Design of Photonic Quasi crystal Fiber for Wide band MidIR Supercontinnum Generation

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ABSTRACT

A chalcogenide (ChG) photonic quasi-crystal fiber (PQF) for wideband mid-IR (MIR) supercontinnum generation (SC) is designed. The numerical demonstration of Supercontinnum generation in the proposed Photonic Quasi Fiber spans from 2 to 15 µm wavelengths for a pulse power of 2 kW. Besides, the proposed Photonic Quasi Fiber offers a high birefringence (10^{-3} to 10-2) from 3.5 to 15 µm wavelengths and exhibits a low confinement loss ($10^{-7}$to 10^{-1}) for the wavelengths from 2 to 15 µm with single mode behavior. The polarized spectral broadening of continuum is realized for the first time from 2 to 15 µm using the proposed Photonic quasi fiber with a length of 8 mm. Thus, the proposed Photonic Quasi Fiber based Super Continuum source is a good candidate for applications such as optical communication, early cancer diagnostics and optical sensing.

Keyword: *Nonlinear optics, Photonic quasi-crystal fiber, Photonic crystal fibers, Supercontinuum generation.*

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1. INTRODUCTION

Ultra-broadband Supercontinnum sources have demand in various applications from material processing to medical [1, 2, 3]. In particular, the broadening of the Supercontinnum spectrum greatly depends on the structural and the pump pulse parameters as well as material properties of the medium. The quality of the SC is greatly improved by controlling the non-linearity, group velocity dispersion (GVD), Confinement loss and birefringence of the optical fibre. These properties are extensively engineered by micro-structured optical fibres (MOFs), which have been considered as a dominant medium in supercontinnum generation (SCG). Unfortunately, the use of silica MOFs in the infrared wavelengths above 2.5 µm are limited by high material absorption [3]. Hence, the attention has turned to non-silica MOFs that include tellurite, fluoride and chalcogenide (ChG) glasses. These superior properties of ChGs are utilized to generate wideband SuperContinuum in MidIR.

The variety of ChG glass Microstructured Optical Fiber such as photonic crystal fiber (PCF) [4], photonic bandgap fiber [5], microporous fiber [6], suspended core fiber [7] and large mode area (LMA) fiber [8] have been analysed theoretically and experimentally in order to tailor the linear and non-linear properties to enhance the SCG.

Recently, Cheng et al. have fabricated $AsSe_2As_2S_5$ (core-clad) hybrid MOF which was pumped with three different wavelengths of 3.062, 3.241 and 3.389 µm for Supercontinnum Generation from 1.256 to 5.400 µm [9]. Further, Kubat et al. have numerically modeled the MidIR-Supercontinnum Generation in the three wavelength ranges of 12.5 µm, 10.7 µm and 10.6 µm in the As-Se/GeAsSe (core/clad) fiber with core diameter of 8, 10 and 20 µm at the length of 2m and 3m, respectively [10]. Besides, Tang et al. have proven the possibility to achieve a low loss in GeAsSe fiber (0.083 dB/m) at a wavelength of 6.6 µm [11]. Very recently, Yu et al. have reported the experimental results on SC spanning from 1.8 to 10 µm by pumping at 4 µm wavelength in a small core GeAsSe/GeAsS (core/clad) fiber with a length of 11 cm [12]. Among the various MOFs, we prefer the six-fold symmetry PQF due to its single mode maintaining characteristics up to an air-filling ratio of 0.525. In the recent past, the PQFs have been used widely to tune the fiber characteristics such as single mode behaviour [13], large mode area [14], birefringence [15], dispersion [16] and non-linearity [17]. Besides GVD and non-linearity, the polarization is also an essential characteristic in the dynamics of Supercontinnum generation in mid IR region. Generally, a high birefringence can be achieved in the microstructured optical fiber by following any one of the structural variations such as elliptical air holes, holes with liquids and non-uniform air holes. However, extending a high birefringence and a low confinement loss (CL) beyond 10 μm wavelength is restricted in the PCF by means of an air-filling fraction. The maximum value of air-filling ratio to maintain the single mode nature in PCF is 0.44 [18]. This value restricts the increase of the air hole size which in turn results in high losses for fundamental mode (FM) in longer wavelengths.

In this paper,the propose numerical demonstration of GeAsSe Photonic Quasi Fiber for MidIR Supercontinuum Generation. We utilize the unique characteristics of PQF (V number =π for the air-filling ratio of 0.525) [19] which offers a great flexibility in increasing the air hole size without compromising the single mode nature of the fiber. Further, the high transparency of $Ge_{11.5}$ $As_{24}Se_{64.5}$ ChG glass in the mid-band region of IR (2-15 μm)is exploits. Besides, the optimized low loss PM PQF shows ZDWs at 4.33 and 4.46 μm for X and Y polarized modes with a non-linearity of 0.2 W^{-1} m^{-1}. These characteristics of the proposed PQF can act as a promising candidate for polarization preserved supercontinnum generation in MidIR region. Furthermore, the numerical demonstration of the Supercontinuum generation for a low peak power of 2 kW at pump wavelength of 4.1 μm results in a broad continuum from 2 to 15 μm wavelengths in the proposed fiber for the length of 8 mm.

2. DESIGN OF THE PROPOSED PHOTONIC QUASI FIBER:

In this section, the design of the proposed low loss polarized maintaing Photonic Quasi Fiber for Super Continuum Genration is discussed. Fig. 1 shows the cross sectional view of the proposed Photonic Quasi Fiber . The fiber consists of air holes with two different diameters that are distributed in the $Ge_{11.5}$ $As_{24}Se_{64.5}$ background. The arrangement of air holes follow the six fold symmetry with four rings of Photonic Quasi Fiber structure. The air hole to air hole spacing is denoted as pitch, λ and fixed as 8 μm, since, below this value the field does not confine into the core. On the other hand, when λ exceeds 8 μm, the Confinement Loss increases and concurrently, birefringence gets reduced. This structure has two large air holes in the first ring with a diameter of d_L, varies from 6.4 to 6.6 μm. The lower limit of d_L is determined based on the previous study on high birefringence [19]. On the other hand, the upper limit of d_L is fixed such that the merging of adjacent air holes during the fabrication can be avoided.

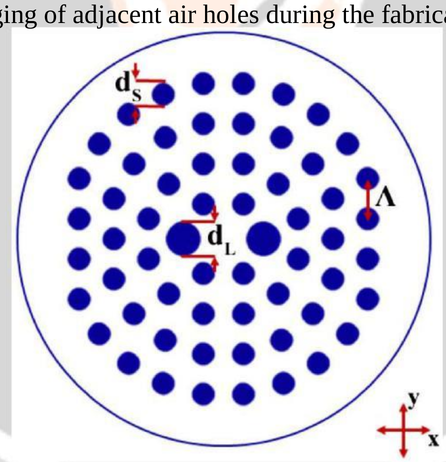

Fig -1: Cross section of proposed polarized maintaing Photonic Quasi Fiber. White back-ground and blue circle signifies $Ge_{11.5}$ $As_{24}Se_{64.5}$ glass and air holes, respectively.

3. MODEL CHARACTERISTICS OF PROPOSED PHOTONIC QUASI FIBER:

In this section, as a first step, the effective index of Fundamental Mode for the proposed PQF by using the full vectorial finite element method (FEM)is calculated. This effective index is an elementary parameter to estimate the linear properties such as Confinement Loss, birefringence, group velocity dispersion (GVD) and higher order dispersions (HODs).

3.1 Confinement loss and birefringence

In this sub-section, the air hole diameters of d_S and d_L in order to achieve the low CL and the high birefringence, respectively is optimized.

Fig.2 shows the confinement loss of fundamental mode as a function of wavelengths when d_S = d_L = 3.8 μm and 4.2 μm for X and Y polarization modes. From the figure, it is very clear that the CL gets decreased while the diameter of the air hole, d_S is increased. In addition, the CL increases when the wavelength increases. In particular, the CL is maintained lesser than 0.1 dB/m and 0.05 dB/m when diameter of the air holes are 3.8 µm and 4.2 µm, respectively, for all the wavelengths from 2 to 15 µm. According to report on [20], single mode behaviour is found to be $V_{PCF} < \pi$ for air filling ratio of 0.44. This criteria restrict the extending of air hole diameter in PCF. At the same time, six-fold symmetry PQF explore that $V_{PQF} < \pi$ is obtained up to the air filling ratio of 0.525. This lime-lighting property of PQF offers the high degree of freedom to vary the air hole diameter of d_S from 3.8 to 4.8 µm for fixed λ of 8 µm in order to achieve d_S/λ ratio variation from 0.475 to 0.525 to sustain the single mode behavior. Hence, the maximum limit of d_S exceeds 4.2 µm, d_S/λ ratio is increased above 0.525 that has disturb the single mode behavior in the proposed PQF. Therefore, we fix the proposed PQF with the diameter of the air hole (d_S) as 4.2 µm (i.e: to achieve the maximum limit of air filling fraction of 0.525 to sustain the single mode behavior in the proposed PQF), since, it greatly exhibits a low Confinement Loss without disturbing single mode nature for the wide wavelength region from 2 to 15 µm. Generally, the 6-fold symmetry PQF possesses very low birefringence (10^{-7}) due to the absence of asymmetric core structure.

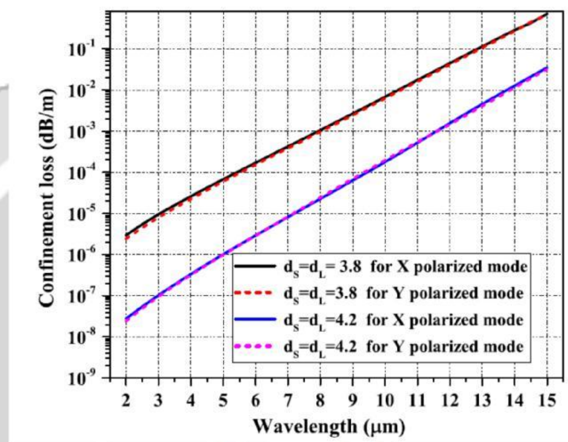

Fig -2: Variation of confinement loss against wavelengths when $d_S = d_L$ = 3.8 µm and 4.2 µm for X and Y polarized mode

Fig. 3 shows the variation of phase and group birefringence as a function of wavelengths for two different diameters of d_L such as 6.4 and 6.6 µm. From Fig. 3, it can be seen that the birefringence gets increased when the wavelength is increased. This is because of the increment in the difference between the effective indexes of two orthogonally polarized modes. Further, the increase in large air hole diameter, d_L eventually increases the birefringence because of the change of core structure from symmetric to asymmetric. When d_L is fixed as 6.4 µm, the proposed ChG PQF exhibits the birefringence in the range from $1.8 * 10^{-4}$ to $7.4 * 10^{-2}$ for the wavelengths from 2 to 15 µm. On the other hand, when d_L is increased to 6.6 µm, the birefringence gets increased in the order of $2.46 * 10^{-4}$ to $9.86 * 10^{-2}$ for the wavelengths from 2 to 15 µm. Amongst the two d_L values, we fix 6.6 µm, since, it reinforces the high birefringence for a broad wavelength region from 2 to 15 µm. Furthermore, the beat length of $Ge_{11.5} As_{24}Se_{64.5}$ PQF varies in the range of 8 mm to 0.1 mm for 2 to 15 µm wavelengths.

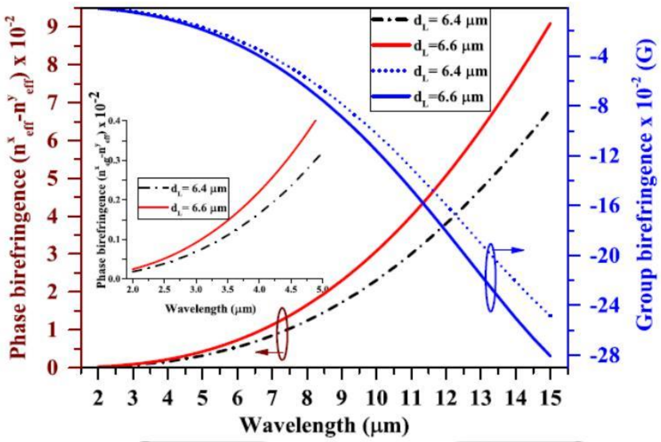

Fig -3: Variation of phase birefringence and group birefringence against wavelengths for d_L = 6.4 µm and 6.6 µm when d_S =4.2 µm. Inset, variation of phase birefringence for a wavelength range of 2 to 15 µm.

3.2 Calculation of birefringence using electrical field distribution

The proposed PQF is highly birefringence, the need for a polarizer in the output of the Photonic Quasi Fibre based Supercontinnum source is not required while the pump polarization is aligned along any one of the principal axes. Moreover, the preserved polarization in the proposed Photonic quasi fibre improves the nonlinear interactions, hence, the power required to generate the SC is very minimal. Furthermore, the proposed PQF can generate two continua simultaneously with orthogonal polarizations which allows an additional degree of freedom to tune the properties of the SC. Hence, the results of Fig. 4 confirm that the proposed $Ge_{11.5}As_{24}Se_{64.5}$ PQF has prominent PM characteristics for SC generation in the wide wavelength range from 2 to 15 µm at dL = 6.6 µm. Figure 4. (a) (b) shows the electric field distribution for X and Y polarized FMs of the proposed $Ge_{11.5}$ $As_{24}Se_{64.5}$ PQF in the wavelengths of 4.1 and 15 µm, respectively. Figure 4 represent the field confinement of FM for X and Y polarized modes with a high B value of 2.14 × 10−3 at a wavelength of 4.1 µm. Subsequently, Figs. 4 (c) and (d) depict the field confinement of FM for X and Y polarized modes with an ultra-high B value of 9.86 × 10−2 at a wavelength of 15 µm.

3.3 Dispersion

In this sub-section, the dispersion characteristics of the proposed polarized maintaining Photonic Quasi Fiber is discussed. The variation of dispersion against wavelengths for both fast and slow axes of the proposed PM PQF is shown in Fig. 5. One can observe that the dispersion value for both fast and slow axis has the same value of -2.836 (ps/Km.nm) when the wavelength is 4.1 µm. Moreover, the ZDW of the slow and fast principle axes modes are observed at 4.33 and 4.46 µm, respectively. Hence, we have selected the source pump wavelength at 4.1 µm in order to realize a wide-band parametric spectrum. From the Fig. 5, it is clear that the fast axis mode possesses the high anomalous dispersion values compared to slow axis mode beyond the wavelength of 8 µm. This is because of large second derivative of the effective index of the fast axis mode

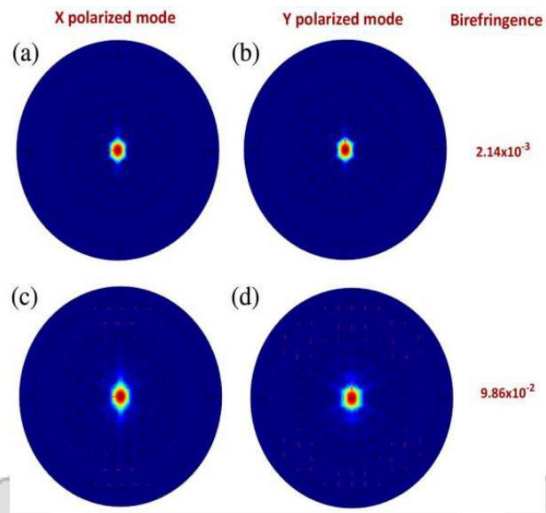

Fig - 4: Electric field distributions of FM for the proposed PQF in the wavelengths of 4.1 µm [(a) and (b)] and 15 µm [(c) and (d)] for X and Y polarized modes.

up to the wavelength of 15 µm. These results of this sub-section describe that the proposed polarized maintaing Photonic Quasi Fiber shows the negative dispersion in the lower wavelengths up to 4.2 µm and less positive dispersion regime beyond the wavelengths of 4.4 µm. Thus, this dispersion profile of both the X and Y polarized modes are expected to enhance the continuum broadening for a wide range of wavelengths in MIR.

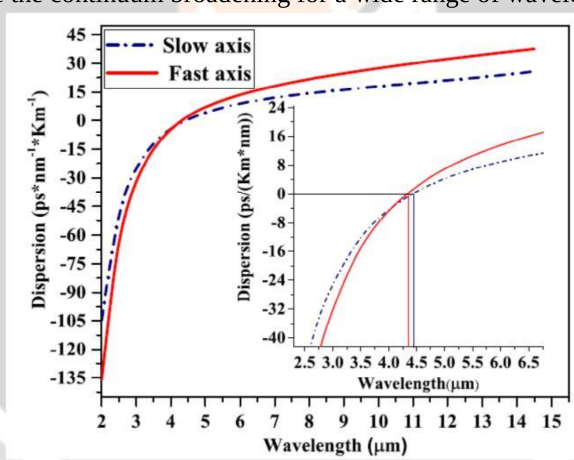

Fig - 5: Changes in dispersion characteristics for the slow and fast axes of the proposed PQF as a function of wavelengths. Inset, changes in dispersion characteristics for a wavelength range of 2 to 6.75 µm for the slow and fast axes.

4. SUPERCONTINNUM GENERATION

Figures. 6 (a) and 6 (b) illustrate the Supercontinnum broadening along the slow (0°) and fast (90°) axes with a power level of −30 dB for various lengths of the proposed PQF. A pulse of 50 fs with a peak power of 2 kW is polarized at 0° and 90° with respect to the X axis of the proposed PQF. When the input pulse is launched into the fiber for a length, L, of 3 mm, the spectrum of slow and fast axes experiences a strong SPM, because, L = 3 mm > L_{NL} (= 2.16 × 10−3 m and 2.13 × 10−3 m for the slow and fast axes, respectively) and L = 3 mm < L_D (=1.2 × 10−2 m and 1.1 × 10−2 m for the slow and fast axes, respectively). At first, SPM dominates in the spectral broadening followed by the soliton fission in which HOSs break up into fundamental solitons around the length of 5 mm for both the slow (L_f = 5.1 × 10−3 m) and fast axes (L_f = 4.8 × 10−3 m). Further, the propagating solitons undergo continuous red shift due to the Raman self-frequency shift for both the axes. Eventually, the spectrum is broadened for the wavelengths from 2 to 15 µm (~2.9 octaves) for both the axes. Further, it is noted that the output spectrum phase evolution of the two orthogonally polarized modes are different due to minimal variation in ZDW, nonlinear lengths and γ for both the axes. Nevertheless, it can also generate almost the same spectrum bandwidth with the

same input peak power and pulse duration for both the axes. Moreover, the results in Figs. 6 (a) and 6 (b) have confirmed that the Supercontinnum spectrum broadening does not change beyond 15 μm for the PQF length of 7 mm for both the axes.

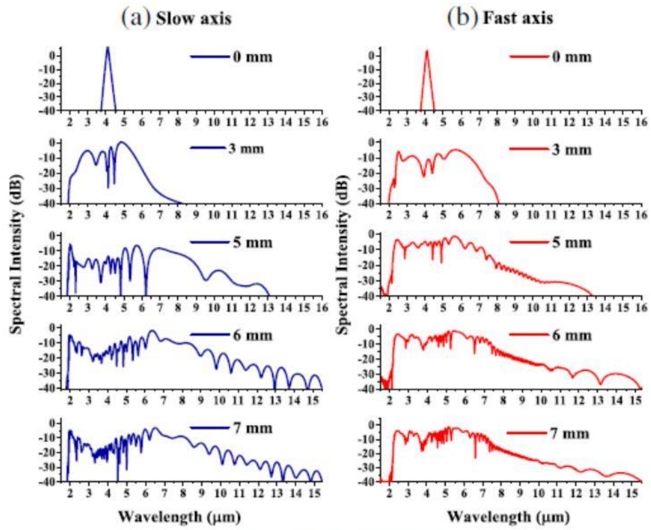

Fig - 6: Numerical demonstration of SC broadening along (a) slow axis (0°) and (b) fast axis (90°) for various lengths of the proposed PQF. The 50 fs input pulse has been launched at the peak power of 2 kW.

5. CONCLUSIONS

In this paper, the Supercontinnum generation in $Ge_{11.5}As_{24}Se_{64.5}$ polarized maintaining Photonic Quasi Fiber is demonstrated. The proposed PQF is designed with two large air holes near the core which provide a birefringence value in the order of 10^{-4} to 10^{-2} for the wide range of wavelengths from 2 to 15 μm. Further, we exploit the unique property of six-fold symmetric PQF (V number = π for the air-filling ratio of 0.525) that provides the flexibility to increase the cladding air hole diameter beyond the limit for PCF. Therefore, the low CL of 10−7 to 10−1 has been achieved for the wavelengths range from 2 to 15 μm with single mode behavior. Further, the polarization preserving spectrum of SC has broadened from 2 to 15 μm wavelengths in the PQF length of 8 mm when the input pulse is at the pump wavelength of 4.1 μm. The enhanced spectral broadening characteristics of Supercontinnum generation in the proposed polarized maintaining photonic quasi fiber can be exploited for applications from medical to material processing.

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