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CONFINEMENT LOSS CHARACTERISTICS OF SQUARE LATTICE PCFS WITH As_2S_3 SUBSTRATES FOR DIFFERENT NUMBERS OF AIR-HOLE RINGS

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Abstract. In this paper, we use As_2S_3 substrates to design three new solid-core photonic crystal fiber (PCF) structures with five, six, and seven air-hole rings, respectively, arranged in a square lattice. We study and analyze the confinement loss characteristics of three structures with the change of lattice constant (Λ), filling factor (d/Λ), and the number of air-hole rings to optimize them at the central wavelength λ = 4.5 µm. The obtained PCFs have almost the same loss characteristics, however, their values have large differences between the structures. Among them, small confinement loss is the advantage of the structures in this study. The minimum loss obtained in the As_2S_3 substrate square-lattice PCF structure for the seven-ring case is most efficient for supercontinuum generation (SCG).

Keywords: *Square lattice, Photonic Crystal Fibers, Confinement Loss.*

I. INTRODUCTION

Conventional optical fibers can perform very well in radio and telecommunications equipment but have many limitations in terms of flexibility in their structure and design. In 1996, Russell announced a new optical fiber called photonic crystal fiber (PCF), since then PCF has attracted a lot of research attention from scientists around the world [1]. It brings a new achievement in optical fiber technology with special transmission characteristics and has many practical applications such as optical transmission systems, sensor fabrication [2], and supercontinuum generation (SCG) [3- 4]. PCF is a type of optical fiber with a cyclic structure made of small tubes (such as capillary tubes) filled with air arranged in the form of a circular, hexagonal, square lattice, etc light confinement in the core region not only for solid core fibers but also for hollow core fibers, which is not possible with conventional optical fibers. The light transmission mechanism in solid core PCF and hollow core PCF is different. The research on solid core PCF has given many important results and applications in science and technology [5]. One of the important applications of PCF is supercontinuum generation [6-8]. Important characteristics of PCF include effective mode area, dispersion, and loss. While SCG performance depends on those characteristics. Therefore, we need to optimize PCF to obtain the best characteristics of PCF suitable for high-performance SCG. Loss is one of the important

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characteristics of SCG, the smaller the PCF loss the better. Losses in PCF can be introduced by various means such as intrinsic material absorption, scattering, bending, connector loss, confinement loss, and more. The confinement loss can be reduced by proper design of structure parameters in PCFs, and consequently, mode leakage to cladding is avoided.

In recent years, there have been many research publications on solid core PCF with square lattice applied to supercontinuous generation such as studying the influence of structure parameters on PCF characteristics. However, the limitation of these claims is the use of substrates such as BK7 and SiO_2. Although these substrates have high purity, high chemical resistance, and high transparency, their low nonlinear refractive index and wavelength limitation not exceeding 2 µm result in low SCG efficiency. Meanwhile, Chalcogenide glass (ChG) is attracted by nonlinearity 500 times higher than that of ordinary silica [9], and the properties of PCF are obtained over the long wavelength range. ChG is a multi-component inorganic material mainly composed of elements such as Sulfur (S), Selenium (Se), Tellurium (Te) Arsenic (As), Antimony (Sb) Germanium (Ge), and Silicon (Si). Works on ChG substances such as As_2Se_3 [10], and As_2S_3 [11] give good results.

In this paper, we study the confinement loss characteristic of As_2S_3 substrate square-lattice PCF with structures with different numbers of air-hole rings to find optimal structures for SCG. We chose the As_2S_3 substrate because the nonlinear refractive index of As_2S_3 equals $n_{As_2S_3} = 420\times10^{-20} m^2/W$ [12] is nearly 157 times greater than that of fused silica with a refractive index of 2.74×10^{-20} m^2/W at 1053 nm [13]. The nonlinear refractive index of As_2S_3 is also higher than that of most other nonlinear glasses [14]. A high nonlinear refractive index is important for enhancing SCG efficiency. Lumerical Mode Solution software has been used to design square PCF structures and simulate their properties with the variation of the lattice constant *Λ* and filling factor *d/Λ* to select the PCF with the small confinement loss.

II. NUMERICAL MODELING

In this work, we use the software Lumerical Mode Solution [15] based on the finite element method to design three square lattice photonic crystal fibers with the number of air-hole rings decreasing from inside to outside, respectively. This means that the core diameter increases gradually in the three crystal fibers, as shown in Figure 1. First, we carried out the design of the PCF structure with eight air-hole rings. Then, we proceed to remove an innermost air-hole ring near the core, at this time the structure becomes PCF with seven air-hole rings (Figure 1.a). Similarly, we continued to remove 2 and 3 proximal air-hole rings from the original design to obtain a PCF structure with six (Figure 1.b) and five (Figure 1.c) air-hole rings. In addition to changing the number of air-hole rings in the PCFs, we also change the lattice constant (*Λ*) and the filling factor (*d/Λ*). Where D_C is the diameter of the air holes and Λ is the distance between the centers of two adjacent air holes. We use the lattice constants 1.0 µm and 2.0 µm, while the filling factor varies from 0.3 to 0.5 with a step of 0.05. The large core diameter is determined according to the formula shown in Figure 1. As_2S_3 used as the substrate material to create the difference in refractive index between the core and the crust to help limit the light in the core is better.

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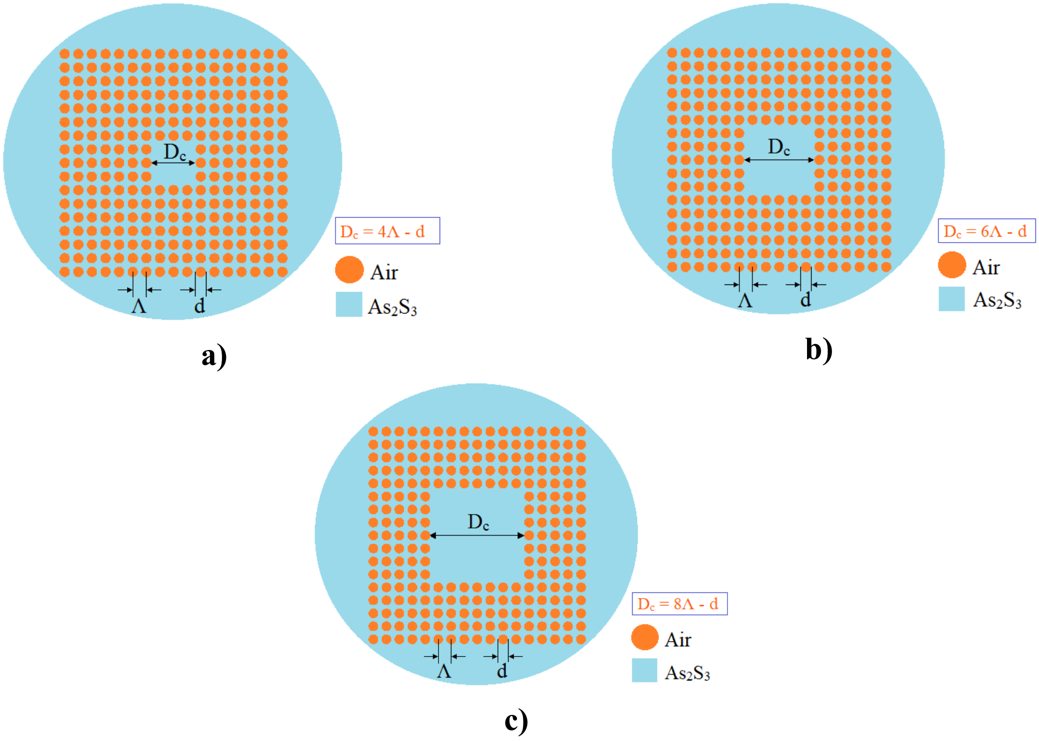

Fig. 1. *Geometrical structure of square lattice PCF with As_2S_3 substrate in three cases: a) seven rings, b) six rings, c) five rings*

The nonlinear refractive index of As_2S_3 was obtained using the Sellmeier equation (1) [16] with the corresponding coefficients shown in Table 1.

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

The values of the conformance factors $A_1 \ldots A_3$, and $B_1 \ldots B_3$ are listed in Table 1 and is the wavelength of light in µm.

Table 1. *The Sellmeier's coefficients of the As_2S_3 substrates.*

Sellmeier's coefficients						
Material	**A_1**	**A_2**	**A_3**	**B_1 [µm^2]**	**B_2 [µm^2]**	**B_3 [µm^2]**
As_2S_3 [17]	1.898	1.922	0.876	0.0225	0.0625	0.1225

The confinement can be calculated using the attenuation constants (α_m) as follows [18-20]:

$$L_C = 20\, log(e) * \alpha_m \quad (2)$$

$$L_C = 0.08686 k_0 l_m [n_{eff}] \quad (3)$$

The unit of confinement loss is [dB/m], where $k_0 = \frac{2\pi}{\lambda}$ is the wave constant in free space, λ is the operating wavelength. A PCF with a large core-shell refractive index difference (due to the difference between the refractive indices of As_2S_3 and air) will have a small confinement loss.

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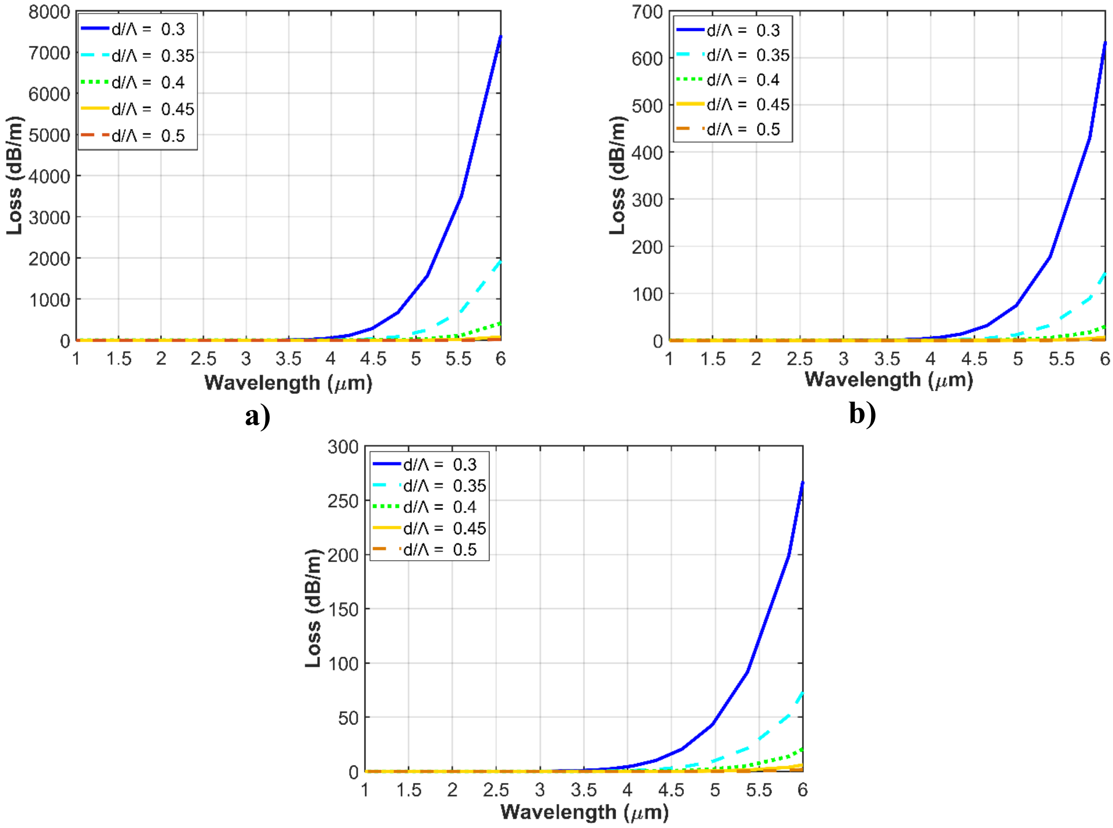
III. RESULTS AND DISCUSSION

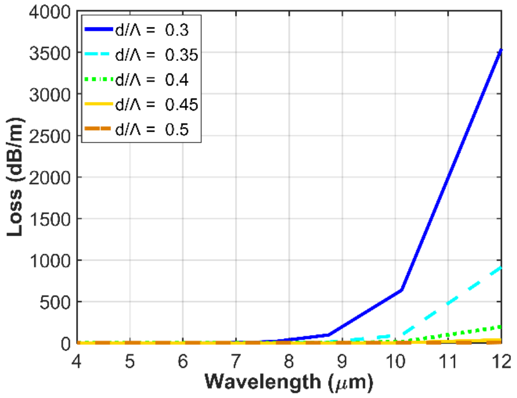
The confinement loss characteristics of PCFs with the change of lattice constant (*Λ*) and filling factor (*d/Λ*) are shown in Figures 2 and 3. As observed, the confinement loss value (L_c) is the largest for the case of PCF with seven air-hole ring structures in both lattice constants with the filling factor varying from 0.3 ÷ 0.5. The confinement loss characteristic gradually decreases from 0.3 ÷ 0.5 µm. However, there is a slight change in some cases. Specifically, for the lattice constant *Λ* = 1.0 µm (Figure 2), when the fill factor decreases (*d/Λ* = 0.3 ÷0.5), the confinement loss value decreases gradually in all three cases. Meanwhile, the confinement loss value decreased significantly from fiber with fill factor *d/Λ* = 0.3 ÷0.4 for lattice constant *Λ* = 2.0 µm (Figure 3) but increased slightly at the remaining wavelengths.



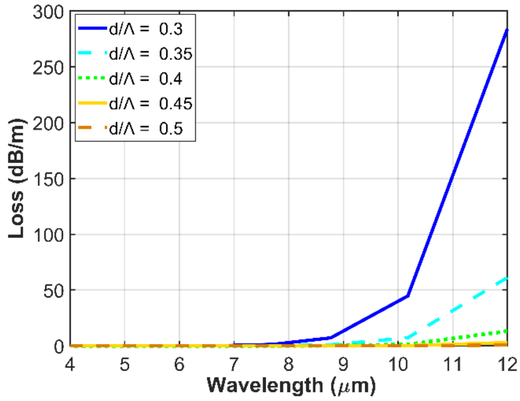
c)

Fig. 2. *Confinement loss characteristics of PCFs with Λ = 1.0 µm, d/Λ = 0.3 ÷ 0.5 for the cases: a) seven rings, b) six rings, c) five rings.*

Table 2 presents the PCF confinement loss values at a pump wavelength of 4.5 µm. The confinement loss value (L_c) decreases in the case of increasing lattice constant (Λ) because the refractive index of the core region and the crust region has a large difference. The lowest value confinement loss for the seven rings, six rings, and five rings cases is 5.61×10^{-10}dB/m, $2.1\text{x}10^{-9}$dB/m, and 6.2×10^{-8} dB/m. The small confinement loss value is one of the important factors for efficient supercontinuum generation.



a)



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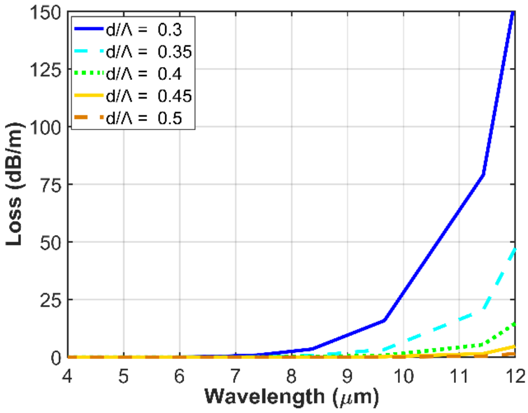

c)

Fig. 3. *Confinement loss characteristics of PCFs wit--h Λ = 2.0μm, d/Λ = 0.3 ÷ 0.5 for the cases: a) seven rings, b) six rings, c) five rings*

Table 2. *Fiber confinement loss values at pump wavelength of 4.5 μm with different lattice constants and variable fill factor from 0.3 to 0.5.*

λ (μm)	**d_l/Λ**	**L_c (dB/m)**					
		Λ = 1.0 (μm)			**Λ = 2.0 (μm)**		
		Seven rings	**Six rings**	**Five rings**	**Seven rings**	**Six rings**	**Five rings**
4.5	0.3	305.03	22.78	16.37	$1.1.10^{-3}$	$4.45.10^{-4}$	$1.86.10^{-3}$
	0.35	33.47	3.16	3.1	$2.85.10^{-5}$	$2.101.10^{-5}$	$1.87.10^{-3}$
	0.4	3.463	0.423	0.624	$2.86.10^{-5}$	$2.15.10^{-5}$	$1.2.10^{-5}$
	0.45	0.356	0.065	0.13	$2.05.10^{-8}$	$4.75.10^{-8}$	$9.2.10^{-7}$
	0.5	0.037	$9.4.10^{-3}$	0.028	$5.61.10^{-10}$	$2.1.10^{-9}$	$6.2.10^{-8}$

IV. CONCLUSION

In this paper, we used different lattice constants and varied the number of air holes to optimize the confinement loss at the pump wavelength of λ = 4.5 μm. The lowest confinement loss is obtained for the PCF seven air-hole rings structure at lattice constant Λ = 2.0 μm corresponding to the fill factor *d/Λ* = 0.5. It is important that when increasing the value of the fill factor and decreasing the number of air-hole rings, increasing the core diameter helps to obtain a lower value of confinement loss. Low confinement loss PCF has great benefits for telecommunications such as the fabrication of optical devices and medical diagnostics.

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