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Effectiveness of phase-conjugated twin waves on fiber nonlinearity in spatially multiplexed all-optical OFDM system

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ABSTRACT

In this paper, we investigate the effectiveness of using phase-conjugated twin waves (PCTWs) technique to mitigate fiber nonlinear impairments in spatially multiplexed all-optical orthogonal frequency division multiplexing (AO-OFDM) systems. In this technique, AO-OFDM signal and its phase-conjugated copy are directly transmitted through two identical fiber links. At the receiver, the two signals are coherently superimposed to cancel the phase noise and to enhance signal-to-noise ratio (SNR). To show the effectiveness of proposed technique, a spatially multiplexed AO-OFDM system is demonstrated by numerical simulation. AO-OFDM signal and its phase conjugated copy are optically generated by using optical coupler-based inverse fast Fourier transform (OIFFT)/fast Fourier transform (OFFT). The generated signal includes 29 subcarriers where each subcarrier is modulated by 4-quadrature amplitude modulation (4QAM) format at a symbol rate of 25 Gsymbol/s. The results reveal that transmission performance is considerably improved where the transmission distance of the proposed system is increased by ∼45% as compared to that of original system without PCTWs technique.

1. Introduction

AO-OFDM systems have attracted considerable interests in recent years due to their intriguing ability to transmit higher data rate as compared to the conventional optical OFDM systems [1,2]. To enhance the spectral efficiency, the AO-OFDM systems employ a spectral efficient multi-level modulation format, such as m-array QAM (mQAM) format [2,3]. However, the achievable transmission distance is limited due to the distortion effect caused by fiber nonlinearity and amplified spontaneous emission (ASE) noise from the optical amplifiers. Specifically, AO-OFDM system that employs a high-order modulation format is highly sensitive to fiber nonlinearity such as self-phase modulation (SPM), cross phase modulation (XPM) and four-wave mixing (FWM) effects [4,5]. The interaction of fiber nonlinearity with ASE noise may cause a random phase noise, which is difficult to compensate due to its random nature.

Several compensation techniques have been proposed and demonstrated to mitigate fiber nonlinearity impairments. For instance, digital-back-propagation (DBP) technique was proposed to eliminate nonlinear distortion by inverting the distorted signal at the receiver digitally [6,7]. However, DBP requires solving the inverse nonlinear Schrödinger equation (NLSE) for the channel and is computationally expensive. The optical based compensation techniques were also proposed to suppress the nonlinear phase noises in the optical domain to reduce the processing time. The optical diversity transmission based on the coherent superposition of light waves have also been reported in recent years to mitigate fiber nonlinearity [8,9]. In this technique, an optical signal and its replicas have been simultaneously transmitted through multi-core/fiber and they have been coherently superimposed at the reception. Furthermore, in order to achieve the full benefit of coherent superposition, the nonlinear distortions need to be decorrelated using some types of scrambling functions [10]. The performance of the system has been improved in the presence of nonlinear phase noise, where a SNR has been observed to be directly proportional to the number of superimposed signals. However, the spectral efficiency is inversely proportional to the number of cores. A mid-link optical phase conjugation (OPC) technique has been proposed to cancel the nonlinear distortion [11–13]. However, the effectiveness of nonlinearity cancellation of OPC technique has been governed by symmetry conditions where the OPC has been inserted at the middle point of the link. This condition can significantly reduce the flexibility in an optical network. Another interesting method called phase-conjugated twin waves (PCTWs) has been proposed to cancel the nonlinear distortion by

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transmitting a signal and its phase-conjugated copy on the two signaling dimensions [14,15]. The nonlinear distortion cancellation can be achieved by coherently superimposing twin waves. The effectiveness of the PCTWs technique has been demonstrated by transmitting PCTWs on two orthogonal polarization states [14]. Moreover, the PCTWs technique has been investigated on different wavelengths [15]. The PCTWs technique has also been implemented in two different subcarriers frequency where half OFDM subcarriers have been transmitted as phase-conjugated of other subcarriers [16,17]. However, by using PCTWs technique, the system sacrifices half of the spectral efficiency. In order to increase the spectral efficiency, a phase-conjugated pilot (PCP) technique has been proposed to cancel the fiber nonlinearity by transmitting a portion of the OFDM subcarriers as phase-conjugates of other subcarriers [16].

In this paper, effectiveness of the PCTWs technique on the nonlinear phase noise in spatially multiplexed AO-OFDM is analytically modeled and numerically demonstrated. In this technique, the AO-OFDM signal and its phase-conjugated copy are simultaneously transmitted through two orthogonal optical paths. At the receiver, the two signals are coherently combined to cancel the correlated distortion and to maximize the SNR. A numerical results show that the proposed scheme significantly improves nonlinearity tolerance and considerably enhances achievable transmission distance. The transmission distance of the proposed system that employs 4QAM format is increased by ~45% as compared to that of original system without PCTWs technique.

The rest of the paper is organized as follows. Section 2 describes the basic principle of effect PCTWs technique on the nonlinear phase noise. The proposed all-optical OFDM system setup is presented in Section 3. The simulation results are presented in Section 4, where the impact of PCTWs technique on the transmission performance of proposed system is demonstrated in detail. Finally, a conclusion is drawn in Section 5.

2. Basic principle

The propagating PCTWs trough two orthogonal dimensions leads to anticorrelated nonlinear distortions on the two waves [14,18]. The distortions can then be cancelled by linear superposition. In fact, the nonlinear distortions of two waves become anticorrelated if the symmetrical dispersion map is adopted. The symmetrical dispersion map can be implemented in various schemes such as inline symmetric dispersion compensation [19], lumped dispersion compensation [20] and electrical predispersion compensation (pre-ECD) [21]. There are many schemes have been reported to implement the inline symmetric compensation using dispersion compensating fiber (DCF). The alternately using pre- and post- dispersion compensation sections over fiber link has been proposed to diminish the Kerr nonlinearity [19,22], and using pre- and post- dispersion compensation sections in each fiber span in which the dispersion compensation is split into two sections of the equal dispersion amount placed before and after the standard single mode fiber (SSMF) [19,23].

The simplified diagram of a spatially multiplexed transmission link based on PCTWs technique, in which the phase-conjugated twin waves are transmitted over two identical fiber links, is shown in Fig. 1. In our system, to cancel the nonlinear distortions, the PCTWs are spatially transmitted over two identical fiber links, which have the same lengths, fiber parameters, and optical amplifiers. The dispersion is compensated by adopting inline symmetrical dispersion map using two DCFs in each span, in which the first DCF pre-compensate half dispersion of SSMF, while the second DCF compensate the residual dispersion. In fact, to achieve the full benefit of proposed technique and to minimize the cost of implementation, two signals should be transmitted over a multi-core fiber link with integrating optical amplifiers. In long haul transmission link, the nonlinear distortion is induced by fiber nonlinearity and its interaction with ASE noise [6]. That means the nonlinear distortion consists of two types of distortion and one of them has random nature. The proposed technique is able to cancel the nonlinear distortion due to fiber nonlinearity. Unfortunately, both distortions that caused by interaction between ASE noise and fiber nonlinearity (parametric noise amplification [24]) and noise of optical amplifiers cannot be cancelled by PCTWs technique due to their random nature. The PCTWs are coherently superimposed at the receiver site to produce a received signal with lower nonlinear distortion. At the end of the transmission link, the optical field of twin signals can be expressed as:

$$\begin{aligned} u_1(z,t) &= u(0,t) + \delta u_1, \\ u_2(z,t) &= u^*(0,t) + \delta u_2, \end{aligned} \tag{1}$$

where $u_1(z,t)$ and $u_2(z,t)$ are the optical fields of signal and its phase-conjugated copy at end of fiber links, respectively, z is the transmission distance, $u(0,t)$ and $u^*(0,t)$ are the optical fields of transmitted signal and its phase-conjugated copy. Here δu_1 and δu_2 represent the distortions of $u_1(z,t)$ and $u_2(z,t)$ signals, respectively. The distortions of δu_1 and δu_2 are caused by fiber nonlinearity, parametric noise amplification and ASE noise and thus they can be expressed as:

$$\begin{aligned} \delta u_1 &= \delta u_{1NL} + \delta u_{1R} \\ \delta u_2 &= \delta u_{2NL} + \delta u_{2R} \end{aligned} \tag{2}$$

where δu_{1NL} and δu_{2NL} are distortions due to fiber nonlinearity while δu_{1R} and δu_{2R} are random distortions due to parametric noise amplification and ASE noise. After coherent superposition of PCTWs and averaging the received signal, the field of received signal becomes;

$$u(z,t) = \frac{u_1(z,t) + u_2^*(z,t)}{2} = u(0,t) + \frac{\delta u_{1NL} + (\delta u_{2NL})^*}{2} + \frac{\delta u_{1R} + (\delta u_{2R})^*}{2} \tag{3}$$

In the proposed system, both waves are modulated by the same optical carrier before they are launched to propagate over two identical fiber links with symmetrical dispersion map, leading to anticorrelation between nonlinear distortions of two waves, $\delta u_{1NL} = -(\delta u_{2NL})^*$ [18]. Therefore, it is possible for the nonlinear distortions of two waves to cancel each other out when they are coherently combined [14,18]. However, the random distortion of the received signal is included in term $[\delta u_{1R} + (\delta u_{2R})^*]/2$. At receiver site, the phase noises of two signals contribute to produce a random phase noise in the received signal after coherent superposition. Therefore, random phase noise of the received signal, ϕ_R, can be expressed as:

$$\phi_R = \frac{\phi_{1R} + \phi_{2R}}{2}, \tag{4}$$

where ϕ_{1R} and ϕ_{2R} are the random phase noises due to distortions δu_{1R} and δu_{2R}, respectively. It can be concluded from Eq. (4) that the PCTWs technique is able to mitigate the random phase noise rather than cancel it. The phase noise variance of received signal $\sigma^2_{\phi_R}$ can be written as:

$$\sigma^2_{\phi_R} = \frac{\sigma^2_{\phi_{1R}} + \sigma^2_{\phi_{2R}}}{4}, \tag{5}$$

where $\sigma^2_{\phi_{1R}}$ and $\sigma^2_{\phi_{2R}}$ are the variances of random phase noise of signal and its phase-conjugated copy, respectively. Both phase noises, ϕ_{1R} and ϕ_{2R}, are induced randomly inside optical amplifiers by ASE noise and its interaction with nonlinear fiber impairments such as SPM, XPM and FWM. It is well-known that the phase noise variance depends on the intensity of transmitted signal at certain magnitudes of fiber and amplifier parameters [4,6]. Fortunately, the intensities of the signal and its phase-conjugated copy are equal, yielding