Spectral narrowing in the propagation of chirped pulses in single-mode fibers

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A theoretical study of the nonlinear propagation of picosecond chirped pulses in single-mode fibers is presented. We show that, under appropriate conditions, spectral narrowing—rather than broadening, as is generally believed—is induced, owing to the interplay of self-phase-modulation and dispersion. For downchirped pulses at a wavelength of 0.9 μm and a peak power as low as 0.1 W, substantial spectral narrowing occurs.

Propagation of chirped-frequency optical pulses in fibers has been investigated by several authors in connection with (temporal) pulse compression schemes.[1–3] Little attention has been paid to the effect of self-phase-modulation (SPM) on the spectrum of initially chirped pulses. Because of the existence of frequency chirping from mode-locked dye[4] and semiconductor[5,6] lasers, nonlinear chirped-pulse propagation is an important subject for nonlinear fiber optics and high-bandwidth optical fiber communications.[7,8] It is generally believed that the effect of SPM is to produce spectral broadening on the pulse. We show here that this is not always the case with chirped pulses, where downchirped pulses in the normal group-dispersion region ($\lambda < 1.3$ μm for typical fiber) can experience spectral narrowing.

In this Letter we analyze the influence of an initially imposed frequency chirp on the temporal and spectral evolution of a pulse propagating in a fiber in the normal-dispersion regime, taking into account the effects of dispersion, SPM, and attenuation. We consider as especially interesting the case of large negative frequency chirp, where significant spectral narrowing is possible. The spectral width of a 70-ps pulse at 0.9 μm with an initial chirp of -10^{-2} ps^{-2} and 1 W of peak power can be reduced by a factor of $\cong 3$ after propagation through $\cong 1.8$ km of monomode silica fiber.

The propagation of an optical pulse in a single-mode fiber is described by the generalized nonlinear Schrödinger equation,[9]

$$i\partial E/\partial z = -i\alpha E/2 + (\beta_2/2)\partial^2 E/\partial t^2 + i(\beta_3/6)\partial^3 E/\partial t^3 - \Gamma|E|^2 E\,, \qquad (1)$$

where the mode-propagation constant $\beta(\omega) = n(\omega)\omega/c$ was expanded as $\beta(\omega) = \beta_0 + \beta_1(\omega - \omega_0) + \beta_2(\omega - \omega_0)^2 + \beta_3(\omega - \omega_0)^3$, ω_0 is the central frequency of the pulse, and $E = E(z,t)$ is the pulse envelope. Equation (1) was written in a reference frame moving with the pulse's group velocity $v_g = 1/\beta_1$ and includes the effects of second- and third-order dispersion (β_2 and β_3), fiber loss (α), and fiber nonlinearity ($\Gamma = n_2\omega_0/cA_{\rm eff}$, where n_2 is the Kerr coefficient and $A_{\rm eff}$ is the effective mode area).

Equation (1) was solved numerically by using the split-step fast-Fourier-transform method.[10] At the entrance of the fiber we assumed a chirped Gaussian pulse:

$$E(0,t) = E_0 \exp[(iC_0 - 1/T_0{}^2)t^2]\,, \qquad (2)$$

where C_0 is the chirp parameter.

In the numerical simulations, the parameters were chosen on the basis of the characteristics of pulsed gain-switched semiconductor lasers operating at a wavelength of 0.9 μm and a pulse width $T_{\rm FWHM} = \sqrt{2\ln 2}\,T_0 = 70$ ps. The chirp parameter was varied between -10^{-2} and $+10^{-2}$ rad/ps^2, and the peak power was varied between 0.1 and 1 W. The fiber parameters were chosen on the basis of realistic fused-silica single-mode fibers with $A_{\rm eff} = 12.6$ μm^2, $\beta_2 = 28.4$ ps^2/km, $\beta_3 = 2.82 \times 10^{-2}$ ps^3/km, and $\alpha = 5 \times 10^{-6}$ cm^{-1}. The spectral and temporal width were characterized using rms values.[9]

Figure 1 shows the rms spectral width of the pulse, normalized to the initial spectral width, for the cases of positive and negative initial chirp and various initial peak powers. The propagation distance in the fiber is normalized to the characteristic attenuation length $L_0 = 1/2\alpha = 1$ km.

For positive values of the initial chirp we observe, as expected, a monotonic spectral broadening with propagation due to SPM. However, when the initial chirp is negative we observe spectral narrowing instead of broadening. We also note a minimum in the spectral width that occurs near $z/L_0 \cong 1.8$ and that the spectral narrowing is accentuated as the peak power of the initial pulse is increased.

The spectral compression observed in Fig. 1 can be intuitively understood considering the process of SPM on the propagating pulse, which will have the frequencies of the leading edge downshifted and the frequencies of the trailing edge upshifted. Therefore, in the case of an initially downchirped pulse, both the trailing and leading edges of the pulse will experience a spectral shift in the direction of the central frequency. Note that the anomalous group-velocity dispersion tends to shorten the pulse duration, which increases the peak intensity and thus enhances the effect of SPM.

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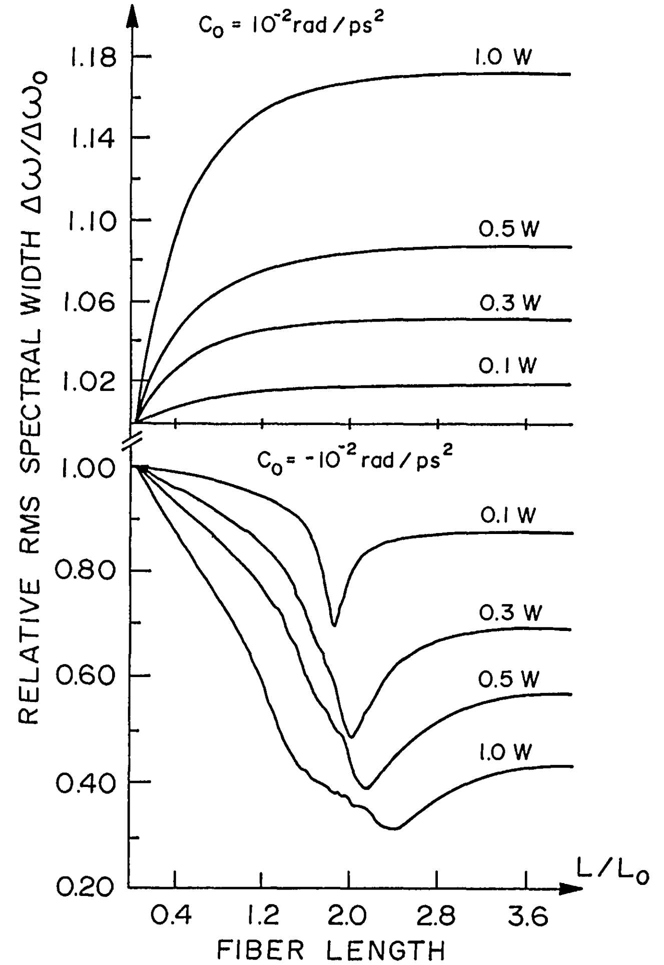

Fig. 1. Normalized spectral width (rms) of chirped pulses along the fiber for various initial peak powers. $L_0 = 1/2\alpha$.

Figure 2 shows the rms width (normalized to the initial pulse width) of the propagating pulse for initially positive and negative chirp parameters. In the case of positive chirp the pulse broadens monotonically during its propagation. On the other hand, for an initially downchirped pulse a minimum pulse duration is observed at almost the same position of the maximum spectral compression; after that point, the pulse assumes a positive value for the chirp, and the effect SPM is that of spectral broadening.

In order to understand these results further, let us introduce approximations that will allow analytical expressions. First, we neglect third-order dispersion (our numerical simulations proved this approximation excellent); second, consider a very small propagation distance where attenuation can be neglected ($z \ll L_0$); and third, we assume a weak nonlinearity. Before analyzing the effect of the (weak) SPM, let us write the expressions for the linear propagation case. In the absence of any nonlinearity, a chirped Gaussian pulse propagates in such a way that its pulse duration and chirp at a distance z are given by

$$T(z) = T_0\left[\frac{1 + C_0^2T_0^4(1 - z/z_0)^2}{1 + C_0^2T_0^4}\right]^{1/2}, \tag{3}$$

$$C(z) = C_0(1 - z/z_0)T_0^2/T^2(z), \tag{4}$$

where $z_0 = -C_0/2\beta_2(1/T_0^4 + C_0^2)$ is the position within the fiber where the pulse width is minimum and the chirp is zero. In the linear case the field of the propagating pulse is essentially given by Eq. (2) with T_0 and C_0 replaced by $T(z)$ and $C(z)$, respectively. Assume now that the nonlinearity is so weak that its effects can be considered as a small perturbation to the linear case. Thus we write

$$E(z,t) = E_0' \exp[(iC - 1/T^2)t^2 - i\Gamma|E|^2z], \tag{5}$$

where $E_0' = E_0(T_0/T)[(1 - iCT^2)/(1 - iC_0T_0^2)]^{1/2}$. Since the nonlinearity is stronger near the central part of the pulse, we approximate the Gaussian phase in Eq. (5) by a parabola:

$$\exp(-i\Gamma|E|^2z) \cong \exp\{-i\Gamma|E_0'^2|z[1 - 2t^2/T^2(z)]\}. \tag{6}$$

Relation (6) states that near the peak of the pulse, where most of the energy travels, the effect of SPM is that of introducing a linear chirp,

$$C_{\text{SPM}} = 2\Gamma|E_0'|^2z/T^2(z). \tag{7}$$

In this approximation the pulse is still Gaussian and its spectral width is

$$\Delta\omega(z) \cong \Delta\omega_0 \frac{T_0}{T} \frac{\sqrt{1 + C_{\text{tot}}^2T^4}}{\sqrt{1 + C_0^2T_0^4}}, \tag{8}$$

where $C_{\text{tot}} = C(z) + C_{\text{SPM}}(z)$ is the total chirp and $\Delta\omega_0 = \sqrt{1 + C_0^2T_0^4}/T_0$ is the initial pulse spectral

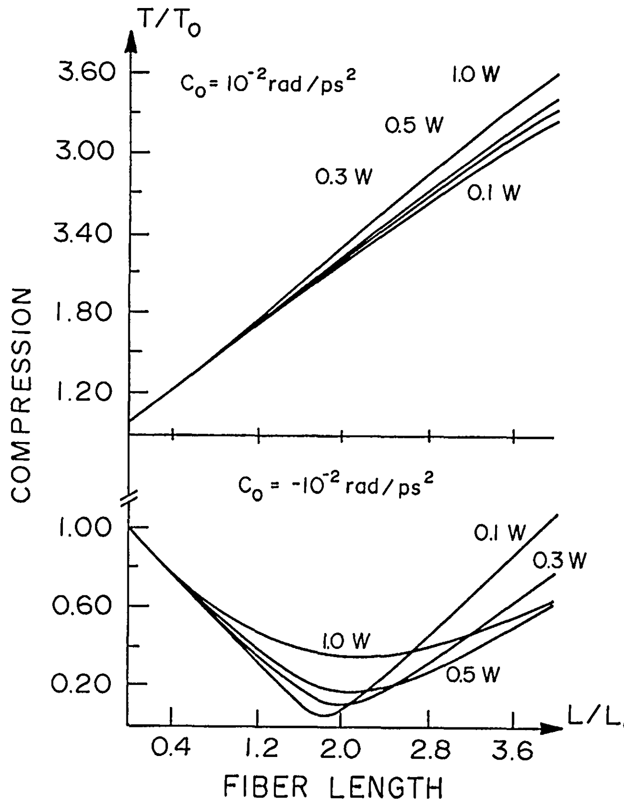

Fig. 2. Normalized pulse duration (rms) of chirped pulses along the fiber for various initial peak powers. $L_0 = 1/2\alpha$.

width. In order to see whether we have spectral broadening or narrowing, we can look at the sign of the first derivative of $\Delta\omega(z)$. From relations (4)–(8) we can compute this derivative as

$$\left.\frac{\partial \Delta\omega}{\partial z}\right|_{z=0} = 2\Delta\omega_0 \Gamma |E_0{}^2| C_0 T_0{}^2/(1 + C_0{}^2 T_0^4)\,. \qquad (9)$$

This equation shows that the spectrum narrows when C_0 is negative and that the initial rate of spectral narrowing is proportional to the input power. We also note that the initial rate of spectral narrowing is maximum for a chirp parameter $C_0 = -1/T_0{}^2$.

In conclusion, we studied the nonlinear propagation of chirped pulses through monomode fibers in the normal group-dispersion region. Initially downchirped pulses in realistic fibers may experience significant spectral narrowing owing to SPM at modest power levels. This effect should be observable with mode-locked Ti:sapphire or gain-switched semiconductor lasers and represents a limitation to (temporal) pulse compression schemes that use fibers.

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