VIETNAM ACADEMY OF SCIENCE AND TECHNOLOGY
INSTITUTE OF PHYSICS

ADVANCES IN APPLIED AND ENGINEERING PHYSICS VI

PUBLISHING HOUSE FOR SCIENCE AND TECHNOLOGY

CONTENTS

ISBN: 978-604-9985-13-3

DISPERSIONS OF SOLID-CORE SILICA PCFS INFILTRATED WITH WATER AND ETHANOL FOR SUPERCONTINUUM GENERATION

Lanh Chu Van[1], Vu Nguyen Quang[1], My Linh Nguyen Thi[1], Vu Tran Quoc[2], Trang Chu Thi Gia[1], Huyen Dinh Thi[1], Thuy Nguyen Thi[3], Khoa Dinh Xuan[1]

[1]Department of Physics, Vinh University, 182 Le Duan, Vinh city, Vietnam

[2]Thu Khoa Nghia High School for The Gifted, Chau Doc city, Vietnam

[3]Hue University of Education, Hue University, 34 Le Loi street - Hue city, Vietnam

E-mail: *chuvanlanh@vinhuni.edu.vn*

Abstract. In this paper, we compare solid-core silica photonic crystal fibers (PCFs) infiltrated with water and ethanol. We examine the dispersion curves and values as well as the zero-dispersion wavelengths (ZDWs) of the PCFs which have a hexagonal cladding. Our results suggest that the PCFs can be optimized for supercontinuum generation (SG) applications.

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

I. INTRODUCTION

Photonic crystal fibers (PCFs), also known as microstructured optical fibers (MOFs), are new generation of optical waveguides that were discovered by J. C. Knight and his colleagues in 1996 [1]. In a solid-core PCF, the central silica core is surrounded by a periodic array of air holes along the distance of optical propagation. When light passes through the PCF, the presence of air holes in the cladding region eventually reduces the effective refractive index compared when light passes through the core silica that has total internal reflection [2].

Some of the important aspects of PCFs include effective refractive index, effective mode area, dispersion, and loss [3]. Investigations on these characteristic quantities lead to the development of PCFs' fiber optic technology applications [4]. These quantities can be controlled by the PCF structure such as the substrate material, lattice shape, air hole shape and diameter, air hole distance (lattice constant), and liquid or gas infiltration [5-7]. In addition, the optical waveguiding mechanisms are completely different when the PCF core is solid or hollow [8]. Among the important aspects of PCFs, dispersion attracts much attention from scientists because it dominates many applications in fiber optic technology. Some of these applications are the development of solid-state photonic crystal fibers for nonlinear optics [9], supercontinuum generation [10], fast dynamic compensation [11].

In this paper, we used the Lumerical Mode Solutions software [12] to design a solid-core silica PCF infiltrated with water and ethanol for supercontinuum generation (SG) applications. We choose water and ethanol because these are common, non-toxic liquids. We compare their dispersion curves and zero-dispersion wavelengths and have found that the structure of the PCFs with these liquids can be optimized for their desired fiber optic technology applications.

ISBN: 978-604-9985-13-3

II. MODELING AND THEORY

Fig. 1 shows the schematic illustration of the solid-core silica PCF infiltrated with water and ethanol. The PCF has 8 rings of concentric air holes which are arranged in a hexagonal lattice. The air hole diameters (*d*) is varied from 1 to 4 µm with 0.5 µm intervals, and the lattice constant (Λ) is set as 5 µm.

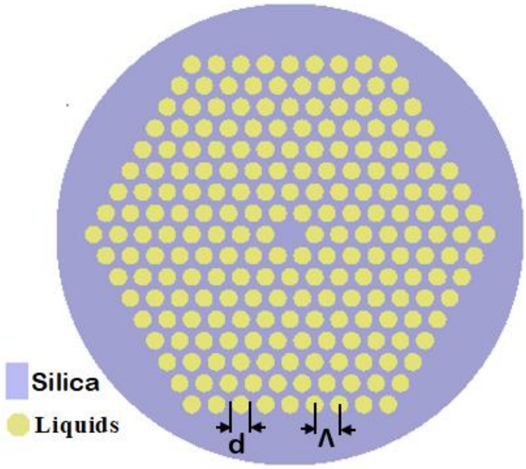

Fig. 1. *Schematic illustration of the solid-core silica PCF infiltrated with water and ethanol*

For our calculations using the Lumerical Mode Solutions software [12], we used the refractive indices of the PCF components. Fig. 2 shows the real parts of refractive indices of silica [13], water [14], and ethanol [14] from 0.5 to 2.0 µm.

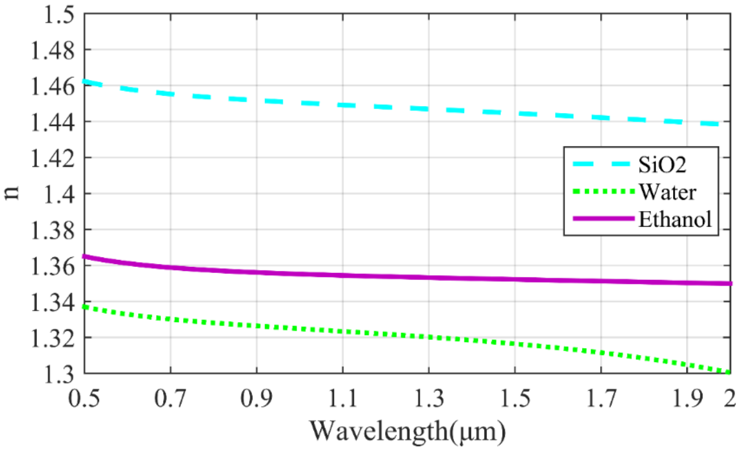

Fig. 2. *Real parts of the refractive indices of silica[13], water, ethanol [14] from 0.5 to 2.0 µm*

III. RESULTS AND DISCUSSION

Fig. 3 shows the calculated dispersion curves of the solid-core silica PCFs infiltrated with water and ethanol for different air hole diameters. The lattice constant of the two PCFs are the same (Λ = 5 µm), and their air hole diameters (*d*) range from 1.0 to 4.0 µm.

For both water and ethanol infiltration, the behavior of the dispersion curves of the solid-core silica PCFs is similar. From 0.5 to 0.9 µm, the dispersion curves are very steep, and their slopes are very large. On the other hand, from 0.9 to 1.6 µm, the dispersion curves are almost flat and their slopes are close to zero. The dispersion also increases with increasing air hole diameter. In all cases, the flattest dispersion curve, which indicates nearzero dispersion, occurs when the air hole diameter is 1.0 µm. This result is similar to those observed in Refs. [15–17] and suggest that such PCFs are suitable for SG [18].

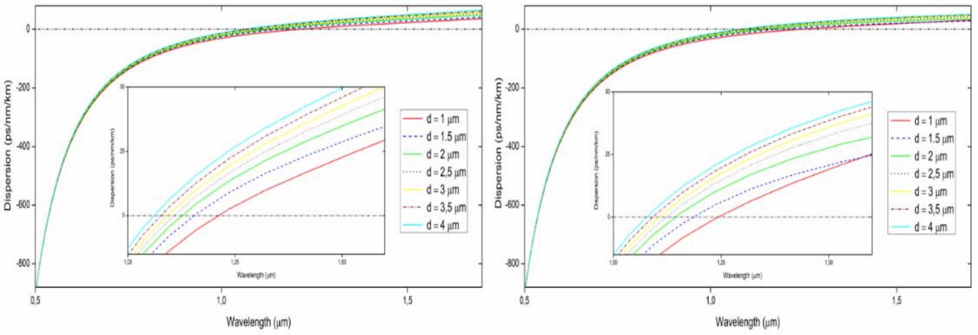

Fig. 3. *Dispersion curves of solid-core silica PCFs infiltrated with water (left) and ethanol (right) for different air hole diameters*

We then compare the effect of water and ethanol on the dispersion of the solid-core silica PCFs. It can be seen in Fig. 1 that the dispersion of the PCF infiltrated with water is higher than that of the PCF infiltrated with ethanol. This observation is always true for different wavelengths and air hole diameters. Table 1 shows the dispersions of both PCFs at 1.55 µm (near-infrared, NIR). When the air hole diameter is 1.0 µm, the dispersions of the PCFs infiltrated with ethanol and water are 22.2 and 26.0 (ps/nm/km), respectively. The difference between these dispersions is the lowest and is equal to 3.8 (ps/nm/km). In contrast, when the air hole diameter is 4.0 µm, the dispersions of the PCFs infiltrated with ethanol and water are 43.7 and 53.7 (ps/nm/km), respectively. The difference between these dispersions is the highest and is equal to 10 (ps/nm/km).

Table 1. *Dispersion at 1.55 µm of solid-core silica PCFs infiltrated with water and ethanol for different air hole diameters*

Air hole diameter, *d* (µm)	**Dispersion, *D* [ps.(nm.km)$^{-1}$]**	
	Water	**Ethanol**
1.0	26.0	22.2
1.5	31.7	22.8
2.0	38.2	30.0
2.5	42.7	35.2
3.0	46.4	38.8
3.5	49.9	41.4
4.0	53.7	43.7

Since the solid-core silica PCFs infiltrated with water and ethanol exhibit zero-dispersion wavelengths (ZDWs), Table 2 shows these values which are all within the NIR region. For the same air hole diameter, the PCF infiltrated with ethanol has a longer ZDW than the PCF infiltrated with water. When the air hole diameter is 1.0 µm, the longest ZDWs of the PCFs infiltrated with ethanol and water are 1.235 and 1.212 µm, respectively. The difference between the ZDWs between the two liquids is high with 23 nm. On the other hand, when the air hole diameter is 4.0 µm, the longest ZDWs of the PCFs infiltrated with ethanol and water are 1.066 and 1.075 µm, respectively. The difference between the ZDWs between the two liquids is lower and is equal to 9 nm.

Table 2. *Zero-dispersion wavelengths (ZDWs) of solid-core silica PCFs infiltrated with water and ethanol for different air hole diameters*

Air hole diameter, *d* (µm)	**Zero-dispersion wavelength, ZDW (µm)**	
	Water	**Ethanol**
1.0	1.212	1.235
1.5	1.155	1.196
2.0	1.127	1.136
2.5	1.108	1.127
3.0	1.092	1.096
3.5	1.123	1.073
4.0	1.075	1.066

For these results, the optimum dispersion for solid-core silica PCFs infiltrated water and ethanol can be achieved when the air hole diameter is 1.0 µm. Interestingly, our results are better than those reported in Ref. [19].

IV. CONCLUSION

We have compared the dispersion of solid-core silica PCFs infiltrated with water and ethanol. We have shown that the PCF infiltrated with ethanol with an air hole diameter of 1.0 µm can exhibit optimum dispersion. Our results are very important in fiber optic technology development, particularly for SG applications.

REFERENCES

[1] J. C. Knight, T. A. Birks, P. S. J. Russell, and D. M. Atkin, All-silica single-mode optical fiber with photonic crystal cladding *Opt. Lett.* 21 (19), 1996, pp. 1547-1549.

[2] T. A. Birks, J. C. Knight, and P. S. J. Russell, Endlessly single-mode photonic crystal fiber *Opt. Lett.* 22 (13), 1997, pp. 961-963.

[3] J. C. Knight, Photonic crystal fibres *Nature* 424 (6950), 2003, pp. 847.

[4] R. Buczyński, Photonic crystal fibers *Acta Phys. Pol. A* 106, 2004, pp. 141-168.

[5] J. M. Fini, Microstructure fibres for optical sensing in gases and liquids *Meas. Sci. Technol.* 15, 2004, pp. 1120-1128.

[6] A. H. Bouk, A. Cucinotta, F. Poli, and S. Selleri, Dispersion properties of square-lattice photonic crystal fibers *Opt. Exp*ress 12, 2004, pp. 941-946.

[7] M. Hossain, A. Bulbul, M. Mukit, and E. Podder, Analysis of optical properties for square, circular and hexagonal photonic crystal fiber *Opt. Photonics J.* 7 (11), 2017, pp. 235-243

[8] J. C. Knight, J. Broeng, T. A. Birks, and P. S. J. Russell, Photonic band gap guidance in optical fibers *Science* 282 (5393), 1998, pp. 1476-1478.

[9] R. Buczynski, J. Pniewski, D. Pysz, R. Stepien, R. Kasztelanic, I. Kujawa, A. Filipkowski, A. J. Waddie, and M. R. Taghizadeh, Dispersion management in soft glass all-solid photonic crystal fibres *Opto-Electron. Rev.* 20 (3), 2012, pp. 207-215.

[10] J. Pniewski, T. Stefaniuk, H. L. Van, V. C. Long, L. C. Van, R. Kasztelanic, G. Stępniewski, A. Ramaniuk, M. Trippenbach, and R. Buczyński, Dispersion engineering in nonlinear soft glass photonic crystal fibers infiltrated with liquids *Appl. Opt.* 55 (19), 2016, pp. 5033-5040.

[11] K. D. Xuan, L. C. Van, V. C. Long, Q. H. Dinh, L. V. Mai, M. Trippenbach, and R. Buczyński, Influence of temperature on dispersion properties of photonic crystal fibers infiltrated with water *Opt. Quant. Electron.* 49 (2), 2017, pp. 87.

[12] Lumerical Solutions, Inc. http://www.lumerical.com/tcad-products/mode/

[13] I. H. Malitson, Interspecimen comparison of the refractive index of fused silica *J. Opt. Soc. Am.* 55 (10), 1965, pp. 1205-1209.

[14] K. Moutzouris, M. Papamichael, S. C. Betsis, I. Stavrakas, G. Hloupis, and D. Triantis, Refractive, dispersive and thermo-optic properties of twelve organic solvents in the visible and near-infrared *Appl. Phys. B* 116 (3), 2014, pp. 617-622.

[15] L. C. Van, T. Stefaniuk, R. Kasztelani, V. C. Long, M. Klimczakd, H. L. Van, M. Trippenbach, and R. Buczynski, Temperature sensitivity of photonic crystal fibers infiltrated with ethanol solutions *Proc SPIE* 9816, 2015, pp. 98160O-1.

[16] K. D. Xuan, L. C. Van, V. C. Long, Q. H. Dinh, L. V. Mai, M. Trippenbach, and R. Buczyński, Influence of temperature on dispersion properties of photonic crystal fibers infiltrated with water *Opt. Quant. Electron.* 49 (2), 2017, pp. 87.

[17] H. V. Le, V. L. Cao, H. T. Nguyen, A. M. Nguyen, R. Buczyński, and R. Kasztelanic Application of ethanol infiltration for ultraflattened normal dispersion in fused silica photonic crystal fibers *Laser Phys*. 28, 2018, pp. 115106.

[18] M. L. V. Tse, P. Horak, F. Poletti, N. G. R. Broderick, J. H. V. Price, J. R. Hayes, and D. J. Richardson Supercontinuum generation at 1.06 μm in holey fibers with dispersion flattened profiles *Opt. Express* 14 (10), 2006, pp. 4445-4451.