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COMPARISON OF DISPERSION CHARACTERISTICS OF SOLID-CORE PHOTONIC CRYSTAL FIBERS WITH As_2S_3 AND $Ge_{20}Sb_5Se_{75}$ SUBSTRATES FOR SUPERCONTINUUM GENERATION

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Abstract. In this work, we present two new solid-core photonic crystal fibers (PCFs) structures with As_2S_3 and $Ge_{20}Sb_5Se_{75}$ substrates, and the cladding consists of eight rings of air-holes arranged in a circular lattice. We analyze and compare the dispersion characteristics of the two structures with the change of lattice constant (Λ) and filling factor (d_1/Λ) in the first lattice ring. The PCF structures obtained dispersion characteristics diverse including all-normal dispersion and anomalous dispersion with 1 or 2 zero-dispersion wavelengths (ZDW). Flat dispersion and closeness to the zero-dispersion curve in the long wavelength range are the advantages of these structures. The circular lattice PCF structure with the As_2S_3 substrate possesses flat dispersion and is closer to the zero-dispersion curve than the structure with the $Ge_{20}Sb_5Se_{75}$ substrate. Based on analysis and comparison, we have proposed structures with optimal dispersion and pump wavelength suitable for supercontinuum generation with a wide, flat, and smooth spectrum.

Keywords: *Photonic crystal fibers (PCFs), dispersion, all-normal dispersion, anomalous dispersion, circular lattice.*

I. INTRODUCTION

In today's optical fiber technology, photonic crystal fibers (PCFs) are a topic of great interest to scientists around the world. The idea of photonic crystal fibers was introduced by Yep and his colleagues in 1978 [1]. Developing from that idea, in 1992 the first photonic crystal fiber with an air core was invented by P. Russell and reported at the optical conference in 1996 [2]. It brings a new achievement in optical fiber technology with special transmission properties and has many practical applications such as optical transmission systems, sensor fabrication [3], and supercontinuum generation (SCG) [4-5].

Dispersion is an important characteristic of photonic crystal fibers, which determines the spectral expansion efficiency during supercontinuum generation. Therefore, optimizing the dispersion feature is always targeted by researchers. The dispersion characteristic of photonic crystal fibers can be controlled by varying the lattice structure parameters such as lattice constant (Λ) and air-hole diameter (d). Recently, studies on solid core PCF with silica substrate have been widely studied [6, 7, 8], because Silica has the advantages of purity, high chemical resistance, and high transparency. However, the limitation of Silica is its low nonlinear refractive index and its wavelength limit does not exceed 2 micrometers leading to low SCG efficiency. Meanwhile, Chalcogenide (ChG) glasses are said to be attractive because it has a nonlinearity 500 times higher than that of conventional silica [9] and the properties of PCF are obtained in the long wavelength range. The search for supercontinuum (SC) sources reaching into the mid-infrared (mid-IR) region (which covers the 2–20 µm electromagnetic spectral range) has drawn much attention in recent years. Mid-IR SC is considered to be a new source highly applicable in the fields of spectroscopy, sensing, biology, metrology, and defense [10, 11]. ChG glasses have been proposed as promising candidates for use in IR fibers because of their wide transparent window that covers the atmospheric IR windows of 3 µm to 5 µm and 8 µm to 12 µm, strong glass forming tendency, good stability against crystallization, and good chemical durability to resist corrosion compared with other non-oxide glasses [12, 13]. The ChG glasses are multicomponent inorganic materials mainly composed of elements such as Sulfur (S), Selenium (Se), Tellurium (Te) Arsenic (As), Antimony (Sb) Germanium (Ge), and Silicon (Si) [14]. Some recent works using ChG glass give good results such as As_2Se_3 [15], As_2S_3 [16-20], and $Ge_{20}Sb_5Se_{75}$ [21-23]. However, in the above works, the authors did not emphasize the role of the difference in air-hole diameters in the lattice rings for the dispersion characteristics of PCF.

In this paper, we design two new structures of circular lattice photonic crystal fibers which emphasize the difference between the air-hole diameters in the first lattice ring compared to the remaining lattice rings to improve the characteristic dispersion. We analyzed in detail the dispersion characteristic of PCF with As_2S_3 and $Ge_{20}Sb_5Se_{75}$ substrates with the change of lattice constant (Λ) and filling factor (d_1/Λ). These two substrates have a very high nonlinear refractive index, which is equivalent and have values of $n_{As_2S_3} = 420\times10^{-20} m^2/W$ [24] and $n_{Ge_{20}Sb_5Se_{75}} = 4.29\times10^{-18} m^2/W$ [25], respectively. In addition, we compared the dispersion characteristics of the two PCF structures and optimized the dispersion characteristics to find structures with flat, near-zero dispersion in the long wavelength range suitable for SCG.

II. NUMERICAL MODELLING

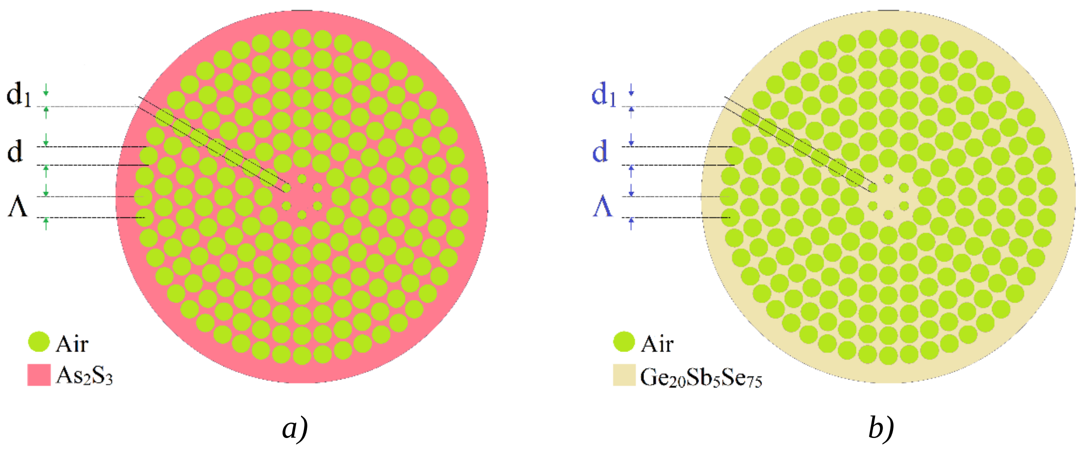

Fig 1. *Geometries of circular lattice PCF structure with two (a) As_2S_3 and (b) $Ge_{20}Sb_5Se_{75}$ substrates*

In this paper, we use Lumerical Mode Solution [26] software based on the finite element method to design two circular lattice photonic crystal fibers with eight air-hole rings shown in Figure 1. As_2S_3 and $Ge_{20}Sb_5Se_{75}$ are two substances belonging to Chalcogenide glass used as the substrate material. The circular lattice is used because it is highly symmetric, confines light to the core well, and improves the nonlinearity of the

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fiber. The work [27] has demonstrated that the first ring lattice near the core directly determines the dispersion characteristic.

Developing from that idea, we designed PCFs with an air-hole diameter in the first round of d_1 corresponding to a filling factor of d_1/Λ varying from 0.3 to 0.8 with a step of 0.05. Meanwhile, d is the air-hole diameter in the remaining lattice rings and the filling factor in these lattice rings has a constant value of d/Λ = 0.95. We investigate the dispersion characteristics of PCFs with the change of filling factor d_1/Λ and lattice constants Λ of 1.0 µm, 1.5 µm, 2.0 µm, and 2.5 µm, respectively.

The refractive index of As_2S_3 and $Ge_{20}Sb_5Se_{75}$ were obtained using the Sellmeier equation (1) [28] with the corresponding coefficients shown in Table 1.

$$n^2(\lambda) = 1 + \frac{A_1\lambda^2}{\lambda^2 - B_1} + \frac{A_2\lambda^2}{\lambda^2 - B_2} + \frac{A_3\lambda^2}{\lambda^2 - B_3}. \qquad (1)$$

Table 1. *The Sellmeier's coefficients of the two As_2S_3 and $Ge_{20}Sb_5Se_{75}$ substrates*

Material	A_1	A_2	A_3	B_1 **[µm²]**	B_2 **[µm²]**	B_3 **[µm²]**
***As_2S_3* [29]**	*1.898*	*1.922*	*0.876*	*0.0225*	*0.0625*	*0.1225*
***$Ge_{20}Sb_5Se_{75}$* [25]**	*4.7610*	*0.06994*	*0.8930*	*0.0356*	*0.6364*	*491.72*

Total dispersion (D) is a function of wavelength that depends on the effective refractive index of the propagation mode and can be calculated as in equation 2 [30].

$$D = -\frac{\lambda}{c}\frac{d^2\,\mathrm{Re}\left[n_{\mathrm{eff}}\right]}{d\lambda^2}. \qquad (2)$$

Where, $Re[n_{eff}]$ stands for the real part of the effective refractive index obtained from the simulations and c is the speed of light in a vacuum.

III. RESULTS AND DISCUSSION

Figure 1 presents the dispersion characteristics of PCF with the change of lattice constant (Λ) and filling factor (d_1/Λ). Looking at the figure, we see that the circular lattice structure has dispersion that varies with different wavelengths, the obtained dispersion curves include all-normal dispersion and anomalous dispersion with one or two ZDWs.

Specifically, in PCF with As_2S_3 substrates, the all-normal dispersion curve usually only appears in fibers with the filling factor d_1/Λ = 0.5 corresponding to the lattice constant Λ = 1.0 µm (Fig1.a_1), anomalous dispersion with a ZDW appears when d_1/Λ < 0.5. Meanwhile, anomalous dispersion curves with two ZDWs appear when d_1/Λ > 0.5. It can be seen that the change of the filling factor (d_1/Λ) has caused the appearance of diverse dispersion characteristics of PCF. At the lattice constant Λ = 1.5 µm (Fig1.a_2), there are three anomalous dispersion curves with one ZDW (d_1/Λ = 0.3 - 0.45) and seven anomalous dispersion curves with two ZDWs (d_1/Λ = 0.5 – 0.8). Furthermore, investigating larger lattice constants (larger cores) with Λ = 2.0 µm (Fig1.a_3) and Λ = 2.5 µm (Fig1.a_4), all-normal dispersion and anomalous dispersion with two ZDWs no longer appear, but only anomalous dispersion curve with a ZDW in these two cases. Thereby,

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we can conclude that dispersion characteristics can be more strongly controlled in small core PCFs because of their strong light confinement.

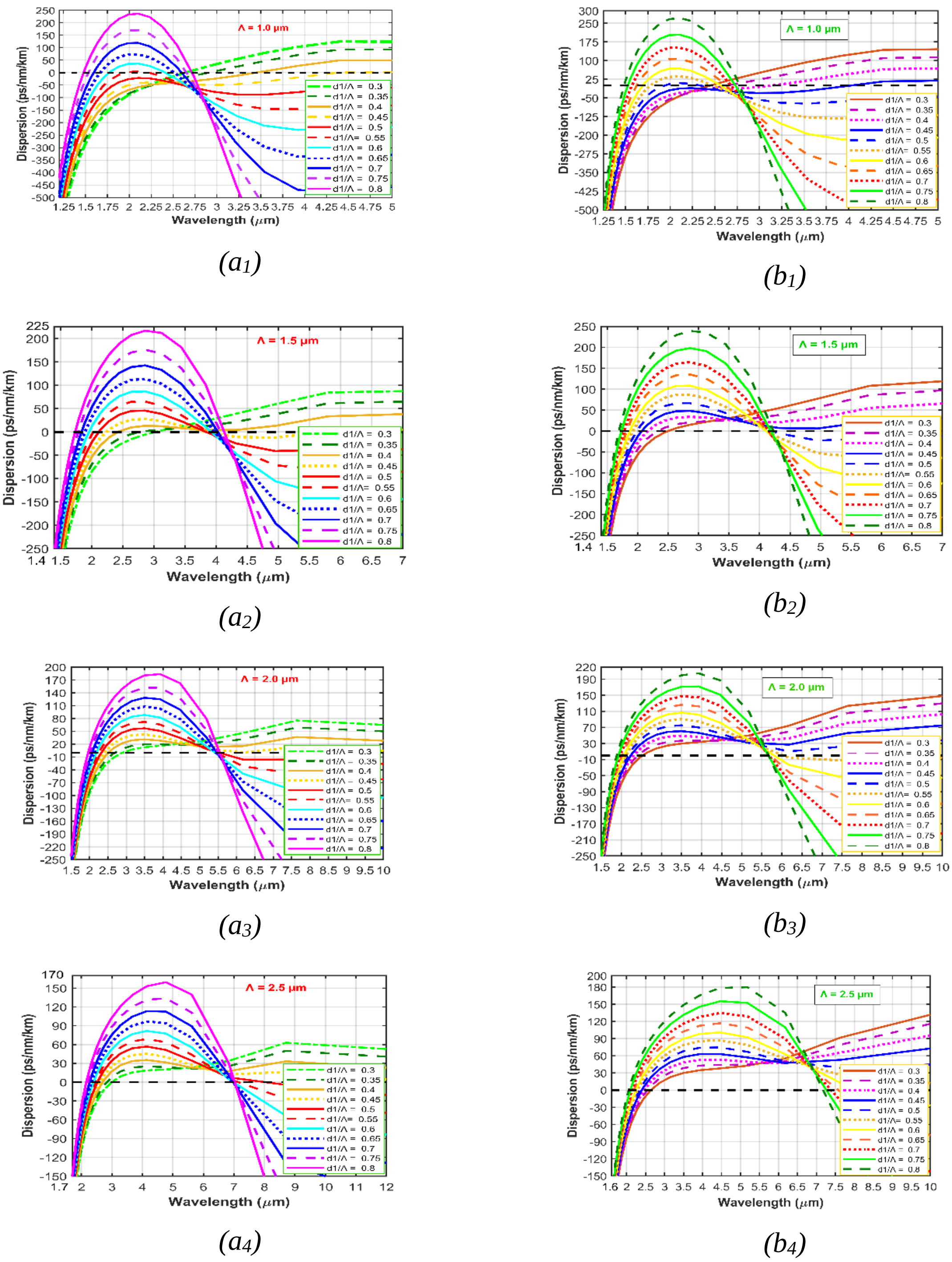

Fig 2. *The dispersion as a function of wavelength of PCFs with various d_1/Λ and Λ for* ***a)*** *As_2S_3 and* ***b)*** *$Ge_{20}Sb_5Se_{75}$ substrates.*

On the other hand, in all cases of PCF with $Ge_{20}Sb_5Se_{75}$ substrate investigated, an all-normal dispersion does not appear, which is different for the structures with As_2S_3 substrates. Specifically, for lattice constants Λ = 1.0 µm (Fig1.b_1) and Λ = 1.5 µm (Fig1.b_2), anomalous dispersion with a ZDW is achieved at filling factor d_1/Λ = 0.3-0.45 and anomalous dispersion curves with two ZDWs obtained with d_1/Λ > 0.45. While, for

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Λ = 2.0 µm and Λ = 2.5 µm, only anomalous dispersion occurs with a ZDW at all filling factors. This helps to increase the validity of the above conclusion.

Table 2. *The structural parameters of the proposed PCFs.*

Material	Name of fiber	Λ (µm)	d_1/Λ
As_2S_3	F_1	1.0	0.5
	F_2	1.0	0.4
	F_3	1.5	0.55
$Ge_{20}Sb_5Se_{75}$	F_4	1.5	0.4
	F_5	1.0	0.5

Dispersion is one of the important factors determining SCG performance. Therefore, fiber structures with flat dispersion, close to zero dispersion curves, and zero dispersion wavelength (ZDW) compatible with pump wavelength have always been the goal of dispersion optimization. In the case of PCF structure with As_2S_3 substrate, we select fibers with optimal dispersion for both all-normal and anomalous dispersion regimes with one and two ZDWs. The F_1 fiber is the only fiber that has an all-normal dispersion regime and is very favorable for SCG with high coherence. While F_2 and F_3 fibers have anomalous dispersion regimes with one and two ZDW, respectively. On the other hand, F_4 and F_5 are the optimal fibrous structures selected with the $Ge_{20}Sb_5Se_{75}$ substrate. Fiber F_4 has an anomalous dispersion regime with one ZDW and has flat dispersion in the long wavelength range, while F_5 has an anomalous dispersion regime with two ZDWs. The proposed optimal fibers with structural parameters are shown in Table 2.

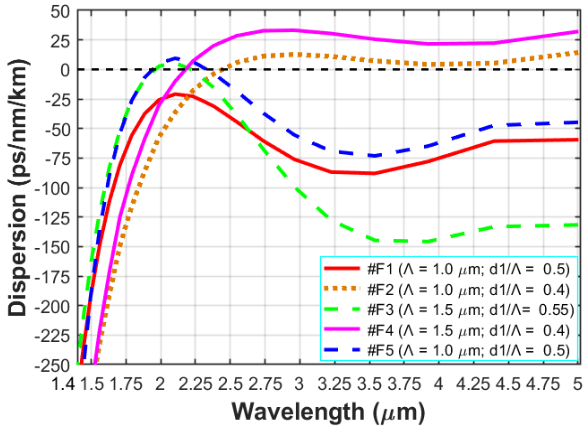

Fig 3. *The dispersion properties of the proposed PCFs*

The dispersion characteristics of the proposed fibers F_1, F_2, F_3, F_4, and F_5 are shown in Figure 3. It can be seen that the proposed fibers have flat dispersion, close to zero dispersion curve in the wide wavelength range, which is a decisive factor in the creation of ultra-wideband SC.

Table 3 shows the dispersion value at the pump wavelength of the proposed fibers. The all-normal dispersion curve F_1 has a maximum dispersion value of -20.916

[ps.(nm.km)$^{-1}$], at wavelength 2.103 µm, so we choose the pump wavelength for F_1 fiber to be 2.2 µm. Threads F_3, F_4, and F_5 have the same pumping wavelength as F_1 which is 2.2 µm. Whereas fiber F_2 exhibits anomalous dispersion with a ZDW at wavelength 2.445 µm, the pump wavelength of this fiber is chosen to be 2.5 µm. The dispersion value of F_2 fiber at pump wavelength 2.5 µm is 3.2 [ps.(nm.km)$^{-1}$]. Meanwhile, the dispersion value at pump wavelength 2.2 of fibers F_1, F_3, F_4, and F_5 are -22.32 [ps.(nm.km)$^{-1}$], 0.948 [ps.(nm.km)$^{-1}$], 2.873[ps.(nm.km)$^{-1}$], and 7.209 [ps.(nm.km)$^{-1}$], respectively.

Table 3. *The value of dispersion is calculated at the pump wavelength of the proposed PCFs.*

#	***Pump wavelength* (µm)**	***D* (ps.(nm.km)$^{-1}$)**
F_1	2.2	-22.32
F_2	2.5	3.2
F_3	2.2	0.948
F_4	2.2	2.873
F_5	2.2	7.209

IV. CONCLUSION

The dispersion characteristics of circular lattice PCFs with As_2S_3 and $Ge_{20}Sb_5Se_{75}$ substrates with the new design were analyzed and compared. The dispersion characteristic is varied, controlled, and improved through the change of the filling factor d_1/Λ and the lattice constant Λ. The PCF structure with the As_2S_3 substrate exhibits an all-normal dispersion, and anomalous dispersion with one or two ZDWs. While in the PCF structure with the $Ge_{20}Sb_5Se_{75}$ substrate only anomalous dispersion is obtained. The proposed fibers with suitable pump wavelength have flat dispersion and close to zero dispersion curves in the long wavelength range suitable for supercontinuum generation.

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