

COMPARISON OF DISPERSION CHARACTERISTICS OF SOLID-CORE PCFs INFILTRATED WITH PROPANOL AND ETHANOL

Le Tran Bao Tran¹, Dang Van Trong¹, Vo Thi Minh Ngoc^{1,3},
 Truong Thi Chuyen Oanh¹, Ho Thi Anh Thu¹, Tran Ngoc Thao¹, Vu Dinh Long¹,
 Tran Viet Thanh¹, Nguyen Thi Thuy, Chu Van Lanh^{1*}

Abstract: In this paper, we propose the solid-core photonic crystal fibers (PCFs) with hexagonal cladding infiltrated with propanol in the air-holes. The dispersion characteristics and zero-dispersion wavelengths of these PCFs have been compared with previous publications and analyzed in detail. By investigating the dependence of the dispersion characteristics on the air-hole diameters, we determine the optimal structures with 1 μm of that. The PCF infiltrated with propanol exhibits flatter and smaller dispersion characteristic and the zero-dispersion wavelength shifted towards a longer wavelength, 24 nm compared with ethanol permeable PCFs [17]. This result shows that structure with a diameter of air-holes by 1 μm is suitable for supercontinuum (SC) generation in the near-infrared wavelength range.

Keywords: Photonic crystal fibers; Dispersion; Nonlinear optics; SC generation.

1. INTRODUCTION

Photonic crystal fibers (PCFs) were proposed for the first time in 1996 [1, 2], and then it has attracted much attention of research groups in the world. They consist of a central defect region surrounded by an array of air-holes that run along the fiber length. With such a structure, PCFs exhibit unusual properties which cannot be realized in traditional optical fibers [3].

PCFs have more flexibility in design and fabrication than conventional optical fibers, e.g., different light guiding mechanisms, type of lattice, lattice constant, shape and size of holes, variety of background materials, or penetration into the air-hole with various gases or liquids [4]. PCFs with regular hexagonal, square, and circular lattice in the cladding were analyzed in previous publications [5-7]. For PCFs with the same structural parameters and infiltrating gases or liquids, the hexagonal lattice gave the smallest effective mode area of the fundamental mode [8]. A small effective mode area is crucial for SC generation because it increases the nonlinearity of the fiber [9]. Several functional aspects of fibers with hexagonal lattices were studied, such as geometry [10], confinement loss [11], the possibility of broadband infrared SC generation [12], dispersion engineering [13], temperature sensitivity [14], the influence of temperature [15], optimization of optical properties [16]. In the publication [17], the authors proposed a solid-core PCF with a hexagonal lattice that is infiltrated with ethanol to generate SC but the less flat dispersion has affected SC efficiency. Propanol with a linear refractive index of 1.38 larger than that of ethanol 1.36 would be a candidate to overcome these limitations.

So, we designed a solid-core PCF with a hexagonal lattice in the cladding, infiltrated with propanol which is a homologous series of ethanol [20]. The characteristics of dispersion for PCFs infiltrated with propanol and ethanol [17] were compared. The results show that the PCFs with propanol give more optimal dispersion than ethanol PCFs.

2. DISPERSION CHARACTERISTICS

A solid core PCF with 8 rings of air-holes which are ordered in a hexagonal lattice and infiltrated with propanol or ethanol (Fig.1) was designed by Lumerical Mode Solutions software [21]. The diameter of the air-holes (d) varies from 1 to 4 μm and the lattice constant (Λ) is 5 μm .

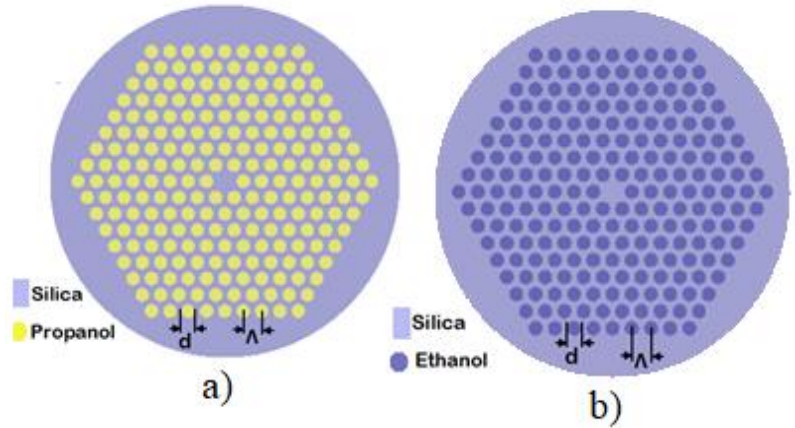


Figure 1. The geometrical structures of solid-core PCFs with hexagonal lattices in the cladding infiltrated with liquids: a) propanol and b) ethanol [17].

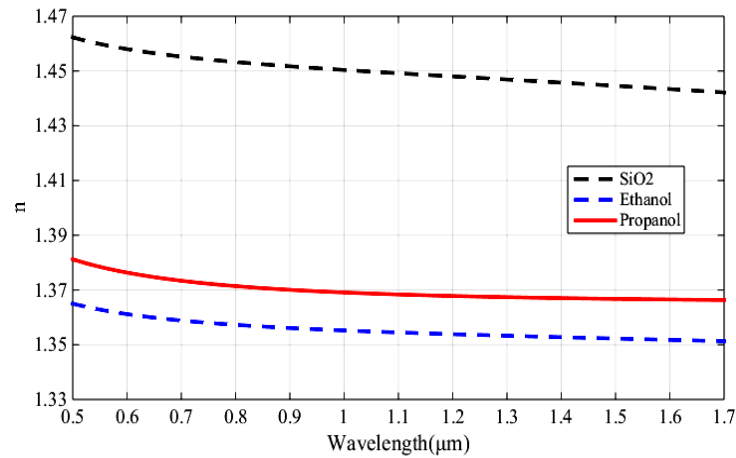


Figure 2. The real parts of the refractive index of propanol, ethanol, and fused silica.

The dependence of the refractive index on the wavelength of ethanol and propanol is calculated by Eq.1 and 2, respectively [18] while the fused silica's refractive index can be obtained using Eq.3 [19], where λ is the wavelength in micrometers.

$$n_{\text{Ethanol}}^2(\lambda) = 1 + \frac{A_{11}\lambda^2}{\lambda^2 - B_{11}} + \frac{A_{21}\lambda^2}{\lambda^2 - B_{21}} \quad (1)$$

with coefficients: $A_{11} = 0.83189$, $B_{11} = 0.00930 \mu\text{m}^2$, $A_{21} = -0.15582$, $B_{21} = -49.4520 \mu\text{m}^2$.

$$n_{\text{propanol}}^2(\lambda) = A_0 + \frac{A_1}{\lambda^2} + \frac{A_2}{\lambda^4} + \frac{A_3}{\lambda^6} \quad (2)$$

with coefficients: $A_0 = 1.36485$, $A_1 = 0.00429404081 \mu\text{m}^2$, $A_2 = -0.000064823380 \mu\text{m}^4$, $A_3 = 0.000003418 \mu\text{m}^6$.

$$n_{Fused\ silica}^2(\lambda) = B_0 + \frac{B_1\lambda^2}{\lambda^2 - C_1} + \frac{B_2\lambda^2}{\lambda^2 - C_2} + \frac{B_3\lambda^2}{\lambda^2 - C_3} \quad (3)$$

with coefficients: $B_0 = 1$; $B_1 = 0.6694226$, $B_2 = 0.4345839$, $B_3 = 0.8716947$, $C_1 = 4.4801 \times 10^{-3} \mu\text{m}^2$, $C_2 = 1.3285 \times 10^{-2} \mu\text{m}^2$, $C_3 = 95.341482 \mu\text{m}^2$.

The real part of the refractive index of the penetrated liquids is lower than that of silica, where this value for propanol is greater than that of ethanol, as presented in Fig.2. This difference helps us enhance light confinement in the core of the PCFs.

The dispersion characteristic of a PCF is usually flexibly controlled by varying the lattice parameters such as the diameter of air-holes and the infiltrating liquids. Fig.3 displays the results of numerical simulation of dispersion characteristics of the designed PCFs according to the change of diameter of air-holes ($d = 1.0, 1.5, 2.0, 2.5, 3.0, 3.5, 4.0 \mu\text{m}$ with the lattice constant $\Lambda = 5 \mu\text{m}$). The shape of the dispersion curves of PCF for both liquids is similar in the surveyed wavelength region. The dispersion increases rapidly i.e. the slopes of these curves are large in the range of $0.5 - 0.9 \mu\text{m}$ of the wavelength. When it crosses the zero-dispersion line, it starts to get closer to the horizontal axis and is flat. Although the negative dispersion is large, its flatness is an essential factor for SC generation. The increase of the diameter of air-holes causes the dispersion to rise, because the larger air-holes are, the lower the light confinement receives. In all cases, the flattest and the smallest dispersion are achieved with $d = 1.0 \mu\text{m}$. This result is similar to the previous report [13–15], the flatness and smallness of the dispersion are the outstanding advantages of the PCFs, which any research is aiming for since they are suitable for generating SC with the broader and smoother spectrum [17].

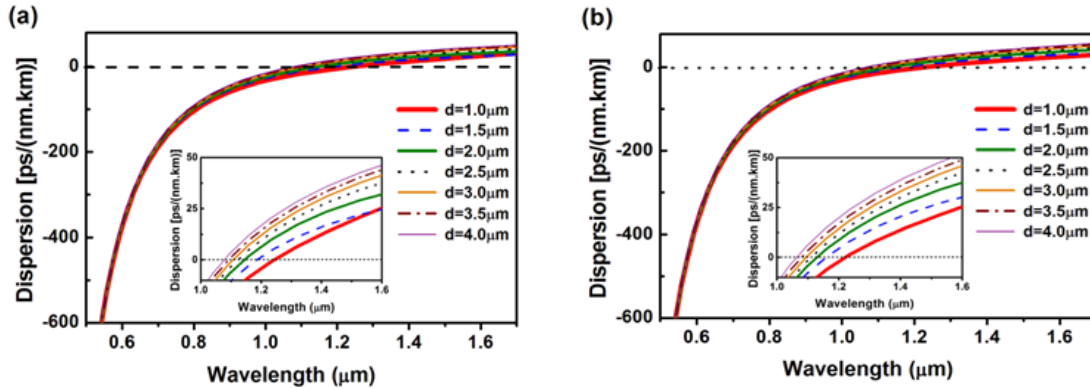


Figure 3. Dispersion characteristics as a function of wavelength for various air-hole diameters, and infiltrated with a) propanol and b) ethanol [17].

The PCF infiltrated with ethanol [17] has a greater dispersion than that of propanol for the same wavelength and the air-holes diameter because of its less light confinement. In Tab.1, the values of dispersion for both cases at $1.55 \mu\text{m}$ wavelength are manifested. As the diameter equals $1.0 \mu\text{m}$, the smallest dispersion for ethanol and propanol are 22.2 ps/nm/km and 19.3 ps/nm/km , respectively, the difference between these two values is 2.9 ps/nm/km , which is significant if PCFs are used in SC generation. The dispersion reaches its maximum value when the air-hole diameter is $4.0 \mu\text{m}$, the highest dispersion of PCF with ethanol is 43.7 ps/nm/km while this value is 37.2 ps/nm/km for propanol PCF. In this case, the difference in dispersion between the two liquids (6.5 ps/nm/km) is

quite large. For each wavelength, the dispersion characteristics of PCF infiltrated with propanol is flatter and smaller than for PCF infiltrated with ethanol [17].

The zero dispersion wavelength (ZDW) is one of the important properties of dispersion because it directs the pumped wavelength of the sources in SC generation. The ZDW shift towards the long wavelength governs the application of PCFs in the near-infrared region. Tab.2 exposes the ZDW of the PCF infiltrated with propanol is higher than that of ethanol, i.e. the ZDW shifted towards the longer wavelength. Moreover, with the increasing of air-holes diameter, the ZDW of PCFs reduces for both liquids. The same phenomenon was observed for the PCF filled with water [15]. As the diameter of air-holes is 1.0 μm , the maximum value of ZDW for the PCF infiltrated with propanol and ethanol is 1.259 μm and 1.235 μm , respectively. These values go down to 1.075 and 1.066 μm , respectively with the diameter of air-holes equals 4.0 μm . The shift of ZDW of PCF infiltrated with propanol is 24 nm longer than that of PCF with ethanol. This result is better in comparison with the data from the publication [14]. PCF with $d = 1 \mu\text{m}$ is the most optimal structure that can be selected for SC generation.

Table 1. The dispersion of PCFs with various air-hole diameters at 1.55 μm wavelength.

λ (μm)	d (μm)	D [ps.(nm.km) ⁻¹]	
		propanol	ethanol
1.55	1.0	19.3	22.2
	1.5	17.5	22.8
	2.0	24.1	30.0
	2.5	29.5	35.2
	3.0	33.1	38.8
	3.5	35.4	41.4
	4.0	37.2	43.7

Table 2. The value of the ZDW for the PCFs with various air-hole diameters.

d (μm)	ZDW (μm)	
	Propanol	Ethanol
1.0	1.259	1.235
1.5	1.213	1.196
2.0	1.181	1.136
2.5	1.162	1.127
3.0	1.144	1.096
3.5	1.123	1.073
4.0	1.075	1.066

3. CONCLUSIONS

In this work, the dispersion characteristics of solid-core PCFs with hexagonal lattice in the cladding, infiltrated with propanol and ethanol were studied numerically. The optimal propanol PCF ($d = 1\mu\text{m}$) was chosen to show potential for SC generation because of the outstanding advantages of dispersion such as flat dispersion curve, small dispersion value, and long-wavelength ZDW.

Funding information: *This research is funded by Vietnam National Foundation for Science and Technology Development (NAFOSTED) under grant number 103.03-2020.03 and Vietnam's Ministry of Education and Training (B2021- DHH-08).*

REFERENCES

- [1]. J.C. Knight, T.A. Birks, P.St.J. Russell, D.M. Atkin, Opt. Lett. 21(19), 1547 (1996).
- [2]. T.A. Birks, J.C. Knight, P.St.J. Russell, Opt. Lett. 22(13), 961 (1997).
- [3]. J.C. Knight, Nature 424, 847 (2003).
- [4]. J.M. Fini, Meas. Sci. Technol. 15(6), 1120 (2004).
- [5]. R. Buczyński, J. Pniewski, D. Pysz, R. Stepień, R. Kasztelanic, I. Kujawa, A. Filipkowski, A.J. Waddie, M.R. Taghizadeh, Opto-Electron. Rev. 20(3), 207 (2012).
- [6]. A.H. Bouk, A. Cucinotta, F. Poli, S. Selleri, Opt. Expr. 12(5), 941 (2004).
- [7]. M.M. Haque, M.S. Rahman, M. Samiul Habib, M. Selim Habib, S.M.A. Razzak, J. Microw. Optoelectron. Electromagn. Appl. 12(2), 44 (2013).
- [8]. Md.B. Hossain, Ab.Al. Bulbul, Md.Ab. Mukit, Et. Podder, Opt. Photon. J. 7(11), 235 (2017).
- [9]. R. Buczyński, Acta Physica Polonica A 106(2), 141 (2004).
- [10]. T. Baghdasaryan, T. Geernaert, F. Berghmans, H. Thienpont, Opt. Expr. 19(8), 7705 (2011).
- [11]. Y.E. Monfared, A.R.M. Javan, A.R.M. Kashani, Optik 124(24), 7049 (2013).
- [12]. M. Klimczak, G. Stepniewski, H. Bookey, A. Szolno, R. Stepień, D. Pysz, A. Kar, A. Waddie, M.R. Taghizadeh, R. Buczyński, Opt. Lett. 38(22), 4679 (2013).
- [13]. J. Pniewski, T. Stefaniuk, L.V. Hieu, C.L. Van, C.V. Lanh, R. Kasztelanic, G. Stepniewski, A. Ramaniuk, M. Trippenbach, R. Buczyński, App. Opt. 55(19), 5033 (2016).
- [14]. C.V. Lanh, T. Stefaniuk, R. Kasztelani, C.L. Van, M. Klimczak, L.V. Hieu, M. Trippenbach, R. Buczyński, Proc. of SPIE 9816, 98160O-1 (2015).
- [15]. D.X. Khoa, C.V. Lanh, H.D. Quang, M.V. Luu, M. Trippenbach, R. Buczyński, Opt. Quant. Electron. 49(2), 87 (2017).
- [16]. C.V. Lanh, H.V. Thuy, C.L. Van, K. Borzycki, D.X. Khoa, T.Q. Vu, M. Trippenbach, R. Buczyński, J. Pniewski, Laser Phys. 29(7), 075107 (2019).
- [17]. L.V. Hieu, C.L. Van, N.T. Hue, N.M. An, R. Buczyński, R. Kasztelanic, Laser Phys. 28(11), 115106 (2018).
- [18]. K. Moutzouris, M. Papamichael, S.C. Betsis, I. Stavrakas, G. Hloupis, D. Triantis, Appl. Phys. B. 116(3), 617 (2014).
- [19]. I.H. Malitson, J. Opt. Soc. Am. 55(10), 1205 (1965).
- [20]. <http://www.inchem.org/documents/ehc/ehc/ehc102.htm>.
- [21]. Lumerical Solutions, Inc. <http://www.lumerical.com/tcad-products/mode/>.

TÓM TẮT

SO SÁNH CÁC ĐẶC TRƯNG TÁN SẮC CỦA CÁC PCF LỖ ĐẶC ĐƯỢC THÂM THẤU PROPANOL VÀ ETHANOL

Trong bài báo này, chúng tôi đề xuất các sợi tinh thể quang tử lỗ đặc (PCF) có lớp vỏ mạng hình lục giác được thấm thấu propanol trong các lỗ khí. Các đặc trưng tán sắc và bước sóng tán sắc không của các PCF đã được so sánh và phân tích chi tiết. Bằng cách khảo sát sự phụ thuộc của các đặc trưng tán sắc vào đường kính lỗ khí, chúng tôi xác định được cấu trúc tối ưu có đường kính lỗ khí bằng 1 μm . PCF được thấm thấu propanol có đặc trưng tán sắc phẳng hơn, nhỏ và bước sóng tán sắc không dịch chuyển về phía bước sóng dài hơn 24 nm so với PCF thấm thấu ethanol [17]. Kết quả này phù hợp cho việc tạo phát siêu liên tục (SC) trong dải bước sóng cận hồng ngoại.

Từ khóa: Sợi tinh thể quang tử; Tán sắc; Quang phi tuyến; Phát siêu liên tục.

Received 20th August 2021

Revised 28th September 2021

Accepted 11th November 2021

Author affiliations:

¹Department of Physics, Vinh University, 182 Le Duan, Vinh City, Viet Nam;

²Hue University of Education, Hue University, 34 Le Loi Street - Hue City, Viet Nam;

³Huynh Thuc Khang High School, La Grai district, Gia Lai Province, Viet Nam.

*Corresponding author: chuvanlanh@vinhuni.edu.vn.