OPTIMIZATION OF OPTICAL PROPERTIES OF $Ge_{20}Sb_5Se_{75}$-BASED PHOTONIC CRYSTAL FIBERS

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Abstract: In this paper, we present a new design of solid-core photonic crystal fiber (PCF), a $Ge_{20}Sb_5Se_{75}$ substrate with a hexagonal lattice structure. The fiber characteristics are studied in the long-wavelength range (from 1.5 µm to 7.0 µm). A full modal analysis and optical properties of designed photonic crystal fibers with lattice constant Λ and filling factor d/Λ are presented in terms of chromatic dispersion, effective refractive index, nonlinear coefficients, and confinement loss. All-normal and anomalous flat dispersion with high nonlinearity and low confinement loss are the outstanding advantages of these photonic crystalline fibers. From there, three optimal structures with $\Lambda = 2.0$ µm, $d/\Lambda = 0.35$; $\Lambda = 2.5$ µm, $d/\Lambda = 0.3$ and $\Lambda = 3.0$ µm, $d/\Lambda = 0.3$ are selected and analyzed in detail for application in supercontinuum (SC) generation.

Keywords: Photonic crystal fiber; dispersion characteristics; chalcogenide; effective mode area; confinement loss; supercontinuum generation.

1. Introduction

In recent years, photonic crystal fibers (PCFs) have been extensively studied in all theories, simulations, and experiments because their optical characteristics can be flexibly controlled through the selection of structural parameters such as fiber core diameter, air hole diameter, lattice constant, substrate material, air hole or hollow-core filling materials. Changing these factors causes significant changes in the optical characteristics of PCFs, this also makes the application of photonic crystal fibers more and more abundant [1], [2]. In optical communication and sensing fields, PCFs have many advantages over conventional optical fibers [3]. In particular, PCFs with high nonlinearity and flat dispersion are good foundations for supercontinuum generation (SCG) [2], [4]. The improvement of the properties of PCFs such as effective refractive index, dispersion properties, effective mode area, nonlinear coefficients, and confinement loss has always been a hot topic attracting many researchers. Among them, dispersion properties are an important factor in the design of PCFs, as it determines the efficiency of SCG. In particular, PCFs with flat dispersion, multiple zero-dispersion wavelengths (ZDWs), and high negative dispersion [4], [5] dominate nonlinear effects in SC generation such as four-wave mixing, self-phase modulation, Raman scattering, soliton, etc. In addition, PCFs with ultra-flat dispersion and low confinement loss are used to generate a broader bandwidth of SC spectrum [6].

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Although silica-based-PCFs have extensively been studied with numerous advantages, silica has a weak nonlinear index. More importantly, any optical applications of silica PCFs should not exceed the limit of 2 µm of wavelength because of their intrinsic losses [7], [8]. Therefore, non-silica glass PCFs must be expected to enhance the application of microstructured optical fibers. Among them, chalcogenide glasses exhibit the strongest glass nonlinearities (typically 500 times stronger than traditional silica glasses [9]). Designing an optical fiber with high nonlinearity, negative dispersion, and large birefringence is a continuous challenge for researchers. In addition, maximizing the bandwidth for the SCG also plays a significant role in the applications of this group of materials.

Currently, numerous studies have demonstrated that nonlinear coefficients change drastically, and ZDW of optical fibers shifts towards longer wavelengths in the range of 4.0 µm-5.0 µm by designing different structures of chalcogenide glass-based PCFs in general and $Ge_{20}Sb_5Se_{75}$-based PCFs in particular [8]-[12]. Furthermore, $Ge_{20}Sb_5Se_{75}$-based PCFs are preferable to silica in fabricating fibers because of their low softening temperature.

In this paper, $Ge_{20}Sb_5Se_{75}$ was used as a host material to ensure high nonlinearity in the broad wavelength region from 1.5 µm to 7.0 µm. Hexagonal lattice PCF was studied with with lattice constant Λ and the same diameters of air holes d. Three optimal structures (Λ = 2.0 µm, d/Λ = 0.35; Λ = 2.5 µm, d/Λ = 0.3 and Λ = 3.0 µm, d/Λ = 0.3) with normal and anomalous dispersion have been proposed to analysis of effective mode area, nonlinear characteristics and confinement loss are of great significance in using these PCFs to generate SC.

2. Modeling and theory

Figure 1a represents the cross-section of the hexagonal lattice PCFs, designed in this research. The structure consists of eight rings of air holes, arranged in an orderly manner in the cladding region. The air holes have the diameter d, the distance between the air holes is lattice constants Λ, and the small core of the PCFs has a diameter determined by the equation $D_c = 2\Lambda - d$. The small core structures help the electromagnetic modes propagate in PCFs over a wide range of wavelengths.

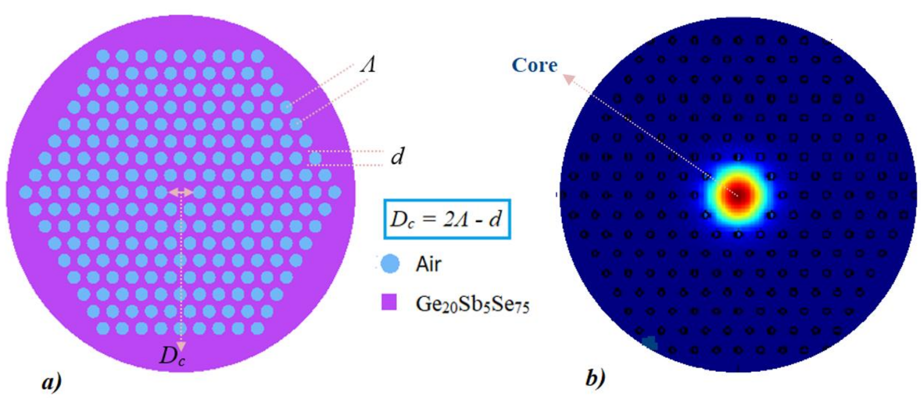

Figure 1: *Geometrical structure (a) and light confined (b) in PCFs with hexagonal lattice and $Ge_{20}Sb_5Se_{75}$ substrate*

In simulations, the PCFs were considered with lattice constant changing from 2.0 to 3.0 µm with a step of 0.5 µm. The filling factor d/Λ is chosen in the range of 0.3-0.8 with a jump of 0.05. A commercial software, Lumerical Model Solution, has been used to calculate the optical parameters of the PCF by using a finite difference method. With such design parameters, the light is confined to the core (Figure 1b).

The mode profiles associated with the eigenvectors and the propagation constants corresponding to the eigenvalues are calculated. Specifically, the chromatic dispersion coefficient (D) of PCFs was calculated from effective refractive index n_{eff} values versus the wavelength as Equation (1) [7].

$$D(\lambda) = -\frac{\lambda}{c}\frac{d^2\,\mathrm{Re}[n_{eff}]}{d\lambda^2}, \tag{1}$$

where Re [n_{eff}] is the real component of the effective refractive index at wavelength λ for each mode and c is the vacuum light speed. Here we have two types of dispersion: normal dispersion state ($D < 0$) and anomalous dispersion state ($D > 0$). The wavelength at which D is suppressed is called the zero-dispersion wavelength (ZDW).

The refractive index of $Ge_{20}Sb_5Se_{75}$ substrate was calculated according to the Sellmeier Equation (2), with the respective parameters listed in Table 1 [12].

$$n^2(\lambda) = 1 + \frac{A_1\lambda^2}{\lambda^2 - \lambda_1^2} + \frac{A_2\lambda^2}{\lambda^2 - \lambda_2^2} + \frac{A_3\lambda^2}{\lambda^2 - \lambda_3^2}. \tag{2}$$

Table 1: *Coefficients of $Ge_{20}Sb_5Se_{75}$ substrate to Equation (2)*

Sellmeier coefficients	Values
A_1	4.7610
A_2	0.06994
A_3	0.8930
λ_1^2 [µm^2]	0.0356
λ_2^2 [µm^2]	0.6364
λ_3^2 [µm^2]	461.72

Following equation can be used to calculate the nonlinear coefficient (γ) of PCFs, which is dependent on the design of cladding structural parameters [8].

$$\gamma(\lambda) = \frac{2\pi}{\lambda}\frac{n_2}{A_{eff}}, \tag{3}$$

where n_2 is the nonlinear refractive index of $Ge_{20}Sb_5Se_{75}$, $n_2 = 4.29 \times 10^{-18}$ m^2.w^{-1} [12] and A_{eff} is the effective mode area of the fiber. The nonlinearity characteristic A_{eff} of PCF is computed from [8]

$$A_{eff}(\lambda) = \frac{\left(\iint |E(x,y)|^2\,dxdy\right)^2}{\iint |E(x,y)|^4\,dxdy}, \tag{4}$$

where $E(x, y)$ is the field distribution of the fiber mode.

The confinement loss (L_c) is another significant characteristic to consider when designing PCFs with a limited number of air holes, and can be calculated by equation (5) [13].

$$L_c = 8.686 \frac{2\pi}{\lambda} \mathrm{Im}[n_{\mathrm{eff}}(\lambda)], \tag{5}$$

where Im[n_{eff}] is the fictitious component of the n_{eff}.

3. Results and Discussion

The real part of the effective refractive index corresponding to the fundamental mode in the wavelength range from 1.5 μm to 7.0 μm was determined and shown in Figure 2.

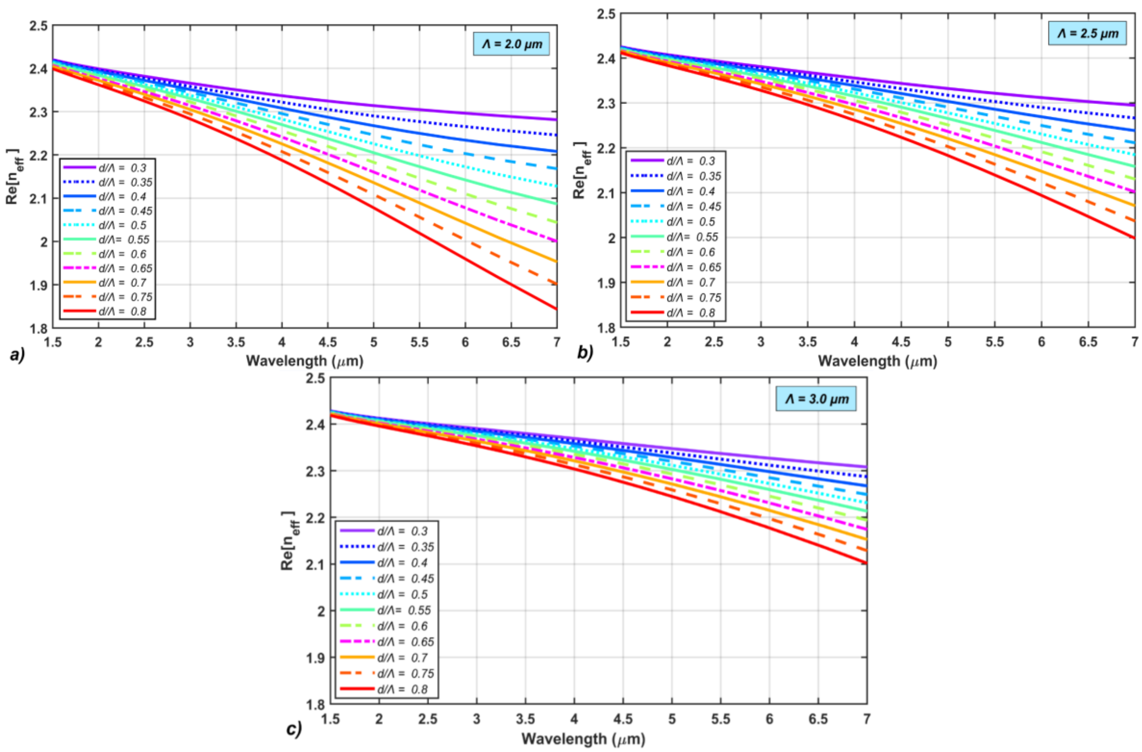

Figure 2: *The real part of effective refractive index defend the wavelength of PCF with various d/Λ for the cases of a) Λ = 2.0 μm, b) Λ = 2.5 μm and c) Λ = 3.0 μm*

In all cases, the effective refractive index decreases monotonically with increasing wavelength due to stronger penetration of long wavelengths into the cladding of PCFs. The variation of the lattice constant *Λ* and the filling factor *d/Λ* also significantly changes the value of the effective refractive index. At a particular wavelength, increasing *d/Λ* causes a decrease in the effective refractive index of PCFs, but increasing *Λ* makes this value increase. It can be seen that the change of effective refractive index is mainly influenced by two parameters: filling factor *d/Λ* and lattice constant *Λ*.

The dispersion parameters of the fundamental mode are one of the important factors in the generation of SC, as they are directly related to the waveguide propagation of different wave components, which propagate at different speeds in the medium. The material and structure of the fibers often govern the value, the number of ZDWs, and the flatness of the dispersion. The total dispersion coefficient D calculated as the combined effect of waveguide dispersion (D_w) and material dispersion (D_m) is given as Equation (1).

Figure 3 shows the dependence of dispersion characteristics on wavelength and the variation d/Λ of the PCF. These graphs show that the dispersion characteristics depend significantly on the diameter of the air holes and the lattice constant. PCF has a small-core diameter (Λ =2.0 µm), and dispersion characteristics are quite diverse with completely normal or anomalous dispersions with two ZDWs, and relatively large slopes (Fig. 3a). This is because with a smaller core, the dispersion of the waveguide is more obvious, and therefore the total dispersion curve changes more strongly [14]. In the investigated wavelength region, dispersions are usually found when d/Λ = 0.3-0.35, while the remaining PCFs exhibit anomalous dispersion with two ZDWs. In particular, we observe that the dispersion is flat and closest to the horizontal axis in the case of d/Λ = 0.35. The normal flat dispersion is very beneficial for the efficiency of SC generation in extending the output pulse.

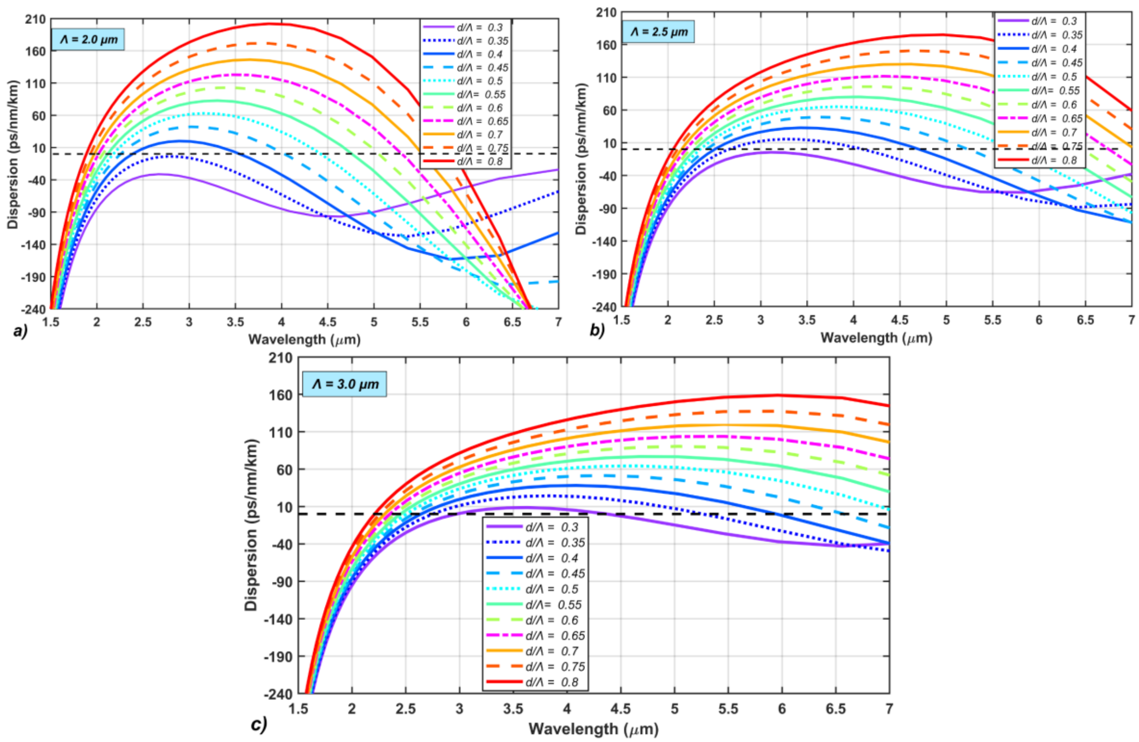

Figure 3: *Dispersion based on wavelength of PCF with various d/Λ for the cases a) Λ = 2.0 µm, b) Λ = 2.5 µm and c) Λ = 3.0 µm*

When the lattice constant Λ =2.0 µm, we obtain dispersion curves similar to the case a) (Fig. 3b) but the slope is much decreased. When d/Λ > 0.65, the dispersion curves have a ZDW. Here there is only one completely normal dispersion curve corresponding to d/Λ = 0.3 which has very high flatness over a wavelength range from 2.2 µm to 7.0 µm.

The characteristic properties of dispersion, including the displacement of ZDW, are strongly influenced not only by the filling factor but also by the value of the lattice constant. Specifically, when increasing the lattice constant Λ = 3.0 µm, the normal dispersion characteristics disappear in the investigated wavelength region, leaving only anomalous dispersions with one or two ZDWs. Although the dispersion curve ($d/\Lambda = 0.3$) has a transition from completely normal to anomalous dispersion, the flatness is maintained in the range of 3.0 μm-4.5 μm of the wavelength (Fig. 3c). From the above results, we propose three structures with optimal dispersion: flat, very close to zero and wide wavelength range with $\Lambda = 2.0$ μm, $d/\Lambda = 0.35$; $\Lambda = 2.5$ μm, $d/\Lambda = 0.3$ and $\Lambda = 3.0$ μm, $d/\Lambda = 0.3$, called $\#F_1$, $\#F_2$ and $\#F_3$ respectively. Their structural parameters are presented in Table 2.

Table 2: *Structural parameters of the proposed PCFs*

#	Λ (μm)	d/Λ	D_c (μm)
$\#F_1$	2.0	0.35	3.3
$\#F_2$	2.5	0.3	4.25
$\#F_3$	3.0	0.3	5.1

Fig. 4 shows the dispersion characteristics of the proposed PCFs. $\#F_1$ and $\#F_2$ fibers have completely normal and flat dispersion curves suitable for supercontinuum generation with a broad spectrum while $\#F_3$ fibers have anomalous dispersion curves with two ZDWs at 2.92 μm and 4.38 μm, respectively. Selected PCFs with diverse dispersion may be suitable for SC generation with the desire to observe more nonlinear effects such as four-wave mixing, self-phase modulation, and soliton with suitable input pulses. The center wavelengths of the input pulses (pump wavelength) chosen for $\#F_1$ is 2.75 μm, and for $\#F_2$ and $\#F_3$ are 3.15 μm.

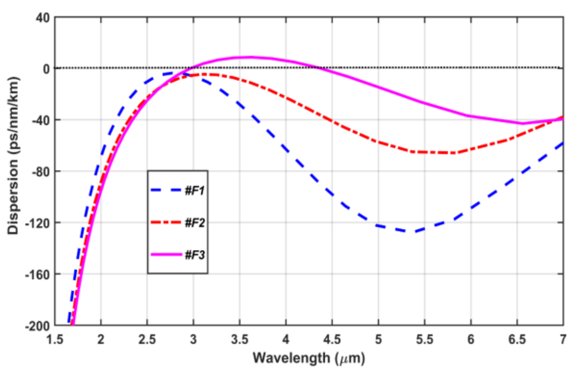

Figure 4: *Wavelength dispersion of the proposed PCFs*

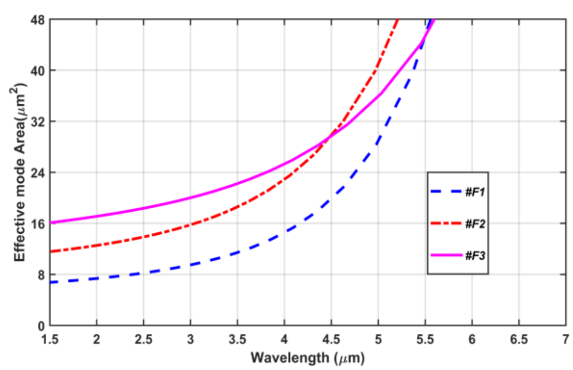

Figure 5: *Effective mode area in wavelength of the proposed PCFs*

The effect of the wavelength change (λ) on the effective mode area (A_{eff}) of the proposed PCFs is shown in Fig. 5. The increase in wavelength makes the value of the effective mode area value increase. $\#F_1$ and $\#F_2$ fibers have this curve almost the same, where the effective mode area of $\#F_2$ fiber is higher than that of $\#F_1$ fiber. The highest value of the effective mode area in the studied wavelength belongs to the $\#F_3$ fiber, that is, the nonlinear coefficient (γ) of this fiber is the lowest compared to other fibers because the nonlinear coefficient is inversely proportional to the effective mode area (Equation 3) while $\#F_1$ fiber has the highest value of the nonlinear coefficient (Fig. 6). High nonlinear PCF is most desirable for SC generated with input energies as low as pico joules (pJ).

The confinement loss characteristics (L_c) of the fundamental mode for #F_1, #F_2, and #F_3 fibers are determined in Fig. 7. In the wavelength region from 1.5 µm to 4.5 µm, there is not much difference in the value of both three fibers. The confinement loss of #F_1 fiber increases suddenly when the wavelength is greater than 4.5 µm, while #F_2 fiber has a lower confinement loss. In particular, the confinement loss of #F_3 fiber is the lowest, this curve almost coincides with the horizontal axis in the range wavelength of 1.5 µm-6.0 µm, from the wavelength of 6.0 µm onwards L_c gradually increases to a value greater than 200 dB/m.

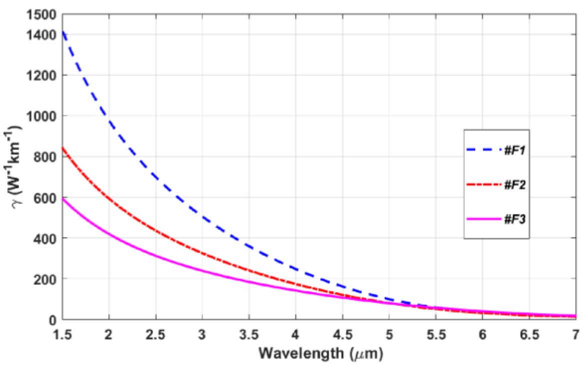

Figure 6: *Nonlinear coefficients of the proposed PCFs*

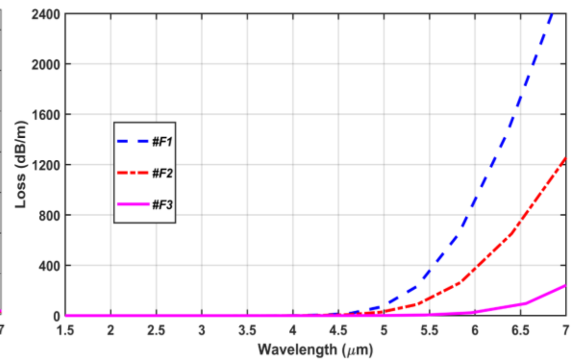

Figure 7: *Confinement loss characteristics of the proposed PCFs*

Table 3: *Values of characteristic quantities calculated at the pump wavelength of the proposed PCFs compared with previously reported values*

Optimized PCFs	Substrate	The pump wavelength (µm)	D (ps.[nm.km]$^{-1}$)	γ (W^{-1}km^{-1})	L_c (dB/m)
[7]	Silica	1.03	-3.81	131.1	4.04×10^{-14}
[10]	Tellurite	2.45	60	378.1	-
[11]	As_2S_3	4.7	32.6	393.8	-
***#F*₁**	$Ge_{20}Sb_5Se_{75}$	2.75	-3.69	580.2	2.32×10^{-14}
***#F*₂**	$Ge_{20}Sb_5Se_{75}$	3.15	-4.52	290.5	3.32×10^{-14}
***#F*₃**	$Ge_{20}Sb_5Se_{75}$	3.15	3.56	235.3	3.43×10^{-14}

The values of the characteristic quantities for calculating the nonlinearity of the proposed PCFs are calculated at the pump wavelength, quoted in Table 3. Among them, the dispersion magnitude of #F_3 fiber is the smallest because it is closest to the zero-dispersion line, its value is 3.56 ps.nm^{-1}.km^{-1} at a pump wavelength of 3.15 µm. Meanwhile, the dispersion values at the pump wavelength of #F_1 and #F_2 fibers are -3.69 ps.nm^{-1}.km^{-1} and -4.52 ps.nm^{-1}.km^{-1}, respectively. The larger the core diameter designs are, the larger the effective mode area is, so the nonlinear coefficient decreases in the studied wavelength region. The maximum and minimum values of A_{eff} are 20.42 µm and 8.85 µm^2 for #F_3 and #F_1, respectively. Besides, the largest core fiber #F_3 has the smallest nonlinear factor of 235.3 W^{-1}.km^{-1}, and here the values of the smaller core fibers #F_1 and

#F_2 are 580.2 $W^{-1}.km^{-1}$ and 290.5 $W^{-1}.km^{-1}$, respectively. The advantage of these selected PCFs is that their L_c values are extremely low, around 10^{-14} dB/m. Comparing this result with the results obtained with similar structures using Silica, Tellurite, and As_2S_3 substrates in the works [7], [10], [11], it is shown that the results from our work sum up many outstanding advantages. The dispersion magnitudes of our structure is smaller and the nonlinear coefficient is higher than that of other publications. The dispersion magnitudes of *#F_1, #F_2, #F_3* are all less than 5 $ps.nm^{-1}.km^{-1}$ while those of [10], [11] are 60 $ps.nm^{-1}.km^{-1}$ and 32.6 $ps.nm^{-1}.km^{-1}$. The nonlinear coefficient of *#F_1* is 580.2 $W^{-1}.km^{-1}$, it is larger than that of the work [7] approx 449 $W^{-1}.km^{-1}$. In particular, the flat wavelength band of the *#F_2* is very broad (4.8 µm), ranging in the average dispersion range of -30 $ps.nm^{-1}.km^{-1}$. While T. Huanga et. al. [10] shown that the flat wavelength band is only 0.7 µm in the vicinity of the 60 $ps.nm^{-1}.km^{-1}$dispersion region. With the flat normal and anomalous dispersion properties, characteristic quantity values such as dispersion, effective mode area, nonlinear coefficients, and confinement loss as analyzed above, the selected PCFs are very suitable for SC generation.

4. Conclusion

In this work, the optical characteristics of small-core $Ge_{20}Sb_5Se_{75}$-based PCFs are studied under the influence of filling factor and lattice constant. In order to obtain support for the broadband of output spectral, we studied numerically the optical properties of the fiber in the terms of dispersion properties, effective mode area, nonlinear coefficients, and confinement loss.

At this pump wavelength 2.75 µm, fiber *#F_1* with Λ = 2.0 µm, d/Λ = 0.35 has the all-normal dispersion characteristic of -3.69 $ps.nm^{-1}.km^{-1}$, nonlinear coefficient of 580.2 $W^{-1}.km^{-1}$, and effective mode area of 10.02 μm^2, correspondingly. Fiber *#F_2* with Λ = 2.5 µm, d/Λ = 0.3 also operates in all-normal dispersion meanwhile #F_3 with Λ = 3.0 µm, d/Λ = 0.3 performs an anomalous dispersion. The pump wavelength has been selected of 3.15 µm to consider the broadband of SC generation to fibers *#F_2* and *#F_3*. The dispersion characteristic of *#F_3* fiber is the smallest with a value of 3.56 $ps.nm^{-1}.km^{-1}$ at the pump wavelength of 3.15 µm, this value of fiber *#F_2* is equal to -4.52 $ps.nm^{-1}.km^{-}$1. At this wavelength, fiber *#F_2, #F_3* have effective mode areas of 16.5 µm, 20.42 μm^2, and nonlinear coefficients of 290.5 $W^{-1}.km^{-1}$, 235.3 $W^{-1}.km^{-1}$, respectively.

One advantage of these selected PCFs is that the values of L_c are very small, and approximate 10^{-14} dB/m for three fibers at their pump wavelength. The obtained values open up many application possibilities in the field of optical communication, which can especially be considered for SC generation.

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TÓM TẮT

TỐI ƯU HÓA CÁC ĐẶC TRƯNG QUANG HỌC CỦA SỢI TINH THỂ QUANG TỬ NỀN $Ge_{20}Sb_5Se_{75}$

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Trong bài báo này, chúng tôi trình bày một thiết kế mới của sợi tinh thể quang tử (PCF) lõi đặc, chất nền $Ge_{20}Sb_5Se_{75}$ với cấu trúc mạng lục giác. Những đặc trưng của sợi được nghiên cứu trong dải bước sóng dài (1.5 µm-7.0 µm). Sự phân tích mode đầy đủ và các đặc tính quang học của sợi tinh thể quang tử được thiết kế với hằng số mạng Λ và hệ số lấp đầy d/Λ được trình bày dưới dạng tán sắc màu, chiết suất hiệu dụng, hệ số phi tuyến và mất mát giam giữ. Tán sắc phẳng hoàn toàn thường và dị thường với độ phi tuyến cao và suy hao thấp là những ưu điểm nổi bật của các sợi tinh thể quang tử này. Từ đó, ba cấu trúc tối ưu với Λ = 2.0 µm, d/Λ = 0.35; Λ = 2.5 µm, d/Λ = 0.3 và Λ = 3.0 µm, d/Λ = 0.3 được lựa chọn và phân tích chi tiết để ứng dụng trong phát siêu liên tục.

Từ khóa: Sợi tinh thể quang tử; đặc trưng tán sắc; chalcogenide; diện tích mode hiệu dụng; mất mát giam giữ; phát siêu liên tục.