# Ultrahigh-bit-rate soliton communication systems using dispersion-decreasing fibers and parametric amplifiers

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Received August 31, 1995

We study analytically and numerically soliton communication links made by use of dispersion-decreasing fibers and parametric amplifiers. We show that bit rates greater than 100 Gbits/s (one channel, one polarization) can be achieved with large amplifier spacings (as high as 120 km). The Raman effect and soliton interactions are compensated through optical phase conjugation, whereas fiber losses and third-order dispersion are handled through tailoring of the dispersion profile of a dispersion-decreasing fiber. 

Soliton-based optical communication systems are attracting considerable attention because of their potential for significantly increasing the capacity of long-haul light-wave systems.[1,2] However, even though an ideal fundamental soliton is a robust wavepacket, its propagation through practical fibers can lead to serious limitations on the design of communication systems. Fiber loss is certainly the most harmful property, limiting the overall system performance in both linear and nonlinear regimes.[1] For soliton communication systems, the loss compensation can be achieved by insertion of amplifiers periodically along the link. This technique has been the subject of intense experimental and theoretical studies.[2,3] It makes use of the concept of guiding-center or average solitons. However, the conditions of applicability of this regime limit the soliton duration to approximately 10 ps in dispersion-shifted fibers. Reduction of soliton widths below this value, while maintaining practical amplifier spacings, leads to increasing emission of dispersive waves that are resonantly amplified periodically, undermining soliton stability.[4] Stable propagation in such a regime can be achieved only if narrow-band filters and fast saturable absorbers are inserted along the fiber link.[5]

An interesting approach to modifying the soliton propagation characteristics is to vary slowly (relative to the dispersion length) the group-velocity dispersion (GVD) along the fiber length. Such dispersion-varying fibers have been fabricated with various GVD profiles by tapering the core of the optical fiber[6] and used for purposes such as soliton compression and soliton train generation. For communication applications, one can compensate for the decrease of self-phase modulation that is due to fiber losses by exponentially decreasing the GVD at the same rate as the energy loss. In such exponentially decreasing dispersion fibers (EDDF's), a fundamental soliton propagates without changes in its width even if the soliton loses a large fraction of its energy during propagation.[7,8] In principle, if the soliton energy at the end of one EDDF is restored to the original level before the next EDDF, an ideal soliton will propagate throughout the entire fiber link without a lower limit on the soliton duration imposed by the periodic amplification scheme. However, as the soliton width decreases, higher-order nonlinear and dispersive effects become important and ultimately limit the bit rate. The most important higher-order nonlinear effect affecting solitons is intrapulse Raman scattering.[9,10] In this Letter we study how stable transmission of ultrashort solitons (<3 ps) in dispersion-decreasing fibers can be achieved in the presence of the Raman effect and third-order dispersion.

The propagation of short pulses through a fiber with axially varying dispersion is described by a generalized nonlinear Schrödinger equation

$$\frac{\partial u}{\partial z} + \frac{i}{2}\beta_2(z)\frac{\partial^2 u}{\partial t^2} - i|u|^2 u = -\frac{\alpha}{2}u - iT_R u\frac{\partial |u|^2}{\partial t} + \frac{1}{6}\beta_3\frac{\partial^3 u}{\partial t^3}, \quad (1)$$

where standard notation has been used[9] and $\beta_2(z)$ is the GVD varying as $\beta_2(0)\exp(-\alpha z)$, with $\beta_2(0)$ the GVD at the input end of the EDDF. Other parameters are $\alpha = 0.21$ dB/km, $T_R = 6$ fs, and $\beta_3 = 0.05$ ps$^3$/km. In the absence of the Raman term ($T_R = 0$) and the third-order dispersion ($\beta_3 = 0$), one can show that Eq. (1) supports solitons in an EDDF.[7,8] However, for sufficiently short solitons, the Raman term downshifts the soliton mean frequency. Large drifts of the soliton mean frequency can change the conditions of propagation by changing the GVD locally. The sliding rate of the soliton mean frequency $\nu_m(z)$ associated with the Raman effect is given by $\mathrm{d}\nu_m(z)/\mathrm{d}z = -4T_R|\beta_2(z)|/(15\pi {T_s}^4)$,[10] with the soliton width $T_{\mathrm{FWHM}} = 1.763T_s$. For an EDDF of length $L_A$ the shift of the soliton mean frequency relative to the carrier frequency is given by

$$\nu_m(z) = -\frac{4}{15\pi}\frac{T_R}{{T_s}^4}|\beta_2^{\min}|\exp(\alpha L_A)\frac{[1-\exp(-\alpha z)]}{\alpha}, \quad (2)$$

where $\beta_2^{\min}$ is the GVD at the EDDF end and $L_A$ is the amplifier spacing. The change in GVD associated with this frequency shift is given by $\Delta\beta_2(z) = 2\pi\beta_3\nu_m(z)$. As short solitons propagate along an EDDF they experience lower dispersion because $\Delta\beta_2(z)$ is negative for positive values of

0146-9592/96/020116-03$6.00/0 

$\beta_3$. Since the balance between the GVD and the Kerr effect is compromised, solitons become corrupted, leading to pulse distortions.

How can one compensate for the effects of soliton self-frequency shift that invariably occur for ultrashort solitons ($T_s < 3$ ps)? In this Letter we propose tailoring the GVD profile of the fiber in such a way that the balance between the GVD and the self-phase modulation is approximately maintained locally at all points between two amplifiers. Such a balance is system dependent by necessity since the frequency shift in Eq. (2) depends both on the bit rate (through $T_s$) and on the amplifier spacing. The optimum profile is given by $\beta_2^{\text{opt}}(z) = \beta_2(z) - 2\pi\beta_3\nu_m(z)$ and, with Eq. (2), can be written as

$$\beta_2^{\text{opt}}(z) = \beta_2^{\min} \exp[\alpha(L_A - z)] + \beta_3 \frac{8}{15}\frac{T_R}{{T_s}^4}|\beta_2^{\min}| \times \exp(\alpha L_A)\frac{[1 - \exp(-\alpha z)]}{\alpha}. \tag{3}$$

Figure 1 shows the optimum GVD profile for several soliton widths with $\beta_2^{\min} = -0.1$ ps$^2$/km and $L_A = 100$ km. Note the rapidly increasing difference in the optimum GVD profiles for picosecond and subpicosecond solitons. For solitons wider than 2 ps the last term in Eq. (3) is negligible, and one can use EDDF's. However, for shorter solitons, the optimum GVD profile should be designed according to Eq. (3). Interestingly, for subpicosecond solitons the fiber must have a positive dispersion along most of its length at the frequency of the input signal. However, as mentioned above, the shift of the soliton mean frequency can be so large that solitons always experience anomalous GVD appropriate to its peak power.

So far we have discussed how a soliton can be maintained during one stage of amplification. In long-haul communication links solitons propagate over many amplification stages. If no form of soliton control is applied between two amplifiers, the Raman-induced frequency shift will accumulate over multiple stages and put great constraints on the design of the optical fibers making up the link. In this case, because the frequency shift is large, each fiber would need to be designed to have a specific GVD profile for a specific input wavelength. However, these constraints can be overcome if one makes use of parametric amplifiers.

An ideal parametric amplifier converts an input electromagnetic field $E(t)\exp(-i\omega t)$ to $\eta E^*(t)\exp[-i(2\omega_p - \omega)t]$, where $\omega_p$ is the frequency of the pump of the parametric amplifier and $\eta$ is the efficiency of the four-wave mixing process [one can counteract low conversion efficiencies by inserting an additional (erbium-doped fiber) amplifier just after the parametric amplifier]. It has been shown[11,12] that such amplifiers can compensate exactly the Raman-induced frequency shift over two identical amplification stages because of midway optical phase conjugation. Parametric amplifiers have recently been realized (within an optical fiber) in the context of dispersion compensation.[13] For small frequency shifts, parametric amplifiers can be pumped at the carrier frequency of the input signal, and EDDF's can be used without introducing distortions. However, if the bit rate needs to be increased further by a decrease in the soliton duration, the pump frequency $\omega_p$ must be set halfway between the soliton input and output frequencies to ensure the recovery of the proper frequency at the next fiber input. Moreover, the conjugation of a soliton train strongly reduces interaction among solitons by inverting their relative motion. As long as the distance of periodic collapse $\xi_p$ (corresponding to twice the distance at which a pair of solitons would collide) is much larger than the total fiber span, no significant soliton interaction will take place because interactions occurring over one span will be reversed in the next one.

We can now evaluate the maximum bit rates achievable in communication links made by use of dispersion-varying fibers and parametric amplifiers. With the total frequency shift fixed at $\Delta\nu(L_A)$ so that the GVD change $\Delta\beta_2$ over one amplifier spacing is fixed and with Eq. (2) at $z = L_A$, the normalized soliton width $T_s$ is given by

$$T_s = \left[\frac{8}{15}T_R|\beta_2^{\min}|\exp(\alpha L_A)L_{\text{eff}}\frac{\beta_3}{\Delta\beta_2}\right]^{1/4}, \tag{4}$$

where $L_{\text{eff}} = [\exp(\alpha L_A) - 1]/\alpha$. The maximal bit rate $B$ is then given by[1]

$$B = \frac{1}{2q_0T_s} = \frac{1}{2T_s\ \ln[2r|\beta_2^{\min}|L_{\text{eff}}/(\pi {T_s}^2)]}, \tag{5}$$

where $2q_0T_s$ is the bit slot and $r$ is the ratio of the collapse distance to the amplifier spacing $L_A$. We set $r = 4$ to ensure that the soliton interaction is small over one amplifier spacing and remains small over transoceanic distances because of the periodic optical phase conjugation.

Figure 2(a) shows the limiting bit rates for three different values of $\beta_2^{\min}$ when $\Delta\beta_2 = -0.02$ ps$^2$/km is relatively small, allowing the use of EDDF's without introducing significant distortions. For such a design,

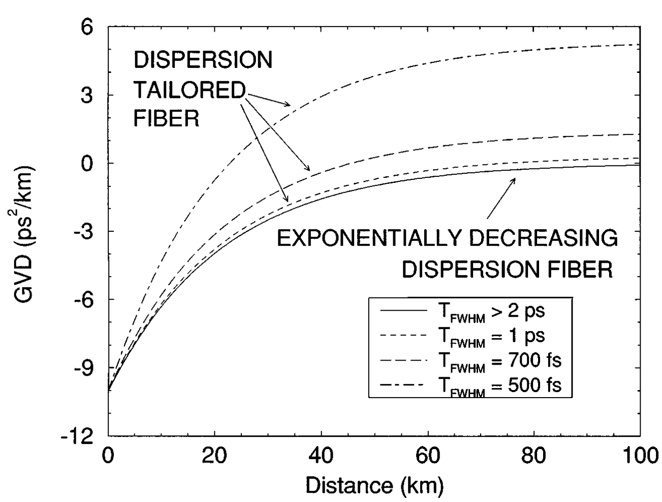


Fig. 1. Optimum GVD profiles for several soliton durations in a 100-km fiber for $\beta_2^{\min} = -0.1$ ps$^2$/km and $\beta_3 = 0.05$ ps$^3$/km. An exponential profile can be used for soliton widths of >2 ps.

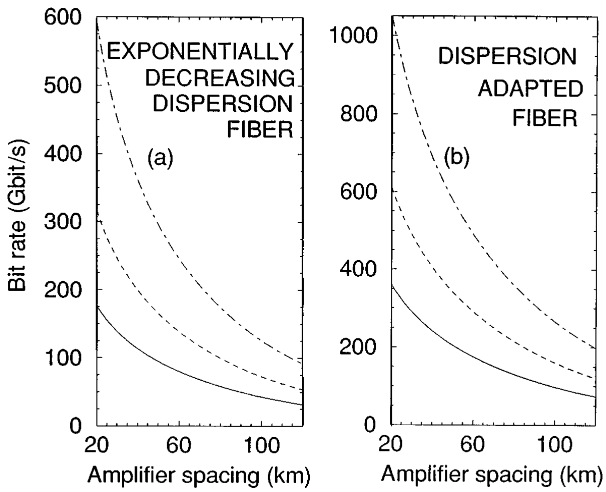


Fig. 2. Limiting bit rates as a function of amplifier spacing for transoceanic fiber links for (a) an EDDF and (b) a dispersion-tailored fiber. The solid, dashed, and dotted–dashed curves are for $\beta_2^{\min} = -0.5$, $-0.1$, and $-0.02\ \mathrm{ps^2/km}$, respectively.

soliton durations range from 2.7 to 1.2 ps for bit rates of 40 to 125 Gbits/s when $L_A = 100$ km. Higher bit rates ranging from 120 to 350 Gbits/s can be achieved when $L_A = 40$ km by use of solitons of widths 0.6–1.3 ps. It is worth noticing that large amplifier spacings require relatively high GVD at the input fiber end. High GVD increases the Raman-induced frequency shift and forces the use of broader solitons to limit the frequency shift to an acceptable value. This behavior results in lower bit rates for large amplifier spacings.

In Fig. 2(b) we show the limiting bit rates when the solitons are allowed to shift considerably such that the GVD is reduced by 1.57 $\mathrm{ps^2/km}$ at the end of every span. To ensure the appropriate conditions for soliton propagation, the fiber GVD profile must be adapted following Eq. (3). Note that Eq. (2) remains valid since the effective GVD, as experienced by the soliton, is still exponentially decreasing. For such a fiber design, bit rates are nearly the double of the values of Fig. 2(a). This increase is a direct consequence of allowing larger frequency shifts.

Extensive numerical simulations for bit rates in the range 50–150 Gbits/s and amplifier spacings of 50–100 km show generally good agreement with analytical predictions. However, for low values of $|\beta_2^{\min}|$ ($< 0.2\ \mathrm{ps^2/km}$) and for very short solitons ($T_s <$ 800 fs) dispersive waves are continuously generated and eventually lead to the destruction of solitons after typically a few thousand kilometers. One can explain this by noting that, for these very high-bit-rate systems, at a given point in the fiber the GVD is varying considerably over the soliton spectral width (because of the third-order dispersion), resulting in a perturbation of the soliton. Insertion of fast saturable absorbers after the amplifiers is likely to permit stable propagation over transoceanic distances by damping the dispersive waves. Numerical simulations have shown that the use of dispersion-flattened fibers can also prevent generation of dispersive waves by lowering the third-order dispersion.

In our analysis, we have neglected amplifier noise and considered ideal optical phase conjugation and the exact GVD profile for the dispersion-adapted fiber. The effects of the noise are expected to be strongly reduced by the optical phase conjugation,[14] whereas the effects of nonideal conjugations and nonideal GVD profile still remain to be investigated.

In conclusion, we have shown that the use of dispersion-decreasing fibers combined with parametric amplifiers (which periodically phase conjugate the signal) can increase the capacity of soliton communication links by approximately 1 order of magnitude. The frequency shift that is due to the intrapulse Raman scattering is compensated by parametric amplifiers. For relatively low bit rates (<100 Gbits/s) one can use EDDF's. However, for very high bit rates (>100 Gbits/s) the dispersion profile of the dispersion-decreasing fiber should be tailored to provide the appropriate dispersion to the soliton.

This research was supported by the Fonds pour la Formation de Chercheurs et l'Aide à la Recherche of the Quebec Government (Canada) and by the U.S. Army Research Office.

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