Improving the efficiency counting of Cherenkov detector by using high transmittance photonic crystal materials

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Received: 31 January 2022 / Accepted: 27 March 2022 / Published online: 9 May 2022 © The Author(s) 2022

Abstract
In this study, a new type of photonic crystal (PC) designed as a transmitter. The transmittance spectra of the one-dimensional (1D) photonic crystal which are consist of silicon dioxide/magnesium fluoride (SiO₂/MgF₂). We are simulated the results using different incident angles, and the results showed a high transmittance (99.5%) within the wavelength range of (200–700 nm). Simulations of two-dimensional (2D) photonic crystals were studied, as well as the transmittance values were investigated. As a transmitter, photonic crystals in a one-dimensional array of SiO₂ and MgF₂ with periodicities N = 5 were employed around the wall of the Cherenkov counter vial. The high transmittance of the SiO₂/MgF₂ PC allows Cherenkov light to pass without any losing in its initial incident intensity which improves the Cherenkov counting efficiency, which is utilized in a wide range of applications. By replacing the traditional polyethylene (generally used to fabricate the walls of the counter vial) with the high transmittance photonic crystal SiO₂/MgF₂ which is allow to the most of the emitted Cherenkov radiation to reach the photomultiplier tube without any losing in its way to the tube. Subsequently, the efficiency of the Cherenkov counter was improved. Comparing the counting efficiency for both the polyethylene and the SiO₂/MgF₂ photonic crystal, it was found that the counting efficiency will be increased by 15% in one-dimension and 9.5% in two-dimensions if the polyethylene walls of the vial were replaced by SiO₂/MgF₂.

Keywords Photonic crystals · SiO₂/MgF₂ · Cherenkov detector · Transmittance
1 Introduction

Cherenkov counters are employed in a variety of fields, including high-energy and nuclear physics detectors at particle accelerators and nuclear reactors; cosmic ray detectors, particle astrophysics detectors, and neutrino astronomy as well as in biomedicine for labeling certain biological molecules (Grupen 2012). We employed photonic crystals to improve the Cherenkov counting efficiency by utilizing a high transmittance photonic crystal material. Photonic crystals are of great importance in many applications because of the periodic structure of different materials that form a specific bandgap, optical properties such as reflectivity and transmittance can be improved (Grupen 2012; Aly and Eissa 2017).

Cherenkov radiation is creating when a charged particle moves faster through transparent media than the speed of light in that medium (Eissa and Aly 2014). Any transparent liquid or solid can be used as a medium. Cherenkov radiation has a continuous range of wavelengths stretching from the ultraviolet to the visible region, with a peak at approximately 420 nm (Cerenkov 1934). As a result, the radiation is within the detection range of a liquid scintillation counter photomultiplier tube (with a wavelength of maximum sensitivity of 420 nm) (LSC). Local polarization along the direction of light of the charged particle causes Cherenkov photon emission, which is followed by the emission of electromagnetic radiation when the polarized molecules return to their original states (L’Annunziata 2012). Cherenkov radiation has a conical wave front, which means it is released in the direction of particle movement as a cone (Gruhn et al. 1980).

The Cherenkov counting technique is utilized by the LSC to measure Cherenkov radiation. In water, the radionuclide’s energy threshold for Cherenkov counting is 0.263 MeV (Cerenkov 1934). As a result, $^{90}$Sr and $^{90}$Y are above the threshold energy, with maximum beta energies of 0.546 and 2.280 MeV, respectively. Thus, using the Cherenkov counting technique to test radionuclides is a viable option. The threshold energy for Cherenkov generation varies with the medium’s index of refraction and is lower for media with a greater index of refraction.

When Cherenkov radiation is produced in large quantities, it can be used to accurately detect radioactivity (Burden and Hieftje 1998). By detecting the intensity of Cherenkov radiation, therapeutic protons, photons, and gamma-ray beams can be created (Belcher 1953; Jang et al. 2012) with 20-ml capacity polyethylene plastic (1-mm wall thickness) and low-potassium borosilicate glass sample vials (Kyoung Won Jang 2014).

The interaction with the propagation of electromagnetic waves in which the refractive index changes periodically in one, two, and three-dimensions utilizing an artificial materials is the advantage of photonic crystals (PCs) (L’Annunziata and Passo 2002). Photonic band gaps (PBGs) and photon localization develop as a result of PCs, which are important in the optical and photonic worlds (Eissa and Aly 2013). PBGs are a frequency zones that provide effective control over the propagation of incident electromagnetic waves which are owing to destructive interference at the constituent materials’ interfaces (Aly et al. 2015). Periodic structures of several materials have been used to design the photonic crystals with good transmittance. Recently, PCs are wide spread in different applications owing to its ability for photons trapping such as energy harvesting (Aly and Sayed 2017, 2018; Aly et al. 2018), and wave guiding. In addition there are crucial applications in force sensors and precise measurements (Kippenberg and Vahala 2008), optomechanical interaction (Aspelmeyer et al. 2014) has piqued interest, and it allows a new platform for enabling on-chip manipulation of light propagation (Xiong and Wu 2018) because of an optomechanical crystal idea (Xiong et al. 2016).
In the present work, photonic crystal structures that can transmit all emitted Cherenkov photons and pass the blue light which are produced by Cherenkov radiation phenomena. All the light can pass through a wall made of a high-transmittance photonic crystal without losing its incident intensity, which can be used to improve the Cherenkov radiation counting efficiency. By replacing the traditional polyethylene of the vial walls with our photonic crystal SiO$_2$/MgF$_2$ composite, we can improve the efficiency by approximately 15% compared. The efficiency of the Cherenkov counter was improved based on photonic crystal materials. Comparing the counting efficiency for both the polyethylene and the SiO$_2$/MgF$_2$ photonic crystal, we found that the counting efficiency will be increased by 15% in one-dimension and 9.5% in two-dimension if the polyethylene walls of the vial were replaced by SiO$_2$/MgF$_2$ to polyethylene efficiency.

2 Experimental suggestion

Water and trace amounts of $^{90}$Sr ($^{90}$Y) isotopes were contained in a plastic bottle. With the generation of light, the $\beta$-particles pass through the water. As a result, the light strikes the polyethylene bottle. Cherenkov radiation is emitted by beta particles in the forward direction (Mietelski et al. 2005; El-Shemy et al. 2022).

A photonic crystal was used to cover polyethylene. Water serves as the medium, and polyethylene serves as the substrate, that is, a water-photonic crystal-polymer. In a vial containing water, photonic crystals, and polyethylene, the blue light emitted by the Cherenkov process travels through the water and strikes the photonic crystals material.

1D PCs is composed of multilayers having the form (AB)$^N$, where A is silicon dioxide (SiO$_2$), B is magnesium fluoride (MgF$_2$), and N is the number of periods as shown in Fig. 1. This structure is designed and optimized to achieve a high transmittance. Thus, the choice of these materials is made on the basis of low absorption and low refractive index with small low index contrast in the wavelengths of interest. Silicon dioxide (SiO$_2$) and Magnesium fluoride (MgF$_2$) as a low refractive index layer (1.45 & 1.37) respectively, are used in several applications owing to high transmittance (Butt et al. 2016). Also, we have studied the dispersion relation of each SiO$_2$ and MgF$_2$, and we get the results that, the refractive indexes of SiO$_2$ and MgF$_2$ are almost constant in the range of wavelengths from 400 to 1100 nm, therefore, satisfied by insert the refractive index as a single value (Malitson 1965; Tan 1998; Dodge 1984). MgF$_2$ photonic crystals are commonly used in solar cells because of their high transmittance. (Wan et al. 2016; Yu et al. 2020; Lu et al. 2020). Silicon dioxide (SiO$_2$) and magnesium fluoride (MgF$_2$) can be used in many fields such as protective multifunctional coatings (Mashtalyar et al. 2017), medical fields (Kao et al. 2011), biomedical applications (Tian and Liu 2015), optical coating fields (Zhang et al. 2019), antireflective coatings (Zuccon et al. 2014; Lin et al. 2011; Piao et al. 2019), surface corrosion resistance (Sarkar et al. 2020; Mashtalyar et al. 2020), and solar membrane distillation (Shin et al. 2020). These layers together are achieved a graded refractive index from the air for distillation water to verify high transmittance in the visible spectrum (Wang et al. 2012). Therefore, Owing to the high transmittance of the PCs employed, the light is transmitted through the wall of the vial without diminishing its incidence strength toward the two detectors.

The fabrication process of a periodic structure on a SU-8 photoresist is using a mass transport effect (Kang et al. 2006). There is one or two exposures of the sample to the two-beam interference pattern were applied to fabricate 1D/2D periodic structures. The
incident angle (θ) and the rotational angle (α) can be adjusted to obtain structures with different periods and shapes (Zhang et al. 2013; Wu et al. 2013). The further discussions about the fabrication process of each one and two-dimensional PCs are reported by Xiao Wu in 2013 (Wu 2013). In addition, the development of a uniform template and the thorough removal of the barrier layer are critical for the production of 2D PCs. We employed a combination of two-steps anodization and cathodic polarization. At 9 °C, the initial anodization step was carried out at 40 V in 0.3 M oxalic acid. Following the removal of the oxide layer, a second anodization was carried out for 10 min under the same conditions, followed by a barrier-thinning procedure. By using cathodic polarization and a pore widening method, the pore diameters were increased and the barrier oxide layer was totally eliminated. Cathodic polarization was carried out in a 0.5 M neutral KCl solution at 10 C for 10 min with a continuous applied voltage of 4 V, with the pore-widening process carried out in reference (Sharma et al. 2007).

Fig. 1  a Schematic diagram for transmitting light production by Cherenkov Effect in the LSC; b Schematic high transmittance photonic crystal
2.1 Theoretical calculations

In the proposed design shown in Fig. 1, we have used the Fig. 1b to getting a high transmittance photonic crystal (PhCs) to using in focusing the Cherenkov light in Fig. 1a. PCs in a one-dimensional array of Silicon dioxide (SiO₂) and Magnesium fluoride (MgF₂) with periodicity N=5 are employed as high transmittance around the bottle’s surface. The Cherenkov light is focused on a wall formed of photonic crystal materials with strong light transmittances, such as Silicon dioxide (SiO₂) and Magnesium fluoride (MgF₂). Due to the high transmittance PCs employed, the light will be transmitted through the wall of the vial without diminishing its incidence strength toward two detectors.

We will demonstrate a mathematical treatment with a simple one-dimensional photonic crystal structure to explore the propagation of electromagnetic waves through photonic crystal structures and identify the optical properties of these periodic structures (1DPC) as shown in Fig. 1b. The transfer matrix method (TMM) was used to analyze the incident electromagnetic radiation on this structure. For a both transverse magnetic (TM) and transverse electric (TE) waves, this method is based on the analysis of the electric field interaction within the structure along the specified direction in terms of dynamical and propagating matrices, where the dynamical (D) matrices can be written in the following form (Born and Wolf 1999; Aly and Hanafey 2011).

\[
D_m = \begin{pmatrix}
1 & 1 \\
\ n_j \cos \theta_j & -n_j \cos \theta_j
\end{pmatrix}
\text{For TE Waves}
\]

and,

\[
D_m = \begin{pmatrix}
\cos \theta_j & \cos \theta_j \\
\ n_j & -n_j
\end{pmatrix}
\text{For TM Waves}
\]

where \( j = 1, 2, 3, \ldots \)

while the propagation matrices (P) take the form:

\[
P_m = \begin{pmatrix}
\cos \varphi_m + i \sin \varphi_m & 0 \\
0 & \cos \varphi_m - i \sin \varphi_m
\end{pmatrix}
\]

where \( \varphi_m = \frac{2 \pi d_m}{\lambda} n_m \cos \theta_m, \ m = 1, 2, \ldots \)

The matrix characterizing the interaction between the incident electromagnetic waves and the structure and then will be obtained using the previous formulae for the dynamical and propagating matrices.

\[
M_{(a)} = \begin{pmatrix}
m_{11} & m_{12} \\
m_{21} & m_{22}
\end{pmatrix} = D_1 P_1 D_1^{-1} D_2 P_2 D_2^{-1}
\]

The elements \( m_{11}, m_{12}, m_{21}, \) and \( m_{22} \) were computed for TE waves, which can also be obtained for TM waves using the same analysis, and \( a = d_1 + d_2 \) is the lattice constant. Finally, we calculated the transmittance and reflectance using the following expressions:

\[
R = |r^2|,
\]
3 Results and discussion

The present results and discussions are presented in two stages: first, we study the optical properties of one-dimensional photonic crystals to obtain the optimum conditions for a high-transmittance structure. In the second part, we display the transmittance spectrum of two-dimensional photonic crystals composed of a cylinder hole of air with radius \( r \) that is repeated for \( N \) periods in a host material to be useful for our application.

3.1 One-dimensional photonic crystals

For our simulation, we used MATLAB software to analyze the transmittance and reflectance spectra of the proposed structure. Silicon dioxide (\( \text{SiO}_2 \)) and magnesium fluoride (\( \text{MgF}_2 \)) are the proposed structures in our study, with refractive indices of 1.45 and 1.37, respectively. To improve the counting efficiency of the Cherenkov counter, we employ a photonic crystal material with high transparency in this study.

The angle at which Cherenkov light emerges can be estimated using the following Eq. 7 (Frank 1960).

\[
\cos \theta = \frac{1}{n\beta}
\]

where \( n \) is the reflective index of the medium, and \((\beta) = \frac{\nu}{c}\) is the relative phase velocity of the particle, which can be calculated using Eq. 8.

\[
\beta = \sqrt{1 - \left(\frac{1}{E/511 + 1}\right)^2}
\]

Using Eq. 8 for \(^{90}\text{Sr} \) \(^{90}\text{Y} \) \([\beta \ (0.546 \text{ MeV}) = 0.875 \text{ and } \beta \ (2.284 \text{ MeV}) = 0.983]\), respectively. Cherenkov radiation emitted at the angles equal to \((\theta_{\text{max}})_1 = 30.85^\circ \) and \((\theta_{\text{max}})_2 = 40.1^\circ \) for energies of 0.546 and 2.284 MeV, respectively. The possible angles of incident Cherenkov photons on the reflective materials (photonic crystals) can be calculated using Eq. (9).

\[
\theta_{\text{incident}} = 90^\circ - \theta_{\text{max}}
\]

The values of the incident angle \((\theta_{\text{incident}})\) were approximately 50° and 60° for energies 2.284 MeV and 0.546 MeV, respectively. The transmittance at the angles of 50°, 60°, and 70° is the focus of our computations.

The transmittance of the \( \text{SiO}_2/\text{MgF}_2 \) composite at an incident angle of 50° is extremely high, as shown in Fig. 2, which reaches 99.5% for a wide range of wavelengths (0–800 nm).
Figure 3 shows that the transmittance of the SiO$_2$/MgF$_2$ composite is still high values (98.5\%) at the incident angle = 60° over a wide range of wavelengths (200–700 nm).

When the incident angle was 70°, as shown in Fig. 4, the transmittance of the SiO$_2$/MgF$_2$ composite was high (98\%) over a wide range of wavelengths (250–700 nm).

As a result of the high transmittance values over a wavelength range (200–700 nm) with different angles (50°–70°) using a photonic crystal of composite SiO$_2$/MgF$_2$ in a Cherenkov counting application, this composite can be employed to pass Cherenkov light to the detectors while maintaining its initial incidence intensity.

The counting efficiency of Cherenkov counters is improved by employing this high-transmittance photonic crystal (SiO$_2$/MgF$_2$) compared to the traditional polyethylene, where the counting efficiency could be increased by approximately 15%.

### 3.2 Two dimensional photonic crystals

Here, we devoted our results by using two-dimensional photonic crystals for the present application (Cherenkov detector) with high transmittance materials as shown in Fig. 5 for
Fig. 4 Transmittance spectrum at 70° incident angles of dielectric photonic crystal with $n_1 = 1.45$, $n_2 = 1.37$, $d_1 = 5$ nm, $d_2 = 10$ nm, and number of periods $N = 5$

Fig. 5 Transmittance spectrum for the considered 2D PCs as in p color figure. The considered structure is composed of cylinder air at the host material of MgF$_2$, where lattice parameter $(a) = 80$ nm, the radius of air cylinder $= 0.3$ a, and the number of periods $(N) = 7$

the normal incidence. Also, we study the effect of incident angle on the transmittance of the considered structure as shown in Fig. 6. We can notice in Fig. 5, the considered structure is composed of a cylinder hole of air with radius $(r)$ that is repeated for $N$ periods in a host material from MgF$_2$, where the lattice parameter $(a) = 80$ nm, the radius of the air
cylinder = 0.3 a, and the number of periods (N) = 7. Here, the structure is characterized by high transmittance in the wavelength range of 250 nm to 650 nm, and increasing the incident angle is inversely related to the transmittance of the structure, as shown in Fig. 6.

Table 1 show that the values of the transmittance percentage for the wavelength range of (200–700 nm), using the 1D photonic crystal at incident angles of θ = 50°, 60°, and 70°).

| Lambda (nm) | Transmittance % | θ = 50° | θ = 60° | θ = 70° |
|-------------|-----------------|---------|---------|---------|
| 200         | 99              | 97.5    | 91.3    |
| 250         | 98.9            | 97.3    | 92.5    |
| 300         | 98.8            | 97.6    | 93.9    |
| 350         | 98.9            | 97.9    | 95      |
| 400         | 99              | 98.2    | 96      |
| 450         | 99.1            | 98.5    | 96.6    |
| 500         | 99.3            | 98.7    | 97.2    |
| 550         | 99.4            | 98.9    | 97.6    |
| 600         | 99.5            | 99      | 97.9    |
| 650         | 99.53           | 99.2    | 98.2    |
| 700         | 99.6            | 99.3    | 98.5    |
The transmittance values were excellent (approximately 100%) for all the wavelengths and angles, which is essential for our application.

However, Table 2 shows the transmittance percentage using the 2D photonic crystal at the same wavelengths and angles of 1D. There is a fluctuation in the transmittance values at different wavelengths and angles, but the transmittance values are still high (80%–100%), especially in the wavelength range of 250–600 nm, which is sufficient to transmit the Cherenkov radiation.

The small decrease in the transmittance values for the 1D photonic crystals compared to the 2D one is due to the real fact of increasing the radiation absorption when using a 2D photonic crystal.

The present structures of one-dimensional PCs can be fabricated by using electron ion beams lithography (Watt et al. 2005; Tandon 1992) and spray pyrolysis. However, the two dimensional PCs can be fabricated by a variety of self-assembly masks, including anodic porous aluminum (Sai et al. 2006), spin-coated spheres (Sun et al. 2007, 2008), and evaporated Ag islands (Chang and Chen 2011). We aim to design a fundamental structure with a low cost and highly transmission property in visible spectrum as like a different published papers in photonic crystal fiber coupler and photonic integrated networks (Rohini Priya et al. 2016; Shanmuga Sundar et al. 2018).

### 3.3 Theoretical calculation of counting efficiency

To calculate the efficiency of counting, the area under the curve of the transmittance spectrum was measured for both the PC polyethylene and SiO$_2$/MgF$_2$ composite. From the calculations, an increase in the value of the area under the curve implies that the counting efficiency has improved.

Figure 7 show that the simulated results of the transmittance spectrum for polyethylene as a 1D photonic crystal which the thickness is 100 nm and refractive index is $n = 1.52$ at different incident angles (50°, 60°, and 70°). First, the area under the curve of the transmittance spectrum of polyethylene was calculated for the same angles separately, and then the average of the area under the curves for all angles was determined by using Eq. (10), and its value was approximately $A_{avg1} = 47,597$. Second, the

| Lambda (nm) | Transmittance % |
|-------------|-----------------|
|              | $\theta = 50^\circ$ | $\theta = 60^\circ$ | $\theta = 70^\circ$ |
| 200          | 29              | 34              | 30              |
| 250          | 100             | 99              | 99              |
| 300          | 99              | 99              | 93              |
| 350          | 99              | 99              | 97              |
| 400          | 99              | 90              | 68              |
| 450          | 93              | 88              | 68              |
| 500          | 93              | 78              | 51              |
| 550          | 100             | 99              | 96              |
| 600          | 88              | 99              | 67              |
| 650          | 80              | 64              | 39              |
| 700          | 85              | 65              | 39              |
transmittance spectra of SiO$_2$/MgF$_2$ were simulated by replacing polyethylene with a photonic crystal (SiO$_2$/MgF$_2$) and utilizing the same thickness and angles. The average of the area under the curves for the various angles was then determined using Eq. (10), which is $A_{avg2} = 54,799$.

$$A_{avg} = \frac{A_{\theta=50^\circ} + A_{\theta=60^\circ} + A_{\theta=70^\circ}}{3}$$  \hspace{1cm} (10)

where $A_{avg}$ average of the area under curves.

$$\epsilon = \frac{A_{avg1}}{A_{avg2}} \times 100,$$  \hspace{1cm} (11)

where $\epsilon$ is the counting efficiency, and $A_{avg1}$ and $A_{avg2}$ are the averages of the area under the curve for composite (SiO$_2$/MgF$_2$) and polyethylene, respectively.

The results obtained by using Eq. (11) and showed that the present 1D photonic crystal improves the efficiency by 15%. Here, we can say that the counting efficiency of the Cherenkov counter was improved when utilizing a high-transmittance photonic crystal material (SiO$_2$/MgF$_2$) instead of polyethylene. Similarly, we calculated the efficiency in 2D photonic crystals as shown in Fig. 8, which equals 9.5%.

Finally, we can say that, by replacing the traditional walls (polyethylene) of Cherenkov counter by photonic crystals in each 1D and 2D photonic crystals can enhance the optical properties of Cherenkov radiation. Wherein, the highly transmission structures allows Cherenkov light to pass without losing its initial incident intensity to reach the photomultiplier tube without losing its way to the tube. Therefore, the PCs are considered as a promising point in the field of Cherenkov counter.

The efficiency of the Cherenkov counter was improved. Comparing the counting efficiency for both the polyethylene and the SiO$_2$/MgF$_2$ photonic crystal, it was found that the counting efficiency increased by 15% in one-dimension as well as 9.5% in the case of two-dimension if the polyethylene walls of the vial were replaced by SiO$_2$/MgF$_2$. 

Fig. 7 transmittance spectra in 1D at incident angle 50°, 60°, and 70° of polyethylene as a photonic crystal at $n = 1.52$, $d = 20$ nm, and the number of periods $N = 5$. 

![Transmittance Spectra](image)
Conclusion

Using a high transmittance photonic crystal (SiO$_2$/MgF$_2$) composite with a periodicity of N = 5 instead of polyethylene increased the counting performance of the Cherenkov detector by approximately 15%. The transmittance spectra for the wavelength range (200–700 nm) were simulated for both the polyethylene as a photonic crystal and SiO$_2$/MgF$_2$ composite at angles of 50°, 60°, and 70°, and it was found that the transmittance values were high, especially when using the SiO$_2$/MgF$_2$ photonic crystal, which is useful for some applications such as Cherenkov radiation counting. Simulations of the transmittance for 1D and 2D photonic crystals were investigated, and it was found that the transmittance values were sufficiently high enough (85–99.5%) in the wavelength range (300–600 nm) using the 1D and 2D photonic crystals for the Cherenkov radiation transmittance, to enhance the counting efficiency. Comparing the counting efficiency of the photonic crystals polyethylene and SiO$_2$/MgF$_2$, by using the area under the curve method, we can improve the counting efficiency by 15% in 1D and 9.5% in 2D with replacing the traditional polyethylene by SiO$_2$/MgF$_2$ composite. The vial wall is made up of a transmittance photonic crystal layer; this system will aid in transmitting the light of Cherenkov without losing incidence intensity, potentially improving counting efficiency.

Fig. 8 transmittance spectrums for the considered 2D PCs. The considered structure is composed of cylinder air at host material of polyethylene, where a lattice parameter (a) = 80 nm, the radius of air cylinder (r) = 0.3 a, number of periods (N) = 7, and at a different incident angle.
Funding
Open access funding provided by The Science, Technology & Innovation Funding Authority (STDF) in cooperation with The Egyptian Knowledge Bank (EKB). The authors declare no Fund. Availability of data, code, and material Requests should be addressed to any author.

Declarations

Conflict of interest
The authors declare no conflicts of interest.

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