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Phase Noise Compensation for Coherent Orthogonal Frequency Division Multiplexing in Optical Fiber Communications Systems

In this paper, the Coherent Optical (CO) systems using Orthogonal Frequency Division Multiplexing (OFDM) for dispersion compensation is demonstrated. The Quadrature Amplitude Modulation QAM-OFDM transmitter signal was controlled by the Mach-Zender Modulator (MZM) which modulates the laser source with wavelength of 1550nm. The heterodyne receiver with dual-polarization optoelectronic down-converter is used to obtain good coherent detection without using optical phase locked loop. The analytical part was done using a software simulator. All the proposed system components were simulated using VPIphotonics simulation software for testing CO-OFDM system. The transmitted signal, optical spectrum, eye diagram and constellation diagram was obtained to evaluate system performance.

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1. Introduction

Orthogonal frequency-division multiplexing (OFDM) is a multi-carrier technique that has been deployed in optical fiber communications. A multi-carrier system sends information over N -frequency-division-multiplexed (FDM) channels, each modulated by a different carrier. The total bit rate of the OFDM stream is the sum of bit rates in all narrowband channels. These narrowband channels are also called tones and OFDM is also called multi-tone modulation. Each tone in OFDM can use a different modulation inside it, for example, BPSK, QPSK, and QAM [1]. Coherent optical OFDM (CO-OFDM) has been proposed to combat fiber chromatic and polarization-mode dispersion [2]. Therefore, it can be used to compensate for fiber chromatic dispersion in ultra-long haul communications links [3]. Also, it shows that the CO-OFDM system could provide a feasible solution to the mitigation of Polarization Mode Dispersion (PMD) in existing installed fiber links [4,5].

The simulation was done by an advanced optical communications system simulation package designed for professional engineering called VPIphotonics simulating software by VPIsystems. VPIphotonics, represents an optical communications system as an interconnected set of blocks. Each block is simulated independently using the parameters specified by the user for

that block and the signal information passed into it from other blocks [6].

This paper discusses coherent optical OFDM communications system, gives overview on coherent detection and shows that detection without using optical or electrical Phase Locked Loop (PLL) is possible. As well, details of proposed communications system are explained and explanation of simulation of CO-OFDM system and some simulation results of the CO-OFDM system are presented.

2. Coherent Detection

The most advanced detection method is coherent detection, where the receiver computes decision variables based on the recovery of the full electric field, which contains both amplitude and phase information. Coherent detection thus allows the greatest flexibility in modulation formats, as information can be encoded in amplitude and phase, or alternatively in both in-phase (I) and quadrature (Q) components of a carrier. At the receiving end, the receiver first adds a locally generated optical wave to the incoming information-bearing signal and then detects the combination. Coherent detection requires the receiver to have knowledge of the carrier phase, as the received signal is demodulated by a local oscillator (LO) that serves as an absolute phase reference. There are two basic demodulation formats, depending on how the signal is mixed with the local oscillator

which gives heterodyne or homodyne detection [7].

The received signal is detected either synchronously or asynchronously. The synchronous detection is more sensitive than asynchronous detection therefore it is used in good coherent optical detection. Traditionally, carrier synchronization has been performed by a phase-locked loop (PLL). Optical systems can use one of the following ways:

(i) An optical PLL (OPLL) that synchronizes the frequency and phase of the LO laser with the TX laser.

(ii) An electrical PLL where down-conversion using a free-running LO laser is followed by a second stage demodulation by an analog or digital electrical VCO whose frequency and phase are synchronized.

PLL's are sensitive to propagation delay in the feedback path, and the delay requirement can be difficult to satisfy. The principle of polarization insensitivity for CO-OFDM system use Feed-forward (FF) carrier synchronization overcomes the propagation delay problem [4]. In addition, as a FF synchronizer uses both past and

future symbols to estimate the carrier phase, it can achieve better performance than a PLL which, as a feedback system, can only employ past symbols.

3. CO-OFDM Transmission System

A coherent CO-OFDM transmission system is shown in Fig. (1). At the transmitter, the OFDM symbol is generated as follows: NQAM input QAM symbols are zero-padded to obtain NFFT input samples for inverse FFT (IFFT), N_G non-zero samples are inserted to create the guard interval, and the OFDM symbol is multiplied by the window function [8]. Two Mach-Zehnder modulators (MZMs) encode the RF OFDM signal onto an optical carrier and perform pulse shaping. Two MZMs are needed, one for each polarization (I and Q). The laser diode output is used as a CW source is split into two orthogonal polarization components, which are modulated separately and combined in a polarization beam splitter (PBS). Also, it can be added modulation format (e. g. NRZ or RZ) to the optical signal for increase the sensitivity of receiver.

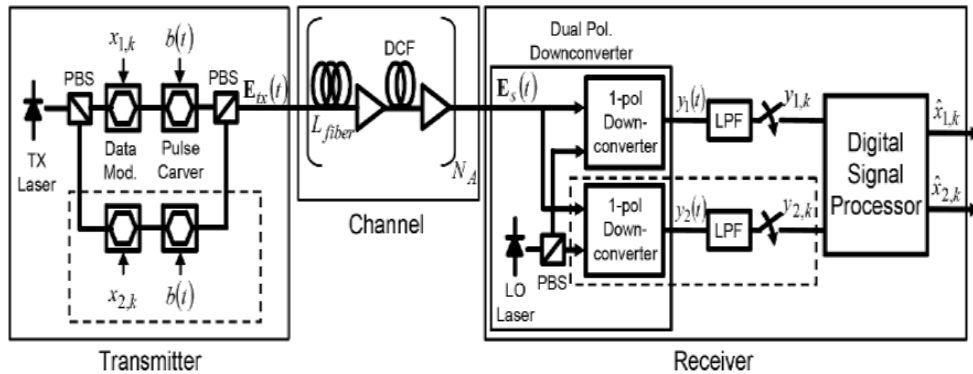


Fig. (1) Coherent transmission system

The first stage of a coherent receiver is a dual-polarization optoelectronic down-converter that recovers the base-band modulated signal. A dual-polarization down-converter is shown inside the receiver of Fig. (1). The output of a local oscillator laser must be added to the received signal with an identical polarization before photo-detection; alternatively, a polarization diversity receiver can be used [9]. The local oscillator (LO) laser is polarized at 45° relative to the polarized beam split (PBS), and the received signal is separately demodulated by each LO component using two single-polarization down-converters in parallel. The four outputs are the I and Q of the two polarizations, which has the full information of electrical field of optical signal at end of fiber $E_s(t)$.

A single-polarization down-converter, involve the LO laser is aligned in the certain

polarization. Down-conversion from optical pass-band to electrical base-band can be achieved either by a homodyne or by a heterodyne receiver. In case of the heterodyne receiver, the local oscillator and transmitter (TX) lasers differ by an intermediate frequency (IF), and an electrical LO is used to down-convert the IF signal to base-band.

The carrier is not shown in OFDM system because it represents pulse shape or modulation format (e.g. NRZ or RZ). In this simulation, the modulation format is set inside TX of (QAM-OFDM) to NRZ modulation format. The transmitted signal can be written as:

$$E_{Tx}(t) = \begin{bmatrix} E_{Tx,1}(t) \\ E_{Tx,2}(t) \end{bmatrix} = \sqrt{P_t} \sum_k x_k b(t - kT_s) e^{j(\omega_c t + \phi_s(t))} \quad (1)$$

where T_s is the symbol period, P_t is the average transmitted power, $b(t)$ is the pulse shape (e.g.,

non-return-to-zero (NRZ) or return-to-zero (RZ)), ω_s and $\phi_s(t)$ are the frequency and phase noise of the TX laser, and $x_k=[x_{1,2},x_{2,k}]^T$ is a 2×1 complex vector representing the k -th transmitted symbol.

4. Simulation Analysis for CO-OFDM System

The experiment setup is illustrated in Fig. (2). This system is simulated by using VPIphotonic

simulation software. The experimental setup of CO-OFDM system uses direct up/down conversion architecture and intermediate frequency (IF) architecture. This setup can operate either on direct up/down conversion architecture or direct up/IF down-conversion architecture by select the analog switch in clock either to clock recovery or to electrical local oscillator.

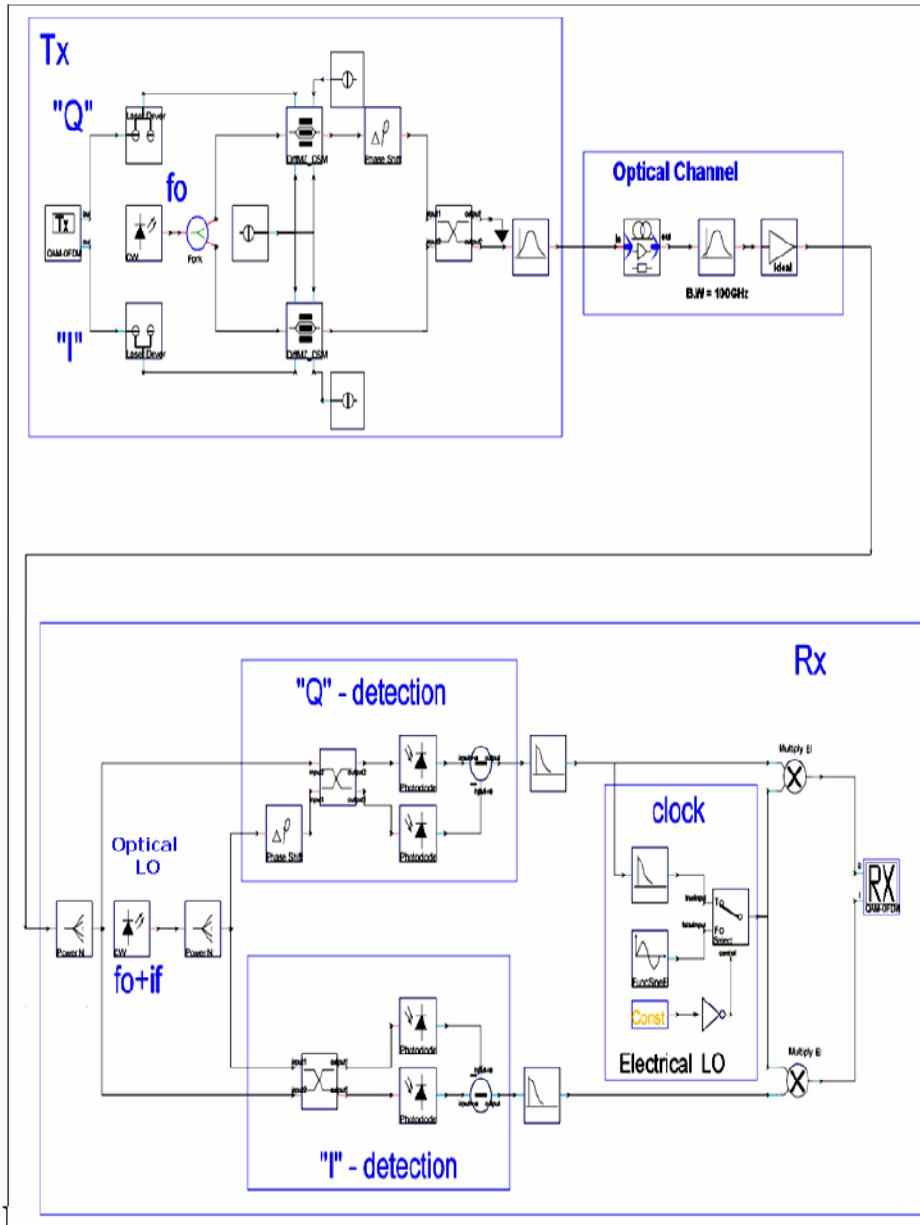


Fig. (2) The experiment setup of CO-OFDM communication system

In the direct up-conversion architecture, the optical transmitter consists of QAM-OFDM transmitter with I and Q signals and modulation format of NRZ, CW laser with optical frequency (f_0) as optical source, two Mach-Zender modulators (MZM's) to up-convert the real/imaginary parts of the QAM-OFDM

transmitter, from the RF domain to the optical domain, i.e., each MZM is respectively driven by the real or imaginary part of the transmitter signal, and fiber couplers to recombine outputs of two MZM's and lunched to the optical channel.

In the direct down-conversion (homodyne) architecture, the OFDM optical receiver involves dual-polarization optoelectronic down-converter uses two pairs of balanced receivers and an optical 90° hybrid to perform optical I/Q detection. The RF OFDM receiver performs OFDM base-band processing to recover the data. The advantages for such direct-conversion architecture are (i) no need for image rejection filter in both transmitter and receiver, and (ii) significant reduction of the required electrical bandwidth for both transmitter and receiver [10].

In the IF down-conversion system (heterodyne), the optical OFDM signal is first down-converted to an intermediate frequency IF and the electrical I/Q detection is performed. The heterodyne receiver involves dual-polarization optoelectronic down-converter, CW local oscillator laser running with optical frequency ($f_o + IF$), electric LO used for down-conversion of the IF signal to base band. In a coherent receiver, a local oscillator (LO) is required to down-convert the received signal. In general, the LO will have random phase fluctuations relative to the transmitter oscillator. The distortion due to transmitter laser and receiver LO phase noise will then appear as a random rotation of points in the received constellation [11].

Optical channel involves the optical fiber and optical amplifier. Optical signal-to-noise ratio (OSNR) can be set from 20dB to 50dB by adding amplifier spontaneous emitting (ASE) noise to the optical signal.

Zero-padding encoding is used to generate the OFDM signal, so that the clock signal and modulated signal do not overlap in frequency as shown in Fig. (3). It was shown that in the noiseless case with ZP-OFDM, the transmit symbol can be recovered regardless of the channel zero locations [12].

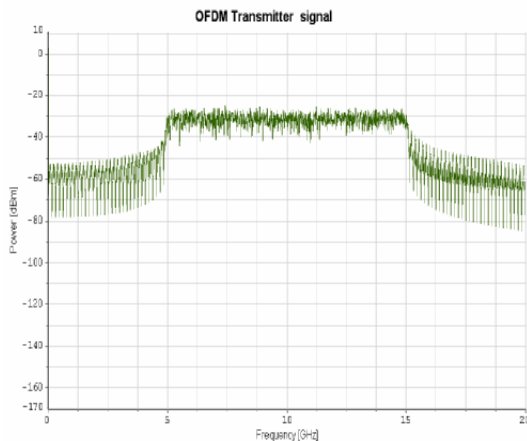


Fig. (3) Zero-padding OFDM transmitter signal

One of the parameters governing performance is the laser source linewidth. For different laser and LO linewidth (LW) values

(10^5 , 10^6 and 10^7) Hz, clock (eye diagram of receive signal) can be observed as shown in Fig. (4). The influence of laser and LO linewidth on the received constellation diagram is shown in Fig. (5). This test was performed under OSNR of 35dB and laser driver bias of 0.03.

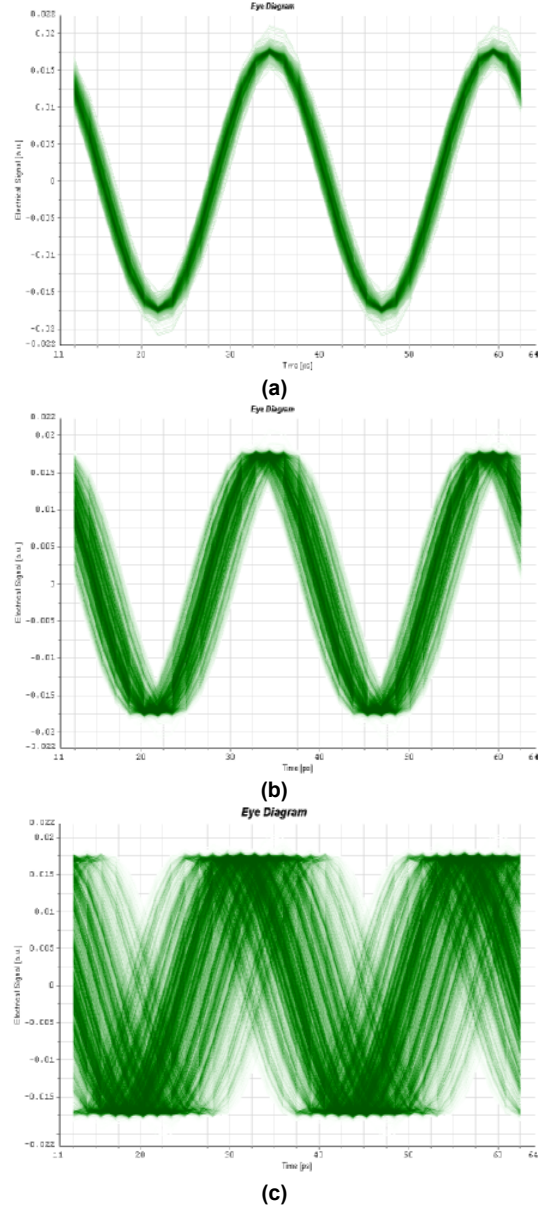
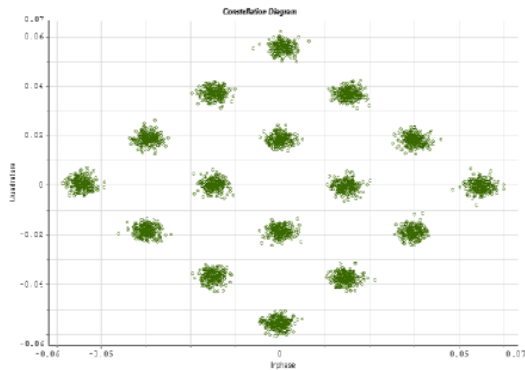
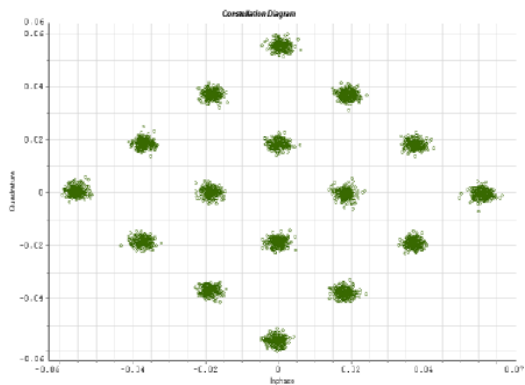


Fig. (4) The Influence of laser linewidth on the received eye diagram (a) LW= 10^5 Hz, (b) LW= 10^6 Hz, (c) LW= 10^7 Hz

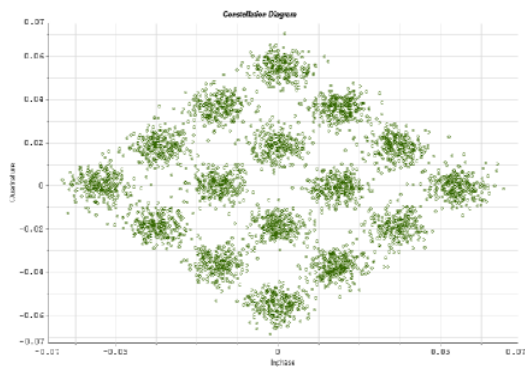
The clock information (phase and frequency mismatch between transmitter and receiver) is contained in the "laser LO" beat term that is extracted at the receiver using an electrical filter and used for down-conversion and phase correction.



(a)



(b)



(c)

Fig. (5) The influence of laser and LO linewidth on the received constellation diagram (a) $LW=10^5$ Hz, (b) $LW=10^6$ Hz, (c) $LW=10^7$ Hz

The performance of the proposed method depends on the strength of the extracted clock signal, which can be tuned by dividing the In-phase (I) and Quadrature (Q) MZM's slightly asymmetrical, i.e., the MZM is slightly biased. Therefore, the eye-diagram and the constellation diagram are the best with bias of 0.05V and they

become worst with bias of 0 and 0.1V, as shown in Fig. (6).

The optical ASE noise is modeled as white Gaussian noise, and laser phase noise is assumed to be white frequency noise. The influence of phase noise in OFDM systems is two-fold, i.e., it generates a common phase rotation of all the sub-carriers in one symbol and a cross-leakage between the sub-carriers named inter-carrier interference (ICI).

The receiver performance of CO-OFDM system with influence of noise is shown in Fig. (7), in which, the experiment system is tested with OSNR of 20dB, 35dB and 50dB, respectively. The effect of OSNR on the optical spectrum, constellation diagram and clock signal is plotted. The influence increasing of OSNR on the received optical spectrum is making the noise level under -47dB. Also, the constellation diagram becomes clearer with increasing OSNR because the strength of the extracted clock signal becomes high. Figure (8) illustrates the relation between the BER and the laser source linewidth at OSNR of 25dB and 35dB. For OSNR of 25dB, lower BER (10^{-5}) at laser linewidth of 10kHz. The BER increased slightly for linewidth of 100kHz and it became very high with 10MHz and the system failed to detect optical signal. For OSNR of 35dB, lower BER of 2×10^{-6} at laser linewidth of 10kHz. The BER increased slightly for linewidth of 100kHz and reached to 10^{-4} for linewidth of 10MHz and the system still at suitable operation.

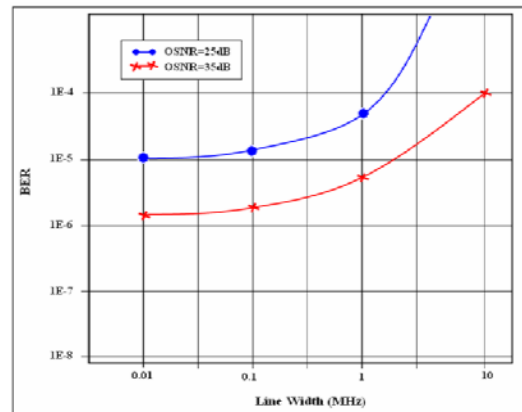
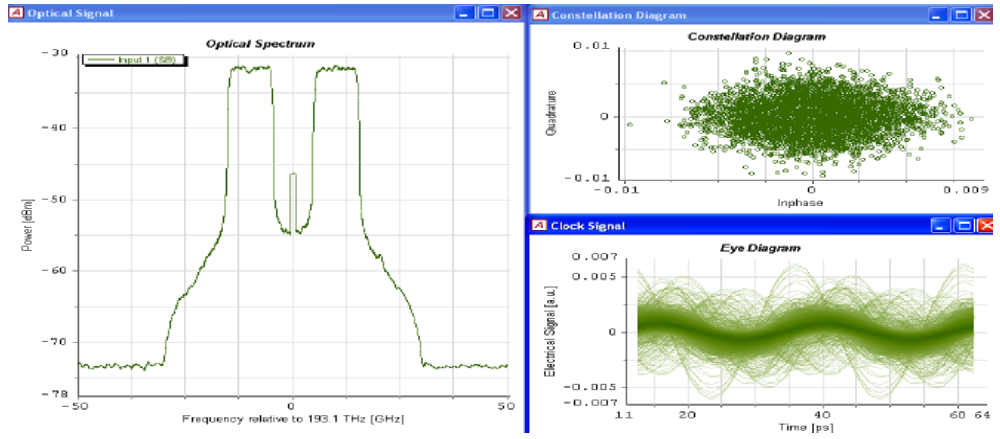
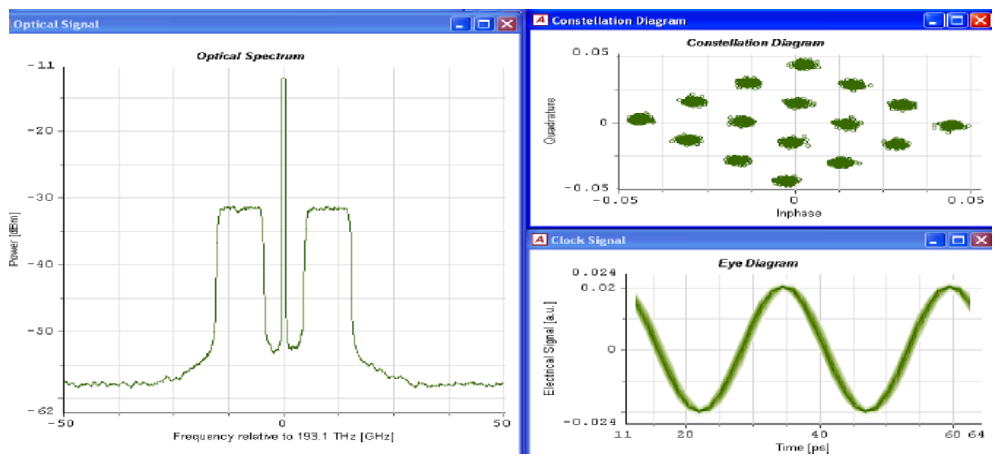


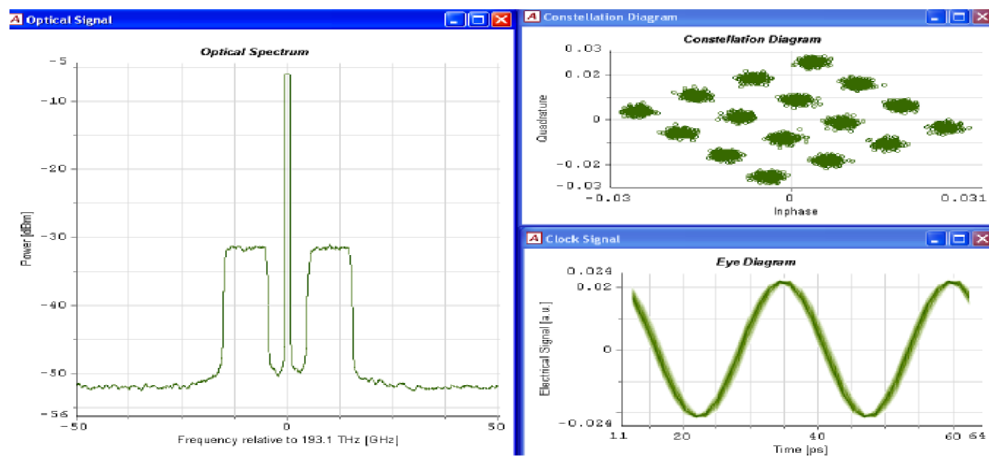
Fig. (8) Relation of laser source linewidth with BER at different OSNR



(a)

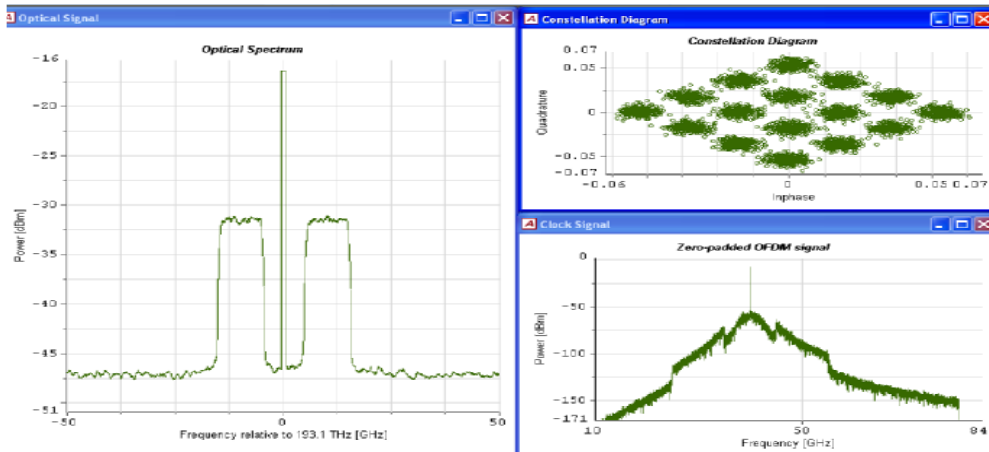


(b)

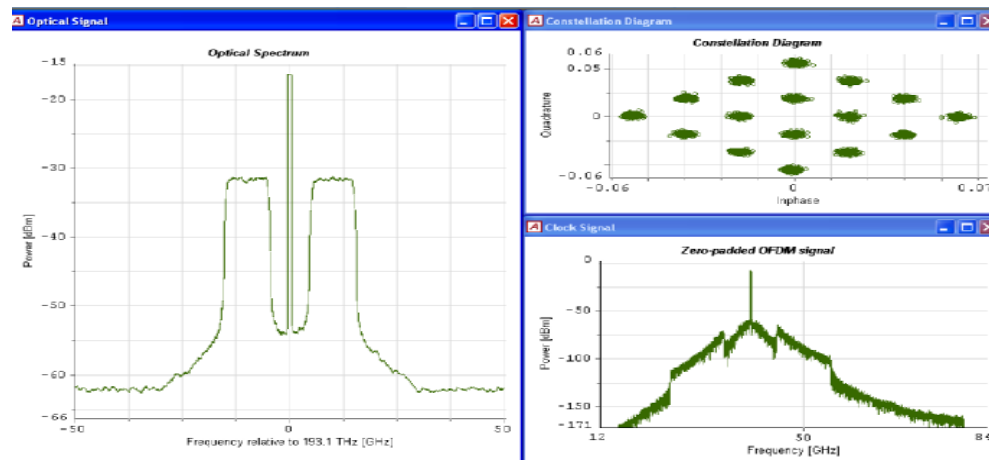


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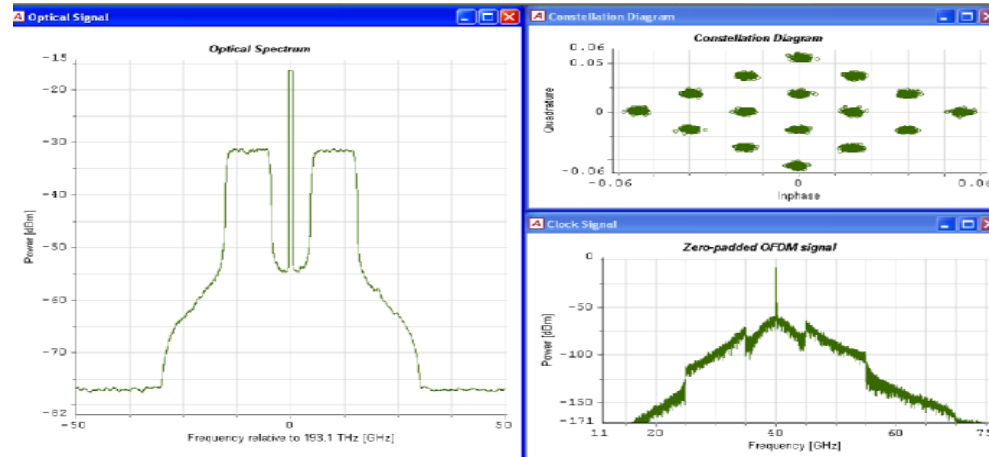
Fig. (6) The effect of changing MZM bias on the receiver performance at bias of (a) 0, (b) 0.05V, and (c) 0.1V



(a)



(b)



(c)

Fig. (7) The influence of noise on the optical spectrum, received spectrum and constellation diagram at OSNR of (a) 20dB, (b) 35dB, and (c) 50dB

5. Conclusion

This paper reports and depicts the results of using CO-OFDM telecommunications system in high bit rate optical transmission systems. The drive for higher performance in optical fiber systems can be achieved by coherent detection. The dual-polarization heterodyne down-

conversion is linear process that can fully recover the received signal field. The coherent heterodyne detection of high bit rate OFDM signals without electric or optical-locked loop (PLL) was studied. The analytical study was employing standard optical fibers. The laser linewidth had an effect on the optical

communications system; therefore, the laser linewidth must be set to approximately 10^6 Hz for suitable performance. The suitable system performance obtained by slightly tuning I and Q MZM's to bias of 0.05V.

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