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Partial compensation of Kerr nonlinearities by optical phase conjugation in optical fiber transmission systems without power symmetry

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Abstract

We investigate the suppression of Kerr nonlinearities by optical phase conjugation (OPC) in a fiber transmission system without power symmetry by including all the manifestations of the Kerr nonlinearities. We found that OPC cannot completely compensate for all Kerr nonlinearities in absence of power symmetry, and some nonlinearities may become even worse if one of the nonlinearities is fully compensated. Therefore, it is necessary to optimize the compensation system to eliminate the most dominating nonlinearity. Simulation results are presented to demonstrate the interplay of various kinds of nonlinearities. The need of proper design for transmission systems to suppress the dominating nonlinear effect is shown when all manifestations of Kerr nonlinearity are not compensated simultaneously.

Keywords: Optical fiber communication; Optical Kerr effect; Optical phase conjugation; Spectral inversion

1. Introduction

In high-bit-rate transmission systems, one of the main causes of pulse degradation is nonlinear Kerr effect [1], which is categorized to two kinds: inter- and intra-channel nonlinearity. The inter-channel nonlinearity includes inter-channel four-wave mixing (FWM) and inter-channel cross-phase modulation (XPM). The intra-channel nonlinearity includes single pulse self-phase modulation (SPM), intra-channel FWM (IFWM) and intra-channel XPM (IXPM). It has been reported that optical phase conjugation (OPC) can compensate for one of the nonlinear impairments in various systems, such as the SPM of single pulse [2], inter-channel FWM in wavelength-division-multiplexed (WDM) systems [3], IXPM in 100-Gb/s single channel system [4], and inter-channel XPM in long WDM optical links [5]. Generally, there exists more than one nonlinear impairment in transmission systems. For example, for high-bit-rate single channel systems, single pulse SPM, IFWM and IXPM impair the system performance more or less. For WDM systems, not only inter-channel FWM and XPM but also intra-channel nonlinearities degrade the optical signals. Recently, simultaneous suppression of both SPM and inter-channel XPM by OPC and Raman amplification is shown through numerical simulation [4], and the reduction of the intra-channel nonlinearities by OPC in pseudolinear transmission is reported [6]. Numerous researches have shown that OPC can suppress one or more nonlinear effects in various optical systems. A question arises naturally: can OPC compensate for all the inter- and intra-channel nonlinear effects simultaneously in a transmission line? The answer is positive obviously for systems with power-symmetry. However, for practical systems without power-symmetry, we find that OPC cannot

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completely compensate for all Kerr nonlinearities. Some nonlinear effects may become even worse if one of nonlinear effects is fully compensated. In general, one of the nonlinear effects dominates others in a specific system and the main nonlinear effect may be different in different systems. Proper design of the transmission link with OPC to suppress the main nonlinearity is needed when all manifestations of Kerr effect are not compensated simultaneously.

The remainder of this paper is organized as follows. In Section 2, two specific systems are taken as examples to investigate the compensation for various inter- and intra-channel nonlinear impairments by use of OPC in the absence of power symmetry. Afterwards, the necessary of optimizing the nonlinearity-compensation transmission link with OPC to suppress the dominant nonlinear impairment is shown in Section 3. Section 4 presents the conclusion.

2. Effects of OPC on all the Kerr nonlinearities in the absence of power symmetry

Several groups have demonstrated that the Kerr nonlinearity can be compensated by midway OPC in an ideal system, in which the power and dispersion maps along the link are symmetry about the midway OPC and the odd order dispersions are neglected [2]. Analytically, the field in Schrödinger equation could be treated as a single pulse or a *pulse train.* Here we treat the field as a pulse train. Since in a WDM system all the inter- and intra-channel nonlinearities are originated from the nonlinear Kerr effect of the *pulse train* launched into the system, OPC can completely compensate for all the inter- and intra-channel nonlinear effects simultaneously in an ideal system.

It should be noted the modulation instability (MI) effect in transmission link can be interpreted in terms of a FWM process between the amplified spontaneous emission (ASE) noise and the signals, which is phase-matched by SPM [7]. The ASE noise is randomly generated and amplified by MI process along the fiber link. Focusing an ASE noise generated at somewhere of the first fiber span, we can deduce that the amplified noise can be compensated to its original power level at the symmetrical position about the OPC location. Therefore, the MI effect can be partially suppressed by midway OPC, which is demonstrated recently [8].

Any practical system is not a power-symmetry transmission link. Even the use of distributed Raman amplification is limited by the double Rayleigh backscattering. We present two cases to investigate the effect of OPC on all Kerr nonlinearities in absence of power symmetry. The system configurations of the two cases are shown in Fig. 1, which are composed of two spans of fibers with an optical conjugator (combined with an amplifier to compensate for the power loss of OPC and fiber absorption) between the two fibers. This configuration is called scaled translational symmetry link [9] where the dispersion parameters of the two spans fibers D_1 and D_2 have scaled mirror symmetry, and $D_1L_1 = D_2L_2$ (if there is no OPC, $D_1L_1 = -D_2L_2$), where L_1 and L_2 are the length of the first and the second span fiber, respectively.

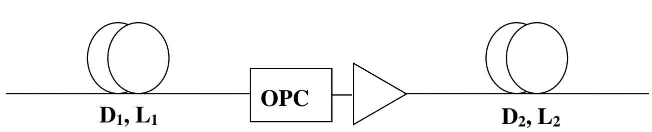

Fig. 1. Configuration of the scaled translational symmetry link.

In the first case, a 40 Gb/s nonreturn-to-zero (NRZ) WDM system is considered. Concentrating on the inter-channel FWM and single pulse SPM, the spectra of two channels near zero dispersion wavelength are shown in Fig. 2. The main parameters used in the simulations are peak power of signal pulse $P_0 = 10$ dBm, $\alpha = 0.21$ dB/km, $\gamma = 1.5$ km^{-1}/W, the dispersion parameter of the center channel $D_1 = 0.08$ ps/nm/km, $L_1 = L_2 = 120$ km, and the dispersion-slope of fiber is neglected. The channel spacing is 80 GHz. The input spectrum is presented in Fig. 2(a) and the output spectra are shown in Fig. 2(b)–(e). Fig. 2(b) corresponds to the power-symmetry system ($\alpha_2 = -\alpha_1$) without OPC. It can be seen that the spectra of the two channels are broadened, which results from single pulse SPM. Meanwhile two new frequency components appear at frequencies of -80 and 160 GHz, respectively, due to the inter-channel FWM. The number of FWM-induced frequency components will increase rapidly with the channel number, thus for the general multi-channel WDM systems with constant channel spacing, the coherent interference between the FWM-induced frequency components and the signal will degenerate the system performance seriously. In the power-symmetry system with OPC, the output spectrum is presented in Fig. 2(c), which shows that OPC can suppress all the Kerr effects in this case. Considering practical power-asymmetry sys-

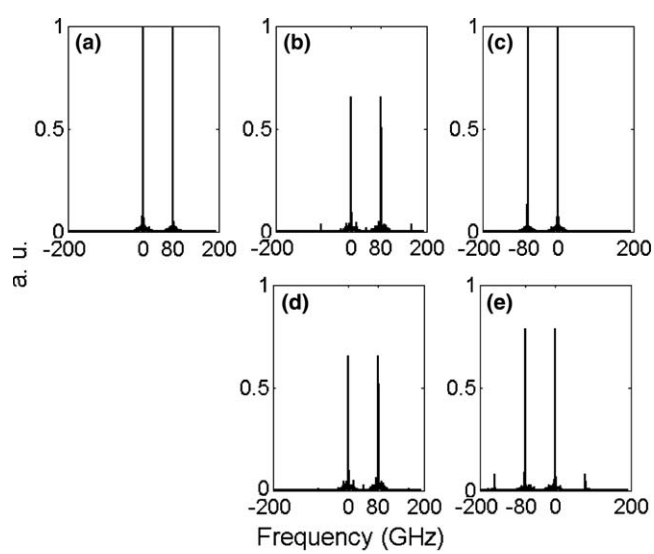

Fig. 2. The spectra of two channels in WDM system. (a) Input spectrum. Output spectrum of (b) power-symmetry system without OPC, (c) power-symmetry system with OPC, (d) power-asymmetry system without OPC, (e) power-asymmetry system with OPC.