# Symmetric Slope Compensation in a Long-Haul WDM System Using the CRZ Format

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***Abstract*—In this letter, we numerically compared symmetric and asymmetric dispersion slope compensation schemes in a long-haul, chirped-return-to-zero, wavelength-division-multiplexed system. Symmetric compensation has significant advantages over asymmetric compensation. We elucidate the physical reasons and the system implications.**

***Index Terms*—Chirp, chirped return-to-zero, fiber communications systems, phase modulation, wavelength-division-multiplexing.**

## I. INTRODUCTION

CURRENT wavelength-division-multiplexing (WDM) systems have a substantial amount of third-order dispersion, so that it is often necessary to separately compensate for the dispersion of individual channels at either the beginning or the end of the transmission or both [1]–[3]. In a linear system, it would make no difference where the dispersion compensation was done. However, modern-day systems are significantly impacted by the Kerr nonlinearity. Signal pulses in the outer WDM channels undergo a large amount of expansion due to higher-order dispersion, which combined with the nonlinear interpulse interaction, leads to signal degradation if the dispersion compensation is done improperly. Simulations indicate that symmetric compensation leads to less signal degradation than asymmetric compensation [4], [5]. More recent testbed experiments by Bergano *et al.* [2], [3], that emulate undersea transmission, used symmetric slope compensation, as opposed to older experiments that did not [1]. These results imply that it is preferable to use symmetric compensation in long-haul dense WDM systems. In this letter, for the first time, we elucidate the physical reason for the better performance of symmetric compensation and the implications for future system design.

In order to determine the physical reason for the advantage of symmetric compensation over asymmetric compensation, we systematically increased the complexity of our system, beginning with a single pulse propagating in an optical fiber, then moving to a single channel without amplified spontaneous emission (ASE) noise, next adding ASE noise, and finally moving to full WDM simulations. Our studies show that this effect is due to the nonlinear interpulse interaction inside a single channel, and it is not significantly affected by ASE noise or by interchannel interactions. In this letter, we focus on presenting the results of our single-channel studies without ASE noise because these results most clearly elucidate the physical origin of the advantage that symmetric compensation has. In particular, we focus on a case in which the average dispersion in the transmission line differs significantly from zero, as is the case for most channels in a WDM system. We note that this issue of individual channel compensation only occurs in WDM systems with a significant third-order dispersion. It would not be an issue in a single-channel transmission system. The dispersion map that we used for this study has a segment with $D_1 = -2.125$ ps/nm·km of length $L_1 = 160$ km, and $D_2 = 17.0$ ps/nm·km of length $L_2 = 20$ km at 1.55 $\mu$m, corresponding to the point at which the average dispersion is zero. We assume a dispersion slope $dD/d\lambda = 0.075$ ps/nm$^2$·km, and a channel that is displaced 4.8 nm from the point of zero average dispersion. After the appropriate conversions, we find that $\beta_1'' = 3.128$ ps$^2$/km, and $\beta_2'' = -21.22$ ps$^2$/km. The amplifier spacing is 45 km, the fiber loss is 0.21 dB/km, the Kerr coefficient $n_2$ is $2.6 \times 10^{-16}$ cm$^2$/W, the effective area $A_{\mathrm{eff}} = 50$ $\mu$m$^2$, and the total propagation distance is 5040 km. These parameters correspond to the experiments of Bergano *et al.* [2], [3], except that our dispersion map period is smaller. We chose the map period so that the dispersion management strength parameter $\gamma = 2[(\beta_1'' - \overline{\beta}'')L_1 - (\beta_2'' - \overline{\beta}'')L_2]/\tau_{\mathrm{FWHM}}^2$ [6] corresponds to the value at which earlier studies [7] showed the largest power margin. For our simulations in this section, we chose a phase modulation $\phi = -A\pi\cos(\Omega t)$ with a modulation depth $A = -0.6$, where $\Omega/2\pi$ is the bitrate of the signal, which equals 10 Gb/s. We verified that this value of $A$, which corresponds to an average power of 0.25 mW, yields almost the largest eye opening. This system is shown schematically in Fig. 1. We determine the evolution by solving the nonlinear Schrödinger equation, modified to take into account spatially varying gain and loss, third-order dispersion, and ASE noise, as described in [8].

Chirped-return-to-zero (CRZ) pulses undergo a somewhat complex evolution; however, this evolution is dominated by the linear dispersion, which is one of the major reasons that we refer to this system as quasi-linear. The other major reason is that the largest source of noise-induced signal degradation has intensity fluctuations due to signal-spontaneous beat noise, just like in a linear system [9]. Consequently, it is possible to take advantage of the initial chirp, by properly choosing the overall average dispersion to compress the final pulse so that its duration at the end of the transmission is smaller than at the beginning [10]. We always chose the overall dispersion to achieve

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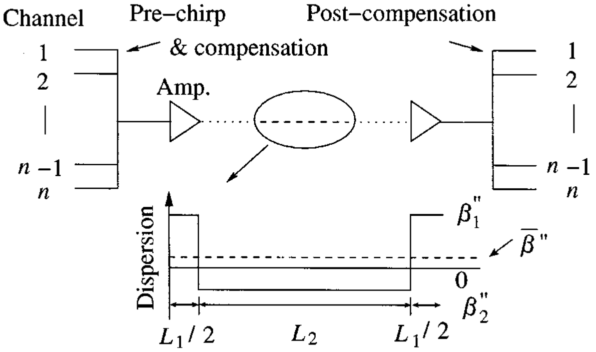

Fig. 1. Schematic illustration of the WDM transmission system used by Bergano *et al.* [2], [3].

the maximum compression. The nonlinearity leads to a small offset in the total average dispersion that we found as part of our investigation. Keeping the overall system parameters the same, we examined three dispersion slope compensation schemes: 1) precompensation—only adding the dispersion compensation at the beginning; 2) post-compensation—only adding the compensation at the end; and 3) symmetric compensation—adding equal amounts of compensation at the beginning and at the end. After the dispersion compensation, we find the overall average dispersion of the whole transmission line $\overline{D} = 0.041$ ps/nm·km ($\overline{\beta}'' = -0.052$ ps$^2$/km). So the line is undercompensated. We do our compensation by adding two segments of fiber 10 km in length with $D = 93.5$ ps/nm·km to the transmission line. For precompensation, both segments are at the beginning; for postcompensation, both segments are at the end; for symmetric compensation, both segments are split between the beginning and the end.

Fig. 2 shows the input and outputs of a 64-b pulse train that went through the transmission link in all three configurations. The output pulses are compressed to less than half their initial pulse duration. Moreover, Fig. 2(c) and (d) suggests that most of the degradation from asymmetric compensation is due to nonlinearly induced timing jitter from interpulse interactions.

In order to explore the physical reason why symmetric slope compensation reduces the intersymbol interference due to nonlinearly-induced timing jitter, we considered a case in which we only launched two pulses, separating by 100 ps. Using the definitions

$$\langle t\rangle = \frac{\int t|q(t)|^2\,dt}{\int |q(t)|^2\,dt} \quad \text{and} \quad \langle f\rangle = \frac{\int f|\tilde{q}(f)|^2\,df}{\int |\tilde{q}(f)|^2\,df} \tag{1}$$

we carefully traced the pulse positions along the transmission link, then we calculated the offsets of the pulse positions in the time and frequency domains separately according to

$$\Delta t = \langle t\rangle - t_0 \quad \text{and} \quad \Delta f = \langle f\rangle - f_0 \tag{2}$$

where $q(t)$ and $\tilde{q}(f)$ are the pulse profiles in the time and frequency domains, respectively, and $t_0$ and $f_0$ are the initial positions of the pulses. We calculated the pulse positions at the end of each map, and in order to retrieve the individual pulse shapes in the middle of the transmission link, we added a dispersive correction each time we detected the pulses, whose size was calculated by setting the total dispersion after the dispersive correction to optimally balance the initial chirp, so that the pulses are maximally compressed. We found the results shown in Fig. 3. For each of the three cases, we also show $\Delta = \int_0^Z D(z')\,dz'$ the total dispersion accumulation, where $Z$ is the propagation distance along the optical fiber. We note that there is a substantial frequency shift in all three compensation schemes. There is a tendency for the pulses to initially attract due to nonlinearity, just as in the case of solitons, and the pulses must shift their frequencies in opposite directions to attract. This frequency shift, followed by the motion of the pulses toward each other, leads to timing jitter. However, in the case of symmetric compensation, the dispersion reverses its sign midway through the transmission. As a consequence, two pulses that initially attracted each other begin to repel, and the effect is for the motion in the second half of the transmission to nearly erase the motion in the first half of the transmission.

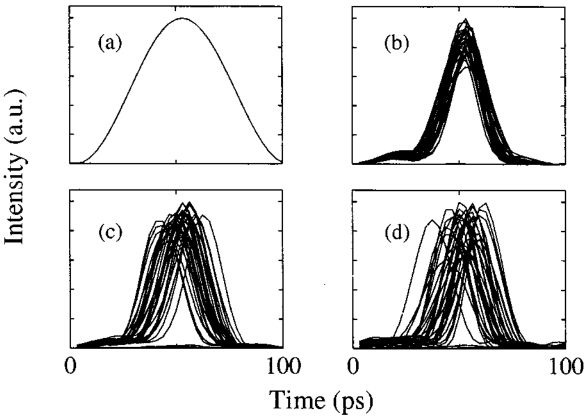

Fig. 2. Optical eyes before and after the transmission line. We show (a) the input and (b)–(d) the output with (b) symmetric compensation, (c) pre-compensation, and (d) postcompensation.

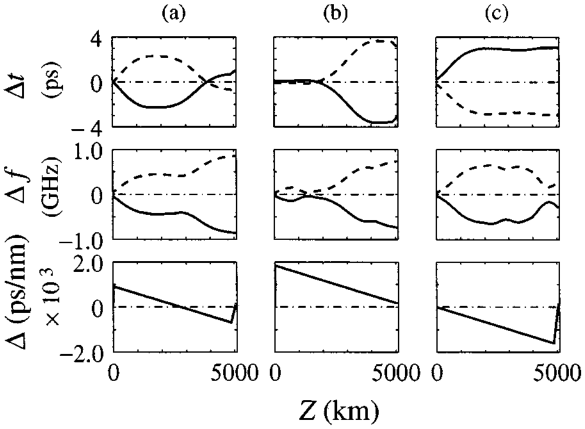

Fig. 3. The offset of the CRZ pulse pairs in the time and frequency domains, as well as the accumulated dispersion in the individual configurations. (a) Symmetric compensation. (b) Precompensation. (c) Postcompensation. The dashed line corresponds to the earlier pulse, and the solid line corresponds to the later pulse.

These results have important implications for system design. Dispersion compensation is commonly used in most systems with single-channel data rates at 10 Gb/s, and there is typically a substantial overlap between neighboring pulses in any

10-Gb/s system, whether it is based on a return-to-zero or a non-return-to-zero (NRZ) format. (In the latter case, the pulses may consist of several bits.) The nonlinear pulse attraction results in timing jitter, particularly of isolated marks in an NRZ system. However, by carefully designing the dispersion map to be nearly symmetric, it is possible to minimize this effect.

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