Dispersion-tailored active-fiber solitons

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Received July 5, 1996

We show analytically that tailoring the fiber dispersion appropriately can cause optical solitons to propagate unperturbed, without emission of dispersive waves, in a distributed-gain fiber amplifier with a nonuniform gain profile. We apply our scheme to a bidirectionally pumped fiber amplifier and discuss the importance of higher-order nonlinear and dispersive effects for short solitons.

In most soliton communication systems, fiber loss is compensated for by periodic amplification of solitons with lumped amplifiers.[1] Because solitons experience fiber loss continuously but are amplified discretely all along the link, their stability is maintained only in the average-soliton regime,[2] in which the amplifier spacing is a small fraction of the soliton period. This requirement basically sets a lower limit of ~10 ps on the soliton width and consequently limits the bit rate to ~20 Gbits/s.[1] One way to operate the light-wave system beyond the average-soliton regime is to employ distributed gain within the transmission fiber itself. Recent experiments have used distributed amplification for fibers as long as 90 km.[3,4] Of course, if such a technique is used for long-haul systems, periodic pumping is necessary. Moreover, from a practical standpoint, the pump-station spacing should be more than 50 km. Unfortunately, for these lengths gain nonuniformities owing to pump absorption make it impossible to compensate exactly for the distributed, but constant, loss all along the amplifier, leading to perturbation of the solitons.

We propose to tailor the dispersion profile in distributed amplifiers in such a way that, in spite of the nonuniform distributed gain, unperturbed soliton propagation is guaranteed. Tailoring of the dispersion profile in passive fibers is a powerful technique to control nonlinear pulse propagation: loss-matched, exponentially dispersion-decreasing fibers have been shown to support short solitons.[5–7]

In this Letter we find analytically which dispersion profile for a given nonuniform gain distribution will result in perfect compensation of distributed loss and gain all along the fiber, so that solitons can propagate unperturbed over long distances. We illustrate this concept with bidirectionally pumped fiber amplifiers, allowing for asymmetric pumping from the two ends. We discuss the application of such distributed amplifiers to a real system by taking into account the higher-order effects of intrapulse Raman scattering and third-order dispersion (TOD) in numerical simulations.

We start with the general pulse-propagation equation, which, after both distributed gain and dispersion are allowed for, takes the form[1]

$$i\frac{\partial u}{\partial \xi} + \frac{1}{2}p(\xi)\frac{\partial^2 u}{\partial \tau^2} + |u|^2 u = \frac{i}{2}[g(\xi) - \alpha_s]u + \frac{i}{2}\left(\frac{T_2}{T_0}\right)^2 g(\xi)\frac{\partial^2 u}{\partial \tau^2} + \frac{1}{2}\left(\frac{T_2}{T_0}\right)\xi\frac{\mathrm{d}g}{\mathrm{d}\xi}\frac{\partial u}{\partial \tau} + \tau_R u\frac{\partial |u|^2}{\partial \tau} + \frac{i}{6}\frac{\beta_3{}^{\mathrm{eff}}(\xi)}{T_0|\beta_2(0)|}\frac{\partial^3 u}{\partial \tau^3}, \quad (1)$$

where $p(\xi) = |\beta_2(\xi)/\beta_2(0)|$ is the normalized group-velocity dispersion (GVD) profile, $g(\xi)$ is the distributed-gain profile, and α_s is the total signal loss coefficient that is due to absorption by both glass and dopants. The propagation distance is normalized to the dispersion length at the input end of the fiber amplifiers: $\xi = z/L_D(0)$, where $L_D(0) \equiv T_0{}^2/|\beta_2(0)|$. Further, τ is the time in the comoving reference frame, normalized to the characteristic pulse width T_0, that relates to the full width at half-maximum as $T_{\mathrm{FWHM}} = 1.763\ T_0$. For simplicity, we have assumed the gain spectrum to be homogeneously broadened with a dephasing time T_2 and to be at resonance with the optical carrier frequency. The second and third terms on the right-hand side of Eq. (1) account for gain dispersion and the effect of the gain distribution on the group velocity, respectively. The remaining two terms of Eq. (1) denote intrapulse Raman scattering and TOD. The TOD coefficient is position dependent because of the nonuniform gain profile: $\beta_3{}^{\mathrm{eff}}(\xi) = \beta_3 + 3g(\xi)T_2{}^3$.

First, we neglect all higher-order terms, i.e., the last four terms on the right-hand side of Eq. (1). This approximation is justified when the soliton width T_0 is larger than a few picoseconds and $|\beta_2|$ is not too small. We now show how to tailor the dispersion profile $p(\xi)$ such that it exactly balances with gain and loss, in spite of axial nonuniformities. For this purpose we introduce the new optical field v and propagation distance η (Ref. 8):

$$v \equiv \frac{u}{\sqrt{p}}, \qquad \eta \equiv \int_0^\xi p(\xi')\mathrm{d}\xi' \quad (2)$$

and rewrite Eq. (1) as

$$i\frac{\partial v}{\partial \eta} + \frac{1}{2}\frac{\partial^2 v}{\partial \tau^2} + |v|^2 v = i\left[\frac{g(\eta) - \alpha_s - \mathrm{d}p/\mathrm{d}\eta}{2p(\eta)}\right]v. \quad (3)$$

0146-9592/96/241978-03$10.00/0

When the right-hand side of this equation is equal to zero, i.e., in terms of the original variable ξ when

$$\frac{1}{p}\frac{\mathrm{d}p}{\mathrm{d}\xi} = g(\xi) - \alpha_s\,, \qquad (4)$$

Eq. (3) reduces to the ideal nonlinear Schrödinger equation.[1] Clearly, under such conditions solitons will propagate stably without emission of any dispersive waves. For a given signal loss α_s and a fixed gain profile $g(\xi)$, the dispersion profile of the fiber should be tailored as

$$p(\xi) = \exp\left\{\int_0^{\xi}[g(\xi') - \alpha_s]\mathrm{d}\xi'\right\}\cdot \qquad (5)$$

This equation is a generalization of the exponential profile of passive electronic data display fibers to active fibers and reduces to the case of electronic data display fibers when the fiber is unpumped, i.e., $g(\xi) = 0$.[7] Note that thus each pumping configuration of a distributed amplifier requires a different GVD profile to match the gain distribution.

A simple way to profile the GVD in a fiber is to concatenate pieces of fiber with different GVD's after approximating Eq. (5) with a piecewise-constant function. One can also fabricate a continuously varying GVD profile by altering the core diameter during manufacture. A change in core diameter, however, also affects both self-phase modulation and the signal loss owing to absorption by the glass host.[1] These changes are, however, often negligible when the dispersion profile $p(\xi)$ varies slowly with ξ. We note that soliton collisions are fully symmetric in the above configuration, unlike with lumped-amplifier systems, making dispersion-tailored active fibers compatible with wavelength-division multiplexing. Moreover, the average dispersion in our system is generally smaller than that of a loss-matched electronic data display fiber.

As an example, we consider a distributed amplifier that is bidirectionally pumped with a possibility of different pump powers at the two ends. Because of the pump loss α_p, resulting from absorption by both glass host and dopants, the gain profile along the amplifier length is nonuniform. If gain saturation is neglected, the gain profile can be written as[1]

$$g(\xi) = g_1\exp(-\alpha_p\xi) + g_2\exp[\alpha_p(\xi - L)]\,, \qquad (6)$$

where g_1 and g_2 are related to the pump powers at $\xi = 0$ and $\xi = L$, respectively. Applying Eq. (5) results in a fiber dispersion with the following profile:

$$\ln p(\xi) = \frac{g_1}{\alpha_p}[1 - \exp(-\alpha_p\xi)] + \frac{g_2}{\alpha_p}\exp(-\alpha_p L)[\exp(\alpha_p\xi) - 1] - \alpha_s\xi\,. \qquad (7)$$

When these amplifiers are used for long-haul communication it is convenient to equalize the dispersion at the two ends of the amplifier, i.e., $p(L_A) = p(0) \equiv 1$. Using Eqs. (6) and (7), we obtain the following condition for the strengths of the two pump beams:

$$g_1 + g_2 = \frac{\alpha_s\alpha_p L}{1 - \exp(-\alpha_p L)}\cdot \qquad (8)$$

Note that we still have the freedom to choose the relative strengths of the two pumps. For five different pump ratios g_1/g_2 we show the gain profiles in Fig. 1(a) and the corresponding dispersion profiles in Fig. 1(b). In all five cases we have taken the total signal loss to be $\alpha_p/L_{D0} = \alpha_s/L_{D0} = 0.62$ dB/km (0.4 dB/km owing to the dopants) and the total pump loss as $\alpha_p/L_{D0} = 0.315$ dB/km; these losses are extracted from the cross-section data for silicate L22 fiber.[9] Further, we take $\beta_2(0) = -0.5$ ps^2/km and $L = 60$ km. When the pump ratio is smaller than 1, i.e., when the pumping is stronger at the end of the distributed amplifier, the maximum dispersion approaches zero. In this situation TOD may become important on reduction of the pulse width. When the pump ratio is larger than 1 the average value of $|\beta_2|$ increases. Here intrapulse Raman scattering will eventually become important as the pulse width is reduced.

To estimate the importance of higher-order effects, we numerically solved Eq. (1) with the following simplifications. We neglected the position dependence of the TOD and used $\beta_3^{\mathrm{eff}}(\xi) \approx \beta_3 = 0.05$ ps^3/km. Gain dispersion introduces an energy loss into the system. However, because the spectral width of the solitons considered here is much smaller than the amplifier bandwidth (~30 nm for erbium-doped amplifiers), this energy loss will remain small and can be compensated for experimentally.[3,4] For similar reasons we neglect the effect of the gain distribution on the group velocity. The dephasing time is $T_2 = 100$ fs, and the Raman time is $T_R = 6$ fs.

In Fig. 2 we show the soliton evolution for three cases. In Fig. 2(a) a 4-ps soliton ($T_{\mathrm{FWHM}} = 4$ ps) propagates through a symmetrically pumped distributed amplifier ($g_1/g_2 = 1$). The peak power of the soliton follows almost exactly the dispersion profile $|\beta_2(z)|$ of Fig. 1, while its width remains constant. The Raman spectral shift is in this case negligible. In Fig. 2(b) the soliton width is reduced to 2 ps while

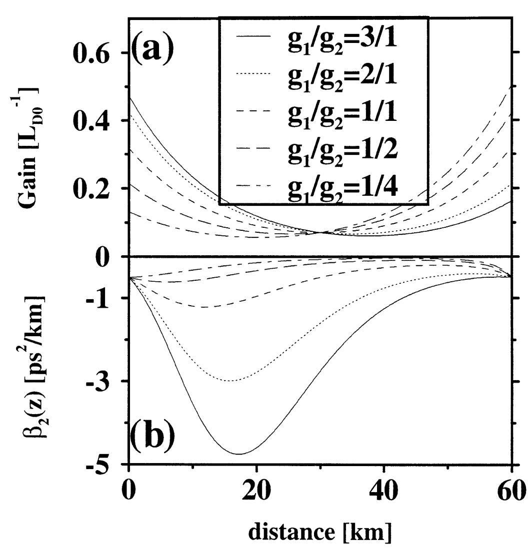

Fig. 1. (a) Gain and (b) dispersion profiles allowing for unperturbed soliton propagation for five different pump ratios g_1/g_2 as indicated.

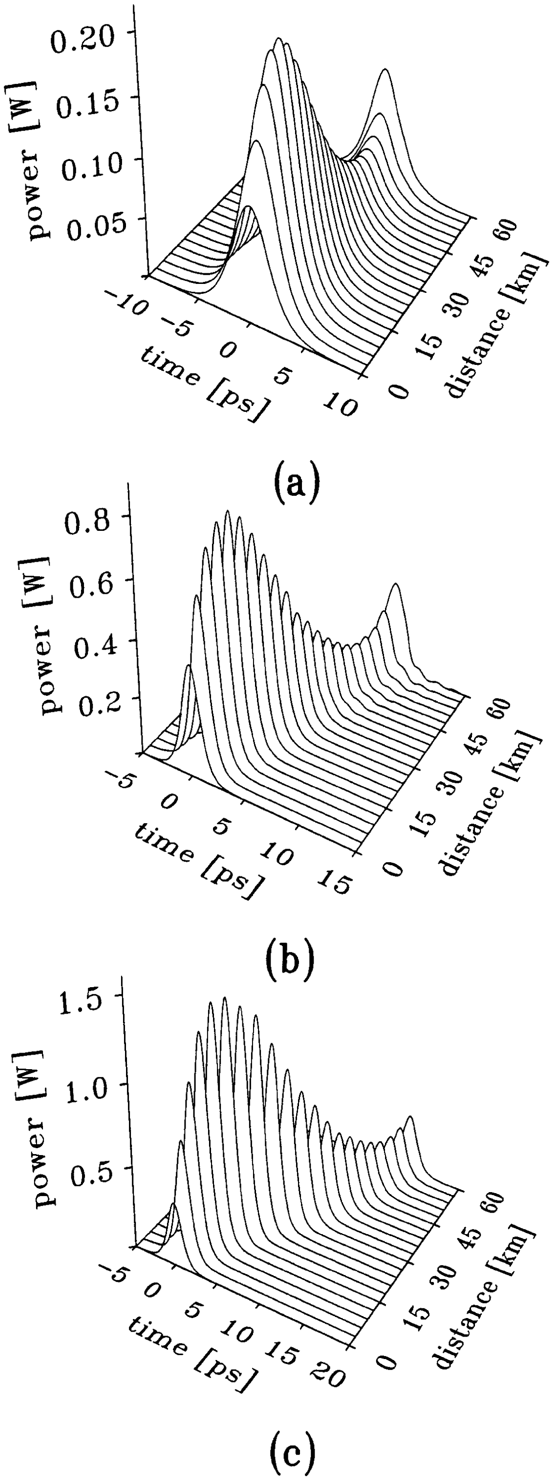

Fig. 2. Soliton evolution through a distributed fiber amplifier with appropriately tailored dispersion in three cases: (a) $T_{\mathrm{FWHM}} = 4$ ps, $g_1/g_2 = 1/1$; (b) $T_{\mathrm{FWHM}} = 2$ ps, $g_1/g_2 = 1/1$; (c) $T_{\mathrm{FWHM}} = 2$ ps, $g_1/g_2 = 2/1$. Other parameters are given in the text.

all other parameters are kept the same. The trailing oscillations, clearly visible from $\xi = 45$ km onward, are a clear sign that TOD is perturbing the soliton. After only one amplifier length, the FWMH of the pulse has increased 32%, whereas the peak power has decreased 18%, indicative of dispersive-wave emission. One way to suppress the effects of TOD is to change the asymmetry in the pump: Figure 2(c) shows again a 2-ps soliton, but now with pump ratio $g_1/g_2 = 2$, i.e., stronger pumping at the beginning of the fiber. The accompanying dispersion profile (see Fig. 1) has a higher value of the average dispersion than in the symmetric pumping case. Indeed, hardly any dispersive waves are emitted, as is indicated by the small reduction of the peak power (~2%) and a relatively small increase in the FWHM (~2.5%). The Raman spectral shift, however, in this case is 20% of the soliton spectral width (FWHM). This shift may be compensated for by insertion of optical filters at the pump stations. From our results we estimate the limit for unperturbed soliton propagation to be ~3 ps for a 60-km pump-station spacing. Note, however, that even below this limit solitonlike pulses can propagate over a few amplifier lengths.

In conclusion, we have shown how to tailor the dispersion profile in a fiber amplifier with nonuniform gain and loss in such a way that perfect soliton propagation is in principle possible. We have illustrated our design with the example of bidirectionally pumped distributed amplifiers and have shown that the higher-order effects are of little consequence for pulse widths down to $T_{\mathrm{FWHM}} \approx 3$ ps while $\langle \beta_2 \rangle \approx 1$ ps^2/km. It should be noted, however, that the amplifier length that allows for such short solitons is dependent on the type of fiber: larger absorption cross sections will decrease the practical amplifier length.[9] For narrower solitons the higher-order effects may become too strong to ensure unperturbed soliton operation.

This research is supported through funding by the Netherlands Organization for Scientific Research, the Fonds pour la Formation de Chercheurs et l'Aide à la Recherche of Québec (Canada), and the U.S. Army Research Office.

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