Highly coherent supercontinuum generation in a polarization-maintaining CS₂-core photonic crystal fiber

FENG XU,1 JINHUI YUAN,1,* CHAO MEI,1 BINBIN YAN,1 XIAN ZHOU,2 QIANG WU,3 KUIRU WANG,1 XINZHU SANG,1 CHONGXIU YU,1 AND GERALD FARRELL 4

1State Key Laboratory of Information Photonics and Optical Communications, Beijing University of Posts and Telecommunications (BUPT), Beijing 100876, P. R. China.
2Research Center for Convergence Networks and Ubiquitous Services, University of Science & Technology Beijing (USTB), Beijing 100083, P. R. China.
3Department of Physics and Electrical Engineering, Northumbria University, Newcastle upon Tyne, NE1 8ST, United Kingdom.
4Photonics Research Centre, Dublin Institute of Technology, Dublin, Ireland.

*Corresponding author: yuanjinhu81@bupt.edu.cn

Received XX Month XXXX; revised XX Month, XXXX; accepted XX Month XXXX; posted XX Month XXXX (Doc. ID XXXXX); published XX Month XXXX

In this paper, we design a polarization-maintaining CS₂-core photonic crystal fiber (PM-CCPCF). The two air holes at x-direction are infiltrated with C₂H₅OH in order to introduce the birefringence. By optimizing the structure parameters of the PM-CCPCF, it is demonstrated that the x-polarization fundamental mode has all-normal dispersion profile and the corresponding y-polarization fundamental mode has anomalous dispersion profile for pump wavelength 1.76 μm. Then, we investigate the supercontinuum (SC) generations when different fiber lengths, pump peak powers, and pump pulse widths are chosen, respectively. Simulation results show that for the x-polarization and y-polarization fundamental modes, highly coherent SCs can be generated by appropriately choosing the fiber length and pump pulse parameters. Finally, nonlinear propagation dynamics are analysed when the optimized fiber length and pump pulse parameters are used. The bandwidth of the SCs generated for x-polarization and y-polarization fundamental mode can be up to 0.82 and 1.26 octave, respectively. © 2018 Optical Society of America

OCIS codes: (320.6629) Supercontinuum generation; (060.5295) Photonic crystal fibers; (060.2420) Fibers, polarization-maintaining

http://dx.doi.org/10.1364/AO.99.099999

1. INTRODUCTION

Supercontinuum (SC) generation has been attracting great research interests because of its extensive applications in wavelength-tunable light source, optical communication, optical coherence tomography [1-4]. The physical mechanism of the SC generation is resulted from a variety of nonlinear effects such as self-phase modulation (SPM), simulated Raman scattering (SRS), four-wave mixing (FWM), soliton fission (SF), etc. [1, 5-7]. The SC can be generated when pump pulse is respectively launched into the normal and anomalous dispersion regions of the nonlinear media [8, 9]. Photonic crystal fiber (PCF) is one of ideal nonlinear media for the SC generation due to its controllable group-velocity dispersion (GVD) and enhanced nonlinearity [5]. In practical applications, the bandwidth and coherence are considered as the two important performance parameters of the SC source. From the previous reports, when pump pulse works in the normal dispersion region of the PCF, the SF is benifical to the large bandwidth, but the noise induced by the soliton dynamics will degrade the coherence of the SC [12, 13]. As the field of optical frequency metrology and synthesis develops, some works focus on obtaining the SC with high coherence in the PCFs. In 2011, Hooper et al. reported the SC generation in a PCF designed with all-normal GVD [14]. In 2014, Li et al. proposed a tapered silica PCF to achieve self-similar compression of picosecond pulse for generating the SC [15]. In 2017, Petersen et al. demonstrated mid-infrared SC generation in a large-mode-area chalcogenide PCF taper [16]. In 2018, Saini et al. investigated the coherent SC generation in chalcogenide W-type co-axial optical fiber, step-index tellurite fiber, and rib waveguide [17-19]. In the same year, Nguyen et al. obtained mid-infrared SC with good coherence in cascaded tellurite and chalcogide fibers [20].

Recently, liquids including carbon disulfide (CS₂), ethanol (C₂H₅OH), carbon tetrachloride (CCl₄), and nitrobenzene (C₆H₅NO₂) are considered as nonlinear materials for the SC generation [21-24]. Among these liquids, the CS₂ has large nonlinear index (about 2 orders of magnitude than silica) and broad transmission range (visible to mid-
The Taylor expansion of the propagation constant dispersion coefficient at propagation distance where cross-section of the fiber as [1, 39] nonlinear coefficient, which can be calculated by integration over the directions [37]. In this paper, we design a polarization-maintaining CS2-PCF and generated the SC of over 10 μm in the two polarization [36]. Zhao et al. designed a highly nonlinear polarization-maintaining PCF and generated the SC of over 10 μm in the two polarization directions [37]. In this paper, we design a polarization-maintaining CS2-core photonic crystal fiber (PM-CCPF). The two air holes at x-direction are filled with C2H5OH to introduce the birefringence. When the coupling effect between the modes of the PM-CCPF are excited, respectively.

2. NONLINEAR THEORY MODEL

When the coupling effect between the x-direction and y-direction is neglected, the short pulse propagation in each direction of the PM-CCPF can be respectively described by modified generalized nonlinear Schrödinger equation (GNLSE) as [5, 38],

\[
\frac{\partial A}{\partial z} + \frac{\alpha_0}{2} A - \sum_{n=2}^{\infty} \frac{i^{w_n} \beta_n(z) \partial^{w_A}}{m!} = \left( 1 + \tau_{\text{shock}} \frac{\partial}{\partial t} \right) \left[ (1-f_m) |A|^2 + f_m \mu A \right] e^{-i \int A(t-t')^2 dt' },
\]

where \( A(z, t) \) represents the slowly varying envelope, \( \alpha_0 \) is the linear loss of the PM-CCPF, and \( \beta_n(z)(m = 2, 3, \ldots, 12) \) is the m-order dispersion coefficient at propagation distance \( z \) and calculated from Taylor expansion of the propagation constant \( \beta(z) \). The GVD parameter \( D \) is used to characterize the dispersion. The relationship between \( D \) and \( \beta(z) \) can be described as

\[
D = -\frac{2\pi c}{\lambda} \beta(z),
\]

where \( c \) represents the light velocity in vacuum, \( \gamma(z) \) is the Kerr nonlinear coefficient, which can be calculated by integration over the cross-section of the fiber as [1, 39]

\[
\gamma = \frac{2\pi}{\lambda} \left( \int n_2(x, y) |F(x, y)|^2 dxdy \right) / \left( \int |F(x, y)|^2 dxdy \right),
\]

where \( n_2(x, y) \) is non-linear refractive index of CS2 which is chosen as 2.7 × 10^{-10}. \( F(x, y) \) represents the distribution of the electric field. Nonlinear dispersion corresponds to the effect of self-steepening (SS), which can be described as [5, 40]

\[
\tau_{\text{shock}} = \frac{\gamma_1}{\gamma_0} \frac{\gamma_0}{\alpha_0} = 1 + \frac{1}{n_2} \frac{dn_2}{d\omega} \text{ at } \omega = \omega_0 - \frac{1}{\lambda} \frac{d\lambda}{d\omega} \text{ at } \omega = \omega_0,
\]

where \( \gamma_1 \) is the derivation of \( \gamma_0 \) and the second and third items at the right hand represent the wavelength dependence of \( n_2 \) and effective mode area \( A_{\text{eff}} \) respectively. The last part of Eq. (1) represents the reorientational nonlinearity among all the nonlinear effects and 6/7 is used in this work [28]. Because of large \( f_m \) the influence of Raman scattering can be neglected. Temporal exponential decay function \( \mu \text{e}^{-\mu t} \) is the response function of reorientational nonlinearity, where \( \mu = 10 \text{ ps}^{-1} \) is the decay rate.

The degree of coherence \( g^{(1)}_{\text{CS2}} \) is used to characterize the quality of the SC generated [8, 40, 42]

\[
g^{(1)}_{\text{CS2}}(\lambda, t_1 - t_2) = \left| \left\langle A^*_1(\lambda, t_1) A_2(\lambda, t_2) \right\rangle \right| \left( \left\langle |A_1(\lambda, t_1)|^2 \right\rangle \left\langle |A_2(\lambda, t_2)|^2 \right\rangle \right)^{1/2},
\]

where \( A(\lambda, t) \) represents the spectrum amplitude in the frequency domain. The angular brackets represent the ensemble average over independently pairs of spectra, i.e. \( A_1(\lambda, t) \) and \( A_2(\lambda, t) \), which are obtained from 50 shot-to-shot simulations with different random noise at wavelength \( \lambda \). We take \( t_1 - t_2 = 0 \) and the random noise is defined as \( \sigma = \eta \sqrt{N} \exp(i2\pi U) \) [5, 43], where noise amplitude \( \eta \) is chosen as \( 1 \times 10^{-3} \) in our simulation.

3. DESIGN OF THE PM-CCPCF

The cross-section of the PM-CCPF is shown in Fig. 1(a). From Fig. 1(a) three rings of air holes are arranged with a hexagonal lattice. The \( \Lambda \) represents the hole-to-hole pitch, and \( r_1 \) and \( r_2 \) denote the radii of the central and cladding holes, respectively. The specific geometry parameters of the PM-CCPF are given in Table 1. The central gray hole is infiltrated with the CS2 whose Sellmeier equation is given as following [23, 31]

\[
n_{\text{CS2}} = 1.580826 + 1.52389\times 10^{-2} \lambda^{-2} + 4.8578\times 10^{-4} \lambda^{-4} - 8.2863\times 10^{-5} \lambda^{-6} + 1.4619\times 10^{-5} \lambda^{-8}.
\]

The cladding material is the silica. To introduce asymmetry, the two air holes at x-direction are infiltrated with the C2H5OH whose linear
The effective refractive index is given in Ref. [21]. The selective-filling and sealing techniques can be used to infiltrate the liquids [44, 45]. Fig. 1(b) shows the electrical field distributions of x-polarization and y-polarization fundamental modes at wavelength 2.5 μm calculated with the full-vector finite element method. From Fig. 1(b), the two electrical field distributions clearly show the birefringence.

By changing the structure parameters $r_2$ and $D$, the dispersion profiles of the PM-CCPCF can be flexibly adjusted. Figs. 2(a) and 2(b) show the $\beta_2$ curves of the fundamental modes along the $x$ and $y$ directions calculated as functions of $r_2$, respectively. With the increase of $r_2$, the effective refractive index difference between the core and cladding region becomes larger, and the overall trend of the GVD decreases gradually, as seen from Figs. 2(a) and 2(b). When $r_2 < 0.75$ μm, the x-polarization fundamental mode shows all-normal dispersion while the y-polarization fundamental mode will always experience anomalous dispersion. Figs. 2(c) and 2(d) show $\beta_2$ of the x-polarization and y-polarization fundamental modes as functions of $D$, respectively. From Figs. 2(c) and 2(d), with the increase of $D$, the dispersion the value of $\beta_2$ gradually increases at the shorter wavelength and decreases at the longer wavelength. When $D = 2.15$ μm, the x-polarization fundamental mode appears all-normal dispersion.

We finally select $r_2 = 0.7$ μm and $D = 2.15$ μm, which ensure that the x-polarization fundamental mode keeps all-normal dispersion and y-polarization fundamental mode experiences a period of anomalous dispersion. Figs. 3(a) and 3(b) show the relationships between the GVD parameter $D$, $\gamma$ and wavelength. From Figs. 3(a) and 3(b), the $D$ value of x-polarization fundamental mode is always less than 0, and the $D$ value of y-polarization fundamental mode is larger than 0 between the two zero-dispersion wavelengths (ZDWs) of 1.75 and 2.91 μm. In addition, the effective mode areas in the two polarization axes will increase as the wavelength increases. Thus, for the x-polarization and y-polarization fundamental modes, $\gamma$ reduces from 834 to 0.80 W-1m-1 and from 8.37 to 0.86 W-1m-1 in the wavelength range of 1.0 to 3.0 μm, respectively. To show the difference between the two polarization directions, the birefringence $B$ of the PM-CCPCF is shown in Fig. 3(c), where the $B$ can be up to $5 \times 10^{-3}$ at wavelength 3 μm.

**Table 1. Geometry Parameters of the PM-CCPCF**

<table>
<thead>
<tr>
<th>Geometry</th>
<th>$D$ (μm)</th>
<th>$r_1$ (μm)</th>
<th>$r_2$ (μm)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>2.15</td>
<td>0.9</td>
<td>0.7</td>
</tr>
</tbody>
</table>

![Fig. 3. The GVD parameter $D$ (black solid lines) and nonlinear coefficient $y$ (blue dashed lines) of (a) x-polarization and (b) y-polarization fundamental modes of the PM-CCPCF. (c) The birefringence $B$ of the PM-CCPCF versus wavelength.]

### 4. SIMULATION RESULTS AND DISCUSSION

#### A. Influence of the PM-CCPCF length

We first investigate the influences of the fiber length on the temporal and spectral profiles and coherence when pump pulse with center wavelength 1.76 μm, width $T_0 = 80$ fs, and peak power $P_0 = 1000$ W is coupled into the x-polarization and y-polarization fundamental modes, respectively. Figs. 4(a) and 4(c) show the temporal and spectral profiles for the x-polarization fundamental mode, which experiences the all-normal dispersion. Because pump pulse experiences all-normal dispersion, the SPM dominates the spectral broadening. As the fiber length is increased from 3 to 9 cm with an interval of 1.5 cm, the temporal and spectral widths increase gradually, as seen from Figs. 4(a) and 4(c). The relationships between $g_{12}^{(1)}$ and wavelength with noise amplitude $1 \times 10^{-3}$ are shown in Fig. 4(e). From Fig. 4(e), $g_{12}^{(1)}$ maintains 1 in the wavelength range considered.

Figs. 4(b) and 4(d) show the temporal and spectral profiles for the y-polarization fundamental mode, which experiences the anomalous dispersion under the same condition. The pump pulse is located in the anomalous dispersion region of the PM-CCPCF, so the soliton dynamics play an important role in the spectral broadening. Soliton number is defined as $N = (L_0/L_{NL})^{1/3}$, where the dispersion length $L_0$ and nonlinear length $L_{NL}$ are respectively defined as $[5, 43]$

$$L_0 = \frac{T_0^2}{\vert \beta'' \vert}, \quad L_{NL} = \frac{1}{\gamma P_0}. \tag{7}$$

In this case, $N$ is calculated as 87. Therefore, many small peaks can be observed in Fig. 4(b), corresponding to the lower-order solitons. In addition, because of the reorientational nonlinearity existing in the CS$_2$, solitons will occur to red-shift and separate within a short propagation distance [28]. Therefore, many solitons are separated after a 3-cm long PM-CCPCF, which extends the long wavelength sides. With the increase of the fiber length, the satellite separates to the right side and more satellites become obvious due to the SF. Moreover, because of perturbation induced by the higher-order dispersions and resonance matching condition, the blue-shifted dispersive waves (DWs) are
generated at the short wavelength sides. Fig. 4(d) shows that the spectral width can reach the maximum value covering from 1.13 to 2.71 μm when fiber length is 4.5 cm. However, with further increase of the fiber length, the spectral width keeps almost unchanged except for appearing disorder at the shorter and longer wavelength sides. Fig. 4(f) shows the relationships between $g^{(1)}_{12}$ and wavelength. From Fig. 4(f), when the fiber length is 4.5 cm, $g^{(1)}_{12}$ is almost 1 in the wavelength range considered. When fiber length is longer than 4.5 cm, many dips emerge and the coherence starts to degrade. It indicates that if we want to obtain highly coherent SC with the $y$-polarization fundamental mode, the length of the PM-CCPCF needs to be chosen appropriately.

B. Influence of $P_0$

When pump pulse with center wavelength 1.76 μm and width $T_0 = 80$ fs is launched into a 4.5 cm-long fiber, we investigate the influences of $P_0$ on the temporal and spectral profiles and coherence. Figs. 5(b) and 5(d) show the temporal and spectral profiles of the $x$-polarization fundamental mode which experiences the all-normal dispersion when $P_0$ increases from 500 to 3100 W. When $T_0$ is fixed, the spectral broadening depends on the nonlinear phase shift $\phi_{\max}$, which is defined as

$$
\phi_{\max} = \frac{L_{\text{eff}}}{L_{\text{NL}}} = \gamma P_0 L_{\text{eff}},
$$

where $L_{\text{eff}}$ represent the effective propagation distance. The spectral width is proportional to $P_0$. Therefore, with the increase of $P_0$, the spectrum becomes broader due to the SPM, and the number of oscillation peaks also increases. It is found that $g^{(1)}_{12}$ always maintains 1 when the noise amplitude is fixed at $1 \times 10^{-3}$, as seen from Fig. 5(e).

The temporal and spectral profiles of the $y$-polarization fundamental mode which experiences the anomalous dispersion are shown in Figs. 5(b) and 5(d). According to Eq. (7), $N = 62, 86, 110, 132$, and 153 with the increase of $P_0$ from 500 to 3100 W. Therefore, the satellites shown in Fig. 5(b) become larger and the solitons move toward the original position at the same time. From Fig. 5(d), the spectrum gradually becomes broader as $N$ increases. When $P_0 = 3100$ W, it is worth noting that when the solitons are close to the second ZDW (2.91 μm), the soliton self-frequency shift (SSFS) can be cancelled by the spectral recoil from the red-shifted DW [46, 47]. Although the spectral width is larger, the oscillation is more severe than that of lower $P_0$ and some dips emerge because of the degradation of the coherence with the increase of $N$, as shown in Figs. 5(d) and 5(f). In Ref. [5], when $N < 10$, the coherence is good. However, in this work, the coherence of $\sim 1$ can be obtained even if $N = 62$ or 87. The main reason is that the reorientational nonlinearity response of the CS$_2$ can effectively improve the coherence [31]. In addition, the modulation instability (MI)
length $L_{NL}$ is calculated as $\sim 16L_{NL}$, which is equal to 1.1, 0.53, 0.33, 0.23, and 0.17 cm for different $P_0$ and much less than the propagation length. However, for narrow pulse of 80 fs, the influence of the MI can be significantly reduced, and good coherence can be still maintained [40, 43]. By taking the bandwidth and coherence into consideration, it is found that $P_0 = 1000$ W is the optimum power value.

C. Influence of $T_0$

Except for the fiber length and $P_0$, $T_0$ has also important influence on the temporal and spectral profiles and coherence. When $P_0$ is chosen as 1000 W and the fiber length is fixed at 4.5 cm, $T_0$ is changed from 80 to 600 fs. Figs. 6(a) and 6(c) show the temporal and spectral profiles of $x$-polarization fundamental mode which experiences the all-normal dispersion. With the increase of $T_0$, the temporal width becomes larger while the spectral width becomes smaller because of stronger nonlinear effect for the narrower pulse. Fig. 6(e) shows $g_{12}^{(1)}$ of the generated SC. From Fig. 6(e), $g_{12}^{(1)}$ is equal to 1 in the whole wavelength range because the SPM is the dominant effect.

![Fig. 6](image)

**Fig. 6.** (a) Temporal and (c) spectral profiles and (e) degree of coherence $g_{12}^{(1)}$ of $x$-polarization fundamental mode for different $T_0$. (b) Temporal and (d) spectral profiles and (f) $g_{12}^{(1)}$ of $y$-polarization fundamental mode for different $T_0$.

Figs. 6(b) and 6(d) show the temporal and spectral profiles of $y$-polarization fundamental mode which experiences the anomalous dispersion. $N = 87, 163, 326, 489, \text{ and } 652$ as $T_0$ increases from 80 to 600 fs. When $T_0 = 80$ fs and 150 fs, lots of small peaks emerge in the time domain, which is caused by the SF. Correspondingly, the spectra are broadened. The soliton separation distance is proportional to $T_0$ [5]. Therefore, we cannot observe the apparent SF when $T_0$ is increased from 150 to 600 fs because of the short fiber length. When $T_0 > 80$ fs, the coherence will be severely degraded, as shown in Fig. 6(f). The main reason is that modulation instability becomes important when $T_0$ is larger than 100 fs. Thus, $T_0 = 80$ fs is the best choice.

5. NONLINEAR PROPAGATION DYNAMICS

Based on the above results, we choose the optimized pump parameters and propagation length $L$ as shown in Table 2. Figs. 7(a) and 7(b) show the temporal and spectral evolutions of $x$-polarization fundamental mode which experiences the all-normal dispersion. With the increase of the fiber length, the SPM leads to the broadening of the pulse and spectrum in the time and frequency domains. Highly coherent SC generated covers from 1.32 to 2.33 μm (0.82 octave). The severe oscillation appears at the end of the propagation.

<table>
<thead>
<tr>
<th>Table 2. Optimized Pump Parameters and Characteristic Lengths</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Parameters</strong></td>
</tr>
<tr>
<td><strong>$T_0$ (fs)</strong></td>
</tr>
<tr>
<td><strong>Propagation Length</strong></td>
</tr>
<tr>
<td><strong>Characteristic Lengths</strong></td>
</tr>
</tbody>
</table>

Figs. 7(c) and 7(d) show the temporal and spectral evolutions of $y$-polarization fundamental mode which experiences the anomalous dispersion. The soliton dynamics dominate the nonlinear evolution. The calculated characteristic lengths for $y$-polarization direction are also shown in Table 2. $N = 87$, which is suitable for generating a wider SC. In addition, the reorientational nonlinear response can also maintain good coherence despite large $N$. $L_{SSFS}$ (0.53 cm) is much less than the propagation distance (4.5 cm), but the influence of MI can be efficiently reduced when narrow pulse (< 100 fs) is used. It can be seen from Figs. 7(c) and 7(d) that the solitons start to separate at $x = 2$ cm and the spectrum is broadened quickly. However, soliton fission distance, $L_{fiss} \approx L_{SSFS}$ [5], is calculated as 2.9 cm for $y$-polarization direction, which is longer than the numerical result. The comparison of $L_{fiss}$ and soliton fission distance shown in Fig. 7(c) (~2 cm) proves that the reorientational nonlinear response can accelerate the process of soliton fission. Because of the SSFS and DWs, the spectra at the short and long wavelength sides are extended with the increase of the fiber.
length, and highly coherent SC is generated in the wavelength range of 1.13 to 2.71 μm (1.26 octave).

6. CONCLUSION
In summary, a PM-CCPCF is designed with the CS2 and C2H5OH filled in the core and two cladding holes. The PM-CCPCF has all-normal dispersion profile for the x-polarization fundamental mode and anomalous dispersion profile for the y-polarization fundamental mode. It is shown that highly coherent SCs can be generated from 1.32 to 2.33 μm (0.82 octave) and from 1.13 to 2.71 μm (1.26 octave) when pump pulse with $T_0 = 80$ fs and $P_0 = 1000$ W and the PM-CCPCF with a length of 4.5 cm are used. It is believed that our research results can find important application in obtaining the fiber-based SC source.

Funding Information. The National Natural Science Foundation of China (61875238 and 61475023), Beijing Youth Top-notch Talent Support Program (20150000268833ZK08), Fund of State Key Laboratory of Information Photonics and Optical Communications (Beijing University of Posts and Telecommunications) P. R. China (IPPC2017ZZ05), Shenzhen Science and Technology Innovation Commission (JCYJ20160331141313917) and Research Grant Council of Hong Kong (PolyU152144/15E).

References


