of Cherenkov emitted photon of wavelength $\lambda = 420$ nm can be calculated from equation 11 and the energy is $E = 4.73 \times 10^{-19}$ Joule.

$$\bar{E} = hv = h \frac{C}{\lambda} \quad (11)$$

Where $\bar{E}$ is average energy, h is plank constant (6.625×10^{-34} J.sec), C is the speed of light = 3×10^{17} nm/sec and the photon wavelength is $\lambda = 420$ nm. Then, the total power was calculated using equation 12^[20] and the value was 4.52 μ Watt.

$$Power = n \times \bar{E} \times 0.99 \quad (12)$$

Where the value 0.99 is the reflectivity.

4.2. Cherenkov radiation as an electric power source

The intensified Cherenkov light may fall on the GaAs solar cell at the output gate as shown in Figure 10.

Figure 10 Schematic diagram for intensified light produced by Cherenkov effect and GaAs solar cell.

The spectral response of the GaAs was displayed by S. Mazzucato et al [21], where the results shows external quantum efficiency (EQE) 25 % - 55 % for wavelength range 400 – 900 nm as reported in the reference [20] . Also, the EQE of the GaAs device was reported 19% –74% at a wavelength range of 375 – 450 nm[22]. So the GaAs solar cell device is convenient for absorption of the Cherenkov light, but the more efficient device is the triple-junction solar cell which used for output power investigation.

The absolute efficiency of cell energy conversion (η)^[20]

$$\eta(\%) = \frac{P_{out}}{P_{in}} \quad (13)$$

Where P_{out} is the output power from the cell and P_{in} is the total power. For the mentioned GaInP/GaAs/ Ge solar cell, where the input power (P_{in}) 4.52 μ watt, the output power (P_{out}) was found 1.45 μ watt. If used small activity for the radioactive source $^{90}\text{Sr}(^{90}\text{Y})$, $A=1$ mCi, then the output power was found 1.45 nwatt. Applications for output micro/nano-watt power source are nuclear batteries^{[20],[23],[24],[25]}, medical instrumentation systems, scientific and engineering instruments, and also radio and radar receivers^{[26],[27],[28]}.

5. Conclusions

Reflective layers made by using PCs in a one-dimensional array consists of $\text{Al}_2\text{O}_3/\text{TiO}_2$ which were used as reflectors in the vial in the Cherenkov system to intensify the light. The reflectivity of this array reached 100% in Cherenkov wavelength (400-600nm) at different incident angles (50°-89°). Many reflections are useful to intensify the Cherenkov light which passes through the window made from high transmittance PCs in 1D ($\text{SiO}_2/\text{Si}_3\text{N}_4$). These layers are located on the wall of the vial from polyethylene. This system helps to intensify the blue light produced from Cherenkov radiation. The intensified light has power equal (1.45 μ watt/1.45 nwatt) which can be used for micro/nano-power source applications.

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Figures

Figure 1

Schematic diagram for intensified light production by Cherenkov Effect.

Figure 2

The n_1 and n_2 structures of Al₂O₃/ TiO₂ composite in 1 DPC.

Figure 3

Reflectance spectra at 50o incident angles of dielectric photonic crystal with $n_1 = 1.43$, $n_2 = 2.65$, $d_1 = 150$ nm, $d_2 = 50$ nm and number of periods $N = 5$.

Figure 4

Reflectance spectra at 60o incident angles of dielectric photonic crystal with $n_1 = 1.43$, $n_2 = 2.65$, $d_1 = 150$ nm, $d_2 = 50$ nm and number of periods $N = 5$.

Figure 5

Reflectance spectra at 70o incident angles of dielectric photonic crystal with $n_1 = 1.43$, $n_2 = 2.65$, $d_1 = 150$ nm, $d_2 = 50$ nm and number of periods $N = 5$.

Figure 6

Reflectance spectra at 80o incident angles of dielectric photonic crystal with $n_1 = 1.43$, $n_2 = 2.65$, $d_1 = 150$ nm, $d_2 = 50$ nm and number of periods $N = 5$.

Figure 7

Reflectance spectra at 89o incident angles of dielectric photonic crystal with $n_1 = 1.43$, $n_2 = 2.65$, $d_1 = 150$ nm, $d_2 = 50$ nm and number of periods $N = 5$.

Figure 8

Transmittance spectra for photonic crystal SiO₂ /Si₃N₄ composite at $\theta=0$, $N=5$, $n_1=1.55$, $n_2=2.0167$, $d_1=20$ nm and $d_2=10$ nm.

Figure 9

The n_1 and n_2 structures of $\text{SiO}_2/\text{Si}_3\text{N}_4$ composite in 1 DPC as a transmittance

Figure 10

Schematic diagram for intensified light produced by Cherenkov effect and GaAs solar cell.