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Realization of attenuator and amplifier using photonic crystal fiber

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Abstract

The present paper realises the attenuator and amplifier of electromagnetic signals with silicon-based, square-type photonic crystal fiber. In this research, the input signal varies from 30 eV to 30,000 eV, which lies within the x-ray regime. The operational mechanism deals with the electric field distribution in the structure, which is carried out using the plane wave expansion technique. The numerical outcomes affirm that the increasing and decreasing amplitudes of incident signals occur at the output end of the fiber. The intrinsic mechanism of such an interesting result is nonlinear properties of field distribution at a different value of lattice spacing and the diameter of the proposed fiber's air holes. Finally, the immediate upshot's outcome resembles the amplifier and attenuator about the optical system.

Keywords: - Photonic crystal fiber; Attenuator, Amplifier; Electric field distribution; Plane wave expansion method

1. Introduction

Research on the 2-D photonic structure is a hot arena nowadays due to many exciting applications that have been realised about the current research scenario in optical technology. Moreover, it is found that a 1-D photonic structure has attained a mature stage because of its possible fabrication [1]. However, a 3-D photonic structure is in the infant stage now because of suffering from fabrication feasibility [2]. Therefore, the maximum amount of research work has been focusing on a 2-D photonic crystal structure. Further, the best example for the same is photonic crystal fiber [3]. Though research on photonic crystal fiber has been started before two decades only, many works have been concentrated on different exciting applications. However, recently, with crystal fiber's help, various claims relating to biomedical sensing, computer networking, environment, and communication have been proposed [4-9]. For example, Ref. [4] deals with the computation of human hemoglobin, where Ref. [5] measures potassium chloride concentration using a similar type of structure. Similarly, optical computer memory application can be realised through the Ref. [6]. Further photonic crystal fiber-based UV light torch is proposed in the Ref. [7], which could solve the problem related to the contamination of germs in the water. Again Ref. [8] and Ref. [9] deals with the optical MUX/ DEMUX and transmitter, receiver application. Pressure sensing of 1D photonic crystal for quantum well structured has been thoroughly discussed [10]. Nevertheless, the above said research deals with different noteworthy forms. The present work bestows a new type of claim with the help of square type photonic crystal fiber. When X-ray signal incident to the photonic crystal fiber, the output signals will have either less or more energy than the input energy. So we can say that if the energy of the output signal will be less than the input signal, then the phenomenon is called demodulation, which attenuates the input signal (fiber is said to be attenuator). On the other hand, suppose the output signal will be more energy than the input signal. In that case, the phenomenon is called modulation, which amplifies the input signal (fiber is said to be an amplifier). To understand the same in better ways, we discuss the working principle in section 2. The general mathematical formulation is mentioned in section 3, where section 4 discusses the result and discussion. Finally, the conclusion part of the work is presented in section 5.

2. Working principle

This research aims to increase and decrease the amplitude of energy related to the input signal. That means the value of output energy would be either decreased or increased by the proposed optical fiber. For example, the input energy of the x-ray regime is incident to the proposed structure, and then emerging signal from the fiber would have less or more energy, which refers to the attenuating or amplifying the signal as compared to the input energy. The proposed optical fiber structure is shown in Fig. 1.

Fig.1.Schematic diagram of (a) photonic crystal fiber, (b) internal structure of photonic crystal fiber and (c) Mechanism to realise the attenuator and amplifier.

In Fig.1(a), it is seen that photonic crystal fiber with a square type structure. Further, in Fig. 1(b), there are 24 numbers of air holes have been arranged regularly in such a way that the central region is realised through as defect because of not appearing of air holes in the middle. Moreover, the background material of the same is considered as silicon. The reason for choosing such material is that a silicon-based optical circuit will be compatible with the optoelectronic circuit. The size of the structure varies as per the desired output (whether output energy is more or less than input), which is discussed in the result and interpretation section. Further focusing the operational mechanism, high energy of 30 eV to 30,000 eV is applied to the aforementioned photonic crystal fiber, and the fiber is designed in such a way that it will either alleviate or aggravate to the input counterpart. As far as the intrinsic mechanism of this research is concerned, the configuration of the proposed photonic structure, such as lattice constant of structure and radius of air holes play a vital role because the output results differ from different structure parameters, which is clearly realised in the result and interpretation section. As far as the internal mechanism is concerned, the transportation of electric field distribution in the photonic crystal fiber determines the emerging signal from the proposed fiber that appeared at the output end. To realise the same in a better way, let us focus on the following diagram, Fig. 1(c), which shows the complete information.

Here the energy of 30 eV to 30,000 eV incidents to the proposed silicon-based photonic crystal fiber, then the structure is designed in such a way that it will either enhance or reduce its energy, and this increasing or decreasing of energy shall appear at the output end of the fiber. Such impressive result is possible due to the nonlinear properties of the proposed fiber pertaining to the electric field distribution. Before going to analyzes the mathematical formulation relating to the generation of the filed distribution in the fiber, let us concentrate on the coupling efficiency between source to the fiber, and it can be written as [11]

$$\eta = \eta_g \times \eta_a \times \eta_r, \quad 1(a)$$

η_g , η_a and η_r are coupling efficiency between source and fiber concerning geometry, reflection, and angular factor. The values of η_a would be '1' as the size of the source is less than the proposed photonic crystal fiber. Similarly, the η_r depends on the following expression as

$$\eta_r = \frac{4RI_{\text{substrate}} \times RI_{\text{airhole}}}{RI_{\text{substrate}} + RI_{\text{airhole}}} \quad 1(b)$$

Putting the reference of the substrate silicon(3.6) and air holes, the $\eta_r = 90\%$. Further, the angular coupling efficiency factor can be written as

$$\eta_a = 1 - \cos\theta \quad 1(c)$$

The efficiency between substrate and fiber is 90 %,so η_a is 1. So considering equation 1, putting the values of coupling efficiencies are about 90%.

3. Mathematical formulation of photonic crystal fiber

The general mathematics to find out the electric field distribution in the fiber is derived from the Maxwell's electromagnetic differential equations and the same dot and curl equation can be written as [12]

$$\nabla \times \vec{E}(\vec{r}, t) + \frac{\partial \vec{B}(\vec{r}, t)}{\partial t} = 0 \quad 2(a)$$

$$\nabla \cdot \vec{B}(\vec{r}, t) = 0 \quad 2(b)$$

$$\nabla \times \vec{H}(\vec{r}, t) - \frac{\partial \vec{D}(\vec{r}, t)}{\partial t} = 0 \quad 2(c)$$

$$\nabla \cdot \vec{D}(\vec{r}, t) = 0 \quad 2(d)$$

Here $\vec{E}(\vec{r}, t)$, $\vec{H}(\vec{r}, t)$ are the electric and magnetic fields, and $\vec{B}(\vec{r}, t)$ and $\vec{D}(\vec{r}, t)$ are the magnetic induction fields and displacement

Considering free from current and charges, the above said equations can be written as

$$\nabla \times \vec{E}(\vec{r}) + i\omega\mu\vec{H}(\vec{r}) = 0 \quad 3(a)$$

$$\nabla \cdot (\mu\vec{H}) = 0 \quad 3(b)$$

$$\nabla \times \vec{H}(\vec{r}) - i\omega\epsilon\vec{E}(\vec{r}) = 0 \quad 3(c)$$

$$\nabla \cdot (\epsilon\vec{E}) = 0 \quad 3(d)$$

where $\omega > 0$ is the angular frequency.

Further combining these equations, we can write

$$\nabla \times \left[\frac{1}{\epsilon(\vec{r})} \nabla \times \vec{E}_k \right] = -\frac{\omega^2}{c^2} \vec{E}_k \quad (4)$$

The solution of electric field equation can be written as

$$\vec{E}_k = \sum_G \vec{h}_k - G \exp(i(\vec{k}-\vec{G}) \cdot \vec{r}) \quad (5)$$

From Maxwell's equations, the full-vector wave equation is found out for electric field where $\vec{k}$ is the wave vector, and $\epsilon(\vec{r})$ is a value of the dielectric constant in the structure. The proposed structure is signified as a periodic cell, which includes a crystal structure and its defects. Since the structure is periodic nature, we can convey $\vec{E}_k$ as a sum of plane-waves based on Bloch theorem: where $\vec{G}$ is a lattice vector in reciprocal space. The dielectric constant $\epsilon(\vec{r})$ is characterized by a Fourier expansion. Further, photon particles' interaction with structure material leads to a nonlinear characteristic due to the periodic nature of the crystal. The induced polarization PO of nonlinear optical medium is originated by the susceptibility coefficients as [13-14]

$$\vec{P}_0 = \epsilon_0 \vec{E} Y^{(1)} + \epsilon_0 \vec{E}^2 Y^{(2)} + \epsilon_0 \vec{E}^3 Y^{(3)} \quad (6)$$

Where $Y^{(1)}$, $Y^{(2)}$ and $Y^{(3)}$ are the 1st, 2nd and 3rd order susceptibility coefficients correspondingly. Here the structures do not have $Y^{(2)}$ which is seen in noncentrosymmetric photonic crystals. The 3rd order takes place for both centrosymmetric and non-centrosymmetric media and the proposed structures show this susceptibility which provides to Kerr nonlinearity.

The induced polarization of the medium can be written for monochromatic electric field, $\vec{E} = \vec{E}_0 \cos \omega t$ is

$$\vec{P}_0 \approx \epsilon_0 (Y^{(1)} + \frac{3}{4} Y^{(3)} |\vec{E}_t|^2) \vec{E}_0 \cos \omega t \quad (7)$$

Further taking into consideration of the following susceptibility as a sum of linear YL and nonlinear YNL terms, the index of refraction are often written in terms of the energy of light

$$\text{Energy}_{\text{Out}} = n_0 + \frac{3Y^{(3)}}{8n_0} \times |\vec{E}_t|^2 \quad (8)$$

4. Result and discussion

The plane wave expansion technique is used to find out the electric field distribution inside the silicon-based photonic crystal fiber with the help of Equations 4 and 5. Before going to realise the result, let us focus on the structure parameter, including the nature of the material and configuration of the same. Further, considering an operational mechanism, it is understood that signal with energy for 30 eV to 30,000 eV incidents to the structure. For example; we consider 30 eV, 70 eV, 100 eV, 300 eV, 700 eV, 1000 eV, 3000 eV, 7000 eV, 10000 eV, 30000 eV as input signal for the sake of simulation purposes. So, with the help equations 4 and 5 and applying the PWE technique, electric field distribution at the output end of the fiber has been computed. Even though simulation has presented for a different configuration, we show the lattice spacing of 10 nm and diameter of holes 8 nm corresponding to the input signal of 30 eV, which is shown in Fig. 2.

Fig. 2. Distribution of electric field at energy 30 eV, $a=10$ nm and $d=8$ nm.

Fig. 2 shows the electric field's variation at the output end of the fiber, which represents the output energy of 30 eV for lattice spacing of 10 nm and diameter air holes of 8 nm. In this figure, length and breadth are taken along x and y, respectively, where the electric field distribution of output ($V/\mu m$) is taken along the z-axis. The peak electric field is shown in the figure (red colour), which signifies that the signal is emerging from for the said photonic structure. More clearly, it is shown that the peak electric field at a particular position of fiber (inset in the figure). Similarly, the peak electric field corresponding to other modes of propagation can be found. Finally, the amount of energy in terms of eV is computed using Eq. 8. As far as the configuration of structure is concerned, the lattice spacing of the structure and diameter of air holes play a vital role. For example, different lattice spacing and the air holes' diameter bestows different outcomes pertaining to the same input.

To summarize the above statement, it is found that the energy for the lattice spacing of '10 nm' and diameter of air hole of '8 nm' is found 14.383 eV, which is less as compared to the input energy of 30 eV. This implies that the input energy (30 eV) is attenuated because the output energy is lower (14.383 eV). Similarly, we have simulated the input energy of 30 eV for the different lattice spacing values, varying from 10 nm to 350 nm. The result of corresponding to lattice spacing of 1 nm, 10 nm, 20 nm, 30 nm, 40 nm, 49 nm, 50 nm, 60 nm, 100 nm, 150 nm, 160 nm, 170 nm, 180 nm, 190 nm, 200 nm, 210 nm, 220 nm, 350 nm is found 0.047 eV, 4.622 eV, 18.486 eV, 14.383 eV, 74.581 eV, 59.889 eV, 60.104 eV, 65.165 eV, 240.417 eV, 461.289 eV, 524.845 eV, 592.5 eV, 664.257 eV, 740.113 eV, 8200.699 eV, 9041.270 eV, 9922.846 eV, 25114.640 eV respectively with respect to 30 eV as input signal. After analysing the above said numerical result, it is understood that the output energy value is less than 30 eV for lattice spacing up to 30 nm, and output energy is more than 30 eV for lattice spacing more than 30 nm.

So it is realised that the proposed structure behaves as an attenuator for the value of lattice spacing up to 30 nm and amplifier for lattice spacing more than 30 nm. The above-said explanation was for 30 eV only, but we have made a simulation for input energy, which varies from 30 eV to 30 000 eV. Similarly, with the help of the same modulus operandi, the simulations for all input energy have been made. The entire output result for realising both attenuator and amplifier are plotted in Fig. 3(a) to Fig. 3(j) corresponding to the lattice spacing of 1 nm, 10 nm, 20 nm, 30 nm, 40 nm, 49 nm, 50 nm, 60 nm, 100 nm, 150 nm, 350 nm, respectively.

Fig. 3. Comparison of output and input energy with respect to lattice spacing at incident of (a) 30 eV, (b) 70 eV, (c) 100 eV, (d) 300 eV, (e) 700 eV, (f) 1000 eV, (g) 3000 eV, (h) 7000 eV, (i) 10000 eV, and (j) 30000 eV.

In the Fig. 3, energy in eV is taken along the vertical axis, where lattice spacing in nm is taken in the horizontal axis. In these graphs, two types of colour are chosen, such as input (green colour) energy to the structure and output (red colour) energy emerging from the structure. It is found that input energy remains constant pertaining to the lattice spacing with respect to each graph. Further output energy increases with the increasing of lattice spacing because of size of the entire structure increases as the increase of lattice spacing. It also indicates that larger structure allows more signal as compared to the smaller one. Moreover, the variation of the output energy is found nonlinear (equation (6-7)) as the principle of generation of the electric field is realised nonlinear at the output end of fiber. It is also envisaged that the output energy is less or more than the input signal, which is decided by the structure's configuration and nature. For example, output energy is less than input for certain values of 'a', referred to as attenuation of the input signal. Similarly, it is more at certain values of 'a', referred to as an amplification of input signal. For example; the proposed structure could be realised as attenuator for lattice spacing less than 30 nm, 50 nm, 60 nm, 100 nm, 160 nm, 180 nm, 200 nm, 350 nm for the input of 30 eV, 70 eV, 100 eV, 300 eV, 700 eV, 1000 eV, 3000 eV, 7000 eV, 10000 eV, 30000 eV respectively. Similarly amplification of the signal could be found for lattice spacing more than 30 nm, 50 nm, 60 nm, 100 nm, 160 nm, 180 nm, 200 nm, 350 nm for the input of 30 eV, 70 eV, 100 eV, 300 eV, 700 eV, 1000 eV, 3000 eV, 7000 eV, 10000 eV, 30000 eV respectively.

5. Conclusion

In this paper, the attenuation and amplification of the input signal can be realised through the silicon-based photonic crystal fiber. The operational principle deals with the transportation of the signal through numerical computation, which is carried out with the help of the plane wave expansion technique. The numerical investigation indicates that the configuration of the proposed photonic structure and nature of material plays a vital to decide the application of attenuation or amplification. The research outcomes affirm that silicon-based photonic crystal fiber could be suitable for both attenuator and amplifier.

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***Compliance with ethical standards:-** No part in this article is copied from any sources. Aside this, we have not submitted this article to any journals. Beside this, we have gone through journal's website (author's instruction) and carefully read out the ethical statement for the same. We agreed with the ethical standards of

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Figures

Figure 1

Schematic diagram of (a) photonic crystal fiber, (b) internal structure of photonic crystal fiber and (c) Mechanism to realise the attenuator and amplifier.

Figure 2

Distribution of electric field at energy 30 eV, $a=10$ nm and $d=8$ nm.

Figure 3

Comparison of output and input energy with respect to lattice spacing at incident of (a) 30 eV, (b), 70 eV, (c) 100 eV, (d) 300 eV, (e) 700 eV, (f) 1000 eV, (g) 3000 eV, (h) 6000 eV, (i) 9000 eV, and (j) 30000 eV.