Mid-infrared supercontinuum generation using low peak pump power in $\text{As}_{38}\text{Se}_{62}$ based chalcogenide photonic crystal fiber

S Vyas$^{(a)}$, N S Shiong$^2$, A Kumar$^1$, G Sharma$^1$, Jaiverdhan$^1$, V K Chandna$^1$, G Singh$^3$

$^1$ Electronics and Communication Engineering Department, Jaipur Engineering College & Research Centre (JECRC), Jaipur, 302022, India
$^2$ Institute of Nano Optoelectronics Research and Technology (INOR), Universiti Sains Malaysia, Penang, 11800, Malaysia
$^3$ Electronics and Communication Engineering Department, Malaviya National Institute of Technology (MNIT), Jaipur, 302017, India

$^{(a)}$sandypvyas@gmail.com

Abstract. A supercontinuum (SC) based chalcogenide $\text{As}_{38}\text{Se}_{62}$ PCF for broadband mid-infrared light source is numerically reported. For the computational studies, the design of the proposed structure is made up of three rings of air holes with circular and elliptical shapes. The proposed structure provides excellent nonlinear coefficient and dispersion optimization. For the analysis, the finite difference frequency domain (FDFD) method is employed. Due to the high nonlinear refractive index and optimizing design of $\text{As}_{38}\text{Se}_{62}$ chalcogenide glass, an effective mode area of 40.5972 $\mu\text{m}^2$ is obtained. The dispersion characteristic of the proposed structure has a zero-dispersion wavelength at 3.89 $\mu\text{m}$. The nonlinear coefficient is 761 W$^{-1}\text{km}^{-1}$ at the wavelength of 4 $\mu\text{m}$. Dispersion is almost flat from 2 $\mu\text{m}$ up to 10 $\mu\text{m}$. The supercontinuum spectrum calculated ranges from 2 $\mu\text{m}$ to 9 $\mu\text{m}$. The presented structure is appropriate for medical imaging, optical coherence tomography and optical communications.

1. Introduction

Researchers have studied holey optical fibers or photonic crystal fibers (PCFs) for nearly two decades. The established optical fiber is made up of a cladding and a core. In traditional optical fiber systems, the cladding refractive index is taken lower as compared to the core refractive index. Light passes within the center of the fiber due to the total internal reflection. In the last few years, there has been rapid development in the field of fiber devices and photonic crystal fibers. Photonic crystal fibers are mainly of two types, one hollow-core PCF and the other solid-core PCF. The PCF is formed by an unconventional cladding structure, with periodic patterns of air-vents throughout the fiber. The effective refractive index is reduced by air vents and the coupled light is directed within the core [1-3].

Due to the unique properties of PCFs, there are many applications in the field of sensors and fiber light sources compared to conventional fibers or bulk media. Changes in the size, shape, and position of vents in the microstructured cladding as well as the appropriate choice of a foundation material permit the transmission, dispersion and even nonlinear properties of fibers to be controlled. The dispersion characteristic of any PCF depends on its internal structure. The main feature of PCF is its unique
dispersion behaviour, which includes ultra-flat dispersion characteristics, zero-dispersion wavelength shifting, as well as chromatic dispersion optimization [4-5].

Higher-order dispersions including third-order dispersion along with several nonlinear processes, namely, self-phase modulation, self-steepening, cross-phase modulation, stimulated Brillouin scattering, four-wave mixing and stimulated Raman scattering are responsible for supercontinuum (SC) generation. It is typically evolved by bringing out ultra-short laser pulses (picoseconds, femtoseconds) in extremely nonlinear holey optical fibers with injecting close to zero-dispersion wavelength (ZDW). The transfer of ZDW is done using the modification in geometric parameters of the PCF appropriately, allowing supercontinuum to be generated in a desideratum spectral belt. In the modern-days, SC light source is being used in many scopes namely telecommunication, nonlinear microscopy, optical metrology, cosmological studies, ultrashort pulse generation and optical coherence tomography. The PCF is the most appropriate means for producing an effective SC due to ZDW and group velocity dispersion (GVD) can be controlled in PCF. Dispersion is a major factor for the generation of the SC spectrum, with the help of this creating better SC generation in a certain division. The first condition to achieve a broad spectrum is a low and flat dispersion curve. This can be acquired in PCF geometry by making appropriate changes in the circumference of the core, the circumference of the air vents and the gap between air vents [6-7].

Due to the utility of supercontinuum light sources, a lot of progress has been made in this area over the years. However, SC technology is still in its early days and requires more work beyond 5 micron IR frequencies for industrial applications. Highly nonlinear soft glasses are used for better results in the mid-IR division, namely chalcogenide (As2Se3, As2S3, GeAsSe), heavy metal oxide, Tellurite (TeO2), and ZBLAN. Chalcogenide glass-founded PCFs (made of S, Se, or T) have high-quality photonic utility compared to all other available infrared fibers for nonlinear applications. The broad transmission window, controlled dispersion in infrared range, and large nonlinearity up to hundred times higher than ZBLAN and silica glasses make chalcogenide glass the most suitable material for SCG [8-9].

Non-silica glasses are used for applications in the mid-infrared range, where As2Se3 and As18Se62 chalcogenide glasses are more prevalent because their nonlinear coefficient (~100 times larger) is higher than silica. As18Se62 glass attracts researchers more because of its distinct properties, it has higher stability against crystallization during drawing than As2Se3. SC spectrum broadening cannot achieve more than 2.5 μm in silica material due to absorption, so it is not suitable for the mid-IR region. As18Se62 has a transparency of 2 to 10 μm, in addition, it is a low loss material and has a glass transition temperature (Tg) of 165°C which is suitable for SCG in the mid-IR region [10-11].

Several studies have reported that As18Se62 chalcogenide glass is a low-loss material and is suitable for SCG. Mazhorova et al. demonstrated As18Se62 glass capillaries used as waveguides in the mid-IR range, and fabrication of capillaries by drawing techniques. These capillaries showed low-loss transmission in mid-IR light [10]. Venck et al. fabricated As18Se62 glass microstructured optical fiber by casting method and obtained ZDW at 4.84 micron. In this research, the glass has an absorption peak of about 4.56 micron because of the appearance of Se–H chemical bonds [12]. Numerical and experimental effects on SCG have been presented by Möller et al. in the As18Se62 material from 1.7 to 7.5 μm with 320 fs pulses having ZDW at 3.5 μm [13]. Recently, Ghosh et al. reported on SC expanding from 3.1 to 6.02 micron and from 3.33 to 5.78 micron by pumping at 4 micron and 4.53 micron, respectively [8].

The presented article shows the desired result by modifying the dimension of the air hole in the cladding as required. Here a solid-core PCF is designed to have a dispersion graph in the anomalous zone, with the help of which a chalcogenide-based material produces a broad SC in the mid-infrared zone. The article is organized in the following order. Section 2 describes linear, nonlinear parameter modelling and SC generation. Section 3 introduces the PCF structure fabricated with As18Se62 chalcogenide glass. This section discusses numerical simulations and dispersion plots, nonlinear multiplier and effective mode area. In the next part 4, supercontinuum generation with designed PCF is presented. The investigation of SC generation dealing with the generalized nonlinear Schrödinger equation is also studied in this section. The last segment establishes the results.
2. Numerical model of generation of supercontinuum in PCF

The generalized nonlinear schrödinger equation (GNLSE) is used to study SC generation, taking into account the loss, stimulated Raman scattering, high order dispersion and frequency dependence of nonlinear operate. GNLSE is demonstrated as [5]

\[
\frac{\partial A}{\partial z} + \frac{\alpha}{2} A - \left( \sum_{n=2}^{\infty} \beta_n \frac{\partial^{n+1} A}{\partial z^n} \right) = i \gamma \left( 1 + \frac{i}{\omega_0} \frac{\partial}{\partial t} \right) A(z,t) \int_{-\infty}^{\infty} R(t')|A(z,t-t')|^2 dt'
\]

(1)

where \( A(z,t) \) represents electric field envelope, calculated using the split-step Fourier method, \( \alpha \) represents linear loss, time is represented by \( t \), \( \omega_0 \) represents carrier frequency, \( \beta_n \) represents \( n \)th derivative of the propagation constant \( \beta \), \( z \) represents distance, \( \tau \) represents retarded time travelling at the envelope group velocity and \( \gamma \) represents the nonlinear coefficient, expressed as [14]

\[
\gamma = \frac{n^2 \omega_0}{c A_{\text{eff}}}
\]

(2)

where \( c \) denotes speed of the light in the vacuum, \( n^2 \) represents nonlinear refractive index of fiber \( \text{As}_{38}\text{Se}_{62} \) is \( 1.13 \times 10^{-17} \) (m²/W) [4]. The expression of \( A_{\text{eff}} \) denotes the effective cross sectional of the fiber to the wavelength as [15]:

\[
A_{\text{eff}}(\lambda) = \left( \frac{\int_{-\infty}^{\infty} |E|^2 dx \, dy}{\int_{-\infty}^{\infty} |E|^4 dx \, dy} \right)^{1/2}
\]

(3)

where \( E \) is electric field distribution of the optical fundamental mode of \( \text{As}_{38}\text{Se}_{62} \) PCF cross section. The delayed Raman response function \( R(t) \) in given equation can be written as [16]

\[
R(t) = (1 - f_r) \delta(t) + f_r \frac{\tau_1 + \tau_2}{\tau_1 \tau_2} \exp \left( -\frac{t}{\tau_2} \right) \sin \left( \frac{t}{\tau_1} \right)
\]

(4)

The equation includes the Raman contributions of instantaneous electronic and vibrations \( \delta(t) \). Parameter \( \tau_1 \) relate the inverse of the phonon oscillation frequency and the parameter relates \( \tau_2 \) is the bandwidth of the Raman gain spectrum of the material. The values of the parameters applied in this work for \( \text{As}_{38}\text{Se}_{62} \) chalcogenide glass: \( \tau_1 = 23.14 \, \text{fs} \), \( \tau_2 = 157 \, \text{fs} \) and \( f_r = 0.1 \), represent the fractional contribution of the delayed Raman Response [8].

3. Design of the \( \text{As}_{38}\text{Se}_{62} \) chalcogenide glass PCF

In this section, we have worked on the design of the \( \text{As}_{38}\text{Se}_{62} \) PCF for the study of optical properties. The main objective behind designing PCF is to achieve high nonlinearity and small and flat dispersion in the anomalous dispersion zone. The figure (1) exhibits a cross-section view of the introduced fiber. The cladding area is made up of three rings of different sized air holes. The first ring and the second ring are formed by circular air vents of different diameters so that better light confinement can be obtained in the central area. Elliptical-shaped air vents have been applied to achieve low and flat dispersion in the third ring. The parameters of air vents in the cladding are tabulated in Table 1. The difference between two adjacent holes is determined by the pitch.
Figure 1. The introduced $\text{As}_{38}\text{Se}_{62}$ PCF structure

Table 1. Design parameters of fiber introduced.

| Ring  | Diameters Air- Holes | Pitch ($\Lambda$) |
|-------|----------------------|-------------------|
| Ring-1 | 5.075 $\mu$m           |                   |
| Ring-2 | 5.8 $\mu$m             | 7.25 $\mu$m       |
| Ring-3 | $d_y=6.525 \mu$m   | $d_x=5.8 \mu$m   |

The geometric parameters of the PCF have been chosen such that with their help the dispersion in the anomalous zone and the wavelength of zero-dispersion near the inject wavelength available in the mid-infrared zone can be achieved. The Sellmeier equation is employed to determine the refractive index as a function of wavelength, using the following Sellmeier equation for $\text{As}_{38}\text{Se}_{62}$ [8].

$$n^2(\lambda) = 3.7464 + \frac{3.9057\lambda^2}{\lambda^2-(0.4073)^2} + \frac{0.9466\lambda^2}{\lambda^2-(40.082)^2}$$

The finite-difference time-domain (FDTD) mechanism has been applied to investigate the optical effects of the designed PCF. The sum of the current waveguide dispersion $D_{W}(\lambda)$ and material dispersion $D_{M}(\lambda)$ in any fiber determines the chromatic dispersion $D_{C}(\lambda)$ of the fiber [5].

$$D_{C}(\lambda) = D_{M}(\lambda) + D_{W}(\lambda)$$

$$D(\lambda) = -\frac{\lambda}{c} \frac{d^2}{d\lambda^2} \text{Re} [n_{\text{eff}}(\lambda)] = -\frac{2\pi c}{\lambda^2} \beta_2(\lambda)$$

where $\lambda$ represents the operating wavelength, $n_{\text{eff}}$ represents effective refractive index of the fiber and $\beta$ represents propagation constant.

Numerical simulations of the optimized PCF design have achieved a broad dispersion over the anomalous zone as portrayed in figure (2). A wavelength of zero-dispersion at 3.89 $\mu$m has been obtained with dispersion in the anomalous region that is suitable for pumping the PCF with a peak pulse at the inject wavelength of 4 $\mu$m.
The two important parameters for obtaining a comprehensive supercontinuum are the nonlinear multiplier and the effective area obtained from the fundamental mode of fiber. This part simulated a numerically optimized design to obtain nonlinear coefficients and effective area values and is plotted in figure (3) for wavelengths taking the obtained results. At a inject wavelength of 4 μm, the nonlinear multiplier is evaluated as \( \gamma = 761 \text{ W}^{-1} \text{ km}^{-1} \) and the effective mode area \( (A_{\text{eff}}) = 40.5972 \text{ µm}^2 \).

**Figure 3.** The nonlinear multiplier and effective mode area in the As\(_{38}\)Se\(_{62}\) fiber

4. **Simulations of SC in proposed fibers**

The generation of supercontinuum is a complicated phenomenon that involves the creation of a specific combination of multiple nonlinear effects occurring under high-intensity pumping, in consequence broadband spectral coverage, spatial coherence and high-power spectral density. In this segment, we will discuss the generation of supercontinuum. After calculating both the non-linear and linear parameters of the introduced fiber at a inject wavelength of 4 μm, including chromatic dispersion in the anomalous dispersion region close to the wavelength of zero-dispersion. The extrication of GNLSE has been obtained by the symmetric split-step Fourier method for input pulses in both the time and frequency domains. The electric field distribution of the propagating mode is demonstrated by figure (4). Figure (5) depicts spectral evolution in fiber length of 1.33 kW, and 252 fs, input pulse having a secant hyperbolic pulse profile shown as [5,11]
\[ A(z = 0, t) = \sqrt{P_0 \text{sech} \frac{t}{T_0}} \exp \left( -i \frac{c}{2} \frac{t^2}{T_0^2} \right) \]  

(8)

where \( P_0 \) represents peak power and \( T_0 \) represents input soliton time span. The wide-band SC spanning from 2000 nm to 9000 nm was obtained by pumping the inject at 4 \( \mu \)m pump wavelength was obtained from 200 mm long PCF. The spectral growth of the 1.33 kW input pulse for various distance is displayed in diagram (6).

Some nonlinear processes are mostly responsible for the generation of supercontinuum in anomalous dispersion zone namely self-phase modulation, stimulated Raman scattering, soliton dynamics, and dispersive wave. The process of forming supercontinuum is mainly in two phases, in the first phase spreading because of self-phase modulation (SPM) and the second phase expanding due to stimulated Raman scattering, four-wave mixing and dispersion. After a spread of short distance (mm), the spectrum is split over the pair of peaks, after exiting the initial pump wavelength the number of sub-peaks between the pair of peaks continues to increase, resulting in the generation of spectra [16].

![Electric field distributions in As\textsubscript{38}Se\textsubscript{62} PCF](image)

**Figure 4.** Electric field distributions in As\textsubscript{38}Se\textsubscript{62} PCF

![Evolution of SC spectra at 4 \( \mu \)m pump wavelength](image)

**Figure 5.** Evolution of SC spectra at 4 \( \mu \)m pump wavelength
5. Conclusion
The proposed PCF design has resulted in high nonlinearity of 761 W$^{-1}$Km$^{-1}$ with a significantly effective area of 40.5972 μm$^2$. Extensive SC spectra can be generated even with the use of low pump power from high nonlinearity. Results from simulations of As$_{38}$Se$_{62}$ chalcogenide photonic crystal fibers with a length of 200 mm to SC generation 2 to 9 μm have been achieved. To achieve this, a low pulse peak power of 1.33 kW has been used while taking 252 fs as the pulse duration. The expansion of the SC spectrum depends on the dispersion profile of the fiber and its input characteristics, which have been achieved by changing the PCF parameters. The use of this obtained broadband SC is in the fields of optical metrology, telecommunications, cosmological studies, nonlinear microscopy, optical coherence tomography, and ultra short pulse generation.

References
[1] Sharma M, Konar S 2016 Optics Communications 380 310-319
[2] Pathak P, Zafar R, Kanungo V, Vyas S 2020 Journal of Optical Communications 1
[3] Vyas S, Tanabe T, Singh G and Tiwari M 2016 2016 International Conference on Computational Techniques in Information and Communication Technologies (ICCTICT) (India: Delhi/IEEE) p 607-611
[4] Diouf M, Salem A B, Cherif R, Wague A, Zghal M 2016 Optical Materials 55 10-16
[5] Vyas S, Tanabe T, Singh G and Tiwari M 2016 Ukrainian journal of physical optics 17 132-139
[6] Dinh Q H, Pniewski J, Van H L, Ramaniuk A, Long V C, Borzycki K, Xuan K D, Klimeczak M, and Ski R B 2018 Applied Optics 57 1-9
[7] Gupta V, Kanungo V, Kalia P, and Vyas S 2020 International Conference on Innovative Advancement in Engineering and Technology (IAET-2020) (India: Jaipur/SSRN) p 3548424
[8] Ghosh A N, Meneghetti M, Petersen C R, Bang O, Brilland L, Venck S, Troles J, Dudley J M, and Sylvestre T 2019 J. Phys.: Photonics 1 044003
[9] Vyas S, Tiwari M, Tanabe T and Singh G 2016 Proceedings of the International Conference on Recent Cognizance in Wireless Communication & Image Processing (New Delhi/Springer,) p 409-413

[10] Mazhorova A, Markov A, Ung B, Rozé M, Gorgutsa S, and Skorobogatiy M 2012 Journal of the Optical Society of America B 29 2116-2123

[11] Vyas S, Tanabe T, Tiwari M and Singh G 2016 Chinese optics letters 14 123201

[12] Venck S, St-Hilaire F, Brilland L, Ghosh A N, Chahal R, Caillaud C, Meneghetti M, Troles J, Joulain F, Cozic S, Poulain S, Huss G, Rochette M, Dudley J and Sylvestre T 2020 Laser & Photonics Review 14 1-20

[13] Møller U, Yu Y, Kubat I, Petersen CR, Gai X, Brilland L, Méchin D, Caillaud C, Troles J, Luther-Davies B and Bang O. 2015 Optics express 23 3282-91

[14] Vyas S, Tanabe T, Tiwari M, Singh G 2016 2016 International Conference on Advances in Computing, Communications and Informatics (ICACCI) (India: Jaipur/IEEE) p 2521 – 2526

[15] Kalra S, Vyas S, Tiwari M, Buryy O and Singh G 2018 Acta Physica Polonica A 133 1000-1002

[16] Kalra S, Vyas S, Tiwari M, Ismail Y, Yupapin P, Ali J and Singh G 2020 Journal of Modern Optics 67 920-926