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ANALYSIS OF THE EFFECTIVE MODE AREA CHARACTERISTICS OF SQUARE SOLID-CORE PHOTONIC CRYSTAL FIBERS WITH As_2S_3 SUBSTRATE

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Abstract: This paper proposes a square lattice solid-core photonic crystal fiber (PCF) with an As_2S_3 substrate. We investigate the influence of structural parameters on the effective mode area of photonic crystal fibers based on the finite element method. The analysis results show that the filling factor *(d/Λ)* and lattice constant *(Λ)* strongly affect the effective mode area. We have proposed fibers with an effective mode area suitable for optical fiber technology applications.

Keywords: *Photonic crystal fibers (PCFs), square lattice, the effective mode area, nonlinear coefficient.*

I. INTRODUCTION

In 1992, the photonic crystal fiber (PCF) was invented by P. Russell and the first photonic crystal fiber was reported at the Optical fiber Conference (OFC) in 1996 [1]. Photonic crystal fibers are optical fibers made of a material whose cladding is formed by an ordered arrangement of air-hole running along the length of the fiber. PCF is mainly determined by three parameters including lattice constant *Λ* (distance between the centers of two air-holes), air-hole diameter *d*, and core diameter D_c. Since the invention of photonic crystal fibers, it has been particularly attractive to scientists because of their outstanding advantages over conventional optical fibers in design and fabrication [2]. PCF is designed in a variety of sizes, shapes, lattice types, and substrates...

The effective refractive index, effective mode area, dispersion, and attenuation are characteristic quantities that directly affect the application of PCF. Which, the effective mode area is an important characteristic directly related to the applications of fiber technology. If the effective mode area is large, the loss of PCF will be small, which makes it possible for PCF to be used in sensing, spectroscopy, microscopy, and telecommunications [2]. While a small effective mode area will lead to a large nonlinear coefficient of fiber which can be applied for supercontinuum generation [3-10]. Supercontinuum generation is an important application of PCF that is of particular interest to scientists today.

In recent times, PCF with silica substrates has been widely studied with many outstanding advantages, but silica has a small nonlinear refractive index and any optical application of silica PCF should not be exceeded the limit of 2 µm of wavelength [11, 12, 4, 6]. Meanwhile, chalcogenide (ChG) glasses have been widely used in the study of

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nonlinear optical effects in PCF because of their wide transmission window, low two-photon absorption, high nonlinear refractive index, high nonlinearity in the near-infrared and mid-infrared (MIR) regions. PCFs with ChG glasses have interesting nonlinear properties over a longer wavelength range and offer better supercontinuum generation performance. Among them, As_2S_3 is one of the ChG glasses widely used for spinning thanks to its good thermal stability and glass-forming ability. As_2S_3 is an inorganic compound composed of two elements Arsenic and Sulfur. This compound exists as a bright yellow solid, insoluble in water. Many works on PCFs using As_2S_3 have been reported to date and have achieved encouraging results, i.e., PCF structure with As_2S_3-doped square-shaped holes has very large negative dispersion and high birefringence [13], multifunctional hexagonal lattice dual-core PCF structure incorporating elliptical air-hole for types of chalcogenide materials (As_2S_3 and As_2Se_3) have high birefringence [14], a low confinement loss with double-PCF [15], flat dispersion and high nonlinearity of the As_2S_3 three-bridge suspended-core fiber [16]. However, most of the previous works only focused on the study of hexagonal and circular lattice PCFs without any research on square lattice PCFs

In this paper, we design a square lattice solid-core PCF with an As_2S_3 substrate. We chose PCF with an As_2S_3 substrate because its nonlinear refractive index of $n_2 = 420 \times 10^{-20}$ m^2/W [17] is much larger than that of silica at 1053 nm [18]. The square lattice was chosen for investigation because it is highly symmetric and easy to design. This lattice also possesses some advantages of negative dispersion, low loss, and wide single-mode operating region [19-21]. We analyzed the effect of the change of filling factor (d/Λ) and lattice constant (Λ) on the effective mode area characteristic of PCF. Our results show that our PCF designs are promising for optical fiber technology applications.

II. NUMERICAL MODELLING OF PCFs

We design As_2S_3 substrate solid-core photonic crystal fibers in this section using Lumerical Mode Solutions software [22]. The geometrical structure of PCF is shown in Figure 1. PCF consists of 8 lattice rings arranged in a square lattice defined by the air-hole diameter d and lattice constant Λ. The filling factor of the photonic cladding is determined by the formula $f = d/\Lambda$.

In the simulation, we investigate the changes in the filling factor and lattice constant affecting the effective mode area characteristics. In which, the lattice constant (Λ) changes from 1.0 µm to 3.0 µm with a step of 0.5, and the filling factor $f = d/\Lambda$ changes from 0.3 to 0.8 with a step of 0.05. The core diameter is determined according to the formula $D_c = 2\Lambda - d$, with the largest core diameter D_{cmax} = 5.1 µm corresponding to the filling factor d/Λ = 0.3 of the lattice constant Λ = 3.0 µm and the core diameter has the smallest value D_{cmin} = 1.2 µm corresponding to the filling factor d/Λ = 0.8 of the lattice constant Λ = 1.0 µm. Structural parameters are selected according to the technological requirements commonly used to develop PCFs.

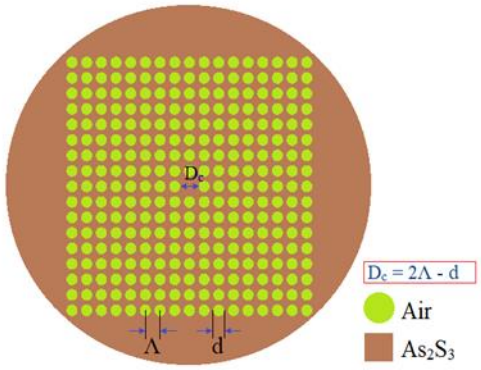

Fig 1. *The geometrical structures of PCFs with square lattice and As_2S_3 substrate*

The effective mode area is an important characteristic of PCF and directly affects the supercontinuum generation efficiency, which is determined by the formula (1) [23]:

$$A_{\mathrm{eff}} = \frac{\left(\int_{-\infty}^{\infty} \int_{-\infty}^{\infty} |E(x,y)|^2 \, dxdy \right)^2}{\int_{-\infty}^{\infty} \int_{-\infty}^{\infty} |E(x,y)|^4 \, dxdy} \qquad (1)$$

Where E is the electric field amplitude.

The refractive index of As_2S_3 is determined by the Sellmeier equation [24], which depends on the wavelength according to equation 2.

$$n^2_{As_2S_3} = 1 + \frac{A_1\lambda^2}{\lambda^2 - B_1} + \frac{A_2\lambda^2}{\lambda^2 - B_2} + \frac{A_3\lambda^2}{\lambda^2 - B_3} \qquad (2)$$

Where λ is the wavelength in micrometers, and the different coefficients are $A_1 = 1.898$, $A_2 = 1.922$, $A_3 = 0.876$, $B_1 = 0.0225 \mu m^2$, $B_2 = 0.0625 \mu m^2$, and $B_3 = 0.1225 \mu m^2$ [25].

III. RESULTS AND DISCUSSION

Figure 2 shows the dependence of the effective mode area (A_{eff}) on the calculated wavelength with the filling factor d/Λ varying from 0.3 to 0.8 for different lattice constants Λ = 1.0 µm, Λ = 1.5 µm, Λ = 2.0 µm, Λ = 2.5 µm, and Λ = 3.0 µm.

It can be seen that, in a given lattice constant (Λ) value, the effective mode area varies with wavelength and has the same shape. Furthermore, the effective mode area decreases as the filling factor d/Λ increases. In the case with the same value of the filling factor d/Λ, as the lattice constant increases, the effective mode area increases.

We have established the value of the effective mode area at 4.5 µm of PCF with different values of the filling factor and lattice constant as shown in Table 1.

At the wavelength of 4.5 µm, the maximum effective mode area value is 112.89 µm^2 for the case d/Λ = 0.3, Λ = 1.5 µm, the large effective mode area can be widely used in fiber optic technology such as sensing, spectroscopy, microscopy, and telecommunications. Meanwhile, the minimum effective mode area value is 3.84 µm^2

with *d/Λ* = 0.8, *Λ* = 1.5 µm. A small effective mode area is always sought for supercontinuum generation efficiency.

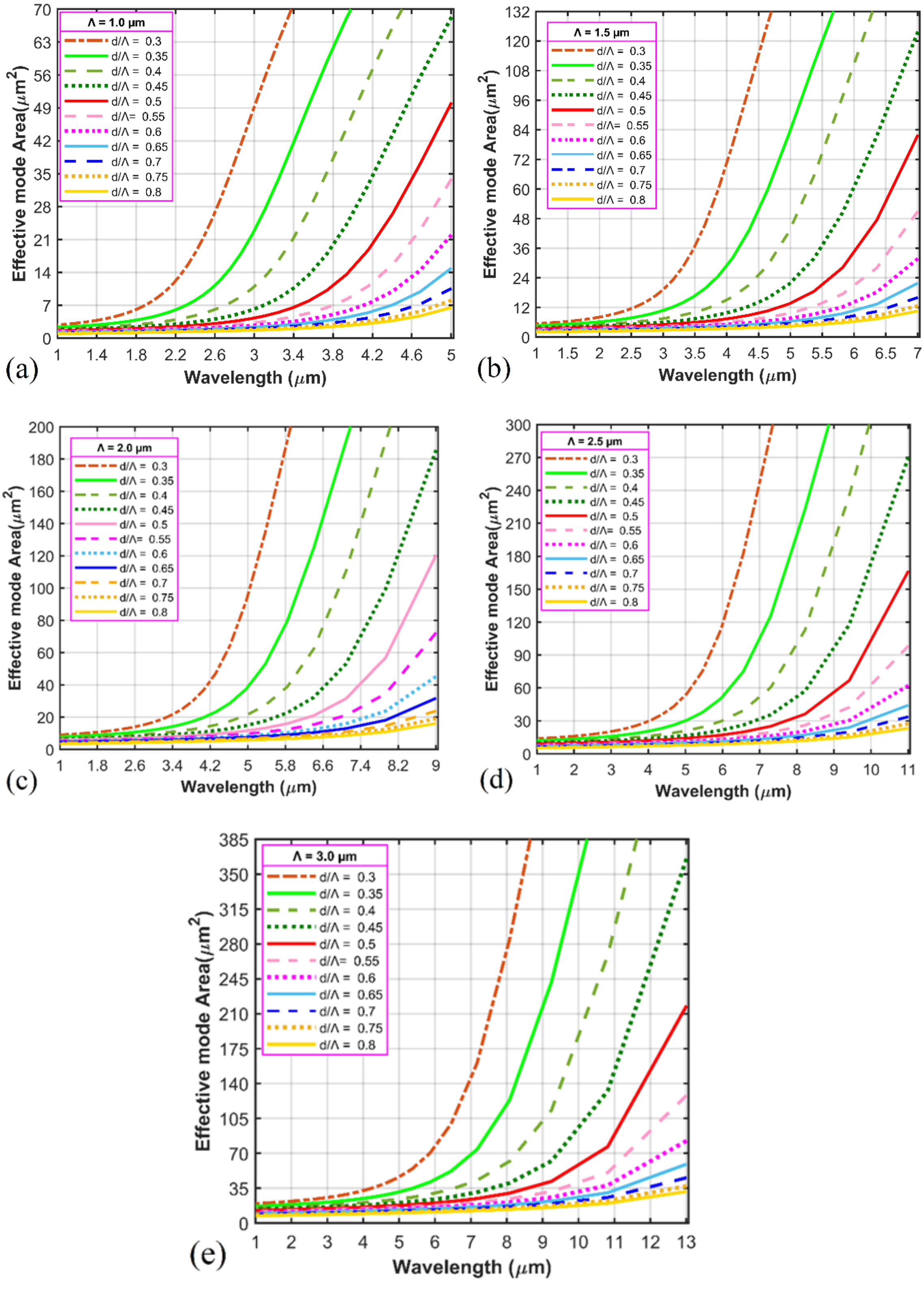

Fig 2. *The effective mode areas as a function of wavelength of the fiber with various d/Λ* ***(a)*** *Λ = 1.0 µm,* ***(b)*** *Λ = 1.5 µm,* ***(c)*** *Λ = 2.0 µm,* ***(d)*** *Λ = 2.5 µm, and* ***(e)*** *Λ = 3.0 µm.*

Table 1. *The effective mode area values of PCF at wavelength 4.5 µm with lattice constant Λ = 1.0 µm, Λ = 1.5 µm, Λ = 2.0 µm, Λ = 2.5 µm, and Λ = 3.0 µm and the filling factor d/Λ varies from 0.3 to 0.8.*

A_{eff} (μm^2)						
λ	***d/Λ***	***Λ* = 1.0 µm**	***Λ* = 1.5 µm**	***Λ* = 2.0 µm**	***Λ* = 2.5 µm**	***Λ* = 3.0 µm**
4.5 µm	0.3	105.55	112.89	56.34	38.49	38.26
	0.35	88.46	50.44	26.34	24.49	27.64
	0.4	69.55	24.52	16.56	18.21	22.25
	0.45	46.83	13.97	12.44	15.06	19.14
	0.5	29.33	9.68	10.17	13.03	16.96
	0.55	17.57	7.45	8.75	11.60	15.31
	0.6	11.13	6.15	7.78	10.53	13.98
	0.65	7.82	5.31	7.00	9.58	12.88
	0.7	5.90	4.70	6.38	8.79	11.73
	0.75	4.75	4.23	5.85	8.08	10.78
	0.8	4.01	3.84	5.36	7.41	9.87

IV. CONCLUSION

In this work, we analyzed the influence of the filling factor *d/Λ* and the lattice constant (*Λ*) on the values of the effective mode area of the As_2S_3 substrate solid-core photonic crystal fiber. These structural parameters strongly influence the effective mode area of PCF. We propose the fiber with the largest effective mode area of 112.89 μm^2 with structural parameters *d/Λ* = 0.3 and *Λ* = 1.5 µm, which has promising applications in sensing, spectroscopy, microscopy, and telecommunications. While the fiber has the smallest effective mode area (*d/Λ* = 0.8, *Λ* = 1.5 µm) of 3.84 μm^2 suitable for supercontinuum generation.

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