Design of optimum supercontinuum spectrum generation in a dispersion decreasing fiber*

XU Yong-zhao (徐永钊)[1], YE Hai (叶海)[1,2], LI Hong-tao (李洪涛)[1], and LING Dong-xiong (凌东雄)[1]**

1. School of Electronic Engineering, Dongguan University of Technology, Dongguan 523808, China

2. Institute of Dongguan-Sun Yat-Sen University, Dongguan 523808, China

(Received 28 March 2015)

In this paper, the optimum supercontinuum (SC) spectrum generation in a dispersion decreasing fiber is presented. Three normalized parameters for the pump pulse and SC fiber are introduced. It is found that the shape of an SC spectrum is uniquely specified by the input soliton order, the normalized dispersion slope and the normalized effective fiber length. For a pumping condition with a given input soliton order and a given normalized dispersion slope, by optimizing the normalized effective fiber length, the residual spectral peak in the SC spectrum can be suppressed effectively, and a broad SC spectrum with optimum spectral flatness can be obtained.

Document code: A **Article ID:** 1673-1905(2015)03-0217-5

DOI 10.1007/s11801-015-5054-6

Supercontinuum (SC) generation has become a very popular technique to obtain desired broadband optical sources. Such broadband sources have been widely applied in diverse research fields, such as optical communication, spectroscopy, microscopy and optical coherence tomography[1-5]. Numerous methods have been reported in SC generation using various lasers and optical fibers. Much effort has been devoted to generate wider and flatter SC spectra. Dispersion-flattened dispersion-decreasing fibers (DFDFs)[6-8], conventional dispersion flattened fiber (DFF)[9] and photonic crystal fibers[10-12] were proven to be successful candidates for flat broadband SC generation. Dispersion decreasing fibers (DDFs), which are usually used in optical pulse compression, have also shown to be appropriate for generating SC spectra[6,13,14]. The SC spectrum broadened over several hundred nanometers can be obtained even if the peak power of the pump pulse is as low as a few watts[14]. The mechanisms of SC generation in DDF are similar to those in DFDF, but the flatness of SC spectra generated in DDFs is poorer because DDF has larger dispersion slope. On the other hand, the SC spectra generated from DDFs still contain a strong residual spectral peak as those from DFDFs, and most of the pump pulse energy is stored in this residual spectral peak. As a result, the power in the spectrally broadened region is quite low. In order to suppress the strong residual spectral peak and improve the distribution of pump power among the SC spectra in DDFs, in this paper, we present a design for optimum SC spectrum generation in a DDF with the purpose of obtaining flat SC. Numerical simulations show that by carefully choosing the fiber parameters and the pumping conditions, the strong residual spectral peak can be suppressed greatly, and a broad SC spectrum with optimum flatness is realized.

Here we introduce an ideal dispersion characteristic in a DDF, which can be expressed as

$$D(\lambda,z)=D_0\left(1-\frac{z}{L_0}\right)+k(\lambda-\lambda_0), \tag{1}$$

where D_0 is chromatic dispersion at the input, i.e., $D(\lambda_0, 0)$, the effective length L_0 is defined as the propagation distance after which the dispersion $D(\lambda_0, z)$ becomes negative (normal dispersion), and k is the dispersion slope of the dispersion profile. In this paper, we assume the pump wavelength as $\lambda_p=\lambda_0=1\ 550$ nm.

We use a generalized nonlinear Schrödinger equation (GNLSE) to model the SC pulse propagation inside the fiber. In a frame of reference moving at the group velocity of the pulse, the GNLSE can be written in its normalized form as[14]

$$\frac{\partial U}{\partial \xi}=\sum_{m=2}^{\infty}\mathrm{i}^{m+1}\delta_m\frac{\partial^m U}{\partial \tau^m}+\mathrm{i}\left(1+\mathrm{i}s\frac{\partial}{\partial \tau}\right)\times$$

$$\left[U(\xi,\tau)\int_{-\infty}^{\tau}R(\tau-\tau')\left|U(\xi,\tau')\right|^2\mathrm{d}\tau'\right], \tag{2}$$

where the field amplitude $U(\xi, \tau)$ is normalized as $U(0,0)=1$. Other variables are defined as

* This work has been supported by the Guangdong Natural Science Fund (No.1414050001224), the National Instrumentation Program (No.2012YQ14000511), and the Guangdong Science and Technology Program (No.2012B090600009).

** E-mail: yongzhaoxu@126.com

$$\xi = \frac{z}{L_{\rm NL}}, \tag{3}$$

$$\tau = \frac{t - z / v_{\rm g}}{T_0}, \tag{4}$$

$$\delta_m = \frac{\beta_m}{m!\gamma P_0 T_0^m}, \tag{5}$$

$$\beta_m = \left(\frac{{\rm d}^m \beta}{{\rm d}\omega^m}\right)_{\omega=\omega_0}, \tag{6}$$

where T_0 is the half-width at 1/e-intensity point, and for a hyperbolic secant pulse, it is related to the full width at half maximum (FWHM) by $T_{\rm FWHM}\approx 1.763T_0$. P_0 is the peak power of the pulse launched into the fiber, $L_{\rm NL}=1/(\gamma P_0)$ is the nonlinear length, $v_{\rm g}$ is the group velocity, γ is the nonlinear parameter, δ_m is the mth order dispersion coefficient in normalized form, $s=(\omega_0 T_0)^{-1}$ is the self-steepening parameter at the carrier angular frequency ω_0 of the pulse, and $R(\tau)$ is the nonlinear response function.

In order to better discuss the effects of pump pulse parameters and fiber parameters on SC generation, we define three dimensionless parameters to describe the conditions for generating SC spectrum by using the method in Ref.[1], which are expressed as

$$N = \left(\frac{\gamma P_0 T_0^2}{|\beta_2|}\right)^{1/2}, \tag{7}$$

$$\varDelta_1 = \frac{\lambda_0^4 k}{(2\pi c)^2 \gamma P_0 T_0^3}, \tag{8}$$

$$\xi_0 = \gamma P_0 L_0, \tag{9}$$

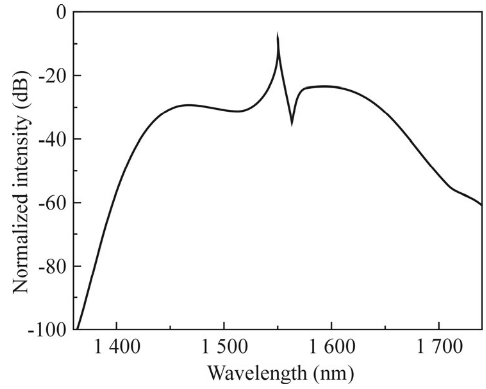
where N is the soliton order of the pump pulse. $\varDelta_1$ and ξ_0 correspond to the real parameter k and L_0, respectively. So we define $\varDelta_1$ and ξ_0 as the normalized dispersion slope and the normalized effective length, respectively.

The input pulses are assumed to have the form of

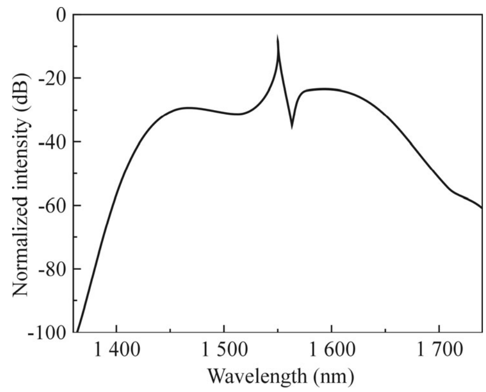
$$U(0,\tau) = {\rm sech}(\tau). \tag{10}$$

We first demonstrate the typical SC generation in DDFs. Fig.1 shows the generated SC spectra which are uniquely specified by the normalized parameters of N, $\varDelta_1$ and ξ_0. The parameters are set to be N=2, $\varDelta_1$=1.17× 10^{-4} and ξ_0=3.51. The spectra are observed at a normalized propagation distance of $\xi=1.2\xi_0$ which corresponds to the real propagation distance of $z=1.2L_0$. The effect of fiber loss is not included.

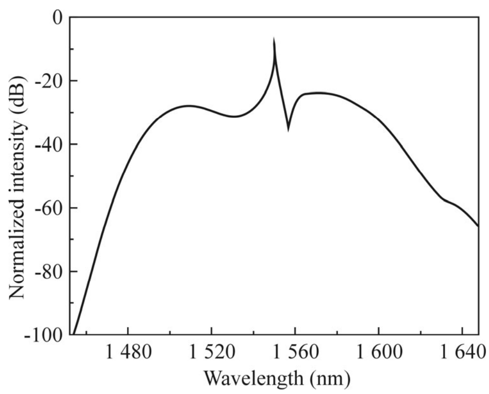
Fig.1(a) and (b) show the SC spectra with a constant pulse duration $T_{\rm FWHM}$=4 ps and various peak powers for the pump pulse. These spectra are almost identical, which have the −27 dB bandwidth of 226 nm. Fig.1(c) shows the SC spectrum with a pulse duration $T_{\rm FWHM}$= 8 ps for the pump pulse, and the −27 dB bandwidth of spectrum is 114 nm. These spectra in Fig.1 have the same shape, and the bandwidths are inversely proportional to the duration of pump pulse $T_{\rm FWHM}$. The above results show that the shape of spectrum is uniquely specified by the normalized parameters N, $\varDelta_1$ and ξ_0.



(a) $T_{\rm FWHM}$=4 ps, γP_0=5.94 km^{-1}, D_0=6 ps/(nm·km), k=5.0×10^{-3} ps/(nm^2·km) and L_0=0.590 km



(b) $T_{\rm FWHM}$=4 ps, γP_0=29.71 km^{-1}, D_0=30 ps/(nm·km), k=2.5×10^{-2} ps/(nm^2·km) and L_0=0.118 km



(c) $T_{\rm FWHM}$=8 ps, γP_0=2.97 km^{-1}, D_0=12 ps/(nm·km), k=2.0×10^{-2} ps/(nm^2·km) and L_0=1.180 km

Fig.1 Typical SC spectra generated from DDFs specified by the normalized parameters of N=2, $\varDelta_1$=1.17×10^{-4} and ξ_0=3.51

The most notable feature of spectra in Fig.1 is that the SC spectra are accompanied by a strong residual spectral peak covering the pump wavelength range. More than

46% of the pump pulse energy is stored in the residual spectral peak. As a result, the two wavelength bands on either side of the pump wavelength are quite low in power. Moreover, the flatness of the spectrally broadened region is poor.

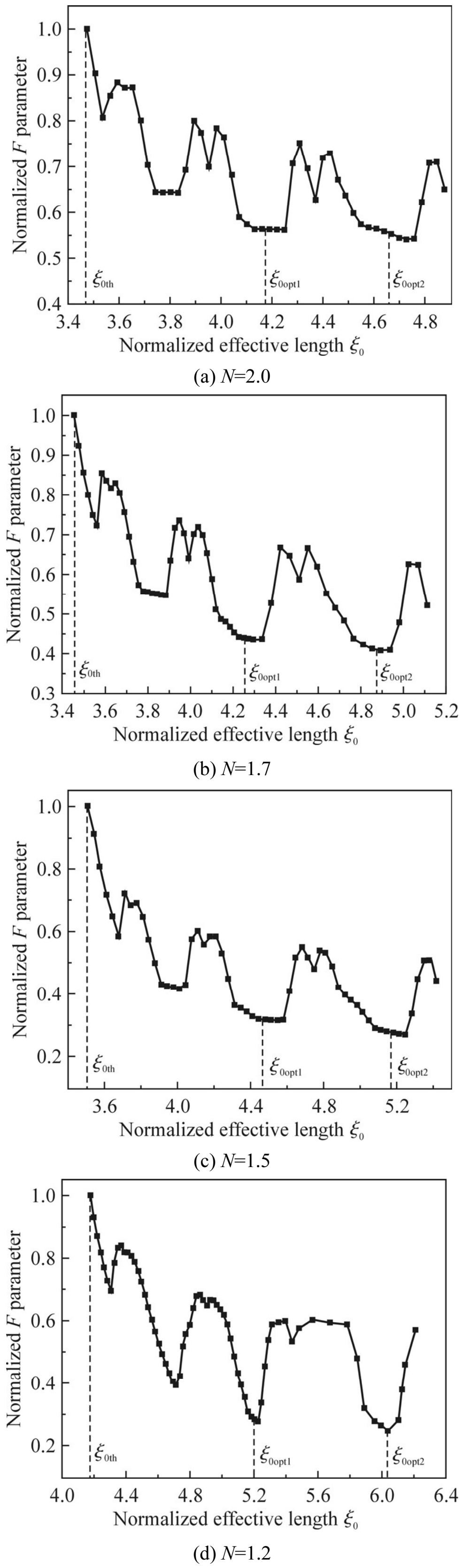
The process of SC generation in DDF is an interplay between nonlinear effect and dispersive effect. SC generation consists of two stages of pulse compression and spectral shaping. In the anomalous dispersion segment of the fiber, the adiabatically decreasing dispersion induces an initial phase of spectral broadening and associated temporal compression. After a propagation distance of about L_0, the spectral bandwidth increases sufficiently to induce the dispersive wave generation with respect to the pump wavelength. After propagating beyond L_0 when the dispersion is normal everywhere, the residual pump components temporally broaden and overlap with the frequency-shifted dispersive waves, facilitating interaction through cross-phase modulation. The combined result of these dynamics leads to a broad and flat SC spectrum generation.

According to the results presented in Fig.1, the shape of the SC spectrum is determined by the normalized parameters of N, $\varDelta_1$ and ξ_0. For a given N and a given $\varDelta_1$, we can optimize ξ_0 to improve the distribution of pump power in the SC spectrum and obtain a flat SC spectrum. To estimate the intensity fluctuation of the SC spectrum, we may introduce the following parameter of

$$F=\int_{\lambda_1}^{\lambda_2}\left[I(\lambda)-I_{\min}\right]\mathrm{d}\lambda , \tag{11}$$

where λ is the wavelength, $I(\lambda)$ is the spectrum intensity, and $I_{\min}$ is the minimum value of $I(\lambda)$ for λ in the range of $\lambda_1<\lambda<\lambda_2$. If a spectrum has a strong residual spectral peak or deep groove, the value of F will be very large. The smaller the value of F, the flatter the SC spectrum.

We change the parameter ξ_0 and fix other parameters of input soliton order N and normalized dispersion slope $\varDelta_1$ in order to observe the effect of ξ_0. As a result, the parameter F of the generated SC spectrum depends on ξ_0, and then we can obtain the curve of $F(\xi_0)$. We keep $\varDelta_1$ constant at -1.17×10^{-4}, and calculate the curve of $F(\xi_0)$ for different N in the range of $1.0\leq N\leq2.2$. For a given value of N, to generate an SC spectrum, ξ_0 needs to exceed a certain threshold of $\xi_{0\text{th}}$. Fig.2 shows the curves of $F(\xi_0)$ for five typical input soliton orders of N=2.0, 1.7, 1.5, 1.2 and 1.0, respectively. For each N, ξ_0 begins from its threshold value $\xi_{0\text{th}}$. There are several notable features in the curves shown in Fig.2. First, the threshold value $\xi_{0\text{th}}$ increases as N decreases. Second, when $\xi_0=\xi_{0\text{th}}$, the F parameter has a maximum value. Third, the curves consist of many peaks and troughs, and both the peak values and the trough values tend to decrease as ξ_0 increases. At the bottom of the trough, we can choose a moderate ξ_0 as an optimal value. In Fig.2, each curve presents four troughs, and the third and the fourth troughs reach relatively small values. So we may choose the optimal value at the bottom of the third and the fourth troughs, which are indicated by $\xi_{0\text{opt1}}$ and $\xi_{0\text{opt2}}$, respectively. As shown in Fig.2, $\xi_{0\text{opt1}}$ and $\xi_{0\text{opt2}}$ are positioned nearly in the middle of the trough. When ξ_0 is in the vicinity of $\xi_{0\text{opt}}$, the parameter F maintains a small value.

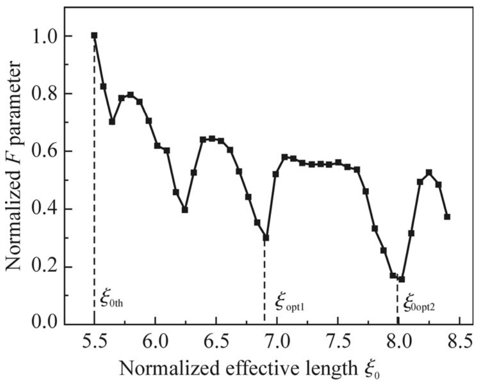


(a) N=2.0

(b) N=1.7

(c) N=1.5

(d) N=1.2



(e) N=1.0

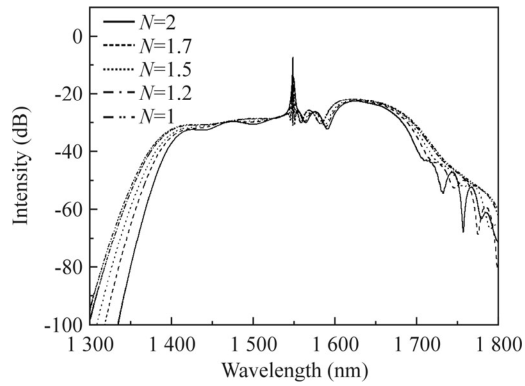
Fig.2 Calculated parameter *F* of the output SC spectrum as a function of ξ_0

Fig.3 shows the spectra generated at ξ_{0opt1} and ξ_{0opt2}. We find that when N>1.5, the flatness of the spectra generated at ξ_{0opt1} is slightly better. On the contrary, when N<1.5, the flatness of the spectra generated at ξ_{0opt2} is slightly better. For the same N, the bandwidth of the spectrum generated at ξ_{0opt2} is slightly broader.

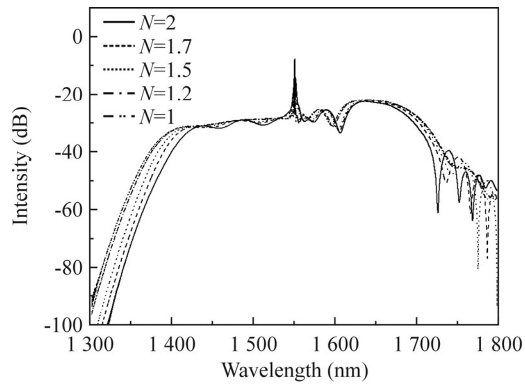
As seen clearly in Fig.3, although the SC spectra still contain a residual spectral peak due to higher-order soliton compression, the residual spectral peak becomes narrow obviously, and its intensity is suppressed greatly. Furthermore, the flatness of the spectra is improved evidently, and the spectrally flat region significantly extends. All the spectra have the −27 dB bandwidth over 280 nm. As N decreases, the residual spectral peak becomes narrower, and its intensity becomes weaker. For N=1 (a fundamental soliton), the residual spectral peak is suppressed to the utmost extent, while the SC spectrum keeps good flatness. Because the dispersion slope of the fiber is not zero, the SC spectra are asymmetric.

Fig.4 shows the calculated ξ_{0opt1} and ξ_{0opt2} as a function of N. For comparison, the threshold value ξ_{0th} as a function of N is also plotted in Fig.4. The curves indicate that the variations of ξ_{0opt1}, ξ_{0opt2} and ξ_{0th} with N follow the similar trend. As N decreases, both ξ_{0opt1} and ξ_{0opt2} increase, and the rate of increase becomes larger. For a lower-order soliton, to generate an optimum SC spectrum, the required optimal ξ_0 is large. For the same N, the value of ξ_{0opt1} is obviously less than that of ξ_{0opt2}. As there are only minor differences between the spectra generated at ξ_{0opt1} and ξ_{0opt2}, we can choose ξ_{0opt1} as the optimal value of ξ_0. If ξ_0 is set in the vicinity of ξ_{0opt1}, we can obtain a desirable SC spectrum with a relatively low value of ξ_0.

We choose ξ_{0opt1} as the optimal value of ξ_0 and calculate the proportion of residual spectral peak energy of the SC spectrum. Fig.5 shows the proportion of residual spectral peak energy as a function of N. It can be seen that the proportion of residual spectral peak energy decreases almost linearly with the decrease of N. When N decreases down to less than 1.2 (N<1.2), the proportion of residual spectral peak energy decreases down to less than 9%. The tradeoff for minimizing the residual spectral peak energy is the decrease of N and the increase of ξ_{0opt}.



(a) $\xi_0 = \xi_{0opt1}$



(b) $\xi_0 = \xi_{0opt2}$

Fig.3 The SC spectra generated at ξ_{0opt1} and ξ_{0opt2}

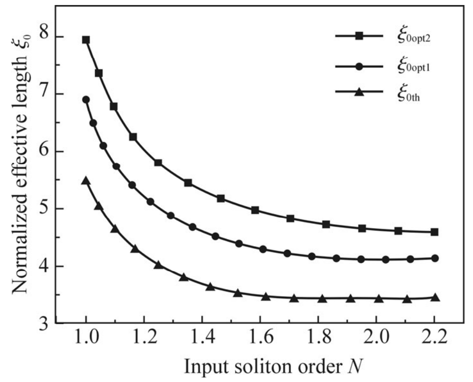


Fig.4 Calculated ξ_{0th}, ξ_{0opt1} and ξ_{0opt2} as a function of input soliton order *N*

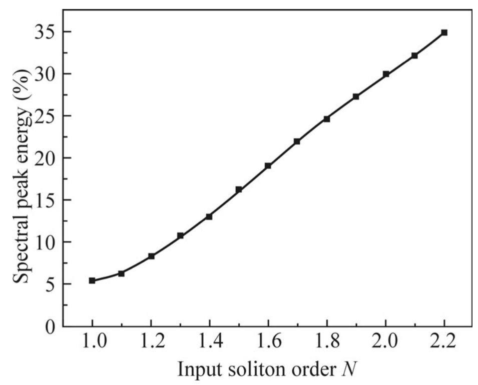


Fig.5 Calculated proportion of residual spectral peak energy of the SC spectrum as a function of input soliton order *N*

In summary, we present the design of optimum SC spectrum generated in a DDF. We introduce three normalized parameters for the pump pulse and SC fiber, and identify that the shape of an SC spectrum is uniquely specified by the normalized parameters of N, Δ_1 and ξ_0. For a pumping condition with a given N and a given Δ_1, by optimizing the parameter ξ_0, the residual spectral peak in the SC spectrum can be suppressed effectively, and a broad SC spectrum with optimum spectral flatness can be obtained. In order to obtain the optimal value of ξ_0, a parameter of F is introduced to estimate the intensity fluctuation of the SC spectrum. The optimal value of ξ_0 depends on N and Δ_1. When N decreases, the optimal value of ξ_0 increases, and the proportion of residual spectral peak energy of the SC spectrum decreases. To obtain an optimum SC spectrum with weak residual spectral peak, an input pulse with lower soliton order is recommended.

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