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Large predispersion for reduction of intrachannel nonlinear impairments in strongly dispersion-managed transmissions

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ABSTRACT

Predispersion for reduction of intrachannel nonlinear impairments in quasi-linear strongly dispersion-managed transmission system is analyzed in detail by numerical simulations. We show that for moderate amount of predispersion there is an optimal value at which reduction of the nonlinear impairments can be obtained, which is consistent with previous well-known predictions. However, we found that much better transmission performance than that of the previous predictions can be obtained if predispersion is increased to some extent. For large predispersion, the nonlinear impairments reduce monotonically with increasing predispersion and then they tend to be stabilized when predispersion is further increased. Thus, transmission performance can be efficiently improved by inserting a high-dispersive element, such as a chirped fiber bragg grating (CFBG), at the input end of the transmission link to broaden the signal pulses while, at the output end, using another CFBG with the opposite dispersion to recompress the signal.

1. Introduction

Nonlinear effects such as intrachannel four-wave mixing (IFWM) and intrachannel cross-phase modulation (IXPM) are the dominate source of bit errors for high-speed long-haul quasi-linear fber-optic transmission systems [1]. Strong dispersion management in combination with a return-to-zero (RZ) modulation format can reduce IXPM-induced timing jitter, but cannot reduce IFWM-induced "ghost pulses" in the signal 0's and amplitude jitter in the signal 1's [2–4]. The existing techniques for reducing the impact of IFWM included: (1) Appropriate predispersion [3,5–7], i.e., by optimizing the amount of predispersion, minimizing the path-averaged pulsewidth over the high power nonlinear sections of the system, overlapping of neighboring pulses is reduced and hence, distortion duo to intrachannel nonlinear effects is minimized. (2) Finding a proper dispersion mapping [8–10], which involves precise dispersion management and power control to achieve zero net dispersion and negligible nonlinear penalty at the end of the link, and hence, incurs massive effort in link construction and management. (3) Appropriate phase modulation [11–19]. The schemes rely on the fact that the phase of the IFWM-induced ghost pulse has a fixed relationship to the phases of the genuine 0's in the bit stream that enter the IFWM process. Thus, the strongest ghosts can be eliminated by tailoring the phase of the surrounding 1's to cause destructive interference between the various contributions to a ghost. However, for a random bit stream, no phase modulation format can achieve destructive interference in several consecutive time slots. (4) Using constrained codes (also known as modulation codes or line codes) [20–25], in which the data are coded in such a way that the worst sequences, which are such a 0 bit surrounded by many 1's, are simply avoided by bit stuffing. However, this will introduce an overhead. (5) Optical phase conjugation (OPC) [26–29], which allows nonlinearity cancelation provide that system's power profile and dispersion are symmetrical with respect to midspan. In real systems, these conditions can only be partially fulfilled. (6) Coherent detection in combination with digital signal processing [30–33]. The drawback of the method is that reconstruction of the transmitted data from the received signal relies on computationally intensive techniques, and real-time digital signal processing is still a challenging problem. IFWM can also be suppressed by subchannel multiplexing [34], alternating of the polarization of consecutive pulses [35], introducing some polarization mode dispersion in transmitters [36], and by using unequally spaced data pulses [37]. However, the realizations of these techniques are always complex and much expensive when the bit rate is up to 40 Gbps.

In this paper we numerically show that intrachannel nonlinear effects such as IFWM and IXPM can be efficiently reduced by introducing a large predispersion to broaden the input pulses (signal 1's) through a high-dispersive device such as a chirped fiber bragg

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grating (CFBG) and then recompressing the pulses at the output end through another device with the opposite amount of dispersion. We noted that Turitsyn et al. [33] proposed the idea of large predispersion and that Kumar et al. [38] recently showed the benefits of predispersion for coherent communication systems. However, the purpose of predispersion in Refs. [33,38] is to simplify the digital signal processing (DSP) in the coherent receiver, whereas in this manuscript, it is proposed to reduce the intrachannel nonlinearities such as IFWM and IXPM in the transmission line. Moreover, the approximation made in Ref. [33] is valid only when the predispersion is very high, whereas as will be shown later, the required predispersion here is not so large and still it appears to provide suppression of nonlinerities. We should also stress that this method is not the standard well-known predispersion technique [3,5–7], which will be analyzed subsequently through numerical simulations.

2. System configuration

Numerical simulation was performed for the transmission link schematically shown in Fig. 1. Ultrashort pulses (representing the signal 1's) from the optical transmitter are first stretched by CFBG1 with large anomalous dispersion and then entered a periodic transmission link. Each section of the link comprises a standard single-mode fiber (SSMF), a dispersion-compensating fiber (DCF), and an EDFA. The SSMF has the same sign of GVD as that of CFBG1 in order that compression of the stretched pulse in the SSMF could be prevented. We assume that the DCF can exactly compensates for chromatic dispersion of the SSMF so that the average dispersion of the transmission link is zero. The EDFA exactly compensates for energy loss produced by the SSMF and the DCF. After transmission, another CFBG2 (having the opposite dispersion of CFBG1) is used to recompress the broadened pulses.

3. Basic equations

The simulation is based on the generalized nonlinear Schrödinger (NLS) equation which takes the form

$$i\frac{\partial u}{\partial \xi} \pm \frac{1}{2}\frac{\partial^2 u}{\partial \tau^2} + |u|^2 u = -\frac{i}{2}\Gamma u + \frac{i}{2}\mu u, \tag{1}$$

where ξ, τ, and u are, respectively, the normalized distance, time, and field envelope in soliton units. The parameters Γ and μ account for, respectively, the fiber loss and the gain of the EDFA. The second term on left side represents GVD where the sign "+" or "−" is chosen, respectively, when the field is transmitted in the SSMF (anomalous GVD) the DCF (normal GVD). The third term on left side represents the Kerr nonlinearity.

Although a pseudo-random bit stream as an input is essential for accurate description of signal transmission in a realistic system, considerable physical insight could be gained with a limited number of input bits [3,37] when we only focus our attention on the suppression of the nonlinearities. Here the input is assumed to be the sum of four bits in the form

$$\begin{aligned} u(0,\tau) &= u_1(0,\tau+3q_0)+u_2(0,\tau+q_0)+u_3(0,\tau-q_0)+u_4(0,\tau-3q_0) \\ &= A_1\mathrm{sech}(0,\tau+3q_0)+A_2\mathrm{sech}(0,\tau+q_0)+A_3\mathrm{sech}(0,\tau-q_0) \\ &\quad +A_4\mathrm{sech}(0,\tau-3q_0) \end{aligned} \tag{2}$$

where $2q_0$ represents the duration of the bit slot and A_j (j = 1,2,3,4) represents the initial peak amplitude of the jth bit. We assume that all "1" bits have the same initial width and the same initial peak amplitude and that the "0" bits have a much smaller peak amplitude than that of the "1" bits. Substituting the input into Eq. (1), we obtain the following set of four coupled equations

$$\begin{aligned} i\frac{\partial u_1}{\partial \xi} \pm \frac{1}{2}\frac{\partial^2 u_1}{\partial \tau^2} + \frac{i}{2}\Gamma u_1 - \frac{i}{2}\mu u_1 = &-(|u_1|^2+2|u_2|^2+2|u_3|^2 \\ &+2|u_4|^2)\ u_1 - u_2^2u_3^* \\ &-2u_2u_3u_4^*, \end{aligned} \tag{3}$$

$$\begin{aligned} i\frac{\partial u_2}{\partial \xi} \pm \frac{1}{2}\frac{\partial^2 u_2}{\partial \tau^2} + \frac{i}{2}\Gamma u_2 - \frac{i}{2}\mu u_2 = &-(|u_2|^2+2|u_1|^2+2|u_3|^2 \\ &+2|u_4|^2)\ u_2 - u_3^2u_4^* \\ &-2u_1u_3u_2^* - 2u_1u_4u_3^*, \end{aligned} \tag{4}$$

$$\begin{aligned} i\frac{\partial u_3}{\partial \xi} \pm \frac{1}{2}\frac{\partial^2 u_3}{\partial \tau^2} + \frac{i}{2}\Gamma u_3 - \frac{i}{2}\mu u_3 = &-(|u_3|^2+2|u_1|^2+2|u_2|^2 \\ &+2|u_4|^2)\ u_3 - u_2^2u_1^* \\ &-2u_1u_4u_2^* - 2u_2u_4u_3^*, \end{aligned} \tag{5}$$

$$\begin{aligned} i\frac{\partial u_4}{\partial \xi} \pm \frac{1}{2}\frac{\partial^2 u_4}{\partial \tau^2} + \frac{i}{2}\Gamma u_4 - \frac{i}{2}\mu u_4 = &-(|u_4|^2+2|u_1|^2+2|u_2|^2 \\ &+2|u_3|^2)\ u_4 - u_3^2u_2^* \\ &-2u_2u_3u_1^*, \end{aligned} \tag{6}$$

In real parameters

$$\xi = \frac{z}{L_D} = \frac{z|\beta_2|}{T_0^2}, \quad \tau = \frac{t-z/v_g}{T_0}, \quad \Gamma = \alpha L_D = \frac{\alpha T_0^2}{|\beta_2|}, \\ \mu = (g_0-\alpha)L_D. \tag{7}$$

where z, t, v_g represent, respectively, distance, time, and group velocity. T_0 is the half-width (at $1/e$-intensity point) of the input "1" bit, β_2 is the GVD coefficient, α is the attenuation constant of the fiber, g_0 is the unsaturated gain parameter of the EDFA, and $L_D = T_0^2/|\beta_2|$ is the dispersion length. We do not include the Raman self-scattering (RSS) and self-steepening effects because, for quasi-linear strongly dispersion-managed transmission, the path-averaged bit width is very large and peak power is very low. Eqs. (3)-(6) and their modified version can be used to describe bits transmission in the SSMF, DCF, EDFA and CFBG. The differences are

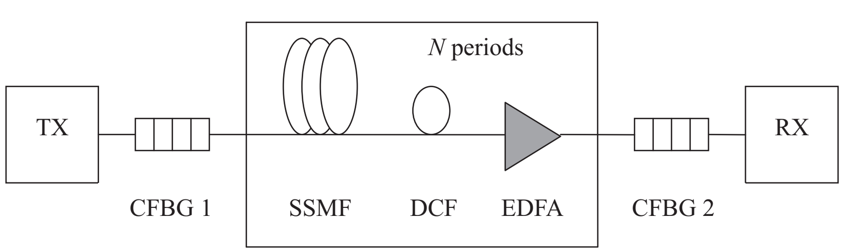

Fig. 1. Schematic diagram of quasi-linear strongly dispersion-managed transmission.