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Optimization and Comparison of Circular and Elliptical PCF for Generation of Slow Light in Optical Communication Using 2d FDTD Method

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Abstract

Effect on generation of a tunable slow rate light can be estimated by fabricating circular and elliptical PCFs. Choosing the background material to be As2Se3 Chalcogenide glass for their investigation. In addition, we have also measured the maximum allowed pump power for undistorted output pulse, Brillouin gain and time delay using same PCFs structure. It reports that, Brillouin.gain is found to be 87.2 dB/m for circular PCF(C-PCF), 90 dB/m for elliptical PCF (E-PCF) and time delay reaches to 138.64ns C-PCF, 142ns for E-PCF. The above results seem to be measured using 1m long PCFs pumped with 100mW for both C-PCF and E-PCF. The simulating result of E-PCF is much more intensity for potential application in optical buffering, data synchronization, optical memories and signal processing etc over C-PCF.

Keywords

High nonlinear PCF • Brillouin gain • FDTD Method

Introduction

Slow light means the possibility of controlling and reducing the group velocity of optical signal, which has been studied extensively since last decade due to its many potential applications, such as optical delay, all optical buffering, data synchronization, optical memories, optical signal processing, microwave photonics, and precise interferometric instruments [1–4]. Slow light can be obtained by various methods, such as Electromagnetically Induced Transparency (EIT) [5], Coherent Population Oscillation (CPO) [6], Stimulated Raman Scattering (SRS) [7], Stimulated Brillouin Scattering (SBS) [8]. Among these methods, SBS has attracted much more attention in generation of slow light in optical fibers. The main advantages of the SBS over other methods are controlling time delay only by tuning the pump power [9], operating at room temperature, compatible with optical telecommunication system and so on. So slow light based on SBS in optical fibers has been recognized as a key technology for designing optical buffers. Because of low Brillouin gain coefficient, the effect of time delay is very weak in conventional fibers, thus the time delay is small. Researchers try to find some special high nonlinear materials or structures as the medium to achieve large time delay. Chalcogenide [10] and tellurite glass fibers [11] were used to improve delay efficiency of SBS slow light in recent years, which shows potential ability in improving the time delay. Chalcogenide and tellurite glass fibers are both high nonlinearity compound fibers. The As2Se3 chalcogenide glass possesses very high nonlinear refractive index [12] and low material loss which makes it promising candidate for nonlinear applications such as slow light and supercontinuum generation [13–16], the Brillouin gain coefficient of As2Se3 chalcogenide PCF is at least two orders larger than that of the PCF made with silica glass. In 2005, silica glass fibers were presented and used to control the group velocity of optical signal in slow and fast light via SBS [17]. In 2006, a time delay of 19ns in As2Se3 single mode fibers via SBS with pump power of 31mW in a fiber of 10m length was presented [18], then a time delay of 37ns over a 5m long As2Se3fiber was demonstrated by Songetal.[10] and the figure of merit (FOM) is 110 times better than that observed in a conventional single-mode fiber. And then Chalcogenide photonic crystal fibers (PCFs) were used to improve the time delay efficiency, realizing 137ns only in a 1m long fiber [12].PCF guides light by means of a lattice of air holes running along the fiber axis. It is well known that the transmitting properties depend on waveguide structure; PCF has many geometric parameters to be tailored for designing PCF, such as diameter of air hole in different layers, diameter of core, pitch, air hole arrangement, air hole layers and so on. It was demonstrated that PCF has unique and remarkable Brillouin scattering properties [19]. The SBS effect in PCFs can be either suppressed or enhanced by designing a certain PCF structure. A enhanced SBS gain of a PCF that is made of Chalcogenide material was reported in Ref. [20], and the SBS gain and tunable slow light of single-mode As2Se3 chalcogenide PCF was reported

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and showed that the time delay experienced by the pulse can be tuned with the pump power and structural parameters of As2Se3-chalcogenide photonic crystal fiber, but the proposed PCF has same size air holes [12]. Up to now, the generation of slow light based on SBS in double-clad As2Se3 Chalcogenide PCFs has not been reported yet. In this paper, we extended our previous work [21] and propose a double-clad As2Se3 Chalcogenide PCF to enhance the efficiency of SBS-based slow light generation. We systematically investigated the slow light induced by SBS in double-clad As2Se3chalcogenide PCFs with different structures, the Brillouin gain of 40dB and time delay of 705ns are achieved with pump power of only 10mW in a 1m long Chalcogenide PCF. This implementation shows that the Chalcogenide PCF can be one of the best candidate medium for practical applications of SBS slow light.

In this article, we have proposed to design and compare, a As2Se3 Chalcogenide circular and elliptical PCFs suitable for tunable slow rate light generation based on SBS. Since slow rate light based on SBS in PCFs has attractive much more intensities for its potential application to optical buffering, data synchronization, optical memories and signal processing. Additionally, our simulation result also offers the improvement of PCF characteristics of maximum pump power for undistorted output pulse, B.gain and time delay etc. More-ever the PCF property such as time delay gained by pulse in designed PCF structure can be tuned with pump power and thereby tunable slow light feature can be obtained from proposed PCF. Such properties can be estimated and compare for both PCFs.

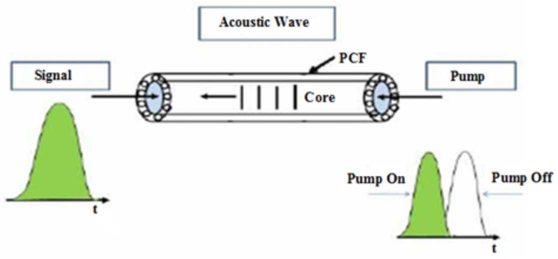

Figure1. The schematic diagram of principle of SBS on PCF.

Mathematical Analysis

SBS is a nonlinear phenomena induced by the interaction between a high intensity pump wave and a low intensity signal wave with the help of an acoustic wave. The two waves have unequal Brillouin frequencies, the difference of which is responsible for the generation of acoustic wave through the process of electrostriction. The acoustic waves produce a periodic modulation of the refractive index is diffracted backward on this moving grating, giving rise to frequency shifted caked stokes wave and antistokes components.

If ωp and ωs are the frequencies of pump and counter propagating signal wave of intensities Ip and Is respectively. Then the coupled nonlinear differential equations are pump and signal waves is specified by the equation.

$$\frac{dI_p}{dz} = -g_B I_p I_s - \alpha_p I_p \quad (1)$$

$$-\frac{dI_s}{dz} = +g_B I_p I_s - \alpha_s I_s \quad (2)$$

By assuming the pump wave as undepleted and (α_s≈α_p) =α, the result of the equations 1 and 2 is specified by the relation as follows:

$$I_s(0)=I_s(L)\exp[g_B P_0 L_{eff}/A_{eff} - \alpha L] \quad (3)$$

$$L_{eff}= \alpha^{-1}(1-\exp(-\alpha L_{eff})) \quad (4)$$

Where L is the real length and Leff is the effective length of the fiber, α is the modal loss of fiber i.e attenuation constant for the fiber.

In the simplest model of SBS, the coupling takes place between two counter propagating optical waves and a longitudinal acoustic wave, which plays the role of the idler wave in the interaction. If two optical waves have the frequency difference equal to the frequency of the acoustic wave, the interaction will efficiently lead to the formation of a dynamic Bragg grating in the core of a fiber which can diffract the light from the higher frequency wave back into lower frequency wave. As a result the signal wave will experience a gain (40).

The Brillouin gain can be expressed as:

$$g_B(\Omega)= \frac{g_p(\Gamma_B/2)^2}{(\Omega-\Omega_B)^2+(\Gamma_B/2)^2} \quad (5)$$

Where gp is the peak value of the Brillouin gain at Ω= ΩB and given the relation as follows:

$$g_p \equiv g_B(\Omega_B) = \frac{2\pi^2 n^7 p_{12}^2}{c\lambda_p^2 \rho_0 v_A \Gamma_B} \quad (6)$$

Here 0 is the density, and P12 is the longitudinal elasto-optic coefficient. The full width at half maximum of the gain spectrum is related to by the relation ; where is the Brillouin linewidth and defined by ,Where is the phonon life time in the material.

The nonlinear coefficient(γ) offered by PCF, related to the nonlinear refractive index of material of PCF and the effective area of propagating mode is as follows:

$$\gamma = \frac{2\pi n_2}{A_{eff}} \quad (7)$$

Where n2 is the nonlinear coefficient of material of PCF and Aeff is the effective mode field area of the propagating mode and is defined as:

$$A_{eff} = \frac{(\iint_{-\infty}^{\infty}|E|^2 dxdy)^2}{(\iint_{-\infty}^{\infty}|E|^4 dxdy)} \quad (8)$$

Where E is the electric field distribution inside the PCF core.

The Brillouin gain coefficient of PCF can be calculated by using the relation [22]

$$G= 10 \log [\exp (\frac{g_B K P_0 L_{eff}}{A_{eff}} - \alpha L)] \quad (9)$$

Where P0 is the pump power and K is the polarization factor and depends on the polarization properties of the fiber. The value of the polarization factor is 1, if the polarization is maintained and it is 0.5 if polarization is not maintained. Although, some results [20],[21], and [42] showed that K=0.667 is more appropriate, for the fiber which is low birefringence and very high polarization beat length. In our simulation K=0.667 has been used.

The maximum allowable pump power, Pmax is the maximum pump power above which the output pulse get distorted related to the Brillouin gain coefficient gB as [20] as follows:

$$P_{max}=21\frac{A_{eff}}{Kg_BL_{eff}} \qquad (10)$$

Once pump power approached to Pmax then the backscattered wave can be generated from the background noise in the fiber, which leads to serious output pulse distortion. Therefore, the value of pump power must be smaller than the Pmax.

The SBS induced time delay per unit length and per unit pump power by slow light fiber devices can be expressed as [20], [22]

$$\frac{\Delta t_d}{P_pL_{eff}}=\frac{g_BK}{A_{eff}\Gamma_B} \qquad (11)$$

PCF Design

For the purpose of optimizing tunable slow light generation performance, the effects of structural parameter based on SBS are symmetrically investigated. For this, we first designed two PCF structure having circular and elliptical air hole ring in their cladding region and analyze its comparison. The transverse cross-sectional view of two designed PCF are shown in fig.2. In fact, a PCF is composed of an array of air hole in a triangular lattice pattern in As2Se3 based Chalocogenide glass. One having identical air hole diameter while other having two different diameters called semi-major and semi-minor distance . As the distance between centre to centre of air holes is called pitch Λ and set to be 1μm and the refractive index of Chalcogenide glass PCF is taken to be 2.886 at 1550nm evaluated by Sellmeir equation not shown here.

Since the diameter of air hole ring change in order to change the mode field area because it plays a vital role for nonlinearity. We designed three circular and elliptical air hole ring PCF and compare their result. However, we are not taken more than 3 air hole ring PCF structure because the time delay offers insignificant on increasing air hole ring in a proposed cladding region. PCFs can be fabricated using standard extrusion and stacking based method as well as air drilling hole method using 2D FDTD method.

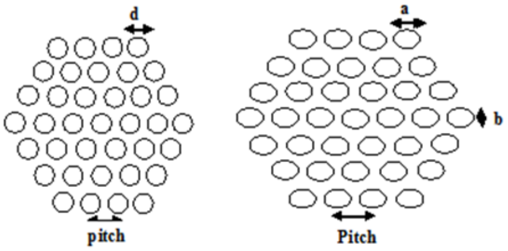

Figure2. Represents the transverse cross-sectional view of proposed highly nonlinear circular and elliptical PCF.

Result and Discussion

The effect of tunable slow light generation basically depends on single mode operation at an operating wavelength. In fact the fundamental mode will couple to higher order modes which have larger Aeff and lower non-linearity in multimode PCF, as a result nonlinear interaction falls which essential for the effect of SBS. To ensure this effect, a Chalocogenide PCF must have single mode operation and normalized frequency V of the PCF can be simply written as [20]:

$$V(\upsilon)=k\Lambda\sqrt{n_{eff.c}^2(\upsilon)-n_{eff.cl}^2(\upsilon)}$$

Where υ is the operating frequency. (υ) is the effective refractive index of fundamentmode confined in the core at frequency υ while (υ) is the effective refractive index of mode spreading over the cladding region at the same frequency υ. The single mode condition of PCF structure is found to be V [20].

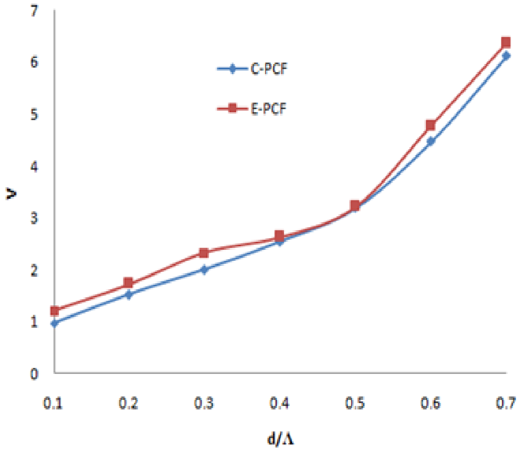

Figure3. V parameter versus diameter/pitch of purposed PCFs.

Fig.3 illustrates the normalized frequency V on of proposed PCFs at an operating wavelength of 1.25μm for single mode operation. It is estimated that the value of normalized frequency becomes 3.19 (i.e more than π value) which is the limiting condition for single mode operation at =0.5 of same wavelength 1.25 μm, hence in order to ensure the single mode condition of proposed PCF the value of is just less than that of 0.5. So we set =0.4 for all simulation of studying electric field distribution pattern, mode field area etc.

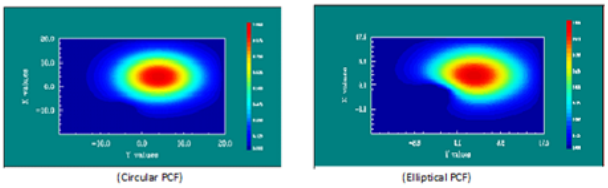

Figure4. Electric field distribution pattern profile of fundamental mode withdia./pitch=0.4 at 1.25μm wavelength.

Fig.4 represents electric field distribution pattern of fundamental mode profile for X and Y polarised of proposed PCFs with =0.4 at communication wavelength of 1.25 μm. It is nicely visualized that light is tightly confined through the core region. In addition, PCF to transmit data in an optical system or communication area. For this, it is very essential to evaluate the effective mode field area of proposed PCFs. It plays a very important role to enhance nonlinear effect in PCFs and has been controlled by tuning the air filling fraction . Fig.5 shows that effective mode field area (Aeff) on of propagating mode of proposed PCFs. It is found that mode field area (Aeff) decreases on increasing , as a result reduction in the core size of PCFs.

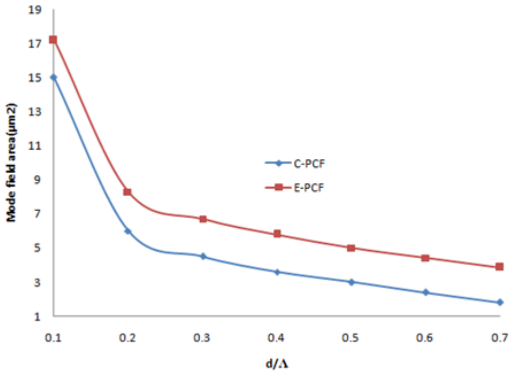

Figure 5. Mode field area versus dia/pitch of purposed PCFs.

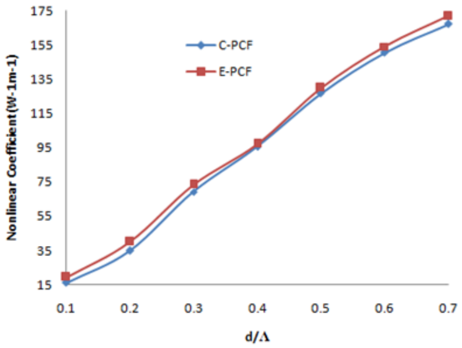

Figure 6. Nonlinear coefficient versus dia. /pitch of purposed PCFs.

The mode field area (Aeff) values are 3.6μm2 and 5.8μm2 for C-PCF and E-PCF on =0.4 at a wavelength of 1250nm. In fact, nonlinearity γ (=) is inversely proportional to mode field area. Nonlinear effects are very advantageous in different optical devices and optical applications such as broadband amplification, channel demultiplexing, wavelength conversion, solution formation,optical switching and many more application. Fig.6 shows the variation of nonlinear coefficient on value. γ increases with increasing of value and it is analyzed that, the proposed PCFs clarifying their values 95.62 W-1m-1 and 97.31W-1m-1 for both C-PCF and E-PCF corresponding values of Aeff are 3.6μm2 and 5.8μm2 respectively for same proposed PCFs structure at on =0.4 .It is evident that, as d/Λ value increases, the core size decrease which restrict maximum allowable pump power(Pmax) for undistorted output pulse from the PCFs. Fig.7 predicts that the maximum allowable pump power on d/Λ value of proposed PCFs. Pmax decrease with decreasing value. Since of proposed PCF is inversely proportional to the mode field area Aeff, hence power handling ability of proposed PCF falls because of confinement of field with in the small core region, as a result reduction in maximum allowed pump power, e.g the value of Pmax of C-PCF is 3.12mW while 5.18mW for E-PCF at =0.4 .

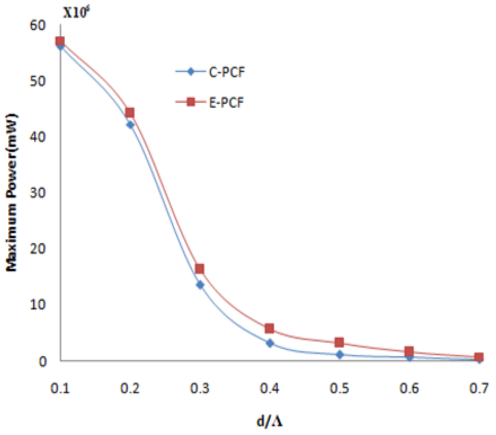

Figure 7. Pump power versus dia./pitch for purposed PCFs.

The confinement loss plays a significant role for features of proposed PCFs. The C.L curve of our proposed PCFs for different value of is shown in fig.8.

The results suggest that, C.L decreases on increasing value, it has large value for small value of =0.1 and vice versa, because of light is much more confined within the small core region, this is due to fact that on increasing air hole diameter d and also the different between effective refractive index of core and cladding increases which in turn higher confinement of light in the core region.

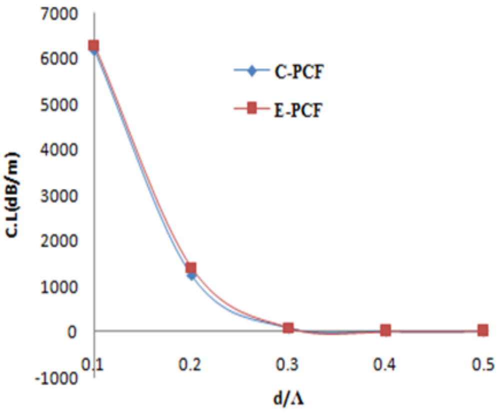

Figure 8. Confinement Loss versus d/Λ of proposed PCF.

Among proposed PCFs, elliptical air hole PCF enhances their confinement of light more in the core region over the circular one. The impact of B.gain on influence of value for 1m length of PCF has been demonstrated in fig.9.

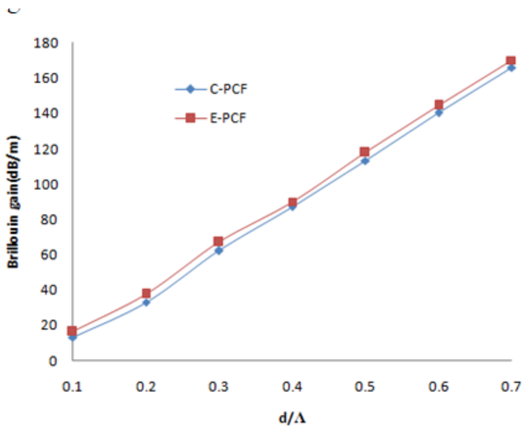

Figure 9. Brillouin gain versus dia/pitch of proposed circular and elliptical PCF.

B.gain increases on increasing the value of , as a result mode field area Aeff propagating mode falls when AFF increases, which leads the light beam is confined with in the smaller core region, thereby significantly improvement of B scattering and ultimately more is the B.gain. It has very small value at =0.1 and large value at =0.4. e.g B.gain is found to be 13.2dB/m and 16.4dB/m for both circular and elliptical PCF at =0.1. Similarly B.g is found to be 87.2dB/m and 90dB/m for C-PCF and E-PCF at =0.4. To verify the theoretical prediction of pump power versus time delay of 1m long PCF with d/Λ=0.4 has been shown in fig.10.

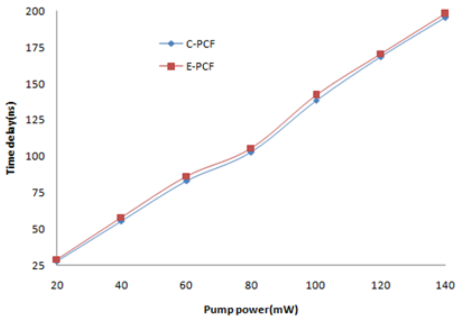

Figure 10. Pump power versus time delay of Circular and elliptical PCF.

It is found that, the time delay in output pulse improved linearly on increasing pump power in both proposed PCFs. The time delay can be tuned between 27.8ns and 138.64ns at pump power of 20 to 100 mW for C-PCF using 1m long PCF with =0.4 while 29ns and 142ns at pump power of 20 to 100 mW for E-PCF using same structural parameter. Experimentally and theoretical evidenced that, E-PCF shows more pump power over C-PCF, hence the desired time delay can be determined by tuning the pump power for our proposed PCF. The above result seems to be applicable for higher optical power which substantially contributes to phonon population in optical communication system.

Conclusion

In conclusion, a highly nonlinear As2Se3 Chalcogenide PCF is proposed and the influence of structures of this kind of fiber on BGS, Brillouin threshold, Brillouin gain as well as tunable slow light generation based on SBS is investigated. We found that the properties of slow light are more affect by varying the air filling fraction in the inner cladding, but less affect by varying the air filling fraction in the outer cladding. We have estimated and clarify that, the PCF having some characteristics like maximum allowable pump power, B.gain and time delay produced by pulse for slow light generation. The same property has been compared and analyze for both circular and elliptical PCFs. It is found that B.gain reaches 87.2dB/m of C-PCF and 90dB/m of E-PCF. In addition, the maximum time delay is obtained as 138.64ns of C-PCF and 142ns of E-PCF by setting to 1m long PCF which pumped with 100mW for both C-PCF and E-PCF. From above comparison, we have been noticed that, E-PCF showed good result over C-PCF even though the fabrication of E-PCF being very difficult. From the above result, it can be compared to earlier report [22, 23] for C-PCF signify that a very high B.gain can be obtained with respect to a very low pump power. But it is evident that E-PCF has more significant improvement of above PCF characteristics. Furthermore, time delay can also be tuned with pump power for same two PCF and hence slow light generation can be obtained from proposed PCFs. These PCFs are highly exceptional to potential application in realization of compact slow light generation.

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