Characteristics of supercontinuum generation in birefringent optical fibers

Y.Zhao, G.D.Khoe, H. de Waardt

Eindhoven University of Technology, Faculty of Electrical Engineering, Electro-Optical communications, P.O.Box, 513, 5600 MB Eindhoven, The Netherlands (Email: y.zhao@tue.nl).

This paper investigates SC generation characteristics in birefringent fibers numerically. Here a modified generalized coupled nonlinear Schrodinger equation is used in the simulation. Results show that the SC generation characteristic is polarization dependent. The polarization dependent characteristics of the SC in birefringent fiber allows us to control and tune the spectrum profile.

Introduction

Supercontinuum (SC) has attracted considerable attentions due to its versatility in many fields such as telecommunication [1], optical metrology [2] and medical science. The SC phenomenon originates from the third-order nonlinearity of the media. In nonlinear optical fibers, both chromatic dispersion and nonlinear effects determine the SC generation characteristics. Different dispersion characteristics will results in different SC spectra. Therefore SC generation in various fibers, such as the dispersion decreasing fiber (DDF), dispersion flattened fiber (DFF), high nonlinear DSF and photonic crystal fiber (PCF), has been investigated and demonstrated. Recently PCF has attracted our attention. As the dispersion and nonlinear properties of the PCF can be controlled by altering the size and arrangement of the air holes, unusual dispersion properties and the enlarged effective nonlinearities can be achieved in PCF. This makes photonic crystal fibers a promising tool for effective SC generation. Recently fully dispersion controlled PCF has been reported [3]. However nonlinear PCFs exhibit significant birefringence at only moderate asymmetries in the core region due to the small core and high index contrast, and the birefringent can be as high as $10^{-4}$. The advantage of the birefringent fiber is in the preservation of the state of polarization. The preserved polarization enhances the nonlinear interaction that is crucial in nonlinear applications. Further more, the interaction of the two orthogonal polarizations in the fiber allows for controlling and tuning the properties of the SC. Recently SC generation in birefringent fiber has been demonstrated and the polarization dependency of SC generation in birefringent fiber has been investigated experimentally [4][5].

In this paper, we investigated SC generation in birefringent fiber theoretically using a modified nonlinear-coupled Schrodinger equation. Based on the numerical model, the polarization dependent characteristics are investigated. Some results are presented and discussed.

Numerical model

The evolution of the two orthogonal polarized modes in birefringent fiber can be expressed by the well-known two-coupled nonlinear Schrodinger equation [6,7]. However as the difference of dispersion coefficient between the two modes can be significant [4] in high birefringent fiber, it is useful to consider the consequences of the difference of the two polarization modes in these equations. Here we extend the coupled
nonlinear Schrodinger equation to describe the evolution of two orthogonal polarization modes in a birefringent fiber related to the difference of the dispersion coefficients. Considering the effects of dispersion, SPM, cross phase modulation, Four wave mixing (FWM), stimulated Raman scattering (SRS) as well as self-steeping, the normalized equation for x-and y-polarization components can be described as

\[
\begin{align*}
\frac{\partial U_x}{\partial \zeta} + \frac{i}{2} \frac{\partial U_x}{\partial \tau} + L_D \sum_{m} \int_{-\infty}^{+\infty} \frac{\partial U_x^{(m)}}{\partial \tau} \frac{1}{\Delta \beta} \frac{1}{\rho} \frac{\partial \rho}{\partial \tau} \left( 1 + \frac{i}{\alpha T_0} \right) \left( \frac{\partial U_x^{(m)}}{\partial \tau} \right) + \frac{1}{2} \frac{\partial^2 U_x}{\partial \tau^2} + \frac{1}{2} \frac{\partial^2 U_x^{(m)}}{\partial \tau^2} + \frac{1}{2} \frac{\partial^2 U_x^{(m)}}{\partial \tau^2}
\end{align*}
\]

(1)

Where

\[
\begin{align*}
\zeta &= z/L_D, \quad \tau = (t - z(\beta_{j,x} + \beta_{j,y})/2)/T_0, \quad U_j = \sqrt{T_0} A_j \\text{ and } \\beta_{j,m} = \beta_{j,m}\left( T_0^{(m)} + T_0^{(m)} \right) / 2, \quad \Delta \beta = \beta_{0,y} - \beta_{0,x},
\end{align*}
\]

(2)

with the symbols and parameters explained in Table 1.

The equation of y-polarization component can be obtained by simply interchanging all the subscripts x and y in equation (1). \(f_1(t), f_2(t)\) and \(f_3(t)\) in equation (1) are the three Raman response functions. They are approximated by [6][7]

\[
\begin{align*}
f_1(t) &= \frac{r_1^2 + r_2^2}{r_1^2 r_2} \exp(-t/\tau_1) \cos(t/\tau_1), \quad f_2(t) = \frac{r}{\tau_2} \exp(-t/\tau_2), \quad f_3(t) = f_1(t) - 2f_3(t)
\end{align*}
\]

(3)

Where \(\tau_1 = 12.2\ fs\) and \(\tau_2 = 32\ fs\). \(r\) can be determined by fitting the relative height of the peak values of parallel and perpendicular Raman gain.

In our numerical simulations, the second order split-step Fourier method and a second order Rung-Kutta method are used to solve the extended nonlinear Schrodinger equation.

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Description</th>
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<tbody>
<tr>
<td>(U_j)</td>
<td>the normalized amplitude of (A_j) ((j = x) and (y))</td>
</tr>
<tr>
<td>(\tau) and (\zeta)</td>
<td>the normalized parameters of time and distance</td>
</tr>
<tr>
<td>(T_0) and (\omega_0)</td>
<td>the pulse width and pulse center frequency</td>
</tr>
<tr>
<td>(\delta)</td>
<td>the normalized parameter due to difference of the group velocity of mode (x) and (y)</td>
</tr>
<tr>
<td>(\Delta \beta)</td>
<td>the phase mismatch due to birefringent (\Delta n = n_x - n_y)</td>
</tr>
<tr>
<td>(\beta_{m,j}^{(l)})</td>
<td>the (m)-order derivatives of the propagation constant with the angle frequency of mode (j)</td>
</tr>
<tr>
<td>(L_D^{(m)})</td>
<td>the (m)-order dispersion length</td>
</tr>
<tr>
<td>(\alpha) and (\gamma)</td>
<td>the loss constant and nonlinear coefficient</td>
</tr>
<tr>
<td>(\rho)</td>
<td>the fractional contribution of the Raman effect, the value used here is 0.18</td>
</tr>
<tr>
<td>(\text{sgn}(\ast))</td>
<td>the sign of (\ast)</td>
</tr>
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Table 1 symbols and parameters used in equation (1) and (2)

**Results and discussions**

In the calculations, the assumed dispersion characteristic of the PCF is shown in Figure 1. The dispersion profile is based on, but different from one real PCF reported in [4]. To ensure the accuracy of the calculations over bandwidths of hundreds of nanometers,
the dispersion coefficient is approximated up to the 6th order in the Taylor series expansion of the propagation constant. The zero dispersion wavelengths for the slow mode and fast mode are 675 nm and 535 nm. In simulations, the pulse width is 200 fs, and assumed to be Gaussian shaped. The repetition rate of the pulse is 80 MHz. The pulse average power is 32 mw.

![Dispersion profile of the PCF.](image1)

Figure 1 Dispersion profile of the PCF.

![SC spectrum generation under different input polarization angle.](image2)

Figure 2 SC spectrum generation under different input polarization angle: (a) 0° (fast axis), (b) 90° (slow axis), (c) 45°, fast mode spectrum. (d) 45°, slow mode spectrum and (e) the linear combination of the fast mode spectrum in (c) and slow mode spectrum in (d). Pump wavelength is 804 nm.

Figure 2 shows one example of our results. The pump wavelength is 804 nm. The fiber length is 1 meter. Here the Figures 2 (a)–(e) show the results for cases where the input polarization is aligned to the fast axis, 45° to the fast axis and to the slow axis. Results show that the spectrum bandwidth is broader when the input polarization is matched with the fast axis. The spectrum shown in Figure 2 (e) is a linear combination of the SC generated separately along the two principle axes of the polarization when the input
polarization angle is 45°. It corresponds to the spectrum recorded by a polarization independent optical spectrum analyzer (OSA). As the pulse power in each polarization axis is the half of the original pump power, the bandwidth of the SC is smaller. However the spectrum is flatter when the input polarization angle is equal to 45°. It suggests that we can control and tune the SC by using birefringent fibers. From the dispersion characteristics of the two polarization modes of the PCF, the fast axis has a smaller and flatter dispersion characteristics compared with that of the slow mode. That is the major reason that the polarization dependent SC occurs. From the SC spectrum of the PCF, we can see several separated peaks in the structure. The development of spectrum structure originates from the higher order soliton compression and soliton fission. As the pulse propagates in the anomalous dispersion region, pulse is compressed and gives rise to the spectrum broadening initially. After a certain distance, the higher order soliton breaks up into several sub-pulses due to the effect of higher order dispersion and SRS. After a certain distance, each pulse develops into a soliton and experiences frequency down shifts. That is the reason why the spectrum components are observed at the long wavelength side. As the different solitons acquire different frequency shifting, they form different peaks in the spectrum structure. The spectrum of different peaks is expected to broaden and merge in a long fiber.

Conclusion
The SC generation characteristics in birefringent PCF fibers are studied numerically in this paper. Results show that the SC generation characteristic in highly birefringent fiber is polarization dependent due to the different dispersion characteristic of the two orthogonal polarization modes. The polarization dependence of the SC generation allows us to control the spectrum. It also allows us to obtain SC spectrum in the orthogonal polarization direction simultaneously.

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References