High-Bit-Rate Soliton Transmission Using Distributed Amplification and Dispersion Management

Zhi M. Liao and Govind P. Agrawal, *Fellow, IEEE*

***Abstract*—We show through numerical simulations that the use of distributed amplification together with dispersion management can permit single-channel speeds of 40 Gb/s over transoceanic distances while maintaining 100-km spacing between pumping stations. We achieve this performance by using a bidirectional pumping scheme and optimizing the dopant density such that the peak-power variations over each fiber span remain below 0.4 dB. The required pump power is less than 80 mW for a dopant density of 200 ions/μm^3.**

***Index Terms*—Nonlinear optics, optical fiber amplifiers, optical fiber communication, optical fiber dispersion, optical solitons.**

SOLITON COMMUNICATION systems are a leading candidate for long-haul lightwave transmission links because they offer the possibility of dynamic balance between group-velocity dispersion (GVD) and self-phase modulation (SPM), the two effects that severely limit the performance of non-soliton systems [1]. Most system experiments employ the technique of lumped amplification and place fiber amplifiers periodically along the transmission line for compensating the fiber loss. However, lumped amplification introduces large peak-power variations, which limit the amplifier spacing L_A to a fraction of the dispersion length L_D [1].

The limitation on the amplifier spacing imposed by lumped amplification can be overcome by using distributed amplification [2]. In this scheme [3], [4], the transmission fiber is lightly doped with erbium ions and is pumped periodically, creating sufficient gain for compensating the fiber loss. Since the gain is distributed throughout the fiber link and compensates the fiber loss locally all along the fiber, soliton peak-power variations can be made much smaller compared with the lumped amplification scheme. Although one expects the pump-station spacing L_A to become comparable and even exceed L_D in the case of distributed amplification, a systematic comparison of the lumped and distributed amplification schemes is not available in the literature. Furthermore, shorter pulses needed at high bit rates are affected considerably by stimulated Raman scattering (SRS), therefore the inclusion of SRS is essential in modeling high-bit-rate systems [5].

In this letter, we report the results of a systematic study and show that distributed amplification provides much better performance compared with the lumped amplifiers at high bit rates. We also show how dispersion management [6], [7] can be used to suppress the SRS-induced soliton self-frequency shift (SSFS) in high-bit-rate systems.

Our approach is based on solving numerically the following generalized nonlinear Schrödinger equation [1]

$$i\frac{\partial A}{\partial z} - \frac{1}{2}\,\beta_2(z)\frac{\partial^2}{\partial t^2} + \gamma|A|^2A = \frac{i}{2}\,[g(z)-\alpha]A + \tau_R A\frac{\partial|A|^2}{\partial t} \tag{1}$$

where β_2 is the GVD parameter, γ is the nonlinear parameter responsible for SPM, α accounts for the fiber loss, and τ_R is the SRS coefficient. Distributed amplification of solitons is included through the gain $g(z)$. To avoid excessive generation of dispersive waves, we optimize the the system design (i.e., dopant density) such that the net gain/loss, $g(z)-\alpha$, deviates from zero as little as possible. For wavelength-division-multiplexed (WDM) applications, it may be difficult to satisfy this requirement for all channels (unless gain spectrum is flattened by using suitable co-dopants). To this end, we solved the three-level rate equations [8] for erbium dopants for the case of bidirectional pumping at 1480 nm and included the saturation of gain with the pump power. We used the split-step Fourier-transform method [5] to compare soliton transmission for lumped and distributed amplification schemes.

We first demonstrate the advantages offered by distributed amplification for a 20 Gb/s system having 100-km pump-station spacing, uniform dispersion with $\beta_2 = -0.5$ ps^2/km, $\gamma = 3.36$ W^{-1}/km, $\tau_R = 3$ fs and $\alpha = 0.23$ dB/km at the operating wavelength near 1.55 μm. The soliton width should be a fraction of the 50-ps bit slot. We choose the input field $A(0,t) = \sqrt{P_0}\ \mathrm{sech}\ (t/T_0)$ with $T_0 = 5$ ps ($T_{\mathrm{FWHM}} = 8.8$ ps). The peak power P_0 corresponds to $N = 1$, where $N = (\gamma P_0 T_0^2/|\beta_2|)^{1/2}$ in the case of distributed amplification and $N = 2.307$ in the lumped amplification case as required in the average-soliton regime [1]. The dispersion length $L_D = T_0^2/|\beta_2|$ is 50 km for such a system, and $L_A = 100$ km is chosen for both cases.

Fig. 1(a) shows soliton evolution for the case of lumped amplification. Since $L_A/L_D = 2$, the soliton develops significant dispersive waves after only three amplifiers and is distorted significantly after six amplification stages. Such a system

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The authors are with the Institute of Optics and Rochester Theory Center for Optical Sciences and Engineering, University of Rochester, Rochester, New York 14627 USA.

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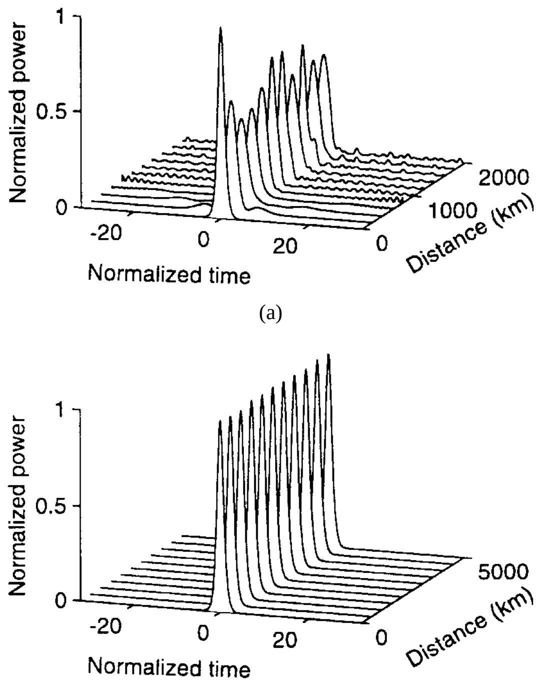


(a)

(b)

Fig. 1. Comparison of (a) lumped and (b) distributed amplification schemes for the case of a 20-Gb/s system designed with 100-km amplifier spacing. Soliton width is 8.8 ps in both cases.

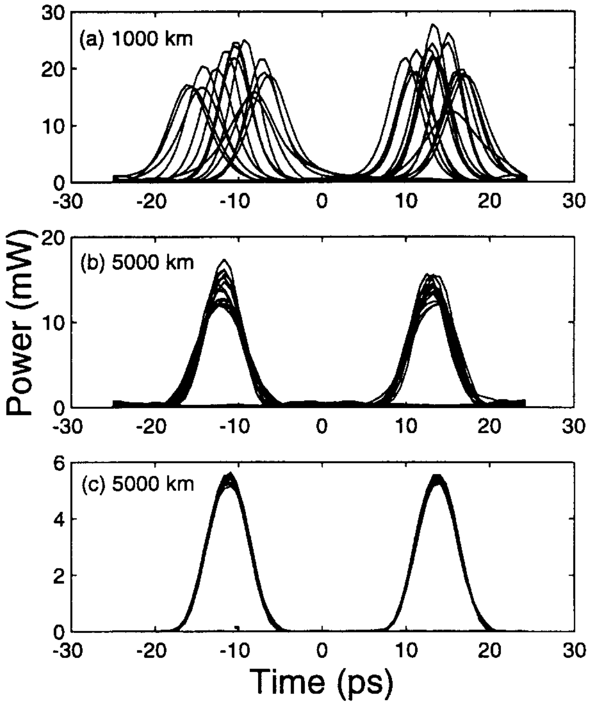
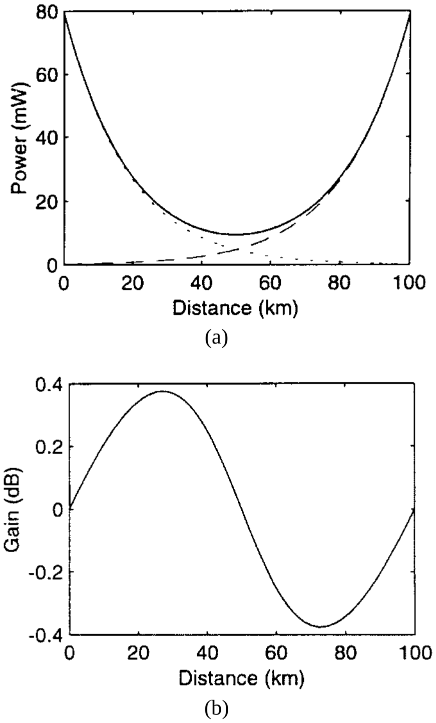


Fig. 2. Two-bit-wide eye diagrams for a 40-Gb/s system in three different operating conditions. (a) after 1000 km without DM. (b) After 5000 km with lumped amplification and DM. (c) After 5000 km with distributed amplification and DM. See text for details.

cannot transmit the 20-Gb/s signal over more than 600 km. Fig. 1(b) shows soliton evolution over 5000 km under identical operating conditions except for distributed amplification, with no visible sign of degradation. The optimum dopant density is found to be only 200 ions/μm^3 when the fiber is bidirectionally pumped using equal pump powers of 79 mW at both ends. A logarithmic plot of the pulse power shows the contribution of residual dispersive waves to remain below the 10^{-5} level even after 5000 km. Simulation of a pseudorandom bit sequence (PRBS) have found little degradation due to soliton interaction because of the large spacing (50 ps) used between the 8.8-ps solitons.

For a bit rate of 40 Gb/s, it was necessary to use a pulsewidth of only 2.5 ps ($T_{\rm FWHM} = 4.4$ ps). Using the same design parameters as for the 20-Gb/s distributed amplification system, the dispersion length is calculated to be only 12.5 km. To account for soliton interaction, we use a 64-bit PRBS in numerical simulations. The two-bit-wide "eye diagram" (unfiltered) displayed in Fig. 2(a) shows the combined effects of SSFS and soliton interaction on the pulse train at a distance of 1000 km. Clearly such a system is inoperable in practice. We have found that both the SSFS and the soliton interaction problems can be solved by combining distributed amplification with dispersion management. Fig. 2(c) shows the eye diagram after 5000 km for a dispersion-managed (DM) system under identical operating conditions. The dispersion map consisted of two 50-km fibers with $\beta_{21} = 0.3$ ps^2/km and $\beta_{22} = -0.38$ ps^2/km, resulting in an average dispersion of -0.04 ps^2/km and a map strength $|\beta_{21}L_1 - \beta_{22}L_2|/T^2_{\rm FWHM} = 1.75$ [9]. As evident in Fig. 2(c), solitons barely move out of their time slot when distributed amplification is used with DM. We also studied the case of lumped amplifiers with DM [10] and found that both SSFS and soliton interaction are reduced in this case as well [Fig. 2(b)] although the system performance is better in the case of distributed amplification [Fig. 2(c)].



(a)

(b)

Fig. 3. (a) Pump power variations over each 100-km section; dotted, dashed, and solid lines represent forward, backward and total pump powers. (b) Net signal gain indicative of soliton-energy variations over the 100-km section.

The most important criterion for designing soliton systems with distributed amplification is to ensure that peak power varies as little as possible over each fiber span. Fig. 3 shows the variation of pump power and the net signal gain defined as $G(z) = \exp(\int_0^z g(z)dz - \alpha z)$ over one fiber span for the results shown in Figs. 1(b) and 2. Since $G(z) < 0.4$ dB, the soliton peak power varies less than 10%, compared with more than 20-dB variation occurring for lumped amplification. In general, peak-power variations become smaller as dopant density is reduced, but at the same time, required pump power increases [3]. In practice, one must choose the dopant density as small as possible for a given amount of pump power.

In conclusion, we have shown that distributed amplification without dispersion management can permit single-channel speeds of 20 Gb/s over transoceanic distances while maintaining 100-km spacing between pumping stations. Higher bit rates require a smaller soliton width, which limits the transmission distance because of the SRS-induced SSFS and soliton interactions. We show that the use of dispersion management in combination with distributed amplification can overcome the effects of SSFS and soliton interaction and permits single-channel speeds of 40-Gb/s over transoceanic distances while maintaining 100-km spacing between pumping stations, provided the system performance is not limited by other effects such as polarization-mode dispersion. Noise issues must also be addressed before such systems become a practical reality. Noise is not expected to be a limiting factor on physical grounds since distributed amplification is the limiting case of closely spaced lumped amplifiers. A detailed analysis is beyond the scope of this letter.

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