High coherent supercontinuum generation in nitrobenzene liquid-core photonic crystal fiber with elliptical air-hole inner ring

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Abstract
A nitrobenzene liquid-core photonic crystal fiber (NLC-PCF) with eight elliptical air-holes in the innermost ring of the cladding is proposed in this work, and this fiber structure can contribute to flexibly adjusting dispersion and constraining the fiber core. The appreciable dispersion is realized by adjusting the structural parameters of NLC-PCF, which is characterized by three zero-dispersion wavelengths (ZDWs), flat dispersion with the fluctuation of fewer than 40 ps nm⁻¹ km⁻¹, and high nonlinearity as high as 5500 W⁻¹ km⁻¹. The propagation of femtosecond pulse and supercontinuum generation (SCG) in NLC-PCF is studied numerically when the pump wavelength is located in the normal and abnormal dispersion region near different ZDW through solving the generalized nonlinear Schrödinger equation (GNLSE) by the split-step Fourier method. The numerical results show that a highly coherent supercontinuum (SC) spanning from 1.3 to 2.8 µm is obtained when the pump pulse with the center wavelength of 1810 nm, the peak power of 1000 W, and pulse width of 50 fs propagated in the 5 cm long NLC-PCF. This research can find applications in the fields of novel liquid-core PCF design and ultrashort pulse propagation.

Keywords Liquid-core photonic crystal fiber · Zero-dispersion wavelength · Flat dispersion · High nonlinearity · Supercontinuum

1 Introduction

In 1996, J. C. Knight and T. A. Birks successfully developed the first PCF in the world (Knight et al. 1996), which is a new type of fiber based on the photonic crystal. The fiber characterized by a photonic crystal cladding of periodic air-hole array can effectively reduce the refractive index of the cladding to less than the refractive index of the fiber core so that the fiber can propagate beams through the total internal reflection (White et al. 2001; Russell 2003; Daojun and Ji 2020). The time and frequency domain evolution of ultrashort laser pulses propagating in a highly nonlinear PCF is affected by a variety of
nonlinear effects, such as self-phase modulation (SPM), cross-phase modulation (XPM), four-wave mixing (FWM), and stimulated Raman scattering (SRS), especially the dispersion characteristics of fiber (Cherbi et al. 2014; Alfano et al. 2021; Genier et al. 2020; Wang et al. 2020; Fanjoux et al. 2017). The new frequency in the pulse spectrum is generated by the interaction between multiple nonlinear effects in the fiber, which expands the narrow-spectrum pulsed laser by several multiples into continuous broad-spectrum light, that is, SCG (Dudley et al. 2006). SC has the characteristics of continuous broadband spectrum, good coherence, stability, and reliability (Raei et al. 2018), it has been widely used in optical coherence tomography, optical communication, optical frequency measurement, and other research fields, as well as the research of many scholars (Ghanbari et al. 2018; Shu et al. 2016; Kilgus et al. 2018; Zorin et al. 2020; Dasa et al. 2020; Kowsari and Saghaei 2018).

High nonlinear PCF is an excellent nonlinear optical medium to generate supercontinuum (Saghaei et al. 2016). In recent years, SCG in liquid-core fibers has attracted more and more attention due to the superior performance of some inorganic solvents (Chemnitz et al. 2017; Ebnali-Heidari et al. 2012), such as carbon disulfide (CS₂) (Junaid et al. 2021), carbon tetrachloride (CCl₄) (Le et al. 2021b), tetrachloroethylene (C₂Cl₄) (Le et al. 2021a), toluene (Hoang 2018), nitrobenzene (Guo et al. 2021) and so on. These inorganic solvents have good transmission properties and large nonlinear coefficients in the visible to near-infrared spectral region, and also exhibit strong non-instantaneous nonlinearity due to the slow molecular motion of liquid (Conti et al. 2010), which is one of the ideal nonlinear mediums for SCG (Kang et al. 2019). In 2020, Mahsa Aliee et al. designed a hollow-core fiber for telecom C band operation by using a 12-fold symmetric photonic quasicrystal lattice and an optofluidic infiltration approach. The simulation results demonstrate a flat dispersion as wide as 500 nm (from 1200 to 1700 nm) around the zero-dispersion wavelength of 1550 nm and an ultralow confinement loss of $2.6 \times 10^{-7}$ dB/m (Aliee 2020). In 2021, Hieu Van Le proposed a PCF with the core infiltrated C₂Cl₄ as a new source of SC, and the SC with 0.8 ~ 2 μm, 1 ~ 2.1 μm, and 1.3 ~ 2.3 μm spectral bandwidth were obtained by optimizing the geometrical structure of the three kinds of fibers (Le et al. 2021).

In this manuscript, a PCF with high nonlinearity, flat dispersion, and three ZDWs is designed for supercontinuum generation. The fiber core is filled with a highly nonlinear liquid material nitrobenzene, which contributes to the high nonlinearity of the fiber. By modifying the geometric parameters of NLC-PCF to optimize the dispersion characteristics, a flat dispersion curve with three ZDWs in the analytical wavelength range is obtained. The generation of SC is numerically simulated using the GNLSE and the influence of the pump pulse on the normal dispersion and the anomalous dispersion is investigated. The highly coherent SC spanning from 1.3 to 2.8 μm is generated under the condition of the pump pulse with the center wavelength of 1810 nm, peak power of 1000 W, and width of 50 fs propagated in the 5 cm long NLC-PCF.

2 Design and theoretical model

2.1 Design of nitrobenzene liquid-core PCF

The cross-section of the proposed NLC-PCF is shown in Fig. 1a. We assume that the NLC-PCF is made of fused silica glass. It consists of four rings of air holes ordered in a hexagonal lattice, surrounding the central nitrobenzene-filled hole, and the inner air holes
are composed of eight elliptical air holes of the same size. Nitrobenzene is chosen for the liquid-core material due to its high nonlinear refractive index (Kedenburg et al. 2014). In particular, nitrobenzene liquid has good transmittance in the near-infrared region and mid-infrared region, so the loss of optical fiber can be ignored in the research process (Van et al. 2020). The inner ring of eight elliptical air-holes can obtain a PCF with three ZDWs and flat dispersion curve. $\Lambda$ is the air-hole spacing; $b$ is the diameter of the air-hole; $D$ is the core diameter; $a$ is the major axis of the elliptical air-hole; $b$ is the minor axis of the elliptical air-hole. Figure 1b shows the refractive index of nitrobenzene and silica. At 1 – 2 µm, the refractive index difference between silica and nitrobenzene is greater than 0.075. Such a large refractive index difference between the core material and the rod material ensures efficient modification of chromatic dispersion. The material dispersion is shown in Fig. 1c. With a suitable fiber design, it is possible to shift the ZDW to a different wavelength or to obtain the dispersion profile which is of interest in this report. The refractive index of nitrobenzene is given by the formula (Guo et al. 2021):

$$n_{\text{nitrobenzene}} = \sqrt{2.31952 + 0.02355/\lambda^2 + 0.00266/\lambda^4 - 0.00259/\lambda^2}$$  (1)
A larger refractive index is beneficial to binding the beam in the core. The use of air holes with a larger diameter and smaller spacing can also restrict the light mode more tightly. The difference in refractive index between the central element of the NLC-PCF structure, nitrobenzene, and silica cause the beam to concentrate in the center of the structure due to the total internal reflection (TIR). The distribution of electric field mode is shown in Fig. 1d. For this reason, nitrobenzene has been used here.

Figure 2 shows the confinement loss at different \( d/\Lambda \) ratios in NLC-PCF. The confinement loss is unique in PCF and is defined as:

\[
L_{c}(\lambda) = -8.686k_0 \text{Im}\left[n_{\text{eff}}(\lambda)\right]
\]

where \( k_0 = 2\pi/\lambda \) is the wavenumber in free space, \( n_{\text{eff}} \) is the effective refractive index of the related mode, and \( \text{Im}\left[n_{\text{eff}}(\lambda)\right] \) is the imaginary part of the effective refractive index, which describes absorption (Aliee 2020). The confinement loss is caused by the fact that the number of air holes in the actual PCF cladding is limited and they cannot completely confine the light in the core, resulting in some leakage and loss in the fiber. The confinement loss has an adverse effect on the PCF performance and plays the most crucial role in the PCF design. It can be controlled and minimized if appropriate measures are taken during the PCF design (Raei et al. 2018).

### 2.2 Theoretical model of pulse propagation

The generalized nonlinear Schrödinger equation (GNLSE) is a nonlinear partial differential equation (PDE) with solitary wave solutions, which can simulate many nonlinear effects of optical pulse propagation in PCF, such as SPM, FWM, second-harmonic generation, SRS, optical soliton, etc. Since GNLSE is a nonlinear partial differential equation, it is difficult to obtain its analytical solution directly, so it is usually solved by numerical methods. The numerical methods for solving GNLSE in this paper are split-step Fourier method (SSFM) (Ibarra-Villalon et al. 2020; Wen et al. 2019). SSFM divides the propagation distance of pulse in optical fiber into many intervals of length \( h \), in which we only consider the dispersion effect and nonlinear effect separately. In the first \( h/2 \) propagation distance, it is assumed that only the dispersion effect works; in the latter \( h/2 \) interval, only nonlinear effects are assumed to work. Then, the output pulse of the previous interval is used as the
input pulse of the next interval, and the process is repeated. Finally, the approximate results of the whole optical fiber propagation process are obtained.

The nonlinear propagation process of pump pulse in NLC-PCF can be described by GNLSE as

$$\frac{\partial A}{\partial z} + \frac{\alpha_0}{2} - \sum_{n \geq 1} \frac{i^{n+1}\beta_n}{m!} \frac{\partial^n A}{\partial t^m} = i\gamma \times \left(1 + \tau_{\text{shock}} \frac{\partial}{\partial t}\right) \times \left[A(z, t) \int_0^\infty R(t') \left|A(z, t - t')\right|^2 dt'\right]$$

where $A$ is the slowly varying amplitude of the pulse envelope, $\alpha_0$ is the fiber loss, $\gamma$ is the nonlinear coefficient, and $R(t')$ is the Raman response function. $\beta_m$ represents the $m^{th}$ order dispersion:

$$\beta_m = \left(\frac{d_m}{d\omega^m}\right)_{\omega = \omega_0} \quad (m = 1, 2, ...)

The nonlinear coefficient in this equation is defined by:

$$\gamma = \frac{2\pi n_2}{\lambda A_{\text{eff}}} \quad (4)$$

The main nonlinear effects in optical fiber, including SPM, XPM, and FWM are determined by nonlinear parameter $\gamma$. $\lambda$ is the wavelength of light. $A_{\text{eff}}$ is the effective mode area, it depends on the design of the fiber. $n_2$ is the nonlinear refractive index.

The equation describing the electric field distribution in PCF is PDE, which cannot be solved analytically. However, it is usually possible to construct equations similar to these PDE, namely numerical model equations, and solve them by numerical methods. The solutions of these numerical model equations are the approximate solutions to the real solutions of the corresponding PDE. Full-Vector Finite Element Method (FVFEM) is used to calculate these approximate solutions. The steps of FVFEM are as follows: the range of the problem area is divided into discrete sub-regions, and each sub-region is represented by an approximate equation; then all the approximate equations are systematically combined as global equations and the final numerical solution is obtained.

FVFEM needs a large amount of calculation, so it can only be analyzed in a limited area. To calculate the electromagnetic field simulation problem in an open area, it is necessary to select the appropriate absorbing boundary conditions. The commonly used absorbing boundary conditions are Perfect Electrical Conductivity (PEC) and Perfectly-matched layer (PML). PEC is an ideal case, and its boundary is a lossless surface that can fully reflect the incident wave. PML assumes that a part of the region is added outside the PCF, which can absorb all the emergent light pulses and will not be reflected. The absorbing boundary condition used in this paper is PEC.

To study the coherence of SC generated in PCF, we introduce the first-order coherence factor of SC (Dudley and Coen 2002):

$$g_{12}^{(1)}(\omega) = \frac{\left\langle \tilde{A}_1^*(L, \omega)\tilde{A}_2(L, \omega) \right\rangle}{\sqrt{\left\langle \left|\tilde{A}_1(L, \omega)\right|^2 \right\rangle \left\langle \left|\tilde{A}_2(L, \omega)\right|^2 \right\rangle}^{1/2}}$$

(5)
In the formula, $\tilde{A}(L, \omega)$ is the spectrum amplitude at the output of the fiber length $L$, $\tilde{A}_1$ and $\tilde{A}_2$ are the Fourier transform of two adjacent pulses, and the angle brackets represent the average of all pulses. \(g_{12}^{(1)}\) reflects the statistical average of a large number of calculation results, reflecting the correlation degree between the light fields obtained by different calculation processes at each wavelength in the whole SC spectral range. As coherence is affected by noise in the SC spectrum, which appears in the SC spectrum due to the existence of SRS and polarization modulation instability (PMI) (Genier et al. 2021), this imposes some limitations on the input pulse width. Therefore, by shortening the input pulse width, the noise in the SC spectrum can be reduced and the coherence improved.

3 Results and discussion

As shown in Fig. 3a, the dispersion curve and the position of the normal and anomalous dispersion regions can be regulated by changing the shape and size of the elliptical air-hole. When the long axis of the elliptical air-hole $a = 660$ nm and the short axis of elliptical air-hole $b = 400$ nm, the required dispersion curve is obtained. From Formula (4), the size of the nonlinear coefficient can be controlled by choosing different materials to change the $n_2$ value of the nonlinear refractive index coefficient and by adjusting the structure of the NLC-PCF to change the effective mode area $A_{\text{eff}}$. Figure 3b shows the effect of changing the size of an elliptical air-hole on the effective mode area and the nonlinear coefficient.

Figure 3c shows the dispersion curves of different core diameters $D$ with $a = 660$ nm and $b = 400$ nm. When the core diameter $D = 1.66$ μm, the NLC-PCF has a flat dispersion with a difference of 40 ps·nm$^{-1}$·km$^{-1}$ on 1~2 μm. Figure 3 (d) shows the effective mode area and nonlinear coefficients for different core diameters. For the PCF with a periodic array with air-holes, the effective mode area $A_{\text{eff}}$ is also related to the parameter air-hole diameter and air-hole spacing. For the fiber designed in this paper, it can be seen from Fig. 3e that the dispersion characteristics of NLC-PCF are also very sensitive to two parameters, air-hole diameter $d$, and air-hole spacing $\Lambda$. It is noteworthy that even though the changes in $d$ and $\Lambda$ are fairly small, the group-velocity dispersion varies significantly. This indicates that the fiber can allow more dispersion modification. Figure 3f shows the effects of different $d/\Lambda$ ratios on the effective mode area and nonlinear coefficient. The structural parameters of the proposed NLC-PCF are shown in Table 1.

The propagation of femtosecond pulse along the proposed NLC-PCF is simulated by solving the GNLSE using the SSFM. The propagation distance and the properties of the pump source are of great significance for the generation of the SC. In this paper, the time and frequency domain evolution of the SC for different propagation distances, and the effects on the time and frequency domain of the SC with the pulse width and peak pulse power varied are investigated separately using the variable-controlled method.

In this work, the SCG in NLC-PCF is also studied when the pump wavelength is located in the normal dispersion region and anomalous dispersion region near different ZDWs, and the coherence degree of SC is analyzed. The 10th-order dispersions at different pump wavelengths are considered to accurately simulating the SCG, as shown in Table 2.

The relationship among fiber length $L$, dispersion length $L_D = T_0^2/\beta_2$ and nonlinear length $L_{NL} = 1/(\gamma \cdot P_0)$ provides an important reference for which of the dispersion and nonlinear effects is more important in optical pulse propagation, where $T_0$ is the width of the pump pulse and $P_0$ is the peak power. Figure 4 shows the evolution of SC along NLC-PCF. The simulation results show that the broadened spectrum from 1.2 μm to 2.5 μm
Fig. 3 Characteristics of the NLC-PCF mode dispersion for the size of different a elliptical air-holes, c the diameter of the fiber core, and e the ratios of d/Λ. The effect on the effective mode area and nonlinear coefficient of different b elliptical air-holes, d the diameter of the fiber core, and f the ratios of d/Λ

| Parameter                  | Value   |
|----------------------------|---------|
| Core diameter(D)           | 1.48 µm |
| Air-hole diameter(d)       | 0.93 µm |
| Long axis of elliptical air-hole (a) | 0.66 µm |
| Short axis of elliptical air-hole (b) | 0.40 µm |
| Hole-to-hole pitch (Λ)     | 1.33 µm |
Table 2 The dispersion coefficient $\beta_m$ calculated at different pump wavelengths

| Pump wavelength | $\beta_2$ (s$^2$/m) | $\beta_3$ (s$^3$/m) | $\beta_4$ (s$^4$/m) | $\beta_5$ (s$^5$/m) | $\beta_6$ (s$^6$/m) | $\beta_7$ (s$^7$/m) | $\beta_8$ (s$^8$/m) | $\beta_9$ (s$^9$/m) | $\beta_{10}$ (s$^{10}$/m) |
|----------------|----------------------|---------------------|---------------------|---------------------|---------------------|---------------------|---------------------|---------------------|-----------------------|
| 1030 nm        | $3.19 \times 10^{-28}$ | $-7.57 \times 10^{-41}$ | $-9.53 \times 10^{-55}$ | $-3.22 \times 10^{-69}$ | $-4.00 \times 10^{-86}$ | $1.24 \times 10^{-98}$ | $-2.85 \times 10^{-111}$ | $5.12 \times 10^{-124}$ | $-6.56 \times 10^{-138}$ |
| 1050 nm        | $2.30 \times 10^{-27}$ | $-4.44 \times 10^{-41}$ | $-8.39 \times 10^{-55}$ | $-3.22 \times 10^{-69}$ | $-2.67 \times 10^{-86}$ | $2.58 \times 10^{-99}$ | $2.88 \times 10^{-112}$ | $-4.76 \times 10^{-126}$ | $3.74 \times 10^{-138}$ |
| 1150 nm        | $6.73 \times 10^{-28}$ | $4.62 \times 10^{-41}$ | $-3.24 \times 10^{-55}$ | $-3.22 \times 10^{-69}$ | $1.89 \times 10^{-86}$ | $6.48 \times 10^{-100}$ | $-1.22 \times 10^{-112}$ | $-7.94 \times 10^{-126}$ | $9.47 \times 10^{-138}$ |
| 1170 nm        | $-6.87 \times 10^{-28}$ | $5.33 \times 10^{-41}$ | $-2.38 \times 10^{-55}$ | $-3.22 \times 10^{-69}$ | $-6.09 \times 10^{-86}$ | $1.39 \times 10^{-98}$ | $-2.78 \times 10^{-111}$ | $4.98 \times 10^{-124}$ | $-8.15 \times 10^{-137}$ |
| 1590 nm        | $-1.31 \times 10^{-27}$ | $-1.44 \times 10^{-40}$ | $1.13 \times 10^{-54}$ | $-3.22 \times 10^{-69}$ | $-3.75 \times 10^{-87}$ | $-4.36 \times 10^{-100}$ | $4.36 \times 10^{-112}$ | $-1.55 \times 10^{-124}$ | $4.08 \times 10^{-137}$ |
| 1610 nm        | $6.06 \times 10^{-29}$ | $-1.54 \times 10^{-40}$ | $1.16 \times 10^{-54}$ | $-3.22 \times 10^{-69}$ | $2.66 \times 10^{-86}$ | $-8.78 \times 10^{-99}$ | $2.29 \times 10^{-111}$ | $-5.30 \times 10^{-124}$ | $1.15 \times 10^{-136}$ |
| 1710 nm        | $1.46 \times 10^{-26}$ | $-2.46 \times 10^{-40}$ | $1.39 \times 10^{-54}$ | $-3.22 \times 10^{-69}$ | $2.28 \times 10^{-86}$ | $-7.93 \times 10^{-99}$ | $2.03 \times 10^{-111}$ | $-4.24 \times 10^{-124}$ | $7.41 \times 10^{-137}$ |
| 1810 nm        | $3.62 \times 10^{-26}$ | $-3.54 \times 10^{-40}$ | $1.62 \times 10^{-54}$ | $-3.22 \times 10^{-69}$ | $2.28 \times 10^{-86}$ | $-4.92 \times 10^{-99}$ | $9.40 \times 10^{-112}$ | $-1.57 \times 10^{-124}$ | $2.26 \times 10^{-137}$ |
| 1910 nm        | $5.39 \times 10^{-26}$ | $-4.29 \times 10^{-40}$ | $1.76 \times 10^{-54}$ | $-3.22 \times 10^{-69}$ | $3.42 \times 10^{-86}$ | $-8.14 \times 10^{-99}$ | $1.83 \times 10^{-111}$ | $-3.81 \times 10^{-124}$ | $7.14 \times 10^{-137}$ |
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is realized by using a chirp-free hyperbolic secant pulse with the central wavelength of 1590 nm, the pulse length of 50 fs, and the peak power of 1000 W as the pump source. The calculated dispersion length $L_D$ of the fiber is approximately 61.6 cm and the nonlinear length $L_{NL}$ of the fiber is approximately 0.037 cm. At the top of Fig. 4a, it can be seen that $L_D > L > L_{NL}$ is satisfied when the propagation distance is 0.3 cm (Husakou and Herrmann 2001), and the group velocity dispersion effect can be ignored. The optical pulse is broadened due to the effect of SPM. With the increase of fiber length, the distance of nonlinear action is longer, so the spectral width of SC increases. And the optical wave breaking (OWB) happened first in the short-wave region due to the disturbance caused by high-order dispersion and the nonlinear effect when the propagation distance is 0.5 cm. The spectral side lobe on the left side of the spectrum and oscillation on the trailing edge of the pulse in the time domain are characteristics of OWB. Due to the self-steepening, the SC spectrum is asymmetric relative to the pump wavelength and there is a tendency for the spectrum to broaden towards the red side of the spectrum. And the solitons generated by cross-phase modulation and the dispersion wave combine different spectral peaks through coupling, and the stimulated Raman scattering extends the spectrum to the red end through cascade stimulated Raman scattering. If the appropriate phase matching conditions are satisfied, each Raman soliton can act as a pump to accelerate the generation of SC by four-wave mixing and dispersion wave interaction. When the propagation distance is 1 cm, the fiber length is close to the dispersion length of the fiber, and the group velocity dispersion and OWB work together. OWB happened on the right side of the spectrum because the dispersion on the long-wavelength side is flattened and smaller than on the short-wavelength side, which leads to the occurrence of OWB at a later time. After the OWB happened, the energy transfer between the different wavelength components helps to smooth out the spectrum. The structure of the oscillation near the pulse front in the time domain is caused by third-order dispersion. When the propagation distance is 3 cm, the SCG has been completed.

Figure 5a, b show the temporal and spectral profiles of the generated SC when the pump pulse with a center wavelength of 1590 nm, the width of 100 fs, and peak power of 100, 500, 1000, and 2000 W is propagated in the 5 cm long NLC-PCF. From Fig. 5a, it can be seen that with the increase of the peak power of the pump pulse, the enhanced SPM effect broadens the spectrum significantly. When the peak power reaches 2000 W, the −60 dB bandwidth of the resulting SC ranges from 1.2 to 2.5 µm. From Fig. 5b, when the peak power of the pump pulse is 100 W, the spectrum is not fully expanded. The spectrum spreads out gradually with increasing peak power, but there are some small oscillations in the spectrum, and the flatness decreases. Figure 5c, d show the
temporal and spectral profiles of the generated SC when the pump pulse with a center wavelength of 1590 nm, peak power of 1000 W, and width of 50, 100, 200, and 500 fs is propagated in the 5 cm long NLC-PCF. It can be seen from Fig. 5c that as the pump pulse width increases, the resulting SC coherence decreases significantly, especially at pulse widths of 200 and 500 fs, where multi-peaked oscillations are observed. From Fig. 5d, some strong oscillations can be observed with increasing pump pulse width, and the flatness of the spectrum decreases.

Figure 6 shows the SC generated in the normal and anomalous dispersion region near three ZDWs and its first-order coherence coefficients when the pump pulse with peak power of 1000 W, the pulse width of 50 fs is propagated in a 5 cm long NLC-PCF, where (a) 1590 nm and (b) 1610 nm are located near the first ZDW, (c) 1170 nm and (d) 1150 nm are located near the second ZDW, (e) 1030 nm and (f) 1050 nm are located near the third ZDW, and (a) 1590 nm, (c) 1170 nm and (e) 1030 nm are located in the anomalous dispersion region, and (b) 1610 nm, (d) 1150 nm and (f) 1050 nm are located in the normal dispersion region. From Fig. 5, in the anomalous dispersion state, the combination of SPM and dispersion leads to complex soliton dynamics, such as the splitting of higher-order solitons into multiple elementary solitons, and the coherence of SC is usually not high due to the modulation instability (MI). In the normal dispersion state, the generation mechanism of SC is mainly SPM and OWB, producing SC with good coherence. With the increase of the central wavelength of the pump pulse, the whole spectrum red-shifted and its bandwidth gradually increased. However, around the same ZDW, the SC spectrum width generated by pumping in the normal dispersion region is higher compared to that in the anomalous dispersion region.

Fig. 5a and b show the spectral and temporal profiles of the generated SC at the output of the 5 cm long NLC-PCF when the peak power is changed; c and d show the spectral and temporal profiles of the generated SC at the output of the 5 cm long NLC-PCF when the width of the pump pulse is changed.
As shown in Fig. 7a, the SCG in the normal dispersion region of the long-wavelength band is simulated when the pump pulse with the peak power of 1000 W and pulse width of 50 fs is propagated in the 5 cm long NLC-PCF. High coherent SC with wide pulse width and good flatness can be obtained in the normal dispersion region. Since the high-frequency component of the pulse propagation is slower than the low-frequency component, we can see that the spectrum redshifts with the increase of the pump wavelength. Figure 7b shows SC generated and its coherence at the pump wavelength of 1810 nm in Fig. 7a. Therefore, we can adjust the position of ZDW by dispersion modulation so that the normal dispersion region falls in the long-wavelength region to obtain the desirable SC.

Fig. 6 The SC generated by the pump pulse in the a c e normal and b d f anomalous dispersion region near three zero-dispersion wavelengths and its first-order coherence factor $g_{12}$.
4 Conclusions

In conclusion, a three ZDWs nitrobenzene liquid core PCF structure for SCG is proposed. The innermost layer of fiber cladding adopts eight elliptical air holes to restrain the fiber core and achieve the normal and anomalous dispersion region. By optimizing the NLC-PCF structure parameters, the flat dispersion curve with the value varying from −25 to 15 ps nm⁻¹·km⁻¹ in the wavelength range from 1 to 2 μm is obtained and the high nonlinear coefficient of 5500 W⁻¹·km⁻¹ is realized. Furthermore, the generation of SC in the designed NLC-PCF is numerically simulated by solving GNLSE. The comparison of the SCG with normal dispersion region and abnormal dispersion region is analyzed and the results show that higher coherence SC is realized in the normal dispersion region. Finally, the highly coherent SC with a spectral width from 1.3 to 2.8 μm is obtained by parameter optimization. This research can provide a feasible method for liquid-core PCF design and obtaining the SC with high coherence and large bandwidth.

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Declarations

Competing interests The authors have no relevant financial or non-financial interests to disclose.

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