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VARIATION IN EFFECTIVE MODE AREA AND NONLINEAR COEFFICIENT OF As_2S_3-BASED CIRCULAR-LATTICE PCF WITH CHANGE IN CORE DIAMETER

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Abstract. A unique circular photonic crystal fiber (PCF) made in As_2S_3 chalcogenide glass is designed in this study. The change in nonlinear optical properties such as effective mode area and nonlinear coefficient is considered with the change in core size. The results reveal that there is a significant difference in the effective mode area values of small-core and large-core PCFs while their curves tend to be similar over the entire wavelength range. Based on the calculation of the effective mode area at the respective pump wavelengths, two fibers with the smallest ones are selected as two good candidates to investigate nonlinear factors. Their high nonlinearities of 387.88 $(W.km)^{-1}$ and 176.33 $(W.km)^{-1}$ at 5 µm and 6 µm, respectively, are important in nonlinear optical applications. These values also demonstrate different degrees of interaction between light and the nonlinear medium for PCFs with various core diameters.

Keywords: *Nonlinearity, Effective Mode Area, Core Diameter Change, As_2S_3 Substrate, Circular Photonic Crystal Fiber.*

I. INTRODUCTION

Recently, microstructure optical fiber, also known as photonic crystal fiber (PCF), has attracted wide interest in scientific research. A PCF is typically an ingle-material-based optical fiber with holes surrounding the core along the fiber's entire length. This type of fiber provides many novel characteristics, such as customizable wavelength dispersion, high nonlinearity, long interaction lengths, and strong confinement of the light field [1,2]. During the fabrication of optical fibers, the nonlinearity is enhanced by modulating dispersion along the fiber's length as well as reducing the effective mode area. With the rapid development of fiber-optic technology, it is possible to achieve these by varying the structural parameters of the PCF, especially the core size. Through extensive research, it has been found that high nonlinear optical fibers are suitable for short-pulse compression, parametric amplification, and supercontinuum generation (SCG) [3-6]. Tran et al. [7] studied the effective mode area for SCG using chloroform PCFs and found the primary limitation on a liquid core to be the difficulty of keeping them completely in the core. Thuy et al. [8] investigated the nonlinear coefficients in solid-core fibers and found that a nonlinear factor of 5398.53659 $W^{-1}km^{-1}$ can be achieved by a PCF with a small core. However, small core fibers have been shown to be detrimental to the brightness of the spectrum if applied to SCG due to their high loss at long wavelengths [9]. They clearly make it difficult to couple with standard silica fibers in the experiment. On the other hand, the publication [7] also showed that the high symmetry of the circular lattice contributes to flexible control of the effective mode area to obtain the desired high nonlinearity.

It is well known that sources of broadband mid-infrared light attract considerable attention from many researchers, due to their broad application potential in optical frequency metrology, astronomical spectroscopy, optical tomography, tunable wavelength conversion, and infrared imaging [10]. To extend the application of PCF to the mid-infrared region, silica fibers lose their advantage because they are strongly absorbed at wavelengths greater than 2.5 µm. Compared to silica, chalcogenide glasses—in particular, As_2S_3—exhibit a larger refractive index and a higher nonlinear index, providing larger mode confinement and higher nonlinearity [11]. High nonlinearity As_2S_3 waveguide has been prepared by Kai et al. [12] for supercontinuum generation. Moreover, chalcogenide glasses are transparent at a mid-infrared wavelength of about 10 µm; in the case of As_2S_3, this can be up to 11 µm. Optical properties of As_2S_3-based suspended-core were studied by Duc et al. [13], who showed that the proposed fibers were able to produce high nonlinear coefficients and very low confinement losses in the survey wavelength range.

In this paper, we design a circular As_2S_3 PCF with six rings of air holes surrounding a solid core. The nonlinearity coefficient and effective mode area are numerically simulated using the finite-element method. The core diameter is then gradually increased for the purpose of studying the change of two above characteristics. The applicability for SCG is found in the two fibers with the smallest effective mode area.

II. THE GEOMETRY AND EFFECTIVE MODE AREA PROPERTIES OF As_2S_3 PCF

In this paper, we design an As_2S_3 PCF with air holes in a circular array around the core. We assume that the air-hole pitch Λ, air-hole diameter d, and fiber core diameter Dc change flexibly. The ratio of the air-hole diameter to the pitch d/Λ is called the filling factor. The refractive index of the chalcogenide glass As_2S_3 is shown in the equation below [14]:

$$n^2(\lambda) = 1 + \frac{B_1\lambda^2}{\lambda^2 - C_1^2} + \frac{B_2\lambda^2}{\lambda^2 - C_2^2} + \frac{B_3\lambda^2}{\lambda^2 - C_3^2} \tag{1}$$

where B_1 = 1.8983678, B_2 = 1.9222979, B_3 = 0.8765134, C_1 = 0.15 µm, C_2 = 0.25 µm, C_3 = 0.35 µm. The nonlinear index coefficient n_2 of As2S3 is 4.2×10^{-18} m^2/W. According to Eq. (1), the refractive index n of As_2S_3 can be computed as shown in Fig. 1, and we obtain the material index n = 2.4 at the wavelength λ = 2 µm.

For the As_2S_3 PCF simulated in this paper, we set Λ = 1 µm and 2 µm while the ratio of the air-hole diameter to the pitch d/Λ is set to 0.3, 0.4, 0.5, 0.6, 0.7, and 0.8. The finite element method is used to simulate the nonlinearity coefficients of PCFs in this paper, and the corresponding program is Lumerical Mode Solutions. Initially, we consider a PCF consisting of six air-hole rings with a core diameter of $D_c = 6\Lambda - d$ as shown in Fig. 2a. At a hole-pitch of

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1 µm, effective mode area A_{eff} of PCF structures is shown in Fig. 2b, and this property of 2 µm hole pitch is presented in Fig. 2c. The results show the effective mode area of the designed PCFs increasing with the filling factor from large to small, for all Λ. This means that the A_{eff} of the fiber with $d/\Lambda = 0.3$ is larger than the other coefficients. On the other hand, the effective area is also demonstrated to be a function of wavelength. In this case, light energy is more concentrated in the PCF core at short wavelengths. That is the reason why in these regions the slopes of the A_{eff} curves are small. At longer wavelengths, the optical field exhibits better penetration into the holes in the cladding, causing the slope to go up significantly. This is also observed in publications [15,16].

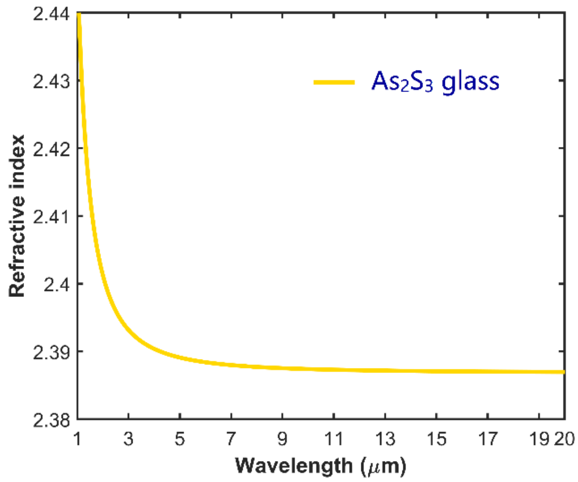

Fig. 1. *Refractive index n of the chalcogenide glass As_2S_3 as a function of the wavelength λ.*

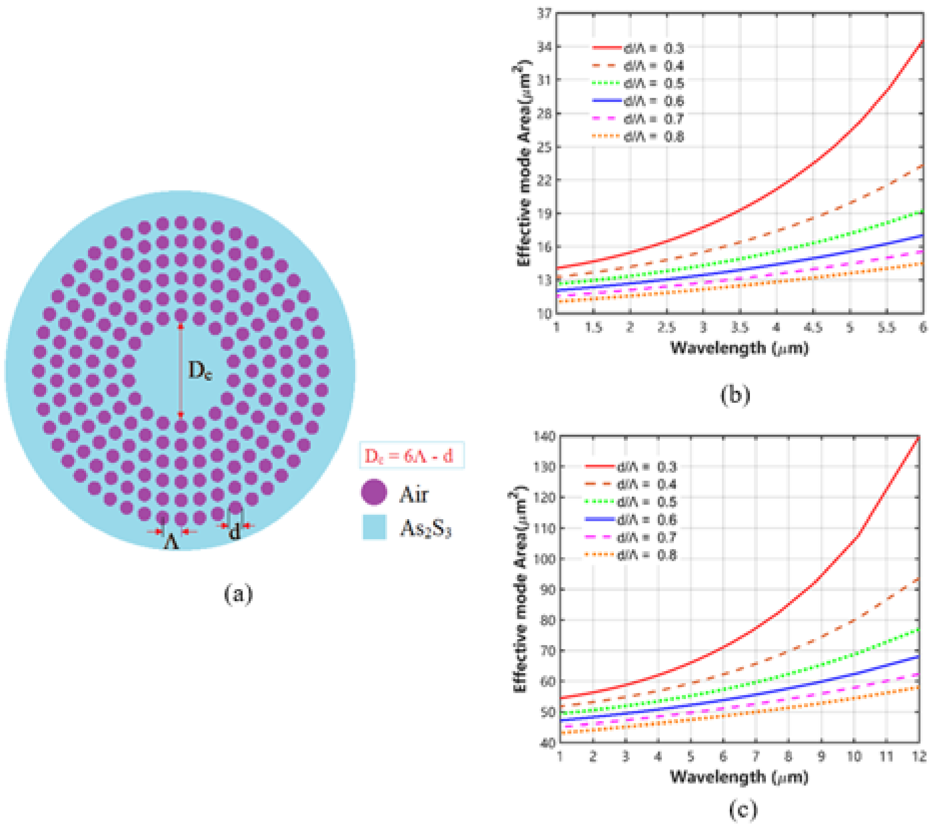

Fig. 2. *For the As_2S_3 PCF, $D_c = 6\Lambda - d$. Structural diagram of PCFs (a), effective mode area Aeff of PCFs as a function of wavelength at a hole-pitch of 1 µm (b) and 2 µm (c).*

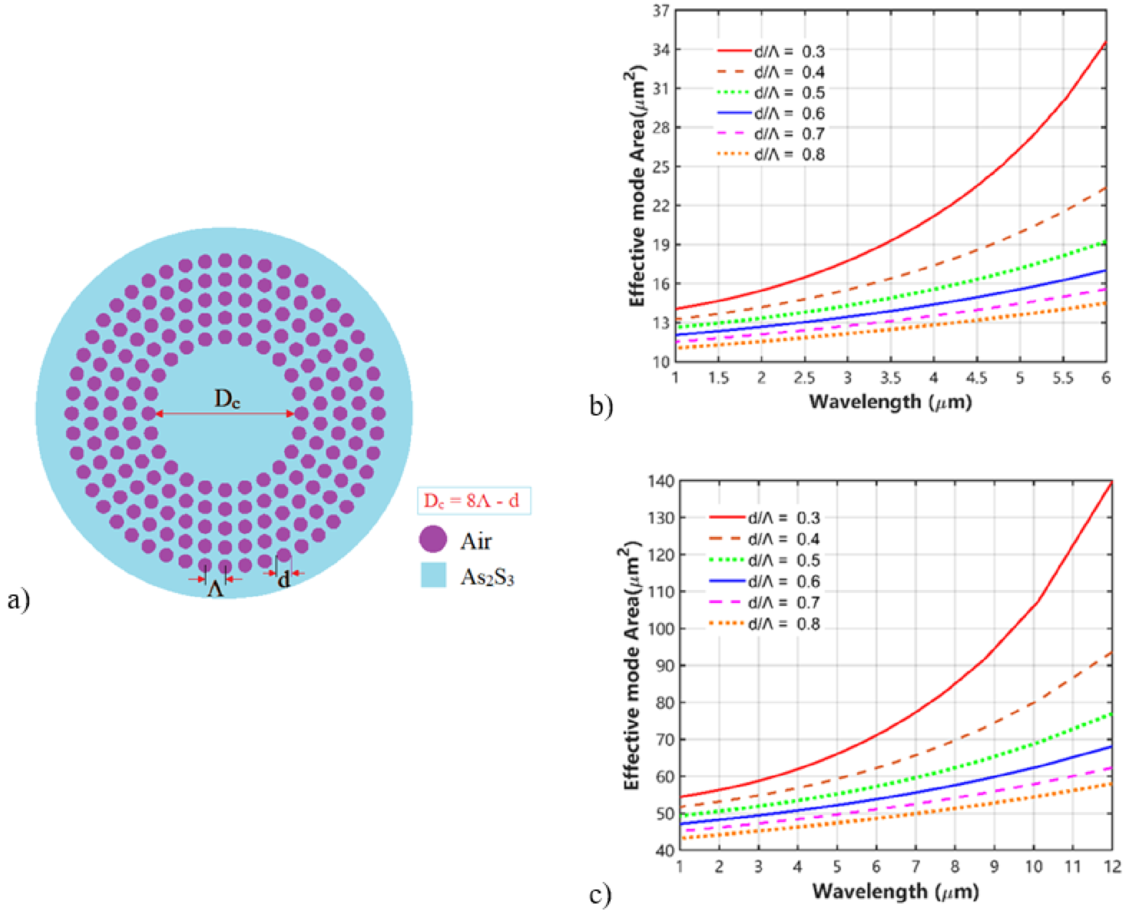

Fig. 3. *For the As2S3 PCF, Dc = 6Λ - d. Structural diagram of PCFs (a), effective mode area Aeff of PCFs as a function of wavelength at a hole-pitch of 1 μm (b) and 2 μm (c).*

In the next stage, we change the core of the PCF by removing the innermost air-hole ring. It means that the core diameter increases according to the formula $D_c = 8\Lambda - d$., Fig. 3a. At this point, most of the states of the effective mode area curves are similar to the case $D_c = 6\Lambda - d$. Publication [17] proved that the degree of interaction between light and the nonlinear medium is enhanced in PCFs with large cores. Indeed, the PCFs in Figs. 3b and 3c allow the support of conduction modes inside the core at longer wavelengths than that of Fig. 2. Therefore, it can be predicted that an increase in core size also strongly affects the A_{eff} of the fibers. To test the above hypothesis, we calculate the effective mode area values of the PCFs with different D_c at the respective pump wavelengths. It is known that PCFs designed with a near-zero flatness of chromatic dispersion can produce the desired SC with the appropriate input pulse. The center wavelength of the input laser for fibers with small D_c is 5 µm and 6 µm for fibers with large D_c. The data is shown in Tables 1 and 2.

Table 1. *The A_{eff} values of PCFs with $D_c = 6\Lambda - d$ at 5 μm.*

A_{eff} (μm²) at 5 μm						
d/Λ Λ (μm)	0.3	0.4	0.5	0.6	0.7	0.8
1	26.4	19.94	17.18	15.57	14.47	13.6
2	66.04	59.32	55.24	52.2	49.69	47.42

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Table 2. *The A_{eff} values of PCFs with D_c = 8Λ - d at 5 μm.*

A_{eff} (μm²) at 6 μm						
d/Λ Λ (μm)	0.3	0.4	0.5	0.6	0.7	0.8
1	43.8	34.17	30.21	27.87	26.21	24.93
2	115.69	105.69	99.69	95.34	91.71	88.51

The results from two above tables indicate that the A_{eff} value at the pump wavelength rises with the increase in the hole pitch and the decrease in the filling factor, consistent with Figs. 2 and 3. As expected, the gain becomes much more pronounced as the cores of the PCFs are further expanded. This demonstrates that the effective mode area is not only a function of wavelength but also a function of core size.

III. SIMULATION RESULTS OF NONLINEAR COEFFICIENT

In particular, we acknowledged the highest A_{eff} value of 115.69 μm² for fiber with *d/Λ* = 0.3. However, a high value of the nonlinear coefficient *γ* requires the mode area to be as small as possible. This is due to the following relationship [18]:

$$\gamma = \frac{2\pi}{\lambda}\frac{n_2}{A_{eff}}. \quad (2)$$

From formula 2, two structures with the smallest A_{eff} corresponding to the cases of D_c are selected with the aim of achieving the best SCG efficiency. That is fiber with *Λ* = 1 μm, *d/Λ* = 0.8, D_c = 5.2 μm and *Λ* = 2 μm, *d/Λ* = 0.8, D_c = 7.2 μm. Their nonlinear curves are depicted in Fig. 4. Obviously, the fiber with a smaller D_c confines light at a shorter wavelength range. Its nonlinear coefficient is higher than that of the other fiber because its A_{eff} is smaller. The nonlinearities of two proposed fibers are 387.88 W^{-1} km^{-1} at 5 μm and 176.33 W^{-1} km^{-1} at 6 μm, respectively. These values are higher than previously reported [19,20], even up to 12 times for the circular lattice [21]. A higher nonlinearity coefficient is beneficial in SCG.

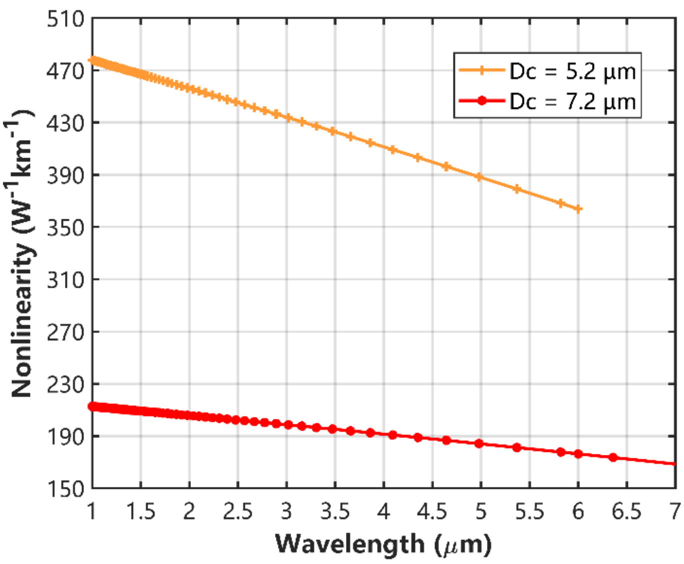

Fig. 4. *Nonlinearity coefficient of the proposed PCFs.*

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IV. CONCLUSION

In this paper, an As_2S_3 PCF with air-hole layers in a circular array around the solid core is designed. For structural parameters Λ = 1μm and 2 μm, d/Λ = 0.3-0.8, and $D_c = 6\Lambda - d$, the As_2S_3 PCFs present a raised effective mode area with wavelength and hole pitch, while it decreases with the filling factor. When considering the variation of core diameter, the variation of the effective mode area can be observed more clearly. Such PCFs allow light conduction at longer wavelength regions than small core ones. Accordingly, we have demonstrated that mid-infrared SCG can be efficiently generated in two As_2S_3 PCFs with the smallest A_{eff}. The efficiency of SCG will be enhanced thanks to the high nonlinearity of the selected fibers.

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