Constant Envelop Minimum-Shift Keying OFDM Coherent Optical Communication System

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***Abstract*—In this paper, we propose a constant envelop minimum-shift keying orthogonal frequency division multiplexing (CE-MSK-OFDM) modulation scheme. This scheme can mitigate the inherent drawbacks of CE quadrature phase shift keying OFDM (CE-QPSK-OFDM) and MSK-OFDM. Advantages of the proposed CE-MSK-OFDM modulation scheme are theoretically investigated. A CE-MSK-OFDM coherent optical experimental system is presented. In our experiment, 2.5 Gb/s CE-MSK-OFDM signal and 2.5 Gb/s CE-QPSK-OFDM signal are transmitted over a 100 km standard single mode fiber (SSMF) without phase compensation to check its advantages in mitigating intercarrier interference (ICI). In addition, performance under large fiber launch power is also measured to check its advantages in counteracting fiber nonlinear impairments. The experimental results show that the proposed system performs well in decreasing ICI and peak-to-average power ratio (PAPR) as the theoretical analysis reveals.**

***Index Terms*—Average received optical power, constant envelop (CE), intercarrier interference (ICI), minimum-shift keying (MSK), orthogonal frequency division multiplexing (OFDM), peak-to-average power ratio (PAPR), quadrature phase shift keying (QPSK).**

I. INTRODUCTION

ORTHOGONAL FREQUENCY DIVISION MULTIPLEXING (OFDM) is a promising technique because of its high spectral efficiency. Optical OFDM [1] shows an excellent resistance to chromatic dispersion (CD) and polarization mode dispersion (PMD). It also fully exploits the advantages of fast Fourier transform (FFT) and inverse fast Fourier transform (IFFT). All of these advantages make optical OFDM gain more substantial interest. However, high peak-to-average power ratio (PAPR) and inevitable intercarrier interference (ICI) seriously restrict the development of optical OFDM inherently.

Many techniques have been proposed to mitigate PAPR in OFDM system, such as pre-distortion scheme [2], coding scheme [3], probability scheme [4] and signal transformation scheme [5]. All of these schemes are generally applied to address PAPR problem at the cost of reducing spectral efficiency, increasing complexity, or degrading performance of OFDM system.

Recently, constant envelop orthogonal frequency-division multiplexing (CE-OFDM) [6], is proposed to mitigate PAPR. It is implemented through transforming conventional OFDM signal by a phase modulator, thus the transformed signal has a constant envelop. In theory, CE-OFDM can decrease PAPR effectively, and thus it enjoys the ability to counteract fiber nonlinearity. However, the higher-order terms of phase modulated signal are inevitable, so each data is spread over multiple subcarriers in CE-OFDM system [7], and this spread in frequency domain would induce a large ICI. Therefore, a technique to mitigate ICI problem in CE-OFDM communication system is required.

On the other hand, to decrease ICI in OFDM system, minimum-shift Keying (MSK), as a continuous phase modulation scheme [8], is proposed [9]–[11]. Compared with the widely used quadrature phase shift keying (QPSK) scheme [12], MSK can engender a fast roll-off side-lobe spectrum and decrease the carrier frequency offset (CFO). MSK-OFDM exhibits a fast roll-off side-lobe spectrum decaying asymptotically as f^{-4} while QPSK-OFDM exhibits a much slower roll-off side-lobe spectrum decaying asymptotically as f^{-2} [13]. Unfortunately, as a correlative coding scheme, MSK-OFDM has a much larger PAPR inherently than irrelative coding scheme [14], such as QPSK-OFDM. Therefore, a technique to counteract PAPR problem in MSK-OFDM communication system is essential.

To the best of our knowledge, no efficient schemes for decreasing PAPR and mitigating ICI together have been proposed. In fact, decreasing PAPR and mitigating ICI are not incompatible in OFDM system. In this paper, the proposed CE-MSK-OFDM modulation scheme can mitigate their inherent shortages of CE-QPSK-OFDM system and MSK-OFDM system together. Theoretical analysis and experiments are presented to investigate the improvement in decreasing ICI and PAPR of the proposed CE-MSK-OFDM coherent optical communication system.

In our experiments, 2.5 Gb/s CE-MSK-OFDM signal and 2.5 Gb/s CE-QPSK-OFDM signal are successfully transported over a 100 km standard single mode fiber (SSMF) without phase compensation. Compared with CE-QPSK-OFDM, CE-MSK-OFDM achieves an improvement about 3.5 dB in the average received optical power at forward error correction (FEC) threshold. In addition, performance of the proposed

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scheme and MSK-OFDM scheme under large fiber launch power is also measured. The average received optical power is set at -25 dBm after 100 km transmission over a SSMF with 21 dBm fiber loss. Performance of MSK-OFDM signal declines rapidly when the fiber launch power is more than 4 dBm. Performance of CE-MSK-OFDM signal does not exhibit a degradation when the fiber launch power is 10 dBm. Therefore, CE-MSK-OFDM can mitigate ICI and tremendously decrease PAPR as the theory pointed out.

The organization of this paper is as follows. In Section II, we present the principle of CE-QPSK-OFDM, MSK-OFDM and CE-MSK-OFDM. The inherent advantages and drawbacks of CE-QPSK-OFDM and MSK-OFDM are given through their principles. Advantages of the proposed CE-MSK-OFDM modulation scheme are also discussed in this section. In Section III, we demonstrate a CE-MSK-OFDM optical coherent communication system and give out our experimental results.

II. PRINCIPLE

A. Principle of CE-QPSK-OFDM

Consider the conventional baseband OFDM waveform during an OFDM block interval,

$$m(t) = \sum_{i=-\infty}^{\infty} \sum_{k=1}^{N} I_{i,k} \cdot q_k(t - iT), \tag{1}$$

where $I_{i,k}$ is the i-th data symbol on the k-th subcarrier, T is the OFDM symbol period, and $q_k(t - iT)$ are the k-th orthogonal subcarrier.

Then transform this baseband signal through a phase modulator,

$$s(t) = A \exp\{j\alpha \cdot m(t)\}, \tag{2}$$

where $\alpha = 2\pi\mu$ is a constant defined as the modulation index and A is the amplitude of this phase modulated signal.

In (2), $|s(t)| = A$ is a constant, therefore the defined baseband CE-QPSK-OFDM signal can enjoy a constant envelop, this contributes to a decrease in PAPR.

Subsequently, up-convert the phase modulated baseband signal to an optical carrier with a frequency of f_c,

$$y(t) = A \exp\{j[2\pi f_c t + \alpha \cdot m(t) + \varphi]\}. \tag{3}$$

where φ denotes the phase noise. For real-valued $m(t)$, (3) defines a phase modulated signal with a lowpass equivalent representation of $A \exp\{j[\alpha \cdot m(t) + \varphi]\}$, and its envelop is $|A \exp\{j[\alpha \cdot m(t) + \varphi]\}| = A$.

During fiber propagation, CD causes a time varying amplitude optical complex envelop [12], it leads to a phase to amplitude conversion in dispersive system, so the bandpass CE-QPSK-OFDM signal in optical transport link can not achieve a 0 dB PAPR. However, CE scheme has tremendously decreased PAPR compared with conventional OFDM modulation schemes.

To obtain a real-valued $m(t)$, we construct a conjugate symmetric data vector [6], and subsequently feed this vector into an IFFT function block. $s(n)$, the output of this block, is the real-valued baseband OFDM signal required.

Though CE-QPSK-OFDM scheme can decrease PAPR effectively, it bears a larger ICI compared with conventional OFDM modulation schemes as its data symbol energy is spread in frequency domain. In other words, each data laying on one subcarrier is spread over multiple subcarriers. This frequency expanding phenomena can be explained by the Taylor series expansion of CE-QPSK-OFDM signal in terms of $m(t)$ [7],

$$\begin{aligned} s(t) &= A \exp\{j\alpha \cdot m(t)\} \\ &= A\{1 + j\alpha \cdot m(t) - \frac{\alpha^2 \cdot m(t)^2}{2!} - \frac{j\alpha^3 \cdot m(t)^3}{3!} \\ &\quad + \cdots + \frac{[j\alpha \cdot m(t)]^n}{n!} + \cdots\}. \end{aligned} \tag{4}$$

The higher-order terms are inherent in Taylor series expansion and they are not negligible when α is big enough. It means that many higher-frequency components are induced, or it can be said that the data symbol laying on a subcarrier induces many high frequencies laying on other subcarriers. This spread in frequency domain leads to a large ICI.

For a small-valued modulation index, the higher-order terms are negligible and only the first two terms contribute,

$$s(t) = A \exp\{j\alpha \cdot m(t)\} \approx A\{1 + j\alpha \cdot m(t)\}. \tag{5}$$

In this condition, CE-QPSK-OFDM signal is not spread in frequency domain. It is essentially equivalent to a conventional OFDM signal though a relatively large DC term is added. Therefore, CE-QPSK-OFDM signal with a small-valued modulation index has no ability to expand in frequency domain. ICI problem caused by these higher-order terms is also successfully avoided.

However, if α is small enough, its in-phase component $\cos\{\alpha \cdot m(t)\}$ is approaching to 1 while the quadrature component $\sin\{\alpha \cdot m(t)\}$ is approaching to 0. In the transport link, $\sin\{\alpha \cdot m(t)\}$ with small energy is easily to be interfered, as carrier-to-noise ratio (CNR) is only determined by the signal amplitude A and additive noise. In addition, the tiny quadrature component is difficult to be detected by optical coherent receiver.

Therefore, modulation index α is an important factor affecting the performance of CE-QPSK-OFDM coherent optical communication system. Proper α should take account of ICI and the sensitivity of coherent receiver. However, decided only by the structure of coherent receiver, its sensitivity is relatively stable, so the selected α can not be so small enough that it can make ICI negligible, and thus ICI becomes an urgent problem to be addressed in CE-QPSK-OFDM coherent optical communication system.

B. Principle of MSK-OFDM

Another important factor contributing to the performance of OFDM communication system is the modulation format. Conventionally, we modulate the input source data through QPSK modulation format. The primary drawback of QPSK format is that it can not make the modulated signal enjoy a continuous phase inherently. It exhibits a slow roll-off side-lobe spectrum decaying asymptotically as f^{-2}. This slow roll-off side-lobe

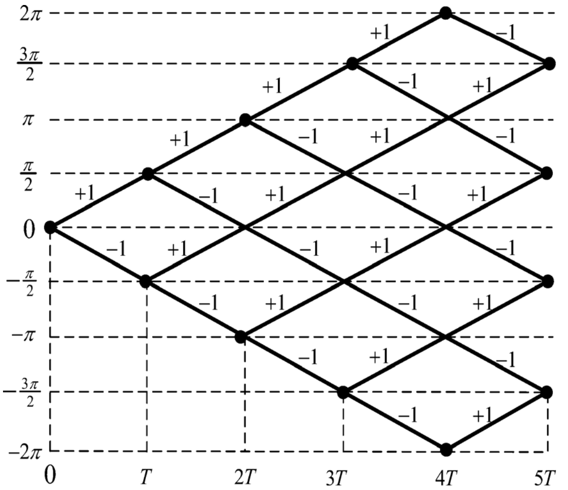

Fig. 1. MSK phase trellis for $h = 1/2$.

spectrum partly contributes to the ICI problem existing in CE-QPSK-OFDM.

Though expansion of CE-QPSK-OFDM in frequency domain is inevitable, we can decrease the higher-order terms to mitigate ICI problem. Therefore, modulation format with a fast roll-off side-lobe spectrum can be a good candidate.

In fact, MSK modulation scheme can mitigate this problem. It enjoys a fast roll-off side-lobe spectrum decaying asymptotically as f^{-4}.

Commonly, baseband MSK signal can be shown as follow,

$$X(t) = \exp\left\{j\left(\theta_n + \alpha_n \cdot \frac{\pi h}{T} \cdot t\right)\right\}, \quad 0 \le t \le T \tag{6}$$

where $\theta_n = h\pi \sum_{q=0}^{n-1} \alpha_q + \phi$ represents a cumulative phase, α_n denotes the input source data, ϕ is the initial phase, T is the MSK symbol period, and h denotes the MSK modulation index. Obviously, the baseband MSK signal has a constant envelop as it adopts a frequency shift keying format.

Fig. 1 presents the phase trellis of MSK signal, it is continuous during a MSK symbol interval. It is also continuous at the sampling time $t = NT$. Therefore, MSK is a continuous phase format, and thus it can enjoy a fast roll-off side-lobe spectrum.

Based on this merit of MSK, MSK-OFDM is proposed to address ICI problem. For convenience, ϕ is assumed to be 0, and then the baseband MSK-OFDM signal can be represented as,

$$s(t) = \sum_{k=0}^{N-1} \exp\left\{j\left(\theta_{k,n} + \alpha_{k,n}\frac{\pi h}{T}t\right)\right\} \cdot \exp\left\{j\frac{2\pi k t}{T}\right\}, \quad 0 \le t \le T \tag{7}$$

where $T = NT_b$ is the OFDM symbol period, N is the number of subcarriers, T_b is the sampling period, and k denotes the k-th subcarrier of OFDM symbol.

For this baseband MSK-OFDM signal $s(t)$, its envelop is defined as,

$$v(t) = \left|\sum_{k=0}^{N-1} \exp\left\{j\left(\theta_{k,n} + \alpha_{k,n}\frac{\pi h}{NT_b}t\right)\right\} \cdot \exp\left\{j\frac{2\pi k t}{NT_b}\right\}\right|. \tag{8}$$

When $N = 2$, $h = 1/2$, $\theta_{0,n} = 0$, $\theta_{1,n} = 0$, $\alpha_{0,n} = 1$, and $\alpha_{1,n} = 1$,

$$\begin{aligned} v(t) &= \left|\exp\left\{j\frac{\pi t}{4T_b}\right\} + \exp\left\{j\frac{\pi t}{4T_b}\right\} \cdot \exp\left\{j\frac{\pi t}{T_b}\right\}\right| \\ &= \left|1 + \exp\left\{j\frac{\pi t}{T_b}\right\}\right|, \end{aligned} \tag{9}$$

$v(t)$ is determined by t, and it is not a constant. Therefore, MSK-OFDM signal does not enjoy a constant envelop, and thus it can not counteract PAPR inherently. Furthermore, as a correlative coding scheme, it sustains a larger PAPR than irrelative coding scheme such as QPSK-OFDM does, so large PAPR becomes a serious problem to be solved in MSK-OFDM optical communication system.

MSK-OFDM signal can be engendered by modulating input source data through N MSK modulators, but this modulation method is too complicated. In this paper, we utilize a simple improved method to get MSK-OFDM signal [9].

MSK-OFDM symbol taking advantages of IFFT can be shown as,

$$s(t)' = \sum_{\nu=0}^{2N-1} U_{\nu,n} \cdot \exp\left\{j\frac{2\pi\nu t}{2NT_b}\right\}, \tag{10}$$

where

$$U_{\nu,n} = \begin{cases} e^{j\theta'_{k,n}}, & \nu = k' \\ 0, & \nu \neq k' \end{cases},$$

and $k' = 2k + h(1 + \alpha_{k,n})$, $\theta'_{k,n} = \theta_{k,n} + h\pi n$.

Fig. 2 shows the normalized spectrum of MSK and QPSK. Obviously, the normalized spectrum of MSK decays much faster than that of QPSK does, and thus the MSK-OFDM modulation scheme can exploit a better performance in decreasing ICI.

C. Principle of CE-MSK-OFDM

Based on the analysis in II.A and II.B, CE-QPSK-OFDM can help MSK-OFDM to mitigate its PAPR, and MSK can help CE-QPSK-OFDM to decrease its higher-order terms. Therefore, CE-MSK-OFDM scheme is proposed in this paper. We modulate the input data by MSK-OFDM scheme and then transfer the baseband MSK-OFDM signal through an optical phase modulator,

$$s_{cm}(t) = A\exp\{j[2\pi f_c t + \alpha \cdot s(t)' + \varphi]\}, \tag{11}$$

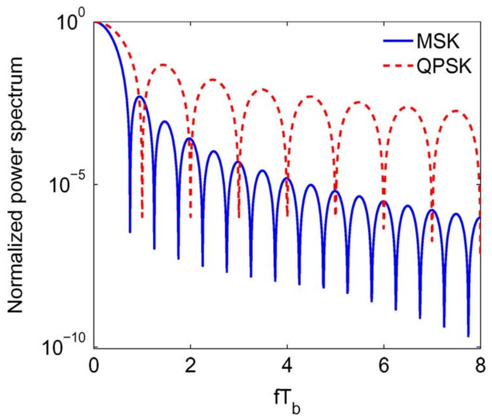

Fig. 2. Normalized power spectrum of MSK and QPSK.

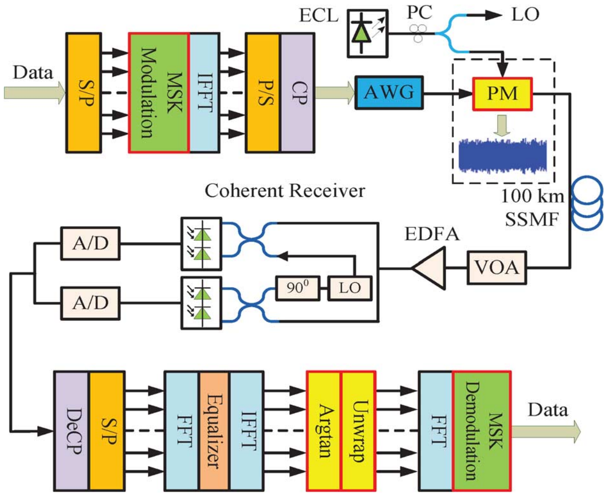

Fig. 3. 2.5 Gb/s CE-MSK-OFDM coherent optical system.

where $s(t)'$ is a MSK-OFDM signal. CE-MSK-OFDM signal $s_{cm}(t)$ has a constant envelop A and a fast roll-off side-lobe spectrum. The proposed modulation scheme fully exploits the advantages of CE and MSK. It also overcomes the inherent shortages of CE-QPSK-OFDM and MSK-OFDM. Therefore, CE-MSK-OFDM signal has a good performance in resisting PAPR and decreasing ICI.

III. EXPERIMENT

A. Experimental Setup

Fig. 3 shows the experimental setup for the proposed CE-MSK-OFDM system. At the transmitter, optical source is a commercially available external cavity laser (ECL) operating at a wavelength of 1550.12 nm with a line-width of about 100 kHz. To make the polarization state of light fixed, a polarization controller (PC) is utilized following ECL. The time-domain OFDM waveform is generated by a MATLAB program with parameters as follows. 50 data subcarriers filled out of 64 total subcarriers. 9 subcarriers around DC are left empty to avoid phase noise distortion. 3 subcarriers in high frequency are empty to address the high frequency distortion. 2 subcarriers are used as pilot subcarriers to estimate the fiber transfer function. According to the MSK-OFDM modulation scheme, 64 subcarriers are mapped into 128 subcarriers, and only the first 64 subcarriers are transmitted [13]. Then to construct a conjugate symmetric data vector, we extend the paralleled 64 subcarriers into 130 subcarriers. Finally, 256 subcarriers are utilized to simplify IFFT complexity and to oversample time-domain sequence. 1/16 cyclic prefix samples and cyclic postfix samples are used to withstand the fiber CD. For every 64 OFDM symbols, 1 synchronization symbol and 2 training symbols are transmitted. The real OFDM waveforms are uploaded into the arbitrary waveform generator (AWG) operating at 10 GSa/s to generate analog signals. Subsequently, the analog waveforms are fed into an optical phase modulator (PM) before being launched into a 100 km SSMF. This process generates an optical signal with constant optical power and varying phase.

In this optical transport link, no signal amplifying device is used to amplify the signal transported. At the receiver, a variable optical attenuator (VOA) and an EDFA are utilized prior to the coherent receiver [15] to add noise and alter the received optical power. In our experiment, to simplify the setup complexity, LO utilized in the coherent receiver is the output of a 1 × 2 optical power splitter following PC at the transmitter. The coherent received signal is subsequently fed into a time-domain scope (TDS) at a sampling rate of 50 GSa/s to implement the A/D conversion. Then download the received signal into a MATLAB program, capture the synchronized signal to pinpoint the start of FFT window, separate the training symbols and data symbols, remove CP. Estimate the transfer function of the optical transport channel by low complexity least squares (LS) technique [16]. Equalize the received signal through a zero-forcing (ZF) equalizer operating in the frequency domain [7] to decrease the linear distortion. Therefore, the IFFT and FFT functional modules are indispensable. Then decompose the phase modulated signal by arc tangent and phase unwrapping blocks. Subsequently, feed the decomposed frequency-domain signal into a FFT block to get a time-domain MSK signal. Then, MSK demodulation block is utilized to demodulate the received MSK signal.

When CE-QPSK-OFDM are transmitted, assignment of the initial 256 subcarriers is the same as that of CE-MSK-OFDM. For every 64 OFDM symbols, 1 synchronization symbol and 2 training symbols are transmitted. The real OFDM waveforms are uploaded into the arbitrary waveform generator (AWG) operating at 5 GSa/s to generate analog signals. At this sample rate, signal rate of CE-QPSK-OFDM, 2.5 Gb/s, is the same as that of the transmitted CE-MSK-OFDM, as the spectrum efficiency of QPSK is up to 2 bit/s/Hz and that of MSK is about 1 bit/s/Hz.

B. Experimental Results

Figs. 4 and 5 show the simulation results on the double sideband (DSB) electrical spectrum of the 2.5 Gb/s CE-MSK-OFDM signal before and after PM with modulation index $\alpha = 0.6$. The impulses over the flat CE-MSK-OFDM spectrum are caused by MSK-OFDM modulation scheme inherently at empty data subcarriers. For an empty data subcarrier,

$$s(t) = \sum_{k=0}^{N-1} \exp\left\{ j \left(\theta_{k,n} + \alpha_{k,n} \frac{\pi h}{N T_b} t \right) \right\}$$

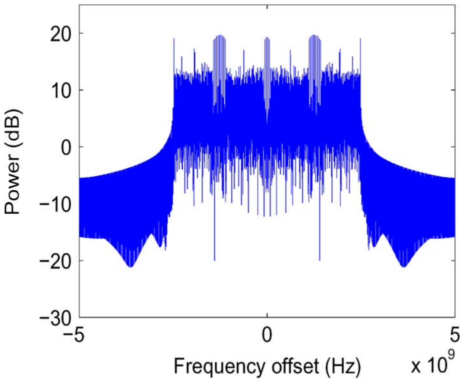

Fig. 4. Simulation result on the electrical spectrum of MSK-OFDM signal before an optical phase modulator.

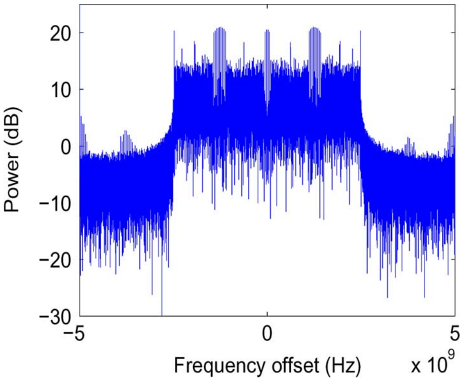

Fig. 5. Simulation result on the electrical spectrum of CE-MSK-OFDM signal after an optical phase modulator with modulation index $\alpha = 0.6$.

$$\cdot \exp\left\{j\frac{2\pi kt}{NT_b}\right\} = \exp\{j\theta_{k,n}\} \cdot \exp\left\{\frac{j2\pi kt}{NT_b}\right\}, \tag{12}$$

where k defines the k-th empty data subcarrier. It is obviously shown that $|s(t)|$, the amplitude of empty data subcarrier, is not zero. This non-zero signal in empty data subcarrier leads to an impulse in DSB spectrum. Signal at the k-th empty data subcarrier is determined by the cumulative phase of that subcarrier and the total number of subcarriers. Moreover, the number of empty data subcarriers decides that of impulses. However, as all subcarriers are orthogonal in frequency domain, these impulses do not affect other subcarriers.

In our experiment, signal with modulation index $\alpha = 0.6$ achieves a good performance. All of the following factors should be considered to improve performance of the proposed scheme. Signal with small modulation index is not easy to be detected by the coherent receiver, and it is easy to be interfered by noise. Signal with large index may lead to a large ICI as the higher-order terms are strengthened. In addition, signal peaks with a low probability caused by IFFT block are automatically cut off by AWG, as the maximum input voltage of AWG is 1 V. This restriction by AWG also contributes to the decrease in performance.

Fig. 6 shows the measured BER performance of CE-MSK-OFDM and CE-QPSK-OFDM signal after 100 km transmission respectively versus average received optical power. BER performance of back to back (B2B) CE-MSK-OFDM is also presented in Fig. 6. At the receiver, EDFA works at power-controlled status. Average received optical power about -34.7 dBm and -31.2 dBm are required respectively for CE-MSK-OFDM system and CE-QPSK-OFDM system at FEC threshold. For B2B CE-MSK-OFDM system, the required average received optical power is -36.3 dBm at FEC threshold. Compared with B2B CE-MSK-OFDM system, CE-MSK-OFDM system after 100 km transmission has a fiber launch power penalty about 1.6 dB. Compared with CE-QPSK-OFDM system, CE-MSK-OFDM system earns an improvement about 3.5 dB in the average received optical power under FEC threshold.

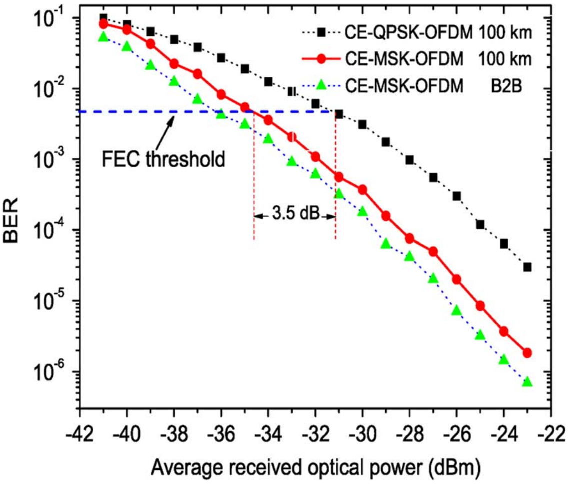

Fig. 6. Experimental result on BER performance of CE-MSK-OFDM and CE-QPSK-OFDM.

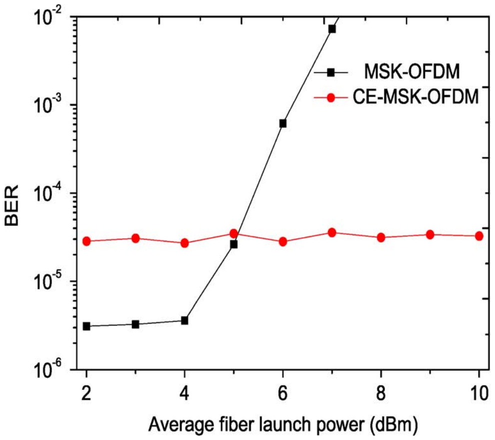

Fig. 7. Experimental result on BER performance of CE-MSK-OFDM and MSK-OFDM under large fiber launch power.

Fig. 7 shows the BER performance of 2.5 Gb/s CE-MSK-OFDM and MSK-OFDM signal under large fiber launch power (p_{inp}). In our experiment, a VOA is employed at the transmitter to alter fiber launch power. Another VOA is utilized at receiver to maintain the received optical power at $p_{\mathrm{rec}} = -25$ dBm after 100 km transmission. Performance of MSK-OFDM signal declines rapidly when the fiber launch power is more than 4 dBm. Performance of CE-MSK-OFDM signal does not exhibit a degradation when the fiber launch power is 10 dBm. The excellent performance under large fiber launch power proves that the proposed CE-MSK-OFDM system is a good candidate in counteracting fiber nonlinear impairments, though the optical carrier signal can not mitigate fiber nonlinearity completely, as CD causes a time varying amplitude optical complex envelop.

IV. CONCLUSION

In this paper, CE-MSK-OFDM modulation scheme is proposed to mitigate ICI and PAPR. Theoretical analysis of CE-QPSK-OFDM, MSK-OFDM and CE-MSK-OFDM is given. A CE-MSK-OFDM coherent optical system is presented. In our experiment, 2.5 Gb/s CE-MSK-OFDM signal and 2.5 Gb/s CE-QPSK-OFDM signal are transmitted successfully over a 100 km SSMF without phase compensation. The proposed CE-MSK-OFDM system achieves an improvement about 3.5 dB in the average received optical power under FEC threshold, compared with CE-QPSK-OFDM system. In addition, performance of the proposed scheme under large fiber launch power is also excellent compared with that of MSK-OFDM. Therefore, the proposed CE-MSK-OFDM coherent optical communication system is promising in mitigating ICI and PAPR.

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