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Effect of Map Strength on Polarization Mode Dispersion in Dispersion-Managed Soliton Systems

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***Abstract*—Solitons in dispersion managed lines have large tolerance to polarization mode dispersion (PMD) because of strong nonlinear trap helped by a power enhancement factor compared with conventional solitons. We present numerical results on the effect of map strength S on PMD and discuss the optimum choice of S in practical soliton systems.**

***Index Terms*—Dispersion management, optical communication, optical soliton, polarization mode dispersion.**

I. Introduction

In higher-bit-rate optical transmission systems, polarization mode dispersion (PMD) is one of the major factors that limit the propagation distance. However, optical solitons can reduce the effect of PMD, compared with linear pulses, due to its nonlinear trapping force (Kerr effect) [1]–[4]. Since large nonlinearity results in the effective reduction of PMD, it is expected that dispersion-managed solitons, which require higher power than conventional solitons with the same average dispersion [5], have an advantage over PMD. The nonlinearity required for dispersion-managed soliton transmission depends on the map strength S, defined as

$$S = \frac{\lambda^2}{2\pi c}\,\frac{D_1 z_1 - D_2 z_2}{t_0^2} \tag{1}$$

where

- D_1 and D_2 — positive and negative group velocity dispersion with corresponding lengths z_1 and z_2, respectively;
- t_0 — input pulsewidth;
- λ and c — wavelength and the velocity of light, respectively.

The resistance of dispersion-managed solitons to PMD is studied in [4] and [6]. In [4], pulse broadening of solitons due to PMD is shown to increase logarithmically with distance. This analysis, however, is limited to an average soliton regime with relatively weak PMD and may not be applied to strongly dispersion-managed systems. In [6], strong dispersion management is shown to be less effective in improving the tolerance to PMD in comparison with conventional solitons. In their calculations, however, nonlinear interaction between neighboring pulses is included, which significantly degrades the transmission performance especially in a regime with large S.

In this letter, we study the dependence of PMD on the map strength in dispersion-managed soliton systems in order to elucidate the trapping effect.

II. Constant Birefringence

Propagation of orthogonally polarized optical pulse components u and v in a dispersion management line is described by the so called coupled nonlinear Schrödinger equation (coupled-NLSE) of the form [8]

$$\begin{cases} i\left(\dfrac{\partial u}{\partial Z} + \delta_g \dfrac{\partial u}{\partial T}\right) + \dfrac{d(Z)}{2}\,\dfrac{\partial^2 u}{\partial T^2} + (|u|^2 + \gamma |v|^2)u \\ \quad +(1-\gamma)u^* v^2 \exp(-4i\Delta\beta Z) = 0 \\ i\left(\dfrac{\partial v}{\partial Z} - \delta_g \dfrac{\partial v}{\partial T}\right) + \dfrac{d(Z)}{2}\,\dfrac{\partial^2 v}{\partial T^2} + (|v|^2 + \gamma |u|^2)v \\ \quad +(1-\gamma)v^* u^2 \exp(4i\Delta\beta Z) = 0 \end{cases} \tag{2}$$

where $\gamma = 2/3$, and T, Z, $\Delta\beta$, and $\delta_g = \delta\beta' z_0/(2t_0)$ represent normalized time, normalized distance, the differential wave number of the orthogonal components and the differential group velocity, respectively. Although (2) is not integrable, we can derive the ordinary differential equation which describes the evolution of pulse parameters by using the variational method with a proper ansatz of the propagating pulse. For the case of a strong dispersion management line, this can be assumed by the following Gaussian-shape pulse:

$$\begin{cases} u(Z, T) = A_u \exp\left(\frac{1}{2} p_u^2 T^2 + i\phi_u\right) \\ v(Z, T) = A_v \exp\left(\frac{1}{2} p_v^2 T^2 + i\phi_v\right) \end{cases} \tag{3}$$

where $\phi_i = (C_i/2p_i^2)T^2 + \kappa_i T + \theta_i$, and $A_i, p_i, C_i, \kappa_i, T_i$, and θ_i are their amplitude, pulsewidth, frequency chirp, frequency, time position and phase, respectively. By employing the variational method to the equation in which the last terms on the left-hand sides of (2) are neglected, we obtain the ordinary differential equations for the difference of frequency and time position in the form

$$\begin{cases} \dfrac{d\Delta\kappa}{dZ} = \dfrac{2\gamma E P^3 \Delta T}{\sqrt{\pi}} \exp(-P^2 \Delta T^2) \\ \dfrac{d\Delta T}{dZ} = 2\delta_g - D\Delta\kappa \end{cases} \tag{4}$$

where $1/P^2 = 1/p_u^2 + 1/p_v^2$ and E is the pulse energy described as $\sqrt{\pi}\,(A_u^2/p_u + A_v^2/p_v)$. Equation (4) shows that $\Delta\kappa$ and ΔT behave periodically along Z in small δ_g, whereas in the linear

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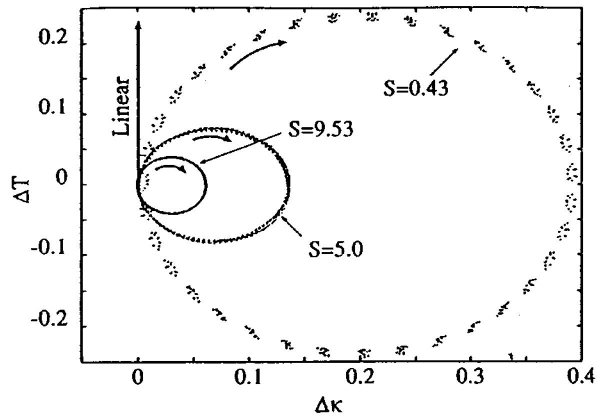

Fig. 1. Trajectories in the $(\Delta\kappa,\ \Delta T)$ plane described in (4) for $S = 0.43, 5.0, 9.53$ with $\delta_g = 0.1$. The dispersion managed line is composed of fibers with anomalous $(nZ_a < Z < nZ_a + Z_a/4, nZ_a + 3Z_a/4 < Z < (n+1)Z_a)$ and normal $(nZ_a + Z_a/4 < Z < nZ_a + 3Z_a/4)$ dispersion with $Z_a = 0.48$.

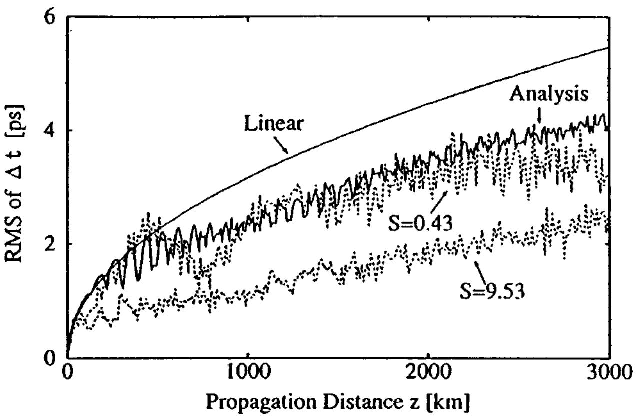

Fig. 2. Evolution of $\sqrt{\langle\Delta T^2\rangle}$ in linear and nonlinear systems with the initial pulsewidth 2ps. Solid lines represent the results of linear and nonlinear systems given by (5) and (6), respectively, and dashed lines are the results of numerical simulation for different $S = 0.43$ and 9.53 obtained by averaging over 50 trials. Dispersion management period $z_a = 10$ km, PMD parameter $\sqrt{\langle\Delta\beta'^2\rangle z_h} = 0.1$ ps/km$^{1/2}$, and $z_h = 0.2$ km. The step size of z in numerical simulation of (2) is set $z_h/20$.

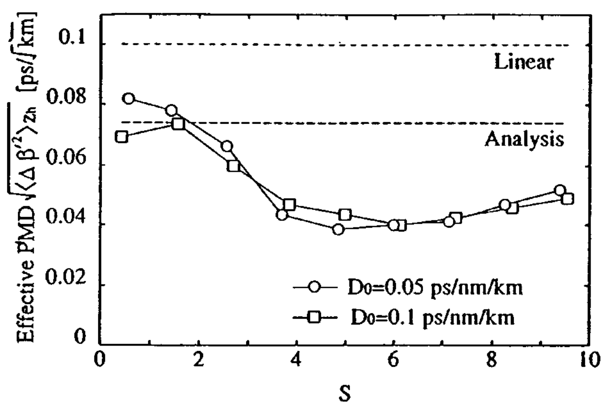

Fig. 3. Effective PMD in dispersion-managed soliton transmission over 3000 km with several values of S, obtained by averaging over 50 trials. $\sqrt{\langle\Delta\beta'^2\rangle z_h} = 0.1$ ps/km$^{1/2}$.

case, $\Delta\kappa = 0$ and ΔT increases linearly. Fig. 1 illustrates the trajectories in the $(\Delta\kappa,\ \Delta T)$ plane at every period of the dispersion map for various S in the case of $\pi/4$ initial polarization axis. The period of these trajectories is short for large S due to large cross-phase modulation (XPM) induced by higher nonlinearity, whereas the pulse broadens considerably by large local dispersion. This implies that nonlinear trap by XPM, referred to as soliton trap [1], depends not only on peak power but on the overlap of polarized components. Hence, nonlinear trap becomes effective for large S in constant birefringence.

III. Random Birefringence

Based on the result obtained above, we expect that power enhancement in strongly dispersion managed solitons helps suppress the effect of PMD also in randomly varying birefringent fibers. In the following, we assume fibers are cascade of short segments with constant length z_h and the group velocity birefringence $\Delta\beta'$. At each segment, the polarization states and $\Delta\beta'$ are random variables following uniform and Gaussian distributions, respectively [3], [9]. In this model, the effect of PMD is measured as $\sqrt{\langle\Delta\beta'^2\rangle z_h}$with the unit of ps/km$^{1/2}$ [10].

We analyze the root-mean-square (rms) of ΔT due to PMD by using (4). Expanding this equation around $\Delta T = 0$ and taking the first order, (4) is reduced to Langevin equation. Furthermore, in a small S regime, replacing the local dispersion d with the average dispersion d_0 under the condition that δ_g is white Gaussian process which has the property $\langle\delta_g\rangle = 0$ and $\langle\delta_g(Z)\delta_g(Z')\rangle = \sigma^2\delta(Z - Z')$, we obtain

$$\sqrt{\langle\Delta T^2\rangle} = \left[2\sigma^2 Z\left\{1 + \frac{\sin(2b|d_0|Z)}{2b|d_0|Z}\right\}\right]^{1/2} \tag{5}$$

where $b = 2\gamma EP^3/\sqrt{\pi}$. Note that $\sqrt{\langle\Delta T^2\rangle}$ in conventional solitons has the same form. On the other hand, when $b = 0$, namely in the linear case, we have

$$\sqrt{\langle\Delta T^2\rangle} = 2\sqrt{\sigma^2 Z}. \tag{6}$$

These equations indicate that rms of ΔT increases in proportional to $\sqrt{Z}$ also in the presence of nonlinearity as long as δ_g dominates the pulse broadening, but the effect of PMD in soliton transmission systems is reduced by $1/\sqrt{2}$ compared with linear systems by the help of nonlinear trap. On the other hand, if the orthogonally polaraized modes are completely trapped, rms of ΔT is found to increase in proportional to $\sqrt{\ln Z}$ [4].

We demonstrate the suppression of PMD-induced pulse broadening due to large nonlinearity in strongly dispersion-managed soliton transmission. Fig. 2 shows comparison of the evolution of $\sqrt{\langle\Delta T^2\rangle}$ in linear and nonlinear systems obtained by the direct numerical simulation of (2) and the one given by (5) and (6). The analytical result of the Langevin equation is in good agreement with the numerical result when $S = 0.43$. Indeed, (5) is valid especially when the average dispersion dominantly characterizes the pulse dynamics in a dispersion-managed line with small S. The suppression of PMD for large S is also demonstrated in Fig. 3, where we show plots of $\sqrt{\langle\Delta\beta'^2\rangle z_h}$obtained from $\langle\Delta T^2\rangle$ measured over 3000 km with the assumption that $\langle\Delta T^2\rangle$ increases in proportional to Z as in the case of linear transmission systems. In Fig. 3, we note that the effective PMD $\sqrt{\langle\Delta\beta'^2\rangle z_h}$ decreases further as we increase S due to large nonlinearity required for the stationary propagation of a dispersion-managed soliton, in a way similar to the case of constant birefringent fibers as demonstrated in Fig. 1. In the region of $S > 5$, however, the effect of PMD does not decrease considerably in spite of large nonlinearity. This is because average nonlinearity over a dispersion management period does not become large due to pulse broadening for large S. In addition, we observe that the dispersive waves which originate from the mismatch between the incident pulse and the exactly stationary pulse in a strongly dispersion managed line [11] may be another dominating factor that brings about pulse distortion in addition to PMD. We also note in Fig. 3 that the effect of PMD is almost irrespective of the average dispersion regardless of S. This is understood by noting that the transmission distance over 3000 km is already far beyond the dispersion distance $<$100 km and thus the nonlinear distance, which indicates that the reduction of PMD is already effective. The effect of PMD can be reduced by increasing the map strength S, whereas intra-channel nonlinear interactions increase [7]. Consequently, in dispersion-managed soliton systems, there seems to exist an optimum value of S which minimizes neighboring pulse to pulse interactions and simultaneously maximizes the PMD resistance which depends on the magnitude of PMD.

IV. Conclusion

We have demonstrated, both analytically and numerically, the tolerance of dispersion-managed solitons to PMD in fibers with constant birefringence as well as random birefringence. In relatively small S regime, the effect of PMD is shown to be reduced considerably by increasing the map strength by the help of enhanced nonlinear trap, however the reduction saturates beyond S of about five.

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