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Effects of pulse chirp on supercontinuum produced in dispersion decreasing fibre*

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The supercontinuum (SC) source plays a key role in wavelength division multiplexing over the optical time division multiplexing (WDM/OTDM) transmission system. The SC produced in dispersion decreasing fibre (DDF) is wider and flatter than that produced in dispersion shifted fibre (DSF). In this paper, a SC producing process in DDF is numerically simulated, the effects of pump pulse chirp on the SC width and flatness are initially studied and the corresponding theoretical explanations are given. Particularly, we have analysed and compared the evolutions of the SC along DDF pumped by different chirp pulses. Several valuable conclusions are obtained.

Keywords: optical time division multiplexing, dispersion deceasing fibre, supercontinuum, chirp
PACC: 4280W, 4265S, 4281W

1. Introduction

The supercontinuum (SC), a very promising means to produce ultrashort pulses over a wide spectral range, is widely used in a great deal of optoelectronics fields, such as wavelength division multiplexing over optical time division multiplexing (WDM/OTDM) transmission system,[1] OTDM–WDM conversion,[2] optical code division multiplexing (OCDM),[3] analogue-to-digital (A/D) conversion[4] and group-velocity dispersion (GVD) measurement.[5]

Width and flatness are the most essential characteristics of the SC, which represent its quality. Many factors influence these, including the peak power,[6] width, chirp, central wavelength of pump pulse and characteristics of the SC fibre. Chirp, a key character of optical pulses, has remarkable effects on SC production.

The dispersion shifted fibre (DSF),[1,4,5] dispersion flattened fibre (DFF)[3] and dispersion decreasing fibre (DDF)[7] can all be used to produce the SC. To our knowledge, the DSF has been widely used as a SC fibre for a long time and the chirp effects in this case were mentioned in Ref.[8]. As a more recent and advanced technology, the SC produced in the DDF is wider and flatter than that in the DSF under the same pump conditions, i.e. average pump power and temporal width of the pump pulse.[7] The comprehensive simulation and analysis of SC production in the DDF are very valuable. Here we initially numerically simulate the effects of the pump pulse chirp on the width and flatness of the SC, we explain the chirped pulse propagation process in the DDF and we obtain a series of useful conclusions about how chirp affects the SC.

2. Theory

A pulse without any chirp has a constant time–bandwidth product $\Delta t\Delta\nu_0$, called the transform limited value, which is related to the pulse profile. (The values of Gaussian and hyperbolic secant pulses are 0.44 and 0.315, respectively.) When a pulse is linearly chirped, its time–bandwidth product $\Delta t\Delta\nu$ is greater than its transform limited value, which is given by

$$\Delta t\Delta\nu = \Delta t\Delta\nu_0\sqrt{1+C^2}, \tag{1}$$

where C is the chirp coefficient. When $C>0$, the frequency at the leading edge of the pulse is lower than that at the trailing edge, so the instantaneous frequency at the centre of the pulse increases with time linearly. This kind of chirp is called positive chirp. Correspondingly, when $C<0$, the reverse result is obtained and the chirp is called negative chirp.

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In the analytic representation of optical pulses, the definition of the chirp coefficient C will be clearly denoted as follows. An ideal Gaussian pulse without any chirp can be described by the function[9]

$$E(T) = \sqrt{P_0}\exp\left[-\frac{T^2}{2T_0^2}\right]. \tag{2}$$

The linearly chirped pulse can be described as

$$E(T) = \sqrt{P_0}\exp\left[-\frac{(1+\mathrm{i}C)T^2}{2T_0^2}\right], \tag{3}$$

where P_0 is the pulse peak power and T_0 is the pulse half width (the width at e^{-1} amplitude of the pulse).

Because the SC spectrum covers a very wide range, our numerical simulations were based on the nonlinear Schrödinger equation with a revision[10]

$$\frac{\partial U}{\partial z} + \mathrm{i}\overline{\beta}_2\frac{\partial^2 U}{\partial T^2} + \frac{\alpha}{2}U = \mathrm{i}\gamma|U|^2U. \tag{4}$$

Here α is the loss coefficient, γ is the nonlinearity coefficient of the fibre, U is not the complex amplitude of a single wavelength optical pulse, but a composite of multi-wavelength pulses

$$U(z,T) = \int_{-\infty}^{+\infty}\xi(\Omega,z)\exp(\mathrm{i}\overline{\beta}_2\Omega^2 z)\exp[\mathrm{i}(\beta_1 z - t)\Omega]\mathrm{d}\Omega. \tag{5}$$

β_1 is the inverse of group velocity, $\overline{\beta}_2$ is the average fibre dispersion coefficient, $\xi(\Omega,z)$ is the complex amplitude when the frequency is ω and the frequency shift is $\Omega(\Omega = \omega - \omega_\mathrm{p})$, and ω_p is the central frequency of the pump pulse. Under this description, the above formula includes the effects of self-phase modulation (SPM), four-wave mixing (FWM) and cross-phase modulation (XPM). Self-steep and self-frequency-shift are not considered because the SC fibre we have used is not long enough to accumulate these effects to show off. The stimulated Raman scattering (SRS) is also not considered because the peak power of the pulse here does not exceed the threshold power.[11] As we know from Ref.[12], the spectrum broadening with propagation in the DDF is like the adiabatic compression, and the pulse peak power is enhanced to lead to a high nonlinearity. In addition, diminishing dispersion makes SPM a more dominant mechanism than the other nonlinear effects of FWM and XPM.[11] These can all lead to a wider and flatter SC spectrum.

When the propagation constant β is Taylor expanded versus Ω, we obtain the average dispersion $\overline{\beta}_2$ as the remainder in Taylor's series[13] $(0 \le 2 \le 1)$

$$\overline{\beta}_2(\Omega,z) = \int_0^1(1-x)\beta_2(x\Omega,z)\mathrm{d}x, \tag{6}$$

where $\beta_2(\Omega,z)$ includes two separated variable parts of $\beta_2(\Omega)$ and $\beta_2(z)$

$$\beta_2(\Omega,z) = \beta_2(\Omega,z_0) + \beta_2(\Omega_0,z) - \beta_2(\Omega_0,z_0). \tag{7}$$

The part $\beta_2(\Omega,z_0)$ can be deployed at Ω=0 to include the high-order dispersions (z_0 remitted)

$$\beta_2(\Omega) = \beta_2(0) + \beta_3(0)\Omega + \frac{1}{2}\Omega^2\beta_4(0) + \cdots. \tag{8}$$

The part $\beta_2(\Omega_0,z)$ represents the dispersion changes along the fibre length z.

3. Simulation and discussion

The numerical simulation set-up is shown in Fig.1. The input pulse is an ideal Gaussian pulse, with a full width at half maximum (FWHM) (T_FWHM=$2(\ln 2)^{1/2}T_0$) of 2ps, a repetition rate of 10GHz, and an initial linear chirp of C defined as in section 2. In the experiment, we successfully gained this kind of pulse by pulse compression.[14] A 2km DDF is used as the fibre to produce the SC. The method we use to solve the nonlinear Schrödinger equation is the split-step Fourier method.

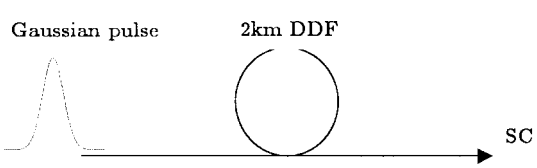


Fig.1. The simulation set-up used for SC production.

The dispersion figure of the DDF is shown in Fig.2. Here λ_p is the central wavelength of the pump pulse (λ_p=1550nm). D_in is the dispersion at the input end of the DDF, while D_out is that at the output end (when $\lambda = \lambda_\mathrm{p}$, we assume D_in=4ps·km^{-1}·nm^{-1}, D_out=–1.5ps·km^{-1}·nm^{-1}. β_3 is 0.081ps·nm^{-2}·km^{-1} and β_4 is remitted.

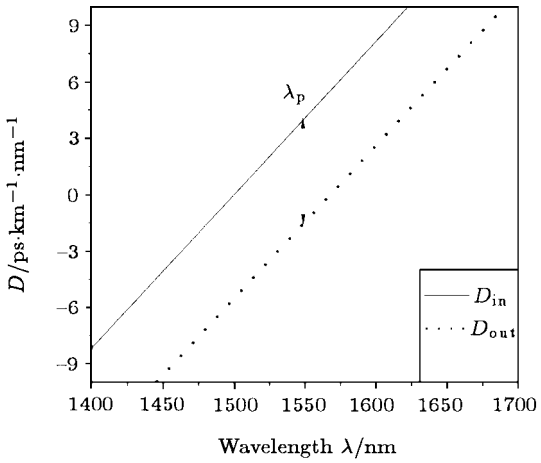


Fig.2. SC fibre dispersion in our numerical simulation, when $\lambda = \lambda_p$, D decreases from 4 to -1.5ps·km^{-1}·nm^{-1}.

The output spectral and temporal widths as functions of the chirp coefficient of the pump pulse are shown in Fig.3. The spectral width here always refers to a width of 20dB. As shown, the three curves belong to three different input average powers. In Fig.3(a), we can see that the width of the SC spectrum increases with the increase of average pulse power. Obviously, higher power leads to more intense nonlinear effects, and thus improves the production of a wider SC spectrum.

When one of the curves is concerned, we notice that the SC spectrum is the widest when the absolute value of the chirp coefficient is close to zero. This can be induced as we explained in section 2. The chirp is related to the frequency diversity between the leading and the trailing edges of a pulse. This frequency diversity weakens the SPM effect, and then weakens the SC generation. To observe the reducing velocity of the SC spectrum width when the chirp coefficient increases or decreases from zero, we can see that this velocity is initially low but expedites extremely when C surpasses a boundary level. According to Fig.3(b), the output SC temporal width equals the initial temporal width of the pump pulse (2ps) near the boundary chirp. Interesting as it is, this phenomenon can be explained as follows. To produce the SC, the pump pulse power needs to reach the threshold for compression of the pump pulse.[6] When the pulse is chirped, the power needed for compression will increase. Therefore, under the same average power, the spectral width of the SC will surely decrease with increasing C. When C reaches the boundary chirp, the pulse will not actually be compressed. When the chirp coefficient surpasses the boundary chirp, the SC is not produced, and hence the width of the spectrum reduces extremely. Furthermore, we can see that different average powers will correspond to different boundary chirp values. The higher the average power is, the higher the boundary chirp will be, and the chirp range for the production of SC becomes wider. This means that the chirp is only needed to be compensated to a value smaller than a certain level for SC generation. This is an important guide in experiment, especially for optical sources with high chirp, such as laser sources of distribution feedback (DFB), semiconductor optic amplifier (SOA) or electronic absorption modulator (EAM). We can also control average optical power to adjust the chirp tolerance range.

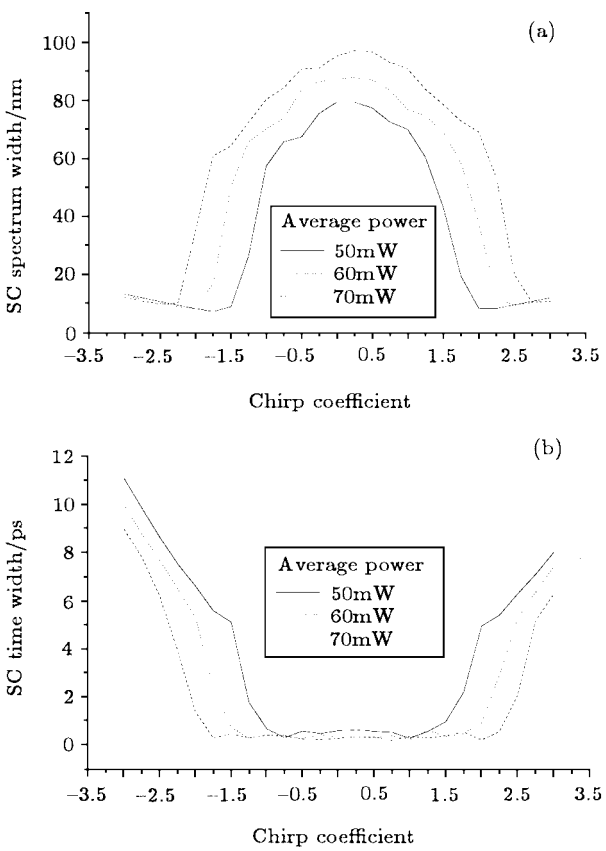


Fig.3. (a) Change of the SC spectrum width as a function of the chirp coefficient. (b) Change of FWHM of the SC as a function of the chirp coefficient.

Figure 4 shows the SC spectrum curves when the chirp coefficient C takes the values of 0, 1.12 and -1.12 with the corresponding SC spectral widths of 79, 67 and 41nm, respectively. The average powers of pump pulses here are all 50mW. Similar to that we analysed above, the SC spectrum is widest and flattest when C=0. Also we can notice that the width and flatness of the SC spectrum is better for C=1.12 than

for C=−1.12. The pulse chirp, especially the negative chirp, will be harmful to SC production.

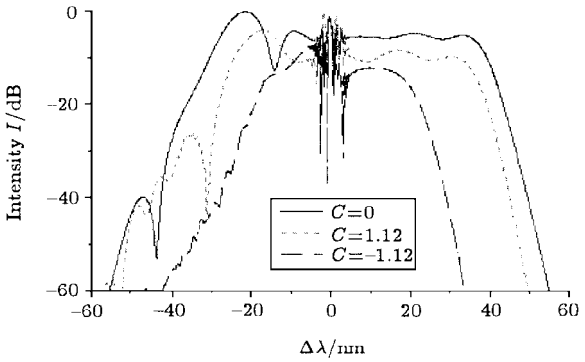


Fig.4. SC spectrum curves with different C.

To explain this phenomenon, we come to the dispersion of the DDF in Fig.2. Decreasing linearly from $D_{\rm in}$=4ps·km^{-1}·nm^{-1} to $D_{\rm out}$=−1.5 ps·km^{-1}·nm^{-1} at $\lambda_{\rm p}$, it is abnormal for the long beginning distance. In this case, positively chirped pulses will be compressed as the negatively chirped pulses are widened conceptually. The narrower the pulses are compressed, the higher the nonlinear efficiency is and the wider the SC spectrum which is generated. In actual experiments, when the chirp compensation in SC generation cannot be precise, this trend will become helpful. We prefer to compensate the chirp to a little positive rather than negative.

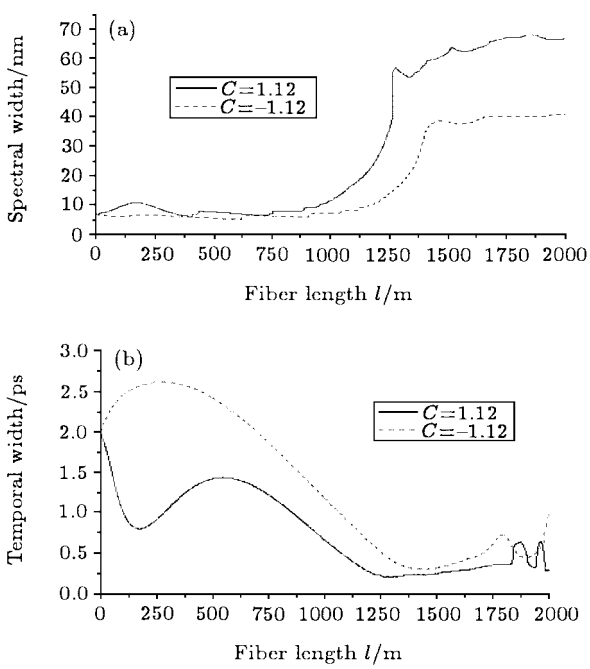


Fig.5. (a) Evolution of the SC spectral width as a function of fibre length. (b) Evolution of the SC temporal width as a function of fibre length.

As shown in Fig.5, in order to analyse in more detail, we are concerned with the evolution of the temporal and spectral widths of the pulse along the DDF. The solid lines represent the pump pulse with a positive chirp, while the dashed lines denote those with a negative chirp. Along the fibre length, we divide the propagation process into four stages.

1. At a distance before approximately 500m, the abnormal dispersion is relatively high (4∼2.6ps·km^{-1}·nm^{-1}), and the temporal and spectral widths are mainly affected by the interplay of the dispersion and the pulse chirp. The temporal width of a negatively chirped pulse is widened due to the abnormal dispersion, while the spectral width decreases a little (from 6.7 to 5.9nm) due to the interplay between the negative chirp and SPM.[15] When the pulse has a positive chirp, its temporal width is narrowed at first. After reaching approximately 200m, the pulse chirp is over-compensated by the abnormal dispersion, and the pulse is a little widened then. The spectral width varies correspondingly. At this stage, the changes of the temporal width of pulses with different chirps are different, and this has a great influence on different SC spectrum results that are discussed below.

2. At a distance from approximately 500 to 1000m, the dispersion is relatively low (2.6∼1.25 ps·km^{-1}·nm^{-1}), and the nonlinear effects are higher than dispersion effects. The pulse is nonlinearly compressed, its temporal width decreases but the spectrum remains relatively constant. Both the peak power and the pulse profile are optimized now for SC production.

3. At a distance from 1000 to 1500m, the dispersion is close to 0 ps·km^{-1}·nm^{-1} (1.25∼−0.12 ps·km^{-1}·nm^{-1}) and the pulse is compressed to its narrowest. As XPM and FWM begin to be effective and SPM becomes the most intense, the spectrum is rapidly widened here. After the spectral width reaches a peak level, whereas the pulse width reaches its minimum, the spectrum will remain nearly constant. As shown in Fig.5, when C=1.12, the SC spectrum width reaches 57.1nm for the fibre length of 1279m, while the corresponding pulse temporal width is 0.217ps. When C=−1.12, the SC spectral width reaches 39.0nm at a length of 1462m, while the pulse width is 0.308ps. Here SC spectral width maxima, as well as the temporal width minima, are different from each other.

4. After going over 1500m, the dispersion becomes normal, the SC bandwidth does not increase remarkably due to the serious walk-off between pulses

with different wavelengths. The definite spectral width is close to its first peak value.

According to the descriptions above, although perhaps not so precise in division of the process, we can see the different chirped pulses have different SC spectral and temporal width evolutions in the DDF. When the pump pulse has a positive chirp, the pulse will be compressed narrower in the first stage. Consequently, in the third stage, it will have a smaller temporal width minimum and a wider SC spectrum than the negatively chirped pulse. In addition, with the clear analyses by fibre stages, we here point out a helpful means for further study on SC production in the DDF.

4. Conclusion

In summary, we have introduced the theoretical and numerical basis of the simulation of SC generation. Then we simulated a process of SC production, using the DDF as the SC fibre, and we analysed the effects of pulse chirp on the width and flatness of the SC spectrum. The relationship between the width of the SC spectrum and the value of C is analysed, and the boundary level of the chirp coefficient for SC production is given. According to these, we have given some useful chirp compensation guidance. Different spectrum curves corresponding to different chirp coefficients are shown. The evolution of the temporal width and the spectral width versus fibre length is analysed and the question of why the SC spectrum is wider for $C > 0$ than for $C < 0$ is discussed. A clear explanation is provided and a helpful means of analysis is described. In addition, the comparison of the results with the SC produced in the DSF[8] can indicate the different pulse width evolution. Unlike the results in the DSF, where the optical pulse widens continuously, it becomes narrower and constant in the DDF due to the adiabatic compression. The time–bandwidth product remains constant and the shape of the output pulse is much better in the DDF. Thus, we have proven that the SC produced in the DDF is more practical in WDM/OTDM system sources.

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