Compensating for dispersion and the nonlinear Kerr effect without phase conjugation

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We propose the use of a dispersive medium with a negative nonlinear refractive-index coefficient as a way to compensate for the dispersion and the nonlinear effects resulting from pulse propagation in an optical fiber. The undoing of pulse interaction might allow for increased bit rates.

In 1979, Yariv *et al.*[1] suggested the use of phase conjugation as a way to compensate for dispersion in optical fibers. Fisher *et al.*[2] then showed that, under appropriate conditions (100% conversion of the signal), phase conjugation can also cancel out the influence of the nonlinear Kerr effect. The recent experimental confirmation[3–5] of the validity of these predictions has renewed the interest in phase conjugation and, simultaneously, has motivated the search for other compensation schemes.[6,7] In this Letter, we suggest such an alternative approach that circumvents the need of a phase-conjugate conversion of the signal. It is well known that in the linear regime one can compensate for the influence of chromatic dispersion in a first dispersive medium by propagating the output signal in a second medium of opposite dispersion parameter. The fulfillment of the condition $\beta_{22}L_2 = -\beta_{21}L_1$ (β_2 is the dispersion parameter; L is the medium length) ensures the pulse restoration at the output of the second medium. This technique is much simpler than phase conjugation, but it cannot compensate for the deleterious effect of nonlinear effects such as self-phase modulation. In the following, we simply propose the use of a dispersive medium with a negative nonlinear n_2 parameter for compensating for both the dispersive and the nonlinear effects of the first medium. Optical fibers are characterized by a positive n_2 coefficient, but other materials such as semiconductors can have a strong negative nonlinearity as well as a high dispersion parameter.[8] This implies that the effect of dispersion and the Kerr effect resulting from tens of kilometers of propagation in a fiber might, in principle, be canceled out after a short additional propagation of the signal in such a material.

The propagation of a light pulse under the influence of dispersion (β_2), self-phase modulation (n_2), and loss (α) is described, in the pulse reference frame ($\tau = t - z/\nu_{g1,2}$), by the lossy nonlinear Schrödinger equation[9]

$$\frac{\partial A_j}{\partial z_j} = -i\,\frac{\beta_{2j}}{2}\,\frac{\partial^2 A_j}{\partial \tau_j^2} - \frac{\alpha_j}{2}\,A_j + i\gamma_j|A_j|^2 A_j\,, \quad (1)$$

where $j = 1, 2$ refers to the medium of propagation. A_j represents the slowly varying envelope of the electric field, and $\gamma = (2\pi/\gamma)n_2/A_{\mathrm{eff}}$, where λ is the optical wavelength and A_{eff} is the effective core area. After propagating in the first medium, the pulse comes out distorted and attenuated. Except for a scaling factor, the attenuation does not affect the reshapping process in the linear regime. Things are different in the nonlinear regime, where amplification is required for the self-phase modulation effect incurred in the first medium to be compensated. With this in mind, the boundary condition at the entrance of the second medium ($j = 2$) should then read as $A_2(z_2 = 0, \tau) = qA_1(z_1 = L_1, \tau)$, where q represents the amplification (or attenuation) factor to be determined below. Notice the absence of phase conjugation in the boundary condition. The conditions that need to be satisfied to ensure ideal pulse reshaping at the output of the second medium can be derived after a suitable change of variables and a rescaling of the governing Eq. (1). We then introduce the new variables

$$\xi_1 = \frac{z_1}{L_1}\,, \qquad \xi_2 = \frac{L_2 - z_2}{L_2}\,, \quad (2a)$$

$$u_1 = \frac{A_1}{a_0}\,, \qquad u_2 = \frac{A_2}{qA_0}\,, \quad (2b)$$

where A_0 represents the peak amplitude at the output of the first medium: $A_0 \equiv \max\{|A_1(z_1 = L_1, \tau)|\}$. With these normalizations, the pulse propagation in the two media is now described by

$$\frac{\partial u_1}{\partial \xi_1} = -i\,\frac{\beta_{21}L_1}{2}\,\frac{\partial^2 u_1}{\partial \tau^2} - \frac{\alpha_1 L_1}{2}\,u_1 + i\gamma_1 L_1 A_0^2|u_1|^2 u_1, \quad (3a)$$

$$\frac{\partial u_2}{\partial \xi_2} = +i\,\frac{\beta_{22}L_2}{2}\,\frac{\partial^2 u_2}{\partial \tau^2} + \frac{\alpha_2 L_2}{2}\,u_2 - i\gamma_2 L_2 q^2 A_0^2|u_2|^2 u_2, \quad (3b)$$

with the boundary condition now written as

$$u_2(\xi_2 = 1,\, \tau) = u_1(\xi_1 = 1,\, \tau)\,. \quad (4)$$

By inspection, it is now easy to conclude, on the basis of Eqs. (3) and (4), that the input pulse shape

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can be recovered at the output of the second medium, i.e, $u_2(\xi_2 = 0, \tau) = u_1(\xi_1 = 0, \tau)$, provided that the following conditions are satisfied:

$$\beta_{22}L_2 = -\beta_{21}L_1\,, \tag{5a}$$

$$\alpha_2 L_2 = -\alpha_1 L_1\,, \tag{5b}$$

$$q = \left(\frac{\beta_{22}}{\beta_{21}}\frac{\gamma_1}{\gamma_2}\right)^{1/2}. \tag{5c}$$

The first condition is the same one that prevails in the linear regime, the second one implies a distributed amplification in the second medium (if the first medium is lossy), and the last one requires lumped amplification (or attenuation) of the signal between the two media to compensate for insufficient (or excessive) nonlinearity of the second medium as well as for unavoidable coupling losses. Returning to the original variables, Eq. (2b) implies that an attenuation by a factor $1/q$ at the output of the second medium would be necessary in the case in which the absolute amplitude must be restored. This would be the case, for example, for repetitive pulse reshaping as in a long-distance communication line, as discussed in the examples below. Semiconductor waveguides might be good candidates for such a compensation scheme. They have a strong negative nonlinearity [e.g., $n_2 \approx -2 \times 10^{-13}$ cm^2/W can be achieved with AlGaAs (Ref. 8)] further enhanced by a small effective core area. The dispersion parameter, although it is relatively high (e.g., $\beta_2 \approx 10^4$ ps^2/km), is too small for compensating for the dispersion with a waveguide only a few centimeters long. But this could be remedied by addition of a grating structure to the waveguide,[10] for example.

To demonstrate the recovery of the initial pulse shape with the proposed scheme and its potential interest for optical communication systems, we illustrate in Fig. 1 the long-distance evolution of two interacting in-phase super-Gaussian pulses, i.e., $A_1(z_1 = 0, \tau) = \sqrt{P_0}\exp\{-[(\tau - \Delta)/T_0]^6\} + \sqrt{P_0}\exp\{-[(\tau + \Delta)/T_0]^6\}$ (where P_0 is the peak power and $\Delta/T_0 = 1.2$ is small enough to enhance the interaction), along a communication line consisting of a periodic sequence of fiber segments (medium 1) of length L_1 spaced by linear ($n_{22} = 0$) waveguides (medium 2) of length L_2 compensating only for the dispersion. Condition (5a) is assumed to be satisfied with $L_2 \ll L_1$ when, for example, a chirped grating[10] is used as a dispersion compensator. An amplifier serves to reestablish the input energy before relaunching the signal into each fiber segment. The parameters are $\alpha_1 = 0.2$ dB/km, $L_1 = 20$ km, $\beta_{21} = -1$ ps^2/km, $T_0 = 15$ ps (implying a dispersion length L_{D_1} equal to 225 km), and $P_0 = 0.28$ mW. The simulation illustrates the gradual deformation of each pulse, which is due to the uncompensated spectral broadening in the fiber segments, followed by a strong interaction. In contrast, the input signal would be perfectly preserved if the ideal conditions [Eqs. (5)] were satisfied (not shown).

To see whether the compensation scheme proposed above could be made simpler, we replace the distributed amplification in the second medium by an increased lumped preamplification (i.e., $q' > q$). One can expect this approximation to be a good one as long as the medium length L_2 is much shorter than the dispersion length L_{D2}.[11,12] Figure 2 confirms that the system behaves quite well even under such nonideal conditions (here the ratio L_2/L_{D2} is equal to 0.089). The initial conditions and the fiber parameters are the same as in Fig. 1, and the waveguide characteristics are such that $q = 8.0$ (e.g., $L_2 = 5$ cm with a grating structure, $n_2 = -2.0 \times 10^{-13}$ cm^2/W, and $A_{\mathrm{eff}_2}/A_{\mathrm{eff}_1} = 0.1$). The lumped amplification approximation is adjusted so that $q' = 9.36$. In Fig. 2 the pulse shapes are only slightly distorted and the pulse widths are well preserved. More generally, the severity of the pulse distortion depends on the pulse shape itself as well as on parameters such as L_2/L_{D_2}, $\alpha_1 L_1$, q', P_0/P_S (P_s is the fundamental soliton peak power), Δ/T_0, and the total propagation length.

We now compare this approach with the so-called average-soliton scheme[11] (also called the guiding-center soliton[12]). The latter exploits the natural tendency

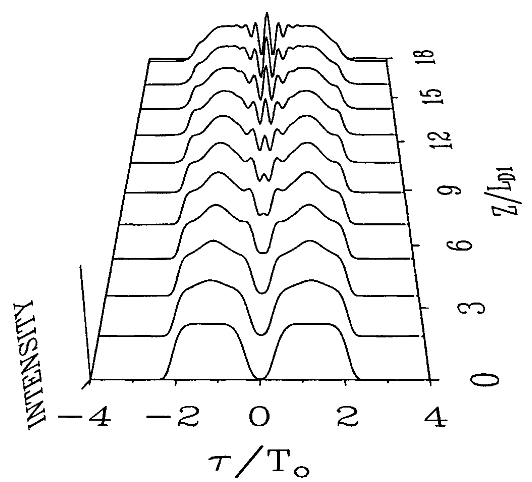

Fig. 1. Signal degradation along a communication line when only the dispersion is compensated for. The propagation distance is normalized to the dispersion length in the fiber.

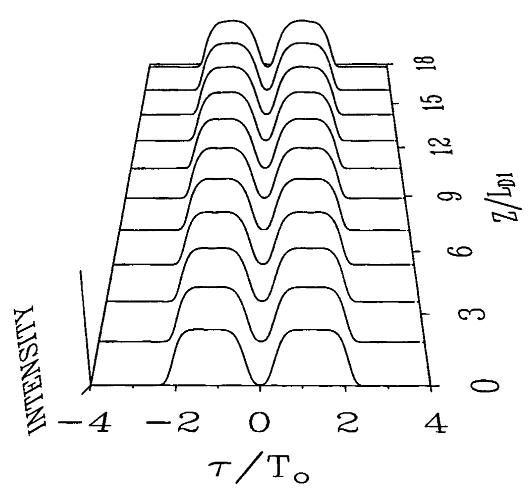

Fig. 2. Signal evolution with the proposed compensation scheme under nonideal conditions. Distributed amplification is replaced with an increased lumped amplification.

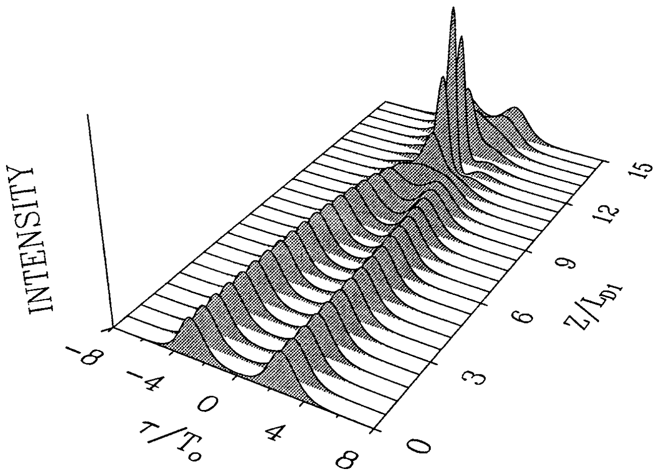

Fig. 3. Pulse interaction in a system based on the technique of the average soliton (without filtering).

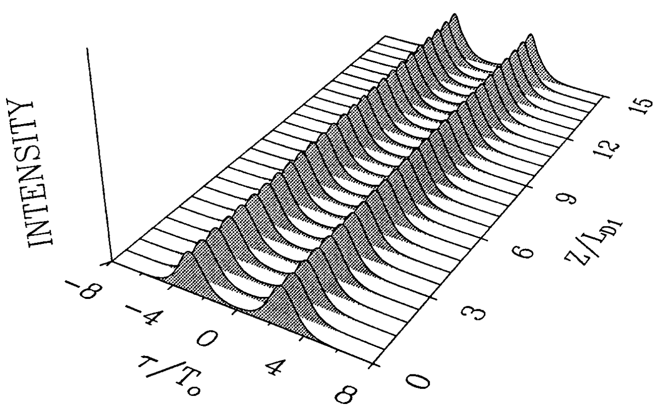

Fig. 4. Evolution of the same signal as in Fig. 3 with the compensation scheme based on a negative nonlinearity.

of the soliton, in the anomalous dispersion regime, to compensate by itself for the dispersion through an equilibrium with the nonlinear effect.[9] This is illustrated in Fig. 3, from which one can see that the system is primarily limited, ultimately, by the mutual interaction between two closely spaced solitons. The initial condition is $A_1\ (z_1 = 0,\ \tau) = \sqrt{P_0}\ \mathrm{sech}[(t - \Delta)/T_0] + \sqrt{P_0}\ \mathrm{sech}[(t + \Delta)/T_0]$, where $P_0 = 0.59$ mW, $T_0 = 20$ ps, and the delay $\Delta = 55$ ps has been chosen small enough to enhance the interaction. The value of the peak power is chosen according to the prescriptions from the average soliton theory.[11,12] The fiber segments are identical with the one considered above. This behavior should be compared with what could be achieved with the scheme suggested in this Letter. The correponding simulation is depicted in Fig. 4 with the same waveguide parameters as in Fig. 2, and again a lumped approximation is used for the amplification (with $q' = 10.1$). This result clearly demonstrates again the effectiveness of this system for undoing pulse interaction and then allowing for increased bit rates. In contrast to the average-soliton approach, with this method the degradation of each pulse, rather than the pulses' interaction, will set a limit on the system. A detailed comparison of the merits of each technique is, however, necessary before one can draw general conclusions. This, as well as an analysis of the effect of two-photon absorption and higher-order dispersion, is the subject of our continuing research.

In conclusion, we have shown that the use of a dispersive medium with a negative nonlinearity offers, in principle, an alternative way to compensate for fiber dispersion and nonlinear effects without the use of phase conjugation. Besides semiconductors, effective n_2 materials based on $\chi^{(2)}{:}\chi^{(2)}$ cascading[13] might be used for obtaining a negative nonlinearity. Experimental observation and engineering trade-off considerations will determine the practicality of the proposed compensation scheme.

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