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Mitigation of phase noise in all-optical OFDM systems based on minimizing interaction time between subcarriers

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ABSTRACT

A new approach to mitigate the phase noise in all-optical OFDM systems is analytically modeled and numerically demonstrated. The interaction time between subcarriers is minimized by shaping the envelopes of QAM subcarriers and making a delay time between even and odd subcarriers. Return-to-zero (RZ) coding is adopted for shaping the envelopes of subcarriers. In addition, the subcarriers are alternately delayed (AD) by optical time delayers. The performance of an all-optical OFDM system, that implements the proposed technique, is analyzed and simulated. This system has 29 subcarriers with symbol rate of 25 Gsymbol/s and is composed of coupler-based inverse fast Fourier transform (IFFT)/fast Fourier transform (FFT) schemes. Each subcarrier is modulated with QAM format before shaping with RZ coding. Due to RZ being more affected by dispersion; a full periodic dispersion map is adopted to keep the total accumulated dispersion low. The results reveal that the nonlinear phase noise (NPN) due to fiber nonlinearity is significantly mitigated when the time delay between the odd and even subcarriers is equal to half the symbol period. The total phase noise variance is reduced from 9.3×10^{-3} to 6.1×10^{-3} rad^2 when employing AD RZ-QAM for a transmission distance of 550 km. Furthermore, both the transmission distance and optical signal to noise ratio (OSNR) are improved when compared to all-optical OFDM systems that adopt traditional QAM modulation formats.

1. Introduction

All-optical OFDM (AO-OFDM) systems, that employ high order modulation formats, are becoming attractive as they can transmit data a higher bit rates when compared to conventional optical OFDM systems [1]. AO-OFDM systems combined with spectral efficient multilevel formats, like m-array quadrature amplitude modulation (mQAM) represent a proven solution to target the upgrade of optical communication systems due to the ability to transmit high bit rate data with good dispersion tolerance [2,3]. However, AO-OFDM signals show high sensitivity to phase noise due to the fiber nonlinearity and laser phase noise [4]. The phase noise due to fiber nonlinearity, such as self-phase modulation (SPM), cross-phase modulation (XPM) and four-wave mixing (FWM), restricts the performance of OFDM systems [5,6]. The interaction between fiber nonlinearity and random noise of optical amplifiers may lead to deterministic as well as stochastic impairments. In addition, the high number of subcarriers and low frequency spacing between subcarriers make both FWM and XPM as major factors for limiting the performance of optical OFDM systems [7]. Subcarrier power, transmission length, number of subcarriers, and number of amplifiers determine the nonlinear phase noise [5].

To enhance the tolerance towards the fiber nonlinearity effects, return-to-zero (RZ) formats have been proposed in many single and multi-channel optical communication systems [8–10]. Moreover, the combination of RZ with DQPSK techniques has been reported as more tolerant to fiber nonlinearity [2]. Although, RZ formats is more tolerant to fiber nonlinearity effects, it is more affected by dispersion [11]. Thereby, dispersion-managed transmission fiber links that include a standard single-mode fiber (SSMF) in alternation with dispersion compensating fiber (DCF) have been employed to minimize accumulated dispersion.

Various schemes have been reported to mitigate the nonlinear phase noise in multichannel systems based on reducing the interaction between subcarriers. Among them, polarization interleaving method has been employed [9,12]. However, polarization

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interleaving is highly sensitive to polarization mode dispersion (PMD) and polarization dependent loss (PDL). The dispersion interleaving method has been proposed to reduce the interface between adjacent channel interference in wavelength-division multiplexing (WDM) techniques [13]. This method utilizes the residual fiber dispersion to mitigate the interference of adjacent channels. Furthermore, the interleaved OFDM (IL-OFDM) has been proposed to reduce the peak-to-average power ratio (PAPR) and phase noise [14,15]. However, the half subcarriers are reserved and the transmission capacity of the system is reduced.

In this paper, we propose a new approach for mitigating the phase noise by minimizing the interaction time between subcarriers. This is accomplished by shaping the envelopes of QAM subcarriers and making delay times among successive subcarriers. After each QAM modulator, a Mach–Zehnder modulator (MZM) is employed to reshape QAM signals and produce RZ-QAM signals with envelopes of cosine shapes. When optical time delayers are inserted in even subcarriers paths, the odd and even subcarriers are alternately delayed (AD) and AD RZ-QAM OFDM signals are produced. The dispersion-managed transmission fiber link is employed to minimize the effect of dispersion on AD RZ-QAM OFDM signal. To keep the time slot for optimum gating at normal frequency, RZ-QAM is converted to QAM before the sampling process by utilizing Mach–Zehnder interferometer (MZI) with delay time equal to half the symbol period [16]. In our approach, we focus on the mitigation of phase noise in single polarization. The polarization multiplexing OFDM system adds other significant interferences between the *x*- and *y*-polarized signals such as the cross-polarization modulation (XPolM). It is very important to discuss our approach in polarization-multiplexing systems in future work. Our analytical model and results reveal that the optimum delay time is equal to half the symbol duration, where the phase noise due to both XPM and FWM are reduced to 1/4 and 1/8 of that of traditional QAM OFDM systems, respectively. In addition, the performance of proposed system is superior to all-optical OFDM systems that adopt QAM techniques.

The rest of the paper is organized as follows. In Section 2, the analytical model of our proposed all-optical OFDM system is described. The schematic of proposed all-optical OFDM system setup is presented in Section 3. The analytical and simulation results are presented in Section 4, where the impacts of delay time on the variance of the total phase noise and transmission distance are studied. The validation of our analytical model using simulation results is presented in the same section as well. Finally, the conclusion is given in Section 5.

2. Analytical model of proposed system

In this section, we provide an analytical model that best describes our all-optical AD RZ-QAM OFDM system. A comparison with traditional QAM OFDM systems is analytically presented to explore the efficiency of proposed phase noise mitigation. Generally, the nonlinear phase noise is caused by fiber Kerr nonlinearity such as SPM, XPM, and FWM [5]. Moreover, the amplified spontaneous emission (ASE) due to optical amplifiers adds a random nonlinear phase noise that mainly affects the SPM, XPM, and FWM phenomena [7]. The analytical model of nonlinear interaction between the optical signal and the nonlinear effects in AD RZ-QAM all-optical OFDM system is derived in this section. The optical field of the all-optical OFDM signal can be written as

$$u(z,t)=\sum_{k=-(N-1)/2}^{(N-1)/2}u_k(z,t)\exp(j\omega_k t), \tag{1}$$

where N represents the total number of subcarriers (assumed odd

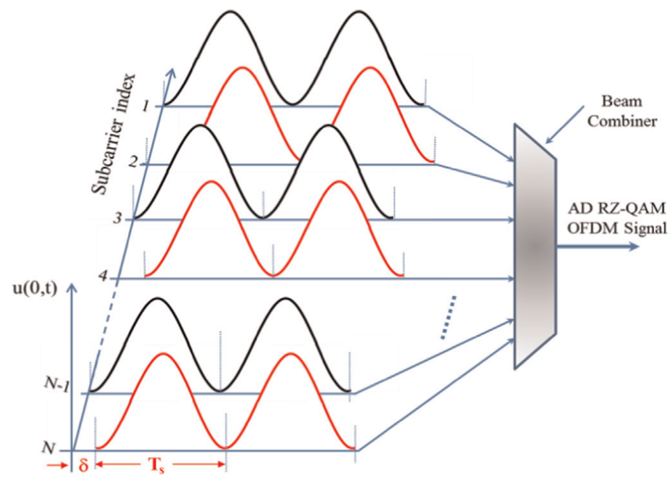

Fig. 1. Illustration of proposed odd and even subcarriers. δ is the delay time and T_s is the symbol period.

without loss of generality), $\omega_k=2\pi k/T_s$ is the frequency offset from the reference optical carrier, T_s is the OFDM symbol time, $u_k(z,t)$, $k\in\{-(N-1)/2,-(N-1)/2+1,\ldots,(N-1)/2\}$, is normalized slowly varying field envelope of a single subcarrier. At the transmitter side, $u_k(z,t)$ is given by

$$u_k(0,t)=\sqrt{\frac{P}{2}}A_k\mathrm{rect}\left(\frac{t-kT_s}{T_s}\right), \tag{2}$$

where P is an optical power of a single subcarrier, A_k is a complex number determined by the QAM constellation, and

$$\mathrm{rect}(t)=\begin{cases}1; & \text{if } 0\le t\le 1,\\ 0; & \text{otherwise.}\end{cases}$$

An optical RZ carver is used after the QAM modulator in order to generate RZ-QAM formats. The RZ carver is composed of an MZM that is driven by a cosine wave with frequency of $f_s=1/T_s$. The RZ-QAM signal has a sinusoidal-like envelope as shown in Fig. 1. By assuming the transfer characteristic of MZM is linear and it is biased at quadrature point, the sinusoidal-like envelope is defined as

$$EN(t)=\frac{1-\cos(2\pi f_s t)}{2}. \tag{3}$$

The RZ-QAM subcarrier can be written as

$$u_{k_{RZ-QAM}}(0,t)=u_k(0,t)EN(t). \tag{4}$$

In our proposed system, the subcarriers are individually modulated by RZ-QAM modulators. After that, the subcarriers that have an even index are delayed from odd subcarriers by time delay δ as shown in Fig. 1. After combining the subcarriers, the transmitted signal can be expressed as

$$u(0,t)=\sum_{k\in O}u_k(0,t)EN(t)\exp(j\omega_k t)+\sum_{k\in\mathcal{E}}u_k(0,t-\delta)EN(t-\delta)\exp[j\omega_k(t-\delta)] \tag{5}$$

where $O=\{-(N-1)/2+1,-(N-1)/2+3,\ldots,(N-1)/2-1\}$ and $\mathcal{E}=\{-(N-1)/2,-(N-1)/2+2,\ldots,(N-1)/2\}$. We define the odd and even subcarriers as

$$\begin{aligned}u_{ok}(0,t)&=u_k(0,t)EN(t), && k\in O\\ u_{ek}(0,t)&=u_k(0,t-\delta)EN(t-\delta), && k\in\mathcal{E}\end{aligned} \tag{6}$$

respectively. The interaction between odd and even subcarriers is governed by both their envelope shape and delay time between them. The average interaction of odd and even subcarriers can be expressed as follows. For any $k \in O$, $i \in \varepsilon$, we have

$$\overline{u_{ok}u_{ei}} = \frac{P}{8T_s}\overline{A_kA_i}\int_0^{T_s}\left[1 - \cos(2\pi f_s t)\right]\left[1 - \cos(2\pi f_s(t-\delta))\right]dt$$
$$= \frac{P}{16}\overline{A_kA_i}\left[2 + \cos(2\pi f_s\delta)\right]. \quad (7)$$

Similarly, the average interaction between odd and odd subcarriers or even and even subcarriers can be written as

$$\overline{u_{ok}u_{oi}} = \frac{P}{8T_s}\overline{A_kA_i}\int_0^{T_s}\left[1 - \cos(2\pi f_s t)\right]\left[1 - \cos(2\pi f_s(t))\right]dt$$
$$= \frac{3P}{16}\overline{A_kA_i}, \ \overline{u_{ek}u_{ei}}$$
$$= \frac{3P}{16}\overline{A_kA_i}. \quad (8)$$

It is clear that (8) represents the interaction of subcarriers for RZ-QAM OFDM system. On the other hand, the average interaction of two OFDM subcarriers that are modulated by traditional QAM format is given by $\overline{u_ku_i} = \frac{P}{2}\overline{A_kA_i}$. That is, the average interaction of RZ-QAM OFDM subcarriers ($\delta = 0$) is 3/8 that of QAM OFDM system, whereas at a delay time of $\delta = T_s/2$, the average interaction of AD RZ-QAM OFDM subcarriers is 1/8 that of QAM OFDM system

2.1. XPM phase noise

It is well known that XPM refers to the nonlinear phase shift of an optical field induced by another field with different wavelength, direction, or state of polarization. In long haul transmission system, the optical signal is commonly transmitted through multi-span optical fiber. Each span is constructed of a single mode optical fiber, a dispersion compensation fiber, and an optical amplifier. In an all-optical OFDM link, the XPM phase noise is accumulated span-by-span [17]. For M spans, the XPM phase noise can be written as

$$\phi_{kXPM}(ML) = 2\gamma L_{eff}(L)\sum_{m=1}^{M}\sum_{\substack{i=-(N-1)/2\\ i\neq k}}^{(N-1)/2}\left|u_i(0,t)\right|^2, \quad (9)$$

where γγ is the nonlinear coefficients, L is length of fiber span, and $L_{eff} = \left(1 - e^{-\alpha L}\right)/\alpha$ with α denoting the attenuation coefficient. For an OFDM system employing QAM modulation, $u_i(0,t) = \sqrt{P/2}A_i$, the XPM phase noise due to interaction of kth subcarrier with other subcarriers can be written as

$$\phi_{kXPM}(ML) = M\gamma PL_{eff}(L)\sum_{\substack{i=-(N-1)/2\\ i\neq k}}^{(N-1)/2}\overline{A_i^2}. \quad (10)$$

For the AD RZ-QAM OFDM system, the odd subcarriers can interact with either odd or even subcarriers. By substituting (7) and (8) in (9), the XPM phase noise can be written as

$$\phi_{okXPM}(ML) = \frac{3\gamma ML_{eff}(L)P}{8}\sum_{\substack{i=-(N-1)/2\\ i\in O,\, i\neq k}}^{(N-1)/2}\overline{A_{oi}^2}$$
$$+ \left(2 + \cos(2\pi f_s\delta)\right)\frac{\gamma ML_{eff}(L)P}{8}\sum_{\substack{i=-(N-1)/2\\ i\in\mathcal{E}}}^{(N-1)/2}\overline{A_{ei}^2} \quad (11)$$

In (11), the first term represents the XPM phase noise due to odd subcarriers while the XPM phase noise due to even subcarriers is characterized in second term. From (11), it is clear that the XPM phase noise is substantially suppressed at $\delta = T_s/2$ compared to that produced in QAM OFDM.

Another important phase noise occurs in links that include optical amplifiers. The optical amplifiers are employed to compensate the power degradation of the optical signal due to fiber attenuation. At the output of each amplifier, an ASE noise field is added to each subcarrier. The ASE noise is effectively defined as a white Gaussian noise with variance of σ^2. The interactions of XPM and FWM with ASE noise produce random nonlinear phase noises. These phase noises generate deterministic as well as stochastic impairments. Furthermore, the interaction of fiber Kerr nonlinearity with ASE noise cannot be compensated in receivers by digital backward propagation or other electrical compensating techniques [5]. In QAM OFDM systems, the nonlinear phase noise due to interaction of XPM with ASE noise through M spans can be expressed as [18,19]

$$\phi_{kXPM}^{n}(ML) = 2\gamma L_{eff}(L)\sum_{\substack{i=-(N-1)/2\\ i\neq k}}^{(N-1)/2}\sum_{m=1}^{M}\left[u_i^*\sum_{\mu=1}^{m}n_{i\mu} + u_i\sum_{\mu=1}^{m}n_{i\mu}^*\right] \quad (12)$$

where $n_{i\mu}(t)$, $\mu \in \{1, 2, \ldots, M\}$, is the complex amplifier noise at the μth span and ith subcarrier which have noise variance of σ_i^2. The nonlinear phase noise variances due to interaction of XPM with ASE can be written as [18]

$$\sigma^2_{\phi^n_{kXPM}}(ML) = 2M(M+1)\gamma^2L_{eff}(L)^2P\sum_{\substack{i=-(N-1)/2\\ i\neq k}}^{(N-1)/2}\overline{A_i^2}\sigma_i^2 \quad (13)$$

For RZ-QAM OFDM system, the phase noise variance due to interaction of XPM with ASE can be determined by substituting (8) in (12):

$$\sigma^2_{\phi^n_{kXPM}}(ML) = \frac{3M(M+1)}{4}\gamma^2L_{eff}(L)^2P\sum_{\substack{i=-(N-1)/2\\ i\neq k}}^{(N-1)/2}\overline{A_i^2}\sigma_i^2 \quad (14)$$

For our proposed system, by substituting (7) and (8) in (12), the phase noise variance due to interaction of XPM with ASE can be expressed as

$$\sigma^2_{\phi^n_{okXPM}}(ML,\delta) = \frac{M(M+1)}{4}\gamma^2L_{eff}(L)^2P$$
$$\times\left[3\sum_{\substack{i=-(N-1)/2\\ i\in O,\, i\neq k}}^{(N-1)/2}\overline{A_{oi}^2}\sigma_i^2 + \left(2 + \cos(2\pi f_s\delta)\right)\sum_{\substack{i=-(N-1)/2\\ i\in\mathcal{E}}}^{(N-1)/2}\overline{A_{ei}^2}\sigma_i^2\right] \quad (15)$$

The effect of odd and even subcarriers is demonstrated in first and second parts of (15), respectively. It is clear that, at $\delta = T_s/2$, the minimum phase noise variance occurs and its magnitude is 1/4 times the phase noise variance for QAM subcarrier. Furthermore, the phase noise variance for RZ-QAM ($\delta = 0$) is 3/8 times the phase noise variance of QAM OFDM system.

2.2. FWM phase noise

In this subsection, the influence of proposed system on the FWM and its interaction with amplifiers noises is demonstrated analytically. In fact, the FWM process is a phase sensitive process where the interaction depends on the relative phases of all subcarriers and its effect accumulates over distances. The FWM process adds a significant fluctuation to the OFDM optical signal because the frequency spacing between subcarriers is equal to the symbol rate. This fluctuation causes a high nonlinear phase noise in OFDM signal. The FWM fluctuation can be defined as

$$\delta u_k(z,t) = j2\gamma \sum_{\substack{h=-(N-1)/2\\ h\neq k}}^{(N-1)/2} \sum_{\substack{i=-(N-1)/2\\ l=h+i-k\\ i\neq l}}^{(N-1)/2} L_{FWM}(z) u_h(z,t) u_i(z,t) u_l^*(z,t) \tag{16}$$

where $L_{FWM}(z) = \left[1-\exp\left(j\Omega^2\frac{\beta_2}{2}z-\alpha z\right)\right]/\left(\alpha - j\Omega^2\frac{\beta_2}{2}\right)$ with β_2 denoting the dispersion profile and $\Omega^2 = {\omega_h}^2 + {\omega_i}^2 - {\omega_l}^2 - {\omega_k}^2$.

To investigate the reduction of FWM fluctuation by employing AD RZ-QAM OFDM technique, the FWM fluctuations for both QAM OFDM and AD RZ-QAM OFDM systems are compared. By substituting (2) in (16), the FWM fluctuation in QAM OFDM system can be written as

$$\delta u_k(z,t) = j\gamma P\sqrt{\frac{P}{2}} \sum_{\substack{h=-(N-1)/2\\ h\neq k}}^{(N-1)/2} \sum_{\substack{i=-(N-1)/2\\ l=h+i-k\\ i\neq l}}^{(N-1)/2} L_{FWM}(z)\left[A_h A_i A_l^*\right] \tag{17}$$

For the proposed system, the magnitude of the phase noise variance is governed by both the envelope shape and delay time between odd and even subcarriers. Table 1 shows the probability of interaction between the subcarriers. For odd subcarriers ($k \in O$), the probability of interaction of an odd subcarrier with two odd subcarriers is 1/4, while the probability of its interaction with even subcarriers is 3/4. By substituting (7) and (8) in (16), the FWM fluctuation in proposed system is:

$$\delta u_k(z,t) = j\gamma P\sqrt{\frac{P}{2}}\left[\frac{(EN(t))^3}{4} + \frac{3EN(t)(EN(t-\delta))^2}{4}\right] \times \sum_{\substack{h=-(N-1)/2\\ h\neq k}}^{(N-1)/2} \sum_{\substack{i=-(N-1)/2\\ l=h+i-k\\ i\neq l}}^{(N-1)/2} L_{FWM}(z)\left[A_h A_i A_l^*\right] \tag{18}$$

From the last equation, the magnitude of $EN(t)(EN(t-\delta))^2$is less than one for any $\delta > 0$. Moreover, both $EN(t)$ and $EN(t-\delta)$vary between zero and one so its effective magnitude is less than one. Therefore, the FWM fluctuation in proposed system is less than that in conventional system.

The reduction of the FWM fluctuation directly influences the random nonlinear phase noise. It is known that the interaction of FWM fluctuation with ASE noise produces random phase noises that degrade the performance of the system [5,20]. Moreover, the ASE noise adds a fluctuation to transmitted signal and produces an additional random phase noise. The nonlinear phase noise due to ASE noise and its interaction with FWM can be written as [18]:

Table 1
Probability of interaction between the subcarriers.

$k\in$	$h\in$	$i\in$	$l\in$	$h, i, l\in$
O	O	O	O	O,O,O
O	ε	O	ε	$\varepsilon, O, \varepsilon$
O	O	ε	ε	$O, \varepsilon, \varepsilon$
O	$\mathcal{E}$	$\mathcal{E}$	O	$\mathcal{E}, \mathcal{E}, O$
ε	O	O	$\mathcal{E}$	O,O,ε
ε	$\mathcal{E}$	O	O	ε,O,O
ε	O	$\mathcal{E}$	O	O,ε,O
ε	ε	ε	ε	$\varepsilon, \varepsilon, \varepsilon$

$$\sigma^2_{\varphi k(n(t)+FWM)}(ML) = \frac{M\sigma_k^2}{\overline{{u_k}^2}} + \frac{4\gamma^2}{\overline{{u_k}^2}} \sum_{m=1}^{M} \sum_{\substack{h=-(N-1)/2\\ h\neq k}}^{(N-1)/2} \sum_{\substack{i=-(N-1)/2\\ l=h+i-k\\ i\neq l}}^{(N-1)/2} L_{FWM}\left\{\overline{{u_h}^2}\,\overline{{u_i}^2}\sigma_l^2 + \overline{{u_h}^2}\,\overline{{u_l}^2}\sigma_i^2 + \overline{{u_i}^2}\,\overline{{u_l}^2}\sigma_h^2\right\}, \tag{19}$$

The first part of the last equation represents the phase noise due to the ASE noise only while the last part represents the phase noise due to the interaction of FWM with ASE noise. In order to explore the effect of employing the proposed approach on the phase noise variance, we analyze the first and last parts of (19) separately. By substituting (2) and (8) in first part of (19), the phase noise variance due to the ASE noise only can be written as

$$\sigma^2_{\varphi k\ n(t)}(ML) = \begin{cases} \dfrac{2M\sigma_k^2}{P\bar{A_k}^2} & \text{For QAM OFDM system} \\ \dfrac{16M\sigma_k^2}{3P\bar{A_k}^2} & \text{For AD RZ–QAM OFDM system.} \end{cases} \tag{20}$$

It is obvious from (19) that the effect of ASE noise on the AD RZ-QAM signal is higher than its effect on the QAM OFDM signal. This phenomenon is because RZ-QAM has lower pulse width than QAM signal. For QAM OFDM system, the last part of (19) can be expressed as

$$\sigma^2_{\varphi kFWM}(ML) = \frac{2\gamma^2 P}{\overline{{A_k}^2}} \times \sum_{m=1}^{M} \sum_{\substack{h=-(N-1)/2\\ h\neq k}}^{(N-1)/2} \sum_{\substack{i=-(N-1)/2\\ l=h+i-k\\ i\neq l}}^{(N-1)/2} L_{FWM}\left\{\overline{{A_h}^2}\,\overline{{A_i}^2}\sigma_l^2 + \overline{{A_h}^2}\,\overline{{A_l}^2}\sigma_i^2 + \overline{{A_i}^2}\,\overline{{A_l}^2}\sigma_h^2\right\}. \tag{21}$$

By substituting (7) and (8) in the last part of (19) and using Table 1 the phase noise variance for kth subcarrier in AD RZ-QAM OFDM system can be expressed as

$$\sigma^2_{\varphi kFWM}(ML,\delta) = \frac{\gamma^2 P}{\overline{{A_k}^2}}\left(\frac{3}{16} + \frac{\left(2+\cos(2\pi f_s\delta)\right)^2}{16}\right) \times \sum_{m=1}^{M} \sum_{\substack{h=-(N-1)/2\\ h\neq k}}^{(N-1)/2} \sum_{\substack{i=-(N-1)/2\\ l=h+i-k\\ i\neq l}}^{(N-1)/2} L_{FWM}\left\{\overline{{A_h}^2}\,\overline{{A_i}^2}\sigma_l^2 + \overline{{A_h}^2}\,\overline{{A_l}^2}\sigma_i^2 + \overline{{A_i}^2}\,\overline{{A_l}^2}\sigma_h^2\right\}. \tag{22}$$

From the last equation, it is clear that, at $\delta = T_s/2$, the phase noise variance due to interaction of FWM with ASE noise is 1/8 times that for QAM OFDM system. In addition, the phase noise variance for RZ-QAM format ($\delta = 0$) is 3/8 times that for QAM OFDM system.

3. All-optical OFDM system setup

In this section, we describe our proposed all-optical OFDM system setup including the transmitter, transmission link, and receiver.

3.1. All-optical OFDM transmitter

The schematic of an all-optical OFDM transmitter is depicted in Fig. 2 [1,21]. The transmitter consists of an optical frequency comb generator (OFCG), wavelength selected switch, optical QAM modulators, RZ carvers, and an optical beam combiner. The OFCG generates 29 subcarriers with frequency spacing of $\Delta f = 25$ GHz from a single laser source. Subsequently, the generated subcarriers are split and applied to optical QAM modulators. In each modulator, the QAM symbol is generated from a pseudo-random bit sequence generator. The QAM encoder is supplied by pseudo-random binary sequence (PRBS) signals with length of $2^{15}-1$. To preserve the orthogonality of the OFDM signals, the OFDM symbol duration is set to 40 ps ($T_s = 1/\Delta f$). That is, no-guard interval is used because the symbol duration is equal inverse frequency spacing. In case of generating QAM OFDM signal, the modulating signals are directly superimposed by using beam combiner. However to generate an AD QAM-RZ OFDM signal, first, the envelope of QAM subcarriers are changed to sinusoidal-like envelope by employing RZ carver after each QAM modulator. The RZ carver is composed of a single MZM, which is driven by cosine signal with a frequency of 25 GHz. The MZM is biased at quadrature bias point. Next, the RZ-QAM subcarriers that have even indices are delayed by a certain time to reduce the interaction time between subcarriers. Finally, the AD RZ-QAM OFDM signal is obtained by superimposing all subcarriers.

3.2. Transmission link

The transmission link utilizes multi-spans of fiber loops. Each fiber span consists of a SSMF, a DCF, and an Erbium doped fiber amplifier (EDFA) as shown in Fig. 2. The SSMF is modeled with an attenuation coefficient α of 0.2 dB/km, CD coefficient of 16 ps/nm/km, an effective area of 80 μm^2, and fiber nonlinearity γ of 1.3 W^{-1} km^{-1}. A full periodic dispersion map is adopted to compensate the dispersion by utilizing a DCF after the SSMF. The DCF has a CD coefficient of −160 ps/nm/km. For compensating the fibers losses, EDFAs (each has a noise figure of 6 dB) are employed at spans of 55 km spacing.

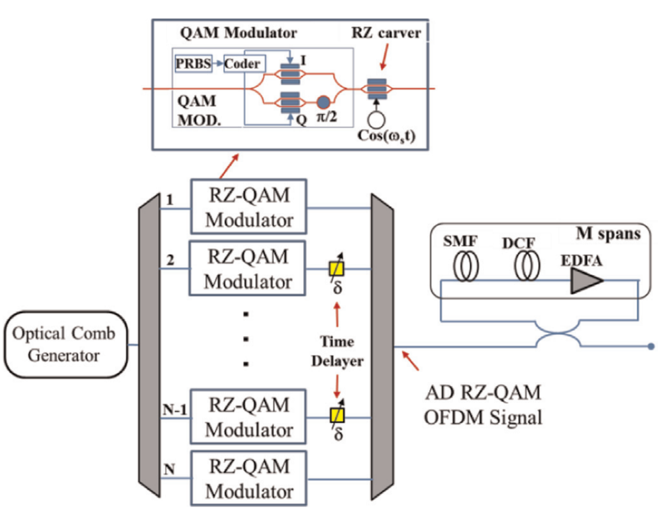

Fig. 2. Schematic of an AD RZ-QAM OFDM transmitter.

3.3. All-optical OFDM receiver

An all-optical OFDM receiver comprises all-optical FFT (OFFT) circuit [22,23] and coherent QAM optical detectors as shown in Fig. 3. The 4-order OFFT circuit is implemented based on three cascaded MZIs, electro-absorption modulators (EAMs), and optical filters. The time delay and phase shift of first MZI are adjusted to $T_s/2$ and 0 rad, respectively. The time delay of two other subsequent parallel MZIs is set to $T_s/2$, while the phase shift of the upper one is set at 0 rad and phase shift of lower one is $\pi/2$ rad . The outputs of 4-order OFFT are applied to demultiplexers to split the subcarriers [1]. In QAM OFDM system, the signals are directly sampled by EAM sampling gates. The output of each EAM is filtered by an optical band-pass filter before demodulating by coherent QAM optical detector.

In our proposed system, the aforementioned receiver is modified by adding one MZI with delay time of $T_s/2$ before each EAM as shown in Fig. 3. In all-optical OFDM, the gating is required after the OFFT. By using the RZ pulse, the time slot for optimum gating becomes shorter, making the gating more difficult. To cope with this problem, we have employed MZI at receiver to convert the received signal into QAM. The delay time between the arms of the MZI is set at $T_s/2$ so that the received signal can interfere with its delayed replica. This allows the RZ signal to be converted to QAM signal at the constructive port. The conversion of RZ-QAM signal to QAM signal before sampling process is useful to keep the time slot for optimum gating at normal frequency [16].

$$u_k = \frac{\sqrt{P}}{4\sqrt{2}} A_k \left\{ \left[1 - \cos\left(2\pi f_s t\right) \right] + \left[1 - \cos\left(2\pi f_s \left(t - T_s/2\right)\right) \right] \right\} = \frac{\sqrt{P}}{2\sqrt{2}} A_k \tag{23}$$

4. Results and discussion

In this section, the analytical model of the proposed system in Section 2 is carried out by MATLAB programming and compared with traditional all-optical QAM OFDM system. Moreover, the performance of our system is demonstrated by simulating the schematics in Figs. 2 and 3. The simulation is performed by VPI-transmissionMaker v9.0 software. The analytical estimation results are also verified by comparing with simulation results. Both the analytical and simulation results are achieved for 29 subcarriers. Each subcarrier is modulated by a RZ-QAM modulator at symbol rate of 25 Gsymbol/s.

4.1. Phase noise results

In order to determine the effect of the delay time on the phase noise variance due to the fiber nonlinearity, we set linewidths

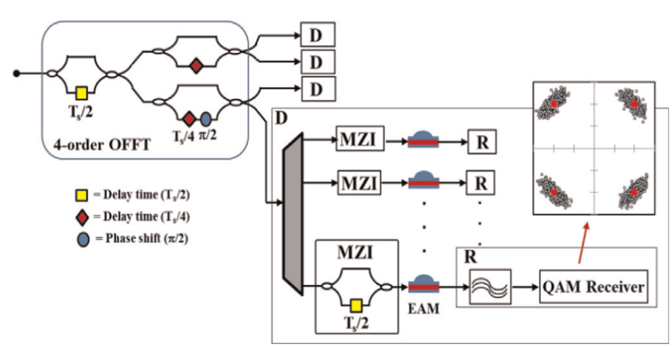

Fig. 3. Schematic of an AD RZ-QAM OFDM receiver.

(LWs) of the laser source and the local oscillator to zero in both Figs. 4 and 5. The dependence of the nonlinear phase noise variance on the delay time δ is shown in Fig. 4. The total phase noise variance is obtained by using both analytical modeling and simulation for a transmission distance of 550 km and subcarrier power of 3 dBm. The analytical results show that the phase noise variance (solid line) is reduced from 9.3×10^{-3}to6.1×10^{-3}rad^2 when the delay time δ is increased from zero to $T_s/2$. Increasing the delay time beyond $T_s/2$ would raise the phase noise variance back due to the increase in the interaction time between the subcarriers. The simulation results (squares) show similar behavior to the phase noise variance that was calculated from analytical model. The analytical and simulation results are in a good agreement.

Fig. 5 shows the influence of proposed approach on the mitigation of phase noise. The results are achieved at a transmission distance of 550 km and a delay time of $T_s/2$. Fig. 5(a) separately illustrates the phase noise variances of XPM, FWM, and ASE noise against subcarrier power. Generally, at low fiber launch power, the phase noise variance is mainly produced by the ASE noise since OSNR is low. When increasing the subcarrier power, the phase noises due to both XPM and FWM increase, whereas the phase noise due to the amplifier noise decreases. It can be seen that, when the AD RZ-QAM OFDM system is employed, the phase noise variances due to FWM and XPM are significantly reduced below that of QAM OFDM system, while the phase noise variance due to ASE noise is increased. For example, at a subcarrier power of 5 dBm, the phase noise variance due to FWM is 0.0034 rad^2 for AD RZ-QAM OFDM system while it is 0.0275 rad^2 for QAM OFDM system. In addition, at the same power level, the phase noise of XPM is reduced from 0.0087 rad^2 for QAM OFDM system to 0.00228 rad^2 for AD RZ-QAM OFDM system. The total phase noise variances of both systems versus the subcarrier power are shown in Fig. 5(b). As expected, the total phase noise variance decreases with increasing the power until an optimum power level then it starts to increase again. The figure also indicates that the optimum power level is 3 dBm for the proposed system, while it is −3 dBm for QAM OFDM system. Furthermore, the proposed system has lower phase noise variances at higher launch powers compared with that of QAM OFDM system. This is because the interaction time between the subcarriers is shorter. The presented simulation results show good agreement with analytical results.

4.2. Performance of proposed system

In this section, the performance of the proposed system is demonstrated by simulation and compared with traditional all-optical OFDM system. All our simulation results of the optical systems are achieved by VPItransmissionMaker 9.0 simulator. In

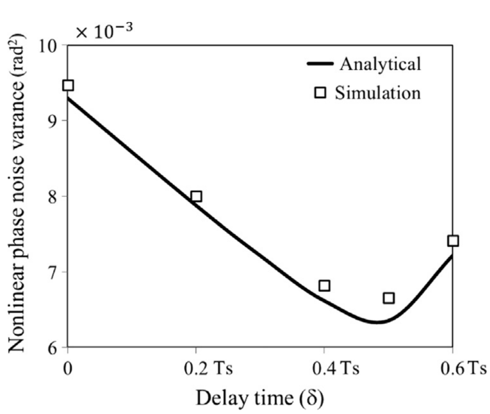

Fig. 4. The dependence of the nonlinear phase noise variance on the delay time δ.

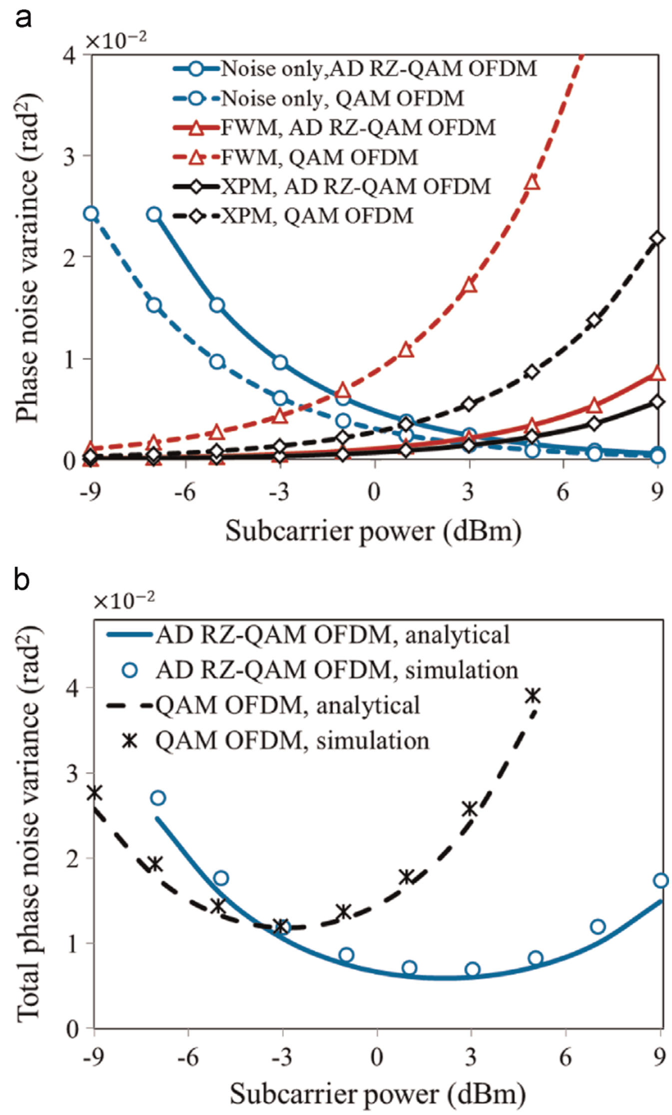

Fig. 5. Influence of proposed modulation format on the phase noise reduction: (a) details of phase noise and (b) total phase noise variance.

addition, all results are obtained without employing any nonlinear compensation program in receiver to investigate the mitigation efficiency of our approach.

To show the improvement in the transmission distance in the presence of fiber nonlinearities, Fig. 6 depicts the BER versus the transmission distance for both AD RZ-QAM OFDM and QAM OFDM systems. The results are obtained for 29 subcarriers at optimum power of each system. The linewidths (LWs) of the laser source and the local oscillator is set to 10^{-5} Hz. Generally, our system is able to transmit the data for longer distance, where the transmission distance for the proposed system is 2090 km at a BER of 10^{-5}, while it is only 1595 km for QAM OFDM system.

Fig. 7 shows the detected eye diagrams for both AD RZ-QAM OFDM and QAM OFDM baseband signals at transmission distances of 550 km and 1100 km. The eye diagrams represent the in-phase component (I) of detected QAM signal. The simulation results are achieved at optimum power of both systems. It is clear that the eye diagrams of the proposed system are clearer in both transmission distances. For both transmission distances, the eye heights of proposed system are larger than that of traditional QAM OFDM system. Moreover, for proposed system, the eye slowly closes with increasing the transmission distance compared with QAM OFDM system. This shows that the proposed system is able to mitigate

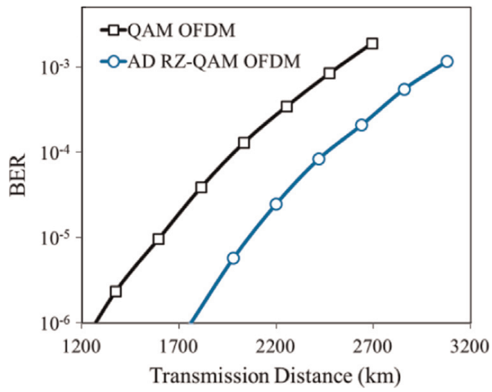

Fig. 6. BER versus transmission distance for both AD RZ-QAM OFDM and QAM OFDM systems.

the fiber nonlinearity impairments.

Finally, the BER performances of proposed and conventional systems are depicted in Fig. 8. The AD RZ-QAM OFDM system always exhibits a superior performance than QAM OFDM system. For a transmission distance of 550 km, the required OSNR for proposed system at BER$=10^{-5}$ is about 22 dB, while the required OSNR for the QAM OFDM system is about 23 dB at same BER. Furthermore, the performances of the systems are characterized for a transmission distance of 1100 km. That is, to obtain a BER of 10^{-5} for both systems, the proposed system requires an OSNR of 1 and 1.2 dB below that required for QAM OFDM system at transmission distances of 550 km and 1100 km, respectively.

5. Conclusion

A new and efficient approach to mitigate the phase noise in all-optical OFDM systems has been analytically modeled and numerically demonstrated. Minimizing the interaction time between subcarriers has been performed by shaping the envelopes of QAM OFDM subcarriers and shifting even subcarriers with respect to odd subcarriers by half the symbol duration. The analytical results show that the phase noise variances of the proposed system, due

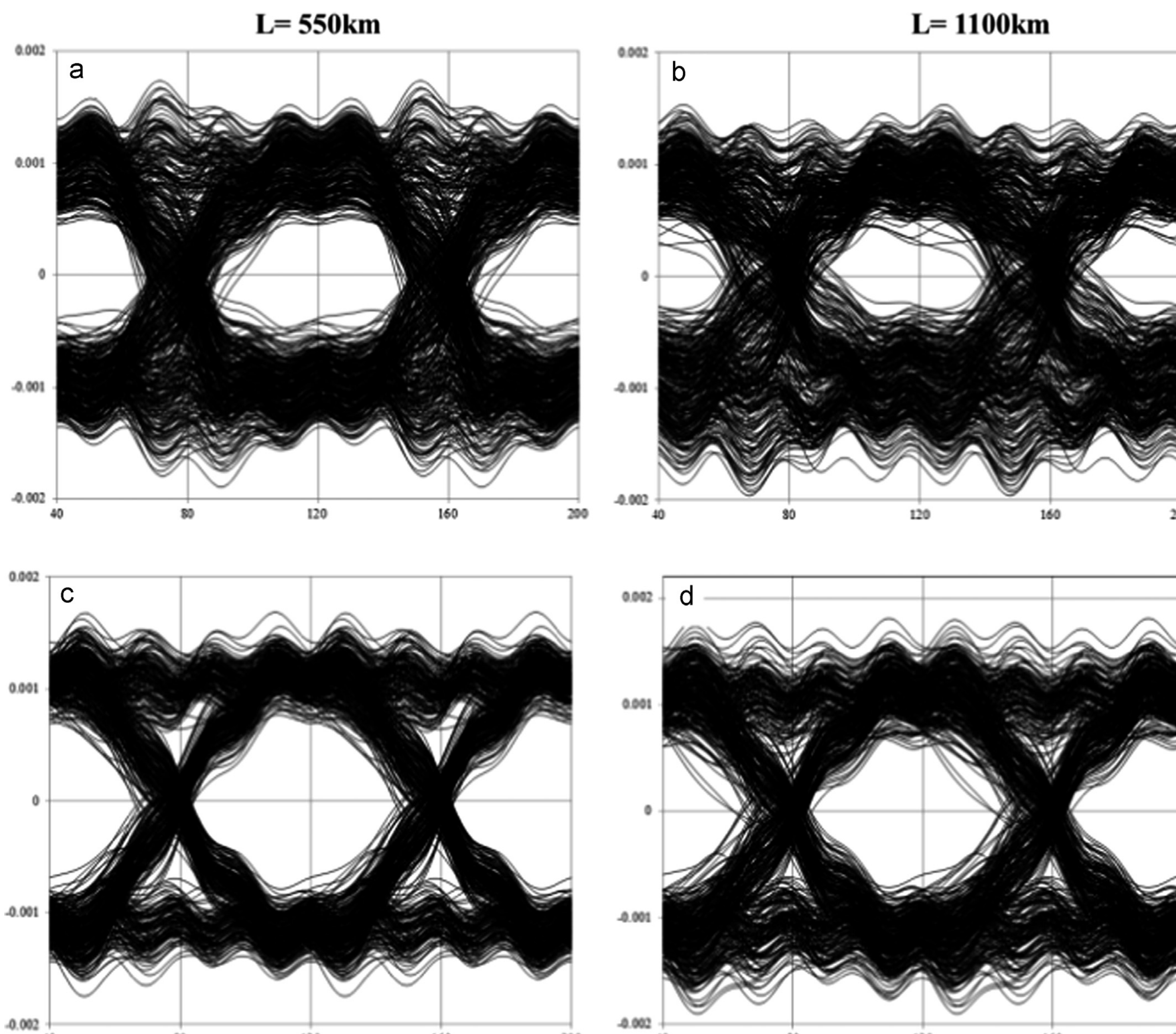

Fig. 7. Eye diagram of in-phase component (I) of received signal at 550 km and 1100 km: (a) and (b) QAM OFDM system, (c) and (d) AD RZ-QAM OFDM system.

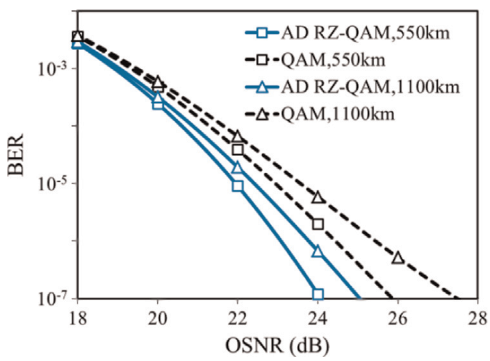

Fig. 8. BER performances of proposed and conventional systems.

to both XPM and FWM, are significantly reduced in the dispersion-managed fiber transmission link, when compared to that of all-optical QAM OFDM systems. Furthermore, at a BER of 10^{-5}, the achievable transmission distance is significantly increased from 1595 km with QAM OFDM system to 2090 km with AD RZ-QAM OFDM system. In addition, at a transmission distance of 1100 km, the required OSNR to obtain a BER of 10^{-5} is improved by 1.2 dB when compared to all-optical QAM OFDM system. Simulation results have been carried out and have been shown good agreement with analytical results.

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References

[1] D. Hillerkuss, R. Schmogrow, T. Schellinger, M. Jordan, M. Winter, G. Huber, T. Vallaitis, R. Bonk, P. Kleinow, F. Frey, 26 Tbit s-1 line-rate super-channel transmission utilizing all-optical fast Fourier transform processing, Nat. Photon. 5 (2011) 364–371.
[2] S.E. Mirnia, A. Zarei, S.D. Emami, S.W. Harun, H. Arof, H. Ahmad, H.M. Shalaby, Proposal and performance evaluation of an efficient RZ-DQPSK modulation scheme in all-optical OFDM transmission systems, J. Opt. Commun. Netw. 5 (2013) 932–944.
[3] Y.-K. Huang, E. Ip, Z. Wang, M.-F. Huang, Y. Shao, T. Wang, Transmission of spectral efficient super-channels using all-optical OFDM and digital coherent receiver technologies, J. Lightwave Technol. 29 (2011) 3838–3844.
[4] D.T. Pham, M.-K. Hong, J.-M. Joo, E.-S. Nam, S.-K. Han, Laser phase noise and OFDM symbol duration effects on the performance of direct-detection based optical OFDM access network, Opt. Fiber Technol. 17 (2011) 252–257.
[5] X. Zhu, S. Kumar, Nonlinear phase noise in coherent optical OFDM transmission systems, Opt. Express 18 (2010) 7347–7360.
[6] A.J. Lowery, S. Wang, M. Premaratne, Calculation of power limit due to fiber nonlinearity in optical OFDM systems, Opt. Express 15 (2007) 13282–13287.
[7] S.T. Le, K. Blow, S. Turitsyn, Power pre-emphasis for suppression of FWM in coherent optical OFDM transmission, Opt. Express 22 (2014) 7238–7248.
[8] K. Cheng, J. Conradi, Reduction of pulse-to-pulse interaction using alternative RZ formats in 40-Gb/s systems, IEEE Photon. Technol. Lett. 14 (2002) 98–100.
[9] R. Tripathi, R. Gangwar, N. Singh, Reduction of crosstalk in wavelength division multiplexed fiber optic communication systems, Prog. Electromagn. Res. 77 (2007) 367–378.
[10] M. Faisal, A. Maruta, Cross-phase modulation induced phase fluctuations in optical RZ pulse propagating in dispersion compensated WDM transmission systems, Opt. Commun. 283 (2010) 1899–1904.
[11] M. Hayee, A. Willner, NRZ versus RZ in 10-40-Gb/s dispersion-managed WDM transmission systems, IEEE Photon. Technol. Lett. 11 (1999) 991–993.
[12] D. van den Borne, S. Jansen, S. Calabrò, N. Hecker-Denschlag, G. Khoe, H. de Waardt, Reduction of nonlinear penalties through polarization interleaving in 2×10 Gb/s polarization-multiplexed transmission, IEEE Photon. Technol. Lett. 17 (2005) 1337–1339.
[13] J.B. Khurgin, S. Xu, M. Boroditsky, Reducing adjacent channel interference in RZ WDM systems via dispersion interleaving, IEEE Photon. Technol. Lett. 16 (2004) 915–917.
[14] Z. Cao, H. van den Boom, E. Tangdiongga, T. Koonen, Interleaved and partial transmission interleaved optical coherent orthogonal frequency division multiplexing, Opt. Lett. 39 (2014) 2179–2182.
[15] W. Long, J. Zhang, D. Wang, J. Han, S. Chen, A.M. Han, G. Gao, H. Leng, L. Liu, W. Zhu, Mitigation of the interference between odd and even terms in optical fast OFDM scheme based on interleaved multiplexing, IEEE Photon. Technol. Lett. 24 (2012) 1160–1162.
[16] J.K. Hmood, K.A. Noordin, H. Ahmad, S.W. Harun, Performance improvement of all-optical OFDM systems based on combining RZ coding with m-array QAM, J. Optoelectron. Adv. Mater. 17 (2015) 33–38.
[17] K.-P. Ho, J.M. Kahn, Electronic compensation technique to mitigate nonlinear phase noise, J. Lightwave Technol. 22 (2004) 779–783.
[18] J.K. Hmood, S.W. Harun, S.D. Emami, A. Khodaei, K.A. Noordin, H. Ahmad, H. M. Shalaby, Performance analysis of an all-optical OFDM system in presence of non-linear phase noise, Opt. Express 23 (2015) 3886–3900.
[19] N. Ekanayake, H.V.R. Herath, Effect of nonlinear phase noise on the performance of-Ary PSK signals in optical fiber links, J. Lightwave Technol. 31 (2013) 447–454.
[20] A.J. Lowery, L.B. Du, J. Armstrong, Performance of optical OFDM in ultralong-haul WDM lightwave systems, J. Lightwave Technol. 25 (2007) 131–138.
[21] D. Hillerkuss, T. Schellinger, R. Schmogrow, M. Winter, T. Vallaitis, R. Bonk, A. Marculescu, J. Li, M. Dreschmann, J. Meyer, Single source optical OFDM transmitter and optical FFT receiver demonstrated at line rates of 5.4 and 10.8 Tbit/s, in: Proceedings of the Optical Fiber Communication Conference, Optical Society of America, 2010, pp. PDPC1.
[22] D. Hillerkuss, A. Marculescu, J. Li, M. Teschke, G. Sigurdsson, K. Worms, S. Ben-Ezra, N. Narkiss, W. Freude, J. Leuthold, Novel optical fast Fourier transform scheme enabling real-time OFDM processing at 392 Gbit/s and beyond, in: Proceedings of the Optical Fiber Communication Conference, Optical Society of America, 2010, pp. OWW3.
[23] J. Leuthold, D. Hillerkuss, M. Winter, J. Li, K. Worms, C. Koos, W. Freude, S.B. Ezra, N. Narkiss, Terabit/s FFT processing–optics can do it on-the-fly, in: Proceedings of the 12th International Conference on Transparent Optical Networks (ICTON), IEEE 2010, 2010, pp. 1–4.