33% RZ-DPSK 10 Gb/s WDM Transmission

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Abstract

200 GHz-spaced 16-channel 40Gbit/s WDM signal transmission is proposed in C-band using 33% return-to-zero differential-phase-shift-keying (RZ-DPSK) format over a 5 spans of dispersion shifted-Anomalous fiber link. A parametric run on each span fiber length is performed (from 25 km up to 100 km). The performance of 16 40 Gb/s 33% RZ-DPSK WDM channels is analyzed using the “Optical Simulation “ software. While, the nonlinearity results related to optical fiber system have been simulated. Results that are given in this work are obtained using MATLAB R2009b (version 7.9.0.529).

الارسال باستخدام التقسيم المتعدد للطول الموجي عند معدل نقل 10 Gb/s
وصيغة تخمين 33% RZ-DPSK

الخلاصة

تم اقتراح ارسال اشارة التي تستخدم التقسيم المتعدد للطول الموجي (WDM) لـ 16 قناة عند معدل نقل 40Gb/s بمسافة بين قناة واخرى 200GHz في حزمة C-Band باستخدام صيغة التضمين 33% RZ-DPSK فوق خمس مدات من رابط ليف غير منتظم مزاح التشتت. تم تأدية التشغيل المعاملي على كل مسافة لطول ليف (من 25 كيلومتر بحدود 100 كيلومتر). تم تحليل الاداء لـ 16 قناة التي تستخدم التقسيم المتعدد للطول الموجي (WDM) عند معدل نقل 40 Gb/s و صيغة التضمين 33% RZ-DPSK باستخدام برنامج "محاكاة بصرية" . بينما، النتائج الغير خطية المتعلقة بنظام الليف البصري قُلّدتْ. تم الحصول على النتائج التي أُعطيت في هذا العمل باستخدام برامج بلغة البرمجة (MATLAB) اصدار 7.9.0.529 (R2009b).

Introduction

Nowadays, various internet applications, such as electronic commerce, video-on-demand (VOD), video phone and conferencing, etc. are emerging and are becoming very popular. In order to support these bandwidth-hungry services, networks which are broadband, easy to manage, secure and transparent to the end users are highly desired. One promising solution is to employ wavelength-division multiplexing (WDM) technique to unleash the enormous bandwidth offered by the optical fiber. In conventional optical fiber transmission systems, intensity modulation is often employed. Recently, optical differential phase-shift keying (DPSK) has attracted much interest for WDM systems, and it has become the format of choice for long-haul optical fiber transmission because of its high robustness in the presence of fiber nonlinearities [1-3]. DPSK was studied around ten years ago in a search for higher receiver sensitivity [4, 5]. Recently, the technical challenge of applying return-to-zero (RZ) DPSK to long-haul WDM transmission has been taken up following the discovery that RZ may reduce fiber nonlinearity phase noise [6]. In this work, we simulate C-band 640 Gbit/s (16-channel, 40 Gb/s)

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WDM transmission over a 100 km DS-Anomalous fiber with 200 GHz-spacing. The transmission scheme of 33% RZ-DPSK format was newly proposed.

3. WDM System

Wavelength division multiplexing (WDM) is a technology that enables the transmission of several optical signals simultaneously at different carrier wavelengths on a single fiber and the separation of the signals by wavelength at the receiving node. By definition, the term wavelength division multiplexing can be used to denote any technique by which two or more optical signals having different wavelengths can be simultaneously transmitted in the same direction over one fiber, and then the wavelengths are separated at the distant end [7].

Fig. (1) shows the implementation of a typical WDM network containing various types of optical amplifiers. At the transmitting end, there are several independently modulated light sources, each one emitting signals at a unique wavelength. Here, a multiplexer is needed to combine these optical outputs into a serial spectrum of closely spaced wavelength signals and couple them onto a single fiber. At the receiving end, a demultiplexer is required to separate the optical signals into appropriate detection channels for signal processing. At the transmitting end, the basic design challenge is to have the multiplexer provides a low-loss path from each optical source to the multiplexer output. Since the optical signals that are combined generally do not emit any significant amount of optical power outside of the designated channel spectral width, interchannel crosstalk factors are relatively unimportant at the transmitting end. A different requirement exists for the demultiplexer, since photodetectors are usually sensitive over a broad range of wavelengths, which could include all the WDM channels [8].

The WDM scheme is the same as frequency division multiplexing (FDM) used in microwave radio and satellite systems. Just as in FDM, the wavelengths (or optical frequencies) in WDM must be spaced properly to avoid interference between adjacent channels [9].

An attractive feature of WDM is the fact that, the only active components of the system are the optical sources and detectors. The multiplexers/demultiplexers are passive and are therefore intrinsically more reliable than active multiplexers [10].

4. Nonlinear Channel Impairments

When the optical power within the fiber is small, the fiber can be treated as a linear medium. In this case, the loss and the refractive index of the fiber can be treated as independent of signal power. But, when the power level becomes high, the nonlinearity effects of the medium come into play. In reality, both the loss (gain) and index depend on the optical power in the fiber. Nonlinearities can place significant limitations on the high speed systems as WDM systems [10, 11].

The nonlinearities in optical fiber can be classified into two categories. The first occurs owing to scattering effects in the fiber medium due to interactions of light waves with phonons (molecular vibrations) in silica medium. The two main effects are Stimulated Brillouin Scattering (SBS) and Stimulated Raman Scattering (SRS). The other category is Kerr effect due to changes in the refractive index with optical power.

The three main effects are Four-Wave Mixing (FWM), Self-Phase Modulation (SPM), and Cross-Phase Modulation (XPM) [10, 11, 12].

One difference between the scattering effect and the Kerr effect is that, stimulated scattering has threshold power level at which the nonlinear effects manifest themselves while Kerr effect does not have such threshold [12].

4.1 Stimulated Scattering

Stimulated scattering effects can be divided into SBS and SRS.

I.Stimulated Brillouin Scattering (SBS)

The SBS is a single-channel effect caused by the interaction of light with sound waves in the fiber [13].

SBS produces gain in the direction opposite to the direction of propagation of the signal, in other words, back towards the source. Thus, it depletes the transmitted signal as well as generates a potentially strong signal back towards the transmitter [10, 11].

Some of the forward propagation signal is redirected backward, resulting in power loss at the receiver. Brillouin scattering is only significant above threshold power level that is equal to [14, 15]:

$$P_{th} = \frac{21A_{eff}}{L_{eff}g_B} \quad \dots(1)$$

where A_{eff} is the effective core area, L_{eff} is the effective interaction length defined as [14]:

$$L_{eff} = \frac{\left[1 - e^{(-\alpha L)}\right]}{\alpha} = \frac{L_A}{L} \quad \dots(2)$$

and α represents fiber loss, L_A represents amplified link length. For optical communication systems L_{eff} can be approximated by 1/α as αL>>1 in practice, g_B is the Brillouin gain, and L is the fiber length.

The threshold power of SBS can be given also in terms of different parameter as follows [16]:

$$P_{th} = 4.4 \times 10^{-3} d^2 \lambda^2 \alpha v \quad \dots(3)$$

where d and λ are the fiber core diameter and the operational wavelength, respectively, and ν is the source bandwidth.

The exact value of the average threshold power depends on the modulation format (RZ versus NRZ) and is typically ~5mW. It can be increased to 10mW or more by increasing the bandwidth of the optical carrier to greater than 200MHz through phase modulation [14].

Therefore, as long as the signal power in the WDM channels does not exceed the threshold, the SBS does not cause significant impact on the system [13].

II. Stimulated Raman Scattering (SRS)

SRS is the nonlinear parametric interaction between the light and molecular vibration [13].

Unlike SBS, SRS scatters light waves in directions, forwards, and backwards. However, using optical isolators can eliminate the backward propagation light. Therefore, the forward scattered light is more concern [12].

Similar to the SBS case, the threshold power P_{th}, defined as the incident power at which half of the power is lost to SRS at the output end of a fiber of length L and it is equal to:

$$P_{th} = \frac{16A_{eff}}{L_{eff}g_R} \quad \dots(4)$$

where g_R is the Raman gain [17].

The threshold power of SRS can be given also in terms of different parameter as follows:

$$P_{th} = 5.9 \times 10^{-2} d^2 \lambda \alpha \quad \dots(5)$$

where d and λ are the fiber core diameter and the operation wavelength, respectively.

4.2 Optical Kerr Effect

The refractive index of many optical materials has a weak dependence by optical intensity I (equal to the optical power per effective area in the fiber) given by:

$$n = n_0 + n_2 I = n_0 + n_2 \frac{P}{A_{eff}} \qquad ...(6)$$

where n_0 is the ordinary refractive index of the material and n_2 is the nonlinear index coefficient. In silica, the factor n_2 varies from 2.2 to 3.4×10^{-8} $\mu m^2/W$. The nonlinearity in the refractive index is known as the Kerr nonlinearity. This nonlinearity produces a carrier-induced phase modulation of the propagating signal, which is called the Kerr effect. In fact, phase modulation due to intensity dependent refractive index induces various nonlinear effects, namely, SPM, XPM, and FWM [8].

I. Self-Phase Modulation (SPM)

The dependence of the refractive index on optical intensity causes a nonlinear phase shift while propagating through an optical fiber. The nonlinear phase shift is given by:

$$\Phi_{nl} = 2\pi.\frac{n_2}{\lambda}.\frac{P}{A_{eff}}.z \qquad ...(7)$$

where λ is the wavelength of the optical wave, and z is the propagation distance. Since the nonlinear phase depends on its own pulse shape, it is called "SPM".

When the optical signal is time varying, nonlinear phase shift results in a broadband spectrum of the optical signal [10, 12, 15].

CD converts this spectral broadening into signal distortion; the combined CD and SPM is a major issue in designing high bit-rate systems [13].

The critical power for SPM is defined as:

$$P_c = 1.2 \times 10^{-2}.\frac{\lambda A_{eff}}{L_{eff}} \qquad ...(8)$$

It can be written in terms of average power as:

$$P_c = 2.2 \times 10^{-3} d^2 \lambda \alpha D_f \qquad ...(9)$$

where D_f is the duty factor [18].

II. Cross-Phase Modulation (XPM)

The intensity dependence of the refractive index can also lead to another nonlinear phenomenon known as cross-phase modulation. It occurs when two or more optical channels are transmitted simultaneously inside an optical fiber using the WDM technique. In such systems, the nonlinear phase shift for a specific channel depends not only on the power of that channel but also on the power of the other channels [14, 17].

The nonlinear phase shift of the signal at the center wavelength λ_i is described by:

$$\Phi_{nl} = 2\pi.\frac{n_2}{\lambda}.z.\left[I_i + 2\sum_{i\neq j} I_j\right] \qquad ...(10)$$

where I_i is the optical power intensity of center channel, and I_j optical power intensity of j^{th} channel.

The first term is responsible for SPM, and the second term is for XPM [10, 12, 15]. The factor of second term in equation (10) has its origin in the form of the nonlinear susceptibility and indicates that XPM is twice as effective as SPM for the same amount of power. The total phase shift now depends on the power in all channels and would vary from bit to bit depending on the bit pattern of the neighboring channels [14, 17]. XPM is effective only when pulses in other channels are asynchronized with the signal of interest, when pulse in each channel travels at different group velocities due to dispersion, they slide past each other while propagating [12, 15].

III. Four-Wave Mixing (FWM)

FWM is a third-order nonlinearity in silica fibers that is analogous to intermodulation distortion in electrical systems. When wavelength channels are located near the zero-dispersion point, three optical frequencies (f_i, f_j, f_k) will mix to produce a fourth intermodulation product f_{ijk} given by:

$$f_{ijk} = f_i + f_j - f_k \qquad \dots(11)$$

When this new frequency falls in the transmission widow of the original frequencies, it can cause severe crosstalk [8].

Fig. (2) shows a simple example for two wavelengths, operating at frequencies f_1 and f_2, respectively, mix to yield signals at frequencies such as $2f_1$- f_2 and $2f_2$-f_1. Thus extra signals can cause interference if they overlap with frequencies used for data transmission. Similarly, mixing can occur between combinations of three and more wavelengths [19].

In general, for N wavelengths launched into a fiber, the number of generated mixing products M is [8]:

$$M = \frac{N^2}{2}(N-1) \qquad \dots(12)$$

If the channels are equally spaced, some of the generated waves will have the same frequencies as the injected waves. Clearly the appearance of the additional waves as well as the depletion of the initial waves will degrade multichannel systems by crosstalk or excessive attenuation [20].

The FWM power is proportional to the interacting signal powers, and can be expressed as:

$$P(f_i + f_j - f_k) = \frac{\eta(f_i, f_j, f_k) 1024\pi^6 \chi_{1111}^2 g^2}{n^4 \lambda^2 C^2} . (\frac{L_{eff}}{A_{eff}})^2 P_i P_j P_k e^{-\alpha L} \qquad \dots(13)$$

where λ is the wavelength, C is the vacuum light speed, n is the core index of refraction, L is the fiber length, α is the linear loss coefficient (attenuation), $P_{i,j,k}$ are launched signal powers, A_{eff} is the effective area of the guided mode, L_{eff} is the effective length, g is the degeneracy factor (g=3 for two waves mixing (i=j), g=6 for three wave mixing (i≠j)), χ_{1111} is the third-order nonlinear susceptibility, and $\eta(f_i, f_j, f_k)$ is the mixing efficiency given by [21]:

$$\eta(f_i, f_j, f_k) = \left(\frac{\alpha^2}{\alpha^2 + \Delta\beta^2}\right) . \left[1 + 4e^{-\alpha L} . \frac{(\sin\left(\frac{\Delta\beta L}{2}\right))^2}{(1 - e^{-\alpha L})^2}\right] \qquad \dots(14)$$

where Δβ represents the phase mismatch and may be expressed in terms of signal frequency differences [21]:

$$\Delta\beta = \left(\frac{2\pi\lambda^2}{C}\right) . |f_i - f_k||f_j - f_k| . \left\{D + \frac{dD}{d\lambda}\left(\frac{\lambda^2}{2C}\right)(|f_i - f_k| + |f_j - f_k|)\right\} \qquad \dots(15)$$

where D is the fiber chromatic dispersion, and its slope $S = \frac{dD}{d\lambda}$.

For sufficiently low fiber chromatic dispersion Δβ≈0 and $\eta \approx 1$. If in addition, all channels have the same power p_{in}, the ratio of the generated power $P(f_i + f_j - f_k)$ to the transmitted power of the channel P_{out} can be written as [22]:

$$\frac{P(f_i + f_j - f_k)}{P_{out}} = \frac{1024\pi^6}{n^4 \lambda^2 C^2} (\frac{D\chi^{(3)} L_{eff}}{A_{eff}})^2 P_{in}^2 \qquad \dots(16)$$

5. Proposed system

The proposed system is designed using binary 33% duty cycle RZ-

DPSK modulation format at 10Gb/s in order to transmit 16 channels over a 100km optical fiber link. The layout of the first simulated system is shown in Fig. (3). The transmitter consisted of 16 channels have frequencies from 192.101 THz to 195.101 THz with channel spacing 200 GHz and with center frequency 193.601 THz. The input signal spectrum occupies a bandwidth of 3 THz. Each channel consisted of a binary data source (PRBS sequence degree equal to 7) feeds the electrical NRZ signal to the Mach-Zehnder Modulator which modulates the electrical signal on the CW DFB tunable laser with linewidth equal to 0.3 MHz, laser power 10 dBm (10 mW). After the data modulation section a pulse carver section is included this consisted of a Mach-Zehnder Modulator driven by a sinusoidal signal generator. The driven signal is biased at the maximum transmission point of the Mach-Zehnder Modulator at half the bit rate between transmission minima (i.e. using a peak-to-peak amplitude of produces RZ pulses with duty cycle of 33%of the bit slot). The Modulator used is Mach-Zehnder Modulator with Modulator excess losses equal to 1 dB.

The WDM channels are combined by a balanced combiner (ideal combiner i.e. a component that perfectly adds the input channels) with the same attenuation on each input that is equal to 0dB. The channels are preamplified by an EDFA booster and transmitted over a 5 spans DS-Anomalous fiber. The booster have saturated output power equal to 15 dB, small signal gain equal to 25 dB and noise figure equal to 3 dB. The amplified channels by booster amplifier are then launched over 5 span DS-Anomalous fiber of 100 km with core diameter of 6µm.Dispersion and dispersion slope are completely compensated before in-line EDFA using an ideal fiber grating. The output of the transmission line are separated by ideal demultiplexer (ideal splitter, i.e. a component that perfectly splits the input signals) into 16 channels to pass through the receiver. The input signal is delayed in one branch by exactly one bit slot.

The single channel receiver composed of:

- An optical Raised Cosine shape filter, with selectable optical filter roll-off equal to 0.5 and 3dB bandwidth, optical filter band width equal to 40dB.
- A InGaAs Avalanche photodiode (Quantum Efficiency 0.75, sensitivity is better than -26dBm with low-noise, responsivity 0.7 A/W and Dark current 50nA).
- An electrical low pass Bessel filter, with selectable 3dB bandwidth equal to 8dB.

The schematic model of the transmitter and receiver 33% RZ-DPSK system is shown in Fig. (4).

The system parameters for optical transmitter, optical fiber, receiver and other system components are given in Table (1).

6. Simulation Results

Figures (5), (6) show the bit patterns at the input and output of optical fiber for channel 1, 8, and 16, respectively. It is noted that the bit patterns of these channels are not overlapped to each other, and the pulse broadening due to dispersion isrelatively small. While figures (7), (8) show the eye diagrams at the input and output of optical fiber for channels 1, 8, and 16, respectively. So as shown in these figures, the eye is opened enough and it is noted that the performance of the system is good enough and the distortion due to dispersion is relatively low. This is because the dispersion at these channels is fully compensated by the in-line dispersion compensated (DC) units.

Fig. (9) shows the threshold optical power versus wavelength at different fiber core diameters. The threshold optical power of SPM is equal to 0.01188 W at 1550 nm with 6µm fiber core diameter. While, Fig. (10) shows the critical optical power of SPM versus fiber length. After 100 km fiber length the critical optical power of SPM is equal to 14.43 mW at 1550 nm. Moreover, Fig. (11) shows the efficiencies of FWM as a function of wavelength channel spacing. The efficiency of FWM at 1000 km is lower than the efficiencies of FWM at 100 km and 500 km and is equal to 63.89 percent for channel separation up to 50 GHz for G.652 SMF, while the efficiencies of FWM at 500 km and 100 km are 89.75% and 99.57%, respectively.

7. Conclusions

16×40 Gb/s WDM transmission was successfully conducted over a 100-km DS-Anomalous fiber link with 640 Gb/s capacity in C-band. A WDM transmission scheme using the 33% duty cycle RZ-DPSK format was used.

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Table (1): The parameters of G.652 single mode fiber and other components.

Simulation Parameters		
Number of Channels	**16**	
Frequency of Channel 1	**192.101 THz (1561.678 nm)**	
Frequency of Channel 16	**195.101 THz (1537.665 nm)**	
Center Frequency	**193.601 THz (1549.578 nm)**	
Bandwidth	**3 THz (24.013 nm)**	
Reference Bit Rate	**40 Gbit/s**	
Fiber length	**100 km**	
Channel spacing	**200 GHz**	
Driver	**33% RZ-DPSK**	
Source linewidth	**0.3 MHz**	
PRBS Order	$2^k - 1 = 7$	
Excess Loss	**1 dB**	
CW power	**10 dBm**	
Photodiode type	**APD**	
Quantum Efficiency	**0.75**	
Dark current	**50 nA**	
Responsivity	**0.7 A/W**	
Sensitivity	**better than -26dBm**	
DS-Anomalous Fiber 100 km		
Losses	**α [dB/km]**	**0.2**
	Chromatic Dispersion D [ps/nm/km]	**2**
	Chromatic Dispersion Slope D' [ps/nm^2/km]	**0.07**
Core Diameter [μm]	**6**	
Core Effective Area [μm^2]	**55**	
System Losses		
Number of Connectors	**2**	
Connector Loss	**1 dB**	
Margin Loss	**6 dB**	
Total Power Losses	**28 dB**	

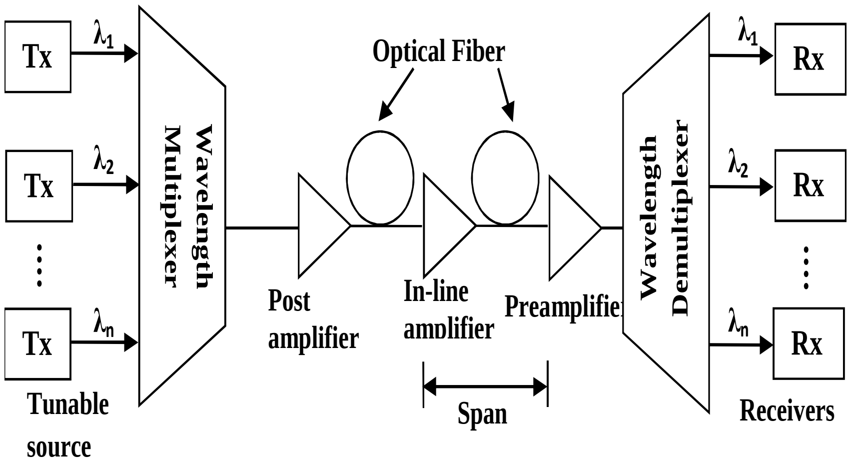


Figure (1): Implementation of a typical WDM network containing various types of optical amplifiers [8].

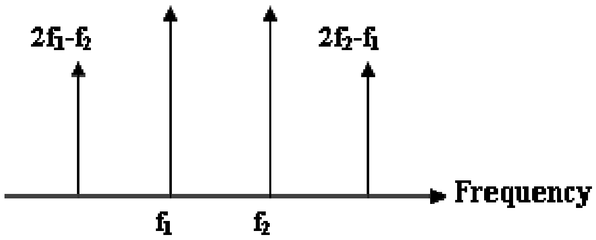


Figure (2) Four-wave mixing with two injected waves at frequencies f_1 and f_2 [20].

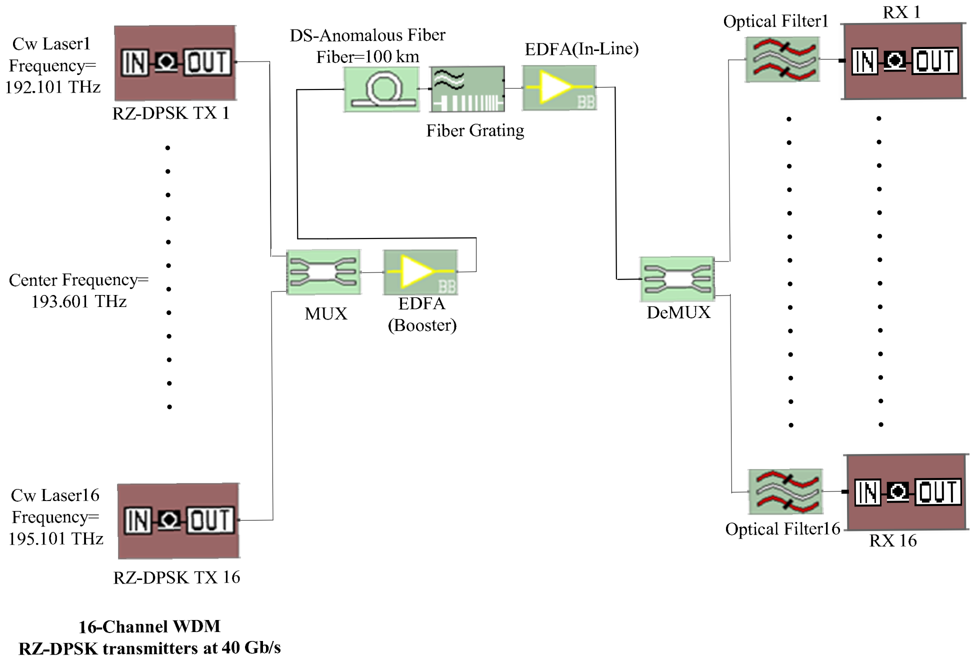


Figure (3): Layout of the proposed system over 100km.

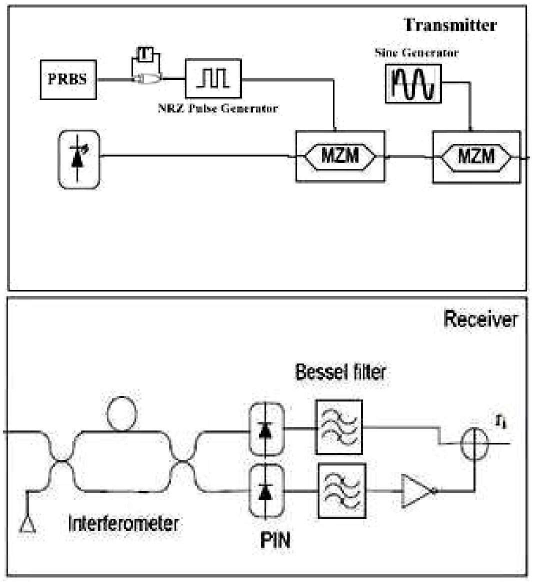
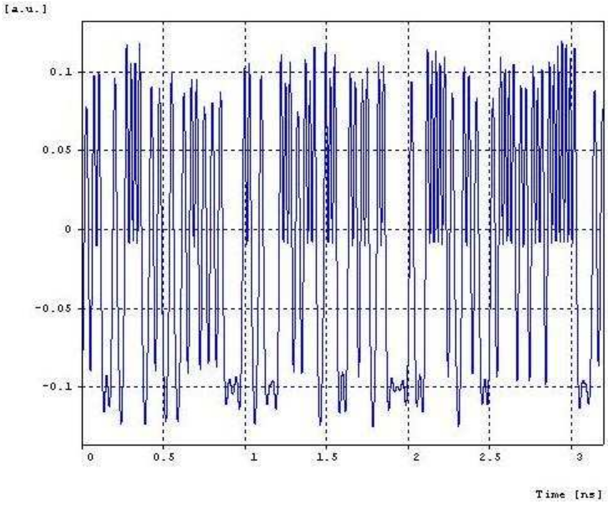
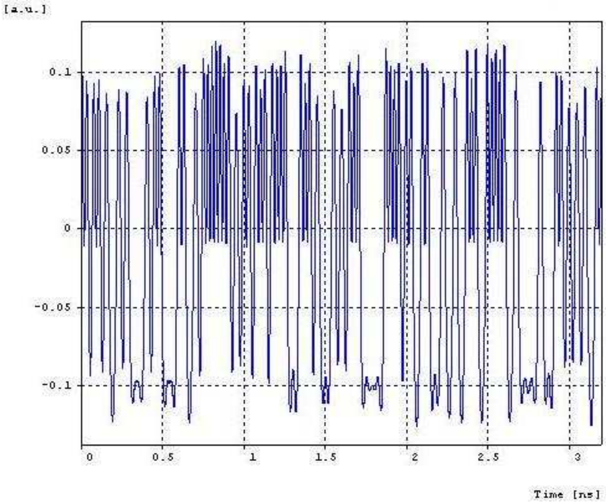


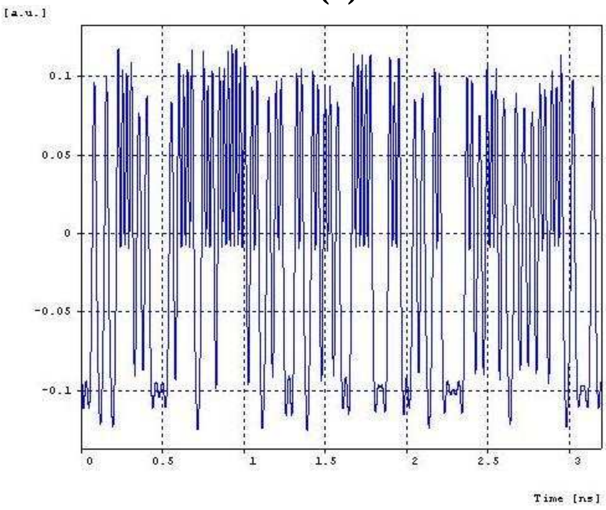
Figure (4): Schematic model of the transmitter and receiver 33% RZ-DPSK system.



(a)

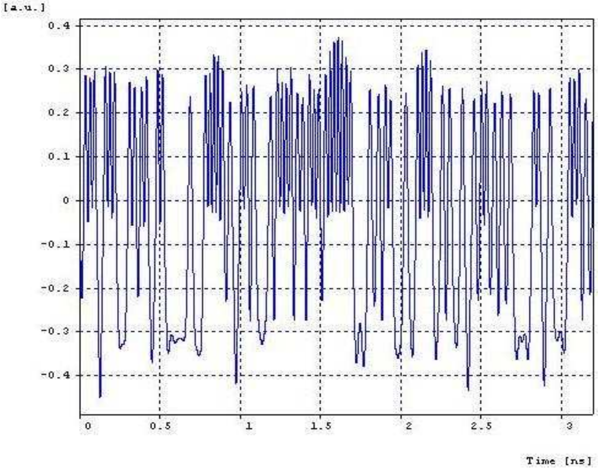


(b)

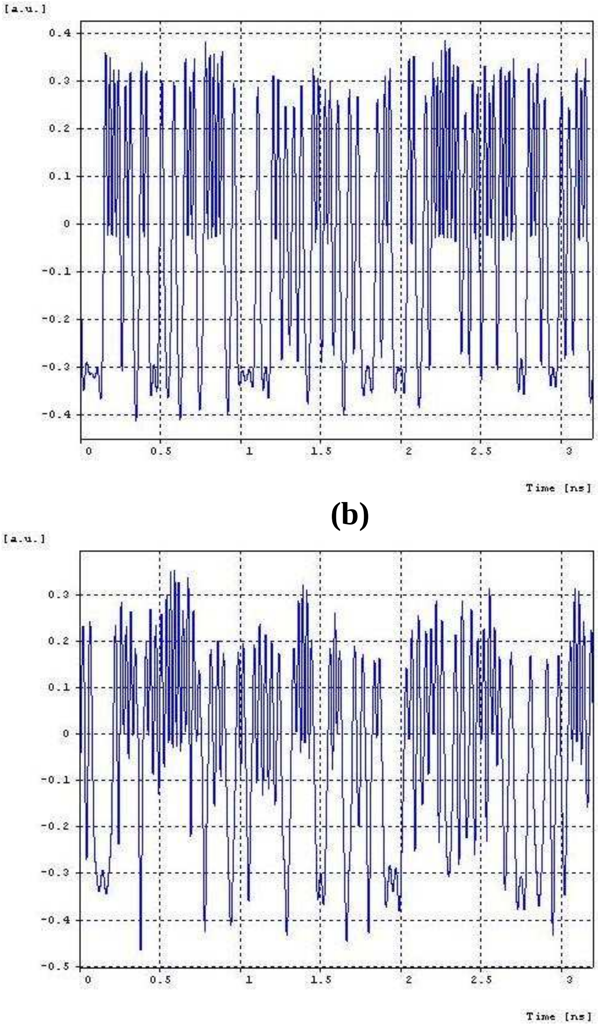


(c)

Figure (5): Bit patterns at the input of (a) channel 1, (b) channel 8, (c) channel 16.



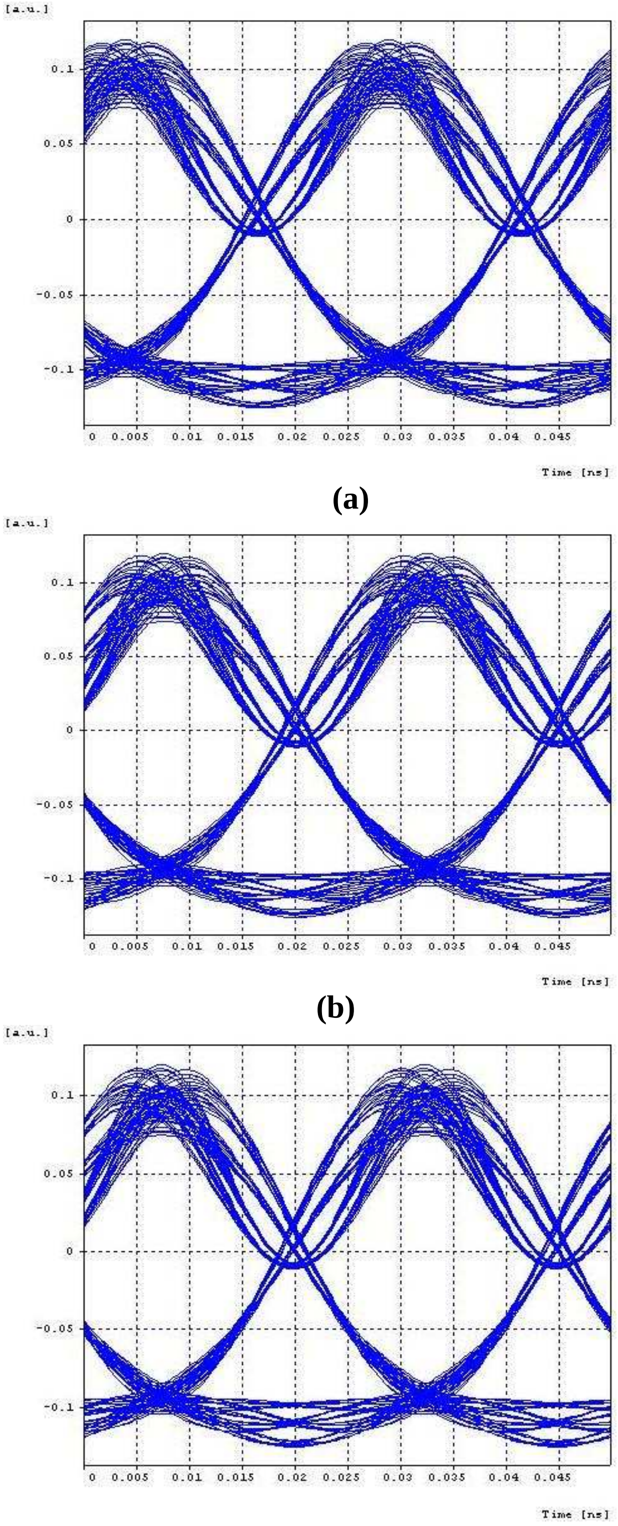
(a)



(b)

(c)

Figure(6): Bit patterns at the output of (a) channel 1, (b) channel 8, (c) channel 16.

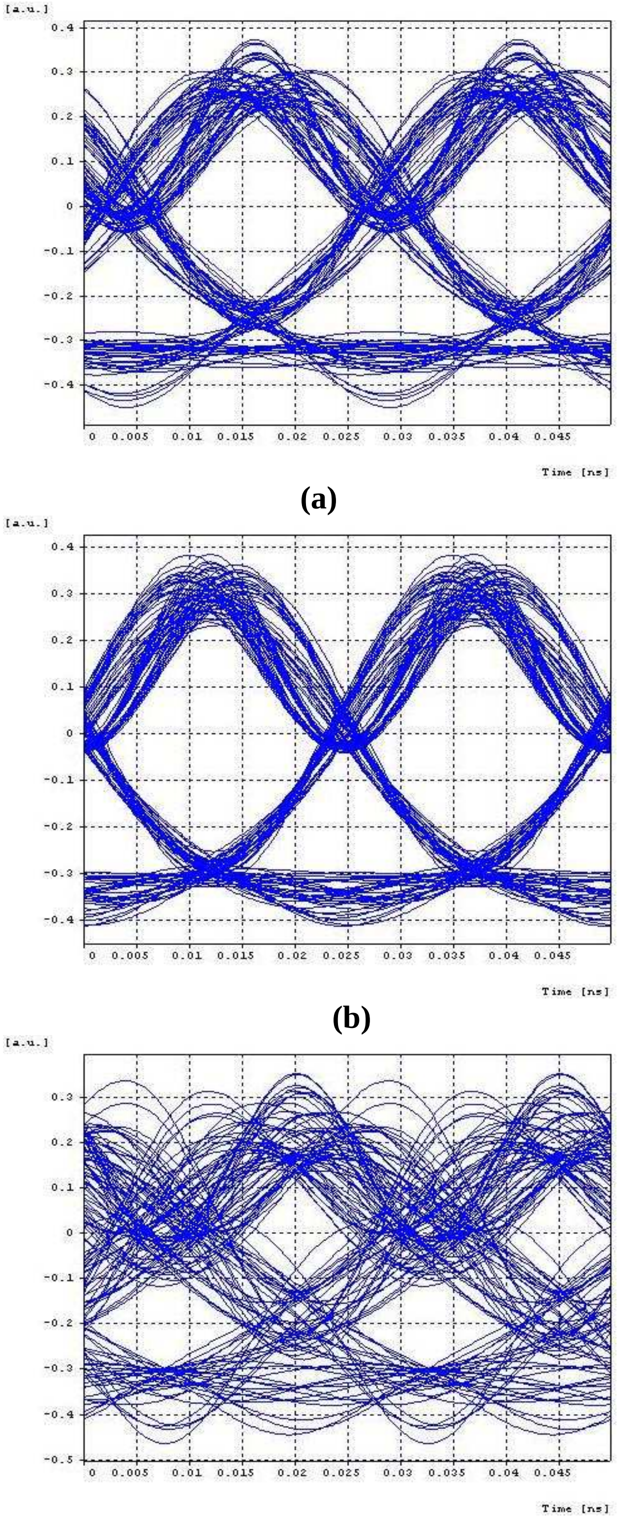


(a)

(b)

(c)

Figure (7): Eye diagrams at the input of (a) channel 1, (b) channel 8, (c) channel 16.



(a)

(b)

(c)

Figure (8): Eye diagrams at the output of (a) channel 1, (b) channel 8, (c) channel 16.

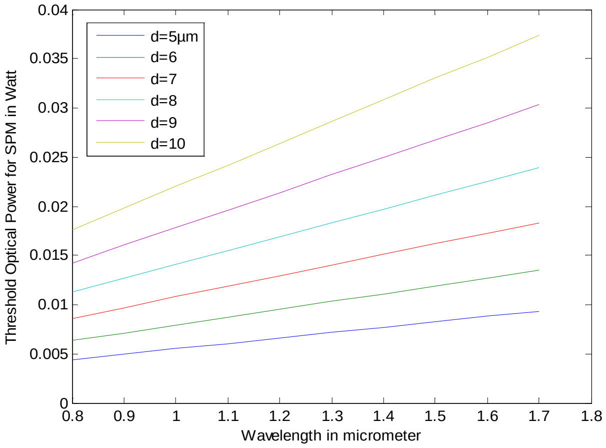


Figure (9) Threshold power of SPM versus wavelength at different fiber core diameters .

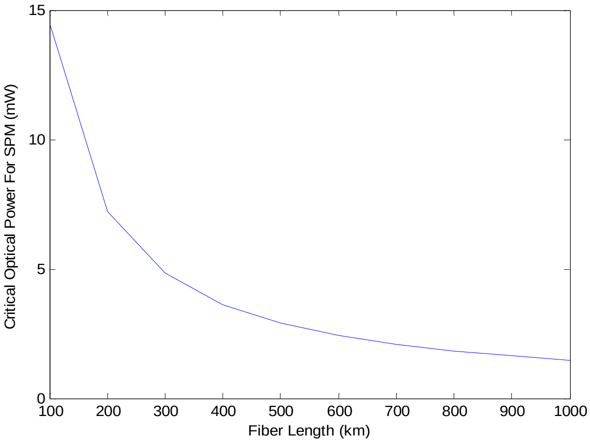


Figure (10) The critical optical power of SPM versus fiber length.

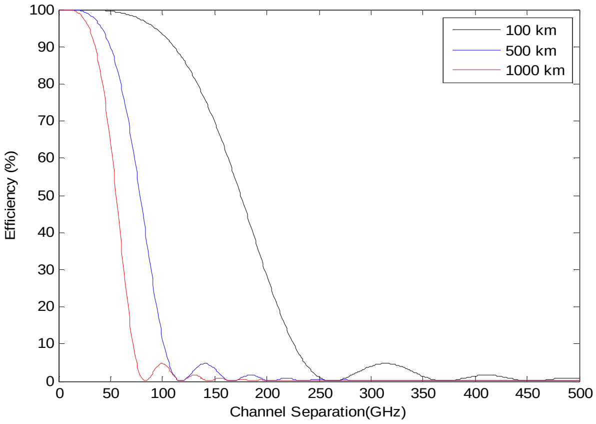


Figure (11) The efficiencies of FWM as a function of wavelength channel spacing.