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Switching Behaviour in an Equi-dimensional Core-Cladding Photonic Crystal Fiber using FDTD Technique

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Abstract. The investigation in this paper shows the switching of transmission intensity in a hollow-core photonic crystal fiber where the radius of the core and the cladding are kept equal. The basic operation relies upon the principle of interference of two optical signals. For the realization of the phenomenon of the interference various combinations of the phase differences are introduced between the two applied signals. At a particular phase difference the resultant output signal is found to be switched from maximum to minimum intensity and vice-versa with the inversion in the phase difference. Again, it is also observed that, the third order nonlinearity plays a vital role in the shaping up of the transmission signal. The structures are designed and simulated using the Finite Difference Time Domain (FDTD) tools.

Keywords. finite difference time domain method; photonic switching; photonic band gap; photonic crystal fiber; third order nonlinearity**.**

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1. Introduction

The emergence of integrated optics in recent years has advanced in such a way that it has opened the door for a vast field of research in optics and photonics. Gradually, developments in the field took place and the researchers now preferred to have integrated photonics over integrated optics [1]. The basic difference between the two is that, the integrated optical devices were controlled electronically, whereas in integrated photonics technology, the devices are controlled by the externally applied photons. Hence, the integrated photonics technology is called as all-optical. With this, the speed of operation of the devices has got more faster, as the wastage of time in nodes at which the optoelectronic conversion of the optical signals were taking place is removed. But still, the matter of concern is to minimize the losses which takes place due to the addition of some external devices for the manipulation of the characteristics of the transmission signal. During this course of time, the invention of the photonic crystal fibers and structures have added a lot of flexibilities to be used for the above mentioned purpose. The ability of the photonic crystal fibers to process the signal within the fiber itself has helped them to find their uses in most of the applications. With the introduction of the nonlinearity to the fiber different optical characteristics have been observed by different researchers in the last decade [2]-[11]. It is because the modification in the cross-section of the fiber which leads to the nonlinearity, is much more easier than that of the ones in conventional fibers. As of now, though the reported loss factor in the photonic crystal fibers does not allow them to be used in the long distance communications purpose, but they are very much useful in the nano-scale integrated devices, where due to their replacement in place of the external components helps the bulkiness of the devices to be reduced more significantly. Again, as a very small size of fiber is used for this purpose, therefore the loss in fiber for the transmission is comparably less than which we realize by the external components used for the same purpose of operation. Reference [2] presents the nonlinear switching characteristics of a coupler implemented in a liquid crystal photonic crystal fiber. The nonlinear properties of the fiber were used to demonstrate all optical switching of short duration pulses, altered by changing the temperature and external electric field. Reference [3] proposes a scheme for single photon controlled switching through an interaction of single-photon stationary light pulses. A number of photonic signal processing systems using a dispersion-shifted nonlinear photonic crystal fiber are discussed in [4]. A work in [5] has shown that a Kerr-nonlinearity-induced profile of the refractive index in the hollow core of a photonic-crystal fiber changes the pass-bands in fiber transmission. In this paper, we have proposed a scheme of photonic switching within the fiber, where the intensity at output of the fiber changes from maximum to minimum and vice-versa with the change in the phase-differences between the input beams in the presence of nonlinearity.

2. Principle of Operation

We have proposed a new model of the Photonic Bandgap (PBG) fibers, in which, the size of the diameter of the core and cladding are taken equal, instead of the traditional approach, where we were taking the radius of the air-hole at the core to be more than that of the ones existing in the cladding. So, here due to the presence of this small air-hole region, a small amount of signal will also be transmitted at the core. Thus, this fiber structure will give us a continuous intensity pattern which will be sinusoidal in nature. This sinusoidal pattern will consist of a maxima and a minima of the intensities in one pulse and this will define the criteria of maximum and minimum intensities. The structure now has to be modelled in such a way that the maxima and minima will be replaced by the minima and the maxima at those corresponding reference points. It means that, if the intensity varies from the maximum to minimum at some reference points of the fiber for one scheme of transmission, then for some other scheme of transmission the intensity has to vary from minimum to maximum again at those corresponding reference points. This phenomena of inversion of the intensity pattern can be termed as photonic switching. Thus, the switching mechanism here is observed on two fixed reference points. Here, we have taken the phenomenon of interference of two light beams as the principle of the operation of the switch. The principle of interference says that the light beams at different phases and frequencies are interfered constructively or destructively in order to give a new resultant intensity pattern. The basic idea behind this scheme of operation is that, the intensity pattern produced due to the interference of two beams of light having a positive phase difference of a certain value incident to the fiber, has to be the inversion of the intensity pattern produced due to the interference of two beams of light at a negative phase difference of the previous value, keeping one of the incident signals constant for both the cases.

3. Structural Analysis

The photonic crystal fiber, as shown in the Fig. 1, is of the length of 1.5 μm, with a radius of 0.55 μm. The air holes are arranged in a circular crystal lattice array and are having the radius of 0.03 μm. The radial distance between the two consecutive air holes is 0.08 μm. The air holes are arranged in six concentric circles. An input signal S and a control signal C, which is the phase shifted signal of the input, are applied at one end of the fiber. At the other end of the fiber the transmission intensity is recorded. The PS is the phase shifter put into the circuit as a representation to show that the two input beams are incident from two different sources of light. As it is not worthwhile to keep two different input laser sources of different phases adjacent to each other near the fiber and apply them on to the fiber, it is better to use a single source of light for both of the actions. For this, the source signal can be passed through a phase shifter device, which will either make the control signal lead or lag the source signal as per requirement, by the same amount. For the leading or the lagging of the control signal the notations C1 and C2 are used and these notations can be used interchangeably for this purpose, such that,

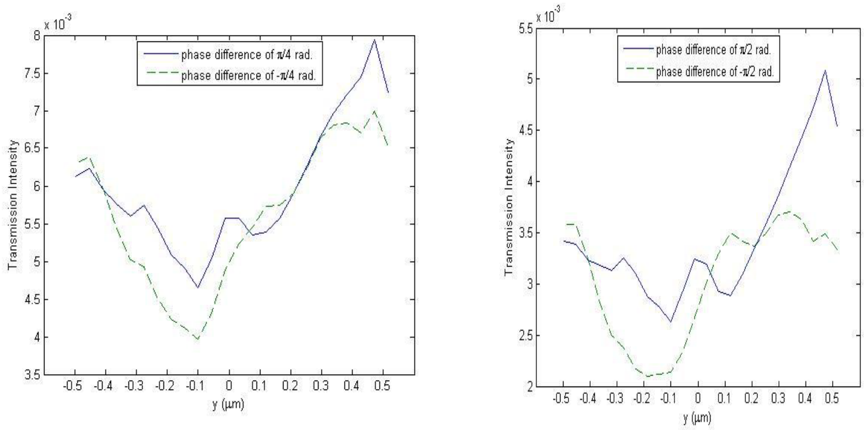
if $\Phi s - \Phi c1 = + \Phi$,

then $\Phi s - \Phi c2 = - \Phi$ and vice-versa.

where, $\Phi s - \Phi c1$ and $\Phi s - \Phi c2$ represents the phase differences between the source signal to the control signals.

Fig. 1. The schematic diagram of the photonic crystal fiber used as an switch. (a) the input source S and the control signal C are incident to the fiber, (b)PS is the phase shifter, (c) Y is the observed output.

The proposed aim of the project is to investigate the switching up of the intensity from maximum to the minimum and vice-versa for the inversion of the phase differences between the source signal and the control signal from $+\Phi$ to $-\Phi$ and vice-versa.



(a) (b)

Fig. 2. Comparison of the outputs for the phase differences of (a) $\pi/4$ rad. and $-\pi/4$ rad. and (b) $\pi/2$ rad. and $-\pi/2$ rad.

The maxima and minima, in Fig. 2, are not observed at the same reference points and both intensity patterns are almost in the same range.

4. Introduction of Nonlinearity into the Fiber

The FDTD model for Kerr-type materials assumes an instantaneous nonlinear response. The nonlinearity is modeled in the relation D = ε0εE, where

$$\begin{aligned}\varepsilon &= n^2 \\ &= (n_0 + n_2 |E|^2)^2 \\ &\simeq n_2^0 + 2n_0 n_2 |E|^2 \end{aligned} \tag{1}$$

Here, the linear refractive index n0 is dimensionless, and the nonlinear refractive index n2 has units of m2 /V2 and this n2 is related to χ(3), i.e., the minimum factor of nonlinearity in silica called the third-order susceptibility, by the relation:

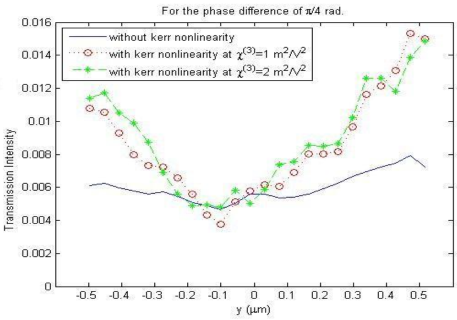
$$n_2 = \frac{3}{8n}(\chi^3) \tag{2}$$

From (1), the latest value of E can be expressed by the following iteration upon the latest value of D and the old value of E:

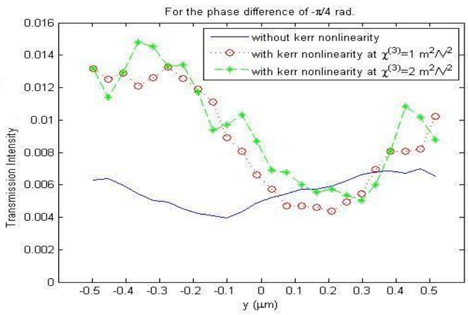
$$E = \frac{D}{n_0^2 + 2n_0 n_2 |E|^2} \tag{3}$$

Knowledge of E then permits another updating of D, and the process repeats cyclically until time stepping is completed. In our work, we took two Gaussian pulses as input signal at one end of the PCF. A certain combination of phase differences are maintained between the two corresponding signals. The intensity profile is recorded at the other end of the fiber. The obtained outputs in the figures 2-5 are the plots between the transmission intensity and the cross-sectional length of the PCF. From fig. 2., we observe that the interaction between the two input signals are very weak due to the difference in phase. With the introduction of Kerr nonlinearity, its task is to simply induce the phase of the delayed signal, so that the phase of propagation of both the signals matches each other, giving rise to the maximum interaction between them and thus enhancing the strength of the output intensity pattern. This interference of two input beams due to the presence of Kerr nonlinearity is called the cross-phase modulation. The nonlinear polarization which we get here is dependent upon the parameter χ(3) and hence by varying the value of χ(3) we can observe the output intensity patterns.

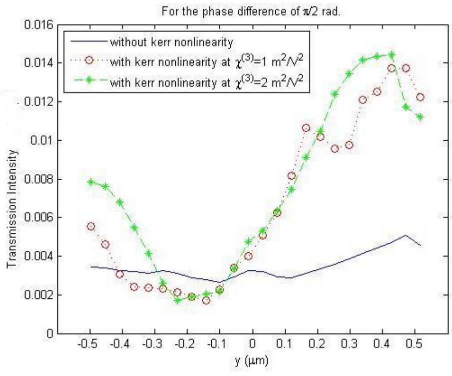
From the results in Fig. 3, we can see that with the introduction of the Kerr effect into the fiber, the intensities in the output are getting doubled or more than that in one of the halves of the fiber, from the center of the cross-sectional length, keeping the other half almost the same . That means, an effect of amplification in intensities is observed at one of the halves of the fiber cross-section. The side of the cross-section in which the amplification takes place depends upon the lagging or leading of the phase differences. For negative phase differences, left half intensities of the fiber cross-section gets amplified and for the positive phase differences, the right half intensities of the fiber is getting amplified. This is due to the mechanism of Supercontinuum Generation, which occurs due to the cross-phase modulation between the two input signals applied at different phases. Again we can also observe that, though there is a very small difference between the intensities for the cases of when χ(3) = 1 m2/V2 and χ(3) = 2 m2/V2 , but for χ(3) = 2 m2/V2, the intensity is maximum.



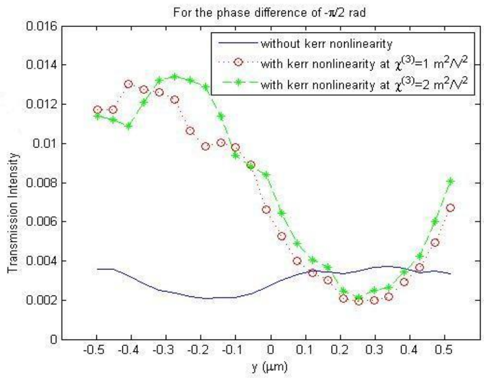
(a)



(b)

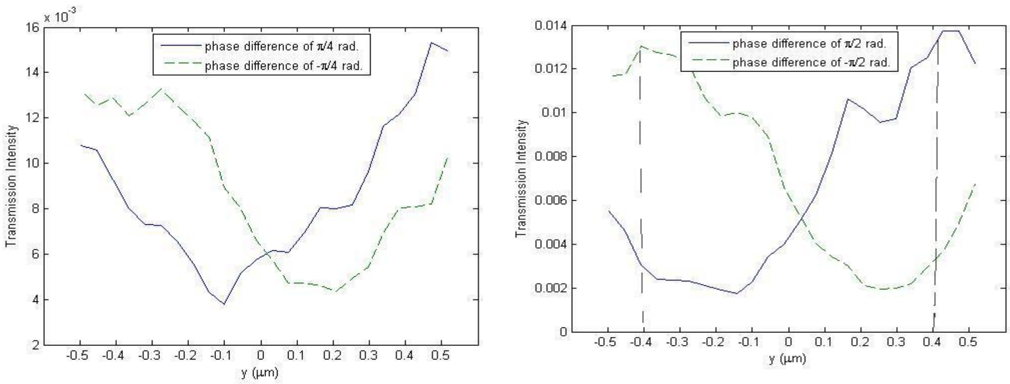


(c)



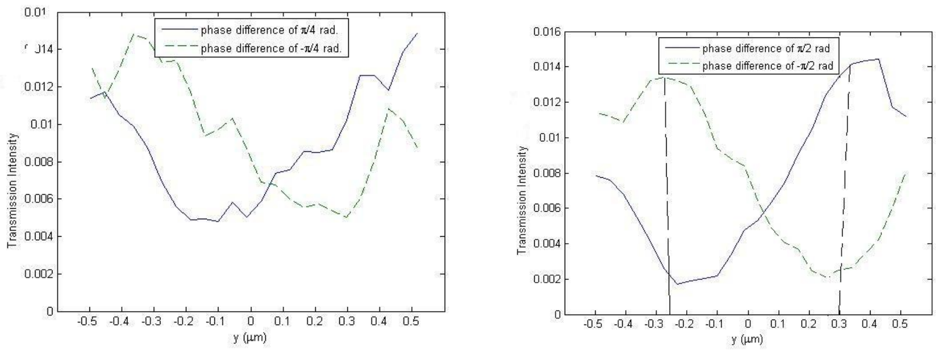
(d)

Fig. 3. Comparison between the intensities of the output signals of the fiber with and without applying nonlinearity for the phase differences of (a) π/4 rad, (b)–π/4 rad, (c) π/2 rad and (d) –π/2 rad.



(a) (b)

Fig. 4. Comparison of the outputs for the phase differences of (a) π/4 rad. and –π/4 rad. and (b) π/2 rad. and –π/2 rad. at χ(3) = 1 m2/V2



(a) (b)

Fig. 5. Comparison of the outputs for the phase differences of (a) π/4 rad. and –π/4 rad. and (b) π/2 rad. and –π/2 rad. at χ(3) = 2 m2/V2 .

From the above Fig. 4 and 5., it is observed that, with the change in phase difference between S and C from π/2 rad. to –π/2rad.; if χ(3) = 1 m2/V2 , the switching operation can be observed at distances 0.4 microns on the both side of the center of the fiber cross-section and similarly, if χ(3) = 2 m2/V2, the switching mechanism takes place approximately at the distances 0.25 microns on the both side of the center of the cross-section of the fiber.

5. Conclusion

Switching mechanism can be realized in the presence of Kerr nonlinearity inside the PCF. For the phenomenon of switching to take place due to two interfering input signals, it is necessary that the two signals must have a phase difference of π/2 rad. If the phase difference between the constant signal and the variable signal is changed from π/2 to –π/2, then for both the values of the nonlinearity coefficient, χ(3) = 1 m2/V2 and χ(3) = 2 m2/V2 , the photonic switching action can be realized. Due to the presence of nonlinearity due to the third order susceptibility of the glass material, the generation of super-continuum takes place and this contributes in the amplification of the intensities at either half of the center of the cross-section of the fiber depending upon the lead or lag of the incident signal pulses in terms of their phases. One of the important advantage in this switching scheme is that as the mechanism is possible within the fiber itself so no more extra components required for the same purpose. Further, the losses due to the connectors and misalignment of the external components which usually takes place in optical circuits can be avoided.

References

[1] JM Senior, *Optical Fiber Communications: Principles and Practice*, 3rd ed. (New Delhi, India: Pearson, 2012).

[2] M Bajcsy, S Hofferberth, V Balic, T Peyronel, M Hafezi, AS Zibrov, V Vuletic, MD Lukin, *Proc. SPIE*. **7226**, 722609 (2009)

[3] KK Chow, C Lin, *Proc. 5th Int. Conf. Optical Internet* (COIN) 26 (2006)

[4] DA Zheltikova, M Scalora, AM Zheltikov, MJ Bloemer, MN Shneider, GD Aguanno, RB Miles, *Phys. Rev*. **E 71**, (2005)026609.

[5] K Saitoh, NJ Florous, T Murao, M Koshiba, *J. Lightwave Technol*. **25(9)**, 2440 (2007)

[6] T Matsiu, K Nakajima, C Fukai, *J. Lightwave Technol*. **27(23)**, 5410 (2009)

[7] M Uthman, BMA Rahman, N Kejalakshmy, A Agrawal, KTV Grattan, *IEEE Photon. J.* **4(6)**, 2315 (2012)

[8] F Poli, A Cucinotta, S Selleri, *Photonic Crystal Fibers: Properties and Applications*, (The Netherlands: Springer, 2007).

[9] T Uthayakumar, RVJ Raja, K Porsezian, *J. Lightwave Technol*. **30(13)**, 2110 (2012)

[10] L An, Z Zheng, Z Li, T Zhou, J Cheng, *J. Lightwave Technol*. **27(15)**, 3175 (2009)

[11] Y Yue, G Kai, Z Wang, Y Lu, C Zhang, T Sun, Y Li, L Jin, J Liu, Y Liu, S Yuan, X Dong, *IEEE Photon. Technol. Lett*. **18(24)**, 2638 (2006).

[12] KR Khan, S Bidnyk, TJ Hall, *Progress in Electromagnetics Research* **M 22**, 179 (2012).

[13] GP Agrawal, Nonlinear Fiber Optics, 3rd ed. (New Delhi, India: Academic Press, 2006)

[14] RM Joseph, A Taflove, *IEEE Trans. Antennas Propagat*. **45(3)**, 364 (1997)