Intrinsic and extrinsic approaches to mitigate FWM

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This article presents the mitigations of Four-Wave Mixing (FWM) using extrinsic and intrinsic methods in fiber optic Dense wavelength Division Multiplexing (DWDM) system design. The presence of FWM introduces excessive sidelobes in the DWDM system, which consumes high input power, lowers spectral efficiency, and increased structural design complexity with network latency. FWM in DWDM introduces more signal distortion and cross talk, which lowers system gain, Q-factor and output signal power that degrades DWDM system performance. In this paper, DWDM system is implemented with Germanosilicate doped EDFA (GS-EDFA) and Reflectivity based Fiber Bragg Grating (R-FBG) to mitigate FWM. The proposed DWDM design achieves high gain of 43.69753 dB, with Q-factor 118.585 and an optimal output signal power using intrinsic and extrinsic methods and reduces the excessive side lobes due to FWM impairments. Influence of input transmission power, the impact of GS-EDFA length over gain and noise figure characteristics, and effects of various pump power are discussed for different modulation formats using 980 nm and 1480 nm pump configurations. Furthermore, this paper also investigates an optimized modulation format and analyzes FWM influencing design parameters such as higher data rate, low channel spacing, and optimum input power over long distance DWDM system transmission. The performance of the proposed DWDM is evaluated through mitigating metrics such as signal power, OSNR, noise figure, gain, and Q-factor.

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Keywords: Intrinsic and extrinsic method, DWDM, GS-EDFA, FBG, Q-factor, BER

1. Introduction

The rapid growth of internet and multimedia applications requires a higher data rate; wider bandwidth and ultra-channel capacity will ensure a DWDM system with the guaranteed Quality of Transmission (QoT) based performance [1]. Increasing transmission capacity of the DWDM system introduces more problems such as higher distortion, more crosstalk, more Inter-Channel Interferences (ICI) and Four-Wave Mixing (FWM) [2]. Optimization of the DWDM system involves several design parameters that influence fiber nonlinearities [3]. DWDM system with EDFA plays a key role in achieving high gain, low noise and wider bandwidth [4]. Unfortunately, conventional EDFA has unequalled gain with more signal distortion and amplified spontaneous and stimulated noises, which degrades DWDM system performance. The performance of the DWDM system is enhanced by introducing various intrinsic and extrinsic techniques [5]. The intrinsic methods involves with different host materials such as germanosilicate (GS), fluorophosphate and Alumino Germano silicate (Al-Ge-Silica) doped EDFA [6]. Whereas filters such as uniform fiber grating, chirp Fiber Brag Grating, gain-flattening filters and DCF provides extrinsic methods. The intrinsic method provides equalized gain for narrow bandwidth, whereas the extrinsic method provides equalized gain for wider bandwidth, further introducing complex limitations.

Optimizing different parameters in the intrinsic and extrinsic methods will mitigate complex limitations in the DWDM system. Gain and noise figure characteristic of EDFA-DWDM system is studied with 980 nm and 1480 nm Pump configuration [7]. Forward pump configuration provides a low noise figure and adopts the system for low channel distortion and cross talk. Gain flattened EDFA is achieved by cascading Fiber brag grating with different host materials such as conventional silica, fluoride, and alumino-germanosilicate doped EDFA. Optimizing modulation format for long haul DWDM transmission is considered as prime focus like new host materials doped with EDFA and cascading gain-flattening filters [8]. DWDM system with RZ modulation format is designed for long-distance transmission over 2500 km with 10 Gbps data rate [9]. RZ modulation with different duty cycles are less adopted for signal distortion, cross talk, and fiber nonlinearities (FWM) [10]. It provides high gain, low BER and high-quality factor. Optimizing parameters such as input power, length of fiber amplifier, channel spacing, data rate, pump power and core size of an optical amplifier are factors that mitigates FWM nonlinearity in a DWDM system [11].

Problem:

- Analyze the new host material for erbium-doped fiber amplifier to provide high gain, output power and low noise figure over a wider bandwidth.

- Achieve high-equalized gain over wider bandwidth, reducing sidelobes and mitigating fiber nonlinearities such as FWM.
- Identify the optimum modulation format for higher data rate transmission for long-distance DWDM fiber optic systems.

The existing method needs device and parametric optimization to provide an efficient design for DWDM with higher bandwidth and bit rate. Since FWM influences parameters such as bit rate, input power, channel spacing, modulation format and core size vary according to the field requirements and meet expert accuracy.

This research paper aims to mitigate the Presence of sidelobes (FWM) by integrating intrinsic method (GS-EDFA) and extrinsic methods (R-FBG). It also performs gain equalization over wider bandwidth by using the extrinsic method. Various pump configurations are analyzed to understand gain and noise figure characteristics for Germanosilicate doped EDFA (GS-EDFA). Furthermore, this article also provides an optimized modulation format for long-distance DWDM system transmission at a higher data rate. This paper performs parametric optimization and reduces fiber nonlinearities, especially FWM in the DWDM system.

The rest of the paper is organized as follows; section 2 presents preliminary studies related to this problem and its features, scope, and remarks. Proposed method and simulations are discussed in section 3. Performance analysis of the proposed method over different configurations is presented in section 4. Section 5 presents the performance analysis of the gain and noise figure. Performance analyses of parameters that are influencing FWM were discussed in section 6. Section 7 presents the overall conclusion and future scope of this research work.

2. Literature survey

In [14] Sanmukh Kaur et al. proposed an Semi-conductor Optical Amplifier (SOA)-based design using RZ and NRZ modulation format and analyzed with input signal power, which controls signal power and pattern length on BER of Narrow bandwidth. Since SOA has, a narrow bandwidth and its applications are limited. In [15] Lubana et al. propose a combined novel amplifier, erbium ytterbium-doped fiber amplifier (EYDFA) Raman hybrid optical amplifier (HOA), for suppressing the FWM issues. The authors in [17] discussed RZ modulations, which are ideal for long-distance fiber-optic WDM transmission. Moreover, this design involves a conventional post-processing unit that provided Complex structure and was more challenging to implement. The work in [9] Jalil Aziz Hamadamin et al. presented an efficient modulation format to achieve high Q-factor, low noise figure and less adapted for fiber nonlinearities. More pulse dispersion and signal attenuation will degrade the performance of the design mentioned above. However, Farman Ali et al. in [2] investigated advance modulation formats to mitigate FWM. This structure is performed with less utilization of channel capacity and bandwidth. High accuracy closed-form expressions for modulation format on FWM suppression are discussed in [22]. In addition, more computational complexity is observed in the implementation of experts' accuracy. Research work in [1] Habib Ullah Manzoor et al. proposed modified Duo binary modulation and achieved over 25 dB reduction in FWM. These kinds of higher-order modulation are resulting in with excessive sidelobes, which degrades system performance. In [7] A. S. Kang et al. presented a two-modulation format at first DPSK-FM modulation format, achieving a 44.37 as q-factor, and in second QAM-FM modulation format providing 38.26 Q-factor with high signal attenuation, cross talk and signal distortion. Harman preet Kaur Sandhu et al. in [21] proposed POLMUX QPSK and have shown FWM reduction of −9.44 dB in Error Vector Mechanism and discussed transmission tolerance challenges. Apart from these discussions, various analytical models are presented to identify a valid modulation format under different considerations to reduce FWM. In general, all these models are limited with applications, complex structure, Q-factor, noise figure and adopted for fiber nonlinearities. Furthermore, pulse dispersion and high signal distortion will help to investigate the design of various dispersion characteristics based on optical fiber with a higher-order modulation format.

The author in [12] proposed low channel WDM design with 200 GHz channel spacing over 120 km distance to suppress FWM sideband power. Bijayananda Patnaik et al. presented 1.28 tbps data transmission using ultra-high channel capacity with high dispersion tolerance, leading to more sidelobes and FWM in [16]. Indeed, the work in [8] Fadil Paloi et al. proposed high data rate transmission over long distance leads to GVD and SPM causing more signal distortion. Research work in [18] Aruna Rani et al. studied SOA design for narrow bandwidth application with channel spacing upto 50 GHZ. In [3] Raghuwanshi et al. discussed DWDM system design using a hybrid amplifier for C and L band applications with narrow channel spacing, which is affected by nonlinear impairments such as dispersion and cross-phase modulation. However, narrow channel spacing favours FWM, introduces more sidelobes, and highly adopted for nonlinear impairments such as FWM, SPM, XPM, and GVD. High channel spacing with fewer channels are implemented to suppress FWM sideband power with the cost of bandwidth crunch and channel capacity. However, the author in [19] presents various combinations of optical amplifiers for a 100-channel SD-WDM system that achieves a gain over 40.41dB and a low gain variation ratio of 0.40. In [20] Aditya Goel et al. proposed a system design for low dispersion characteristics upto ±1 ps/km-nm using single Dispersion Flattened Fiber (DFF). However, this work also investigates attenuation loss and distorted spectral characteristics. Almukhtar Aya et al. investigated new host material based EDFA design and achieved high gain and low noise figure for the short span of 1m fiber length in [23]. The authors in [24] studied an optical system design for an error-free operation with 2.5 dB power penalty and operating at lower bandwidth.

Researchers David B. Talam et al. in [4] is designed AL-G-doped EDFA system with the absence of fiber span and achieved 30 dB gain. In [6] Abdollah Malakzadeh et al. is presented low noise figure, optimum length, and high gain based fiber optic design and implemented for short-distance communication. However, the authors in [11] M. L. Meena et al. proposed CFBG and DCF based low channel DWDM system design to overcome the pulse broadening. The targeted work in [25] presented a single channel WDM design with 90 mm short length CFBG and achieved Q-factor above 18 with low data rate transmission. Furthermore, the author proposes the DPSK modulation for 40-channel DWDM systems, which achieves high gain for 5G applications [26].

After reviewing these models, varying dispersion characteristics in fiber, new doping material based EDFA design and optimum fiber span length combined with FBG will provide low noise figure, high gain and low power penalty and reduce pulse broadening. Furthermore, these preliminary studies are analyzed their suitability for channel capacity, bandwidth utilization and motivated us to investigate these issues to meet field requirements and experts' accuracy. This paper presents high capacity DWDM design using an appropriate modulation format with new host-based EDFA design to mitigate FWM and reduce sidelobes. Furthermore, this paper aims to integrate a new host germanosilicate based EDFA (GS-EDFA) with R-FBG in a high capacity DWDM system with optimal fiber span length to reduce the Presence of excessive sidelobes due to FWM impairments. Furthermore, it also necessitates designing a DWDM system with high equalized over wider bandwidth upon expert accuracy. From preliminary studies, the effects of FWM in the DWDM system are identified by analyzing their influencing parameters such as channel spacing, modulation format, core size, variable length of EDFA with appropriate pump configurations. The proposed DWDM system's performance is evaluated from their mitigating metrics such as Input power, output signal power, Noise power, OSNR, Max Q-factor, Min BER, Gain, Noise figure, Optimum length.

3. Proposed method and simulation

FWM influencing factors such as Min BER, Max Q-factor, OSNR, Noise power are analysed to estimate DWDM system performance. Fig. 1 shows the simulation setup for the proposed green channel DWDM system using R-FBG and using GS doped EDF pump laser.

For 64- channel system design, a different wavelength signal is generated through Continuous Laser. This simulation setup consists of a DWDM transmitter, DWDM Multiplexer, setoff SMF, DCF and R-Fiber Brag Grating. Each DWDM transmitter has continuous Laser, mach-zehnder modulator, pseudo-random Sequence generator and non-return to zero (NRZ) modulation format with 10 gbps data rate. DWDM system is modulated with NRZ modulation technique in the transmitter side to cover the C band (1530 nm – 1580 nm) of the light spectrum. Modulated signal from DWDM transmitter is fed through DWDM Multiplexer with channel spacing of 100 GHz.

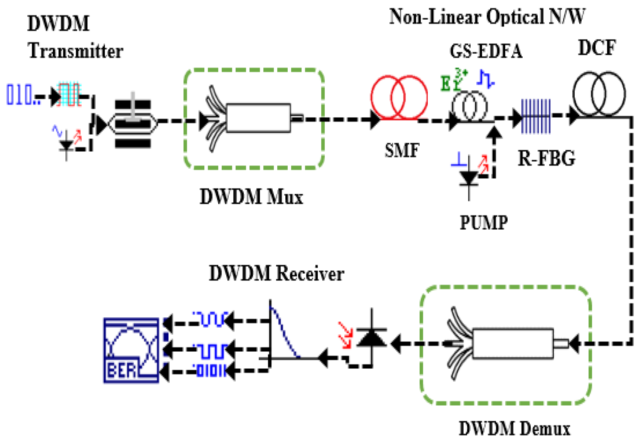

Fig. 1. Proposed DWDM Simulation setup (color online)

DWDM Multiplexer combines all light signals and is transmitted to Single-Mode fiber (SMF) with 150 km length with a reference wavelength 1530 nm. The parametric configuration of SMF setup consists of Attenuation 0.2 dB/km, Dispersion coefficient 16 ps/nm/km, Dispersion slope 0.075 ps/nm^2/km, Beta 2 value of -20 ps^2/km, differential group delay 0.2 ps/km and PMD coefficient as 0.5 ps/(km)^0.5. The basic amplification process is performed by a new host material of Germanosilicate is doped with EDF amplifier (GS-EDFA), which has optimum length of 5 m with an external pump power of 100 mw and a pump frequency of 980 nm. Key parameters such as optimum length and pump power will determine the gain characteristics of the GS- EDFA. This amplification process results in amplified spontaneous emission (ASE) noise, which provides unequal gain.

To achieve flat gain pattern and reduced fiber nonlinearities, reflectivity based Fiber Brag Grating (R-FBG) with reflectivity 0.55 and dynamic noise of 3 dB is used as the gain flattening filter. Gain pattern from R-FBG with order of 64 digital filters provides equalized gain pattern around 1530 nm-1550 nm. Variations in R-FBG's reflectivity reduces side lobes, provides significant tolerance to nonlinearities such as four-wave mixing (FWM), and reduces it to a minimum. The optical signal from the R-FBG filter passes through another SMF fiber of 150 km with reference wavelength 1550 nm, attenuation and dispersion coefficients of 0.2 dB km and 16.75 ps/nm/km, respectively.

In the receiver part, Multiplexed 64-channel signals are separated by the DWDM demux. Each receiver consists of PIN photodiode that converts the light signals into the current with PIN responsivity of 1A/W with dark current 10 nA, Electrical signal from PIN photodiode is passed through low pass Bessel filter. The filtered signal is transmitted through 3R regenerator, which reshapes the signal and passes through BER nalyser. Finally, BER nalyser effectively studies eye diagram characteristics.

4. Performance analysis of proposed method with different channel configurations

The proposed DWDM system using germanosilicate doped EDFA is combined with R-FBG to perform data transmission over 300 km. Germanosilicate doped EDFA provides high gain, low noise figure, low distortion loss and crosstalk. The Reflectivity of FBG is an essential factor, which involves side lobes reduction. Reflectivity range can be calculated from transfer matrix method and it is observed that at 0.55 reflectivity the system provides equalized output gain spectrum without sidelobes. This can be presented in below spectral characteristic comparison section. From Fig. 2(a) shows the existing EDFA based DWDM system with the presence of nonlinearities such as FWM and more cross talk. This will degrade the system performance with reduced output spectrum gain and quality factor and BER as listed in Table 1. Spectral characteristics and BER analyzer output for the 16-channel DWDM system are shown in Fig. 2(a) and (c). Spectral and BER analyzer output characteristics for the proposed system are shown in Fig. 2(b) and (d). The proposed DWDM system using R-FBG and GS-EDFA for 16 channel achieves high gain and very good eye-opening with Max Q- factor of 18.9268 and Min BER of 2.78E-80.

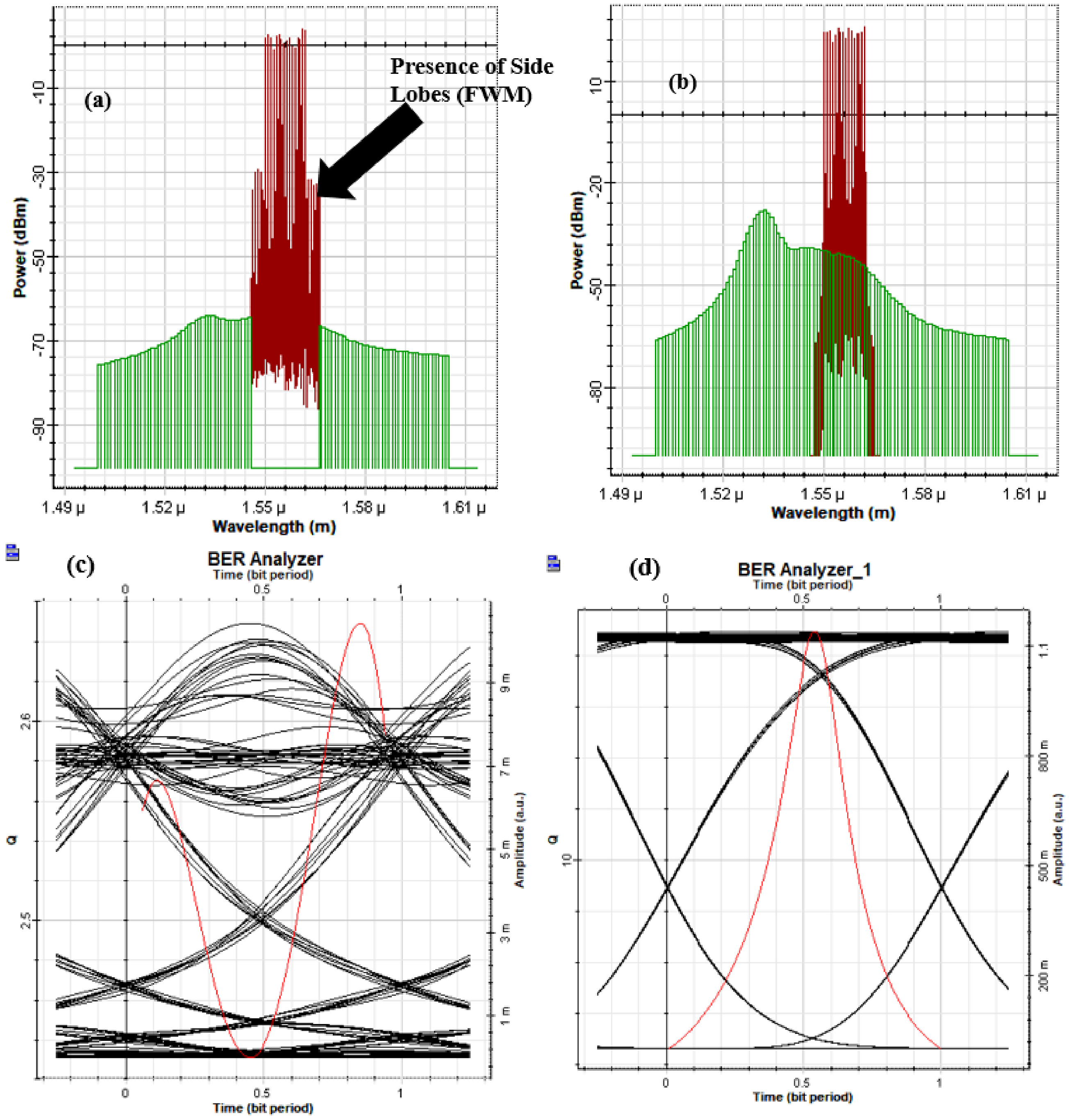

Fig. 2. 16-channel spectrum analyzer output for existing (a) and the proposed method (b) and BER analyzer output for existing (c) and proposed method (d) (color online)

From this analysis, it is observed that the proposed method performs much better than the existing method. This can be observed through the obtained results presented in Table 1.

Similarly, Fig. 3 shows the spectral and BER characteristics of a 32-channel proposed DWDM system using GS doped EDFA with R-FBG. Spectral characteristic of existing method shows that there is a presence of more system nonlinearities with sidelobes indicates this existing system's complexity. This problem can be overcome by demonstrating the proposed method, which provides high gain, low cross talk with good eye opening.

Table 1. Comparison of observed values for existing and proposed DWDM system for 16-Channel

Performance Determining Factors	**Existing DWDM with EDFA**	**Proposed DWDM system**
Gain	9.126039	30.50951
Output signal	5.978829831	27.17169
Max. Q Factor	2.64909	18.9268
Min. BER	0.003076	2.78E-80
Eye Height	-0.00084	0.914936

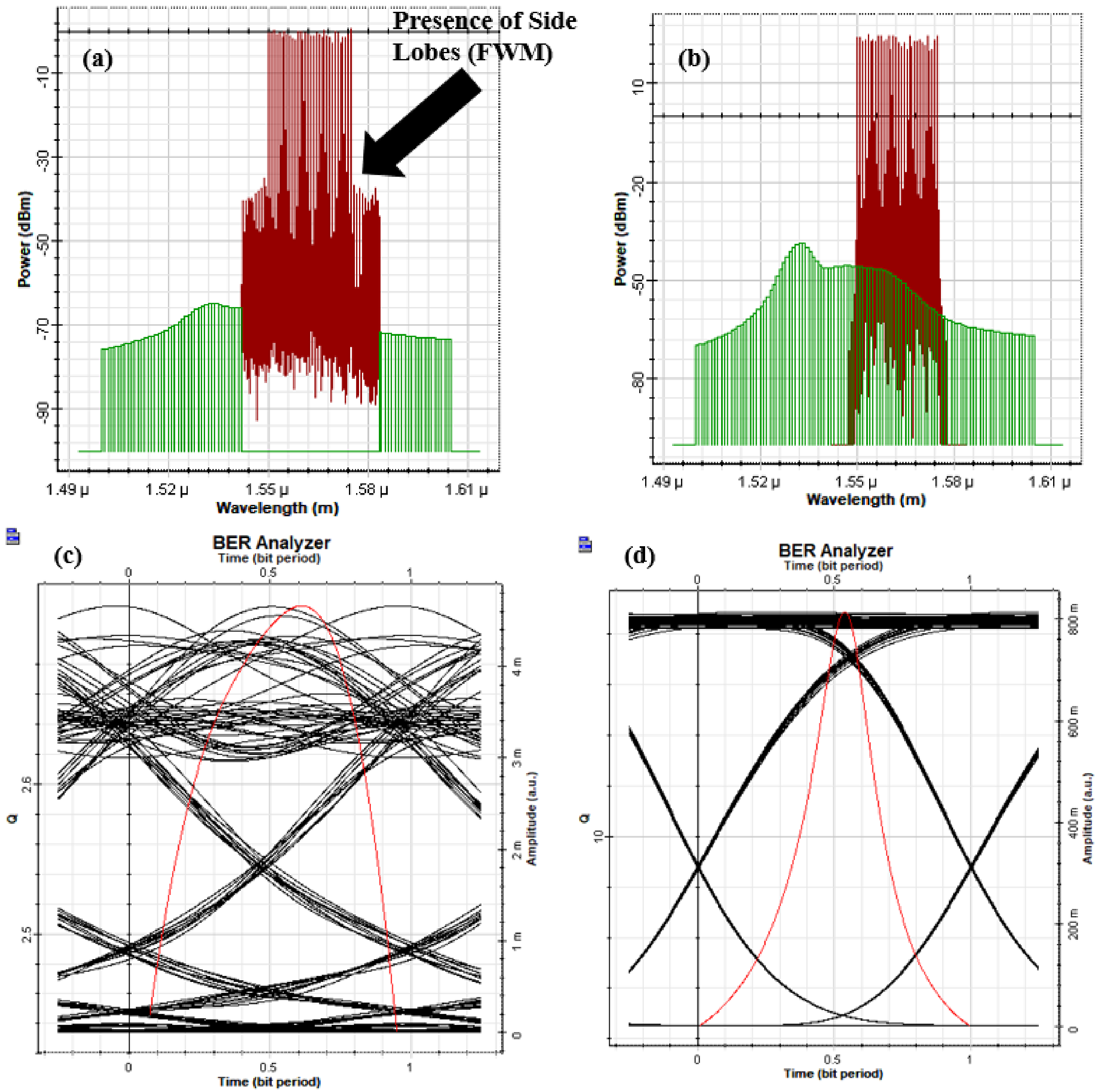

Fig. 3. 32-channel spectrum analyzer output for existing (a) and the proposed method (b) and BER analyzer output for existing (c) and proposed method (d) (color online)

The performance characteristics of the proposed 32-channel DWDM system is presented in Table 2. The existing method shows that increasing the number of channels will affect the system gain and output signal power. Other factors such as Q-factor and BER have attained low value and confirm the Presence of system nonlinearities and higher sidelobes. In the proposed DWDM system, new host material such as germanosilicate doped EDFA (GS-EDFA) is cascaded with R-FBG and performs with lower constraints with higher number of DWDM channels thereby achieving higher equalized gain. The proposed method's performance is evaluated by calculating high gain, output signal, high-quality factor, and BER from iterative simulations.

The output spectrum characteristic of the proposed DWDM system with GS doped EDFA for 64-channel is shown in Fig. 4 (b). Gain and output signal power of the proposed system is obtained as 32.87839 and 29.61403. Simulation results show that the proposed system design is less affected by fiber nonlinearities and system crosstalk. The maximum channel with a high data rate in GS doped EDFA introduces more Amplified Spontaneous Emission noise (ASE). This results slightly reduced BER and Q-factor compared to the proposed 32-channel simulation setup, as discussed in Table 2. The performance determining factors of the proposed DWDM system is enlisted in Table 3. From Table 3, it is concluded that the proposed DWDM system performs much better and it is validated by the results obtained from iterative simulations for 64-channel DWDM system.

Table 2. Comparison of observed values for existing and proposed DWDM system for 32-Channel

Performance Determining Factors	**Existing DWDM with EDFA**	**Proposed DWDM system**
Gain	5.30306	29.00315
Output signal	1.965147	25.37901
Max. Q Factor	2.71915	18.8608
Min. BER	0.002568	1.07E-79
Eye Height	-0.00031	0.647297

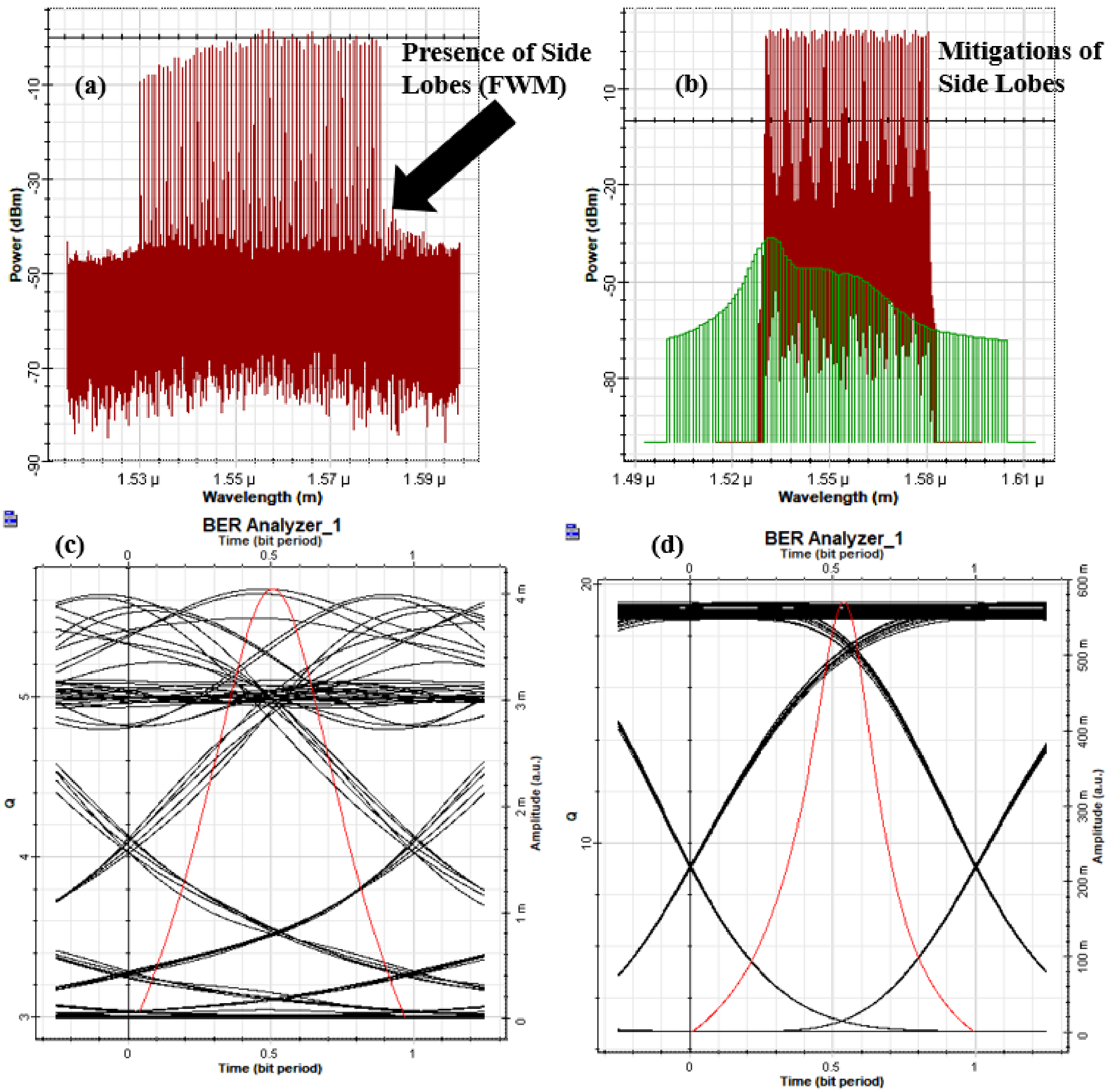

Fig. 4. 64-channel spectrum analyzer output for existing (a) and the proposed method (b) and BER analyzer output for existing (c) and proposed method (d) (color online)

Table 3. Comparison of observed values for Existing and proposed DWDM system for 64-Channel

Performance Determining Factors	Existing DWDM with EDFA	Proposed DWDM system
Gain	3.923131	32.87839
Output signal	0.732977	29.61403
Max. Q Factor	5.67056	13.1308
Min. BER	6.62E-09	9.26E-40
Eye Height	0.001414	1.44831

5. Performance analysis of gain and noise figure

Gain and noise figures are the critical parameters, which determine the efficiency of an amplifier. Factors such as pump power, input signal power, variable length of GS-EDFA, doping concentration and effective core radius of Germanosilicate doped Er^{3+} ions will influence the gain and noise figure of GS- EDFA. DWDM system with low amplifier noise configuration is considered an effective system design. This simulation is performed under the forward pump configuration of GS-EDFA with 980 nm and 1480 nm pump laser frequency. In general, an amplifier with forwarding pump configuration provides gain and low noise figure configuration. For GS doped EDFA, the higher gain is achieved by pumping Er^{3+} ion under 980 nm and 1480 nm pump configuration. Noise figure is the prime factor that degrades the DWDM system's performance under the influence of FWM. The proposed DWDM system is analyzed with FWM mitigating factors such as channel spacing, input power, data rate, length of GS-EDFA. In this section, the proposed DWDM system is analyzed with gain and noise figure of different modulation formats with 980 nm and 1480 nm pumps under the influence of channel spacing is discussed. From the results, it is observed that RZ modulation format at 980 nm pump performs better compared to other modulation formats with different pump frequencies. This shows that RZ modulation format has a low impact over inter-symbol interference (ISI). High Q-factor and Min.BER characteristics for this configuration has been discussed in Fig. 5. Along with channel bandwidth, DWDM channel capacity is improved by increasing more number of channels. Possibility of this existence is only by developing DWDM system with low channel spacing at Max Q-factor and Achievable Min BER. Simulation results are proved that the proposed DWDM system with R-FBG and GS-EDFA achieves high gain, max Q- factor, low noise power, Min BER and low average noise power.

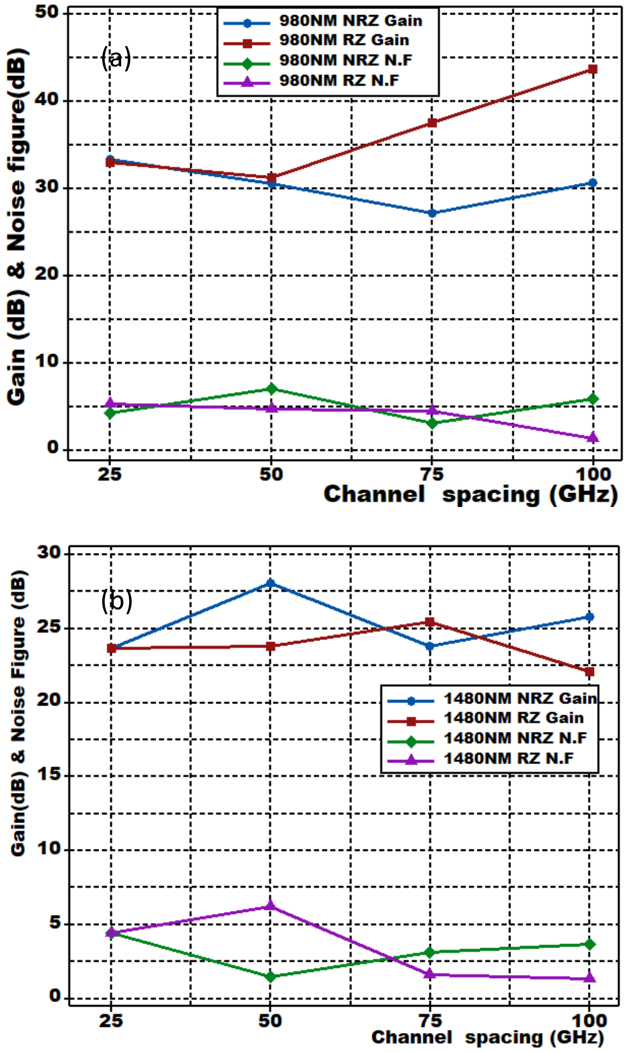

Fig. 5. Gain and Noise figure variation vs channel spacing (a) 980 nm (NRZ&RZ) and (b) 1480 nm (NRZ&RZ) (color online)

Fig. 6 analyzes the gain and noise figure for the variable data rate at NRZ and RZ modulation format with different pump configurations. To meet real world demands, it is necessary to develop a DWDM system with the higher data rate, optimum gain and low noise figure. At pump 980 nm, RZ modulation format provides 28.33969 as better gain at 10 Gbps and achieves a very low average noise figure < 5dB. Furthermore, at 980 nm RZ modulation format achieves Max Q- factor, low BER, low distortion and less affected by fiber nonlinearities such as FWM. Low nonlinearities (FWM) and high data rate transmission will determine the channel capacity of the DWDM system. By analyzing simulation results, it is concluded that RZ modulation format with a 980 nm pump is more suitable for performing high channel capacity of a DWDM system with a high data rate.

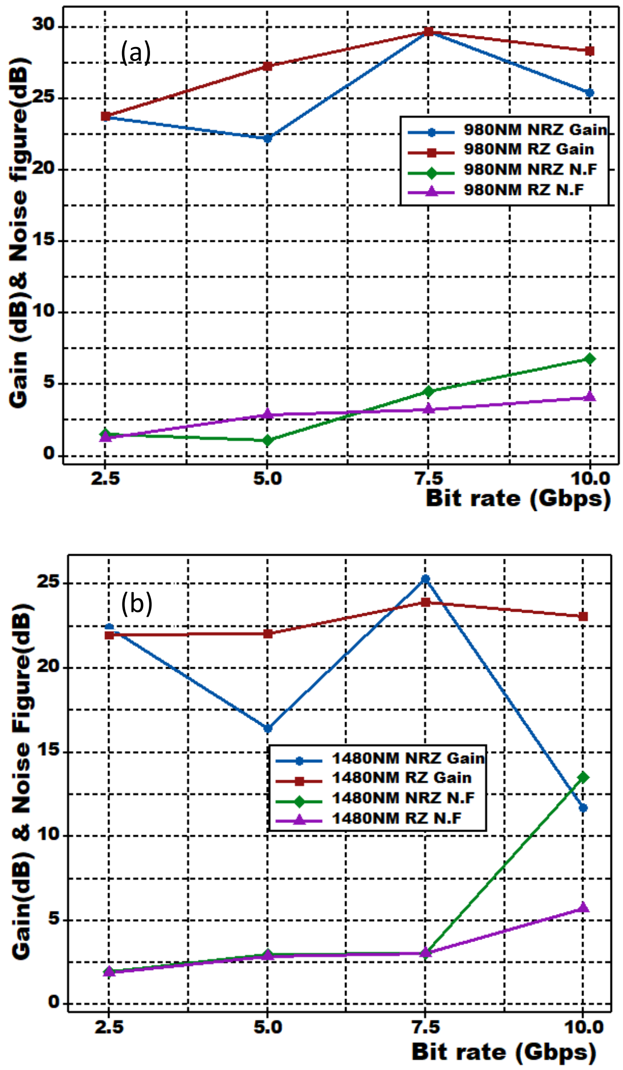

Fig. 6. Gain and Noise figure variation vs Bit rate (a) 980 nm (NRZ&RZ) and (b) 1480 nm (NRZ&RZ) (color online)

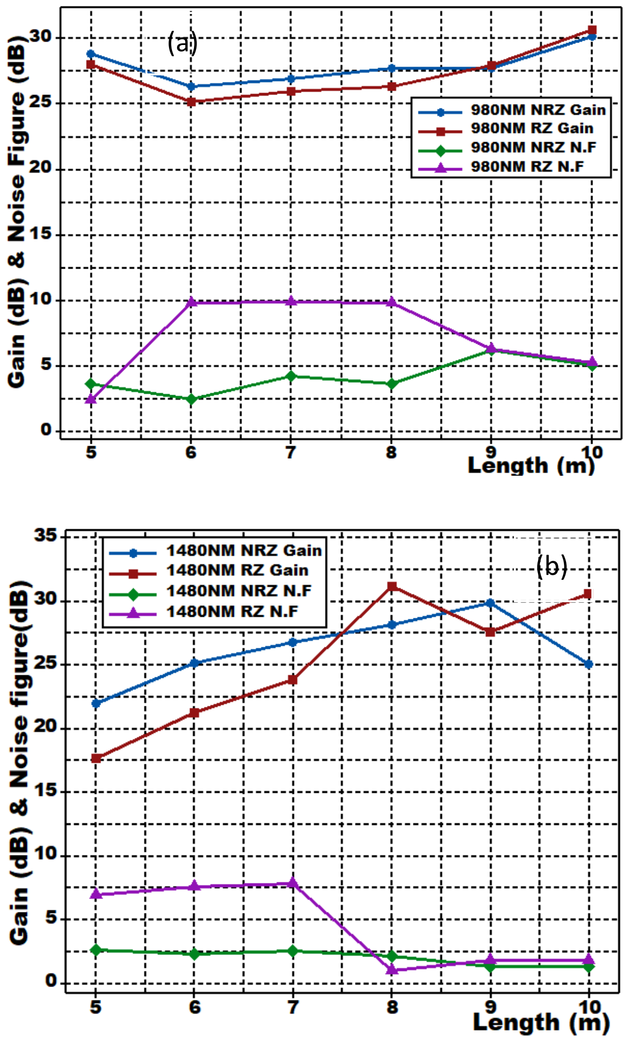

Fig. 7. Gain and Noise figure variations vs length (a) 980 nm (NRZ&RZ) and (b) 1480 nm (NRZ&RZ) (color online)

The proposed DWDM system with a variable length of GS-EDFA are analyzed in Fig. 7, to perform the gain and noise figure characteristics of NRZ and RZ modulation format with a pump frequency of 980 nm and 1480 nm. Increasing length of GS-EDFA accumulates with more amplified spontaneous emission (ASE) noise and inter channel cross talk. This introduces more system nonlinearities and degrades its performance. The quality of transmission is improved by selecting the optimum length of the fiber amplifier. From this result, it is observed that both configurations show appreciable gain at 10 m length. At 980 nm pump, the proposed DWDM system with RZ modulation format provides a very low averaged noise figure. The proposed DWDM iterative simulations are shown better results for FWM mitigating factors such as output noise power of -23.0129, OSNR as 42.34681, and high Q-factor of 60.9263. From these observations, it is concluded that FWM has very low influence in the DWDM fiber optic system with R-FBG and GS-EDFA at 10 m optimal length and shows appreciable gain with low averaged noise figure.

Gain and noise figure performance highly depend on transmission input power, amplifier’s length, and pump power. From the above discussion, 10 m length is considered as an optimum length. In this section, input power varies from -10 dBm to 10 dBm to understand its influence over FWM. In direct modulation format, increasing input power will change the material's refractive index and introduces a more chirping effect. Further increase in input power will lead to more nonlinear effects that degrade the system performance. It is evaluated by changes in the high Q factor and eye diagram characteristics. Fig. 8 shows that NRZ and RZ modulation format show similar performance in both pump configurations with slight gain variations. This can be justified by achieving appreciable gain with low noise figure and their corresponding low noise power, OSNR and high Q- factor discussed in Fig. 12. Specifically, at -10 dBm as low input power, RZ modulation format with 980 nm pump frequency shows a higher gain value of 32.26103 and 1.718185 as an average noise figure. The proposed DWDM system shows that RZ modulation format has Min BER with -10 dBm as optimum input power and insensitive to FWM and other dispersion effects.

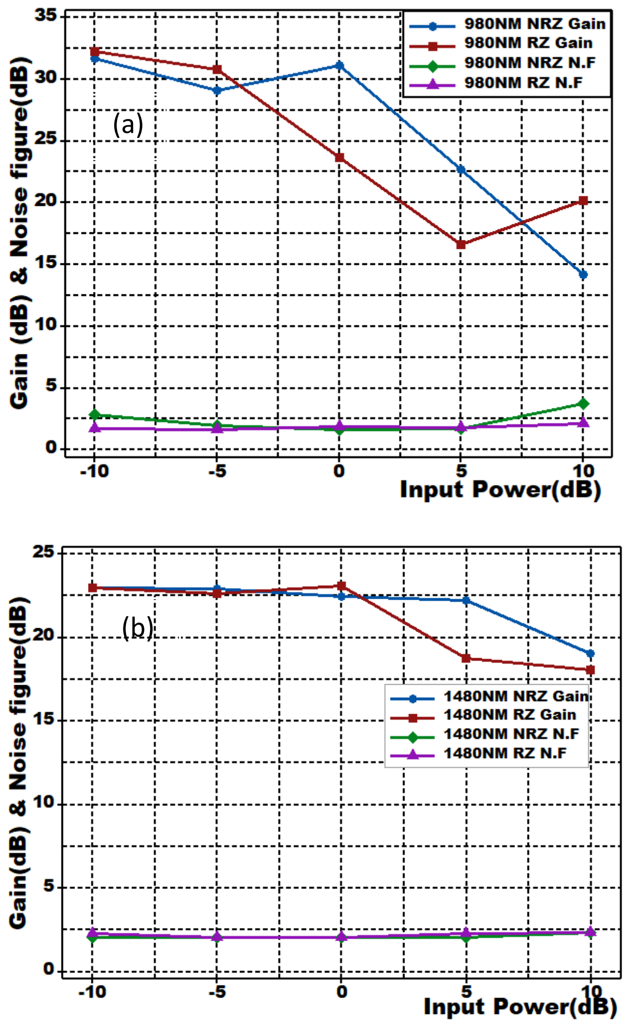

Fig. 8. Gain and Noise figure variation vs input power (a) 980 nm (NRZ&RZ) and (b) 1480 nm (NRZ&RZ) (color online)

6. Performance analysis of FWM influencing parameters

6.1. Channel spacing

For DWDM systems, channel spacing is an important parameter to mitigate FWM. The wavelength difference between adjacent channels in the DWDM system is channel spacing. In this setup, channel spacing varies from ultra-small range (25 GHz) to regular spacing of 100 GHz and the FWM mitigating factors are analyzed. At 980 nm, pump RZ modulation format performs much better than other modulation formats and these results are evaluated in terms of Max Q- factor and gain characteristics in Fig. 9 and Fig. 5. Small channel spacing of 50 GHz in RZ modulation format achieves the Max Q factor of 44.1186. Other factors, such as output noise power, OSNR are relatively influenced by FWM based on channel spacing parameters. At 1480 nm ultra-channel, spacing 25 GHz achieves Min BER of 6.22e-10 that lies in the regular ITU-grid specified BER values of 10^{-9}. Since 1480 nm, pump laser frequency consumes more input transmission power to pump Er^{3+} ions and introduce more noises. Ultra-small channel spacing DWDM can accommodate a maximum number of channels with a higher data rate, which costs increasing more noise power that affects OSNR characteristics and leads to increases FWM that degrades the performance of the DWDM system.

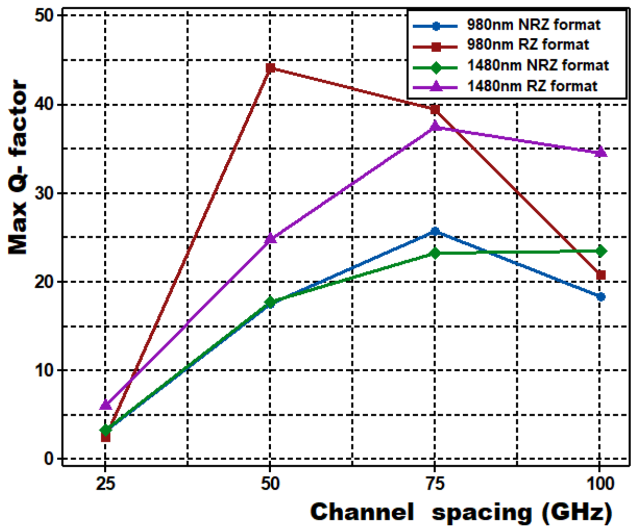

Fig. 9. Variations in Max Q- factor, against channel spacing (color online)

6.2. Bit rate

Fig. 10 shows the influence of varying bit rate from 2.5 Gbps to 10 Gbps, in a proposed GS-EDFA based DWDM using R-FBG. Increasing bit rate introduces more BER and creates high dispersion in DWDM system. Nonlinearity factors such as noise power and OSNR are enhanced due to dispersion in DWDM system, resulting in decreased Q-factor. To meet real world requirements such as high system capacity and maximum bandwidth utilization, it is necessary to design DWDM system with high data rate with low channel spacing. RZ modulation format with 980 nm and 1480 nm achieves an almost identical Max Q- factor and Min BER with low variations. Since the 1480 nm pump consumes more input transmission power and involves more noise and high influences over FWM. It is evident by the fig 10, which provides high output noise power, low OSNR. From Fig. 10, it is observed that both 980 nm and 1480 nm pump configuration, provides similar influence over OSNR and FWM. Whereas Q-factor decreases by increasing data rate, this is because of 1480 nm pump introduces more stimulated emission noises and influences more BER. From simulation results, it is inferred that RZ modulation format at 10 Gbps bit rate, both 980 nm and 1480 nm pump configuration provides a small deviation over OSNR, noise power that influencing FWM and achieves low Q-factor. Fig. 10 show that a higher bit rate with a 1480 nm pump introduces more noise in the proposed DWDM system. Hence, it reduces Q-factor and a further decrease in eye-height with more pulse broadening than 980 nm pump.

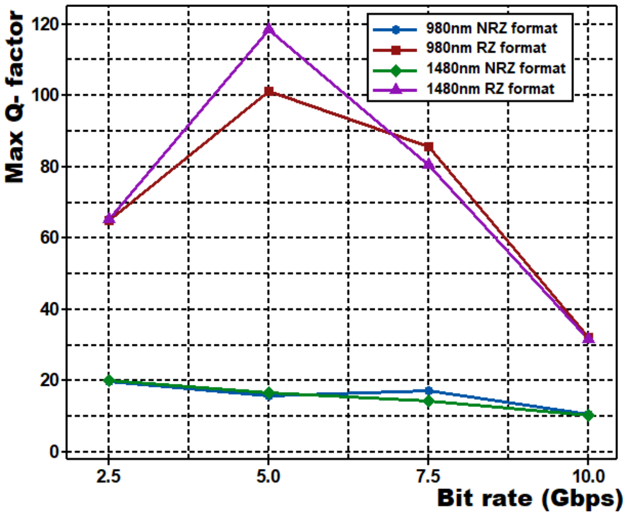

Fig. 10. Variation in Max Q- factor, against Bit rate (color online)

6.3. Input power

Input power is the most important parameter that influences FWM in this proposed GS-EDFA based DWDM using R-FBG for Long haul optical transmission. For mitigating FWM, it is necessary to find the optimized input power for the proposed DWDM system.

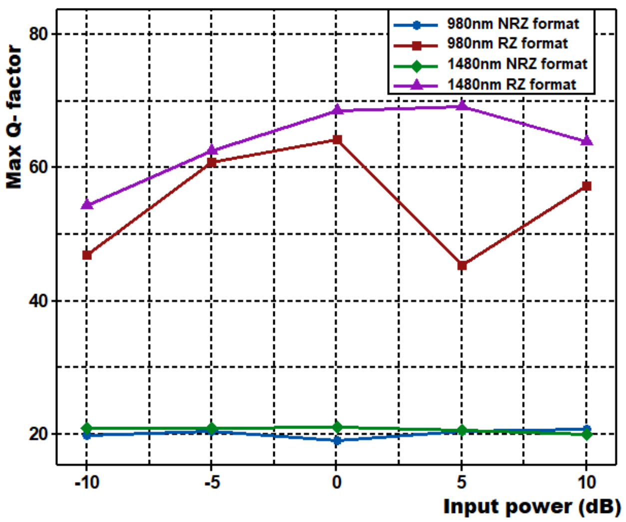

Fig. 11. Variation in (a) Max Q- factor, (b) Output noise and (b) OSNR against Input power (color online)

In general, lowering input power will decrease FWM issues. However, it is a trade-off factor to choose the optimized input power to differentiate NRZ and RZ modulation format performance under 980 nm and 1480 nm pump frequency. For both 980 nm and 1480 nm pump configuration, RZ modulation format at 0 dBm input power presents better performance and achieves Max Q-factor of 64.1824 and 68.5722 respectively. At -10 dBm input power, RZ modulation format provides low noise power and OSNR and it fails to achieve High Q-factor. However, this result shows that the high channel DWDM system requires optimum input power to reach Max Q-factor. From Fig. 11 it is inferred that other factors such as noise power and OSNR for RZ modulation format and its influence over FWM are also lower than the NRZ modulation format. This proves that RZ modulation format has less affected by crosstalk and it has very low distortion. Graphical observations from Fig. 12 conclude that RZ modulation has low fiber nonlinearity (FWM) than NRZ modulation format.

6.4. Pump power

In this section, we discuss the comparison of 980 nm and 1480 nm pump frequency for GS-EDFA-based DWDM system using R-FBG for NRZ and RZ modulation format. Varying pump power from 100 mw to 500 mw for both pump configurations and results is analyzed for Output noise, OSNR, Max Q- factor and Min BER that influence FWM. In both configurations, RZ modulation techniques perform better and it is evident by observing simulation results and followed by graphical represents in Fig. 12.

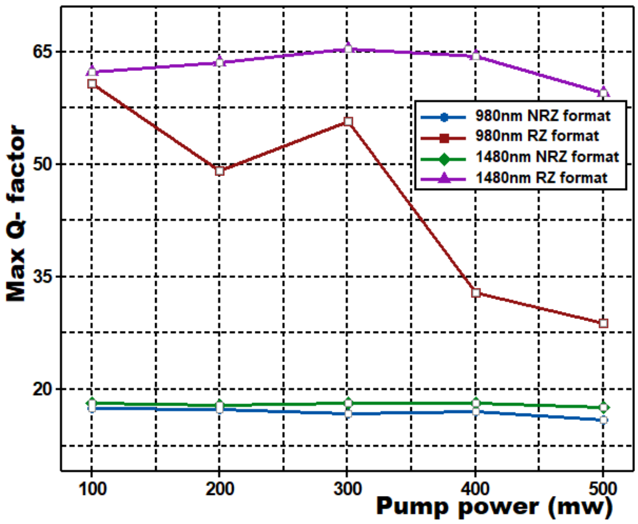

Fig. 12. Variation in Max Q- factor, against Pump power (color online)

It is observed from iterative simulation results that Max Q- factor and Min BER for both pumps at RZ modulation format show better results. This indicates that the influence of FWM is very low in RZ modulation format. Other factors, such as output noise power and OSNR, have also validated this fact by providing better results. From Fig. 13 it is observed that 980 nm pump with RZ modulation format for 100 mw pump power shows Max Q-factor of 60.7761, whereas NRZ modulation has

Max Q- factor of 17.437 with 1.67e-68. High quantum efficiency conversion over 1480 nm achieves Max Q-factor for RZ modulation format with different pump configurations. Meanwhile, for the same 1480 nm pump, the FWM influencing factor such as noise power and OSNR is also high and proves that more noise occurs and consumes high input transmission power.

6.5. Core size

Core size of an optical fiber mitigates FWM in a way such that an increase in core size proportionally reduces Inter Symbol Interferences (ISI) and cross talk and results low FWM. In this proposed DWDM system, optical fiber core radius varies from 80 um to 160 um and simulation results are enlisted for 980 nm and 1480 nm pump configuration. From Fig. 13, it is observed that at 120 um core size, RZ modulation with 980 nm pump has high influence over noise power, OSNR and achieves the value of -24.242 and 35.75285 respectively. At high pump frequency 1480 nm, it provides Max Q- factor of 66.259 for core size 100 um. As a result, that 1480 nm pump is conciliated with more stimulated emission noise, high noise power and low OSNR that influences more FWM than 980 nm pump configuration. Q-factor value for NRZ modulation techniques in both configurations is very low, which shows that for this proposed method, the NRZ modulation format is not suitable for high data rate transmission over long haul DWDM link.

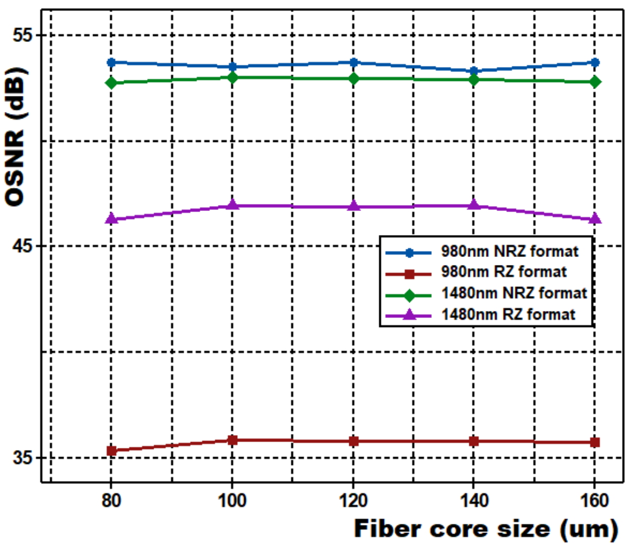

Fig. 13. Variation in OSNR against Fiber core size (color online)

The Practical implementation of this research work has been widely deployed in optical communication. Intrinsic approaches lead to the gain saturation of the GS-EDFA, which can be achieved using optical pump power and wavelength that suppresses FWM issues. Furthermore, extrinsic approaches (R-FBG) can act as an effective filtering and channel selection for an optimal DWDM system, which filters the sidelobes present in the existing approaches. However, the practical implementation of GS-EDFAs and R-FBGs to address FWM nonlinearity and sidelobes in DWDM systems is not only feasible but also opens up a broad future scope for optimizing and enhancing optical communication networks. These methods are well established and can be integrated into existing and evolving optical network infrastructure.

7. Conclusion

This work highlights the influence of FWM in DWDM system design using R-FBG and GS-EDFA for higher data rate over long-distance transmission. Experiments are performed to investigate the influence of input transmission power, impact of GS-EDFA length over gain and noise figure characteristics, and effects of various pump power using different modulation format with 980 nm and 1480 nm pump configurations. The proposed DWDM system's performance with R-FBG and GS-EDFA is studied by analyzing FWM Mitigating factors such as output signal power, noise power, OSNR, equalized gain, high Q-factor and Min BER. The presence of FWM nonlinearity and excessive sidelobes in DWDM system is extinguished by intrinsic (GS-EDFA) and extrinsic (R-FBG) methods to achieve high-equalized gain and low noise figure over 1530 nm-1580 nm bandwidth. RZ modulation format with a 980 nm forward pump shows better performance and suitable for higher data rate transmission over the long haul DWDM system. This research provides low channel spacing (25 GHZ), high data rate (10 Gbps per channel) with optimum input power (-10 dBm) based 64-channel DWDM system to achieve high channel capacity and wider bandwidth utilization. Furthermore, this paper also discussed parametric optimization for metrics such as channel spacing, core size of an optical fiber, data rate, pump power and variable length of GS-EDFA to mitigate FWM. The future scope of this research work extends into the deployment of new host materials for erbium Er^{3+} ion and developing different combinations of hybrid amplifiers to meet user's requirements.

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