Hindawi
International Journal of Optics
Volume 2018, Article ID 2395495, 7 pages
https://doi.org/10.1155/2018/2395495

Research Article

Extended Reach 10 Gb/s Transmission with an Optical I/Q Modulator Using VCSELs over OFDM-Based Multimode Fiber Link

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Received 31 January 2018; Revised 7 March 2018; Accepted 15 March 2018; Published 2 May 2018

Academic Editor: Chenggen Quan

This paper investigates the possibilities of extending the reach of a 10 Gb/s orthogonal frequency division multiplexing- (OFDM-) based multimode fiber (MMF) link with an optical I/Q modulation technique through vertical cavity surface emitting lasers (VCSELs). The proposed I/Q modulation technique comprises two VCSELs in a 90° hybrid combination to produce I/Q modulated OFDM signal. The results show the excellent performance (in terms of BER and Q factor) of the direct-detection optical- (DDO-) OFDM system with the proposed I/Q modulation in comparison to the direct modulation case. The proposed system is able to achieve worst-case BER of about 1.8616×10^{-3} and Q factor of about 10.9949 dB over a 5 km MMF link. The I/Q modulation technique in the DDO-OFDM system has further been investigated for extending the transmission reach of the MMF link using multispan configuration.

1. Introduction

To date, the implementation of MMF links has gained significant attention for high-speed transmission over local area networks (LANs). The main reasons that led to the widespread use of MMF in short-reach applications rely on the availability of necessary bandwidth at low expenses and simplification of the component-to-fiber alignment. In MMF, the signal propagates on different fiber modes with different group velocities that result in differential modal delay (DMD). Over a short distance, the DMD gives rise to intersymbol interference (ISI) with conventional modulation formats. The ISI imposes a limitation on the maximum data speed for a specific length of fiber and causes dispersion limited performance of MMF links rather than noise limited one [1]. Different dispersion compensation techniques have been proposed in the literature like (i) Decision-Feedback Equalizers (DFE) and (ii) Feed-Forward Equalizers (FFE) [2]. No doubt, the DFE/FFE schemes are performing well in single mode fiber (SMF) system [3], but these have limitations to compensate for different characteristics (e.g., chromatic dispersion and modal dispersion) of the MMF system.

However, using OFDM with high-order modulation formats in existing MMF links, the effect of ISI can be minimized due to frequency selective attenuation of the orthogonal channels [4]. Secondly, the partially overlapped spectra of OFDM subcarriers are helpful in achieving high optical spectral efficiency. Thirdly, the RF-to-optical up-down conversion helps in reducing the electrical bandwidth requirement for direct-detection system which is an extremely attractive feature for any high-speed transmission system using OFDM.

With the advancements in laser source technology, the directly modulated VCSELs have become the most preferable laser source for short-range applications due to their attractive attributes, for example, low manufacturing cost, low drive voltage, high modulation bandwidth, low power consumption, and capability of array integration [5]. The short wavelength VCSELs operating at 850 nm wavelength have been proposed for MMF links also that specify high link bandwidth and low ISI penalty [6]. The large active

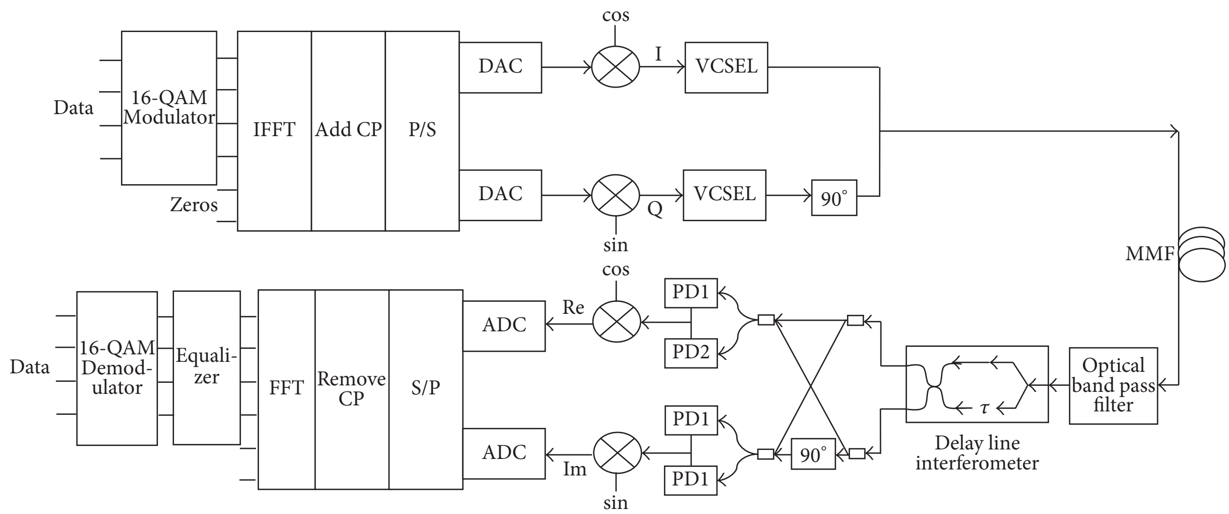

Figure 1: Schematic diagram of the DDO-OFDM system with an optical I/Q modulator using VCSELs for MMF links.

area (~15 μm) and low-source power of VCSELs offered high coupling efficiency for MMF links [7].

Recent extensive studies on MMF links demonstrated enhanced data rates but have limitations in terms of transmission reach (~1000 m). Lowery and Armstrong [8] demonstrated a 10 Gb/s data rate over a 300 m MMF link with the transmission of OFDM signals using zero bias. Further, Deng et al. [9] investigated experimentally 16.375 Gb/s dual-band optical OFDM (O-OFDM) transmission over 200 m MMF using directly modulated VCSELs. The dual-band O-OFDM offers large passband frequency tunability and excellent performance robustness that helps achieve the desired transmission performance with VCSEL modulation bandwidth for cost sensitive applications. Caspar et al. [10] demonstrated 25 Gb/s transmission over 1000 m MMF based on an optimized VCSEL with a single primary mode.

Thus, recent works on MMF links (≥10 Gb/s) using optical OFDM have been able to support transmission up to 1000 m only. Further, the VCSELs have been directly modulated in these researches. In this paper, an optical I/Q modulator using VCSELs is being proposed for 10 Gb/s data rate MMF link with a transmission reach of 5 km. To the best of the authors' knowledge, this paper is a maiden attempt to use an optical I/Q modulation technique for MMF links based on direct detection for extending the transmission reach. As compared to the direct modulation technique using single VCSEL, a considerably improved transmission performance is achieved through the proposed optical I/Q modulation.

2. DDO-OFDM System with I/Q Modulation Using VCSELs

Figure 1 shows a direct-detection system for MMF links which uses an optical I/Q modulator using VCSELs. The OFDM transmitter performs various functions as (i) mapping of data bits into OFDM symbols through inverse fast Fourier transform (IFFT), (ii) inserting cyclic prefix (CP) to combat ISI, and (iii) generating real-time signals through digital-to-analog conversion (DAC).

Thus, data is transmitted in parallel over several subcarriers resulting in a longer symbol period as compared to a serial data transmission for the same total bit rate. Here, equalization is simplified due to the reduced impact of ISI on a longer symbol period. The baseband OFDM signal is defined as [11]

$$S_B(t) = \sum_{k=-(N_{sc}/2)+1}^{k=N_{sc}/2} C_k \exp\left(j2\pi f_k t\right), \tag{1}$$

$$f_k = (k-1)\,t_s, \tag{2}$$

where $S_B(t)$ denotes the baseband OFDM signal, N_{sc} denotes the number of subcarriers, C_k denotes the information symbol or pilot symbol of the k_{th} subcarrier, and f_k is the frequency of the subcarrier. Equation (1) shows one OFDM symbol for simplicity. The resulting baseband OFDM signal is optically modulated with I/Q modulator which comprises two VCSELs to separately modulate the real (I) and imaginary (Q) parts of $S_B(t)$. The use of direct modulation laser is beneficial to improve the capabilities of the optical link in terms of distance-capacity product [12]. Both VCSEL sources are operated at the same wavelength (1550 nm) and the outputs of both VCSELs are combined in a 90° hybrid to produce the I/Q modulated optical OFDM signal.

The VCSELs are the surface emitting semiconducting lasers provided with a laser cavity formed by several epitaxial layers. The output power (P_{out}) of the VCSEL can be calculated as [13]

$$P_{out} = n_i n_o \left(\frac{h\nu}{q}\right)\left(I - I_{th}\right), \tag{3}$$

where n_i represents the injection efficiency, n_o represents the optical efficiency, h represents Planck's constant, ν represents the frequency, q represents the elementary charge, I represents the injected current, and I_{th} represents the threshold

Table 1: VCSEL laser emitter parameters.

Parameter	Value
Test wavelength	850 nm
Operating wavelength	1550 nm
Operating temperature	25°C
Threshold current	1.49538 mA
FWHM linewidth	10 MHz
Linear output power	0.35 mW
Turn on delay	1.73287 ns
P-I slope	0.23405 mW/mA
Relative intensity noise	−150 dB/Hz

Table 2: Different parameters for MMF.

Parameter	Value
Fiber length	5 km
Attenuation	3.0 dB/km
Dispersion	17 ps/nm/km
Gamma cutback factor	0.75
Intermodal bandwidth	−150 dB/Hz

current. The electric field spectrum of the transmitted optical signal is a replica of the baseband RF OFDM signal, with no need for any optical carrier component to be transmitted.

At the receiver, the I/Q modulated optical OFDM signal is directly detected by delay line interferometer with balanced detection. Here, the received signal is first passed through a delay line interferometer before balanced detection of both in-phase and quadrature tributaries. The outputs of the interferometer are further processed with the help of adequate phase shifts. The interferometer helps in converting the phase difference information of two consecutive symbols into intensity information [14, 15]. The delay of interferometer is adjusted to one-symbol duration. This intensity information can be easily detected by the photodiodes, where the resulting photocurrent shows the nonlinear mapping of baseband OFDM signal. The OFDM receiver performs the reverse operation to that of OFDM transmitter as (i) analog-to-digital conversion (ADC), (ii) removal of CP, and (iii) fast Fourier transform (FFT) to convert the OFDM symbols back into data bits [16].

3. Simulation Results

The system shown in Figure 1 has been simulated and 16-QAM modulation technique is being used to map the data bits onto the information symbols. The sampling frequency is set to 10 GHz. The number of OFDM subcarriers is set to 64, while IFFT covers 256 samples and zero padding is set in the middle of the OFDM symbol. The CP length (equal to 12.5%) is also inserted in front of the OFDM symbol to ensure the guard interval. To ensure efficient chromatic dispersion compensation, it is necessary to keep the length of the cyclically extended guard interval longer than the delay spread caused by chromatic dispersion. The baseband OFDM signal is directly modulated with an optical I/Q modulator using VCSELs. The I/Q modulated optical OFDM signal is then launched into the MMF. The different parameters of VCSEL laser emitters and MMF are listed in Tables 1 and 2, respectively.

The simulation results thus obtained are presented in Figures 2–5, respectively. Figure 2 shows the launch and received spectra of 10 Gb/s optical OFDM signal over 5 km MMF link using an optical I/Q modulator and a direct one. The optical spectra significantly show the impact of fiber dispersion on the baseband signal recovery. Figures 2(a) and 2(c), respectively, show the launch spectra and received spectra in an MMF link using optical I/Q modulation. On the other hand, Figures 2(b) and 2(d) demonstrate the respective launch and received spectra in the case of direct modulation using single VCSEL. It is clear that the use of the proposed optical I/Q modulation provides an improved performance with respect to modal dispersion as compared to direct modulation.

In the simulation setup, a single PIN photodiode is employed at the receiver to detect the optical OFDM signal. The proposed 10 Gb/s DDO-OFDM system has been implemented with transmission reach of MMF link varying from 0.1 km to 5 km. The resulting eye and frequency spectra of the system (5 km MMF link with −20 dBm launch power) are shown in Figure 3. Figures 3(a) and 3(b) demonstrate the eye spectra in case of an optical I/Q modulator and direct modulator, respectively. The eye opening is 4.4373×10^{-2} (a.u.) in case of I/Q modulated signal and jitter is 5.5792×10^{-4} ns, whereas the eye opening is 4.2742×10^{-3} (a.u.) in case of direct modulated signal and jitter is 4.9525×10^{-3} ns. Figures 3(c) and 3(d), respectively, demonstrate the frequency spectra in case of an optical I/Q modulator and direct modulator. The frequency spectra illustrate maximum allowable frequency along with the corresponding power. The maximum power in case of I/Q modulated signal is −17.801876 dB, whereas it is −29.079815 dB in case of direct modulated signal.

The performance of the proposed DDO-OFDM system has further been analyzed in terms of bit error rate (BER) and Q factor. These parameters have been assessed with respect to the length of the MMF link. A comparative analysis has been presented for the two cases, that is, using an optical I/Q modulator and using a direct modulator. The corresponding results are shown in Figures 4(a) and 4(b), respectively. It is clear from the results that the DDO-OFDM system with the proposed I/Q modulation outperforms the direct modulation case in terms of BER as well as Q factor. The proposed system with an optical I/Q modulator shows a worst-case BER of about 1.8616×10^{-3} and a Q factor of about 10.9949 dB. The direct modulator, on the other hand, provides worst-case BER of about 2.9750×10^{-2} and Q factor of about 6.0206 dB, over a 5 km MMF link. Table 3 shows a comparative analysis of performance of different systems for MMF links.

With the proposed optical I/Q modulation technique, it thus becomes possible to extend the reach of OFDM-based MMF link up to 5 Km. The reach of the MMF link can further be extended up to 90 km using multispan configuration. However, it is practically impossible in case of direct

Table 3: Comparative performance analysis of the proposed work.

Parameter	Proposed DDO-OFDM system	Lowery and Armstrong [8]	Deng et al. [9]
Data rate (Gb/s)	10	10	**16.375**
MMF	Yes	Yes	Yes
Transmission reach (km)	**5**	0.3	0.2
I/Q modulation	Yes	No	No
BER (worst case)	$\mathbf{6.19635 \times 10^{-3}}$	$\sim 1 \times 10^{-3}$	2.3×10^{-3}
Q factor (worst case)	**11.106108**	--	--

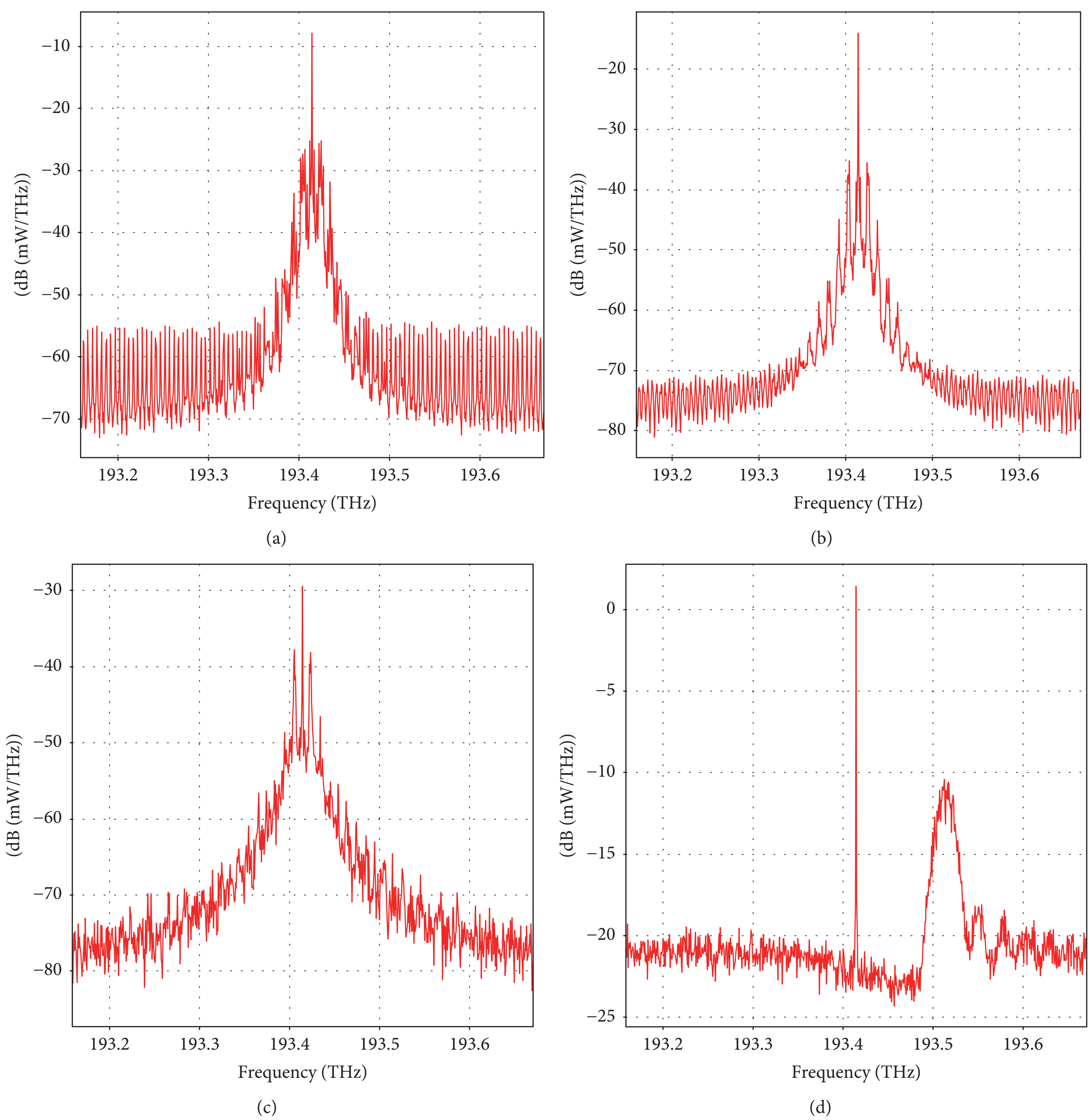

Figure 2: Optical spectra of the optical OFDM signals: (a) launch spectra in case of an optical I/Q modulator; (b) launch spectra in case of a direct modulator; (c) received spectra from the MMF link in case of an optical I/Q modulator; and (d) received spectra from the MMF link in case of a direct modulator.

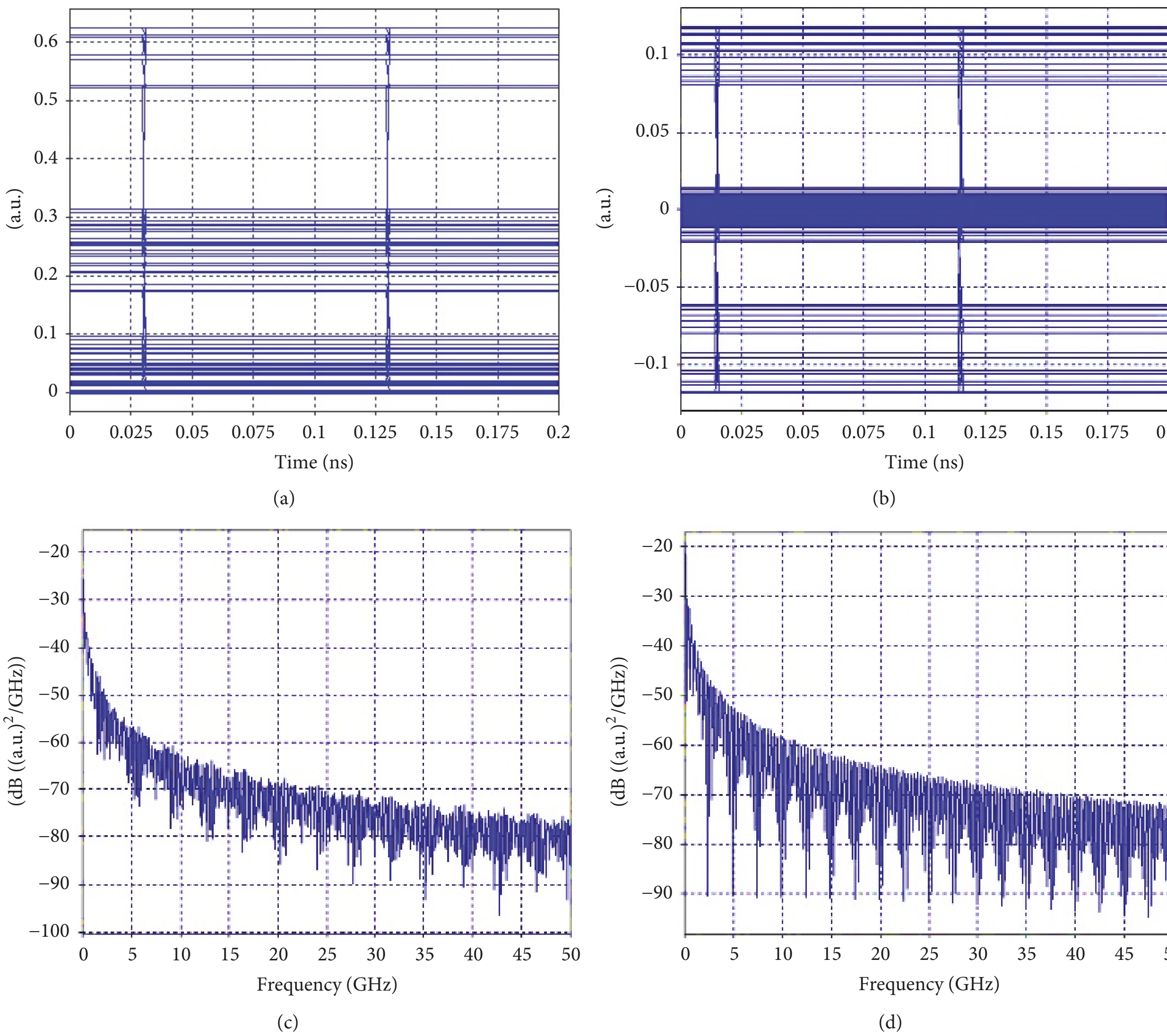

Figure 3: (a) Eye spectra in case of an optical I/Q modulator, (b) eye spectra in case of a direct modulator, (c) frequency spectra in case of an optical I/Q modulator, and (d) frequency spectra in case of a direct modulator.

modulation. Therefore, the performance of the DDO-OFDM system with an optical I/Q modulator has been evaluated for multispan MMF and EDFA, spaced at 10 km apart to achieve a transmission reach of 90 km. The block schematic of the system is shown in Figure 5. The gain of EDFA is adjusted to compensate for the span loss between two amplifiers. The span loss is represented by $\exp(-\alpha l)$, where α is the fiber attenuation coefficient.

The noise figure of EDFA is set to 5 dB and the dispersion coefficient of MMF is set to 17 ps/km-nm. Figures 6(a) and 6(b) show the respective BER and Q factor performance of the system with respect to launch power at 10 Gb/s data rate. It is clear from the figures that the proposed DDO-OFDM system provides excellent performance in terms of BER and Q factor in case of multispan configuration extended up to 90 km.

Thus, it is clear that the proposed optical I/Q modulation technique using VCSELs helps to achieve the extension of short reach in case of MMF links and also opens the possibilities for higher data rates, supporting the efficient bandwidth utilization of the DDO-OFDM system.

4. Conclusion

In this paper, we have proposed an optical I/Q modulation technique using VCSELs for the DDO-OFDM system over 10 Gb/s MMF link. The simulation results prove that improvement in the overall performance of the DDO-OFDM system takes place by the use of the proposed I/Q modulation technique over direct modulation. The effect of modal dispersion is significantly lower in case of I/Q modulated signal

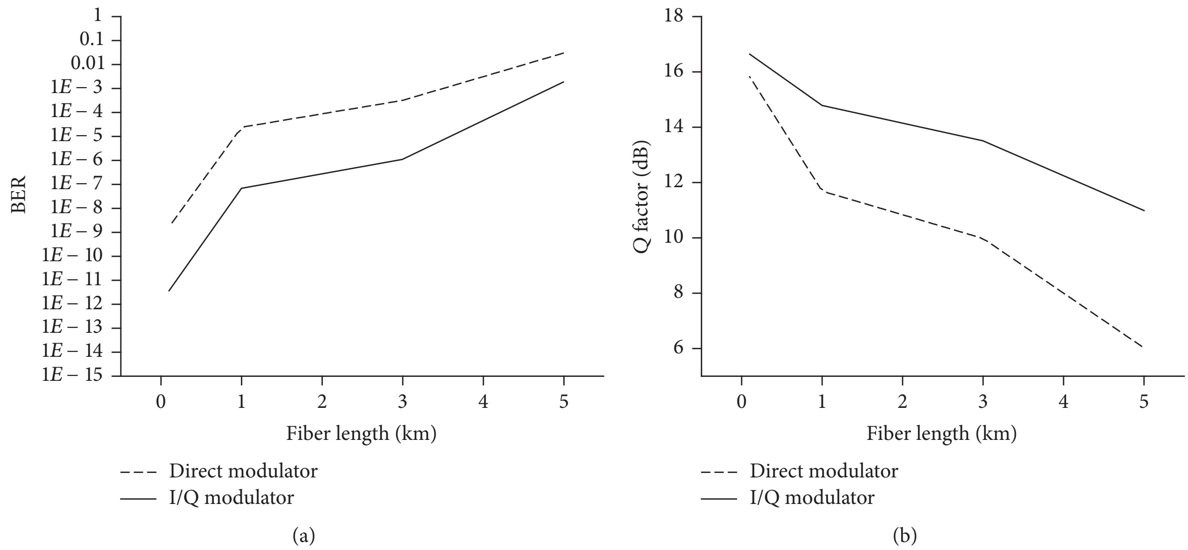

FIGURE 4: Performance analysis of the proposed DDO-OFDM system using an MMF link in terms of (a) BER and (b) Q factor.

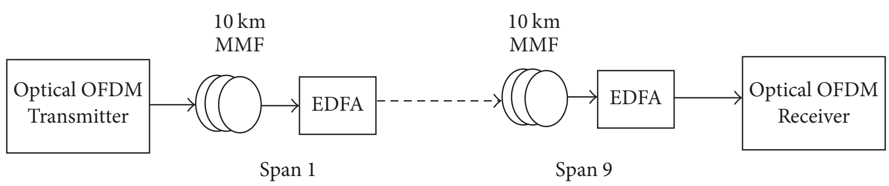

FIGURE 5: DDO-OFDM system in multispan configuration.

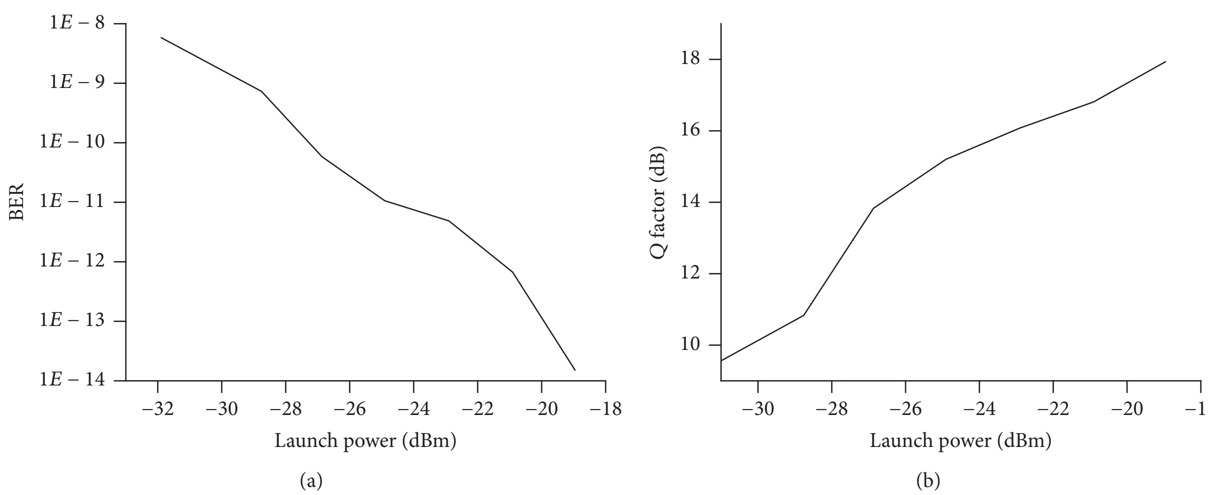

FIGURE 6: Performance analysis of the proposed DDO-OFDM system with respect to the launch power in terms of (a) BER and (b) Q factor.

in comparison to the direct modulated one. The proposed system shows worst-case BER of about 1.8616×10^{-3} and Q factor of about 10.9949 dB, whereas the direct modulator provides worst-case BER of about 2.9750×10^{-2} and Q factor of about 6.0206 dB, over a 5 km MMF link. Therefore, it becomes possible to extend the reach of OFDM-based MMF link up to 5 km using the proposed I/Q modulation. The reach of MMF link has further been extended up to 90 km using multispan configuration with excellent performance.

Conflicts of Interest

The authors declare that there are no conflicts of interest regarding the publication of this paper.

Acknowledgments

Monika Nehra would like to thank the UGC, India, for providing financial assistance in the form of JRF (Award no. 3608, dated 29-02-2016).

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