INFLUENCE OF STRUCTURE PARAMETERS ON THE SUPERCONTINUUM GENERATION OF PHOTONIC CRYSTAL FIBER

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Abstract: *In this paper, we report a numerical calculation of the influence of structural parameters on the supercontinuum generation of photonic crystal fibers. A photonic crystal fiber based on the fused silica glass, eight rings of air holes ordered in a hexagonal lattice, is proposed. Guiding properties in terms of dispersion and confinement loss of the fundamental mode are also studied numerically. As a result, the broadband width of the supercontinuum spectrum will increase when the lattice pitch decreases or the diameter of air hole in the cladding increases. However, the coherence of SC will become worse.*

Keywords: Nonlinear optics; Photonic crystal fiber; Dispersion; Supercontinuum generation.

1. INTRODUCTION

In recent years, photonic crystal fibers (PCFs) have received more attention of many scientists all over the world, because it contains special properties such as single-mode operation [1], high birefringence [2], high nonlinearity [3], easily controllable dispersion characteristics to achieve the flat or ultra-flattened dispersion [4]. So that, PCFs have been applied in many areas for supercontinuum generation, biomedical engineering, and sensing applications [5, 6]. Especially, PCFs enable change dispersion characteristics as well as nonlinear properties by variations in structural parameters such as hole size, arrangement, spacing, shape, lattice constant (Λ) and linear filling factors (f) [7].

Among numerous applications of PCFs, one most popular is the generation of supercontinuum (SC). Due to its interesting characteristics, the SC generation has widely used in optical communication systems, optical coherence tomography, frequency metrology, spectroscopy [8-10]. For efficient broadband SC generation, a PCF with flat dispersion characteristic and highly nonlinear glass is required, together with an ultra-short laser pulse is launched into the normal or anomalous dispersion regions [11, 12]. The high nonlinearity is one of the most important properties, which is generated by using silica or highly nonlinear soft glasses [12, 13]. However, using these types of PCFs usually requires a complex pump system as well as high power. Recently, a new method to achieve the higher nonlinear values of PCFs is using liquid-core [14]. For this, the nonlinear effects generated with shaped dispersion occur rapidly at the first centimeters, while for medium nonlinear fibers it needs a longer length fiber requires, i.e. tens of centimeters. However, high nonlinearity liquids are usually highly toxic which leads to limit their practical applications, as well as more difficult to fabricate the fibers because of toxic, explosive liquids, and expensive soft glasses.

Control of dispersion characteristics is another important way because the flattened dispersion and slope of the dispersion curve always strongly influence on the nonlinear coefficient as well as the shape and wide of the spectrum in the SC generation [15, 16]. Up to now, the dispersion and the nonlinearity of many kinds of PCFs have been studied which is based on the arrangement of air-holes in the cladding or by changing the lattice pitch and linear filling factor in the hexagonal lattice structure [17]. Besides, air-holes are designed in the following square lattice, octagonal lattice, equiangular spiral lattice, and other novel structures that also have similar efficiency [2, 18, 19]. A. Ferrando et al. has reported that the lattice pitch can be changed the position of the zero-dispersion

wavelength (ZDW) as well as the flat dispersion curve achieving over a wide band of wavelength, and the anomalous dispersion region is reduced. Moreover, for a given lattice pitch value, the ZDW is also moved to the right side by increasing the linear filling factors [20]. The ultra-flattened dispersion characteristic of square-lattice PCFs has also been controlled by changing the air-hole diameters and central core diameters. It is indicated that the dispersion slope increases when the lattice pitch rises and vice versa [21]. A mid-infrared broadband SC generation with spanning of 1-14 μm is presented by P. Chauhan et al. by using a 9 mm long fiber of highly nonlinear chalcogenide glass, pumped with 90 fs laser pulse at a peak power of 8.19 kW, and promise for nonlinear applications of photonic devices. The results also showed that an increasing the diameter of air-holes, the ZDW shifted towards the shorter wavelength side. Otherwise, the lattice pitch is increased, the ZDW shifted towards the longer wavelength side [22]. However, the above studies have only focused on generating the SC generation in the optimized structure with fixed parameters. Meanwhile, the influence of internal structure parameters on the SC generation is still of little interest, resulting in a lack of comparable data relating to the SC spectrum. In addition, the realization of a PCF fabrication technology with a complicated structure, i.e. octagonal lattice, square, equiangular spiral fiber, is still so difficult and costly, then tailoring parameters of the internal structure of PCF is considered efficiency way.

In this paper, we present a numerical simulation of the influence of geometrical parameters on the SC generation of PCFs. We analyzed a PCF made of fused silica glass consisting of eight rings of air holes ordered in a hexagonal lattice. The work is organized into two main steps. The first one is to consider the effects of structure parameters on the properties of PCF like characteristics dispersion or confinement loss via changing lattice pitch and filling factor in the cladding. Next, by using the generalized nonlinear Schrödinger equation (GNLSE), the influence of structure parameters on the SC generation was considered.

2. NUMERICAL MODELING OF THE PCFs

Figures 1(a) and 1(b) show a sketch of a PCF and its cross-section. We assume that the fiber is made of fused silica glass, consists of eight rings of air holes arranged in regular hexagonal lattice defined by the lattice pitch Λ and air holes diameter d. The filling factor of the cladding is defined as $f = d/\Lambda$ and is used as a constant filling factor for all rings to simplify future fiber development.

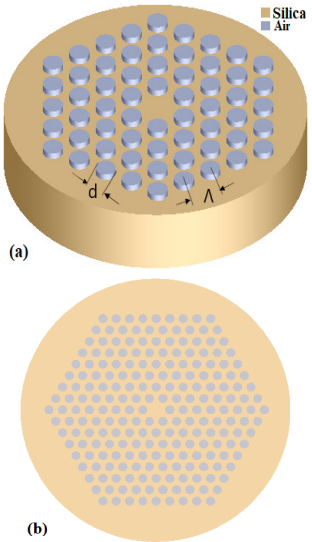


Figure 1. *Sketch of a PCF with solid core (a) and its cross section (b).*

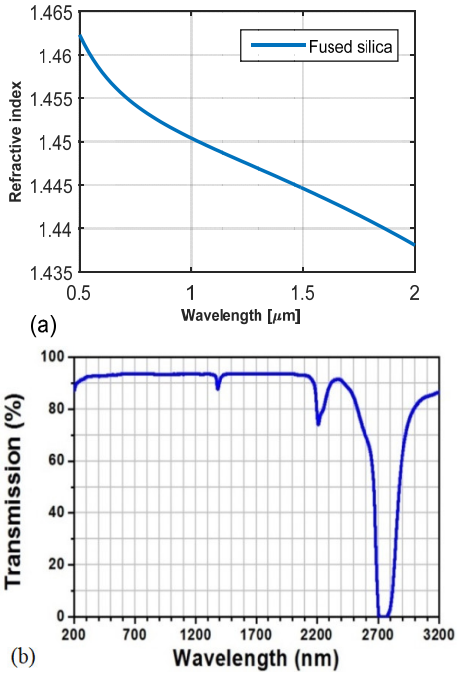


Figure 2. *Real part of refractive index of fused silica (a), transmission of fused silica (b) [23].*

The refractive index of fused silica glass is followed by the Sellmeier equation and it is given by the formula [23]:

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

where B_1 = 0.69675, B_2 = 0.40821, B_3 = 0.890815, C_1 = 4.770112 x 10^{-3} μm^2, C_2 = 1.3377689 x 10^{-2} μm^2, C_3 = 98.02106851 μm^2 are Sellmeier coefficients, λ is the wavelength (μm). The real part of the refractive index of fused silica is shown in Figure 2a.

In the simulation, we have took into account measured transmission of fused silica, as presented in Figure 2b. Numerical analysis was carried out by the Lumerical Mode Solution software [24]. This method is commonly used for calculations of the PCFs properties.

3. SIMULATION RESULTS AND DISCUSSION

3.1. Influence of structure parameters on the dispersion characteristics

To investigate the influence of structure parameters on the dispersion properties, we consider the structures with the lattice pitch Λ changing from 2.0 to 3.5 with changing internal of 0.5 and filling factor changing from 0.2 to 0.5 with changing internal of 0.05. In each case, we have calculated the dispersion characteristics of the fundamental mode as a function of the wavelength in the range of 0.5-2 μm.

Figure 3 shows the characteristics of dispersion for the fundamental mode. For a given Λ value, the increase of the filling factor causes not only an increase in the flattened dispersion but also increases the bandwidth of dispersion range. On the other hand, reducing the filling factor makes dispersion flatter and ultimately becomes monotonic (see Figure 3a-d). The ZDWs have shifted forward smaller wavelengths when filling factor increases. Meanwhile, for a given f value, the dispersion properties are shifted from the normal regime to the anomalous regime and flattened with increasing Λ. For this case, the ZDW forward longer wavelengths with reducing the filling factor (see Figure 3f).

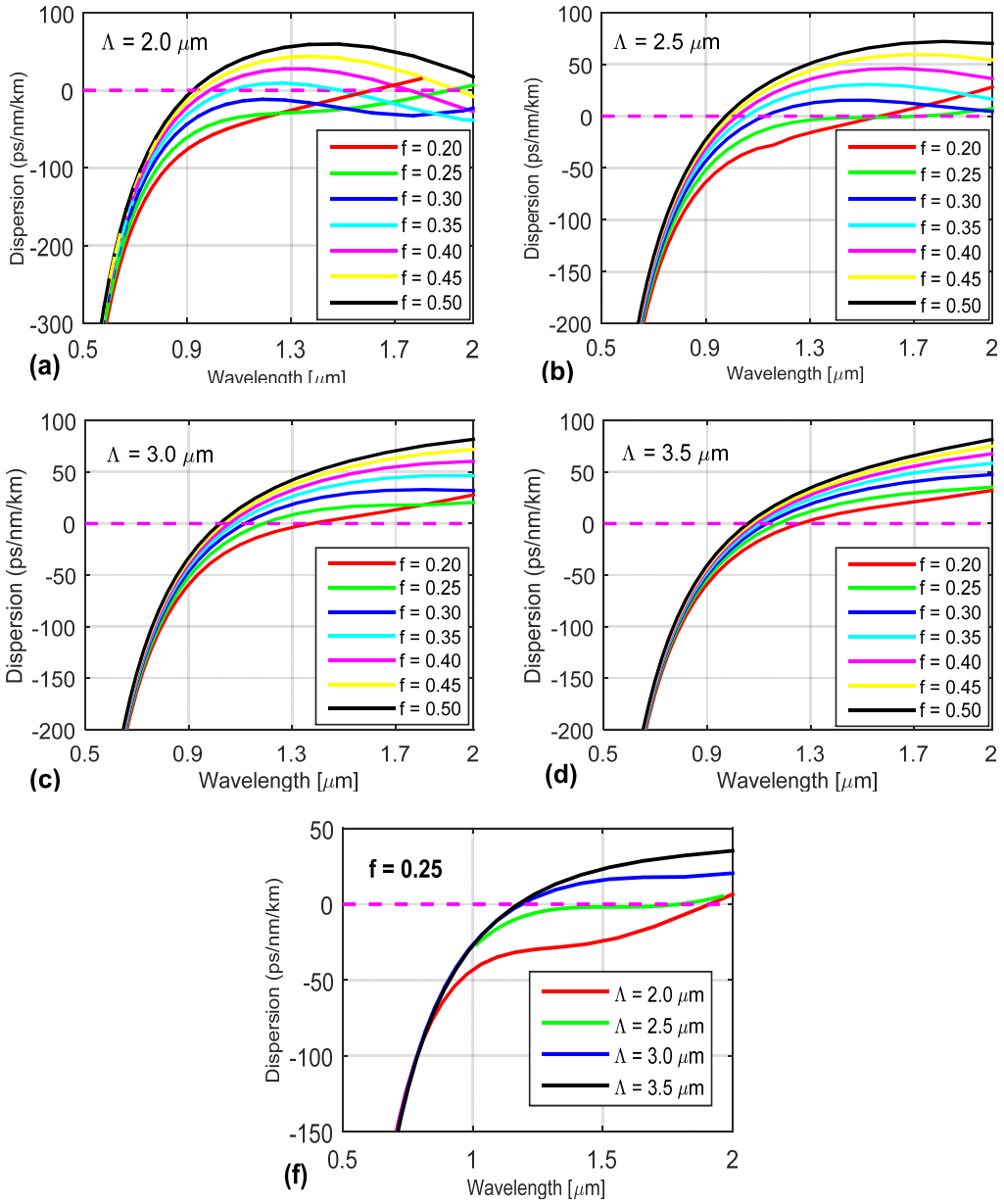


Figure 3. *Dispersion characteristics of the fundamental mode for different lattice pitch Λ and filling factors f.*

3.2. Influence of structure parameters on the loss

We have calculated the confinement loss of the fundamental mode as a function of wavelength for various structure parameters and are plotted in Figure 4. The results show that the losses maintain an overall tendency to increase with increasing wavelength. Besides that, the losses also depend on the structure parameters of PCFs. For a give d value, when we increase lattice pitch Λ the loss also increases. For example, at wavelength of 1.55 μm, confinement loss equal to 4.272, 14.41, 41.76, and 42.1 dB/cm, respectively, for $\Lambda = 2\ \mu m$, $\Lambda = 2.5\ \mu m$, $\Lambda = 3.0\ \mu m$, and $\Lambda = 3.5\ \mu m$ (detail in Figure 4a). Meanwhile, for a give Λ, the loss will decrease when we increase filling factor. In other words, the losses decrease with increasing diameter of air hole (detail in Figure 4b).

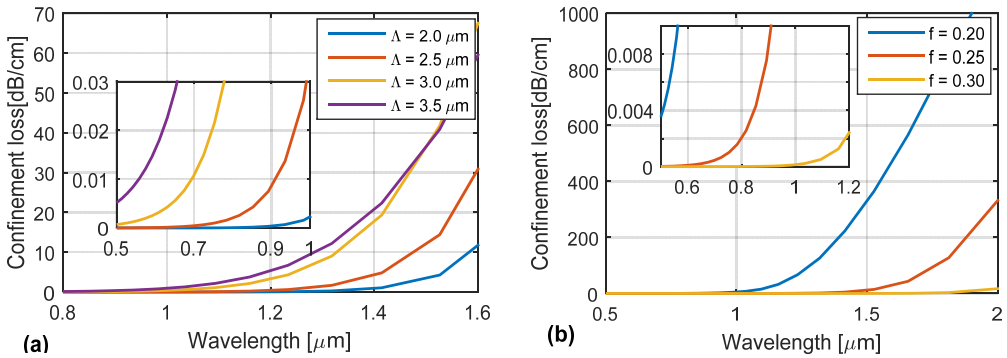


Figure 4. *Confinement loss of the PCFs as a function of the wavelength for various lattice pitches Λ with d = 0.625 μm (a) and various filling factors with Λ = 2.5 μm (b).*

3.3. Influence of structure parameters on the supercontinuum generation of PCFs

To consider the influence of structure parameters on the SC generation of the PCF, the generalized nonlinear Schrödinger equation (GNLSE) were solved by using the split-step Fourier method [6].

$$\frac{\partial A}{\partial z} = -\frac{\alpha}{2}A + \sum_{n\geq 2}\beta_n \frac{i^{n+1}}{n!}\frac{\partial^n}{\partial T^n}A + i\gamma\frac{1}{\omega_0}\left(1+\frac{\partial}{\partial T}\right)\left[(1-f_R)|A|^2 A + f_R A\int_0^\infty h_R(t)|A(z,T-t)|^2 dt\right] \quad (2)$$

where A = A(z, t) is the complex amplitude of the optical field, α represent the total loss in the PCF, β_n are the various coefficients in the Taylor series expansion of the propagation constant around the carrier frequency, γ is the nonlinear coefficient, λ_c is the pump wavelength, and f_R is the fractional contribution of the Raman response, respectively. Meanwhile, $h_R(t)$ represents the Raman response function, and was approximated: $h_R(t) = (\tau_1^2 + \tau_2^2)\tau_1^{-1}\tau_2^{-2}\exp(-t/\tau_2)\sin(t/\tau_1)$.

In simulations, the following parameters were used: the fiber length 40 cm, the pulse of duration 80 fs, the Raman fraction f_R of fused silica glass equal to 0.18, τ_1 = 12.2 fs, τ_2 = 32 fs, the nonlinear refractive index of fused silica $n_2 = 3.0 \times 10^{-20}$ m^2 W^{-1} [4] and the coupled energy 5 nJ at the pump wavelength of 1.06 μm.

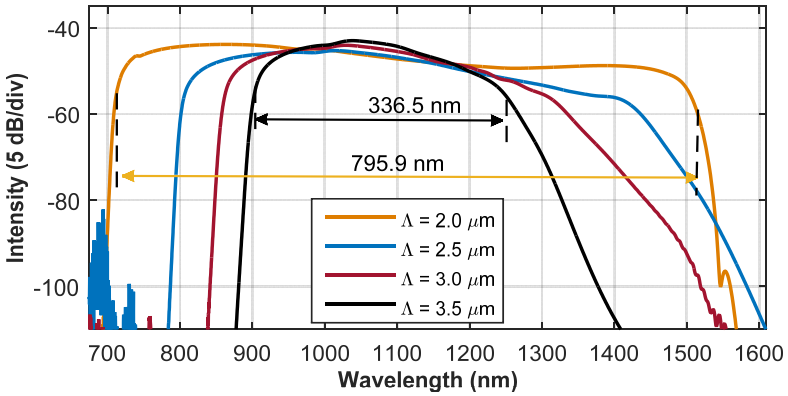


Figure 5. *Numerical simulation of the SC spectrum in the PCF for different lattice pitches with d = 0.625 μm.*

Figure 5 presents the influence of lattice pitch on the SC generation of the PCF when diameter of air hole is constant. The obtained results show that the spectral broadening will decrease when increases a lattice pitch. For example, the broadband width of spectrum

are 336.5 nm, 446.1 nm, 610 nm and 795.9 nm, respectively, for $\Lambda = 2.0\ \mu m$, $\Lambda = 2.5\ \mu m$, $\Lambda = 3.0\ \mu m$, and $\Lambda = 3.5\ \mu m$. This is due to the increase in the lattice pitch makes an increase of loss when light propagates in the fiber. In addition, the increase of the lattice pitch also leads to an increase in the dispersion and effective mode area and then results in a decrease of spectral broadening.

Meanwhile, the influence of the air-hole diameter on the SC generation is illustrated in Figure 6. The results indicated that spectral broadening can be achieved with an increase in the air-hole diameter. The spectral bandwidths are 367.2 nm, 488.1 nm and 638.5 nm for the filling factor of 0.2, 0.25, and 0.3, respectively. This can explain that the increase in the filling factor leads to reduce the confinement loss of the PCF. Simultaneously, the dispersion also shifted from the normal dispersion regime to the anomalous dispersion regime. Therefore, it is expected that a wider SC can be obtained by increasing the filling factor (the air hole diameter), but the coherence of SC will become worse.

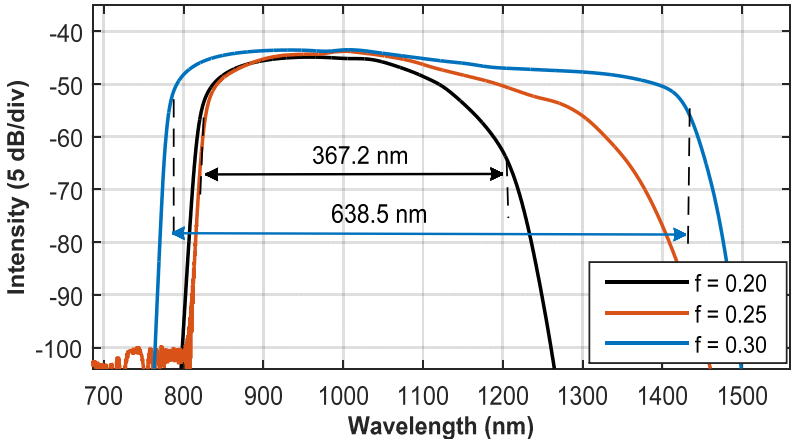


Figure 6. *Numerical simulation of the SC spectrum in the PCF for different filling factors with $\Lambda = 2.5\ \mu m$.*

4. CONCLUSION

In this work, we present a numerical simulation of the influence of geometrical parameters on the SC generation. We analyzed a PCF made of silica glass consisting of eight rings of air holes ordered in a hexagonal lattice. Our numerical simulations demonstrate that the properties of a PCF (including dispersion characteristics, confinement loss) are greatly influenced by its structural parameters. In addition, we are able to control the shape and spectral bandwidth of the SC spectrum in the PCFs by changing the lattice pitch or air hole diameter. The broadband width of the supercontinuum spectrum will increase with the decrease in the lattice pitch or increase the air-hole diameter in the cladding. The increase in the filling factor or decreasing lattice constant leads to reduce the confinement loss of the PCF. The dispersion also shifted from the normal dispersion regime to the anomalous dispersion regime. Therefore, it is expected that a wider SC can be obtained by increasing the air-hole diameter or reducing the lattice constant, but the coherence of SC will become worse.

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REFERENCES

[1]. T.A. Birks, J.C. Knight, and P.S.J. Russell, "*Endlessly single-mode photonic crystal fiber,"* Optics Letters, **Vol. 2(13),** pp. 961-963, (1997).

[2]. X. Li, P. Liu, Z. Xu, and Z. Zhang, "*Design of a pentagonal photonic crystal fiber with high birefringence and large flattened negative dispersion,"* Appl. Opt., **Vol. 54**, pp. 7350-7357, (2015).

[3]. Y.E. Monfared, A. Mojtahedinia, A.R. Maleki Javan, and A.R. Monajati Kashani, *"Highly nonlinear enhanced core photonic crystal* fi*ber with low dispersion for wavelength conversion based on four-wave mixing",* Frontiers of Optoelectronics, Vol. 6(3), pp. 297-302, (2013).

[4]. K. Saitoh, N. Florous, and M. Koshiba, "*Ultra-flattened chromatic dispersion controllability using a defected-core photonic crystal fiber with low confinement losses,"* Opt. Express, **Vol. 13**, pp. 8365-8371, (2005).

[5]. J.M. Dudley, G. Genty, and S. Coen, "*Supercontinuum generation is photonic crystal fiber,"* Review of Modern Physics, **Vol. 78**, pp. 1135-1184, (2006).

[6]. A.M.R. Pinto and M. Lopez-Amo, "*Photonic Crystal Fibers for Sensing Applications,"* Fiber Optic Sensors, **Vol. 2012**, pp. 1-21, (2012).

[7]. X. Li, Z. Xu, W.Ling, and P. Liu, "*Design of highly nonlinear photonic crystal fibers with flattened chromatic dispersion,"* Appl. Opt. **Vol. 53**, pp. 6682-6687, (2014).

[8]. K. Saitoh and M. Koshiba, "*Highly nonlinear dispersion-flattened photonic crystal fibers for supercontinuum generation in a telecommunication window,"* Opt. Express, **Vol. 12**, pp. 2027-2032, (2004).

[9]. H. Wang, C.P. Fleming, and A.M. Rollins (2007), *"Ultrahigh-resolution optical coherence tomography at 1.15 μm using photonic crystal fiber with no zero-dispersion wavelengths",* Opt. Express **15**, 3085-3092.

[10]. W. J. Ling, K. Li, and Y. Y. Zuo, "*Supercontinuum generation in nonperiodic photonic crystal fibers and its application in frequency metrology,"* Applied Mechanics and Materials, **Vol. 302**, pp. 194-199, (2013).

[11]. P.S. Maji and P. R. Chaudhuri, "*Design of all-normal dispersion based on multi-material photonic crystal fiber in IR region for broadband supercontinuum generation,"* Appl. Opt., **Vol. 54**, pp. 4042-4048, (2015).

[12]. P. Jamatia, T.S.Saini, A. Kumar, and R.K. Sinha, "*Design and analysis of a highly nonlinear composite photonic crystal fiber for supercontinuum generation: visible to mid-infrared,"* Appl. Opt. **Vol. 55**, pp. 6775-6781, (2016).

[13]. S. Dai, Y. Wang, X. Peng, P. Zhang, X. Wang, and Y. Xu, "*A review of mid-infrared supercontinuum generation in chalcogenide glass fibers,"* Applied Sciences, **Vol. 8(5),** pp.707-1-28, (2018).

[14]. V.T. Hoang, R. Kasztelanic, A. Filipkowski, G. Stępniewski, D. Pysz, M. Klimczak, S. Ertman, V.C. Long, T.R. Woliński, M. Trippenbach, K. D. Xuan, M. Śmietana, and R. Buczyński, *"Supercontinuum generation in an all-normal dispersion large core photonic crystal fiber infiltrated with carbon tetrachloride,"* Opt. Mater. Express, **Vol**. **9**, pp. 2264-2278, (2019).

[15]. G. Stepniewski, M. Klimczak, H. Bookey, B. Siwicki, D. Pysz, R. Stepien, A.K.Kar, A.J. Waddie, M.R.Taghizadeh, and R. Buczynski, "*Broadband supercontinuum generation in normal dispersion all-solid photonic crystal fiber pumped near 1300 nm,"* Laser Physics Letters*,* **Vol. 11(5)**, pp. 055103, (2014).

[16]. Y. Wang, X. Zhang, X. Ren, L. Zheng, X. Liu, and Y. Huang, "*Design and analysis of a dispersion flattened and highly nonlinear photonic crystal fiber with ultralow confinement loss,"* Appl. Opt., **Vol. 49**, pp. 292-297, (2010).

[17]. H. Xu, J.Wu, K. Xu, Y. Dai, and J.Lin, "*Highly nonlinear all-solid photonic crystal fibers with low dispersion slope,"* Appl. Opt., **Vol. 51**, pp. 1021-1027, (2012).

[18]. S. Roy and P. R. Chaudhuri, "*Supercontinuum generation in visible to mid-infrared*

region in square-lattice photonic crystal fiber made from highly nonlinear glasses," Optics Communications, **Vol. 282 (17)**, pp. 3448-3455, (2009).
[19].A. Agrawal, M.Tiwari, Y.O. Azabi, V.Janyani, B.M.A. Rahman and K.T.V. Grattan, "*Ultrabroad supercontinuum generation in tellurite equiangular spiral photonic crystal fiber,"* Journal of Modern Optics, **Vol.60 (12)**, pp. 956-962, (2013).
[20].A. Ferrando, E. Silvestre, P. Andrés, JJ. Miret, and M.V. Andrés, "*Designing the properties of dispersion-flattened photonic crystal fibers,"* Opt. Express, **Vol. 9**, pp. 687-697, (2011).
[21].M. Zhang, F. Zhang, Z. Zhang and X. Chen, "*Dispersion-ultra-flattened square-lattice photonic crystal fiber with small effective mode area and low confinement loss,"* Optik-International Journal for Light and Electron Optics, **Vol. 125(5)**, pp. 1610-1614, (2014).
[22].P. Chauhan, A. Kumar, and Y. Kalra, *"Mid-infrared broadband supercontinuum generation in a highly nonlinear rectangular core chalcogenide photonic crystal fiber,"* Optical Fiber Technology, **Vol. 46**, pp. 174-178, (2018).
[23].C. Z. Tan, *"Determination of refractive index of silica glass for infrared wavelengths by IR spectroscopy"*, Journal of Non-Crystalline Solids, Vol. **223**, Issues 1–2, 0022-3093, (1998).
[24].Lumerical Solutions, Inc. http://www.lumerical.com/tcad-products/mode/.

TÓM TẮT

ẢNH HƯỞNG CỦA CÁC THAM SỐ CẤU TRÚC TRONG SỰ PHÁT SIÊU LIÊN TỤC CỦA SỢI TINH THỂ QUANG TỬ

Trong bài báo này, chúng tôi trình bày kết quả tính toán số ảnh hưởng của các tham số cấu trúc lên sự phát siêu liên tục trong sợi tinh thể quang tử. Một sợi tinh thể quang tử được chế tạo từ thủy tinh nguyên chất nóng chảy, bao gồm 8 vòng lỗ khí được xếp đều trong mạng lục giác đã được đề xuất cho nghiên cứu. Các đặc tính dẫn sóng của tán sắc và mất mát của phương thức truyền cơ bản cũng được khảo sát bằng phương pháp số. Kết quả cho thấy, độ rộng băng thông của phổ sẽ tăng khi giảm hằng số mạng hoặc tăng đường kính của lổ khí trong lớp vỏ, tuy nhiên, tính kết hợp của phổ giảm.

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

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