Effect of Distributed Raman Amplification on Timing Jitter in Dispersion-Managed Lightwave Systems

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***Abstract*—It is shown that the timing jitter of dispersion-managed soliton systems can be reduced by up to 40% by using a hybrid amplification scheme in which fiber losses are compensated by using erbium-doped fiber amplifiers in combination with backward pumped Raman gain. The jitter is smallest in the case of 100% Raman amplification, but considerable reduction occurs even for partial distributed amplification.**

***Index Terms*—Dispersion management, distributed amplifiers, jitter, nonlinear optics, optical fiber communication, optical solitons.**

DISTRIBUTED RAMAN AMPLIFICATION (DRA) has attracted considerable attention recently as its use improves the signal-to-noise (SNR) ratio, or the Q factor, in periodically amplified dispersion-managed lightwave systems [1]–[4]. In this letter, we show that DRA also helps to reduce the Gordon–Haus timing jitter [5], [6] in such systems. The combination of high SNR and reduced timing jitter makes the DRA scheme very attractive for designing high-speed lightwave systems operating at 40 Gb/s or more.

Optical pulse propagation inside lightwave systems is governed by the nonlinear Schrödinger equation

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

where the dispersion parameter β_2, the nonlinear parameter γ, the distributed gain g, and fiber loss α all vary with z for dispersion-managed lightwave systems. We consider the general case in which the coded pulse train is amplified periodically using a module consisting of a lumped fiber amplifier and a Raman-pump laser injected backward into the fiber to provide the DRA. In this hybrid scheme, total fiber losses $G_{\rm tot}$ are compensated using the combination of lumped and Raman amplification such that $G_R + G_L = G_{tot}$, or equivalently

$$\exp\left(\int_0^{L_A} g(z)\,dz\right) + G_L = \exp\left(\int_0^{L_A} \alpha(z)\,dz\right) \tag{2}$$

where G_R is the Raman gain, G_L is the gain of lumped amplifier, and L_A is the amplifier spacing.

We use the formalism of reference [6] for calculating the timing jitter except for using the Gaussian approximation for the pulse shape

$$A(z,t) = A_0 \exp\left[-\frac{(1+iC)}{2T_0^2}\,(t-t_p)^2 - i\Omega(t-t_p) + i\varphi\right] \tag{3}$$

where the pulse amplitude A_0, width T_0, chirp C, position t_p, frequency shift Ω, and phase φ all depend on z and are found by using the variational method [7]. We have verified that the use of a Gaussian shape, in place of the numerically calculated pulse shape, provides an analytic expression for the timing jitter that is accurate to within a few percent of the actual value.

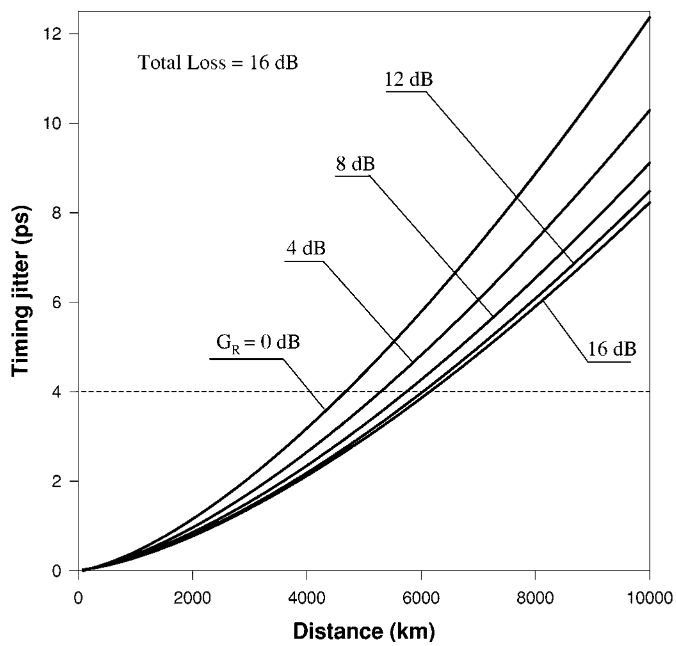

Fig. 1. Timing jitter after each amplifier as a function of transmission distance for several values of Raman gain. Losses are 16 dB over 80 km of amplifier spacing.

Fig. 1 shows timing jitter after each amplifier as a function of transmission distance for several values of the Raman gain for a 40-Gb/s lightwave system designed with 80-km amplifier spacing. The dispersion map has eight periods within each amplifier spacing (dense dispersion management). Each map period consists of two 5-km fiber sections, with dispersion parameters β_2 of 3.9 and -4.1 ps^2/km, respectively. Fiber loss α for both types of fibers is 0.2 dB/km, while $\gamma = 2.5$ W$^{-1}\cdot$km^{-1}. The input pulse parameters (width T_0, chirp C, and energy E_0) are obtained by solving numerically the variational equations [7]. The minimum value of T_0 is kept fixed at 3.39 ps (full-width at half-maximum 5.65 ps) in all cases. In the case of pure lumped amplification, ($G_R = 0$) the input parameters are $T_0 = 4.897$

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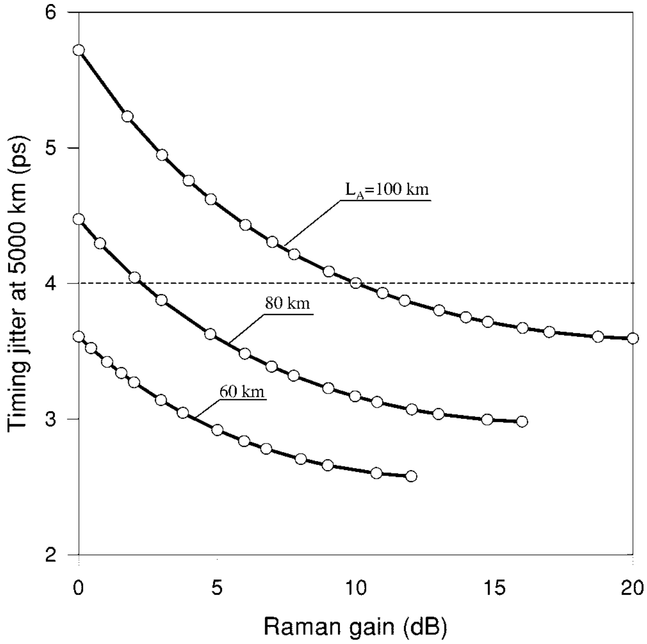

Fig. 2. Timing jitter after 5000 km as a function of Raman gain for amplifier spacings of 60, 80, and 100 km.

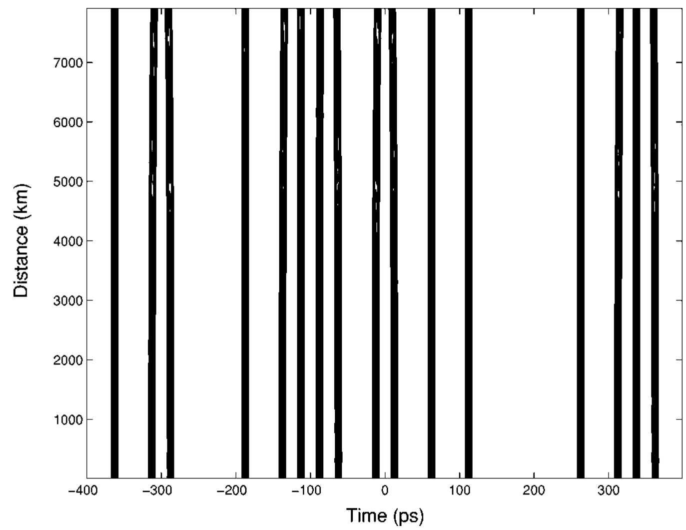

Fig. 3. Contour map of the bit sequence over 8000 km for the 40-Gb/s system employing lumped amplifiers with 100-km amplifier spacing.

ps, $C = -1.02$, $E_0 = 0.178$ pJ, while for pure Raman amplification ($G_R = 16$ dB) $T_0 = 4.694$ ps, $C = -0.92$, and $E_0 = 0.154$ pJ. For other values of G_R, the parameters T_0, C, and E_0 fall in between the above limits while the minimum pulsewidth remains the same. The noise factor $n_{sp} = 1.5$ corresponds to a noise figure of 4.8 dB for lumped amplifiers. For Raman amplification, we use $n_{sp} = (1 - \mathrm{e}^{-h\nu/kT})^{-1} \approx 1.13$ at room temperature [4], [8].

Fig. 1 shows that timing jitter is largest in the case of pure lumped amplification, but reduces as the contribution of DRA increases. The smallest value of jitter occurs when 100% of losses are compensated using DRA. For a 40-Gb/s system, jitter should be below 4 ps (16% of the bit slot). The dashed line in Fig. 1 shows that the Gordon–Haus jitter limits the transmission distance to about 4700 km, when only lumped amplifiers are used, but this limit can be increased to 6200 km by using DRA.

An interesting question is whether the use of DRA can allow a longer amplifier spacing. Fig. 2 shows timing jitter after 5000 km as a function of Raman gain for the 40-Gb/s systems employing a hybrid amplification scheme with amplifier spacings of 60, 80, and 100 km. The systems have six, eight, and ten map periods within each amplifier spacing, respectively, while the other parameters are the same as before. In each case, jitter is reduced by up to 40% by using DRA. More importantly, the use of only lumped amplifiers leads to limiting jitter in excess of 4 ps when L_A exceeds 70 km. In contrast, amplifiers can be placed as much as 100 km apart when an hybrid amplification scheme is employed. The required Raman gain is only 2 dB for 80-km spacing, but becomes 10 dB when amplifiers are 100 km apart.

In conclusion, we have shown that DRA is beneficial for reducing timing jitter. One may wonder whether soliton interaction would limit the transmission distance to below 5000 km for the 40-Gb/s system designs used for Figs. 1 and 2. To answer this question, we have solved (1) numerically using a random sequence of 1 and 0 bits. Fig. 3 shows the contour map of the bit sequence over a transmission distance of 8000 km for the system with 100-km amplifier spacing. As evident from this figure, soliton interaction is weak enough that such a lightwave system is mainly limited by amplifier noise. The use of DRA is beneficial for such systems since it increases the SNR (Q factor) and reduces the timing jitter simultaneously. We expect these benefits to apply even for wavelength-division multiplexed systems.

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