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Effect of initial chirp on supercontinuum generation in dispersion decreasing fibers

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ABSTRACT

Numerical simulations based on generalized nonlinear Schrödinger equation are used to study the effect of initial chirp on supercontinuum generation in dispersion decreasing fibers. The simulation results show that the effect of initial chirp on SC generation is highly related to the choices of pumping conditions and fiber parameters. When the pumping condition and the fiber parameters are different, the effect of initial chirp on SC generation may follow different patterns. To better discuss the effects of pulse parameters and fiber parameters on SC generation, the three normalized parameters: input soliton order, normalized dispersion slope and normalized effective fiber length are introduced. For a given input soliton order and a given normalized dispersion slope, there exists an optimal normalized effective fiber length for generating a flattest SC spectrum. On the condition of normalized effective fiber length in the vicinity of its optimal value, when DDF has small normalized dispersion slope, proper positive chirps can significantly enhance the SC bandwidth, while negative chirps or too large positive chirps suppresses the SC bandwidth. There is a wide range of positive chirps that can enhance the SC bandwidth, but the range of proper positive chirps become narrower as input soliton order decreases; When DDF has a large normalized dispersion slope and the pump pulse is a lower-order soliton, the enhancement of SC bandwidth by initial chirp is insignificant, and the widest SC spectrum is generated when the initial chirp is close to zero.

1. Introduction

In the past decades, supercontinuum (SC) generation in optical fibers has attracted a great of interest due to its promising and revolutionary applications in numerous areas, such as telecommunication, spectroscopy, fiber sensing and optical coherence tomography. Numerous methods have been reported in SC generation using different lasers and nonlinear fibers. Many kinds of optical fibers have been successfully used for SC generation: for example, highly nonlinear silica fibers [1,2], soft-glass fibers [3], photonic crystal fibers [4,5], dispersion-flattened dispersion-decreasing fibers and dispersion decreasing fibers [6–8].

The mechanics of supercontinua generation in those fibers has been investigated experimentally and numerically. The effects of input pulse parameters such as pulse duration, peak power, pulse energy, and central wavelength on the SC generation have been investigated thoroughly. It is well known that pulses emitted from practical laser sources are often chirped. A pulse's initial chirp also has a significant effect on SC generation. Lots of numerical simulations and experimental investigations were carried out to clarify the influence of initial chirp on SC generation in PCF and some useful conclusions were obtained [9–12]. However, the effect of initial chirp on SC generation in DDF and DFDF has not been studied in detail which is different with that in PCF. Literature [13] discussed the effect of initial linear chirp on SC generation in a DDF and found that the widest SC spectrum can be obtained when the initial chirp is nearly zero, SC bandwidth is reduced by the initial chirp (both positive and negative). Literature [14] studied the effects of initial linear chirp on the SC generation in a DFDF and the simulation results indicate that proper positive chirps can significantly enhance the SC generation. Although the mechanics of SC generation in DDF are similar to that in DFDF, the results of Literature [13] are quite different from those of Literature [14]. A natural question is why the dependence of SC bandwidth on initial chirp in DDF is quite different from that in DFDF. To the best of our knowledge, previous literatures did not carry out further discussion on this issue. So it is of great necessity to carry out some research on it. In this paper, we present a detailed numerical study on how the input pulse chirp affects the SC generation in DDFs. We find that the effect of initial chirp on SC generation in DDF is highly related

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to the choices of pumping conditions and fiber parameters. When the pumping condition and the fiber parameters are different, the effect of initial chirp on SC generation may follow different patterns.

2. Model

Here we introduce an idealized dispersion characteristic in a DDF, $D(\lambda,z)$, expressed as

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

where D_0 is chromatic dispersion $D(\lambda_0,0)$ at the input. Effective length L_0 is defined as the propagation distance after which the dispersion $D(\lambda_0,0)$ becomes negative (normal dispersion). k is the dispersion slope of the dispersion profile. In this paper, we assume the pump wavelength $\lambda_p = \lambda_0 = 1550$ nm.

We use a generalized nonlinear Schrödinger equation (GNLSE) to model the 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 [15]

$$\frac{\partial U}{\partial \xi} = \sum_{m=2}^{\infty} i^{m+1}\delta_m \frac{\partial^m U}{\partial \tau^m} + i\left(1 + is\frac{\partial}{\partial \tau}\right) \times \left[U(\xi,\tau)\int_{-\infty}^{\tau} R(\tau-\tau')\left|U(\xi,\tau)\right|^2 d\tau'\right] \quad (2)$$

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

$$\xi = \frac{z}{L_{\mathrm{NL}}}, \tau = \frac{t-(z/v_g)}{T_0}, \beta_m = \left(\frac{d^m\beta}{d\omega^m}\right)_{\omega=\omega_0} \quad (3)$$

$$\delta_m = \frac{\beta_m}{m!\gamma P_0 T_0^m} \quad (4)$$

where T_0 is the half-width (at 1/e-intensity point), for a hyperbolic secant pulse, it related to the full width at half maximum (T_{FWHM}) by $T_{\mathrm{FWHM}} \approx 1.763T_0$. P_0 is the peak power of the pulse launched into the fiber, $L_{\mathrm{NL}} = 1/(\gamma P_0)$ is the nonlinear length, v_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.

The coefficients δ_m from the second order to the third order are expressed as

$$\delta_2 = \frac{\beta_2}{2\gamma P_0 T_0^2} = -\frac{1}{2}\frac{\lambda_0^2}{2\pi c}\frac{D_0}{\gamma P_0 T_0^2}\left(1 - \frac{\xi}{\gamma P_0 L_0}\right) \quad (5)$$

$$\delta_3 = \frac{\beta_3}{6\gamma P_0 T_0^3} = \frac{1}{6}\frac{\lambda_0^3}{(2\pi c)^2\gamma P_0 T_0^3}\left[k\lambda_0 + 2D_0\left(1 - \frac{\xi}{\gamma P_0 L_0}\right)\right] \quad (6)$$

when propagation distance z is near zero, Eq. (4) is dominated by the second-order term

$$-\frac{1}{2}\frac{\lambda_0^2}{2\pi c}\frac{D_0}{\gamma P_0 T_0^2} \quad (7)$$

when z is near L_0, Eq. (4) is dominated by the third order term

$$\frac{1}{6}\frac{\lambda_0^4 k}{(2\pi c)^2\gamma P_0 T_0^3} \quad (8)$$

From the above results, we define three dimensionless parameters

$$\Delta_0 = \frac{\lambda_0^2}{2\pi c}\frac{D_0}{\gamma P_0 T_0^2}, \Delta_1 = \frac{\lambda_0^4 k}{(2\pi c)^2\gamma P_0 T_0^3}, \xi_0 = \gamma P_0 L_0 \quad (9)$$

The normalized parameter Δ_0 coincides with the reciprocal square of the soliton order N, defined as

$$N = \left(\frac{\gamma P_0 T_0^2}{|\beta_2|}\right)^{1/2} \quad (10)$$

The normalized parameter Δ_1 which corresponds to the real parameters k is defined as the normalized dispersion slope. The normalized parameters ξ_0 which corresponds to the real parameter L_0 is defined as the normalized effective length. We expect the output spectrum from a DDF to be uniquely specified by the three normalized parameters N, Δ_1 and ξ_0.

The input pulses are assumed to have the form

$$U(0,\tau) = \mathrm{sec}\,h(\tau)\exp\left(-\frac{iC_p\tau^2}{2}\right) \quad (11)$$

where C_p is the parameter representing the initial linear frequency chirp.

3. Results and discussion

We first demonstrate that in the absence of initial chirp ($C_p = 0$), the spectral shape is uniquely specified by the three normalized parameters Δ_1, N and ξ_0. We assume $\Delta_1 = 1.17 \times 10^{-4}$ and $N = 2$. For a given value of Δ_1 and N, to generate a SC spectrum, ξ_0 needs to exceed a certain threshold value $\xi_{0\mathrm{th}}$. There exists an optimal value of ξ_0 for generating a flattest SC spectrum. In this example, the optimal value of ξ_0 is found to be $\xi_0 = \xi_{0\mathrm{opt}} \approx 3.77$. Fig. 1 shows the generated SC spectra from the DDFs while Δ_1, N and ξ_0 keep constant. The spectra are observed at a normalized propagation distance of $\xi = 1.2\xi_0$ (corresponding to the real propagation distance of $z = 1.2L_0$). The effect of fiber loss is not included.

Spectra (a) and (b) of Fig. 1 show a constant pulse duration $T_{\mathrm{FWHM}} = 4$ ps and various peak powers for the pump pulse. For curve (a), $\gamma P_0 = 5.94\ \mathrm{km}^{-1}$, $D_0 = 6$ ps/(nm/km), $k = 5.0 \times 10^{-3}$ ps/(nm^2/km) and $L_0 = 0.635$ km. For curve (b), $\gamma P_0 = 29.71\ \mathrm{km}^{-1}$, $D_0 = 30$ ps/(nm/km), $k = 2.5 \times 10^{-2}$ ps/(nm^2/km) and $L_0 = 0.127$ km. These results show identical spectra, which have the 27-dB bandwidth of 260 nm. Spectrum (c) of Fig. 1 shows a pulse duration $T_{\mathrm{FWHM}} = 8$ ps for the pump pulse. For curve (c), $\gamma P_0 = 2.97\ \mathrm{km}^{-1}$, $D_0 = 12$ ps/(nm/km), $k = 2.0 \times 10^{-2}$ ps/(nm^2/km) and $L_0 = 1.27$ km. The 27-dB bandwidth of spectrum (c) is 133 nm. These spectra have nearly the same shape, and the bandwidths are inversely proportional to the duration of a pump pulse T_{FWHM}. The above results indicate that in the absence of initial chirp, the shape of a spectrum is uniquely specified by N, Δ_1 and ξ_0. When N, Δ_1 and ξ_0 keep constant, the shapes of the generated spectra will depend on initial chirp despite the fact that the pump pulses and the SC fibers have different actual parameters such pulse duration, peak power, fiber dispersion and fiber length.

The process of SC generation in DDF is an interplay between nonlinear and dispersive effects. SC generation consists of two stages: 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 around L_0, the spectral bandwidth increases sufficiently to induce 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