Performance Improvement of 10 Gb/s Standard Fiber Transmission Systems by Using the SPM Effect in the Dispersion Compensating Fiber

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***Abstract*—The use of dispersion compensating fibers (DCF's) has now emerged as the most practical technique to compensate for the chromatic dispersion in the long-haul, optically amplified standard fiber (1.3 μm zero dispersion) transmission systems. We investigated the effects of SPM in the standard fiber and the DCF in a repeaterless 10 Gb/s transmission system. We show that the SPM in the DCF reverses the spectral broadening in the standard fiber. We further show that the DCF length which offers the widest eye margin decreases as the launching power into the DCF is increased while the ISI penalty remains the same. This results in an increased signal-to-noise ratio (SNR) and hence improvement of the system performance.**

I. Introduction

With the advance of the erbium-doped fiber amplifiers (EDFA's) the transmission limitation imposed by the fiber loss in the 1.5 μm wavelength region has been essentially eliminated. Instead, the limitation imposed by the fiber nonlinearities and dispersion has become the main obstacle in extending the transmission distance of high-speed, long haul standard fiber transmission systems. Among the many methods reported [1]–[5], the use of DCF's to compensate for the chromatic dispersion has been emerging as the most practical technique because of its manufacturability, stability over temperature and wide-band dispersion compensating characteristics. So far, it has been believed that the SPM in the DCF degrades the system performance although the SPM in the standard fiber enhances the performance by compressing the pulse and hence increasing the electrical eye margin at the receiver. For this reason, the previous reports have always emphasized the importance of launching a low power into the DCF in order to minimize the SPM effect in the DCF and to operate the DCF in the linear regime [6]–[13].

In this letter, we show that the SPM effect in the DCF can in fact improve the system performance. We demonstrate, both experimentally and theoretically, that the required length of the DCF which provides the widest electrical eye margin at the receiver, decreases with increasing optical power level into the DCF while the electrical eye margin due to ISI remains the same. The use of the shorter DCF and higher launching power into the DCF provides a higher output power level at the end of the DCF and therefore increases the optical SNR. This results in an improved system performance. The use of the shorter length of the DCF offers an economical advantage as well.

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II. System Description

The system configuration that we considered is a 120-km standard fiber transmission system with a DCF at the receiver as shown in Fig. 1. The total dispersion of the standard fiber was $D_{\mathrm{SMF}} = +2131$ ps/nm at the 1557 nm wavelength. The transmitter was a DFB-laser externally modulated by a zero-chirp $\mathrm{LiNbO_3}$ modulator with NRZ (nonreturn to zero), $2^{23}-1$ PRBS data. The DFB-laser was dithered to suppress stimulated Brillouin scattering (SBS) [14]. The power booster was a two-stage EDFA pumped with two 1480-nm pump lasers. The amplifiers at the receiver side were 980-nm double pumped dual stage EDFA's with a noise figure of 4 dB. The receiver/regenerator consisted of a PIN-HEMT front end and an AGC with a total bandwidth of 8.5 GHz, clock and data recovery circuitry and a decision circuit. We first calculated the signal spectrum at the transmitter, at the output of the 120 km standard fiber and after the DCF to show the spectral broadening by the SPM in the standard fiber and the subsequent spectral compression due to the SPM in the DCF. Then, we calculated the electrical eye margin as a function of total dispersion $D = D_{\mathrm{SMF}} + D_{\mathrm{DCF}}$ for different launching powers into the DCF. A model developed in [15], [16] was used in the calculations.

III. Results

Fig. 2 shows the calculated spectrum of the optical signal at the transmitter, at the input of the DCF and after the compensation by the DCF. In this example the optical input power into the standard fiber and DCF were $P_{\mathrm{SMF}} = +12.5$ dBm and $P_{\mathrm{DCF}} = 0$ dBm, respectively. The linear and the nonlinear fiber parameters that were used in the calculations are summarized in Fig. 1. The DCF had a dispersion of $D_{\mathrm{DCF}} = -1793$ ps/nm which resulted in the widest electrical eye margin at the receiver. The total dispersion of the span was $D = +338$ ps/nm ($D = D_{\mathrm{SMF}} + D_{\mathrm{DCF}}$, where $D_{\mathrm{SMF}} = +2131$ ps/nm) corresponding to undercompensation by 16%. Fig. 2(b) clearly shows the spectral broadening due to the SPM in the 120 km long standard fiber. At this point, the calculated electrical eye margin due to only ISI was found to be 10%

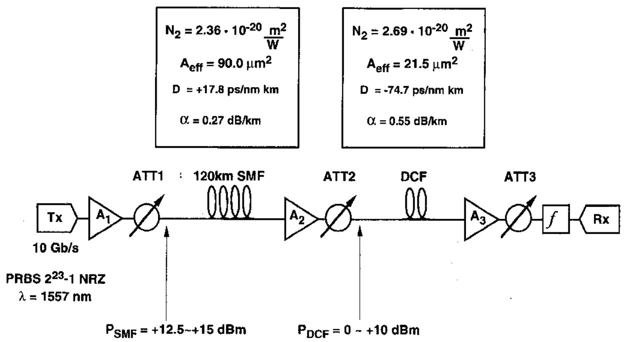

Fig. 1. Transmission system under consideration.

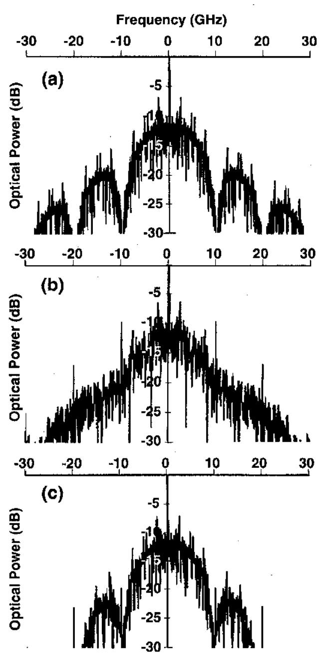

Fig. 2. Spectrum of the optical signal at (a) $z = 0$ km, (b) after 120 km of SMF, and (c) after the DCF.

leading to a bit error rate-floor when the noise from the optical amplifiers is included. Fig. 2c shows that the nonlinear SPM effect in the DCF reconstructs the spectrum of the original optical signal. For the given $P_{\text{SMF}} = +12.5$ dBm and $P_{\text{DCF}} =$ 0 dBm the optical SNR, measured within an optical bandwidth of 0.1 nm, was 34.7 dB resulting in a calculated eye margin at a BER of 10^{-15} of 39.7%.

In Fig. 3, we plotted the calculated eye position as a function of total dispersion for $P_{\text{SMF}} = +15$ dBm and $P_{\text{DCF}} = +10$ dBm and 0 dBm. The "eye position method" plots the eye closure from both "1"- and "0"-levels as a function of the total dispersion and therefore provides a clear picture of where the optimum threshold level should be set. From this figure, we can draw several conclusions. First, the maximum achievable electrical eye margins (without including the ASE noise contributions) are 63.2% for $P_{\text{DCF}} = 0$ dBm, 62.9% for $P_{\text{DCF}} = +5$ dBm and 61.1% for $P_{\text{DCF}} = +10$ dBm, indicating that using a high $P_{\text{DCF}} =$ does not increase the ISI penalty. On the other hand, the use of a high launching power into the DCF increases

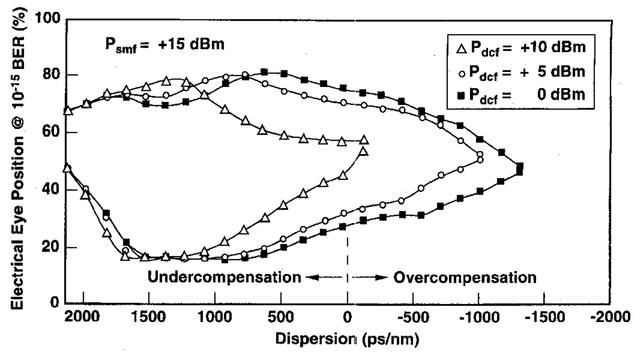

Fig. 3. Calculated Electrical Eye Position as a function of total dispersion for $P_{\text{SMF}} = +15$ dBm at the SMF input and $P_{\text{DCF}} = +10$ dBm, +5 dBm and 0 dBm.

the optical SNR at the receiver and hence improves the system performance. Second, the optimum DCF length needed to achieve the maximum electrical eye margin for $P_{\text{DCF}} = +10$ dBm is shorter than that for $P_{\text{DCF}} = 0$ dBm. For example, for $D_{\text{SMF}} = +2131$ ps/nm, the total dispersion providing the widest electrical eye margin is $D = +786$ ps/nm for $P_{\text{DCF}} =$ 0 dBm while $D = +1384$ ps/nm for $P_{\text{DCF}} = +10$ dBm. Since the dispersion coefficient of the DCF, $d_{\text{DCF}} = -74.7$ ps/nm km, this corresponds to a reduction of 8 km in the required DCF length (from 18 km to 10 km). This reduced DCF length results in a further increase of the signal level and a higher optical SNR at the receiver. The requirement of a shorter DCF length also offers an economical advantage.

Fig. 4 shows the measurement results of electrical eye position as a function of total dispersion D for $P_{\text{SMF}} = +15$ dBm and for $P_{\text{DCF}} = +10$, +5 and 0 dBm. For $P_{\text{DCF}} = 0$ dBm, the measured electrical eye margin for a BER of 10^{-15} is 45.8% at a total dispersion value of $D = +757$ ps/nm. For $P_{\text{DCF}} = +5$ dBm, we measured an electrical eye margin of 46.3% for a total dispersion of $D = +1090$ ps/nm. For the highest power level of $P_{\text{DCF}} = +10$ dBm we measured an electrical eye margin of 41% for $D = +1225$ ps/nm. These measurements confirm that increasing the input power to the DCF does not increase the ISI penalty. Note that the measured eye margins are smaller than the calculated ones because the measured eye margins include the ASE noise contribution. Also, note that the slightly smaller eye margin for $P_{\text{DCF}} = +10$ dBm is believed to be caused by the residual SBS effect in the DCF (the DCF has a four times smaller effective area than the standard fiber). The optical SNR values at the receiver were measured to be 36.6 dB, 36.3 dB and 35.7 dB for $P_{\text{DCF}} = +10$ dBm, +5 dBm and 0 dBm, respectively. In the long distance repeaterless transmission systems where the optical SNR at the receiver is low, the use of high launching power into the DCF increases the optical SNR significantly and thus the overall electrical eye margin significantly. For example, for a 10 Gb/s–240 km repeaterless system using low loss (0.2 dB/km) standard fiber, our calculations show that the system eye margin at a BER of 10^{-15} is 13.5% for $P_{\text{DCF}} = +5$ dBm for an optical SNR = 26.4 dB. The electrical eye margin is only 6.9% when $P_{\text{DCF}} =+ 0$ dBm because of the degradation of the optical SNR with 2.2 dB to 24.2 dB. Fig. 5 shows the calculated elec-

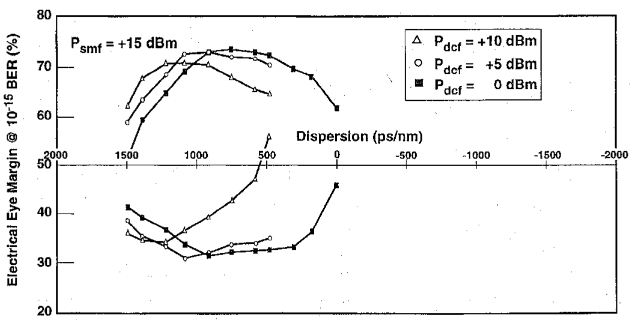

Fig. 4. Electrical eye margin as a function of total dispersion D (dispersion in SMF plus dispersion in DCF) for $P_{\mathrm{SMF}} = +15$ dBm and different levels of launching power into the DCF.

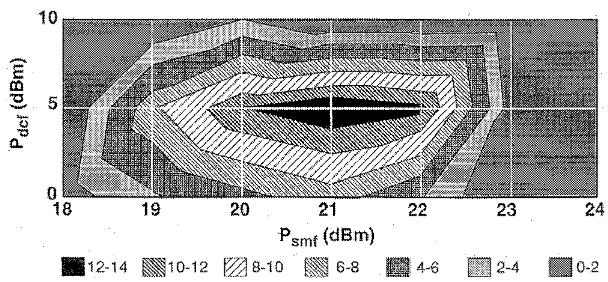

Fig. 5. Contour plot of electrical eye margin @ 10^{-15} BER as a function of P_{SMF} and P_{DCF} after 240 km standard fiber transmission.

trical eye margin at a BER of 10^{-15} after 240 km of standard fiber as a function of P_{SMF} and P_{DCF}. From this figure we can draw several conclusions. First, the widest electrical eye margin of 13.5% is achieved for a launching power of $+21$ dBm into the SMF and $+5$ dBm into the DCF. Second, the figure clearly shows that the electrical eye margin is degraded due to modulation instability (MI) when P_{SMF} is greater than $+21$ dBm. The electrical eye margin decreases due to the MI in the DCF when P_{DCF} is increased beyond $+5$ dBm. When P_{SMF} is smaller than $+21$ dBm and P_{DCF} is smaller than $+5$ dBm, the SNR degrades the system eye margin.

IV. Conclusion

We have investigated the SPM effect in the DCF employed to compensate for the chromatic dispersion in a 10 Gb/s standard fiber transmission system. We have shown that the optimum DCF length which offers the widest electrical eye margin decreases as the launched optical power into the DCF is increased. The use of a higher launching power into the DCF and the resulting requirement of a shorter DCF length increase the optical SNR at the receiver and therefore improves the BER performance of the transmission system. The use of a shorter DCF length also lowers the system cost.

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