Design and Analysis of Single Mode Photonic Crystal Fiber for Generation of Slow light with tunable features

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***Abstract*—Single mode photonic crystal fiber for the generation of tunable slow light using As_2Se_3 and As_2S_3 is designed. The parameters involved in production of slow light such as Maximum allowable pump power, minimum pump power, brillouin gain, time delay obtained by the propagating pulse are analyzed for the above mentioned materials. These two materials experience a same time delay of 110 ns. It is found that the proposed design with the As_2Se_3 material work in low pump power compare to As_2S_3.**

***Keywords*—photonic crystal fiber, stimulated Brillouin scattering, slow light.**

I. INTRODUCTION

Slow light is the of process of slowing down speed of the light by reducing the group velocity by the principle of stimulated Brillouin scattering. It is used in many application such as optical storage, optical buffering which is the temporary storage of light, optical packet switching, jitter correction to achieve constant delay in the occurrence of event, data synchronization, optical signal processing, interferometer for determining the wavelength of light and to check the imperfection of mirror and lens [1] ,[2].

Photonic crystal fiber is used for generation of slow light .The main advantage of PCF over other conventional fiber are it is considered as high nonlinear fiber and it can generate slow light at low pump power, it tightly confines both light and sound acoustic interaction [3]. The propagation of light is `superior than the other fiber .It consist of air holes on the cladding part of the fiber the air hole in PCF is doped with the air whose refractive index is consider as 1and the other part other than air holes is filled with material which has high nonlinearity .This is because in order to achieve SBS the non-linearity should be high.

Slow light can be produced by different methods such as stimulated Raman scattering (SRS) and stimulated brillouin scattering. But the main advantage of simulated brillouin scattering is that it has the possibility of varying the time delay by tuning the pump power .The other advantages of stimulated brillouin scattering is that it can operate at room temperature and it requires moderate pump power[4] . In this paper, we have designed and analyzed the comparison between As_2Se_3 (arsenic triselenide) and As_2S_3 (arsenic trisulfide) doped inside the PCF using FEM (finite element method). The influence of PCF on maximum pump power, minimum pump power, brillouin gain, time delay experienced by the signal have been compared for these two material.

II. SIMULATED BRILLOUIN SCATTERING

The two light beam are sent into the photonic crystal fiber. One beam is a strong laser beam and the other is a weak laser beam which is sent from two ends of the photonic crystal fiber because of the electrostriction both the beam give raise to density fluctuation which produces an acoustic wave (i.e. sound wave) which travels in the direction of pump wave. The acoustic frequency is equal to the frequency of pump and the signal wave. Thus the pump wave produces backward scattering due to the travelling grating this down shift the frequency of pump to that same level of the signal and produces photons simultaneously. Thus due to this grating effect the refractive index changes with frequency which lead to the increase in group index that decreases the group velocity of the pulse. This called as the principle of SBS on slow light [5].

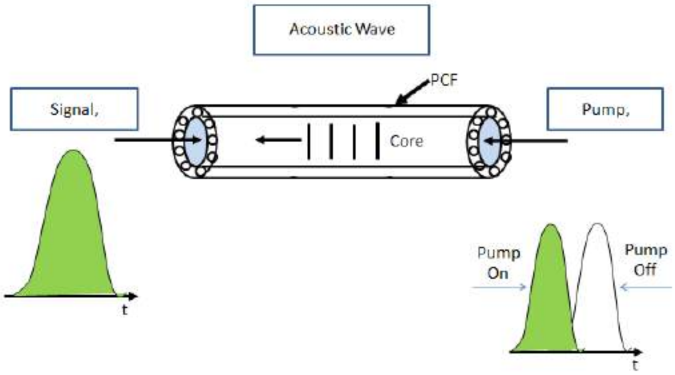

Fig.1.Principle of SBS

III. PRINCIPLE OF SBS ON SLOW LIGHT

In SBS, the coupling between two counter propagating optical waves and a longitudinal acoustic wave takes place. If two signal have the frequency difference equal the frequency of the wave, the interaction can lead to the formation of a fiber Bragg grating within the core of a fiber which can diffract the light from the higher frequency wave into the lower frequency wave[6]. As a result of this the signal wave can experience a gain

$$G_b(\Omega) = \frac{G_p(T_B/2)^2}{(\Omega-\Omega_B)^2+(T_B/2)^2} \quad (1)$$

Where G_p is the peak Brillouin gain at $\Omega=\Omega_B$ which is given by the relation

$$G_B(\Omega) = \frac{2\pi N^7 P_{12}^2}{C\lambda_P^2 \rho_0 V_A} \quad (2)$$

Here ρ_0 is the density and P_{12} is the longitudinal elasto-optic coefficient. The full width at half maximum of the gain spectrum is related to T_B by the relation $V_B = T_B/(2\pi)$; where T_B is the Brillouin line width.

The effective mode area A_{EFF} is defined as

$$A_{EFF} = \frac{(\iint_{-\infty}^{\infty}|E|^2 dxdy)^2}{(\iint_{-\infty}^{\infty}|E|^4 dxdy)} \quad (3)$$

Where E is the electric field distribution of the fiber inside the core. The nonlinear coefficient (γ) of the PCF is given by the relation

$$\gamma = \frac{2\pi n_2}{\lambda A_{EFF}} \quad (4)$$

Where n_2 is the nonlinear coefficient of the material. The Brillouin gain coefficient of the fiber can be calculated using the relation

$$\text{Gain} = 10\log\left[\exp\left(\frac{G_b k p_0 L_{EFF}}{A_{EFF}} - \alpha L\right)\right] \quad (5)$$

Where p_0 is the pump power and k is the polarization factor, while maintaining the polarization this value is considered as 1 and if the polarization is not maintained it is considered as 0.667.

Here we have taken the value of k=0.667.The maximum pump power is defined as

$$P_{max} = 21\frac{A_{EFF}}{kG_b L_{EFF}} \quad (6)$$

The minimum pump power is defined as

$$P_{min} = \frac{\alpha L A_{EFF}}{kG_b L_{EFF}} \quad (7)$$

Where L is the actual length of the fiber which is 5m, α is the attenuation constant of the fiber and L_{EFF} is the effective length of the fiber .It is defined as

$$L_{EFF} = \alpha^{-1}\left(1-e^{(-\alpha L)}\right) \quad (8)$$

The time delay varies based on the pump power and is defined as

$$\frac{T_D}{p_p L_{EFF}} = \frac{G_B P_f}{T_B A_{EFF}} \quad (9)$$

The confinement loss of the fiber can be defined as

$$L_C = 8.686\, K_0\, \mathrm{Im}[n_{EFF}] \quad (10)$$

Where $\mathrm{Im}[n_{EFF}]$ is the imaginary part of effective index.

IV. REFRACTIVE INDEX CALCULATION

The refractive index for the material As_2Se_3 and As_2S_3 are calculated from the Sellmeier equation. Both the material has different Sellmeier equation and Sellmeier coefficients.[7] The Sellmeier equation for $As_2Se_3$is given by the relation

$$n^2(\lambda) = a + \frac{b\lambda^2}{\lambda^2-c} + d\lambda^2 \quad (11)$$

Where a, b, c, d are the sellmeier coefficients of As_2Se_3 material. Fig.2 shows the refractive index value for different wavelength of light. In our simulation we have taken 1.06µm.The refractive index for 1.06µm is 2.886.

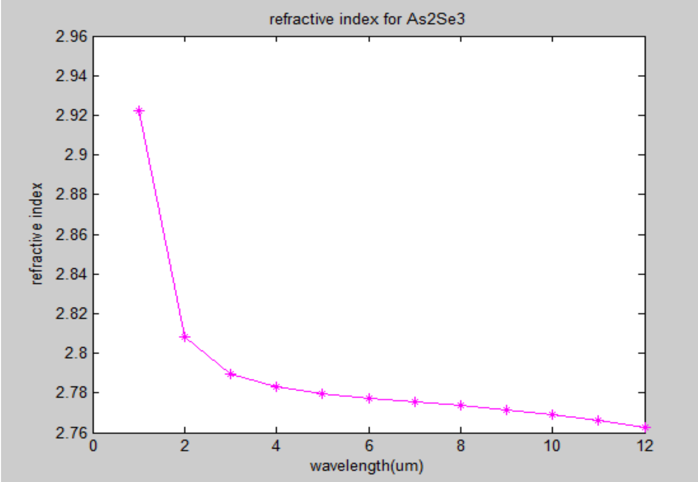

Fig.2 Refractive index of As_2Se_3

The Sellmeier equation for As_2S_3 is given by the relation

$$n^2 = 1 + \frac{a_1\lambda^2}{\lambda^2-{b_1}^2} + \frac{a_2\lambda^2}{\lambda^2-{b_2}^2} + \frac{a_3\lambda^2}{\lambda^2-{b_3}^2} + \frac{a_4\lambda^2}{\lambda^2-{b_4}^2} + \frac{a_5\lambda^2}{\lambda^2-{b_5}^2} \quad (12)$$

Where a_1, a_2, a_3, a_4, a_5 and b_1, b_2, b_3, b_4, b_5 are the sellmeier coefficients of As_2S_3 material. Fig.3 shows the refractive index value for different wavelength of light for As_2S_3 material. The refractive index of $As_2Se_3$for 1.06μm is 2.4693.

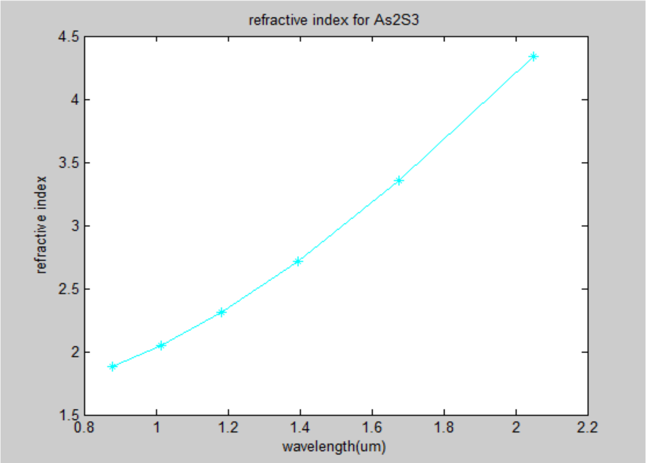

Fig.3 Refractive index of As_2S_3

V. DESIGN

We have proposed the single mode PCF for the generation of tunable slow light. The proposed PCF structure has been illustrated in the fig.4. It consist of 3 rings of air hole which is arranged in triangular lattice pattern doped with two different material As_2Se_3 and As_2S_3.comparison were made for these two material .The diameter of the air holes is represented as‘d’ which is identical for all the air holes and the pitch ‘Λ’ which is the center to center distance of air holes .In this design we have considered the pitch distance as constant 1 μm. The refractive index of As_2Se_3 and As_2S_3 has been taken as 2.886 and 2.4693 at 1.06μm. The effective mode area of PCF varies when‘d’ is changed.

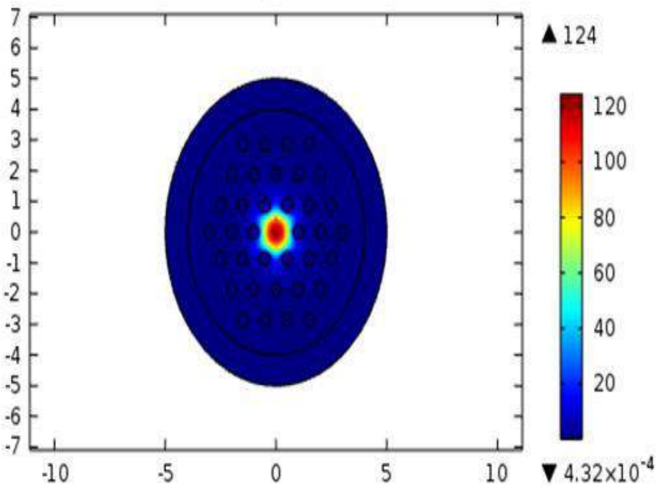

Fig.4 Design of PCF

VI.SINGLE MODE FIBER

In multi-mode photonic crystal fiber the fundamental mode couple with the higher-order modes which has high effective are and lower non linearity. Thus nonlinearity is reduced which needed for Stimulated brillouin scattering effect. This PCF fiber should be in single mode because single modes consist of only one fundamental mode so there will be no coupling of higher order mode. The condition for single mode is that the v parameter that is the normalized frequency of the fiber should be less than π. In order to achieve this single mode operation the value of d/Λ should be less than0.5 [8].

VII. RESULTS

The d/Λ is considered as 0.45 because the single mode operation can be achieved only when d/Λ is less than 0.5.Thus 0.45 is considered for all the material. Air filling fraction (AFF) is the ratio of the diameter of air holes to the pitch. The effective mode area varies based on AFF of the PCF fiber and it is shown in the fig.5.When the air filling factor is increased the effective mode area is reduced .The effective mode area is inversely proportional to nonlinear coefficient which is increased when AFF is increased .From the fig.6 it is determined that As_2Se_3 has high nonlinear coefficient when compared with As_2S_3 material. The maximum pump power (Pmax) is reduced on increasing d/Λ from 0.2 to 0.45.The confinement loss is high when d/Λ=0.2, when d/Λ increases the confinement loss is reduced. This is because when d/Λ is increased the confinement of light will be more thus the confinement loss is also reduced .The confinement loss of the fiber is illustrated in the fig.7. The confinement of light will be smaller when the AFF is reduced and hence the maximum pump power is also decreases .Form the fig.8 it is determined that the maximum pump power of 82mWis achieved for As_2Se_3, which is very low when compared with As_2S_3 material. Similarly the minimum pump power is illustrated in the fig.9.

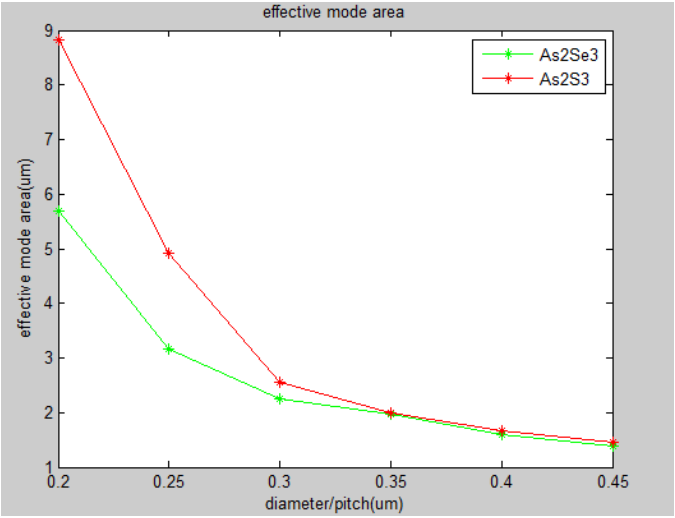

Fig.5. Effective mode area

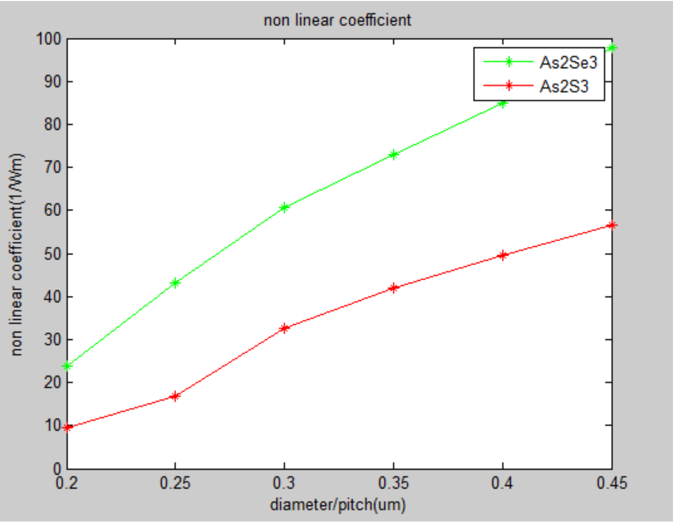

Fig.6.nonlinear coefficient

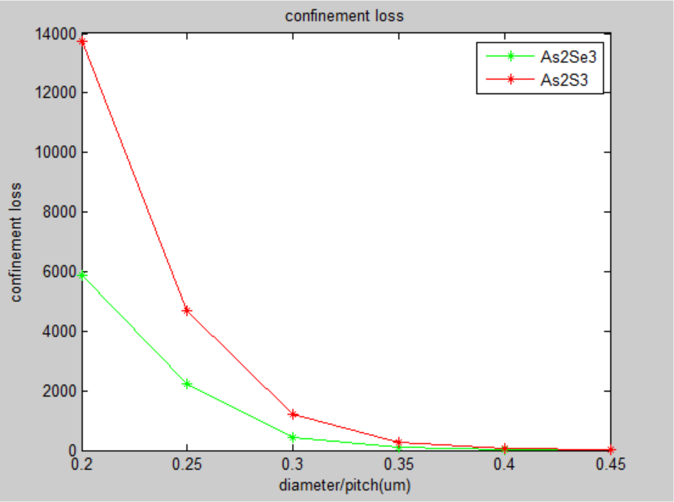

Fig.7. confinement loss

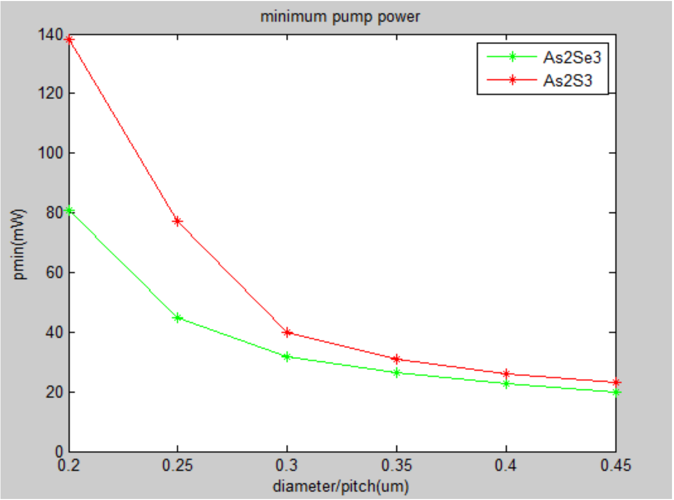

Fig.8.Maximum pump power

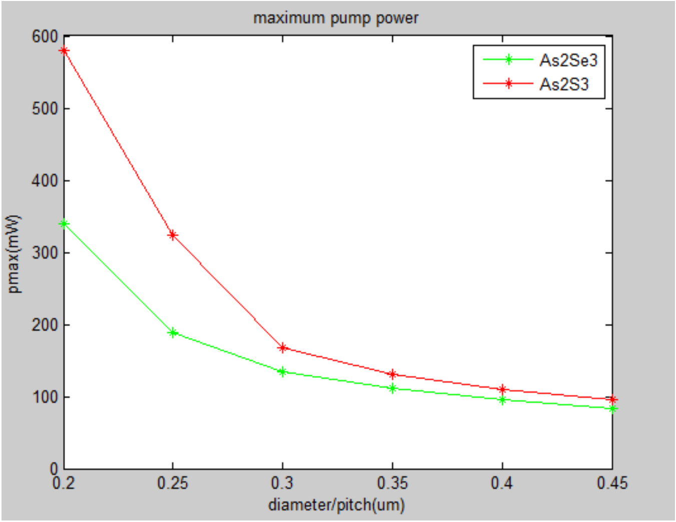

Fig.9.Minimum pump power

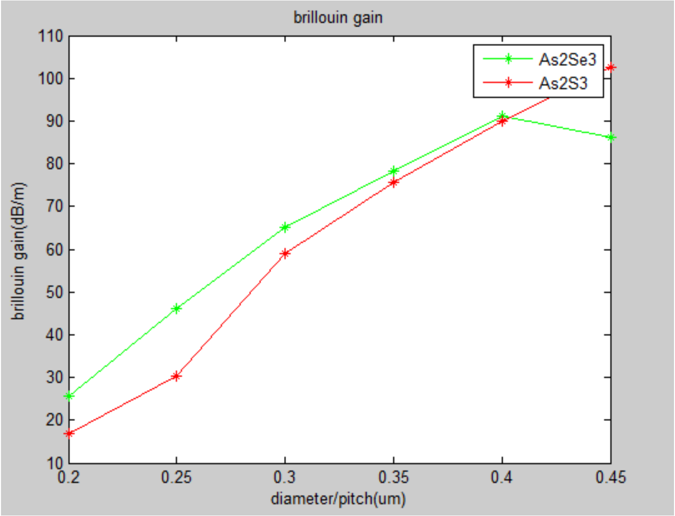

Fig.10.Brillouin gain

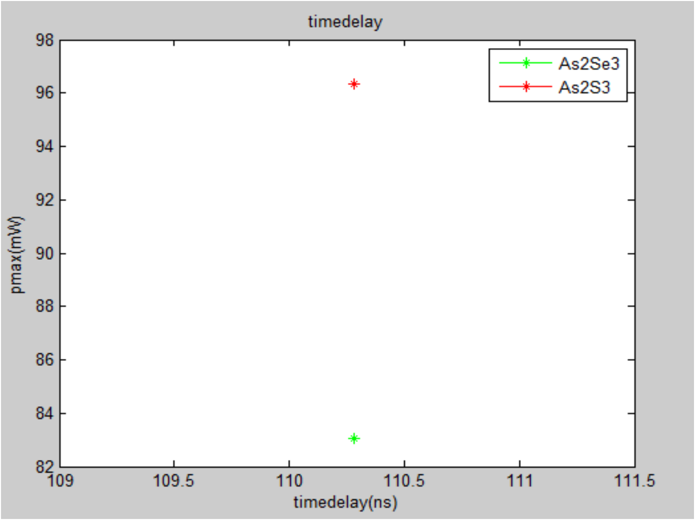

Fig.11.time delay

The influence of AFF on Brillouin gain for 5m length of PCF has been illustrated in Fig.10.The Brillouin gain will increase on increasing the value of d/Λ. When AFF increase the effective mode area decreases. Therefore, on increasing d/Λ, the light is confined inside the smaller core.

At air filling factor d/Λ=0.2 the value of Brillouin gain is low and it will increase on increasing the value of air filling fraction. Influences of the pump power on time delay for a lengthof5m PCF with d/Λ = 0.45 has been illustrated in Fig.11.Time delay increase linearly with increasing pump power .The time delay of upto~110 ns at pump power of 82mW is obtained for As_2Se_3 material when compared with As_2S_3 material the time delay obtained is same but the maximum pump power requirement is low for As_2Se_3 material.

TABLE I
COMPARISION

PARAMETER	As_2Se_3	As_2S_3
BRILLOUIN GAIN	86(dB/m)	102(dB/m)
PUMP POWER	82mW	95mW
NON LINEAR COEEFICIENT	97	56
CONFINEMENT LOSS	1.94	6.27
TIME DELAY	110 ns	110 ns

VIII. CONCLUSION

We have designed and analyzed the comparison of highly nonlinear fiber such as As_2Se_3 and As_2S_3 for the generation of tuneable slow light using SBS principle. The characteristics of fiber for producing slow light such as maximum pump power, minimum pump power, Brillouin gain and time delay experienced by the pulse for the PCF has been calculated and compared. It is found that, both the material produces a time delay of 110ns, but As_2Se_3 requires only less power such as 82mW when compared with As_2S_3 material. Even the confinement loss is also very less 1.94 for As_2Se_3.Thus from the comparison it is concluded that As_2Se_3 has more advantage than As_2S_3 material.

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