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Peak-to-average power ratio reduction in all-optical orthogonal frequency division multiplexing system using rotated constellation approach

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ABSTRACT

In this paper, a new approach for reducing peak-to-average power ratio (PAPR) based on modulated half subcarriers in all-optical OFDM systems with rotated QAM constellation is presented. To reduce the PAPR, the odd subcarriers are modulated with rotated QAM constellation, while the even subcarriers are modulated with standard QAM constellation. The impact of the rotation angle on the PAPR is mathematically modeled. The effect of PAPR reduction on the system performance is investigated by simulating the all-optical OFDM system, which uses optical coupler-based inverse fast Fourier transform (IFFT)/fast Fourier transform (FFT). The all-optical system is numerically demonstrated with 29 subcarriers. Each subcarrier is modulated by a QAM modulator at a symbol rate of 25 Gsymbol/s. The results reveal that PAPR is reduced with increasing the angle of rotation. The PAPR reduction can reach about 0.8 dB when the complementary cumulative distribution function (CCDF) is 1×10^{-3}. Furthermore, both the nonlinear phase noise and the optical signal-to-noise ratio (OSNR) of the system are improved in comparison with the original all-optical OFDM without PAPR reduction.

1. Introduction

All-optical orthogonal frequency division multiplexing (OFDM) system has drawn great attention in recent years due to its potential applications in high-bit-rate transmission systems [1]. Furthermore, this system provides a better tolerance to chromatic and polarization-mode dispersions compared to the conventional systems [2–5]. For instance, the all-optical OFDM system eliminates the requirement of electronics signal processing and thus it is much more feasible for high bit rate transmission system [1,6,7]. However, all-optical OFDM system highly suffers from phase noise which introduces phase rotation for each subcarrier and thus destroys orthogonality of subcarriers [8]. The phase noise is mainly induced from fiber nonlinear effects such as cross-phase modulation (XPM) and four-wave mixing (FWM) [9]. This is evident when adding a number of subcarriers in the time domain for high power transmission signals [10]. The combined signals induce the fiber nonlinear effects and degrades the system performance [11,12]. Therefore, many approaches have been proposed and reported to mitigate fiber nonlinear impairment during transmission of signals in optical OFDM systems where high peak-to-average power ratio (PAPR) reduction is the popular approach.

In both wireless and conventional optical OFDM systems, PAPR reduction is realized in the electrical domain. Various techniques have been developed to reduce PAPR in optical OFDM systems such as amplitude clipping and filtering [13,14]. Although the implementation of clipping technique is simple and less complex, the clipping processes produce a distortion in the optical signal hence increasing the bit error rate (BER). There are also other techniques such as selected mapping (SLM) and partial transmit sequence (PTS) methods which are considered as effective for reducing PAPR in conventional optical OFDM systems [12,15]. However, these methods involve a high computational complexity. Furthermore, the constant envelope of the electrical OFDM waveform has also been adopted to improve the tolerance of MZM nonlinearities and to relax the requirements of digital-to-analog and analog-to-digital converter (DAC/ADC) [16,17]. Indeed, few investigations have been reported on the PAPR reduction techniques in all-optical OFDM systems [18]. They focus on the all-optical OFDM systems, which employ intensity modulation rather than phase

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modulation. Phase pre-emphases method has been proposed to reduce PAPR in all-optical OFDM systems [19].

In this paper, we propose a simple technique to reduce PAPR based on rotated constellation in coherent all-optical OFDM system. In this approach, the subcarriers are divided into odd and even subsets. Then the constellation of odd subcarriers is rotated counter clockwise while the constellation of even subcarriers is remained without rotation. The impact of the rotation angle on the PAPR is mathematically modeled. Then, the resulting PAPR reduction on the total phase noise in all-optical OFDM systems is mathematically modeled and numerically investigated. The simulation results show that the proposed technique provides 0.8 dB PAPR reduction with a better nonlinear impairment tolerance in all-optical OFDM system that employs 29 subcarriers and symbol rate of 25 Gsymbol/s.

The rest of the paper is organized as follows. Section 2 describes the PAPR reduction principle. The effect of rotated constellation method on fiber nonlinearity is discussed in Section 3. The proposed all-optical OFDM system setup is presented in Section 4. The analytical and simulation results are presented in Section 5, where the impacts of rotation angle of constellation on the PAPR and variance of the total phase noise are studied. The validation of our analytical model using simulation results of our systems is given in the same section as well. Finally, a conclusion is drawn in Section 6.

2. PAPR reduction principle

In this section, a new approach to mitigate fiber nonlinear impairment by reducing PAPR is mathematically explained. First, the subcarriers are divided into odd and even subsets. Then, at QAM modulators, the original constellation of odd subcarriers is rotated with an angle of θ (clockwise) while the constellation of even subcarriers is determined by the standard 4QAM constellation as shown in Fig. 1. This approach is suitable for both conventional optical OFDM and all-optical OFDM systems where the constellation is realized in electrical domain. The output of the OFDM transmitter ($u(t)$) is given by

$$u(t) = \sum_{\substack{k=-(N-1)/2\\ k\in\mathcal{O}}}^{(N-1)/2} u_k(t)\exp(j\theta)\exp(j\omega_k t) + \sum_{\substack{k=-(N-1)/2\\ k\in\varepsilon}}^{(N-1)/2} u_k(t)\exp(j\omega_k t), \quad (1)$$

where N represents the total number of subcarriers (assumed odd without loss of generality), $\mathcal{O} \in \{-(N-1)/2+1, -(N-1)/2+3, \ldots, (N-1)/2-1\}$ and $\varepsilon \in \{-(N-1)/2, -(N-1)/2+2, \ldots, (N-1)/2\}$ represent odd and even numbers, respectively, θ, $0 \leqslant \theta \leqslant \pi/4$ is the angle of rotation, $\omega_k = 2\pi k/T_s$ is the frequency offset from the reference optical carrier and T_s is defined as OFDM symbol time. Here $u_k(z,t)$ represents the normalized slowly varying field envelope of kth subcarrier and it is defined as

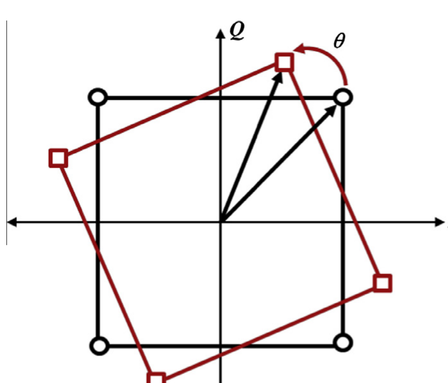

Fig. 1. Rotated 4QAM constellation.

$$u_k(t) = \sqrt{\frac{P}{2}} A_k rect\left(\frac{t-kT_S}{T_S}\right), \quad (2)$$

where; P is the optical power of single subcarrier, $A_k = a_k + jb_k$ is a complex number and is determined by the standard 4QAM constellation and

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

By substituting (2) in (1), the optical field the OFDM signal can expressed as

$$u(t) = \sqrt{\frac{P}{2}}\exp(j\theta) \sum_{\substack{k=-(N-1)/2\\ k\in\mathcal{O}}}^{(N-1)/2} A_k rect\left(\frac{t-kT_S}{T_S}\right)\exp(j\omega_k t) + \sqrt{\frac{P}{2}} \sum_{\substack{k=-(N-1)/2\\ k\in\mathcal{O}}}^{(N-1)/2} A_k rect\left(\frac{t-kT_S}{T_S}\right)\exp(j\omega_k t). \quad (3)$$

The maximum optical field can be obtained when all subcarriers are coherently combined. To achieve this, all subcarriers should be modulated with the same QAM symbol, making the summations of magnitudes of odd and even subcarriers equal to half summation of magnitude of all subcarriers and the angle between them is equal to the rotating angle. Then, the magnitude of optical field of OFDM signal can be written as

$$|u(t)| = \sqrt{\frac{P}{2}}\left|\left[\frac{1+\exp(j\theta)}{2}\right]\right| \sum_{k=-(N-1)/2}^{(N-1)/2} |A_k| \quad (4)$$

By doing some algebra, the magnitude of optical field can be expressed as

$$|u(t)| = \sqrt{\frac{P}{2}}\left|\cos\left(\frac{\theta}{2}\right)\exp\left(j\frac{\theta}{2}\right)\right| \sum_{k=-(N-1)/2}^{(N-1)/2} |A_k| = \sum_{k=-(N-1)/2}^{(N-1)/2} \sqrt{\frac{P}{2}}\cos\left(\frac{\theta}{2}\right)|A_k|. \quad (5)$$

From (5), it can be considered that the magnitude of optical field of kth subcarrier equal to

$$|u_k(t,\theta)| = \sqrt{\frac{P}{2}}\cos\left(\frac{\theta}{2}\right)|A_k|. \quad (6)$$

The PAPR of the signal, $u(t)$, is defined as the ratio of the peak of instantaneous power to the average power, and is given as [13]

$$\mathrm{PAPR} = \frac{\max\left(|u(t)|^2\right)}{E\left[(u(t))^2\right]}, \quad (7)$$

where $E[\bullet]$ is the expectation operator. For 4QAM constellation, the $|A_k| = \sqrt{2}$ because $a_k = b_k = 1$. The magnitude of optical field and the power of kth subcarrier after rotating the constellation can be expressed as

$$|u_k(t,\theta)| = \sqrt{P}\cos\left(\frac{\theta}{2}\right), \quad |u_k(t,\theta)|^2 = P\cos^2\left(\frac{\theta}{2}\right), \quad (8)$$

respectively. The maximum power is occurred when power of N subcarriers are coherently added and it equal to

$$\max\left(|u(t)|^2\right) = \sum_{k=-(N-1)/2}^{(N-1)/2} P\cos^2\left(\frac{\theta}{2}\right) = PN\cos^2\left(\frac{\theta}{2}\right). \quad (9)$$