STUDY ON DISPERSION CHARACTERISTICS OF SQUARE SOLID-CORE PHOTONIC CRYSTAL FIBERS WITH As_2S_3 SUBSTRATE

Dang Van Trong (1), Le Tran Bao Tran (1), Ho Thi Anh Thu (2), Nguyen Thi Thuy (3), Chu Van Lanh (1)

[1] *Department of Physics, College of Education, Vinh University, Nghe An Province, Vietnam*
[2] *Lap Vo 2 High School, Dong Thap, Vietnam*
[3] *University of Education, Hue University, Hue City, Vietnam*

Received on 27/6/2022, accepted for publication on 05/9/2022
DOI: https://doi.org/10.56824/vujs.2022nt5

Abstract: The dispersion characteristics of As_2S_3 solid-core photonic crystal fibers were investigated with the change of structural parameters including filling factor (d/Λ) and lattice constant (Λ). Photonic crystal fiber obtained diverse dispersion including all-normal and anomalous dispersion with two zero-wavelengths dispersion at all values of lattice constant investigated. The dispersion value increases when the lattice constant increases and the filling factor decreases. Photonic crystal fiber has a flat dispersion curve and closeness to the zero-dispersion curve in the long-wavelength range are advantages of this design. Based on the analysis of numerical simulation results, we have proposed two structures with optimal dispersion for the application of supercontinuum generation.

Keywords: Photonic crystal fiber (PCF); square lattice; dispersion; supercontinuum generation.

1. Introduction

In 1978, the idea of PCF was first proposed by Yeh et al., and the fiber core was wrapped by Bragg grating as a 1-D photonic crystal. Developing from that idea, a photonic crystal fiber made from an air-core photonic crystal was invented by Russell in 1992, then the first PCF with a hexagonal lattice was reported by Russell and colleagues at the Optical Fiber Conference (OFC) in 1996 [1]. Since then, researchers have focused on PCF in fiber optic technology. It is designed and engineered for flexibility in light guide mechanism, material selection, lattice type, air-hole shape, and size. Therefore, PCF has many applications in various fields such as fiber lasers, optical amplifiers, nonlinear devices, high-sensitivity sensors, and especially supercontinuum generation (SCG) applications [2].

In recent years, the optimization of important characteristics of PCF such as effective refractive index, effective mode area, attenuation, and dispersion for supercontinuum generation has been studied by scientists. In which, dispersion is an important factor determining the spectral expansion efficiency of supercontinuum. Dispersion characteristics including flatness, dispersion slope, all-normal or anomalous dispersion, and zero-dispersion wavelength (ZDW) can be controlled by changing of structural parameters such as lattice constant and filling factor. Silica PCFs are widely studied because of their outstanding advantages, but silica has a low nonlinear coefficient and high loss in the mid-infrared (IR) region. Furthermore, the optical applications of silica PCF are limited beyond the 2.5 µm wavelengths, making it challenging to generate SC in the infrared region.

Email: dangvantrong0602@gmail.com (D. V. Trong)

Therefore, chalcogenide glass PCFs have been widely used in investigating nonlinear optical effects in PCF because of their wide transmission window, low two-photon absorption capacity, high nonlinear refractive index, and high nonlinearity in the NIR and mid-infrared (MIR) regions. Given the specific composition of chalcogenide glass, its infrared transparency can exceed 10 µm, and its Kerr nonlinearity can be 100-1000 times greater than that of silica glass at 1.55 µm. Thus, PCFs with chalcogenide glasses have interesting nonlinear properties over longer wavelength ranges and provide better supercontinuum generation performance. As_2S_3 is one of the chalcogenide glasses widely used for spinning owing to its good thermal stability and glass-forming ability. Moreover, the n_2 refractive index of As_2S_3 is 420×10^{-20} m^2/W [3], nearly 153 times larger than that of fused silica at 1053, making a very important contribution to the enhancement of supercontinuum generation efficiency. 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 [4], 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 [5], a low confinement loss with double-PCF [6], flat dispersion and high nonlinearity of the As_2S_3 three-bridge suspended-core fiber [7],… However, the limitation in the above works is that the flat dispersion curve extends in the short and non-flat wavelength ranges. In addition, 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, a square lattice solid-core PCF designed with an As_2S_3 substrate has high nonlinearity and a small core diameter. The square lattice was chosen for investigation because it is highly symmetric and easier to design than other types of lattices, square PCFs play an important role in achieving a near-zero ultra-flattened dispersion and low loss that contributes to SC. We analyzed the effect of the change of filling factor (d/Λ) and lattice constant (Λ) on the dispersion characteristic of PCF. From that, two optimal structures ($\Lambda = 3.0\ \mu m$, $d/\Lambda = 0.3$ and $\Lambda = 3.0\ \mu m$, $d/\Lambda = 0.35$) of PCF with flat dispersion in the long wavelength range are proposed to consider for supercontinuum generation.

2. Numerical modeling of PCF

Lumerical Mode Solutions software has been used to design a square lattice solid-core photonic crystal fiber with As_2S_3 as the substrate shown in Figure 1. As_2S_3 was selected as the substrate material to create a difference in the refractive index between the core and cladding to better limit light in the core. PCF is designed with 8 lattice loops with the change of lattice constant (Λ) and filling factor (d/Λ). Where *d* is the diameter of the air holes, and Λ is the distance between the centers of two adjacent air holes. We use lattice constants Λ varying from $1.0\,\mu m$ to $3.0\,\mu m$ with a step of 0.5, while the fill factor d/Λ varies from 0.3 to 0.8 with a step of 0.05. The small core diameter is determined by the formula $D_C = 2\Lambda - d$. The largest core diameter value is D_{Cmax} = 5.1 µm corresponding to the structure $d/\Lambda = 0.3$, $\Lambda = 3.0\ \mu m$, while the structure $d/\Lambda = 0.8$, $\Lambda = 1.0\ \mu m$ has the largest core diameter D_{Cmin} = 1.2 µm. Structural parameters are selected according to the technological requirements commonly used to develop PCFs.

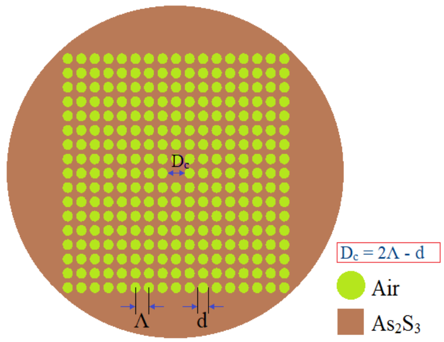

Figure 1: *The geometrical structures of PCFs with square lattice and As_2S_3 substrate*

The dispersion of the fiber consists of the waveguide and the matter dispersion. It is determined by equation 1 [8]:

$$D(\lambda) = -\frac{\lambda}{c}\frac{d^2\,\mathrm{Re}[n_{eff}]}{d\lambda^2}. \tag{1}$$

where c and $\mathrm{Re}\,[n_{eff}]$ are the speed of light in a vacuum and the real part of the effective refractive index of the guided mode, respectively.

The refractive index of As_2S_3 is determined according to the Sellmeier formula [9] shown in equation 2:

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

Values of the fitting coefficients $A_1 \ldots A_3$, and $B_1 \ldots B_3$ are listed in Table. 1 and λ is the wavelength of light in μm.

Table 1: *Sellmeier's coefficients of the material used* [10]

Sellmeier's coefficients						
Material	A_1	A_2	A_3	B_1 [μm^2]	B_2 [μm^2]	B_3 [μm^2]
As_2S_3	*1.898*	*1.922*	*0.876*	*0.0225*	*0.0625*	*0.1225*

3. Simulation results and analysis

The dispersion properties of the optical fibers represent a dominant role in the propagation of short optical pulses that widen the spectrum during SC generation. Figure 2 shows the effect of varying the filling factor (d/Λ) and lattice constant (Λ) on the dispersion (D). A variety of dispersions were obtained including all-normal and anomalous dispersion with 2 zero-dispersion wavelengths (ZDW). When the lattice constant changes, the dispersion regime of the fibers also changes. In particular, as the Λ increases, the number of fibers operating in the all-normal dispersion regime gradually decreases. With $\Lambda = 1.0$ μm, seven all-normal dispersion lines correspond to $d/\Lambda < 0.65$ while the remaining filling factors operate in an anomalous dispersion regime with two ZDWs. The normal complete dispersion curves in the cases of $\Lambda = 1.5$ μm, $\Lambda = 2.0$ μm and $\Lambda = 2.5$ μm are obtained with values of $d/\Lambda < 0.5$, $d/\Lambda < 0.45$, and $d/\Lambda < 0.4$, respectively. With $\Lambda = 3.0\ \mu m$ (Figure 2e), the all-normal dispersion regime is usually only present in fibers with $d/\Lambda = 0.3$. It can be seen that the Λ parameter strongly influences the dispersion properties of PCF. Fibers operating in an all-normal dispersion regime are often significant for SC spectral expansion with flat peaks and high coherence through the support of two basic mechanisms, self-phase modulation (SPM) and optical wave breaking (OWB), which could not be achieved in some previous studies.

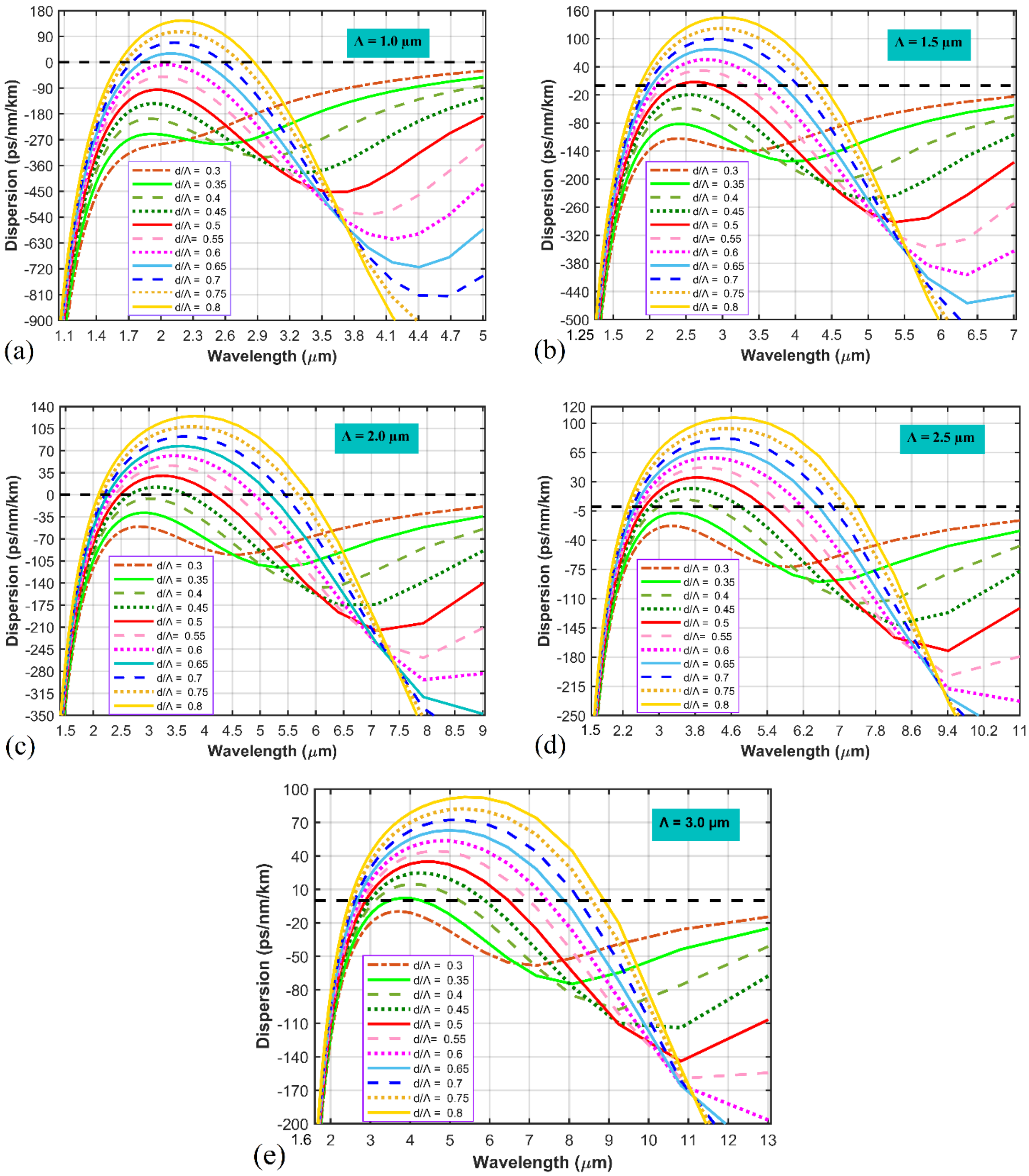

Figure 2: *The chromatic dispersion of PCFs with various d/Λ for (a)* $\Lambda = 1.0\ \mu m$, *(b)* $\Lambda = 1.5\ \mu m$, *(c)* $\Lambda = 2.0\ \mu m$, *(d)* $\Lambda = 2.5\ \mu m$, *and (e)* $\Lambda = 3.0\ \mu m$.

Besides, the change of filling factor d/Λ also affects the dispersion characteristics of the fiber. In each lattice constant value, the dispersion value decreases as the filling factor decreases with the same wavelength value. In particularly, for a given filling factor value, the dispersion value decreases as the lattice constant increases. Table 2 shows the zero-dispersion wavelength value for different filling factors and lattice constants. The values of ZDWs are all in the infrared region, ranging from $1.612\,\mu$m to $8.882\,\mu$m, which is very beneficial for SCG in the infrared region of PCF. It can be seen that, for a given value of d/Λ, the increase of the lattice constant causes the ZDWs to shift to the right, i.e. towards a longer wavelength. The flexible change of the geometrical parameters is an important factor in controlling the dispersion characteristic of PCF.

Table 2: *The value of the zero-dispersion wavelength of PCFs with various* d/Λ *and* Λ

	Λ = 1.0 µm		**Λ = 1.5 µm**		**Λ = 2.0 µm**		**Λ = 2.5 µm**		**Λ = 3.0 µm**	
d/Λ	ZDW_1	ZDW_2	ZDW_1	ZDW_2	ZDW_1	ZDW_2	ZDW_1	ZDW_2	ZDW_1	ZDW_2
0.3										
0.35									3.497	4.279
0.4							2.993	4.198	3.125	5.24
0.45					2.657	3.684	2.804	4.807	2.987	5.889
0.5			2.373	2.896	2.486	4.166	2.683	5.324	2.882	6.471
0.55			2.19	3.3	2.393	4.558	2.602	5.771	2.803	6.984
0.6			2.094	3.589	2.318	4.893	2.532	6.17	2.732	7.443
0.65	1.825	2.382	2.025	3.826	2.255	5.179	2.471	6.538	2.667	7.873
0.7	1.73	2.585	1.966	4.038	2.197	5.447	2.409	6.836	2.604	8.253
0.75	1.667	2.742	1.917	4.227	2.145	5.685	2.357	7.14	2.548	8.577
0.8	1.612	2.869	1.865	4.389	2.093	5.897	2.299	7.399	2.486	8.882

PCF's flat dispersion, close to zero dispersion line, and compatibility of ZDW with pump wavelengths are decisive factors for creating of ultra-wideband SCG. Therefore, fibers satisfying the above conditions are always targeted by scientists for supercontinuum generation. Based on the analysis of PCF dispersion characteristics, we have selected 2 PCF structures with optimal dispersion suitable for supercontinuum generation application. The first fiber $\#F_1$ operates in an all-normal dispersion regime, while the $\#F_2$ fiber exhibits anomalous dispersion with 2 ZDWs. The structural parameters of these proposed fibers are presented in Table 3. In the case of all-normal dispersion, $\#F_1$ fiber is chosen as the most optimal because it has a flat dispersion curve, maximum dispersion value closest to the zero-dispersion curve, and the range of dispersion curve of the $\#F_1$ fiber close to the zero-dispersion curve is the longest compared to other fibers in this case. Similarly, the $\#F_2$ fiber has flat dispersion and is closest to the zero-dispersion curve compared to the remaining anomalous dispersion cases. In addition, the $\#F_2$ fiber has the close range to the zero-dispersion curve as the widest.

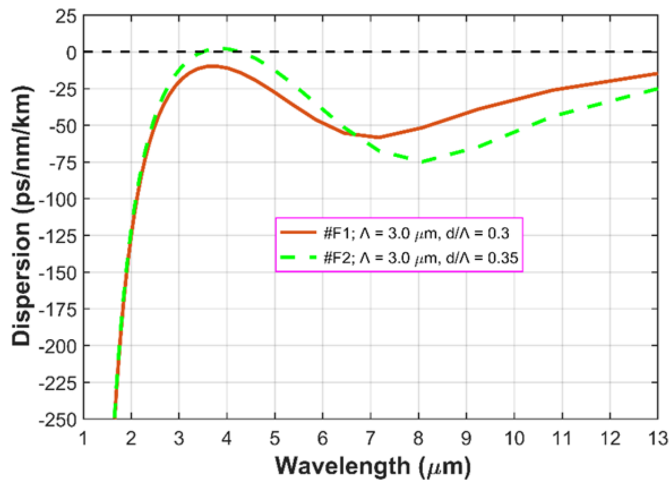

Figure 3: *The dispersion properties of proposed PCFs*

Figure 3 shows the dispersion characteristics of the two proposed fibers in the wavelength range of 1 μm to 13 μm. The results show that both the two proposed PCFs have a flatter dispersion and are closer to the zero-dispersion curve in the longer wavelength range than the dispersion curves of previously published studies [4], [6], [7]. This will result in high performance for supercontinuum generation of the proposed fibers. In principle, the selected pump wavelength should be closed to the wavelength value of the maximum dispersion point or closed to but larger than the ZDWs. This results in the generated SC spectrum having the largest bandwidth. #F_1 fiber has a maximum dispersion of -9.736 $ps.nm^{-1}.km^{-1}$ at wavelength 3.781 µm and fiber #F_2 has 2 ZDWs values of 3.497 µm and 4.279 µm respectively. Therefore, the pump wavelength of 4.0 µm has been chosen for both #F_1 and #F_2 fibers with the desire to create an efficient SCG. The pump wavelength is closest to that of the maximum dispersion #F_1. The dispersion values at the pump wavelengths of the #F_1 and #F_2 fibers are -10.972 ($ps.nm^{-1}.km^{-1}$) and 2.03 ($ps.nm^{-1}.km^{-1}$), respectively.

Table 3: *Structural parameters of two proposed fibers #F_1 và #F_2.*

#	*Λ* (µm)	***d/Λ***	***D_c (µm)***
#F_1	3.0	0.3	5.1
#F_2	3.0	0.35	4.95

4. Conclusion

In this paper, we analyzed the effect of filling factor and lattice constant on dispersion characteristics of solid-core PCF with As_2S_3 substrate. The obtained results show that these structural parameters strongly influence the dispersion characteristics. The obtained dispersions are diverse including all-normal and anomalous dispersion with two zero-dispersion wavelengths. Two fibers with flat all-normal and anomalous dispersion have been studied ($\Lambda = 3.0$ µm, $d/\Lambda = 0.3$ and $d/\Lambda = 0.35$) which are suitable for supercontinuum generation. At pump wavelength 4.0 μm, two fibers #F_1 and

$\#F_2$ have dispersion values of -10.972 ($ps.nm^{-1}.km^{-1}$) and 2.03 ($ps.nm^{-1}.km^{-1}$), respectively. Our simulation results are suitable for fabricating optical fibers as SC emitters with a wide, flat, and smooth spectrum.

Acknowledgments

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, and D.M. Atkin, "All-silica single-mode optical fiber with photonic crystal cladding," *Opt. Lett.*, vol. 21, pp. 1547-1549, 10/1996.

[2] C. V. Lanh, H. V. Thuy, C. L. Van, K. Borzycki, D. X. Khoa, T. Q. Vu, M. Trippenbach, R. Buczyński, and J. Pniewski, "Supercontinuum generation in photonic crystal fibers infiltrated with nitrobenzene," *Las. Phys.*, vol. 30, 035105 (9pp), 02/2020.

[3] M. Asobe, T. Kanamori, and K. Kubodera, "Ultrafast all-optical switching using highly nonlinear chalcogenide glass fiber," *IEEE Photonics Technology Letters*, vol. 4(4), pp. 362-365, 1992.

[4] K. F. Fiaboe, S. Singh, R. Rai, and P. Kumar, "As_2S_3 doped photonic crystal fiber with large negative dispersion and high birefringence," *J. Emerging Tech. Innovative Research.*, vol. 6, pp. 280-285, 3/2019.

[5] A. S. J. Choyon and R. Chowdhury, "Multifunctional chalcogenide (As2S3, As2Se3) dual-core photonic crystal fiber with elliptical air-hole for mid-IR optical communications: Design and analysis," *Optik*, vol. 258, 168857 (11pp), 3/2022.

[6] N. Wang, J. L. Xie, H. Z. Jia, and M. M. Chen, "A low confinement loss double-photonic crystal fibre over 850 nm bandwidth with 26 orbital angular momentum modes transmission," *J. Modern Opt.*, vol. 65, pp. 2060-2064, 7/2018.

[7] T. Peng, T. Xu, and X. Wang, "Simulation Study on Dispersion Properties of As2S3 Three-Bridge Suspended-Core Fiber," *IEEE Access*, vol. 5, pp. 17240-17245, 8/2017.

[8] R. Buczyński, "Photonic crystal fbers," *Acta Phys. Pol. A.*, vol. 106, pp. 141-168, 2004.

[9] S. Kedenburg, M. Vieweg, T. Gissibl, and H. Giessen, "Linear refractive index and absorption measurements of nonlinear optical liquids in the visible and near-infrared spectral region," *Opt. Mat. Express.*, vol. 2, pp. 1588-1611, 2012.

[10] W. S. Rodney, I. H. Malitson, and T. A. King, "Refractive index of arsenic trisulfide," *J. Opt. Soc. Am.*, vol. 48, pp. 633-635, 1958.

TÓM TẮT

NGHIÊN CỨU ĐẶC TRƯNG TÁN SẮC CỦA CÁC SỢI TINH THỂ QUANG TỬ MẠNG VUÔNG VỚI CHẤT NỀN As_2S_3

Đặng Văn Trọng (1), Lê Trần Bảo Trân (1), Hồ Thị Anh Thư (2), Nguyễn Thị Thuỷ (3), Chu Văn Lanh (1)
[1] Khoa Vật lý, Trường Sư phạm, Trường Đại học Vinh, Nghệ An, Việt Nam
[2] Trường Trung học phổ thông Lấp Vò 2, Đồng Tháp, Việt Nam
[3] Trường Đại học Sư phạm, Đại học Huế, Huế, Việt Nam
Ngày nhận bài 27/6/2022, ngày nhận đăng 05/9/2022

Tính chất tán sắc của sợi tinh thể quang tử lõi đặc As_2S_3 được nghiên cứu với sự thay đổi của các thông số cấu trúc bao gồm hệ số lấp đầy (d/Λ) và hằng số mạng (Λ). PCF thu được tán sắc đa dạng bao gồm cả tán sắc hoàn toàn thường và dị thường với hai bước sóng tán sắc bằng không tại tất cả các giá trị của hằng số mạng được khảo sát. Khi hằng số mạng tăng và hệ số lấp đầy giảm thì giá trị tán sắc tăng lên. PCF có tán sắc phẳng và gần với đường tán sắc 0 trong dải bước sóng dài là những ưu điểm trong thiết kế này. Trên cơ sở phân tích kết quả mô phỏng số, chúng tôi đã đề xuất hai cấu trúc có tán sắc tối ưu cho ứng dụng phát siêu liên tục.

Từ khóa: Sợi tinh thể quang tử (PCF); mạng tinh thể vuông; phát siêu liên tục; tán sắc.