Dispersion Compensation for Ultrashort Pulse Transmission Using Two-Mode Fiber Equalizers

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***Abstract*— We numerically simulate ultrashort pulse propagation in dispersion compensated fiber links using two-mode equalizing fibers. By choosing a proper length ratio between the conventional single-mode fiber and the compensating two-mode fiber, both the dispersion and the dispersion slope can be eliminated simultaneously. As a result, dispersion compensated propagation of sub-picosecond pulses should be possible for distances in excess of 100 km. Our analysis shows that for sub-picosecond pulses, dispersion-limited propagation distances offered by this technique may significantly exceed those possible with soliton propagation. We also evaluate nonlinearity limits due to self-phase modulation.**

I. Introduction

With the introduction of Er-doped fiber amplifiers operating at 1550 nm, fiber loss no longer presents a fundamental limit to achieving long transmission distance. Chromatic dispersion then becomes the major factor in limiting picosecond and sub-picosecond pulse transmission for ultrahigh bit rate time-division multiplexed (TDM) networks (e.g., [1]) as well as for code-division multiple-access (CDMA) schemes based on spectral phase coding [2]. In TDM networks both nonlinear (soliton) propagation and linear compensation techniques can be used to combat dispersion, while in CDMA only linear methods are permissible, since the code words do not propagate as solitons. However, dispersion compensation is difficult in the sub-picosecond regime since compensation of both second- and third-order dispersion (i.e., both the dispersion and the dispersion slope) is necessary [3].

In this Letter we analyze the application of two-mode dispersion equalizing fibers [5], [6] for the transmission of ultrashort pulses. We first explore the dispersion characteristics of two-mode fiber equalizers and show that both the dispersion and the dispersion slope can be compensated simultaneously at a specific wavelength if the correct length of equalizing fiber is used. We then investigate dispersion limits for picosecond and sub-picosecond pulse propagation in such compensated fiber links. Finally, we briefly discuss nonlinearity limits for dispersion equalized links and compare our computed results to short pulse soliton propagation limits. Our results show that fiber links utilizing two-mode fiber dispersion equalizers can accommodate linear propagation of sub-picosecond pulses over distances of tens to hundreds of kilometers (e.g., 30 km for 0.6-ps pulses and 150 km for 0.9-ps pulses). For comparison, linear transmission of sub-picosecond pulses in dispersion-shifted fiber (DSF) is severely limited (e.g., 7 km maximum distance for 0.9-ps pulses). Additionally, for sub-picosecond pulses the predicted propagation limits for dispersion equalized fiber links are substantially longer than predicted soliton propagation limits.

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II. Two-Mode Fiber Dispersion Compensator

Research aimed at upgrading standard single mode fibers (SMF) for use in state-of-the-art systems experiments at 1550 nm (where SMF exhibits a large anomalous dispersion D=17 ps/nm/km) has received considerable attention recently, and several dispersion compensation schemes have been investigated [4]. Several groups have utilized special equalizing fiber with large normal dispersion at 1550 nm to equalize the anomalous dispersion in the SMF [5]–[8]. Here we consider the possibility of sub-picosecond dispersion compensation using two-mode dispersion equalizing fiber [5], [6]. The two-mode fiber compensator [5], [6] makes use of the fact that higher-order spatial modes have large negative (normal) waveguide dispersion near the cut-off wavelength. For dispersion compensation a mode converter is placed after the SMF span to convert the fundamental (LP_{01}) mode to the required LP_{11} mode in the equalizing fiber. Since the dispersion slope as well as the dispersion of the LP_{11} mode are opposite to that of the LP_{01} mode in the standard fibers, simultaneous cancellation of second- and third-order dispersion can be achieved. This allows simultaneous dispersion compensation of multiple WDM channels [6] and can also enable propagation of sub-picosecond pulses over substantial fiber lengths, a possibility we examine in our numerical studies below. Simultaneous second and third order dispersion compensation for sub-picosecond pulses has also been reported by Stern *et al.* using a bulk optics approach [3]; the use of fiber equalizers proposed here could provide an all-fiber solution.

The composite link of a SMF and a two-mode equalizing fiber can be regarded as a fiber with equivalent dispersion D_{eq} given as

$$D_{eq} = (R \times D_{SMF} + D_{comp})/(1 + R) \tag{1}$$

where R is the length ratio of the SMF to compensation fiber, D_{SMF} the dispersion of the SMF and D_{comp} the dispersion of the compensation fiber. We have calculated the equivalent dispersion as a function of wavelength, using dispersion data for the two-mode fiber (specifically for the LP_{11}^{ye} mode) reported in [6]. Fig. 1 shows calculated dispersion curves for the optimal length ratio $R_{opt} = 13.054$, as well as for other length ratios ($R = R_{opt} \pm 0.35\%, R = R_{opt} \pm 0.70\%$). For the optimal length ratio, the dispersion curve has zero dispersion

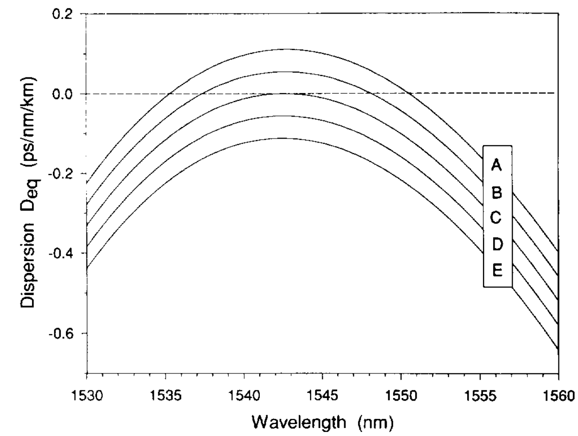

Fig. 1. Various concatenated dispersion curves. Curves A–E correspond to fiber length ratio R= 13.152, 13.103, 13.054, 13.005, and 12.956, respectively. Curve C (R=13.054) has zero dispersion and dispersion slope at λ=1542.6 nm.

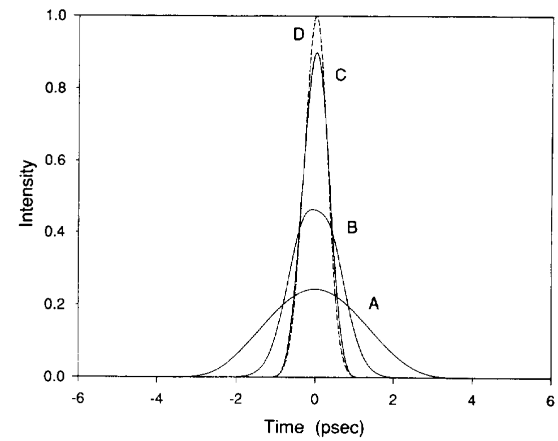

Fig. 2. Pulse shapes restored by dispersion compensator after traveling distance of 5 km. The solid curves A, B, and C show the pulse shapes corresponding to the dispersion curves A, B, and C in Fig. 1, respectively. The dashed-line curve D is the initial pulse with FWHM= 700 fs.

and dispersion slope at 1542.6 nm (curve C in Fig. 1). As the length ratio changes slightly, the dispersion curve shifts up or down significantly. This effect could be used experimentally to fine tune the link for the optimum dispersion compensation.

III. Numerical Simulations

In this section we calculate dispersion-limited propagation distances as a function of initial pulse width for fiber links using two-mode equalizing fibers. We assume that power levels in the fiber are sufficiently small that we can disregard nonlinear effects and consider only linear dispersion. Loss is also ignored since it doesn't affect the pulse shape. The pulse shape after traveling a distance of z can be easily solved by the Fourier transform technique as follows:

$$u(z,t) = \frac{1}{2\pi}\int_{-\infty}^{\infty} U(0,\omega)\exp[-j\beta(\omega)z + j\omega t]d\omega \qquad (2)$$

where $U(0,\omega)$ is the Fourier transform of the normalized input field amplitude $u(0,t)$. $\beta(\omega)$ is the propagation constant, which is derived from the concatenated dispersion function $D_{eq}(\lambda)$. Due to the broad bandwidth of pulses in the sub-picosecond regime, we utilize the exact equivalent dispersion curve rather than the usual Taylor expansion treatment.

Fig. 2 shows calculated pulse shapes at $z = 5$ km assuming input Gaussian pulses centered at 1542.6 nm with a 700-fs intensity full width at half maximum (FWHM) duration. Curves are shown for concatenated links with the optimum SMF to equalizing fiber ratio (R_{opt}), as well as for links with slightly different length ratios ($R/R_{opt} = 1.0035$, 1.007), corresponding to dispersion curves C, B, and A in Fig. 1, respectively. For the optimal ratio $R_{opt} = 13.054$, the output pulse exhibits very little broadening (the input pulse is plotted as the dashed line D as a reference). For comparison, the output pulsewidth using SMF only without equalizing fibers is 400 ps, a broadening of $\sim$ 570 times relative to the input pulse. As we can see from Fig. 2, a length difference of 0.35% causes the output peak power to drop by $\sim$ 50%. This indicates that accurate adjustment of the fiber length ratios is crucial to the success of this technique.

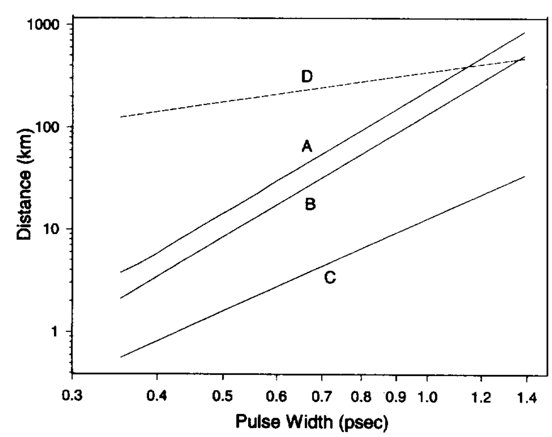

Fig. 3. Transmission distances vs. initial pulse widths for two-mode fiber dispersion compensator (line A), soliton propagation limited by self-frequency shift (line B), and dispersion-shifted fiber (line C). Dashed line D indicates the distance at which nonlinear phase shift reaches 0.5 radians for the two-mode fiber dispersion compensator.

As a pulse keeps broadening with increased distance, its peak intensity decreases correspondingly. We define the point at which the output pulse peak intensity is reduced to one half of the zero-dispersion value as the dispersion-limited propagation distance for the total dispersion-equalized link. The dispersion-limited propagation distance can then be obtained from (2) and is shown in Fig. 3 as a function of initial pulse width (solid line A). Here we consider the compensator with optimal length ratio (curve C in Fig. 1) and assume that all the pulses are centered at this optimal wavelength (1542.6 nm). The dispersion limit (line A) shows a slope very close to four and can approximated by $L = 230\Delta T^4$, where ΔT is the FWHM in picoseconds, and L is the propagation length in km. This proportionality stems from the fourth-order dispersion of the fiber link, which dominates the remaining uncompensated dispersion.

For comparison line C in Fig. 3 shows maximum transmission distance vs. pulse width for a DSF, assuming Gaussian pulses centered at the zero-dispersion wavelength. The distance is again taken as that distance for which the peak intensity is reduced to one half of the dispersionless value. The broadening is dominated by the dispersion slope, which results in a slope of three in the log-log plot. The propagation distance is severely limited (e.g., $\sim$ 3 km for 0.6-ps pulses).

IV. Discussion

In our analysis so far we have neglected nonlinear effects such as self-phase modulation (SPM). However, even at low power levels, nonlinear phase shifts could accumulate during propagation over very long fiber links. Therefore, we have estimated the amount of SPM in fiber links with dispersion compensation at the receiver end. If we postulate a maximum acceptable nonlinear phase shift, this imposes an additional nonlinearity limit on the maximum transmission distance. The dashed line D in Fig. 3 indicates this limit for a 0.5 radian nonlinear phase shift. Here we assume a TDM system with on-off keying and data bits spaced by five pulse widths, 1000 photons/bit receiver sensitivity, and optical amplifiers placed every 50 km along the link. The details of this calculation will be presented elsewhere. For pulsewidths smaller than 0.75 ps, the nonlinear phase shift is less than 0.5 radians over the dispersion-limited propagation distance and can be neglected. For longer pulses the maximum transmission distance is limited by the nonlinear phase shift rather than dispersion. Even accounting for nonlinearities, however, our analysis indicates the possibility of dispersion-compensated sub-picosecond pulse propagation over distances up to a few hundred kilometers.

It is also worth comparing these results with the predicted propagation limits for solitons. For sub-picosecond soliton pulses, propagation is limited by the soliton self-frequency shift, in which the Raman (or time-delayed) portion of the nonlinear refractive index leads to a continuous downshift of the mean frequency as the pulses propagate along the fiber. This also affects the timing of the pulses and eventually degrades the data sequence. From the theoretical work of Gordon [9], this self-frequency shift can be approximated as $\Delta\nu = 0.00129\lambda^2 DL/\Delta T^4$, where $\Delta\nu$ is the frequency shift in terahertz, λ is the wavelength in microns, D is the dispersion in ps/km/nm, and L is the propagation distance in kilometers. Since solitons can only be supported in the anomalous dispersion regime, the pulse must be centered at least one spectral width away from the zero dispersion wavelength. This leads to a minimum dispersion of approximately $D = 0.315S\lambda^2/(c\Delta T)$, where S is the dispersion slope (0.05 $ps/nm^2/km$ for DSF). If we adopt the criterion that the frequency shift should be less than one-sixth of the spectral width [1], we find the distance a soliton can travel in a DSF at 1550 nm is limited by $L = 135\Delta T^4$. This is plotted as line B in Fig. 3. Based on our assumptions, dispersion-equalized fiber links can support linear sub-picosecond pulse propagation over distances approximately two times larger than possible with solitons.

V. Summary

We have analyzed picosecond and sub-picosecond pulse propagation in dispersion compensated fiber links, in which two-mode dispersion-equalizing fiber is assumed to compensate for the dispersion accumulated in a conventional single-mode fiber span. For proper ratios of fiber lengths, both second- and third-order dispersion can be eliminated simultaneously. Our results indicate that distortionless linear propagation of sub-picosecond pulses should be possible over morethan one hundred kilometers. Such sub-picosecond propagation distances would be more than one order of magnitude longer than possible using linear pulse propagation at the zero dispersion wavelength in dispersion-shifted fibers. Furthermore, for sub-picosecond pulses, linear propagation using dispersion-equalized fiber links may allow longer distance transmission than nonlinear propagation using solitons. Of course, this technique is very sensitive to the ratio of the SMF to the two-mode equalizing fiber length. In order to make the system more robust with respect to parameter variations, an auxiliary spectral pulse shaping setup [10], [11] can be used to remove small phase variations remaining after the fiber equalizer or to further extend the propagation distance. Prospects for sub-picosecond dispersion compensation over distances exceeding 100 km should open new possibilities for ultrashort pulse code-division multiple-access as well as ultrahigh bit rate TDM.

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References

[1] M. N. Islam, *Ultrafast Fiber Switching Devices and Systems*. Cambridge, U.K.: Cambridge University Press, 1992.

[2] J. A. Salehi, A. M. Weiner, and J. P. Heritage, "Coherent ultrashort light pulse code-division multiple access communication systems," *IEEE J. Lightwave Tech.*, vol. 8, pp. 478–491, 1990.

[3] M. Stern, J. P. Heritage, and E. W. Chase, "Grating compensation of third-order fiber dispersion," *IEEE J. Quantum Electron.*, vol. 28, pp. 2742–2748, 1992.

[4] *IEEE J. Lightwave Technol.*, Special Issue on Fiber Dispersion Compensation, in press.

[5] C. D. Poole, J. M. Wiesenfeld, A. R. McCormick, and K. T. Nelson, "Broadband dispersion compensation by using the higher-order spatial mode in a two-mode fiber," *Opt. Lett.*, vol. 17, pp. 985–987, 1992.

[6] C. D. Poole, J. M. Wiesenfeld, and D. J. DiGiovanni, "Elliptical-core dual-mode fiber dispersion compensator," *IEEE Photon. Technol. Lett.*, vol. 5, pp. 194–197, 1993.

[7] H. Izadpanah, C. Lin, J. Gimlett, D. W. Hall, and D. K. Smith, "Dispersion compensation in 1310 nm-optimized SMFs using an equalizer fiber, EDFAs and 1310/1550 nm WDM," *Electron. Lett.*, vol. 28, pp. 1469–1471, 1992.

[8] A. J. Antos, D. W. Hall, and D. K. Smith, "Dispersion-compensating fiber for upgrading existing 1310-nm-optimized systems to 1550-nm operation," in *Tech. Dig. Optical Fiber Commun. Conf.*, 1993, paper THJ3, pp. 204–205.

[9] J. P. Gordon, "Theory of the soliton self-frequency shift," *Opt. Lett.*, vol. 11, no. 10, pp. 662–664, 1986.

[10] A. M. Weiner, D. E. Leaird, J. S. Patel, and J. R. Wullert, II, "Programmable shaping of femtosecond optical pulses by use of 128-element liquid crystal phase modulator," *IEEE J. Quantum Electron.*, vol. 28, pp. 908–920, 1992.

[11] J. P. Heritage, E. W. Chase, R. N. Thurston, and M. Stern, "A simple femtosecond optical third-order disperser," presented at CLEO, Baltimore, MD, 1991.