Mitigation of Fiber Nonlinearity Effects in Ultra High-Dense WDM System by Using Fractional Fourier Transform for 32 Channel System

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ABSTRACT

The optical signal is severely degraded when transmitted in the fiber due to both the linear and nonlinear distortions. It is well known that, the linear distortions in single mode fiber include chromatic dispersion (CD) and polarization-mode dispersion (PMD) while self-phase modulation (SPM), cross phase modulation (XPM) and four-wave mixing (FWM) are considered the most among nonlinear distortions. A method called Fractional Fourier Transform (FRFT) has been applied to mitigate fiber nonlinearity impairments. In this work, 10 Gb/s optical fiber system with five spans, each of length 60 km, for three types of modulation formats (Return-to-Zero Differential Phase Shift Keying (RZ-DPSK), Return-to-Zero Differential Quaternary Phase Shift Keying (RZ-DQPSK) and Carrier-Suppressed Return-to-Zero (CSRZ)), single and multi-channel transmission systems are designed and simulated using "OptiSystem (2011) version 10.0" software package. The BER of thirty two channel systems (channel No.16) at bit rate 10 Gb/s per channel, 300 km link length of CSRZ modulation format with channel spacing of 50 GHz at SNR 10 dB without FRFT is $10^{-4.6}$ and $10^{-6.4}$ with FRFT. The BER of thirty two channel system (channel No.16) at bit rate 10 Gb/s per channel, 300 km link length of CSRZ modulation format with channel spacing of 25 GHz at SNR 10 dB without FRFT is $10^{-2.56}$ and $10^{-3.24}$ with FRFT.

Keywords: Nonlinear impairment; FRFT; CSRZ modulation format

تقليل التأثيرات اللاخطية في منظومات التقسيم المتعدد للطول الموجي العالية الكثافة بأستخدام تحويل فورير الجزئي لنظام ذو ٣٢ قناة

الخلاصة

الاشاره الضوئية تتدهور بشده عندما ترسل في ليف ضوئي وذلك نتيجة للتشوهات الخطيه وغير الخطية. كما هو متعارف علية، التشوهات الخطية تتظمن التشتت اللوني(chromatic dispersion) و تشتت حالة الاستقطاب (polarization-mode dispersion) بينما التظمين الطوري الذاتي(self-phase modulation)، التظمين الطوري الصليبي(cross phase modulation) و الخلط الموجي الرباعي(four-wave mixing) تعتبر من اقوى التشوهات غير الخطية. تم استخدام طريقة مقترحة تدعى تحويل فورييه الجزئي (Fractional Fourier Transform) تم تطبيقها لتقليل شوائب الليف غير الخطية. لقد تم في هذه الاطروحه اعتماد نظام ضوئي بسرعه تناقل بيانات ١٠ كيكابت/ثانية مع خمسه دورات كل دوره طولها ٦٠ كم لثلاثه انواع من التضمين (التضمين الطوري التفاضلي RZ_DPSK، التضمين الطوري الرباعي التفاضلي RZ-DQPSK، والتضمين من نوع CSRZ) ، وقد تم اعتماد نظام القناه المفرده ونظام القنوات المتعدده بأستخدام حزمه المحاكاة ألبصريه

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(optisystem v. 10) . نسبه خطأ الرقم الثنائي (BER) لنظام ذو اثنان وثلاثين قناة (القناة السادسه عشر) بسرعه تناقل بيانات ١٠ كيكابت/ثانية، ٣٠٠ كم طول خط النقل، بستخدام التضمين نوع SCRZ ، التباعد بين القنوات ٥٠ كيكا هرتز عند قيمه نسبه قدره الاشاره الى قدره الضوضاء مقدارها ١٠ ديسيبل كانت ١٠-٤,٦ بدون تحويل فورير الجزئي و ١٠-٦,٤ بوجود تحويل فورير الجزئي. نسبه خطأ الرقم الثنائي (BER) لنظام ذو اثنان وثلاثين قناة (القناة السادسه عشر) بسرعه تناقل بيانات ١٠ كيكابت/ثانية، ٣٠٠ كم طول خط النقل، بستخدام التضمين نوع SCRZ ، التباعد بين القنوات ٢٥ كيكا هرتز عند قيمه نسبه قدره الاشاره الى قدره الضوضاء مقدارها ١٠ ديسيبل كانت ١٠-٢,٥٦ بدون تحويل فورير الجزئي و ١٠-٣,٢٤ بوجود تحويل فورير الجزئي.

INTRODUCTION

The Dense Wave division multiplexing(DWDM) technology is widely used in today's telecommunication networks [1]. When an optical signal is transmitted over a fiber, it suffers from linear and nonlinear degrading effects in the fiber. Optical loss or attenuation and Chromatic Dispersion (CD) are linear degrading effects causes distortion for both digital and analog transmission along optical fibers [2]. While Self-Phase Modulation (SPM), Cross-Phase Modulation (XPM), Four-Wave Mixing (FWM), Stimulated Raman Scattering (SRS) and Stimulated Brillouin Scattering (SBS) are nonlinear degrading effects [3]. There are several mitigation methods that used to make a reduction in over all channel impairments, the most important among them are: Modulation Formats [4], Polarization Interleaving [5], Digital Signal Processing (DSP) [6] and the new proposed method is the Fractional Fourier Transform (FRFT) [7], [8]. It will be used because it makes a large mitigation of the fiber nonlinear effects.

Fractional Fourier Transform (FRFT)

Considering pulse evolution with CD, SPM and XPM taking into account in a DWDM system, the corresponding nonlinear Schr¨odinger equation (NLSE) could be described as [7] ;

$$\frac{\partial A_{\mathrm{r}}(z,t)}{\partial z} = -i\frac{\beta^2{}_{\mathrm{r}}}{2}\frac{\partial^2 A_{\mathrm{r}}(z,t)}{\partial t^2} + i\frac{e^{-\bar{\alpha}z}}{L_{\mathrm{NL}}}\left(|A_{\mathrm{r}}(z,t)|^2 + 2\sum_{v\neq r}|A_{\mathrm{v}}(z,t)|^2\right)A_{\mathrm{r}}(z,t) \qquad ..(1)$$

Where

r, v denote the channel labels, A(z, t) indicates the slowly varying complex envelope of input pulses, $LNL=(\gamma Po)^{-1}$ is the nonlinear length (γ is the nonlinear coefficient, Po is the input power of pulses), β_2 is the dispersion coefficient and $\bar{\alpha}$ is the attenuation coefficient. Solving Eq. (1) for the r-th channel in frequency domain if only CD is considered

$$A_{\mathrm{r}}(z,\omega_{\mathrm{r}}) = A_{\mathrm{r}}(0,\omega_{\mathrm{r}})\exp\left(\frac{i}{2}\beta^2{}_{\mathrm{r}}z\omega^2{}_{\mathrm{r}}\right) \qquad ..(2)$$

On the other hand, when fiber nonlinearity is considered separately, the solution for the r-th channel becomes [7];

$$A_{\mathrm{r}}(z,t) = A_{\mathrm{r}}(0,t)\exp(i\phi'_{\mathrm{NL_r}}) \qquad ..(3)$$

$$\phi'_{\mathrm{NL_r}}(L\mathrm{m},t) = \gamma\sum_{m=1}^{N}\sum_{v\neq r}\int_0^{Lm}(|A_{\mathrm{r}}(0,t)|^2 + 2|A_{\mathrm{v}}(0,t+d_{\mathrm{rv}}z - \Delta t\mathrm{rvm})|^2)e^{-\alpha z}\,dz \qquad ..(4)$$

where

d_{rv} is the walk-off parameter, Δt_{rvm} is the delay of v-th channel against the r-th channel at the input of m-th fiber span and Lm is the fiber length of each span. It is obvious to find that CD does not affect the amplitude spectrum of transmitted signal while SPM and XPM have no influence on the pulse envelope. The behavior of CD and Kerr nonlinearities mostly contributes to time and frequency domain respectively [9]. However, they always act on the transmitted signal simultaneously in the fiber links of a DWDM system, resulting in some coupled time–frequency distortion. To our knowledge, Fourier transform (FT) can transform a signal from time domain to frequency domain, which has been widely used in various fields [6]. As an extension of Fourier transform, fractional Fourier transformation (FRFT) is defined as [7].

$$X_P(u) = \sqrt{\frac{1 - i\cot(\theta)}{2\pi}} \int_{-\infty}^{+\infty} x(t) \exp\left(i\frac{t^2 + u^2}{2}\cot\theta - iut\csc\theta\right) dt \quad ..(5)$$

Where

$\boldsymbol{\theta}$=p(π/2), p is the order of FRFT. An FRFTwith $\boldsymbol{\theta}$=π/2 corresponds toclassical Fourier transform while A(z, t) corresponds to an identity operator.

The Work Details

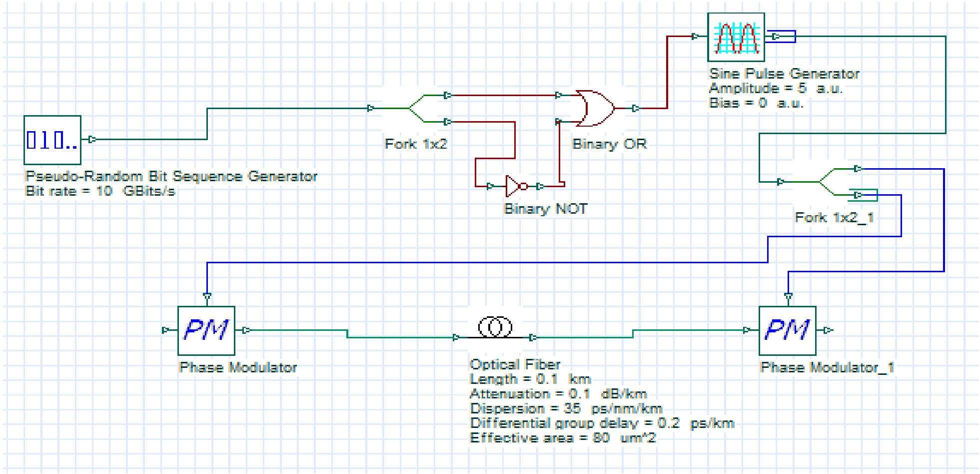
FRFT consists of two phase modulators and a dispersive medium as shown in figure (1). The phase modulators need a parabolic electric driving signal to drive them , but the software didn't have an arbitrary waveform generator to generate the parabolic electric signal ,so a configuration has been proposed as shown in the upper part of figure (1). It consists of Pseudo-Random Bit Sequence Generator (PRBS), sine pulse generator, binary NOT gate and binary OR gate. The sine pulse generator is used to generate parabolic electric driving signal with the help of Binary NOT and Binary OR gates. The reason behind the use of these gates is that the PRBS did not give a stream of binary ones only it gave a random stream of binary ones and zeroes, and that did not make the sine pulse generator to produce a parabolic signal cause the sine pulse generator produce one half cycle when it receive binary one and no half cycle when it receive binary zero ,so by use these gates the sine generator would receive a stream of binary ones only and that by connecting these gates as shown in figure (1). Now, binary one still not changed when it passes through these gates while binary zero will invert to one. In this way the sine pulse generator can receive a stream of binary ones only and thus, give a parabolic electric signal as shown in figure (2). The dispersive medium between the two phase modulators has parameters; these parameters are listed in table (1). The Fractional Fourier Transform is firstly applied to single channel CSRZ modulation scheme with a bit rate 10 Gbit/s and length 300 Km, the purpose of that is to show the effect of FRFT on the spectrum of the transmitted signal especially when the modulation is CSRZ, so it will distort it. It is known that the spectrum of CSRZ is characterized by symmetric sidebands with the carrier suppressed. However, FRFT will devastate its symmetry and offset the center frequency to modify the signal as shown in figure (3). Then the curve of Q-factor versus power (-10 to 10 dBm) was drawn to show the performance of the system without and with FRFT. Then, BER versus SNR were drawn for 8×10 Gbit/s RZ-DPSK, RZ-DQPSK and CSRZ modulation scheme for channel 4(central channel), 100 GHZ channel spacing with &without FRFT. The result shown that in case of CSRZ has the better performance, on this result CSRZ has been chosen as the modulation scheme for 16×10 Gbit/s and 32×10 Gb/s for 200,100 and 50 GHZ (the channel spacing reached to 25GHz in case of 32 channels) channel spacing and FRFT was applied for channel 8 and 16 respectively (central channel). The location of the FRFT in an optical system (for example eight channels system) was shown in figure (4). Here the transmitter includes three cases RZ-DPSK, RZ-DQPSK & CSRZ, also the receivers. Figure (4) showing that the location of FRFT is in the central channel also, in the case of sixteen channels and thirty-two channels optical system.

Simulation Results OF (FRFT)

Firstly it is applied to a single channel, 10 Gb/s bit rate, five span each with 60 km length for CSRZ modulation format. Figure (5) shows the Q-Factor versus input power with and without FRFT for single channel system using CSRZ as modulation format. Figures (6) to (8) display the BER versus SNR for channel No.4, 8×10 Gb/s system, 100 GHz channel spacing with and without FRFT using RZ-DPSK, RZ-DQPSK and CSRZ modulation formats, respectively. The simulation results show that, the system with CSRZ modulation format gives the best performance. Figure (9) shows the BER versus SNR for 8 channels WDM system with date rate 10 Gb/s , channel spacing 200 GHz for channel No.4 with and without FRFT. Figure (10) illustrates the BER versus SNR for 8 channels WDM system with date rate 10 Gb/s, channel spacing 100 GHz for channel No.4 with and without FRFT. Figure (11) depicts the BER versus SNR for 8 channels WDM system with date rate 10 Gb/s, channel spacing 50 GHz for channel No.4 with and without FRFT. Figure (12) shows the BER versus SNR for 16 channels WDM system with date rate 10 Gb/s , channel spacing 200 GHz for channel No.8 with and without FRFT. Figure (13) shows the BER versus SNR for 16 channels WDM system with date rate 10 Gb/s, channel spacing 100 GHz for channel No.8 with and without FRFT. Figure (14) displays the BER versus SNR for 16 channels WDM system with date rate 10 Gb/s , channel spacing 50 GHz for channel No.8 with and without FRFT. Figure (15) demonstrates the BER versus SNR for 32 channels WDM system with date rate 10 Gb/s , channel spacing 200 GHz for channel No.16 with and without FRFT. Figure (16) shows the BER versus SNR for 32 channels WDM system with date rate 10 Gb/s , channel spacing 100 GHz for channel No.16 with and without FRFT. Figure (17) shows the BER versus SNR for 32 channels WDM system with date rate 10 Gb/s , channel spacing 50 GHz for channel No.16 with and without FRFT. Figure (18) displays the BER versus SNR for 32 channels WDM system with date rate 10 Gb/s , channel spacing 25 GHz for channel No.16 with and without FRFT. Thus the Ftractional Fourier Transform has been applied to diffrent optical system envairoment (diffrent number of channels and diffrent channel spacing) and the improvment has been abserved. Table (2) listed the values of the Q-Factors at 0 dBm input power for 8×10Gb/s, 16×10Gb/s and 32×10 Gb/s optical systems for diffrent channel spacing 200, 100 and 50 GHz for each system. In addition, 25 GHz channel spacing was applied for the case of 32×10 Gb/s system.

CONCLUSIONS

The performance of the multichannel optical systems in case of CSRZ modulation format is better than RZ- DPSK and RZ-DQPSK. For example, for 8 × 10 GB/s system, 100 GHz channel spacing for channel No.1 it has been found that the log of BER was -7.6 for CSRZ while -5.5 and -4.4 for RZ-DPSK and RZ-DQPSK respectively at SNR 10dB. So FRFT has been used with CSRZ modulation format. FRFT has been applied to single channel 300 km link length, 10Gb/s bit rate CSRZ modulation format at 0 dBm input power, the value of the Q-factor was 43.5 without FRFT and 78 with FRFT (improved by 34.5 order), the next step was design and simulate a 8×10Gb/s, 16×10Gb/s and 32×10Gb/s, 300 Km link length each with 200, 100 and 50 GHz (25 GHz applied to thirty two channel system) channel spacing with CSRZ modulation format. FRFT has been applied to the mid channel for each system (channel No.4, channel No.8 and channel No.16) respectively. It is noted that, there are an improvements in all these cases, but these improvements vary from one case to another. At SNR 10dB the log of BER for sixteen channels (channel No.8), 200 GHz channel spacing the log of BER improved by 5.05 order, for 100GHz channel spacing the log of BER improved by 3.4 order and for 50GHz channel spacing the log of BER improved by 2.6 order. For thirty two channels at SNR 10 dB (channel No.16), 200 GHz channel spacing the log of BER improved by 11.6 order, for 100 GHz channel spacing the log of BER improved by 3.8 order, for 50 GHz channel spacing the log of BER improved by 1.5 order and for 25 GHz channel spacing the log of BER improved by 0.84 order.



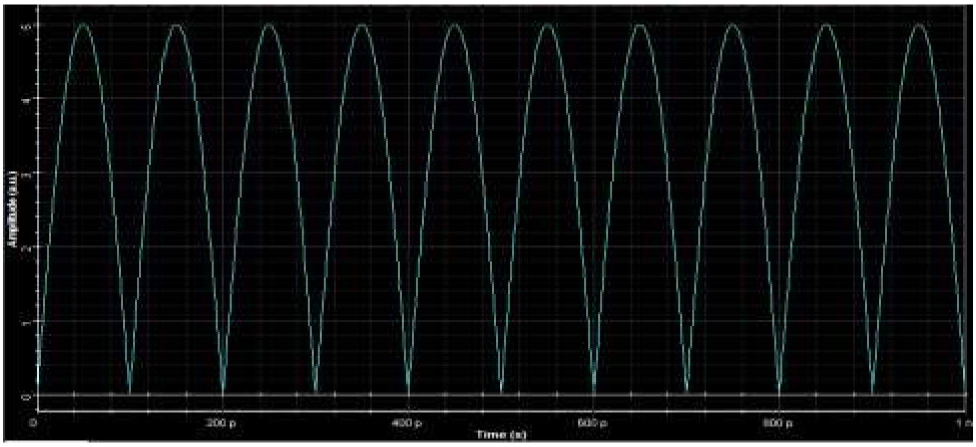


Figure (1): Configuration of FRFT.

Figure (2): Parabolic Electric diriving signal.

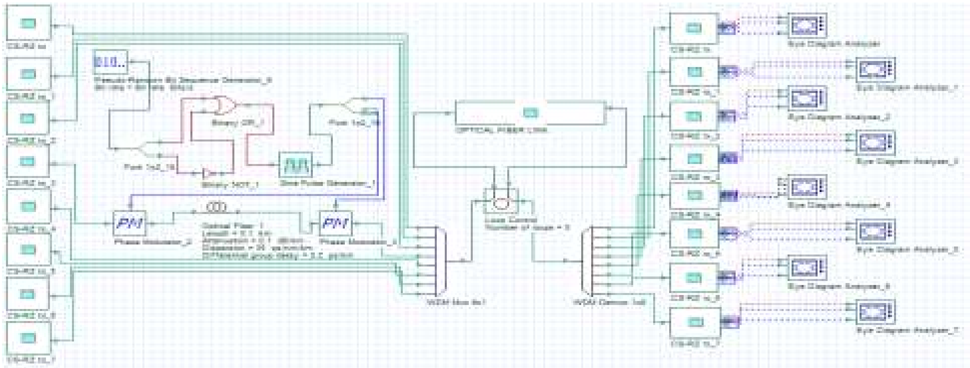
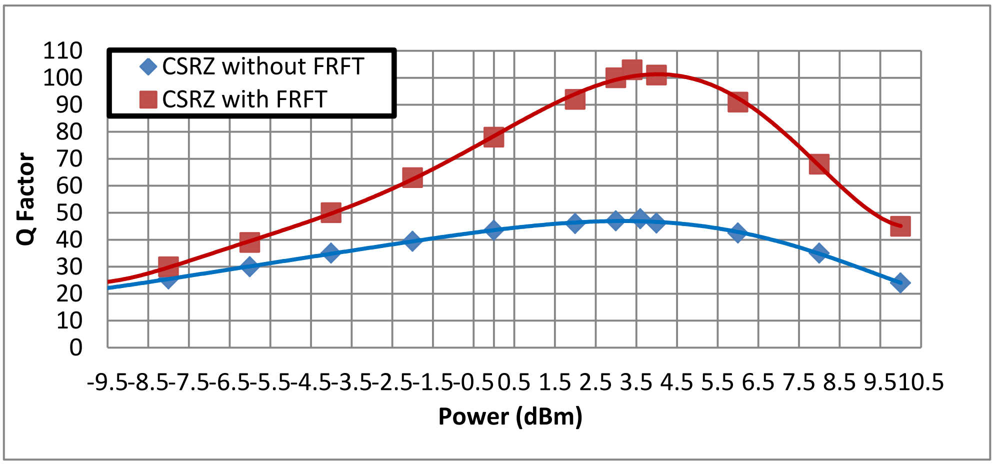
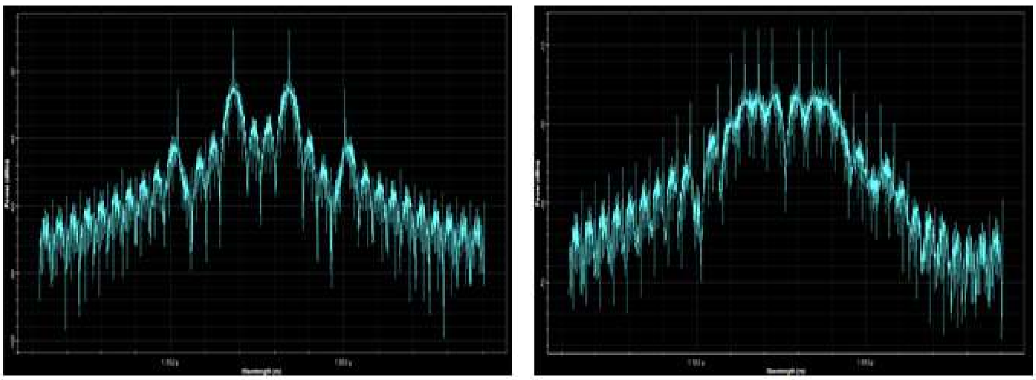


Figure (3):CSRZ spectrum (a) without FRFT, (b) with FRFT.



Figu

re(4): 8×10 Gbit/s system with FRFT.



(a) **(b)**

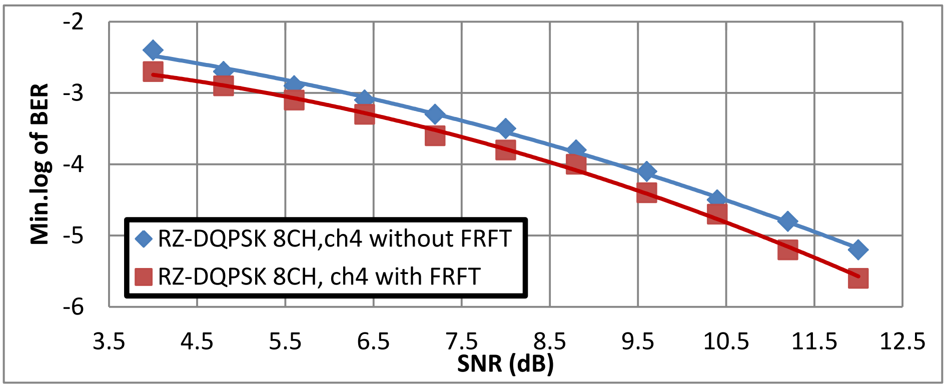


Figure (5): Q-Factor versus input power with and without FRFT for single channel, CSRZ modulation format.

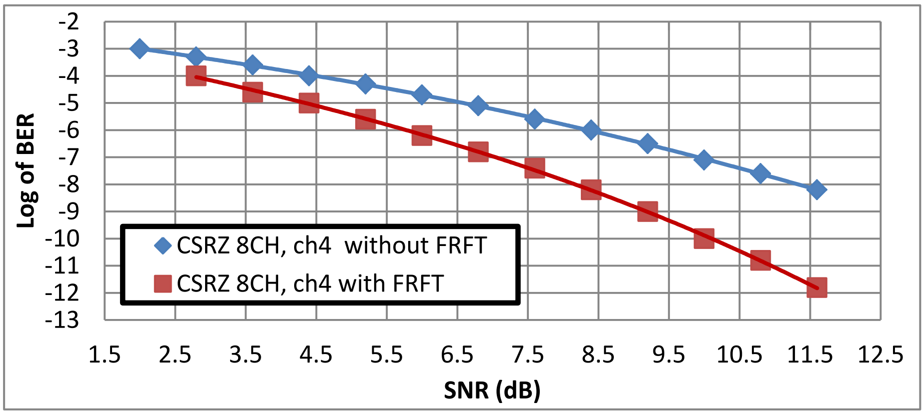


Figure (6): BER versus SNR for channel No.4, 8×10 Gb/s system, 100 GHz channel spacing with and without FRFT using RZ-DPSK modulation format.

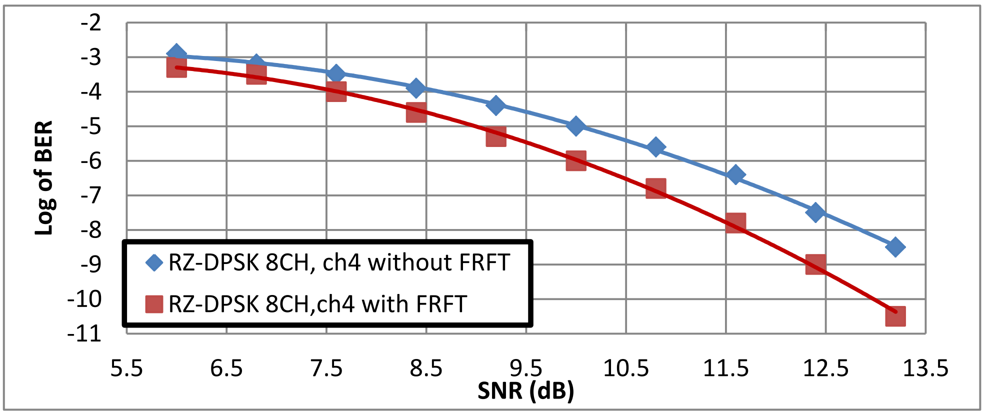


Figure 7: BER versus SNR for channel No.4, 8×10 Gb/s system , 100 GHz channel spacing with and without FRFT using RZ-DQPSK modulation format.

Figure 8: BER versus SNR for channel No.4, 8×10 Gb/s system , 100 GHz channel spacing with and without FRFT using CSRZ modulation format.

Figure 9: BER versus SNR for channel No.4, 8×10 Gb/s system, 200 GHz channel spacing with and without FRFT using CSRZ modulation format.

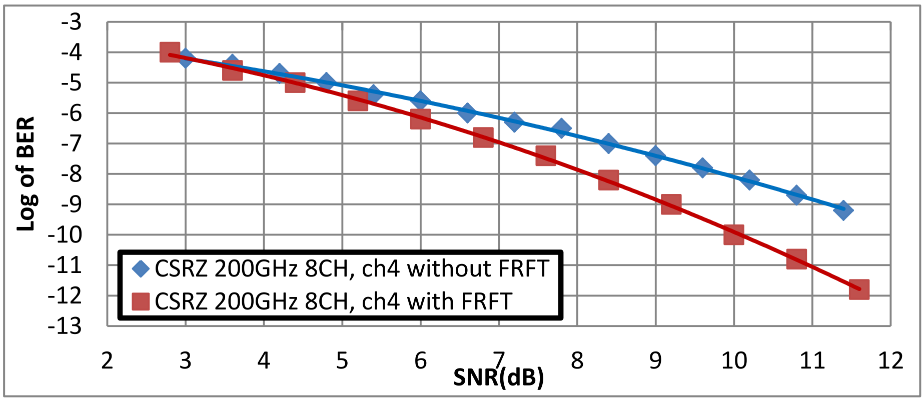
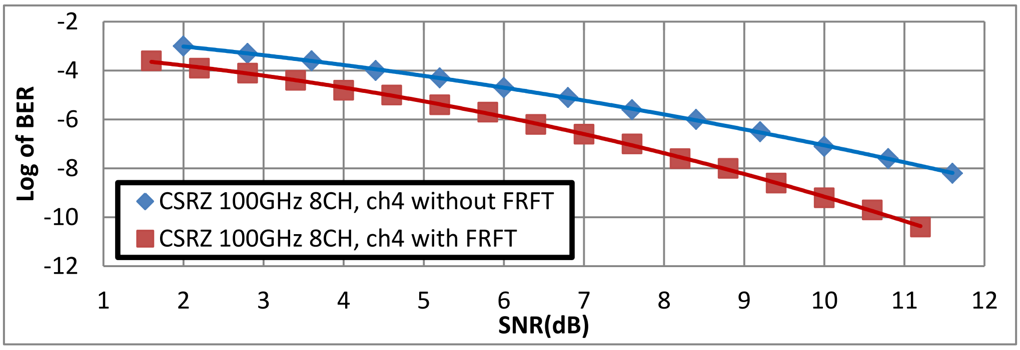


Figure 10: BER versus SNR for channel No.4, 8×10 Gb/s system , 100 GHz channel spacing with and without FRFT using CSRZ modulation format.



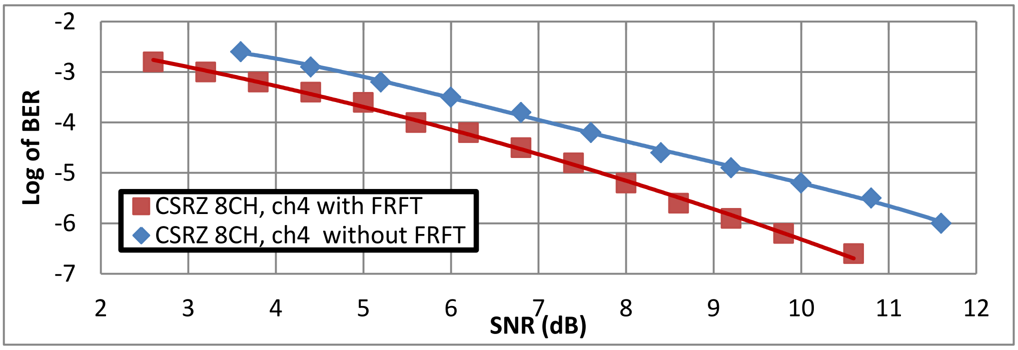


Figure 11: BER versus SNR for channel No.4, 8×10 Gb/s system , 50 GHz channel spacing with and without FRFT using CSRZ modulation format.

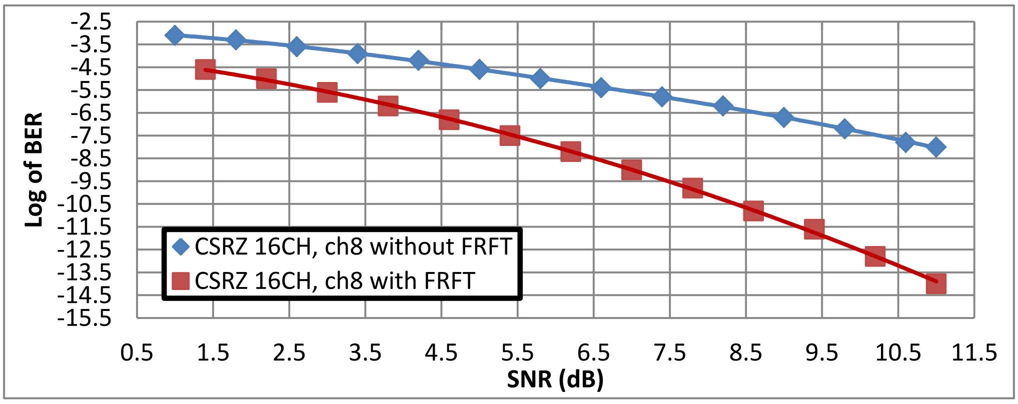


Figure 12: BER versus SNR for channel No.8, 16×10 Gb/s system, 200 GHz channel spacing with and without FRFT using CSRZ modulation format.

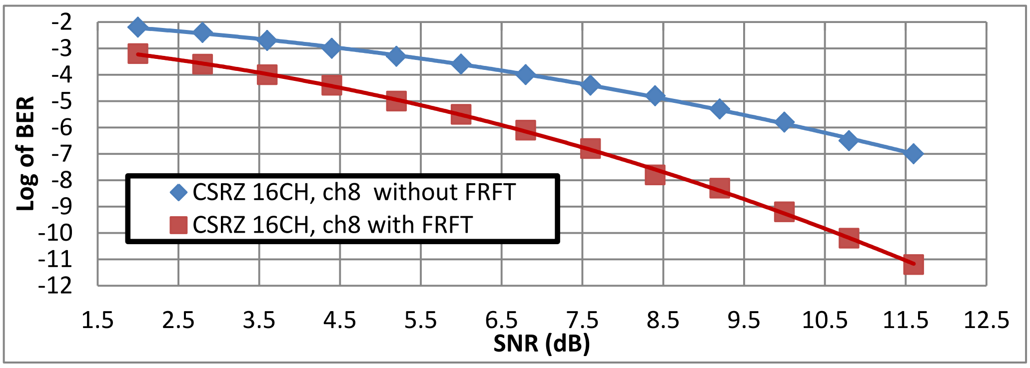


Figure 13: BER versus SNR for channel No.8, 16×10 Gb/s system, 100 GHz channel spacing with and without FRFT using CSRZ modulation format.

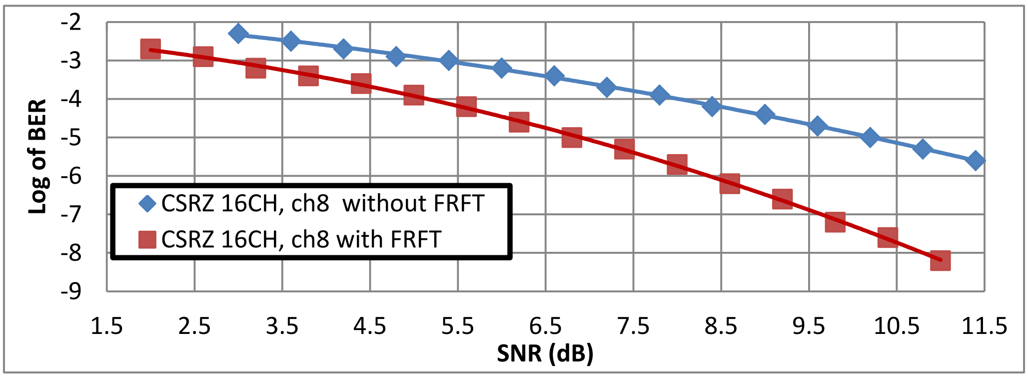


Figure 14: BER versus SNR for channel No.8, 16×10 Gb/s system, 50 GHz channel spacing with and without FRFT using CSRZ modulation format.

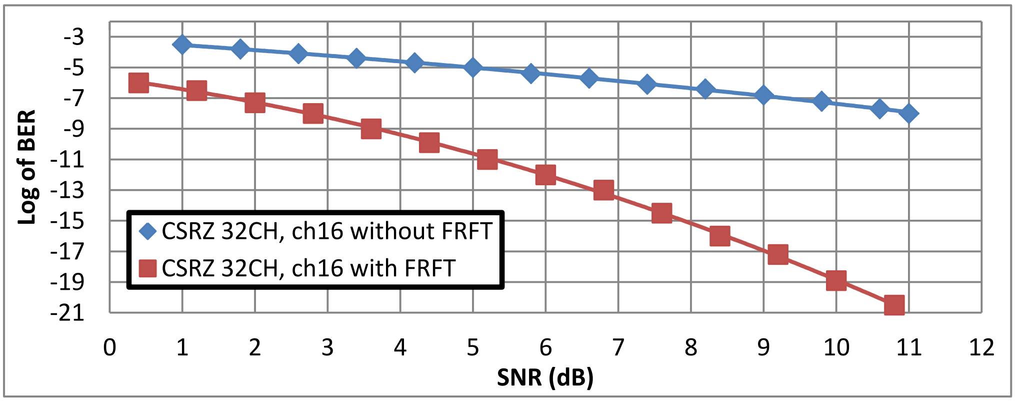


Figure 15: BER versus SNR for channel No.16, 32×10 Gb/s system, 200 GHz channel spacing with and without FRFT using CSRZ modulation format.

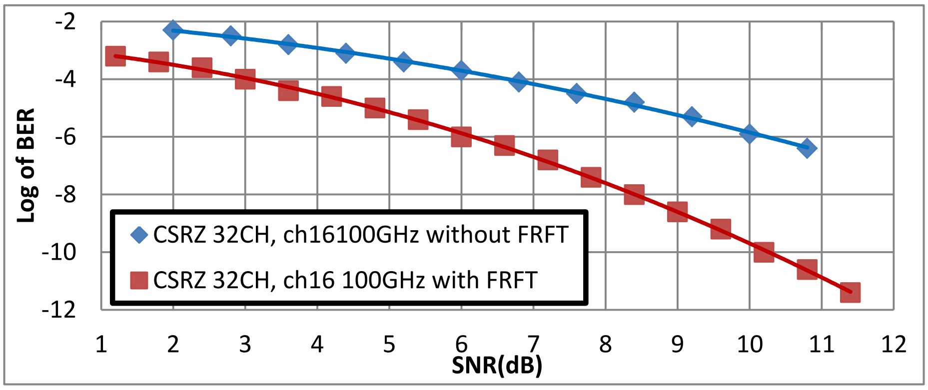


Figure 16: BER versus SNR for channel No.16, 32×10 Gb/s system, 100 GHz channel spacing with and without FRFT using CSRZ modulation format.

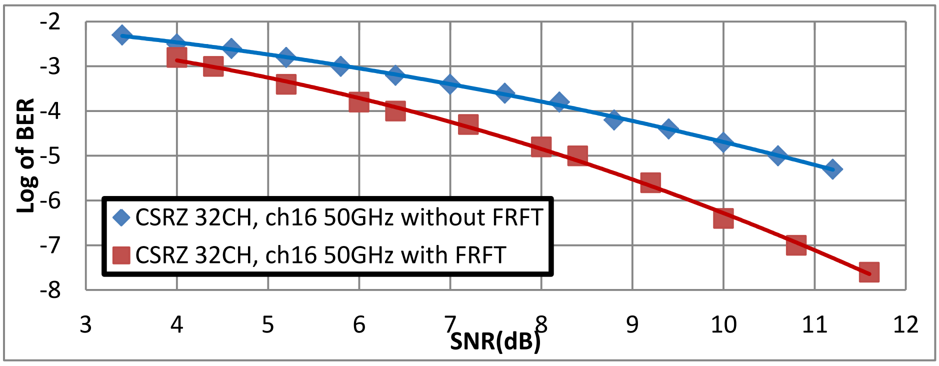


Figure 17: BER versus SNR for channel No.16, 32×10 Gb/s system, 50 GHz channel spacing with and without FRFT using CSRZ modulation format.

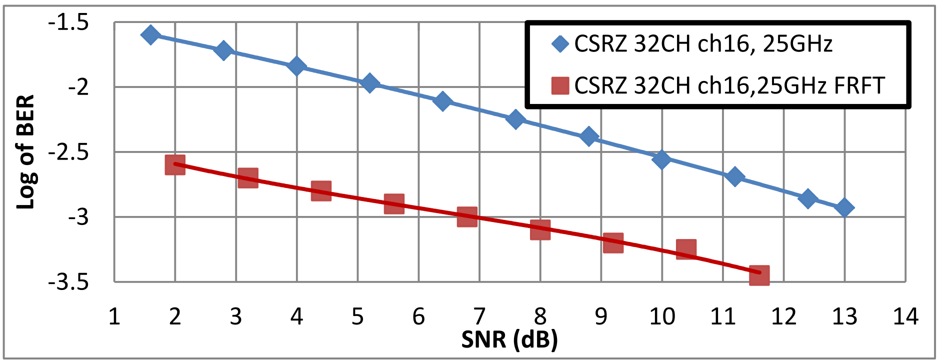


Figure 18: BER versus SNR for channel No.16, 32×10 Gb/s system, 25 GHz channel spacing with and without FRFT using CSRZ modulation format.

Table (1) : Parameters of Dispersive medium.

Parameter	Value
Dispersive optical fiber	
Length	100 m
Attenuation	0.1 dB/km
Dispersion	35 ps/nm/km
Differential group dely	0.2 Ps/km
Effective area	80 um^2

Table (2): values of the Q-Factors at 0 dBm input power for 8×10Gb/s, 16×10Gb/s and 32×10Gb/s optical system for diffrent channel spacing.

Modulation format	Number of Channels																			
	8×10 Gb/s						16×10 Gb/s						32×10 Gb/s							
	Channel Spacing (GHz)																			
	200		100		50		200		100		50		200		100		50		25	
	Without FRFT	With FRFT	Without FRFT	With FRFT	Without FRFT	With FRFT	Without FRFT	With FRFT	Without FRFT	With FRFT	Without FRFT	With FRFT	Without FRFT	With FRFT	Without FRFT	With FRFT	Without FRFT	With FRFT	Without FRFT	With FRFT
CSRZ	**20.11**	**25.12**	**14.00**	**18.54**	**9.45**	**17.16**	**29.97**	**42.55**	**25.17**	**30.24**	**12.13**	**18.03**	**33.78**	**35.26**	**21.20**	**32.52**	**12.115**	**13.61**	**4.46**	**5.00**

REFERENCES

[1]. M. Hussian," Analytical Investigation of 8-Channel Optical Wavelength Division Multiplexing Communication System", Engineering & Technology Journal, Vol.28, No. 3, pp. 552 – 561, 2010.

[2] A. Hussein, " Design of Low Dispersion Flattened Optical Fiber", Engineering & Technology Journal, Vol. 28, No. 16, pp. 4806-4815, 2010.

[3]. G. Keiser, "Optical Fiber Communications", McGraw-Hill, fourth Edition, 2000.

[4]. van den Borne, S. L. Jansen, G. D. Khoe, H. de Waardt, S. Calabro and N. E. Hecker Denschlag, "Polarization interleaving to reduce interchannel nonlinear penalties in polarization multiplexed transmission", Optical Fiber Communication Conference, pp.510 - 517 2004.

[5]. R. Tripathi, R. Gangwar and N. Singh, "Reduction of Crosstalk in Wavelength Division Multiplexed Fiber Optic Communication Systems", Progress In Electromagnetics Research, PIER, 77, pp. 367 – 378, 2007.

[6]. S. J. Savory, G. Gavioli, R. I. Killey and P. Bayvel, "Electronic compensation of chromatic dispersion using a digital coherent receiver", Optical Society of America, Optical Express, Vol. 15, No. 5, pp. 2120-2126 ,2007.

[7]. H. Cheng, W. Li, Y. Fan, Z. Zhang , S. Yu and Z. Yang,"A novel fiber nonlinearity suppression method in DWDM optical fiber transmission systems with an all-optical pre-distortion module", ELSEVIER journal Optics Communications,290, pp.152-157, 2 November, 2012.

[8]. Q. Han, Wei Li and Minghui Yang," An optical waveform pre-distortion method based on time domain fractional Fourier transformation", Optics Communications, Vol.284, No. 2, pp.660-664, 2011.

[9]. F. Li and J. Azana," Simplified system configuration for real-time Fourier transformation of optical pulses in amplitude and phase", Optics Communications, Vol. 274, No. 1, pp. 59-65, 2007.