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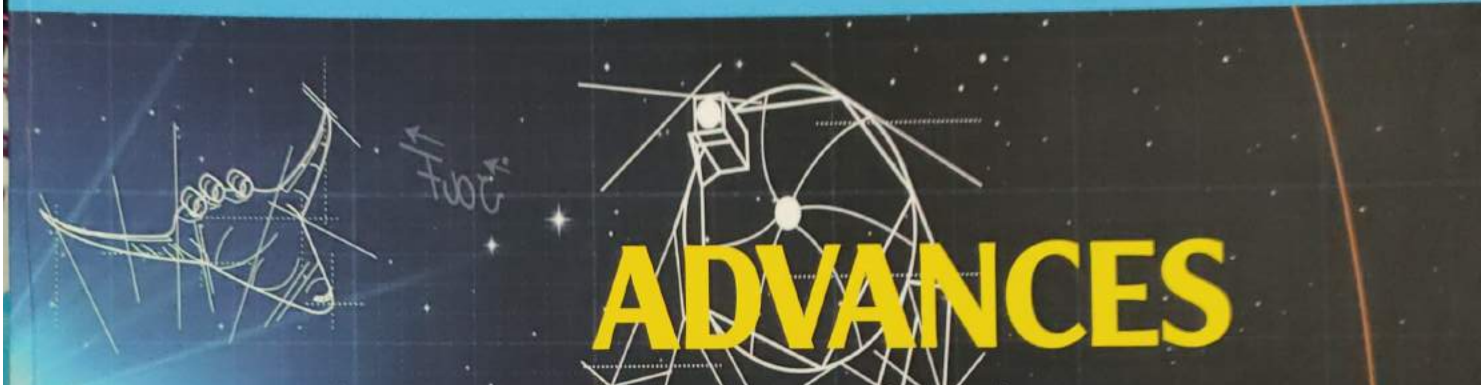

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ANALYSIS EFFECTIVE MODE AREA OF SOLID-CORE PCFS WITH HEXAGONAL LATTICE INFILTRATED WITH METHANOL FOR OPTICAL FIBER TECHNOLOGY

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Abstract. In this paper, we analyzed the effective mode area of solid-core fused silica photonic crystal fiber (PCF) with hexagonal cladding and infiltrated with methanol. We have determined that the largest effective mode area is 367.9970 μm^2 when the air hole diameter is 1 μm and that the smallest effective mode area is 21.1393 μm^2 when the air hole diameter is 4 μm. We have compared these results with a previous publication, and our results give important insights into the PCFs' optical fiber technology applications.

Keywords: *Photonic crystal fibers, dispersion, nonlinear optics, supercontinuum generation.*

I. INTRODUCTION

In 1996, photonic crystal fibers (PCFs) were proposed by J. C. Knight and his colleagues [1] and has then created a revolution in optical fiber technology. For a short period, PCFs have attracted the attention of many scientists around the world because of its very new properties compared to conventional optical fibers such as extremely single-mode fibers [2]. PCFs can guide light in the air core based on the photonic bandgap effect [3] which cannot be done with conventional optical fibers.

In optical fiber technology, the characteristic quantities of PCFs that influence their applications include the effective refractive index, effective mode area, dispersion, and loss. Among these quantities, the effective mode area is much studied by scientists because it is directly related to optic fiber technology applications. When the effective mode area is small, the PCFs' nonlinearity will be large, so the PCFs can be used for supercontinuum generation. On the other hand, if when the effective mode area is large, the PCF loss will be small, and the PCF can be applied in telecommunications, metrology, spectroscopy, microscopy, biology, and sensing [4]. Some publications regarding the effective mode area of PCFs include high-power fiber lasers for kW-operation [5], the experimental demonstration of large-mode-area PCF [6], the PCF sensitivity to longitudinal non-uniformities and the consequences and limitations [7]. Previous reports [8, 9] have also proposed a PCF infiltrated with ethanol. However, using ethanol to enlarge the effective mode area has been found to affect the SG efficiency.

To overcome this restriction, we designed a solid-core fused silica PCF with a hexagonal lattice in the cladding and infiltrated with methanol. We also compared the effective mode areas of similar PCFs infiltrated with ethanol and methanol and with different air hole diameters. Our results show that our PCF designs are promising for optical fiber technology applications.

II. MODELING AND THEORY

We used the Lumerical Mode Solutions software [10] to design a solid-core fused silica PCF infiltrated with methanol. As shown in Fig. 1, the PCF has air holes arranged in a hexagonal lattice consisting of 8 concentric rings of holes. The diameter, *d* of the air holes were varied from 1 to 4 µm, and the lattice constant, Λ was set as 5 µm.

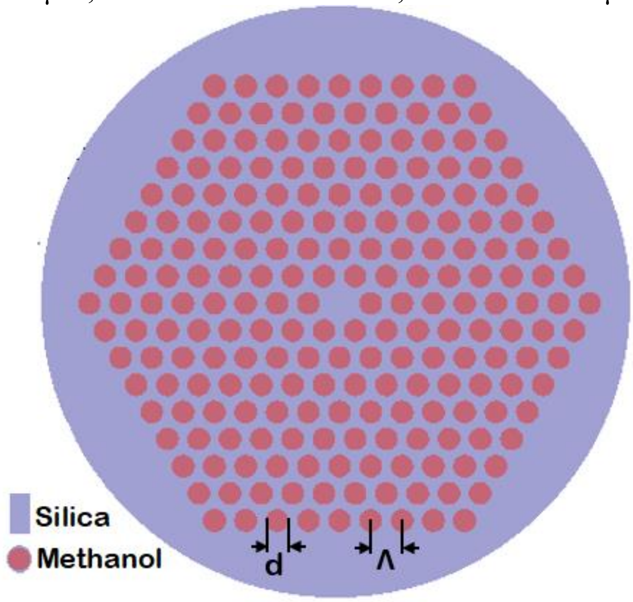

Fig. 1. *Schematic illustration of a solid-core fused silica PCF with hexagonal lattices in the cladding and infiltrated with methanol*

Since the refractive index is dependent on wavelength, the refractive index of methanol can be calculated using Cauchy's equation (Eq. 1) [11], while that of fused silica can be obtained using Sellmeier's equation (Eq. 2) [12]:

$$n^2_{Methanol}(\lambda) = A_0 + A_1\lambda^2 + \frac{A_2}{\lambda^2} + \frac{A_3}{\lambda^4} + \frac{A_4}{\lambda^6} \quad (1)$$

$$n^2_{Fused\ silica}(\lambda) = B_0 + \frac{B_1\lambda^2}{\lambda^2 - C_1} + \frac{B_2\lambda^2}{\lambda^2 - C_2} + \frac{B_3\lambda^2}{\lambda^2 - C_3} \quad (2)$$

where λ is the wavelength in micrometers, and the different coefficients are A_0 = 1.745946239, A_1 = - 0.005362181 μm^{-2}, A_2 = 0.004656355 μm^2, A_3 = 0.00044714 μm^4, A_4 = - 0.000015087 μm^6, B_0 = 1; B_1 = 0.6694226, B_2 = 0.4345839, B_3 = 0.8716947, C_1 = 4.4801×10^{-3} µm², C_2 = 1.3285×10^{-2} µm², C_3 = 95.341482 µm². Figure 2 shows the real parts of the refractive indices of methanol [11] and silica [12] from 0.5 to 2 µm.

In addition, the effective mode area, A_{eff} is an important quantity in designing PCF and is characteristic of the PCF's nonlinearity. A_{eff} can be related to the effective area of the core area defined as [4, 6]:

$$A_{eff} = \frac{\left(\int_{-\infty}^{\infty}\int_{-\infty}^{\infty} |E|^2\, dxdy\right)^2}{\int_{-\infty}^{\infty}\int_{-\infty}^{\infty} |E|^4\, dxdy} \quad (3)$$

where *E* is the electric field amplitude.

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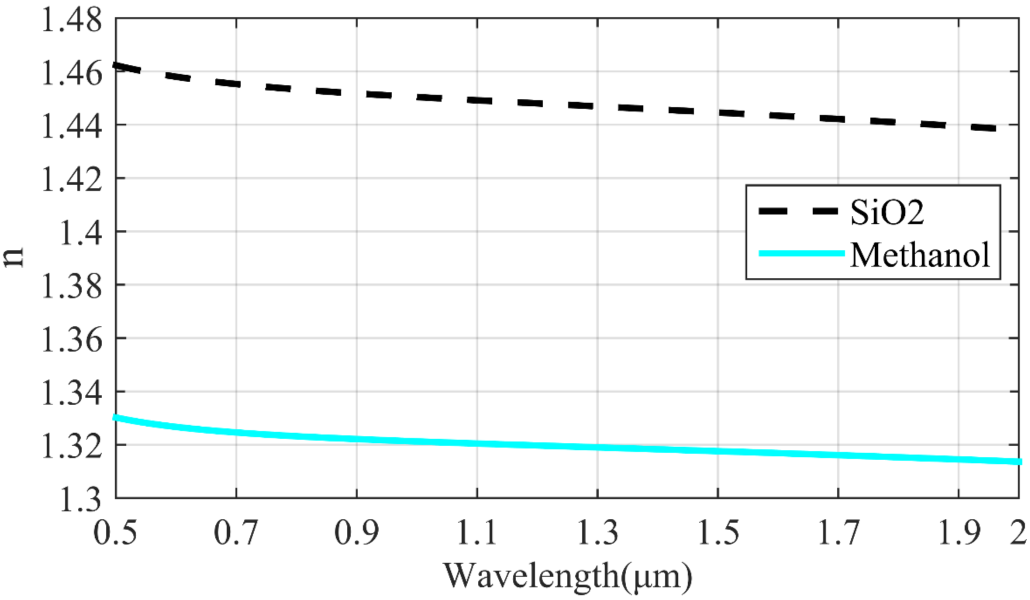

Fig. 2. *Real parts of the refractive indices of methanol [11] and silica (SiO_2) [12]*

III. RESULTS AND DISCUSSION

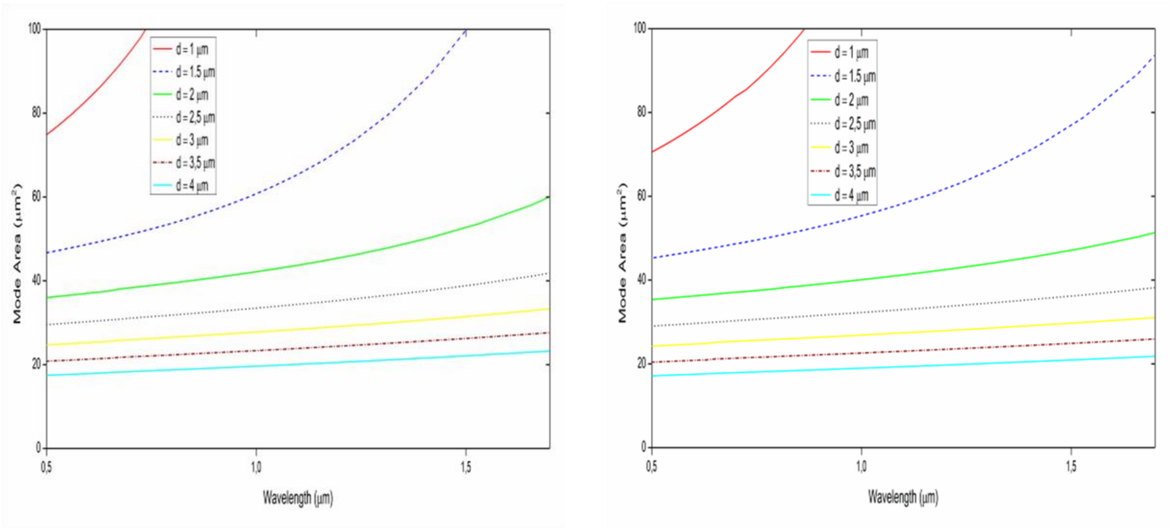

Fig. 3. *Effective mode areas at different wavelengths of PCFs infiltrated with (a) ethanol and (b) methanol and with air hole diameters, d ranging from 1 to 4 μm. The lattice constants, Λ of both PCFs are set as 5 μm*

Figure 3 shows the effective mode areas at different wavelengths of the PCFs infiltrated with ethanol and methanol and with different air hole diameters. The lattice constant is set at 5 μm, and the air hole diameters are 1.0, 1.5, 2.0, 2.5, 3.0, 3.5, and 4.0 μm. Regardless of the solution used, the effective mode area has been found to depend on the wavelength and the air hole diameter. When the wavelength increases and the air hole diameter decreases, the effective mode area increases for both PCFs infiltrated with ethanol and methanol.

When the two PCFs are compared, the effective mode area of the PCF infiltrated with ethanol is higher than that of the PCF infiltrated with methanol. This comparison is always true for the same value of wavelength and air hole diameter. Table 1 shows the comparison of the effective mode areas at 1,55 µm (near-infrared) of both PCFs with different air hole diameters.

Table 1 also shows that the effective mode area is large for a small air hole diameters, and vice versa. For instance, when the air hole diameter is 1,0 µm, the highest effective mode areas of the PCFs infiltrated with ethanol and methanol are 655,1375 and 367,9970 µm^2, respectively. In this case, the difference in the effective mode areas of the two PCFs is the highest which is equal to 287,1405 µm^2. When the air hole diameter is 4.0 µm, the effective mode areas of the PCFs infiltrated with ethanol and methanol are 22,3647 and 21,1393 µm^2, respectively. In contrast to the former case, the difference in the effective mode areas of the two PCFs is the smallest which is equal to 1,2254 µm^2.

For practical applications, PCFs with a large effective mode area such as our PCFs with 1.0-µm air hole diameters can be widely used in fiber optic technology [13], while those with a small effective area such as our PCFs with 4,0-µm air hole diameters can be used for supercontinuum generation [14, 15].

Table 1. Effective mode areas at 1.55 µm of PCFs infiltrated with ethanol and methanol and with air hole diameters, *d* ranging from 1 to 4 µm. The lattice constants, Λ of both PCFs are set as 5 µm.

λ(µm)	d(µm)	A_{eff} (µm^2) Ethanol	A_{eff} (µm^2) Methanol	ΔA_{eff} (µm^2)
1,55	1.0	655.1375	367.9970	287.1405
	1.5	107.1478	80.4935	26.6543
	2.0	54.3076	48.0777	6.2299
	2.5	39.5136	36.6570	2.8566
	3.0	31.8954	30.0279	1.8675
	3.5	26.5802	25.1430	1.4372
	4.0	22.3647	21.1393	1.2254

IV. CONCLUSION

The effective mode areas of solid-core fused silica PCFs with a hexagonal lattice in the cladding and infiltrated with methanol and ethanol were studied numerically. For a PCF infiltrated with methanol, we have determined that the largest effective mode area is 367,9970 µm^2 when the air hole diameter is equal to 1 µm and that the smallest effective mode area is 21,1393 µm^2 when the air hole diameter is 4 µm. Our results show that PCFs we have designed are promising for various optical fiber technology applications.

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