COMPARISON OF OPTICAL NONLINEAR PROPERTIES OF SQUARE AND HEXAGONAL LATTICES SOLID-CORE PHOTONIC CRYSTAL FIBER WITH $Ge_{20}Sb_5Se_{75}$ SUBSTRATE

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Abstract. In this paper, a comparative study is performed on two solid-core photonic crystal fibers (PCFs) with a $Ge_{20}Sb_5Se_{75}$ substrate. These two new photonic crystal fibers are designed using Lumerical Mode Solution software based on the finite element method. In our analysis, the introduced structure is a novel structure of 8 air-hole rings arranged in square and hexagonal lattices. Furthermore, the difference between the air-hole diameter in the first ring compared with the remaining rings is a new feature of our work. The change of the structure parameters including the filling factor and the lattice constant affects the nonlinear coefficient value of PCF. With the same structure parameters, PCF with hexagonal lattice has a higher nonlinear coefficient value than square lattice PCF. Our results are very important in fiber optic technology development, particularly for supercontinuum generation applications.

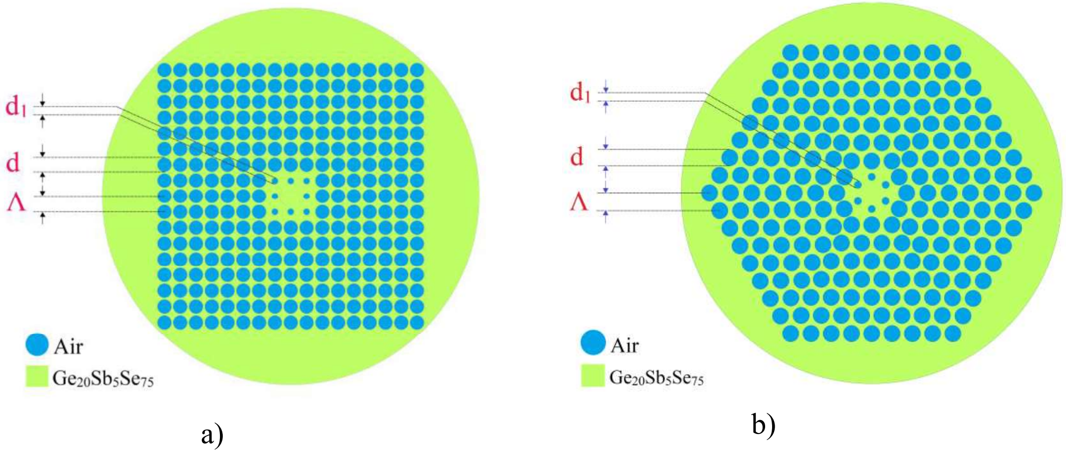
Keywords: *Photonic crystal fibers (PCFs), high nonlinear coefficient, square lattice, hexagonal lattices.*

I. INTRODUCTION

The advent of photonic crystal fibers (PCF) has brought about a remarkable development in fiber optic technology. Compared with conventional optical fiber, PCF is designed and fabricated flexibly. The change of structural parameters such as lattice constant, air-hole size, lattice type, and material,… will drastically change PCF characteristics, this has opened up many applications in fiber optic technology. PCF is used in fiber lasers, optical amplifiers, nonlinear devices, high-power transmission lines, highly sensitive gas sensors [1,2], and especially in supercontinuum generation (SCG) applications [3-6].

PCFs with higher nonlinear coefficients are suitable for various applications including wavelength conversion, optical parametric amplification, and especially good conditions for SCG. In the past, there have been many studies on PCF based on Fused Silica [7-10] because of its high transparency, exceptional purity, and ease of fabrication. However, the disadvantage of Silica is its low nonlinear refractive index and limitation in the infrared (IR) transmission band. Recently, PCF designed with Chalcogenide (ChG) glasses has received much research interest because it has some attractive optical properties such as a high linear refractive index, high nonlinear refractive index, low phonon energy, and large optical transparency extending from the visible to 20 µm [11]. ChG glasses are a multicomponent inorganic material composed mainly of group XVI chalcogen elements, including Sulfur (S), Selenium (Se), Tellurium (Te) with combination with other elements from group XV such as Arsenic (As) and Antimony (Sb) and group XIV such as Germanium (Ge) and Silicon (Si) [12]. The combination of ChG glasses with PCF versatility has been explored and several numerical and experimental demonstrations of coherent SC sources reaching the mid-infrared (M-IR) region have been reported. considered as a new source with high applicability in the fields of spectroscopy, sensing, biology, metrology, and defense [13, 14]. Among the various compositions of ChG glasses, $Ge_{20}Sb_5Se_{75}$ is considered an excellent candidate for mid-infrared nonlinear optics. It has many favorable features including broad spectral transmittance spanning the region from 2 µm to 12 µm and suitability for fiber drawing thanks to its excellent thermal stability against crystallization [15, 16]. Besides, $Ge_{20}Sb_5Se_{75}$ glass is environmentally friendly because it does not contain highly toxic elements such as Arsenide [17]. Several recent works using $Ge_{20}Sb_5Se_{75}$ glass have been reported and obtained encouraging results such as ChG-suspended core PCF structure with flat dispersion and high nonlinearity [18]. M. A. Khamis et al. have created a broadband SC extending from 3.7 µm to 12 µm with a fiber structure with a core made of $Ge_{15}Sb_{15}Se_{70}$ surrounded by double cladding made of $Ge_{20}Se_{80}$ and $Ge_{20}Sb_5Se_{75}$ glasses [19].

In this paper, we present a new design with the difference between the structural parameters in the first lattice ring compared to the remaining lattice rings of PCF with the $Ge_{20}Sb_5Se_{75}$ substrate, with a square and hexagonal lattice. We studied the influence of structural parameters on the PCF nonlinear coefficient. Besides, the nonlinear coefficient comparison was performed between square and hexagonal lattice PCFs to find the structure with the highest nonlinear coefficient for SCG. PCF with hexagonal lattice has a higher nonlinear coefficient than square lattice at the same wavelength value.



a) b)

Fig.1. *Cross-section of the designed PCF (a) Square lattice and (b) Hexagonal lattice.*

II. NUMERICAL MODELLING

Lumerical Mode solution software [20] was used to design two new PCF structures with $Ge_{20}Sb_5Se_{75}$ substrates. The PCF structures consisting of eight air-hole rings arranged in a square and hexagonal lattice are shown in Fig 1. $Ge_{20}Sb_5Se_{75}$ is a substrate material with a high nonlinear refractive index to produce the difference between core and cladding. The diameter of the air-hole in the first ring lattice is d_1, corresponding to a filling factor of d_1/Λ varying from 0.3 to 0.8 in a step of 0.05. Meanwhile, the filling factor of the remaining lattice rings d/Λ remains unchanged by 0.95, where d is the diameter of the air-hole in the 2nd ring onwards. The core diameter is determined by the formula $D_c = 2\Lambda - 1.1d_1$. The PCF nonlinearity is controlled by d_1/Λ and is obtained by the finite element method. The selected lattice constants for the survey include Λ = 1.0 µm, Λ = 1.5µm, Λ = 2.0µm, and Λ = 2.5µm.

The refractive index of $Ge_{20}Sb_5Se_{75}$ is described by the Sellmeier equation below [21]:

$$n^2(\lambda) = 1 + \frac{4.7610\lambda^2}{\lambda^2 - 0.0356} + \frac{0.06994\lambda^2}{\lambda^2 - 0.6364} + \frac{0.8930\lambda^2}{\lambda^2 - 491.72}. \quad (1)$$

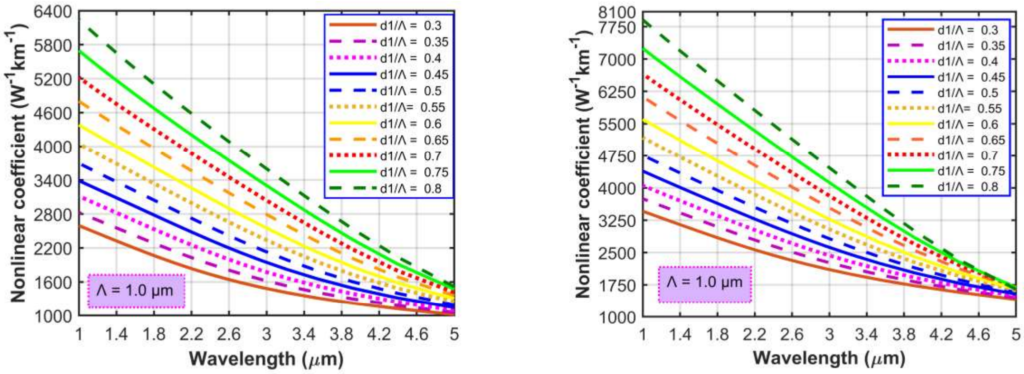
Where λ is the wavelength whose in micrometers.

The PCF nonlinear coefficient is inversely proportional to the effective mode area and is calculated by the formula [22]:

$$\gamma = \frac{\omega}{c}\left(\frac{n_2}{A_{eff}}\right) = \frac{2\pi}{\lambda}\left(\frac{n_2}{A_{eff}}\right) \quad (2)$$

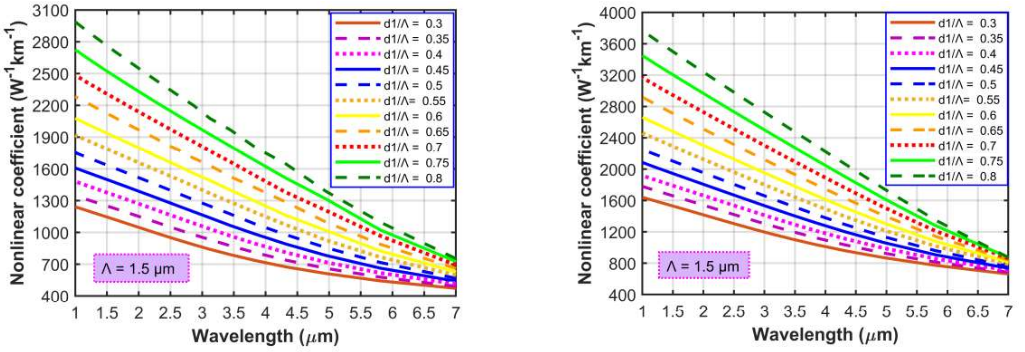
The unit of gamma is ($W^{-1}.km^{-1}$). Where ω is the angular frequency, n_2 is the nonlinear refractive index.

III. RESULTS AND DISCUSSION



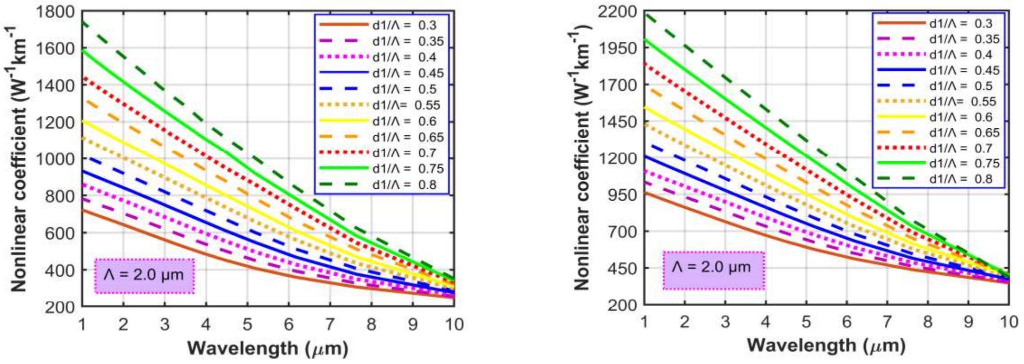
a) **b)**

Fig 2. *The nonlinear coefficient of two solid-core PCFs with Λ = 1.0 µm, d_1/Λ = 0.3 ÷ 0.8 for lattices:* ***a)*** *square and* ***b)*** *hexagonal lattices*



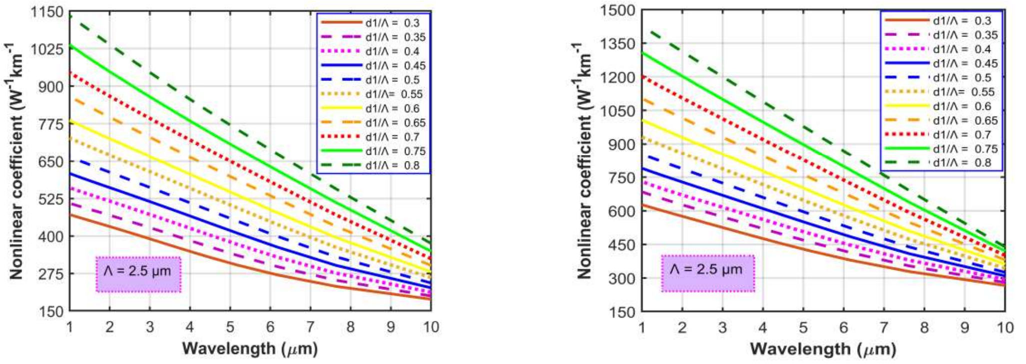
a) **b)**

Fig 3. *The nonlinear coefficient of two solid-core PCFs with $\Lambda = 1.5$ μm, $d_1/\Lambda = 0.3 \div 0.8$ for lattices: **a)** square and **b)** hexagonal lattices*



a) **b)**

Fig 4. *The nonlinear coefficient of two solid-core PCFs with $\Lambda = 2.0$ μm, $d_1/\Lambda = 0.3 \div 0.8$ for lattices: **a)** square and **b)** hexagonal lattices*



a) **b)**

Fig 5. *The nonlinear coefficient of two solid-core PCFs with $\Lambda = 2.5$ μm, $d_1/\Lambda = 0.3 \div 0.8$ for lattices: **a)** square and **b)** hexagonal lattices*

Figures 2, 3, 4, and 5 show the dependence of the nonlinear coefficient on the wavelength with different d_1/Λ and Λ for the square and hexagonal lattice PCF

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structures. It can be seen that both PCF structures have a nonlinear coefficient that varies with wavelength and have the same shape when having the same structural parameters. In addition, the nonlinear coefficient at long wavelengths will have a lower value than at shorter wavelengths. For PCF structures with the same lattice constant, the nonlinear coefficient decreases rapidly with wavelength with a large filling factor (d_1/Λ) and decreases slightly with a small filling factor (d_1/Λ). Furthermore, as the lattice constant increases, the nonlinear coefficient of the fiber decreases.

Table 1. *The value of the nonlinear coefficient of the fibers at 1.55μm wavelength with various lattice constants and the linear filling factor of the first ring.*

λ (μm)	d_1/Λ	$\Lambda = 1.0$ μm		$\Lambda = 1.5$ μm	
		Hexagonal	***Square lattice***	***Hexagonal***	***Square lattice***
1.55	0.30	3032.37	2225.91	1518.25	1136.09
	0.35	3299.05	2452.21	1647.66	1240.49
	0.40	3572.19	2713.37	1776.78	1365.78
	0.45	3871.42	2972.11	1930.19	1488.14
	0.50	4195.16	3247.84	2087.49	1623.48
	0.55	4554.29	3557.75	2274.26	1775.24
	0.60	4932.04	3860.76	2463.78	1921.89
	0.65	5375.01	4221.12	2691.73	2108.11
	0.70	5838.02	4585.24	2922.77	2291.46
	0.75	6352.31	4982.73	3180.78	2503.18
	0.80	6927.45	5446.37	3473.55	2741.65
λ (μm)	d_1/Λ	$\Lambda = 2.0$ μm		$\Lambda = 2.5$ μm	
		Hexagonal	***Square lattice***	***Hexagonal***	***Square lattice***
1.55	0.30	906.52	678.78	598.21	449.70
	0.35	977.48	739.46	651.60	487.37
	0.40	1050.94	811.90	695.85	536.46
	0.45	1144.22	882.49	755.30	582.59
	0.50	1237.74	964.01	816.39	635.92
	0.55	1350.69	1053.61	890.47	695.42
	0.60	1462.31	1141.09	964.22	752.01
	0.65	1598.92	1253.46	1054.90	827.16
	0.70	1735.91	1362.28	1148.24	900.91
	0.75	1892.50	1491.02	1249.50	981.41
	0.80	2063.50	1635.85	1363.51	1081.03

Table 1 shows the nonlinear coefficient values of the square and hexagonal PCF structures calculated at wavelength 1.55 μm with different d_1/Λ and Λ. From table 1, we can see that PCF with a hexagonal structure always has a larger nonlinear coefficient than PCF with a square lattice in all different values of d_1/Λ and Λ.

With d_1/Λ = 0.8 and Λ = 1.0 µm, PCF with hexagonal structure possesses the largest nonlinear coefficient of 6927.45 ($W^{-1}.km^{-1}$) at wavelength 1.55 µm. The high nonlinear coefficient is one of the important contributing factors to supercontinuum generation and is used in various nonlinear optics.

IV. CONCLUSION

The nonlinear coefficients of the solid-core photonic crystal fibers with square and hexagonal lattice types in the cladding were numerically analyzed with the influence of new design parameters. Changing the air-hole diameter in the first lattice ring compared with other lattice rings strongly influenced the properties of PCF. Compared with the square lattice, PCF with hexagonal lattice has a larger nonlinear coefficient value and the largest nonlinear coefficient value is 6927.45 ($W^{-1}.km^{-1}$) at wavelength 1.55 µm. Our results are promising and open up many application possibilities in the field of optics with high nonlinear coefficients.

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