GFDM-OFDM Hybrid Modulation Scheme for IM-DD Optical Communication Systems

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***Abstract*—We propose and demonstrate a novel modulation scheme termed as generalized frequency division multiplexing - orthogonal frequency division multiplexing (GFDM-OFDM) for intensity-modulated direct-detection (IM-DD) optical communication systems. In our scheme, the low-frequency band is allocated to a GFDM signal to achieve a low peak-to-average power ratio (PAPR), while the high-frequency band is filled with an OFDM signal that is robust to frequency-domain variations. By this means, the PAPR of the whole signal can be reduced and the high-frequency fading effects induced by the electronic components can be mitigated, leading to an improved system performance. Simulation results show that our proposed GFDM-OFDM format outperforms OFDM and GFDM formats in terms of optical receiver sensitivity for both the back-to-back (BTB) and 10-km transmissions. The GFDM-OFDM signal achieves receiver sensitivity improvements of approximately 3.0 dB and 1.6 dB, compared to the OFDM and GFDM signals, respectively.**

Keywords-generalized frequency division multiplexing - orthogonal frequency division multiplexing (GFDM-OFDM), intensity-modulated direct-detection (IM-DD), channel characteristics

I. INTRODUCTION

The ever-increasing global information capacity is driving the demand for high bandwidth and low cost in next-generation optical networks [1]. The intensity-modulated direct-detection (IM-DD) methods are attractive for short-reach applications due to the merits of low cost and low power consumption [2]. Among many modulation formats, orthogonal frequency division multiplexing (OFDM) has been intensively studied due to its high spectral efficiency and robust dispersion tolerance [3]. However, the high peak-to-average power ratio (PAPR) of the OFDM signal is a fundamental problem, leading to nonlinear distortions and impairing the system performance [4]. Another issue is that the received signal suffers from signal-to-noise ratio (SNR) roll-off at high frequencies [5], owing to the anti-alias filter in a digital-to-analog converter (DAC) and the bandwidth limitation of electronic components. The frequency response of a practical IM-DD transmission system can exhibit different characteristics in different sub-bands. As illustrated in Fig. 1, the response spectrum can be divided into a slowly declining region and a fast fading region depending on the steepness of the curve.

To decrease the PAPR and alleviate the high-frequency fading effect, various schemes have been proposed, such as discrete Fourier transform-spread (DFT-S) OFDM - discrete multitone (DMT) technique [6] and orthogonal pulse amplitude modulation (PAM) - DMT technique [7]. In these schemes, the slowly declining region and the fast fading region are assigned to different modulation formats, as the roll-off factors in the two regions differ significantly. However, both of them need extra DFT process in the transmitter and inverse DFT (IDFT) process in the receiver. Although the PAPR is decreased, these processes increase the computational complexity, reduce the SNR, and bring noise spread [8].

To achieve a good system performance, a new modulation format is introduced in this paper. Generalized frequency division multiplexing (GFDM) is a flexible multicarrier transmission technique proposed for 5G cellular networks [9]. It preserves most benefits of OFDM and has been used in passive optical networks recently in [10]. In addition, GFDM provides a time-frequency data structure that each GFDM block contains a few subcarriers and multiple sub-symbols per subcarrier, resulting in a low PAPR and flexible resource allocation [11]. By applying a prototype filter to each subcarrier, GFDM can achieve a very low out-of-band radiation, which leads to the decrease of the PAPR and the resistance to carrier frequency offsets [9]. However, GFDM signals suffer from frequency-response variations [12], especially in electronic-bandwidth limited

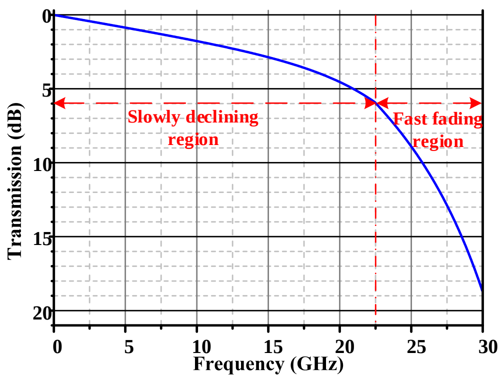

Figure 1. Frequency response of a typical IM-DD transmission system.

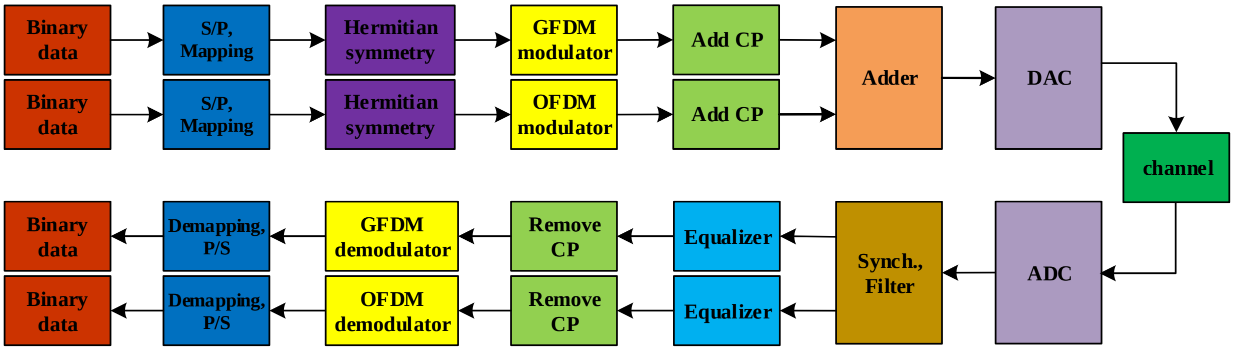

Figure 2. The schematic diagram of an IM-DD GFDM-OFDM optical transmission system. S/P: serial-to-parallel, DAC: digital-to-analog converter, ADC: analog-to-digital converter, synch: synchronization, P/S: parallel-to-serial.

scenarios.

In this work, we propose and demonstrate a novel hybrid modulation scheme termed as GFDM-OFDM, where the low-frequency band is allocated to a GFDM signal while the high-frequency band is filled with an OFDM signal. The slowly declining region favors the GFDM signal, which leads to a low PAPR. While assigning an OFDM signal with low-order quadrature amplitude modulation (QAM) to the fast fading region, the detrimental influence of signal attenuation can be mitigated through a simple equalizer. The GFDM-OFDM signal benefits from both the advantages of GFDM and OFDM, and thus provides a better performance. The feasibility of our scheme is verified by simulations, where a GFDM-OFDM signal, a GFDM signal, and an OFDM signal are generated and transmitted in an IM-DD system for comparisons, respectively. Simulation results show that the GFDM-OFDM signal can achieve a better receiver sensitivity for both the back-to-back (BTB) and 10-km transmissions with respect to the GFDM and OFDM signals. In comparison with the OFDM and GFDM signals, approximately 3.0-dB and 1.6-dB receiver-sensitivity improvements are achieved by using our proposed scheme, respectively. Therefore, the GFDM-OFDM signal exploits the channel characteristics by appropriately assigning GFDM and OFDM signals to different sub-bands, providing an effective scheme to improve the receiver sensitivity in optical communications.

II. Operation Principle

Fig. 2 illustrates the proposed schematic diagram of an optical GFDM-OFDM transmission system. To generate a GFDM sub-signal, the input binary data are firstly encoded and mapped. Each GFDM block contains $K \times M$ complex constellation elements, which can be decomposed into K subcarriers with M sub-symbols. Therein, $\mathbf{d}$ can be written as $\mathbf{d} = (d_0[0],\ldots,d_0[M-1],d_1[0],\ldots,d_{K-1}[M-1])^{T}$, with $d_k[m]$ being the data of the m-th sub-symbol in the k-th subcarrier [14]. Hermitian symmetry is applied to provide a modulated real-valued signal. The GFDM modulation includes inverse fast Fourier transform (IFFT), pulse shaping, and circular convolution operations. The output vector $\mathbf{x} = (x[n])^{T}$ is obtained by superposition of the following expression [14]

$$x[n] = \sum_{m=0}^{M-1}\sum_{k=0}^{K-1} d_k[m]\, g[(n-mK) \bmod MK]\, e^{j2\pi\frac{kn}{K}}, n = 0,\ldots,MK-1, \quad (1)$$

where n denotes the sampling index and the prototype filter g[n] performs a modulo operation to facilitate a circular convolution at the transmitter. Then, a cyclic prefix (CP) is inserted to alleviate the inter-symbol interference incurred by chromatic dispersion effects. The process of an OFDM sub-signal generation is similar to that of the GFDM sub-signal, except that IFFT is performed in OFDM modulation [15]. At last, the GFDM-OFDM signal is obtained by adding the GFDM sub-signal and the OFDM sub-signal in time domain.

At the receiver, to retrieve the transmitted data, the synchronization is firstly performed. Digital filters are employed to separate the two sub-signals, followed by a frequency domain single-tap equalization for the OFDM sub-signal and a multiple-tap equalization for the GFDM sub-signal to tackle the channel's linear impairments. After removing the CP, the demodulation process of the OFDM sub-signal is the inverse operation corresponding to the transmitter. Nevertheless, the GFDM sub-signal requires a slightly complex demodulation method, such as matched filter (MF), zero-forcing (ZF), or minimum mean square error (MMSE) reception [16]. ZF detector is used in our demodulation as it completely removes the inter-carrier interference (ICI) caused by the non-orthogonality [17]. Finally, the recovered data are obtained after demapping and decoding. The error bits of the GFDM and OFDM sub-signals are added to calculate the bit error ratio (BER). As the GFDM sub-signal is allocated to the low-frequency band to reduce the PAPR, the bit errors of the GFDM-OFDM signal mainly come from the OFDM sub-signal in the high-frequency band. Therefore, the OFDM sub-signal is modulated with low order QAM, which provide improved BER performance and better utilization of the high-frequency band.

Fig. 3 shows the power spectral densities of (a) the GFDM sub-signal, (b) the OFDM sub-signal, and (c) the GFDM-OFDM signal, respectively. The total available

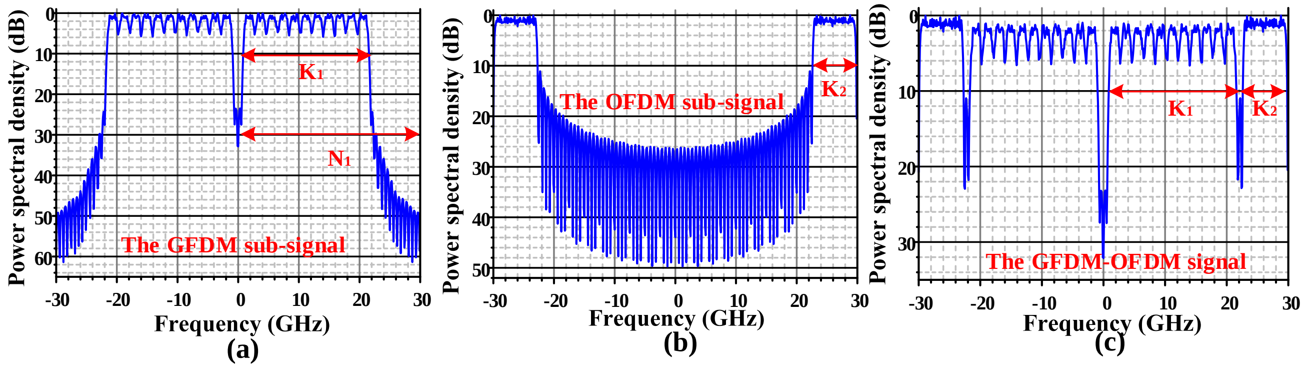

Figure 3. Power spectral densities of (a) the GFDM sub-signal, (b) the OFDM sub-signal, and (c) the GFDM-OFDM signal.

subcarrier number of the GFDM sub-signal is assumed to be N_1, and the allocated sub-symbol number in each subcarrier is M ($M > 0$). The GFDM sub-signal occupies the low-frequency K_1 ($0 < K_1 < N_1$) subcarriers. To keep the total bit number as the same, the number of the allocated OFDM subcarriers K_2 should be calculated as $K_2 = (N_1 - K_1) \times M$. In addition, a subcarrier between the GFDM and OFDM sub-signals is set to null to serve as a guard band [9].

The proposed hybrid modulation scheme is based on the different roll-off factors in the frequency response of the system. The GFDM sub-signal in the low-frequency band exhibits a low PAPR, which is mainly because of the dramatically reduced subcarrier number. Furthermore, signal peak energy is controlled by eliminating the effects of neighboring side-lobes [11]. The GFDM-OFDM signal inherits the low-PAPR characteristics as the GFDM sub-signal occupies most of its signal power. Therefore, the GFDM-OFDM signal avoids the PAPR-induced power efficiency degradation, and results in an improved optical modulation index [4]. Besides, the high resistance to high-frequency fading effects is another important feature of the GFDM-OFDM signal. The OFDM sub-signal in the high-frequency band possesses a large number of subcarriers, thus the channel for each subcarrier can be regarded as flat [18]. Consequently, the high-frequency band will be better exploited by the OFDM sub-signal for mitigating significant signal attenuation. Overall, the GFDM-OFDM signal preserves the main advantages of both GFDM and OFDM signals, leading to an improved receiver sensitivity.

III. SIMULATION AND OPTIMIZATION

A. *Simulation setup*

To verify the feasibility of the proposed method, simulations have been carried out. The simulation setup is provided in Fig. 4. The filter after the signal generator is utilized to simulate the signal attenuation in the practical system. The frequency response of an IM-DD transmission system is experimentally measured and used as the transmission curve of the filter, as shown in Fig 5. A continuous-wave light from a laser is injected into an intensity modulator (IM), which is driven by the electrical signals. The modulated optical signal is then sent into a 10-km standard single-mode fiber (SSMF). A variable optical attenuator (VOA) is employed to change the received optical power. At the receiver, the signals are detected by an erbium-doped fiber amplifier (EDFA) and a photo-detector (PD) and recovered by the offline signal processor. The responsivity of the PD is 1 A/W and the thermal noise power spectral density of the Gaussian noise is 1.8×10^{-25} W/Hz. The digital signal processing (DSP) in the transmitter and receiver has been explicitly illustrated in the diagram of Fig. 2.

B. *Parameter optimization*

It is obvious that the performance of a GFDM-OFDM signal is determined by the parameters of the GFDM sub-signal, the parameters of the OFDM sub-signal, and the bandwidth ratio of the low-frequency band to the high-frequency band. The parameters of the GFDM sub-signal include block structure, filter type, and roll-off factor.

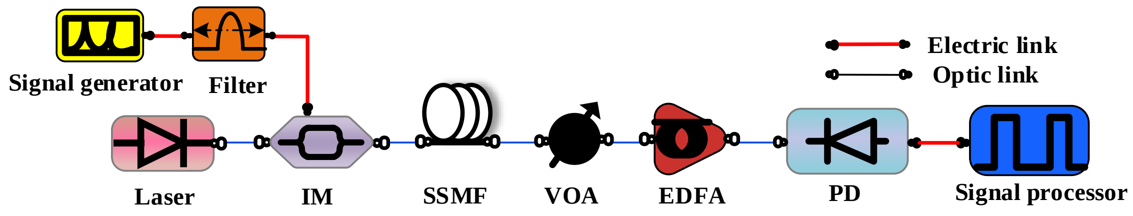

Figure 4. Schematic diagram of the simulation setup.

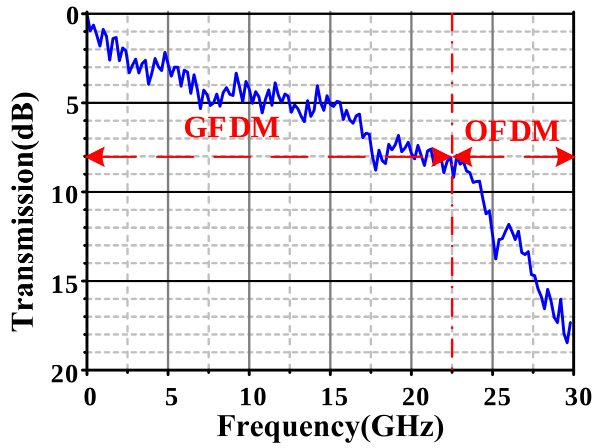

Figure 5. Experimentally measured frequency response of the system at the BTB condition.

Previous study [19] points out that raised cosine (RC) filter performs better than root raised cosine (RRC) filter with respect to PAPR, and a lower roll-off factor contributes to a lower PAPR. Therefore, we use RC filter with a roll-off factor of 0.1 in the following simulations.

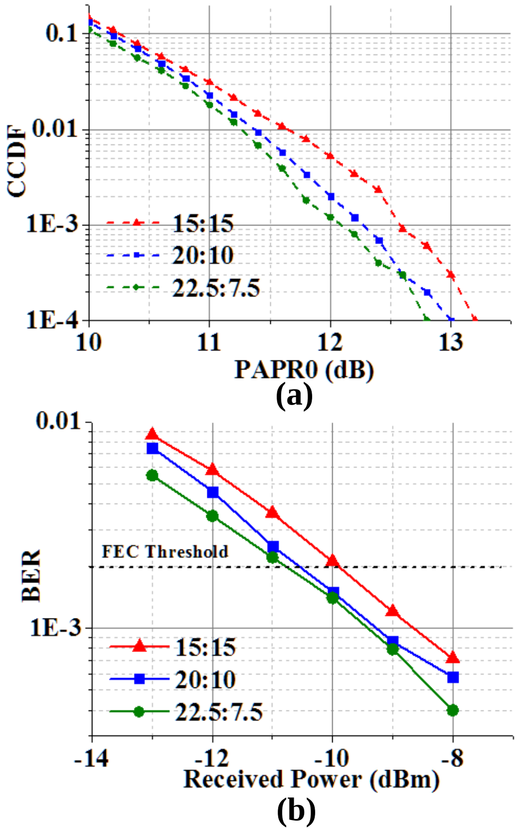

Figure 6. (a) CCDF curves and (b) Optical receiver sensitivities of GFDM-OFDM signals with different bandwidth ratios in the BTB case. FEC threshold: 7% forward error correction threshold (2×10^{-3}).

The influences of the bandwidth ratio and the GFDM block structure are also investigated. As shown in Fig. 5, the slopes of the frequency response differ significantly around 15 GHz and 22.5 GHz. The PAPRs and optical receiver sensitivities of the GFDM-OFDM signals with various bandwidth ratios, i.e. 15:15, 20:10, and 22.5:7.5, are measured in the BTB case. The PAPRs of the signals with 10000 symbols are calculated by using the complementary cumulative distribution function (CCDF). As plotted in Figs. 6(a) and (b), the GFDM-OFDM signal with a bandwidth ratio of 22.5:7.5 performs best in terms of both PAPR and receiver sensitivity. Therefore, the whole band is divided into the slowly declining region, ranging from 0 to 22.5 GHz, and the remaining fast fading region. The attenuation rates for the low-frequency and high-frequency bands are 0.36 dB/GHz and 1.4 dB/GHz, respectively.

As to block structure, we limit our discussions to $N_1 = 8$, 16, and 32 for simplicity, and the allocated sub-symbol number M on each subcarrier changes accordingly from 32 to 8, to maintain the same bit number. However, M should be odd as no ZF receiver exists for even M. Therefore, the total sub-symbol number M_1 is set to $M + 1$, with the 0-th sub-symbol being a guard symbol [9]. The PAPR of an OFDM signal with 256 subcarriers is measured for comparison. As plotted in Fig. 7(a), the PAPR of the GFDM-OFDM signal

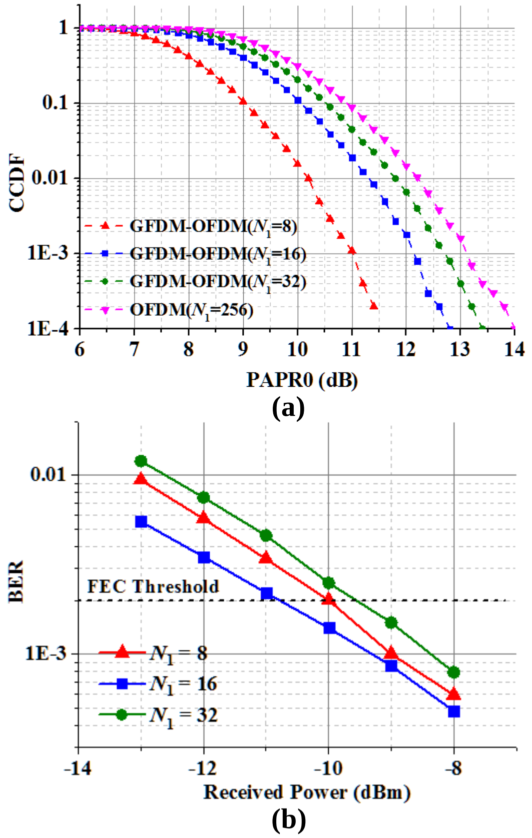

Figure 7. (a) CCDF curves and (b) Optical receiver sensitivities of GFDM-OFDM signals with different block structures in the BTB case.

turns out to be lower than that of the conventional OFDM signal by 2.6 dB when $N_1 = 8$, and 1.3 dB when $N_1 = 16$. The PAPR reduction is 0.7 dB when N_1 is 32. The GFDM-OFDM scheme achieves a significant improvement on PAPR, while DFT-S OFDM reduces the PAPR by 1.0~2.5 dB in [8]. However, the receiver sensitivity of the GFDM-OFDM signal with N_1 being 8 is slightly worse than the case of $N_1 = 16$ as shown in Fig. 7 (b), since it is more sensitive to the frequency-response variations. Besides, it is noteworthy that the increase of the sub-symbol number on each subcarrier will degrade the BER performance because of the much interference in the received signal [20]. Therefore, the case of $N_1 = 16$ is more acceptable as it provides an optimal tradeoff between the PAPR and the BER performance.

IV. RESULTS AND ANALYSIS

After optimizing the parameters, simulations are carried out to investigate the feasibility of our proposed scheme, where the GFDM-OFDM signal, the GFDM and OFDM signals are generated, respectively. For the GFDM signal, the low-frequency and high-frequency bands are assigned to two separate GFDM sub-signals with a guard band between them. Similarly, the two sub-bands of an OFDM signal are filled with OFDM subcarriers. In the simulations, the three signals are generated with the parameters shown in Table 1.

BER curves are measured to calculate the receiver-sensitivity improvement brought by our proposed scheme. The BER versus the received optical power for both BTB and 10-km transmission are shown in Fig. 8. As plotted in Fig. 8(a), at the 7% forward error correction (FEC) threshold of 2×10^{-3}, there are 3.0-dB and 1.6-dB receiver-sensitivity improvements achieved by our proposed scheme with respect to OFDM and GFDM signals, respectively. 2.9-dB and 1.4-dB improvements are also observed after 10-km transmission in Fig. 8(b), respectively. These results show that the GFDM-OFDM signal can achieve better receiver sensitivity than GFDM and OFDM signals. The OFDM signal performs worst in this case as it suffers from a high PAPR. The receiver sensitivity of the GFDM signal is between the other two signals, as the GFDM signal exhibits a low-PAPR characteristic but is easily affected by high-frequency fading effects. As expected, the GFDM-OFDM signal achieves both a low PAPR and strong robustness to high-frequency fading effect, resulting in an improved receiver sensitivity.

TABLE I. PARAMETERS

Parameter	GFDM-OFDM	GFDM	OFDM
Symbol number	10000		
Allocated subcarriers of the low-frequency sub-signal (K_1)	12	12	192
Sub-symbols per subcarrier (M)	16/1	16	1
Modulation scheme for the low-frequency sub-signal	16-QAM	16-QAM	16-QAM
Allocated subcarriers of the high-frequency sub-signal (K_2)	64	4	64
Modulation scheme for the high-frequency sub-signal	4-QAM	4-QAM	4-QAM
CP length (Ncp)	32		
Filter type	RC/RECT	RC	RECT
Roll-off factor	0.1/0	0.1	0

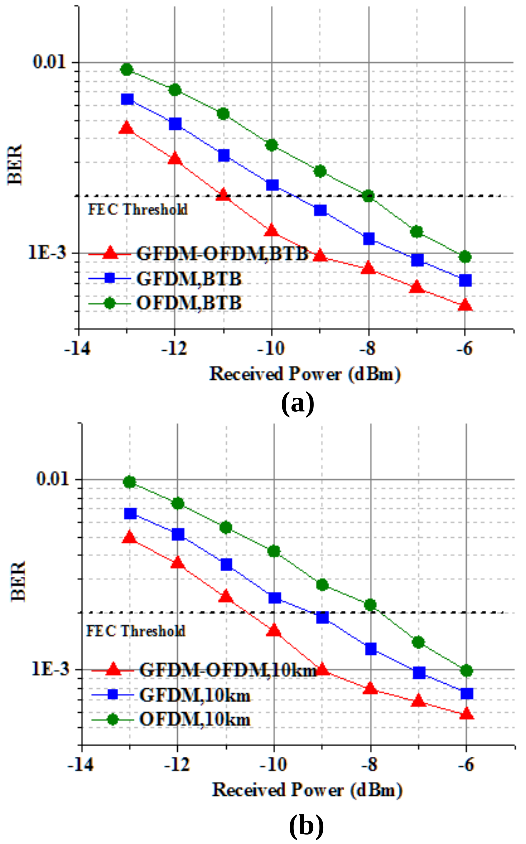

Figure 8. Optical receiver sensitivities of GFDM-OFDM, GFDM, and OFDM signals (a) in the BTB case and (b) after 10-km transmission.

V. CONCLUSION

In summary, we have proposed and demonstrated a novel hybrid modulation technique termed as GFDM-OFDM to improve the receiver sensitivity in an IM-DD system. In our scheme, the GFDM and OFDM signals are properly allocated in different sub-bands according to different channel characteristics. The GFDM-OFDM signal takes advantages of the two techniques and mitigates their detrimental effects. The simulation results verify the feasibility of our scheme. By choosing appropriate parameters, we achieve 3.0-dB and 1.6-dB receiver-sensitivity improvements relative to the OFDM and GFDM signals, respectively. Our proposed scheme provides a promising way to improve the receiver sensitivity for IM-DD applications.

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