

## A New All-Optical Signal Regeneration Technique for 10 GB/S DPSK Transmission System

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### ABSTRACT

The transmission of high power inside the optical fiber, produce amplitude noise, phase noise and other transmission impairments that degrade the performance of optical communication system. The signal regeneration techniques are used to mitigate these nonlinear impairments in the electrical or in the optical domain. All-optical signal regeneration techniques are one of the solutions to mitigate these nonlinear transmission impairments in the optical domain without converting the signal from optical to electrical domain. The existing techniques are not capable enough to attain the Bit Error Rate (BER) less than  $10^{-10}$  with the power penalty less than  $-9$  dBm. In this paper, a new all-optical signal regeneration technique is developed that mitigate amplitude and phase noises in the optical domain. The new optical signal regeneration technique is developed by combining the two existing technique one is 3R (Reshaping, Reamplification and Retiming) regeneration and other is Phase Sensitive Amplification (PSA). The 10Gb/s Differential Phase shift Keying (DPSK) noisy transmission system is used to verify the features of developed technique. The developed technique successfully mitigates the nonlinear impairments from the noisy DPSK system with significant improvement in BER at low power penalty with the additional feature of high Q-factor and an eye open response for the regenerated signal. It is determined that BER of  $10^{-12}$  is achieved at the power penalty of  $-14$  dBm with Q-factor of 42 and an eye opened response. The developed technique in the DPSK system is realized using commercial software package Optisystem. The designed technique will be helpful to enhance the performance existing high-speed optical communication by achieving the minimum BER at low power penalty.

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## 1. INTRODUCTION

The modern optical communication systems require noiseless high-speed transmission of data at long distance [1]. The high-speed transmission of data entails, launching of high power in the optical fiber. The high power transmission inside optical fiber produces various transmission impairments for e.g. scattering losses, linear and nonlinear effects and others in [1]. These transmission impairments produce limitations to yield the optimum data rate at long distance. These transmission impairments are mitigated in two ways i.e. in the electrical domain or in the optical domain. In the electrical domain, the degraded optical signal is converted in an electrical signal to mitigate these transmission impairments using Digital signal processing (DSP), dispersion compensating fiber (DCF), fiber braggging and others in [1]. The electronic signal regeneration has the limited signal regeneration capabilities in terms of data rate up to 5Gb/s [1]. In the

optical domain, all-optical signal regeneration provides the signal regeneration for more than 10Gb/s data rate [2]. Recently, several modulation formats are introduced to transmit the signals at long distance. These modulation formats include On-Off keying (OOK), Phase Shift Keying (PSK), Frequency Shift Keying (FSK) and others in [2]. From these modulation formats, PSK format has captured the interest to be used in transmission systems due to its 3-dB sensitivity and more immune to noise during transmission [2].

## 2. LITERATURE REVIEW

Recently, many techniques are developed to perform the optical signal regeneration. The optical signal regeneration in optical domain have been previously investigated theoretically, numerically and via simulation using different techniques [3]. These techniques include 2R (Reamplify, reshaping) regenerator configuration [3], 3R (Reamplify, reshaping, retiming) [5], phase extraction, pump dithering, Semiconductor optical amplifier (SOA), format conversion and with black box mode [3]. Among these optical signal regeneration techniques, the PSA is widely in used due to its several advantages such as supports the PSK format, simple in design and provides the full control during signal regeneration [3], [4]. However, It is discussed in [3], [4] that PSA alone is not such so much useful in optical signal regeneration, the other techniques must be used together such as; clock recovery, inject locking and others in [2]-[5]. These additional techniques consume enormous power and make design complex so that BER is degraded at more penalty. There are several all-optical signal regeneration techniques are proposed for different data rate, modulation formats as described in Table 1.

Table 1. The existing optical signal regeneration technique

Author and Publication year	Problem	Technique used	Advantages/ Disadvantages	Performance analysis
Carl Lundstrom (2014) [6]	Linear and nonlinear noise mitigation	Phase regeneration and phase extinction. BER of $10^{-9}$ at -9.3 dBm	Noise mitigation with amplification and supports only OOK format	BER v/s received power analysis
Francesca Parmigiani (2014) [7]	Regeneration of phase encoded signals	Phase regeneration of QAM signal of two harmonics of M-ary using PSA attained BER of $10^{-10}$ at -9.1 dBm	Regeneration is performed without phase to amplitude conversion and cannot adjust amplitude noise	BER analysis
Ju Wang (2014) [8]	All optical regeneration for WDM systems	Using optical fiber nonlinearities achieved the BER of $10^{-9}$ .	Remove SBS scattering using single CW pump and can't adjust nonlinear noises	BER V/s OSNR
Lian Jones (2015) [9]	Phase regeneration of M-PSK signal	Phase harmonic regeneration, re-synthesize of phase has achieved the BER of $10^{-10}$ at -9.6 dBm	Partial Phase regeneration is possible and manage only phase noise	BER, Eye diagram v
Alan E. Willner (2014) [10]	Encoding of Amplitude, phase, wavelength, Polarization of an optical wave	AdvancedmModulation techniques are used such PSK, DPSK, DQPSK, QAM are used for high speed optical signal	Perform regeneration, equalization	BER v/s received power analysis
R. Damani(2015) [11]	Optical 3R regenerator for optical clock recovery	Optical Clock Recovery using All-Optical Kerr shutter switching Techniquewith almost zero jitters	All-optical regenerator up to 10Gb/s and suffers from phase noise during recovery of signal at receiver.	BER v/s received power analysis, Eye diagram
Bill Corcoran (2013) [12]	Mitigation of nonlinear impairments	PSA with optical nonlinearity remove over 3dB noise figure in low noise amplification	Provides onlinear mitigation at high transmission power. Because of this additional power is required.	BER v/s received power analysis, Noise figure
Masatoshi Kagawa (2012) [13]	3R regeneration	XPM and FWM based multilevel optical 3R regeneration performed for BPSK and OOK signal	Provides ultra-signal processing and at the receiver NPN noise produces additional losses with each modulation formats	BER analysis
Z. Tong (2012) [14]	Challenges in PSA	SBS mitigation, pump phase modulation, inject locking improves the performance of PSA with mentioned techniques.	Mitigate the SBS effect. Phase noise mitigation. But still suffers from ASE noise at receiver.	Various analysis are performed
Zhiyu Chen (2012) [15]	Phase regeneration for PSK signal	PSA with single pump scheme optimized BER signal fidelity form $10^{-6}$ input BER to $10^{-9}$ output BER by setting the power level of channel and parameters of HNLF	Provides small distance and consumes less power. Suffering from ASE noise when high power is launched inside fiber.	BER, Eye diagram

However, the present techniques are not capable enough to provide the optical signal regeneration for high data rate of more than 10Gb/s signals at lower BER than  $10^{-10}$  at the lower penalty of -9.6 dBm [6]-[15]. There is intense need to develop the techniques that can mitigate nonlinear impairments for high speed transmission systems at low BER than  $10^{-10}$  and at low power penalty than -9.6 dBm.

In this paper, the nonlinear transmission impairments i.e. amplitude and phase noises are mitigated from 10Gb/s Differential Phase Shift Keying (DPSK) transmission system using new all-optical signal regeneration. The new all-optical signal regeneration technique is developed by integrating the two existing techniques one is Phase Sensitive Amplification (PSA) and other is 3R. The PSA technique is designed using single pump configuration that saves 30% power consumption than the existing techniques. The 3R technique doesn't require any clock recovery or other additional circuits to mitigate the noises from the optical signal. It is determined that the developed technique has successfully mitigated the amplitude and phase noises from the noisy 10Gb/s DPSK transmission system. The developed technique attained the low BER at low power penalty with high Q-factor than the existing techniques discussed in Table 1. In the next section, the methodology is discussed to perform the developed all-optical signal regeneration for noisy 10Gb/s DPSK transmission system.

### 3. METHODOLOGY

The optical signal regeneration using proposed technique for 10Gb/s DPSK transmission system is developed in different design steps as shown in Figure 1. Each design step is further consisting of different input blocks that are discussed next in detail.

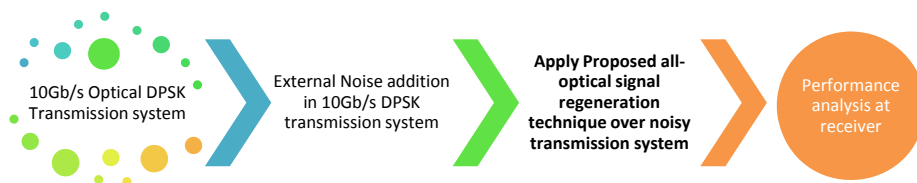


Figure 1. DPSK NRZ transmitter

It is illustrated in Figure 1 that 10Gb/s optical transmission system is designed using different blocks such as; Pseudo Random Binary Sequence (PRBS), NRZ signal generator, continuous wave laser signal and anMZIM modulator. Each block in 10Gb/s optical DPSK transmission system is configured by selecting the parameter values to generate the 10Gb/s optical signal. This 10Gb/s optical signal is given to noise emulator block. The noise emulator block consists of amplitude and phase modulator that includes the amplitude and phase noises in the 10Gb/s optical transmission system. These noises are included in the signal to verify the functionality of developed optical signal regeneration technique. The developed optical signal regeneration technique utilizes the PSA and 3R techniques. The performance of the developed technique is analyzed by comparing the BER at power penalty, Q-factor and eye diagram before and after implementation of developed signal regeneration technique over degraded signal. In the next, simulation setup of new optical signal regeneration for noisy 10Gb/s optical DPSK transmission system is discussed.

### 4. SIMULATION SETUP

The new optical signal regeneration technique for 10Gb/s optical transmission system is developed in Optisystem as demonstrated in Figure 2. The developed model contains mainly four design stages. The design stage 1 consists of the generation of 10Gb/s optical DPSK signal for initiating the transmission of the signals using different blocks as discussed above. The design stage 2 contains the noise emulation process to include the noise in the generated 10Gb/s optical DPSK signal. The design stage 3 includes the development of proposed signal regeneration. In the design step 4, the performance of developed signal regeneration technique is analyzed by defining the BER, an eye diagram and Q-factor before and after signal regeneration technique. Each design step is developed by utilizing the different block available in optisystem library. The different blocks are configured by defining the parameters in the components block property. The optisystem block for different components provides the wide range of values to select for each component. Figure 2 describes the system model of optical signal regeneration technique for noisy 10Gb/s optical DPSK transmission system. It illustrates that first 10Gb/s optical signal is generated using PRBS sequence, NRZ

signal generator, laser signal and a modulator. After that, this optical signal is degraded by noise emulator using amplitude and phase modulator. This noisy signal is optically regenerated and noise mitigation is achieved using the developed technique. The optical signal is converted in the electrical signal to analyze the performance of developed regeneration system using BER, Q-factor and an eye diagram. In the next section, each model is discussed in details with its parameters section and working mechanism.

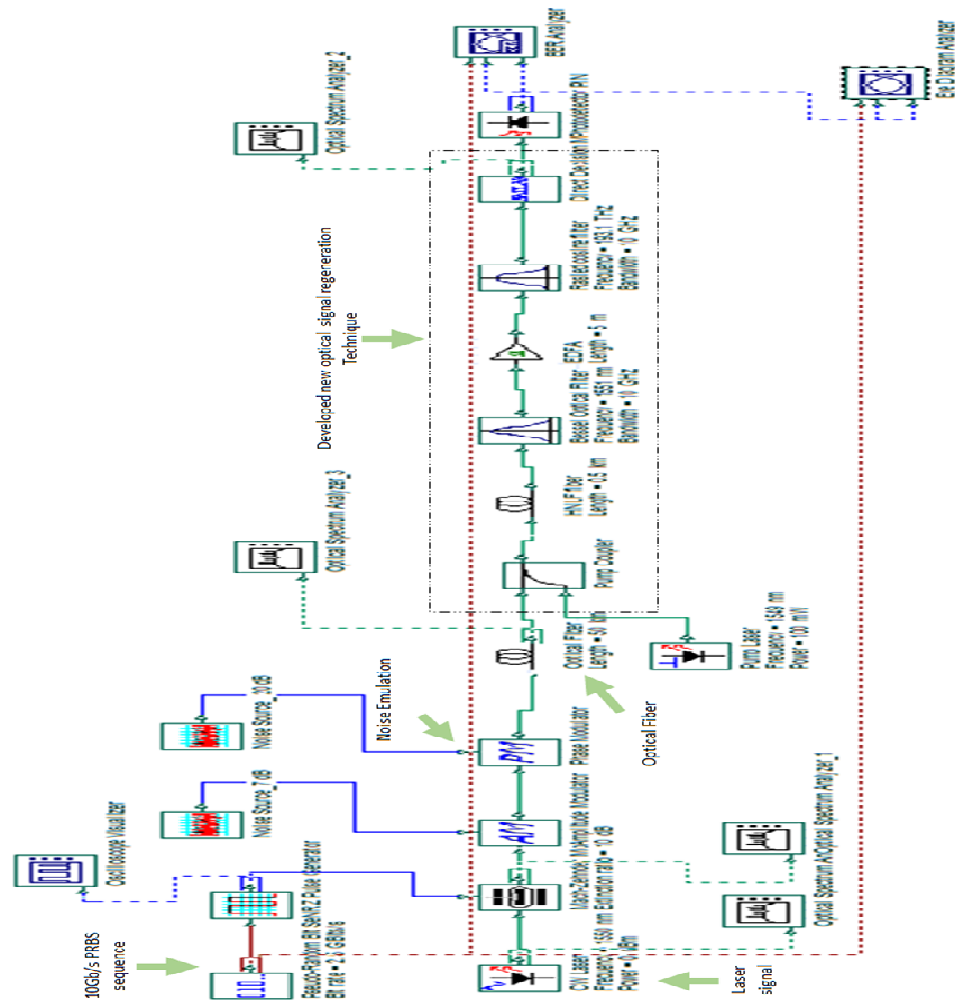


Figure 2. Simulation setup in Optisystem of new optical signal regeneration technique for 10Gb/s transmission system

#### 4.1. 10Gb/s Optical DPSK Transmissions System

The 10 Gb/s optical DPSK transmission system contains the 10Gb/s Pseudo Random Binary sequence at the bit rate of 10Gb/s. The generated sequence is given to NRZ signal generator that produces the 10Gb/s DPSK- NRZ signal. After that, a continuous laser signal is generated of 1550 nm. Both 10Gb/s DPSK- NRZ signal and laser signal are modulated using LiNbO3MZIM modulator. In Figure 2, the arrangement of generating the 10Gb/s optical signal can be seen. The 10Gb/s optical DPSK transmission system is configured using parameters defined in Table 2.

Table 2. Parameters used for generating the 10Gb/s optical DPSK signal

Parameters	Values
Bit Rate	10Gbps
Number of leading zeros	(Time window * 3 / 100 ) * Bit rate
Number of trailing zeros	(Time window * 3 / 100 ) * Bit rate
Operation mode	DPSK sequence with Mark Probability of 0.5
Pulse shape	Gaussian Wave
Amplitude	10 a.u
Bias	0.1 a.u
Rise Time	0.05 bit
Fall Time	0.05 bit
Continuous-wave Laser Frequency	1550 nm
CW laser Power	0.001 W
CW laser linewidth	10 MHz
MZM modulator symmetry factor	-1
MZM modulator negative chipped value	enabled
MZM modulator Extinction ratio	30 dB

#### 4.2. Noise Emulation in 10Gb/s Optical DPSK Signal

Nonlinear phase noise and Amplitude Spontaneous Emission (ASE) noises are externally inserted in 10Gb/s optical DPSK signal to test the developed all-optical signal regeneration. The amplitude and phase noise are generated using amplitude and phase modulators respectively. In Figure 2, it is demonstrated that amplitude noise has the level of 7 dB and phase noise has the level of 20 dB.

#### 4.3. New All-Optical Signal Regeneration Technique for 10Gb/s Noisy Optical DPSK Signal

New all-optical signal regeneration technique is developed by integrating the Phase Sensitive Amplification (PSA) and 3R (Reamplification, Reshaping and Retiming) regeneration technique. Figure 3 shows the optisystem model for developed optical signal regeneration technique.

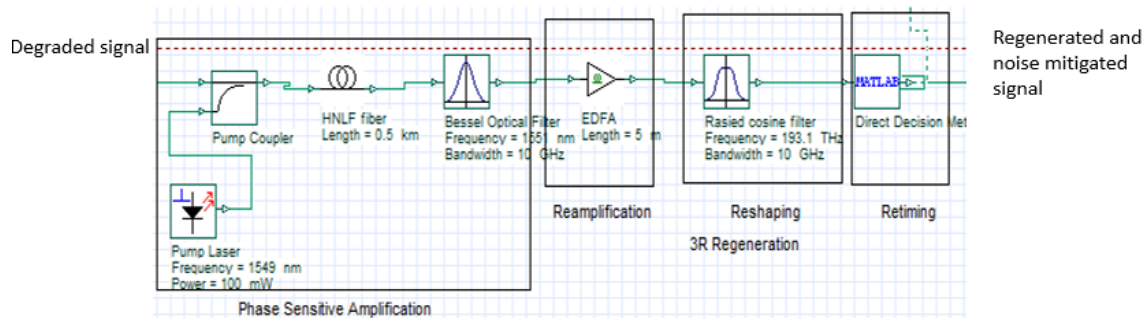


Figure 3. Optisystem Model of New optical signal regeneration technique

The 10Gb/s noisy optical signal is given to PSA model. The PSA model contains the HNLf fiber of 0.5 km length that generates the different spectral components using degenerated FWM. It is defined that optical signal is modulated at 1550 nm and pump signal has the wavelength of 1551 nm. When both these signal are injected in HNLf fiber it generates the idler signal at 1550.5 nm as discussed in [7]. Due to FWM the various spectral components are generated at  $\lambda_s + \lambda_p - \lambda_i$ ,  $\lambda_s - \lambda_p + \lambda_i$ ,  $\lambda_p + \lambda_i - \lambda_p$  and  $2\lambda_s - \lambda_i$ . The FWM components that satisfy the phase mismatch factor  $\Delta k = 2\beta_p - \beta_s - \beta_i$  [9] with in-phase gain in the signal is filtered out. Here the noisy 10Gb/s optical signal is regenerated at 1552.6 nm wavelength with in-phase gain of 3 dB using Equation (1) and (2) [9];

$$G(\phi_s) = (2\vartheta^2 + 1) - 2\vartheta^2 \cos(\phi_n + 2\phi_s) + 2\vartheta \cos \phi_n - 2 \cos 2\phi_s \quad (1)$$

$$\vartheta = \frac{\bar{\gamma} P_P}{(-\Delta k + \gamma P_S - 2\bar{\gamma} P_P)} \quad (2)$$

Where  $\nu$  is the optical frequency, PP is the pump power, Ps is the signal pump power,  $\Delta k$  is the phase mismatch factor,  $\phi_s$  is the phase of the 10Gb/s noisy optical DPSK signal,  $\phi_n$  is the phase of spectral components at which signal is regenerated and  $\bar{\gamma}$  is the nonlinear coefficient. The optical filter has the

wavelength of 1551 nm and bandwidth of 10 GHz. In PSA, phase changes from  $\phi_s = 0$  to  $\pi$  of pump as in equation (1) relates to shifting the modulation by  $\frac{1}{2}$  pump period, which is equivalent to  $\frac{1}{4}$  signal period. In one quadrature amplitude of the signal wave corresponding to the  $\phi_s = 0$ , the signal is amplified by a gain  $g$  but in second quadrature corresponding to  $\phi_s = \pi$  amplitude is deamplified  $1/g$ . This is how the phase noise is removed using PSA. The optimum value of phase is close to  $3\pi/2$  because spectrum then exhibits two peaks with a sharp dip at the original wavelength. The PSA is designed using single pump configuration that saves additional 30% power from present scheme described in Figure 3. The phase sensitive amplification process removes the phase noise from noisy optical signal, but the amplitude noise is still present in the signal. The amplitude noise is mitigated using 3R regeneration technique as defined in Equation (2) [13];

$$S(t) = D(0, t)e^{\frac{i\gamma P_s}{2}} \quad (3)$$

The 3R regeneration technique in optisystem is developed in different steps. In the first step, PSA signal is reamplified using optical amplifier EDFA, the signal is reamplified to raise the level of noise so that noise and signal can be easily distinguished. In the second step the reamplified signal is reshaped using raised cosine filter so that signal can be smooth and the edges should be removed. At this stage, the amplitude noise is removed using the reshaping and reamplification techniques. The signal is delayed because the raised cosine uses the Kaiser window which has the limited bandwidth and window range. In the third step, the reamplified and reshaped signal is retimed using single interferometer developed using direct decision method. Table 3 illustrates the parameters used to develop the optical signal regeneration technique.

Table 3. Parameters used for new optical signal regeneration technique

All-optical signal regeneration stage	Parameters	Values
All-optical signal regeneration stage	Core Radius	2.2 $\mu$ m
	Numerical Aperture	0.24
	Length	5 m
Re-amplification stage	Loss	0.1 dB/Km
	Max. Iterations	50
	Noise threshold	-100 dB
	Roll off factor of	0.25
	Truncate the filter	6 symbols
Reshaping Stage	order of the filter	3
	Ts is the Sampling period	1 ns
	Pump frequency	1550 nm
Pump Configuration	Pump Power	100 mW
	Fiber Length	50 m
	Fiber Length Tolerance	$\pm 3$
	Cutoff Wavelength	< 1650 nm
	Dispersion	-2.5 to +2.0 ps/(nm·km)
Highly Nonlinear fiber	Dispersion Slope	0.019 $\pm$ 0.004 ps/(nm <sup>2</sup> ·km)
	Attenuation	$\leq$ 0.90 dB/km
	Non-Linear Coefficient (Typical)	11.5 W <sup>-1</sup> ·km <sup>-1</sup>
	Frequency	1550 nm
Optical Gaussian filter	Bandwidth	10 GHz
Retiming Stage	Using decision direct method	
	Cut-off frequency	1.89 GHz
Low Pass Filter	Depth	100 dB
	Order	3

The developed technique regenerates the noisy 10Gb/s optical signal with in-phase gain using PSA and reaming noise are mitigated using 3R. The performance of developed optical signal regeneration technique is analyzed by converting the optical signal in the electronic signal using photodetector. The performance is analyzed using BER analysis, Q-factor and eye diagram available in Optisystem. In the next section, results that contain the responses for each design stage are discussed.

## 5. RESULTS AND DISCUSSION

The nonlinear transmission impairments are mitigated using new optical signal regeneration technique for noisy 10Gb/s optical transmission system. The response of transmitted 10Gb/s PRBS sequence and laser signal used as carrier signal are described in Figure 4 and in Figure 5 respectively. This PRBS sequence is mixed with laser signal and given to MZIM modulator to produce the 10Gb/s optical signal shown in Figure 6.

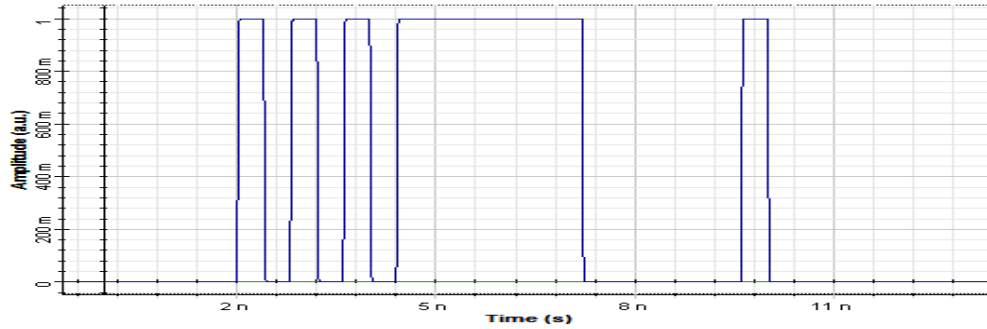


Figure 4. Response of transmitted 10Gb/s PRBS

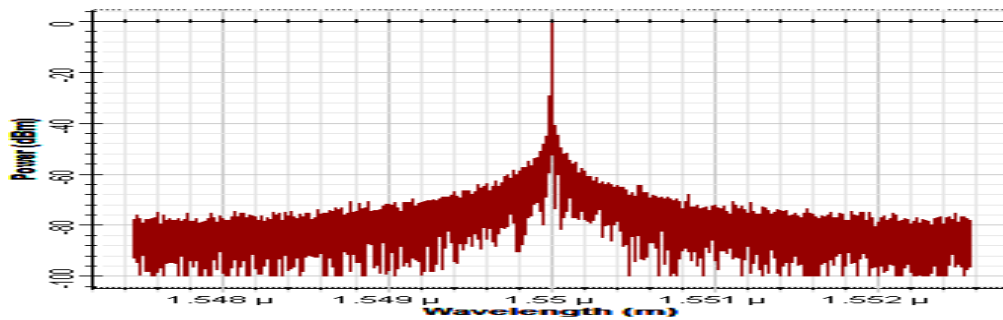


Figure 5. Laser signal

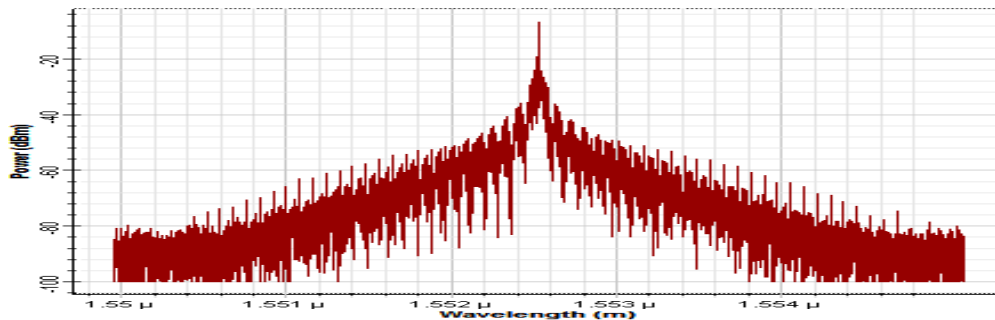


Figure 6. Modulated signal or 10Gb/s optical signal

This optical signal is transmitted over long distanced noisy fiber link of 150 km. The 10Gb/s optical DPSK signal is degraded during transmission as shown in Figure 7. The transmitted PRBS sequence as shown in Figure 4 is degraded as described in Figure 8.

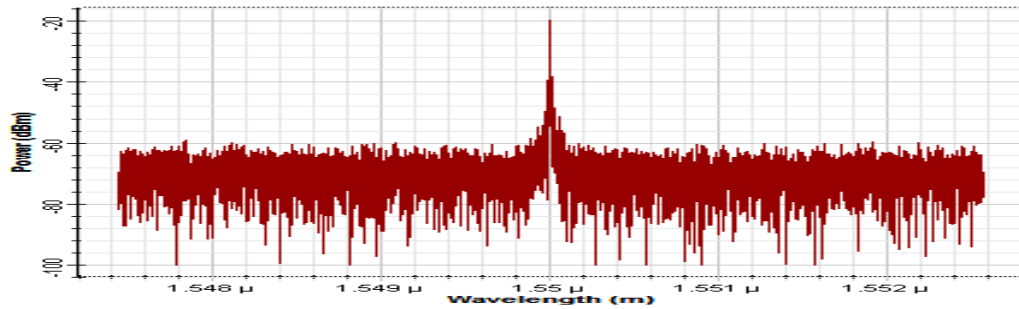


Figure 7. Response of degraded optical signal

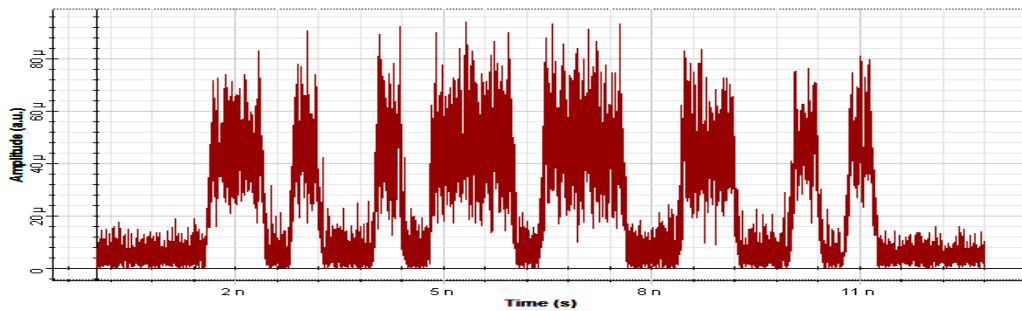


Figure 8. Response of degrades PRBS sequence

When the degraded optical signal is given to new optical signal regeneration technique, the signal is successfully regenerated and also both amplitude and phase noises are mitigated for the degraded signal. The response of PSA mode is shown in Figure 9.

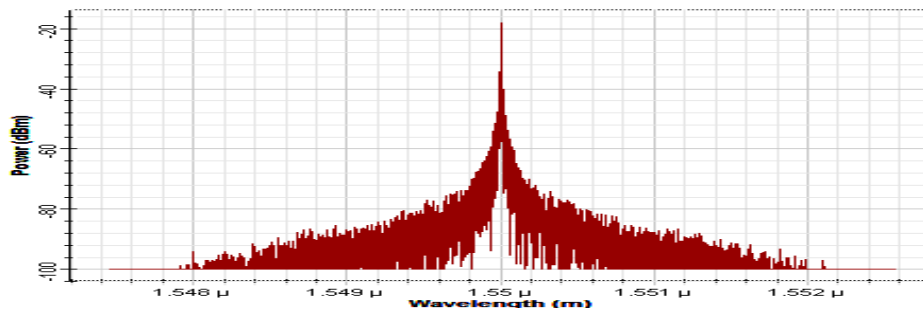


Figure 9. Response of PSA model used in developed optical signal regeneration technique

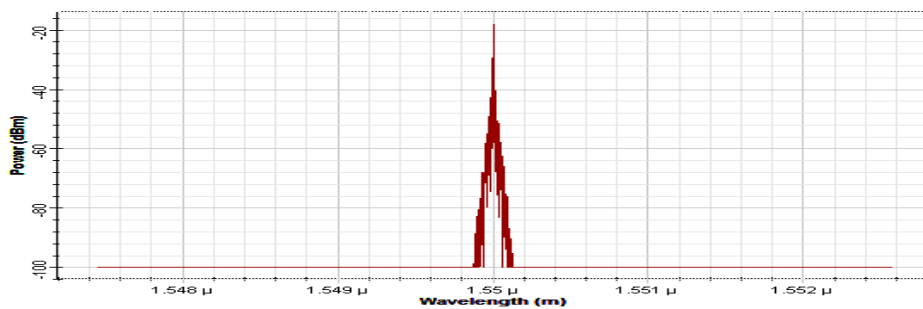


Figure 9. Response of 3R regeneration model used in developed optical signal regeneration



The optical signal received at the end of developed optical signal regeneration mode i.e. at the end of 3R regeneration stage is converted in the electrical signal using photodiode. The electrical signal received at the end of a photodiode is analyzed using oscilloscope available in optisystem electrical visualizer library. The response of received PRBS sequence is demonstrated in Figure 10.

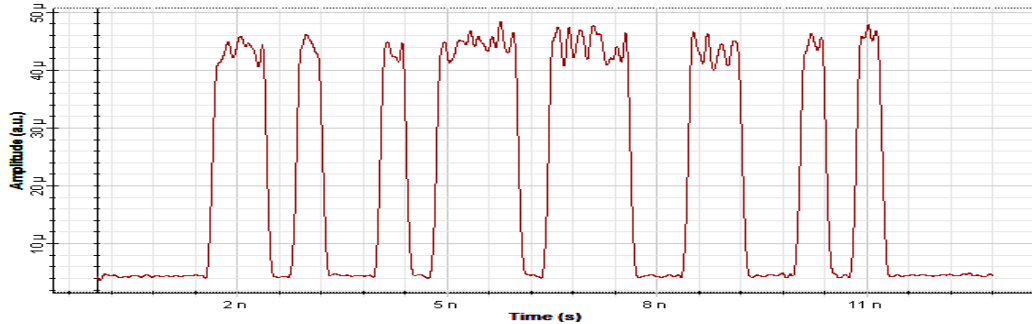


Figure 10. Response of regenerated PRBS sequence using new optical signal regeneration technique

The system performance is analyzed using BER, Q-factor and an eye diagram calculated before and after optical signal regeneration technique. Figure 11 demonstrates the BER, eye diagram and Q-factor before all-optical regeneration. It is defined that BER of  $10^{-5}$ , Q-factor was 9 with jitters in the eye diagram is recorded in the response. When the developed signal regeneration technique is implemented on degraded signal the BER, Q-factor and eye diagram responses are improved as described in Figure 12. It is recorded that after applying the new optical signal regeneration technique BER of  $10^{-12}$ , Q-factor 42 with less jitters in the regenerated signal is achieved is of 42. The significant improvement is recorded in BER, Q-factor and eye diagram pattern for noisy 10 Gb/s DPSK transmission system. Furthermore, the amplitude noise is reduced from 7 dB to 0.9 dB and phase noise reduced from 20 dB to 1.3 dB. Using the proposed optical signal regeneration technique the amplitude noise is reduced 87 % and phase noise is reduced 92% from noisy 10Gb/s DPSK system.

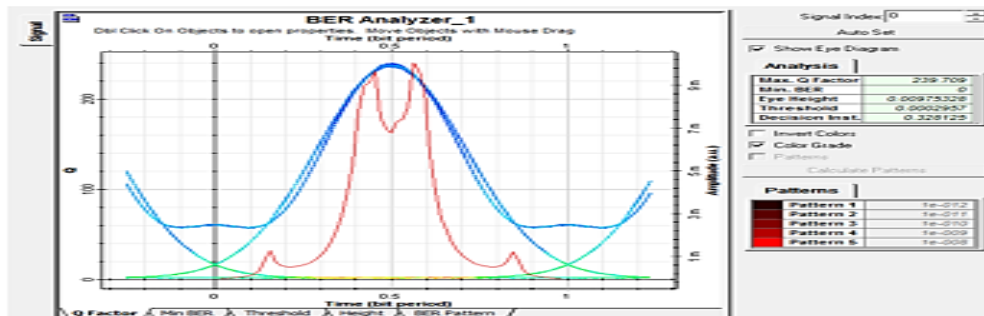


Figure 11. BER and Eye diagram before applying new optical signal regeneration technique over degraded signal

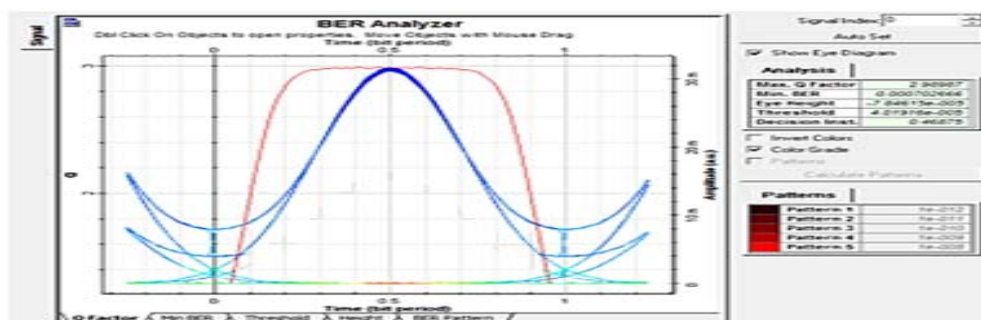


Figure 11. BER and Eye diagram after applying new optical signal regeneration technique over degraded signal

## 6. CONCLUSION

In this work, the optical signal regeneration is performed over noisy 10Gb/s optical DPSk system using the new developed signal regeneration technique. The developed optical signal regeneration technique significantly improved the BER at low power penalty with high Q-factor than existing techniques. The developed technique provides the regeneration and noise mitigation for high data rate degraded signals without converting the signal from optical to electrical domain. The designed system will be useful for high speed communication systems in regenerating the long distance with noise mitigation. In future, the new optical signal regeneration can be enhanced to provide the optical signal regeneration for other modulation formats.

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Bhagwan Das received his Bachelor of Electronic Engineering Degree in 2008 from MUET, Pakistan. He has received his Masters of Engineering Degree (communication engineering) from QUEST, Pakistan in 2013. He is in services with Quaid-e-Awam University of Engineering, Science and Technology since Jan 2011 as Lecturer in Electronic department as a regular employee. He is also professional member of IEEE. He is Registered Engineer in Pakistan Engineering Council and member in Pakistan Engineering Congress. He is currently doing PhD in Electrical Engineering from Universiti Tun Hussein Onn Malaysia (UTHM) under supervision of Assoc. Prof. Dr. Mohammad Faiz Liew bin Abdullah. His research fields of interest are optical communication and signal processing and FPGAs based Energy Efficient design. He successfully published many research articles in SCOPUS, ISI, EI compendex indexed journals. He has presented more than 15 papers in IEEE index conferences held in Vietnam, Thailand, India, Malaysia, and Pakistan. He is nominated international program committee member in International Conference on Computing and Informatics (ICOCI) (ISI index). He reviewed many paper in International Conference on Soft Computing in Data Science 2015 (SCDS2015) (Springer index). Recently, he has reviewed the several articles of “Wireless Personal Communication” Impact factor Journal 0.998 (Thomas Reuters) and “Radio Engineering Journal” Impact factor Journal 0.7 (Thomas Reuters).



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