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Effectiveness of Modulation Formats to Nonlinear Effects in Optical Fiber Transmission Systems under 160 Gb/s Data Rate

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Abstract—Four wave mixing (FWM) in optical fiber is unwanted effect to an optical transmission system, which can severely limit the wavelength division multiplexing (WDM) and lower the transmission efficiency. In this work the robustness of normal Non-Return-to-Zero (NRZ), Return-to-Zero (RZ) and Modified-Duobinary-Return-Zero modulation (MDRZ) to FWM have been evaluated. Furthermore, the system performance is evaluated with the effect of fiber length tuning and applying 160 Gb/s data rate. The findings show that the RZ modulation offers a lower FWM power of −44 dBm at 700 km fiber length than −30 and −38 dBm of NRZ and MDRZ respectively at the same fiber length. Moreover, in terms of system performance at the first channel and 700 km distance, the minimum BER is observed in normal RZ modulation, equal to 1.2×10^{-23}. It is also noticeable that if NRZ and MDRZ modulations are applied, the system performance will be quickly changed and get worse where the BERs are increased to 1.3×10^{-6} and 1.3×10^{-8} consecutively at same channel and parameters.

1. INTRODUCTION

In order to implement dense wavelength division multiplexing (DWDM) systems with high spectral efficiency, it is interesting to note that we can work at high bit rates per channel [1–3]. For WDM systems where the data rate is > 10 Gb/s/channel, the detrimental consequences of dispersion together with nonlinearity have to be conducted to accomplish transmission through each valuable distance. Nonlinear effects are one of the most optical transmission system restrictions. When the total light power inside a fiber is increased, the nonlinear effect becomes uncontrolled and may affect signal efficiency and degrade system performance [4]. One of the major factors that possibly cause interference in transmission systems, in which it has channels arranged to be separated by similar spaces, is called the four-wave mixing (FWM). For optical communication systems, suppressing FWM efficiency is the main objective. A few methods have been used to mitigate the defect of FWM efficiency and also modify the signal output [5–14]. Dispersion administration using fibers with opposite dispersion values is a crucial method in which the whole cumulative dispersal will be kept low. In dispersal-managed systems employing single-mode fiber with dispersal recompense fiber, the large negative value of dispersal of DCF enables us to neutralize the positive dispersal of SMF [15, 16]. In standard transmission distances, the return-to-zero (RZ) and non-return-to-zero (NRZ) modulation forms are employed in most cases. The experiments and surveys have stated that RZ takes into account to be top priority relative to usual NRZ systems [17, 18], as long as typical single-mode fibers are utilized as communication media. On the other hand, due to the narrower optical spectrum of the NRZ format, NRZ can achieve higher spectral efficiency in WDM systems than RZ in the linear pattern. Recently, the optical multiplexers and demultiplexers with the combination of delay lines are one of the considerable various FWM suppression methods implemented [19], in addition to polarization-division multiplexing [20], hybrid amplitude-/frequency-shift keying (ASK/FSK) modulation with prechirped pulses [21], and the channels which

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have unequal spacings, reported in [22, 23]. For all given techniques above, it has been emphasized and proven that features of FWM are connected with the modulation forms along with high date rate. Under high data rate, the FWM crosstalk defect will be changed and depend on the durability of modulation format utilized.

In this paper, we investigate the durability of NRZ, RZ and MDRZ modulation formats to the FWM nonlinear under high data rate of 160 Gb/s and post compensation map. The suggested system design was implemented with different transmission distances and input signal power around 10 dbm.

2. MODELING AND PROPOSED SYSTEM DESIGN

Figure 1 clarifies the suggested system design. Transmitter and receiver are the two basic elements which the suggested system design is made up from. To produce the carrier signal at the transmitter component, the continual wave laser layout (L1–L4) is employed. The frequency of the first channel is adjusted to 191.5 THz, and the interval between every channel and another is 100 GHz. Every channel is modulated with 40 Gb/s bit rate. The external modulator consists of NRZ, MDRZ and RZ transmitter circuits. The transmitter system configuration of every modulation utilized is illustrated in Figure 2. Then, an intensity modulator which is called Mach-Zehnder modulator (MZM), is linked to the transmitter system. The optical link includes seven spans, where each span involves post dispersal map. Also, two erbium-doped fiber amplifiers (EDFAs) are provided to each span in the central of them, which own noise figure magnitude of 4 dB and gains of 20 dB. When the signal is communicated by the channel of the optical fiber, the signal will be detected and obtained at the receiver. An avalanche photo diode (APD) is used to detect the signal to obtain a direct detection. Thereafter, it is transmitted by the low-pass Bessel filter. The BER analyzer is directly connected to the electrical filter which is utilized to produce the diagram. Table 1 illustrates the system simulation parameters.

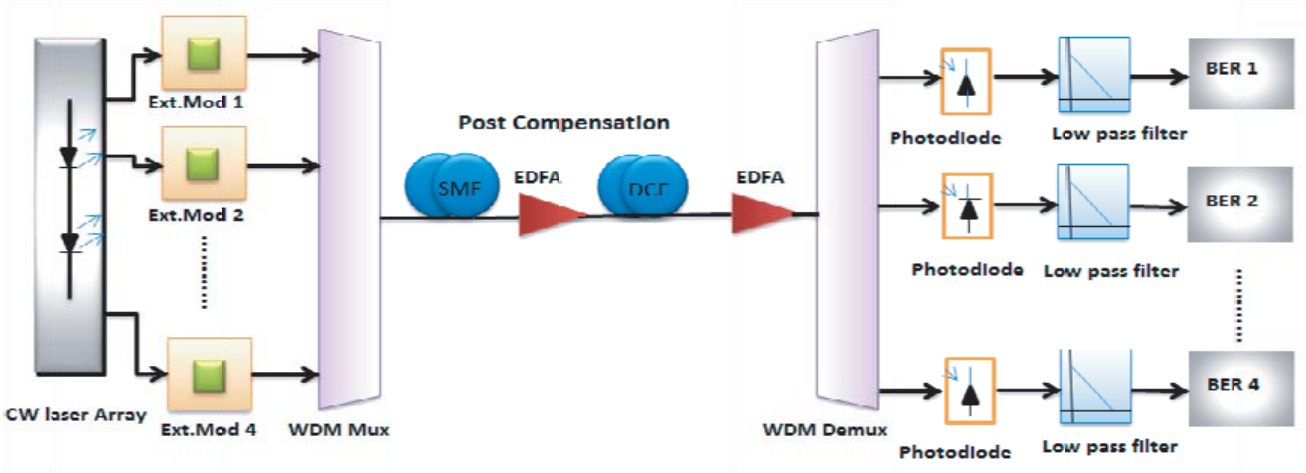


Figure 1. System design of transmitter and receiver of NRZ, MDRZ and RZ.

An avalanche photo diode (APD) which is considered an important part of the intensity modulation/direct modulation is utilized to characterize the bit error rate. If the thermal along with shot noises occur, the probability distribution functions will be Gaussian. It is observed that FWM noises which have probability distribution functions are not Gaussian act. This issue causes disturbance on both thermal and shot noises. Thus, the calculation has relied on Gaussian approximation [24]. Optical amplifier noise is deemed as well. The interference between amplified spontaneous emission (ASE) noise and FWM noise is ignored [25]. In the Gaussian approximation [24], the error probability is written as:

$$P_e = \frac{1}{\sqrt{2\pi}} \int_Q^{\infty} \exp\left(-\frac{t^2}{2}\right) dt \tag{1}$$

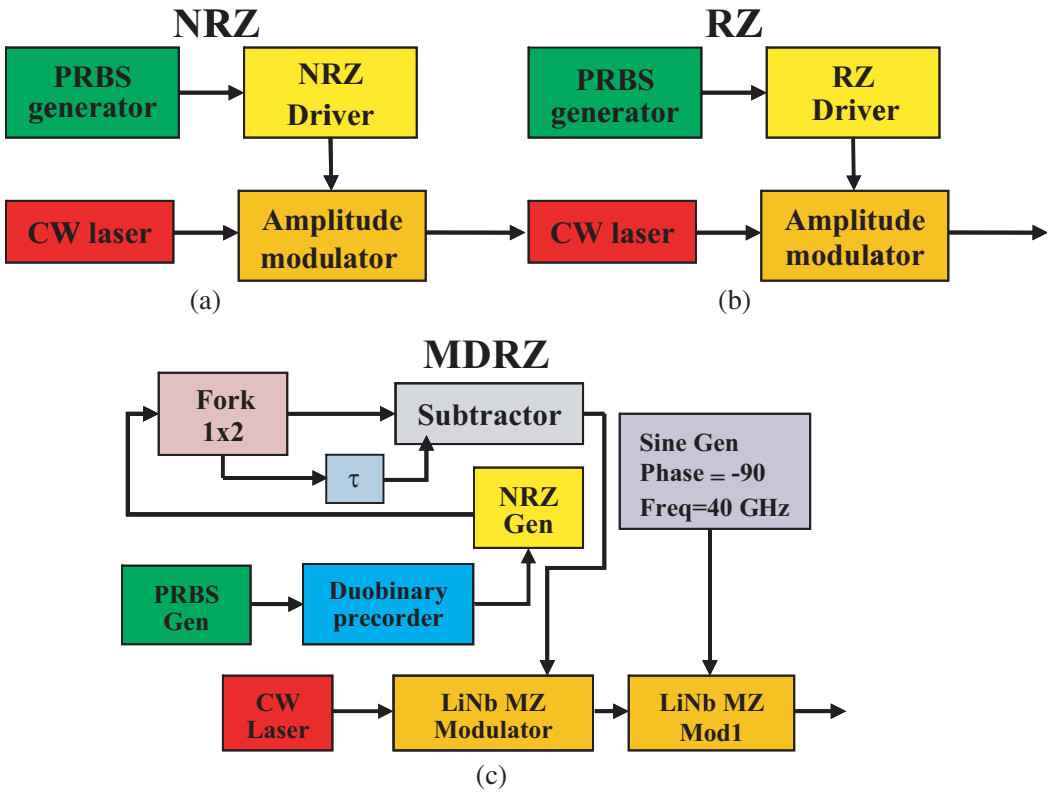


Figure 2. Simulation scheme of optical transmitter for (a) NRZ, (b) RZ and (c) MDRZ.

with

$$Q = \frac{KP_s}{\sqrt{N_{th} + N_{sh} + N_{amp} + 2K^2P_s^2C_{IM}^{(m)}} + \sqrt{N_{th}}} \tag{2}$$

where

$$K = \frac{\eta_d e}{hf} \tag{3}$$

$$P_s = GL_tP_1 \tag{4}$$

$$\Re N_{th} = \frac{Q_0^2}{4}\left(\frac{KP_{s0}}{Q_0^2} -\right)^2 \tag{5}$$

$$\Re N_{sh} = KP_s \tag{6}$$

$$N_{amp} = k_aK^2\left(G-1\right)\left(m+1\right)L_tP_s \tag{7}$$

$$k_a = 4n_{sp}hfB_f \tag{8}$$

$$C_{IM}^{(m)} = \frac{1}{8}\sum_{p\neq q\neq r\neq s}\frac{P_{pqr}}{P_s} + \frac{1}{4}\sum_{p\neq q\neq r=s}\frac{P_{pqs}}{P_s} + \frac{1}{4}\sum_{p=q\neq r}\frac{P_{ppr}}{P_s} \tag{9}$$

Here, $C_{IM}^{(m)}$ is the FWM crosstalk components, P_s a received peak power of the signal light, N_{th} the thermal noise power, N_{sh} the shot noise power, N_{amp} the optical amplifier noise power, η_d the quantum efficiency of the detector, e the electric charge, h the Planck's constant, f the light frequency, G the optical pre-amplifier gain, m the number of nodes, L_t the coupling loss in the optical pre-amplifier, and $P1$ is one channel input power into the preamplifier. In this paper, Q is a Q value corresponding to a required BER, P_{s0} a received peak power of the signal light for a required BER with neither FWM nor ASE, and $\Re = 2eB_fM^x$ where B_f is the electrical filter bandwidth, M the APD current

multiplication factor, and x the APD excess noise factor. Receiver parameters are $B_f = 10\,\text{GHz}x0.7$, $M = 15$, and $x = 0.7$ [24]. It is supposed that an APD whose quantum efficiency ηd of 80% is taken into consideration [26]. In random RZ, the bandwidth will be doubled compared to NRZ, and both P_{pqr} and $Ppqs$ will be multiplied by probability $\frac{1}{4}$ and P_{ppr} multiplied by probability $\frac{1}{2}$ where the total probability of all FWM components equals 1.

$C_{IM}^{(m)}$ is replaced by $C_{RRZ}^{(m)} a C_{RRZ}^{(m)}$ as follows:

$$C_{RRZ}^{(m)} = \frac{1}{4}\frac{1}{8}\sum_{p\neq q\neq r\neq s}\frac{P_{pqr}}{P_s} + \frac{1}{4}\frac{1}{4}\sum_{p\neq q\neq r\neq s}\frac{P_{pqs}}{P_s} + \frac{1}{2}\frac{1}{4}\sum_{p\neq q\neq r}\frac{P_{ppr}}{P_s} \tag{10}$$

In terms of NRZ modulation, the FWM crosstalk will become:

$$C_{NRZ}^{(m)} = \frac{1}{8}\sum_{p\neq q\neq r\neq s}\frac{P_{pqr}}{P_s} + \frac{1}{4}\sum_{p\neq q\neq r\neq s}\frac{P_{pqs}}{P_s} + \frac{1}{4}\sum_{p\neq q\neq r}\frac{P_{ppr}}{P_s} \tag{11}$$

$$\Re P_s = -\frac{Kk_a\left(G-1\right)L_t\left(m+1\right)+}{K\left(4C_{IM}^{(m)} - 1/2Q^2\right)}\Re + \frac{\sqrt{\left[Kk_a\left(G-1\right)L_t\left(m+1\right)+\right]^2 - N_{th}K\left(8C_{IM}^{(m)} - 1/Q^2\right)}}{K\left(4C_{IM}^{(m)} - 1/2Q^2\right)} \tag{12}$$

$$Q = \frac{KP_s}{2\sqrt{N_{th}+N_{sh}+N_{amp}+2K^2P_s^2C_{IM}^{(m)}}} \tag{13}$$

Table 1. Optical transmission system parameters.

Parameter	Unit	Values
Length of fiber, L	km	100 to 700
Input power, P_i	dBm	10
Fiber dispersion, D_c	ps/nm · km	(16.87) in SMF and (−85) in DCF
Cross effective area, A_{eff}	μm^2	(70) in SMF and (22) in DCF
Degeneracy factor, D	–	6
Third order Susceptibility, X_{111}	$m^3/w \cdot s$	6×10^{-15}
Input frequencies, F_{in}	(THz)	191.5–191.8
Channel Spacing, Δ_f	(GHz)	100
Attenuation factor, α	(dB/km)	0.2
Number of channel, N_c	–	4
Total data rate, B	Gb/s	160

3. RESULTS ANALYSIS AND DISCUSSIONS

In this section, the fiber length effect on FWM power with three modulation types which are NRZ, MDRZ and RZ modulation was evaluated. The system performance is simulated in terms of BER under the impact of fiber length tuning. The results are summarized as follows.

3.1. Averaged FWM Crosstalk

System simulation was done with increase of the fiber length values from 100 to 700 km, i.e., seven spans, with all simulated modulations available. Figure 3 explains the FWM versus transmission distance variation under 160 Gb/s. An increase in the transmission distance can increase the FWM crosstalk on the channel and thus decrease the optical system efficiency. At low values of transmission distance, the nonlinear effect has a little effect on system performance, i.e., FWM was low. When power of the

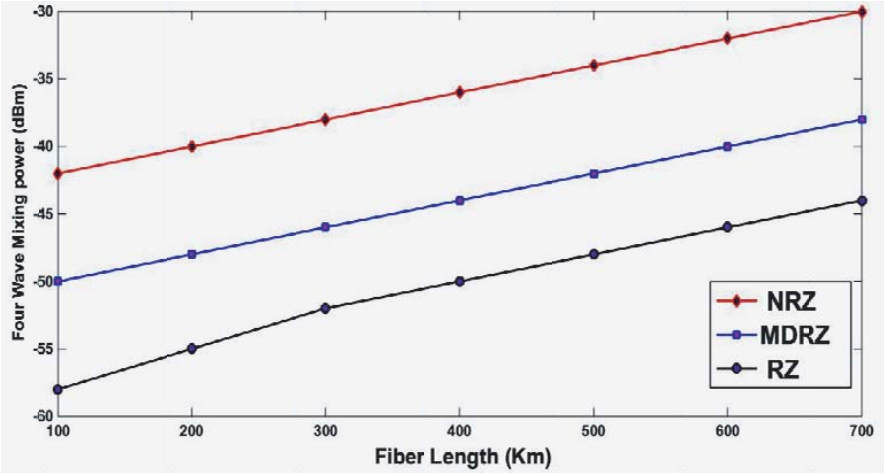


Figure 3. FWM power versus fiber length variation for different modulation.

channel increases, the crosstalk will appear strong and impair the transmission system because it causes depletion of the channel power.

Figures 4(a)–(c) show the optical spectrum of 700 km optical fiber. It is obvious from these figures that the FWM power is high and reaches −30 dBm in NRZ modulation format, while in the available MDRZ and RZ modulations, the FWM powers drop to −38 and −44 dBm, respectively. This means that RZ modulation appears better tolerant to FWM crosstalk than its competitors.

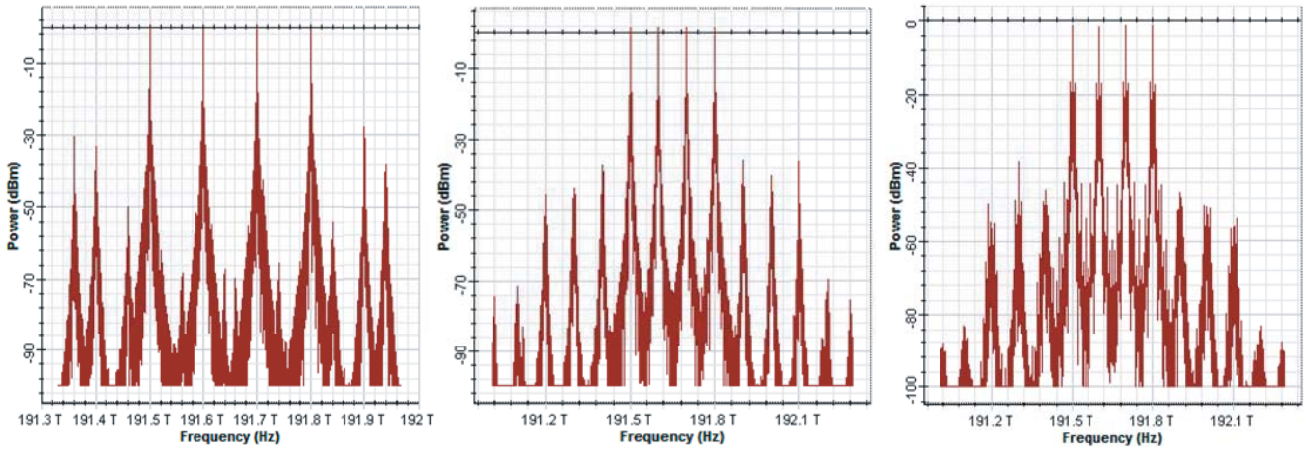


Figure 4. Optical spectrum analyzer after 700 km distance with three modulation formats types. (a) NRZ, (b) MDRZ and (c) RZ.

3.2. Bit Error Rate and Eye Diagram

Figure 5 explains the relation between the fiber length and BER under data rate influence of 160 Gb/s. The system performance has been evaluated by using single mode fiber (SMF) and for three modulation types used. It can be seen that an increment in the transmission distance leads to increase of the bit error rate in the system. The trend of the system performance is similar to all the channels used, i.e., the RZ reveals better system performance. It is observed from Figure 5(a) that at the first channel, the RZ modulation technique offers a minimum BER of 1.2×10^{-23} at transmission distance of 700 km. However with NRZ and MDRZ modulations, the BERs are 1.3×10^{-6} and 1.3×10^{-8} respectively at the same channel and fiber length.

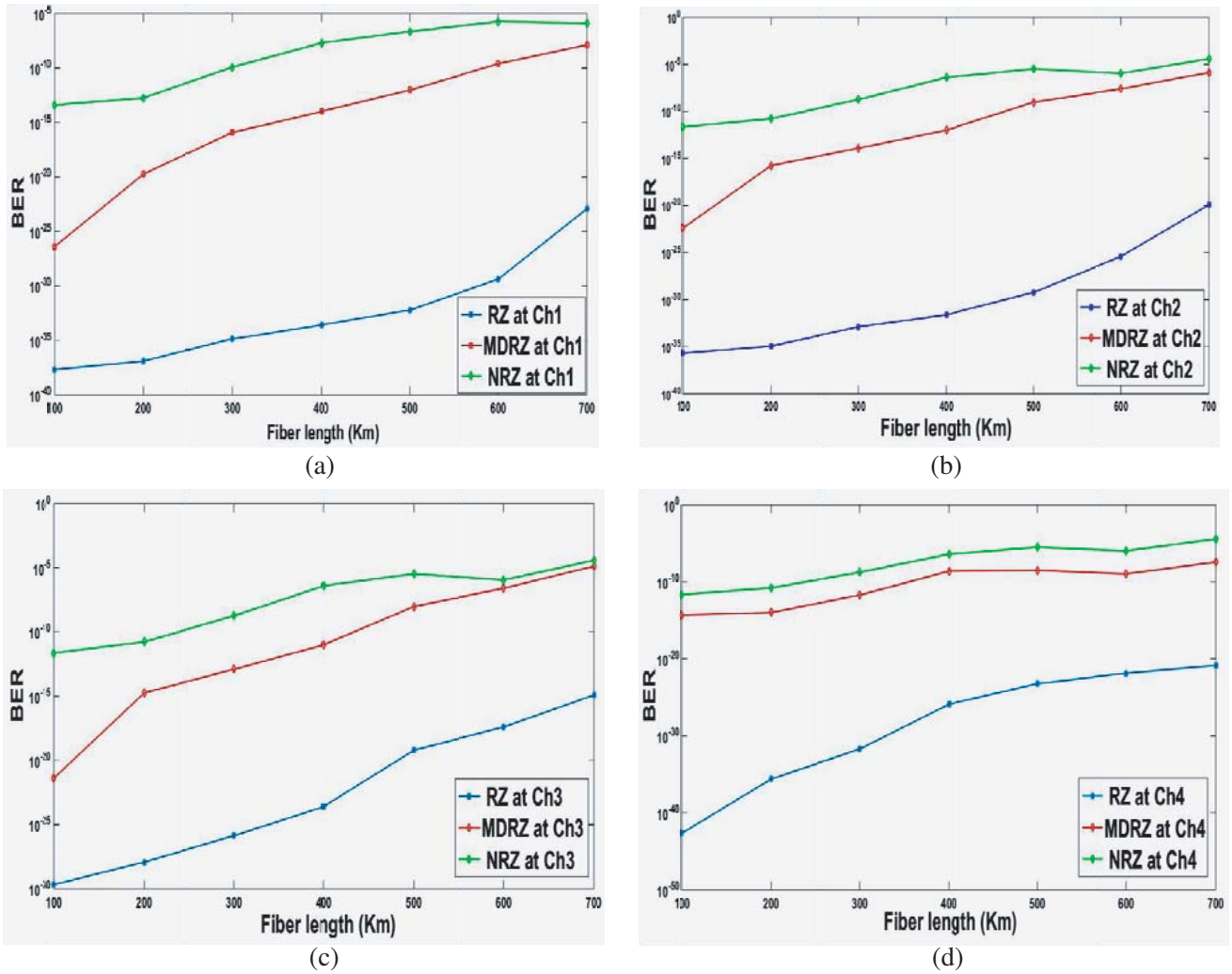
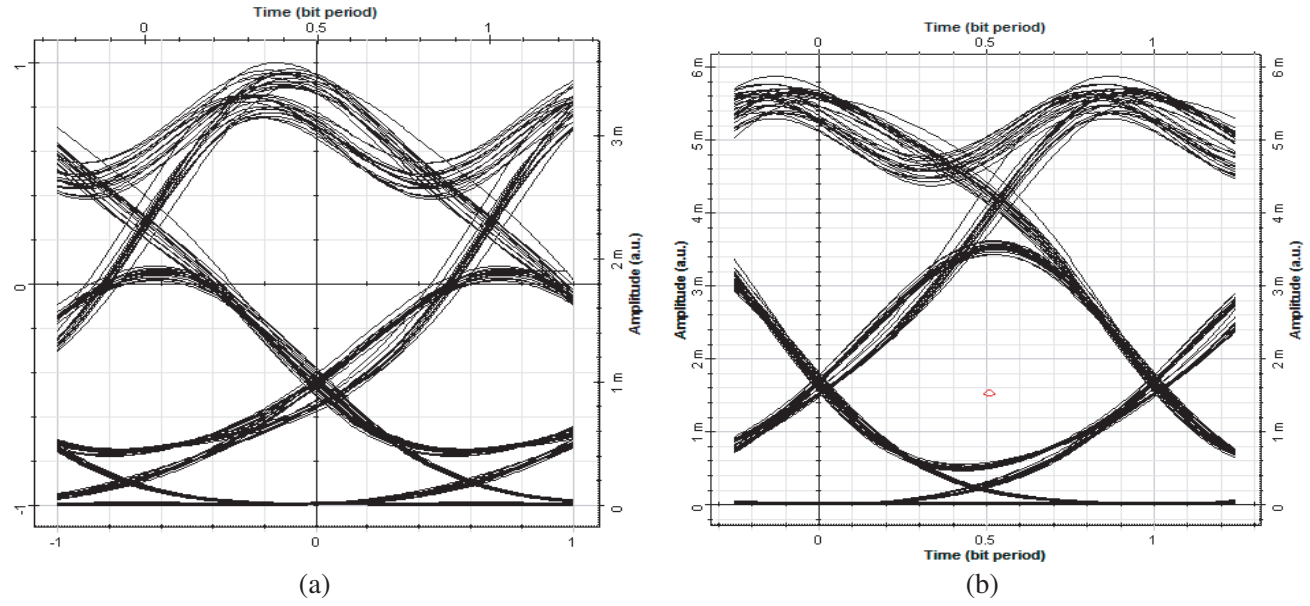
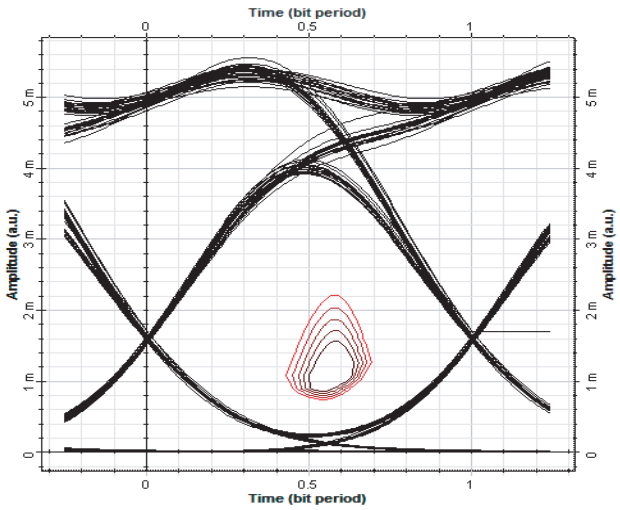


Figure 5. BER versus fiber length for modulation technique of (a) ch1, (b) ch2, (c) ch3 and (d) ch4.





(c)

Figure 6. Performance of eye diagram of modulation technique using (ch1). (a) NRZ modulation, (b) MDRZ modulation and (c) RZ modulation.

More importantly, it can be concluded, from the modulation behavior with high values of both data rate and distance, that RZ modulation reveals more adequacy to nonlinear effect than NRZ and MDRZ. Figure 6 shows the optimum eye diagram for all modulations used after 700 km and measured at the first channel. The eye diagram was clearer with RZ modulation of BER (1.2×10^{-23}). Inversely with NRZ and MDRZ modulation, where the eye diagram has less clarity and high BERs 1.3×10^{-6} and 1.3×10^{-8} at the same channel. More opening eyes diagram means that the RZ modulation has high firmness to nonlinear effect in high data rate, also improving in succeeding rate of receiving bits (1 and 0) detection with little defect or no noise due to the overlapping.

4. CONCLUSION

In this paper, the optical transmission performance has been evaluated under the impact of fiber length tuning and applying high data rate with existence of NRZ, RZ and MDRZ modulation formats. Furthermore, the study is conducted for the effect of fiber length variation to FWM behavior. The findings prove that the RZ incurs the least FWM powers, i.e., −44 dBm, while NRZ modulation incurs the most FWM power of −30 dBm, both at the fiber length of 700 km. In terms of Bit error rate at the first channel, RZ introduces lower BER of 1.2×10^{-23} at a 700 km fiber length than other modulations used. Finally, it can be concluded that the RZ modulation offers more toughness to FWM crosstalk in contract with NRZ and MDRZ modulations even with high data rate values.

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