

Green channel DWDM design using optimized CFBG

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In this paper, performance analysis of 64-channel DWDM is investigated using EDFA and an optimized reflectivity of the cascaded fiber Bragg grating (CFBG) to minimize the presence of more side lobes. The progress of 5G technologies in the telecommunication industry leads to more end-users and higher data traffic, which increases data rate consumption. This introduces more fiber nonlinearities, consumption of high input power, and introducing more sidelobes, thereby degrading DWDM system performance. This research benefit shows that the EDFA and FBG with optimized reflectivity achieve high gain and reduce side lobes. The performance of the proposed experiment can be assessed by computing the quality factor (Q-factor), Bit Error Rate (BER), and output signal-to-noise ratio (OSNR) of a DWDM system embedded with EDFA and CFBG system. The proposed DWDM system is analyzed from comprehensive simulations to achieve high-quality data transmission with low power consumption for long distances. The spectral analysis shows that the absence of side lobes indicates the reduction of four-wave mixing and enhances the system performance. The proposed system performance parameters are investigated and achieved enhanced performance with a better Q-factor of 21.1099, BER of 3.28 E-98, high gain of 37.74 dB, and achieves proper spectral eye-opening.

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1. Introduction

Fiber optic dense wavelength division multiplexing (DWDM) system stands unique and is used widely in today's world for high-speed internet service. Communication through optical cables is a promising technology that enhances the optical communication network's capacity, verifies the increasing growing demands for communication bandwidth and data rate, and extends to long-distance communications [1]. The complexity is high due to the long-distance data travel. It involves transferring a large amount of data over a long distance using a thin fiber medium. Throughout this process, the system experiences various issues and losses. Issues are caused when the optical power goes high, transmission length increases, data rates, a large number of wavelengths [2]. These issues are broadly classified under two categories as linear and non-linear effects. Linear effects are caused due to the dispersion of light inside the fiber, whereas non-linear effects are broadly classified into two major categories. These linearity effects are refractive index-related and scattering-related. Under the former category, the effects produced are four-wave mixing (FWM), self and cross-phase modulation (S&XPM), under scattering-related effects, Stimulated Brillouin & Raman scattering (SB&RS) effects are produced. DWDM can simultaneously transmit multiple information channels over the existing fiber [3].

In Optical data transmission, EDFA amplifiers are needed to increase the transmission capacity of the dense wavelength division multiplexing (DWDM) systems [4]

and achieve the same level amplification of all the system channels. EDFA types of amplifiers are widely used for long distances, and their properties can be varied extrinsically and intrinsically. The advantages of these doped amplifiers are high gain, larger bandwidth, and low noise [5]. Unfortunately, when these fibers are used over long-distance communication, the gain from each channel varies much, and they are not equal throughout the bandwidth [6]. This will reduce the performance of the optical communication system. For efficient modeling in a DWDM system, the need for the flat gain of all the channels was a prerequisite [7]. This can be achieved by changing specific properties of the EDFA. The changes to be made on the fiber amplifiers can be broadly classified into extrinsic and intrinsic modifications [8]. Intrinsic modification moreover deals with the erbium ions' spectral properties; hence, different host materials are used to change the spectral properties. This method, however, limits its boundaries only for small bandwidths. In contrast, extrinsic methods serve wider bandwidths. This method of changing the EDFA property was attained by using a fiber Bragg grating (FBG) [9].

FBG has low insertion loss, and hence it is commonly used to compensate for the dispersion and mitigate FWM in optical communication systems [10]. In an optical bath, DCFs are widely used to lower the overall dispersion. DCFs have a higher negative dispersion coefficient and can be connected to single mode fibers (SMFs) whose dispersion coefficient is positive [11], compensating for the negative dispersion for longer fiber optic cables. Based on the utilization of DCF positions in DWDM

system design, the compensation techniques are called symmetric, pre and post-compensation. [12]. In a long haul system, FBG acts as a dispersion compensator, and it performs filtering and reflecting the signal with low loss and achieves higher efficiency. FBG can be classified into uniform and non-uniform FBG [13]. Uniform FBG has a constant refractive index along with the length of the FBG. CFBG is used to perform chromatic dispersion compensation, which depends on the non-uniform refractive index variation. In chirp grating, all the light pulse wavelengths are simultaneously exited from the reflector, which equalizes the accumulations of chromatic dispersion in an optical pulse [14]. However, In Bragg conditions, grating reflected Bragg's wavelength with twice the amount of grating period Λ and multiplied by refractive index n_{eff} [15].

From Literature, it is noticed that the presence of FWM and sidelobes consumes huge transmission power and reduces the DWDM system performance. Furthermore, it also reduces the quality of the received signal, introduces unwanted noise signals with destructive frequencies, and increases performance latency. These problems result in the optical DWDM system failing to meet futuristic technologies' growing demands. This paper reports the DWDM system with EDFA and modified reflectivity-based CFBGs connected in series. CFBGs are responsible for reducing side lobes, and EDFA performs to achieve high gain in the proposed DWDM network. The reported DWDM configuration has achieved simple fabrications of the short period FBGs. Furthermore, it does not limit the number of WDM channels required to be equalized. The DWDM channels are equalized over a wider band wavelength. In CFBGs, the Bragg wavelength can be tuned using the sidelobes' temperature, strain, or noise intensity. Finally, the proposed DWDM system architecture is evaluated by calculating OSNR, Min.BER, gain, noise figure, and High Q-factor using OptiSystem 14. This paper is organized as follows: Section 2, explains the theoretical concepts of Fiber Bragg grating, Section 3 explains about DWDM simulation setup with EDFA structure implemented in this discussion, Section 4 summarizes the observations arrived based on simulation results, and Section 5 concludes the discussion with future scope.

2. Theoretical study of FBG

In this analysis, uniform FBG maintains the same reflectivity range throughout the Fiber Bragg Grating. The reflectivity of the FBG plays a significant role in attaining flat gain and in the reduction of side lobes [16]. The side lobes are the proof for the existence of four-wave mixing in the system. Four-wave mixing is one of the non-linear parameters which reduces the efficiency of the system. Uniform FBG is used to attain the output gain structure. The fabrication of FBG is done using the increase in temperature and introducing strain over the fiber [17]. FBG is an optical filter. It allows only specific wavelengths of light; the remaining are reflected, which in

turn gets nullified. The FBG filter is constructed by performing periodic perturbations on the core refractive index of the fiber. These perturbations are created by subjecting the fiber surface to the high intensity of UV light [18].

The refractive index $n(z)$ of a CFBG fabricated within a fiber optic cable of n_0 core refractive index can be discussed as

$$n(z) = n_0 + \Delta n(z) \cos\left(\frac{2\pi}{\Lambda} z\right) \quad (1)$$

where $\Delta n(z)$ denotes the amplitude of refractive index perturbation and Λ represents the grating period.

The reflectivity and transitivity of the FBG play an important role in reflecting the light waves. The FBG optical filter reflects the amount of light incident at the core surface is reflected back or sent back without being transmitted at the other end of the fiber. The reflected wavelength of light gets nullified within the core region. The Bragg reflectivity can be varied from its original value to zero [19]. Change in infinitesimal values of the reflectivity gives way to tremendous change for the channel gain of the DWDM channel.

The mathematical equation for reflectivity is obtained from coupled-mode theory.

$$\text{Reflectivity} = R(L_{\text{FBG}}, \alpha) \quad (2)$$

where L_{FBG} represents the length of the FBG filter and α the period of the grating.

$$R(L_{\text{FBG}}, \alpha) = \frac{p^2 \sinh^2(SL_{\text{FBG}})}{S^2 \cosh^2(SL_{\text{FBG}}) + \delta^2 \sinh^2(SL_{\text{FBG}})} \quad (3)$$

where $\delta = (n_{\text{eff}} w/c - \pi/\Lambda)$ represents detuning the Bragg wavelength, n_{eff} the effective grating index, p is the absolute value of coupling coefficient, and $S^2 = p^2 - \delta^2$.

The Coupling coefficient value of the simulated fiber axis perturbed index variation is given as

$$P(z) = \frac{\eta \Pi \Delta n(z)}{\lambda_B} \quad (4)$$

where η = fraction of fiber mode power inside the core. The reflectivity value of FBG reduces the spacing between the channels of the system.

Transmissivity of the FBG is the degree to which the FBG allows light throughout.

From couple-mode theory,

$$\text{Transmissivity} = T(L_{\text{FBG}}, \lambda) \quad (5)$$

$$T(L_{\text{FBG}}, \lambda) = 1 - R(L_{\text{FBG}}, \lambda) \quad (6)$$

where L_{FBG} the length of FBG and λ is the wavelength. This research work is carried out using an EDFA with an optimized reflectivity of FBG, as its fabrication process is simple compared to chirped and non-uniform FBGs. The proposed DWDM system operates over a wider bandwidth (as user's requirements) with more DWDM channels.

3. Simulation setup

A long-reach DWDM network is proposed and simulated by using Optisystem14 software. The diagram in Fig. 1 reported is used for the complete simulation. The long-haul optical DWDM system is modeled for 16, 32, and 64-channels spaced at 100 GHz for 10 Gb/s channel speeds using Single-Mode optical Fiber (SMOF) over 150 km transmission distance. The proposed DWDM system design is investigated by varying the input power level from -10 dBm to 10 dBm. In this work, the reported system is evaluated and compared for FWM mitigations and sidelobe reduction using EDFA embedded with optimized reflectivity of FBG. The proposed Optical DWDM system is designed with a transmitter, receiver, and propagation path. The DWDM transmitter initiates the data transmission through its optical fiber path. The DWDM receiver converts the attenuated optical signals into electrical signals and recovers the originally transmitted data.

The transmitter end has a DWDM transmitter and Multiplexer, generating optical signals with specific wavelengths maximum up to 64 channels with 100 GHz equal spacing. The channel frequency begins from 189.1 THz to 196 THz with a line width of 10 MHz. Each channel transmits at a 10 Gb/s data rate using NRZ format, whose input power is defined as -10 dBm. DWDM Multiplexer multiplexes the (64×1) optical signals passed in a zero insertion loss SMOF. During the reception, (1×64) DWDM Demultiplexer is separated the data and detects it individually. The multiplexed signals are transmitted over 300 km in the optical path. An EDFA of length 5 m is used for amplification with 980nm as external pump power, amplifying the light from the SMOF. The gain pattern of each channel will be unequal. In order to achieve a flat gain pattern, FBG is used. Uniform FBG is used in this simulation. Varying the reflectivity of the FBG results in the reduction of side lobes, and the significance of the four-wave mixing phenomenon is reduced to its minimum. The loop control mechanism is applied to increase the transmission distance that the optical signal travel. EDFA amplifies the signal from the SMF; forward pump power is used for amplification. Signal amplification results in the addition of amplified spontaneous emission (ASE) noise [20]. This leads to unequal EDFA gain. Uniform FBG is used in order to achieve this flat gain. The signal from the filter passes through another SMF fiber of 150 km at the receiver end. The 64-channels output is traveled into the loop control component in the transmission path.

The receiver end is designed with DWDM Demultiplexer (1×64), photodetectors, Bessel low pass filters, 3R Regenerators, and BER analyzers. The demultiplexer channels are operating at the pre-assigned frequencies and split into 64 single wavelengths. The demultiplexer output is passed into photodetectors that convert optical signals into electrical signals [21]. The Amplified Spontaneous Emission (ASE) and shot noise are applied to the proposed setup. The converted electrical signals are filtered by a fourth-order Bessel low pass Filter

(BLPF) and reduce the noise. The BLPF is followed by the 3R Regenerators that perform Re-shaping, Re-amplification, and Re-timing. Finally, the 3R device regenerates the electrical signal into the corresponding original bit sequence. The 3R device is directly connected to the BER analyzer, generating eye diagrams and measuring system performance. By visualizing Eye diagrams, many parameters like Q-factor and BER are computed for each received channel. In this analysis, the FBG is used as a constrained filter. Optical signals with a specific wavelength value are reflected or filtered, and the remaining spectrum is transmitted.

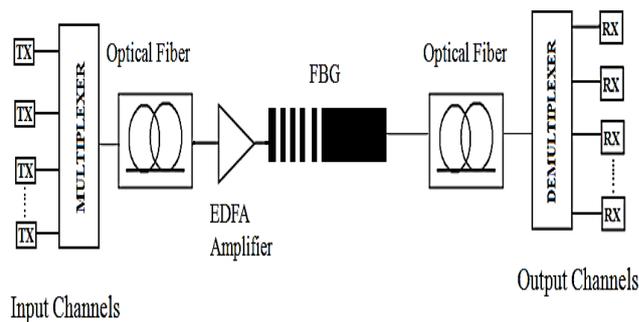


Fig. 1. Wavelength division multiplexing system with FBG

4. Results and discussion

The proposed DWDM system using EDFA is combined with R-FBG to perform data transmission over 300 km. EDFA provides high gain, low noise figure, low distortion loss, and cross-talk. In order to sense the presence of a four-wave mixing present, FBG's are introduced. In this simulation, the optimized reflectivity of CFBG embedded with EDFA reduces the FWM effect and the presence of sidelobes to its minimum, which is evident from the figures and tables below. A comparison of the gain spectrum with and without side lobes, eye-opening, Q-factor, and the bit error rate is tabulated and figured for 16, 32, and 64 channels. The Reflectivity of FBG is an essential factor, which involves side lobes reduction. Reflectivity range can be calculated from the transfer matrix method, and it is observed that 0.55 reflectivity the system provides equalized output gain spectrum without sidelobes. This can be presented in the below spectral characteristic comparison section. From Fig. 2(a) shows the existing EDFA-based DWDM system with nonlinearities such as FWM and more crosstalk. This will degrade the system performance by reducing output spectrum gain, 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 channels achieves high gain and is very good eye-

opening with a Max Q- factor of 19.3265 and Min BER of $5.49 \text{ E-}85$.

Similarly, Fig. 3 shows the spectral and BER characteristics of the 32-channel proposed DWDM system using GS doped EDFA with R-FBG. The spectral characteristic of the existing method shows that the 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, and good eye-opening. The performance characteristics of the proposed 32-channel DWDM system is presented in Table 1. 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 system nonlinearities and higher sidelobes. In the proposed DWDM system, EDFA is cascaded with optimized Reflectivity of FBG and performs low limitations over more DWDM channels achieves high-equalized gain. The proposed method's performance is evaluated by calculating high gain, output signal, high-quality factor, and BER from iterative simulations.

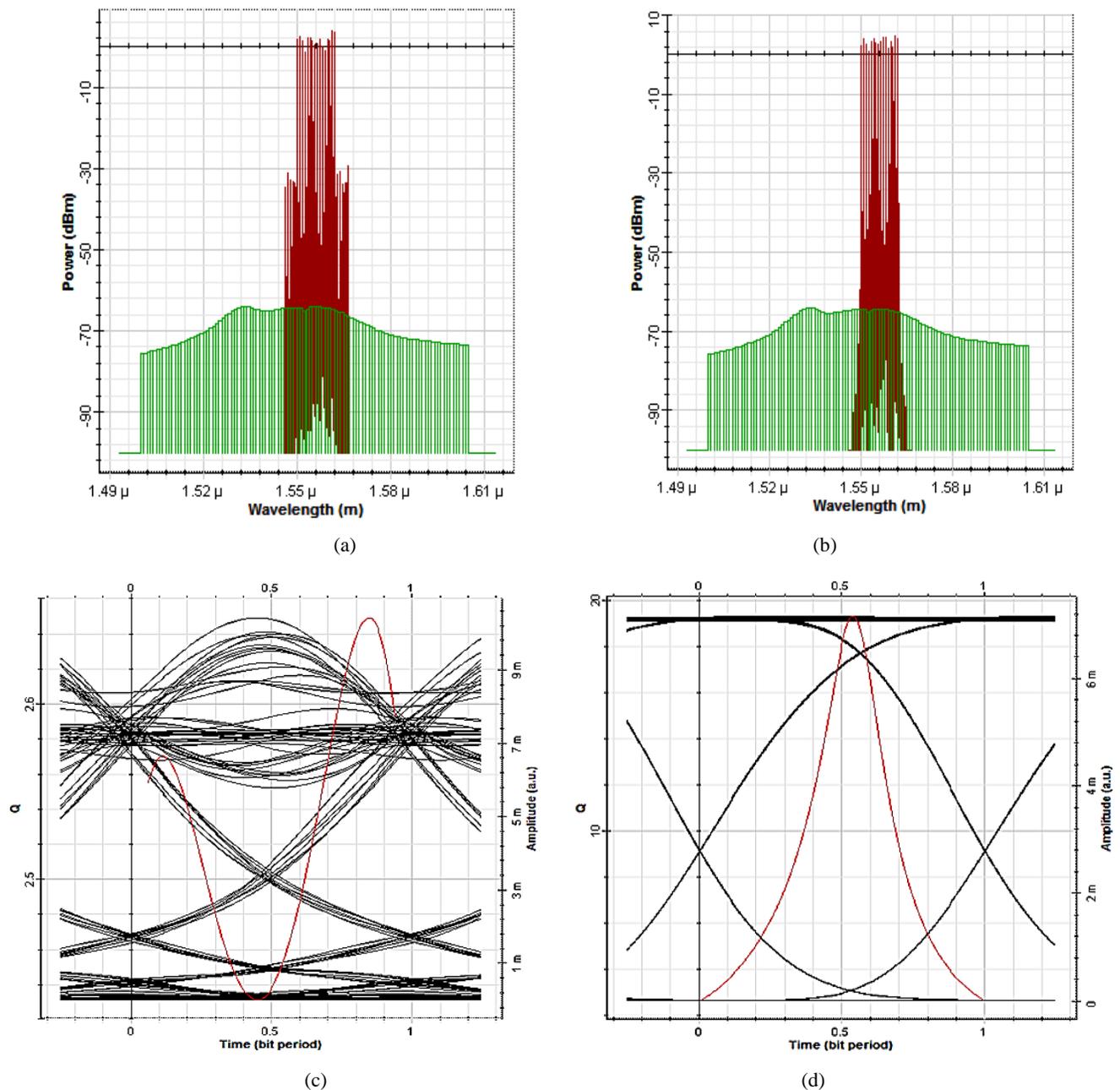


Fig. 2. The spectrum analyzer output (a) Existing and (b) the proposed method. BER analyzer output (c) Existing and (d) proposed method (color online)

The figures given are the simulated results for the setup. Fig. 2(a) and 2(b) are the outputs from a spectrum analyzer that is used to display signal strength as it varies by signal frequency and time. The wavelength and amplitude of the spectral characteristics are represented in the horizontal and vertical axis, respectively. The gain of a 16-channel DWDM system with four-wave mixing effects is evident in figure (a). The presence of side lobes in the gain spectrum indicates the presence of FWM. After varying the reflectivity of the FBG, the effects of four-wave, mixing is denigrated, and the DWDM system output of 16 channel is free from this significant non-linear effect. Fig. 2(b) shows the absence of four-wave mixing. Fig. 2(c) and 2(d), respectively, the BER analyzer outputs with and without four-wave mixing effects. The quality factor and eye-opening are good in that 2(d) and 2(c) show deficient quality and no eye formation. The corresponding numerical results are tabulated below.

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 EDFA, doping concentration, and effective core radius of Er^{3+} ions will influence the gain and noise figure [23]. DWDM system with a low amplifier noise configuration is considered an effective system design. This simulation is performed under the forward pump configuration of 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 [24]. For 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. Forward pump configuration is used to achieve a low noise figure.

Table 1. Monitoring factors comparison of existing and proposed DWDM system

Number of Channel	Monitoring Factor	Existing method	Proposed method
16-channel	Max Q Factor	2.69079	19.3265
	Min. BER	0.00354787	1.7774 E-164
	Eye Height	-0.00075346	0.00581532
32-channel	Max Q Factor	2.66234	18.3356
	Min. BER	0.0030366	3.02 E-148
	Eye Height	-0.00045882	0.00332369
64-channel	Max Q Factor	5.76859	21.1099
	Min. BER	3.7057×10^{-009}	7.811 E-196
	Eye Height	0.00143967	0.00257084

The proposed DWDM system is analyzed with a gain and noise figure of 980 nm under the influence of 100 GHz channel spacing. From these results, it is observed that the 980 nm pump performs better for the proposed method. This result is evident by analyzing the different channel configurations. This shows that the proposed method has a low impact over inter-symbol interference (ISI), achieving high gain, low noise figure, and OSNR. High Q- factor and Min.BER characteristics for these different channel configurations are already discussed in

Figs. 2, 3, and 4. Along with channel bandwidth, DWDM channel capacity is improved by increasing more number of channels. This existence is possible only by developing a 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 EDFA achieves high gain, max Q- factor, low noise power, Min BER, and low average noise power.

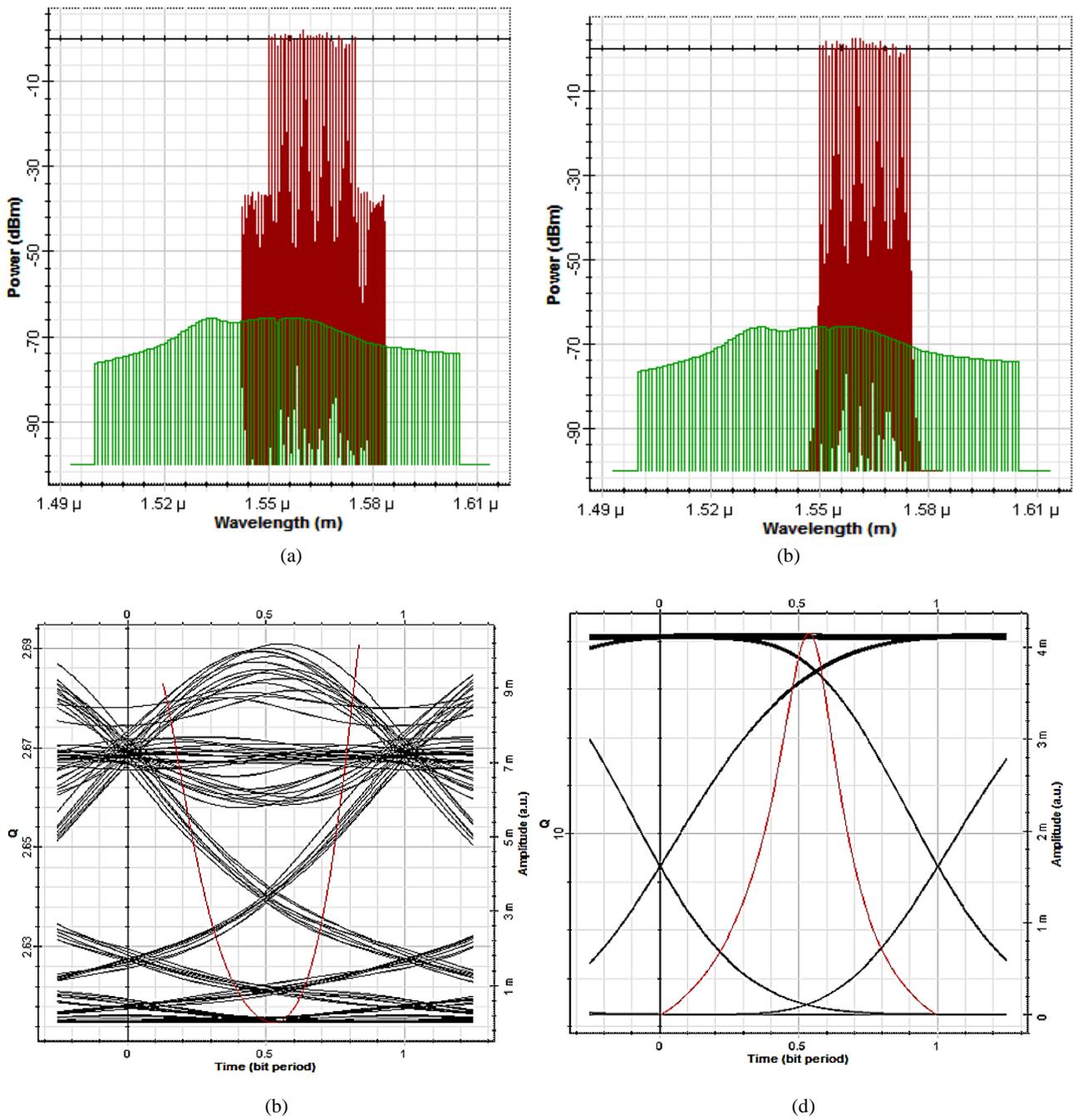


Fig. 3. The spectrum analyzer output (a) Existing and (b) the proposed method. BER analyzer output (c) Existing and (d) proposed method (color online)

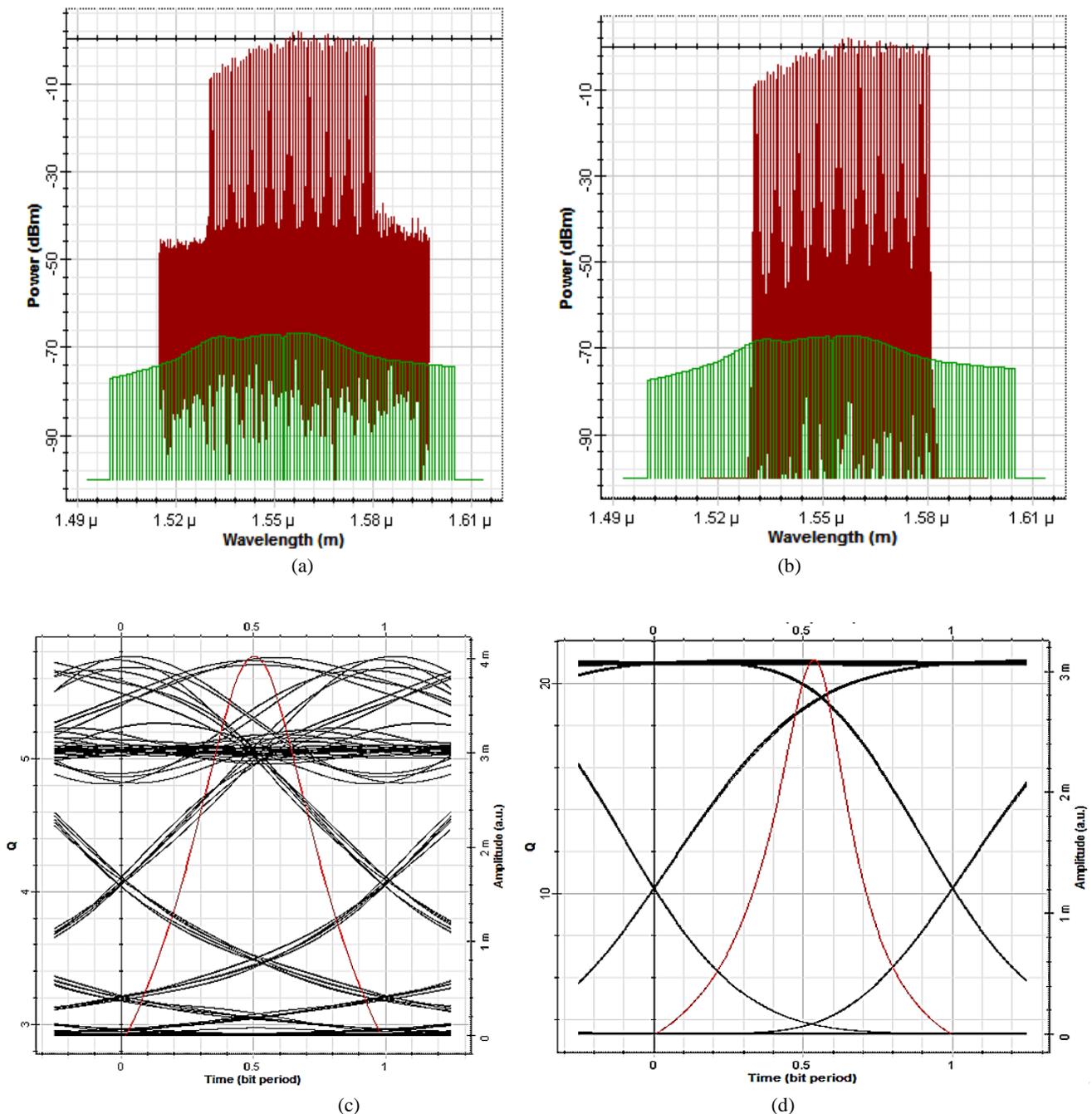


Fig. 4. The spectrum analyzer output (a) Existing and (b) the proposed method. BER analyzer output (c) Existing and (d) proposed method (color online)

From simulation results, the following key findings are observed:

- (i) The Optimized Reflectivity of FBG with SMF is achieved is an efficient technique and provides better performance for longer transmission distance in terms of higher Q-factor, Min.BER.
- (ii) From Fig (5), it is shown that the OSNR does not change for all different channel configurations at the same transmission distance.
- (iii) The performance metrics values are listed in Table 1. The system offers higher performance when using EDFA

Cascaded with optimized Reflectivity of FBG based on its larger gain and low noise figure values.

- vi) It is noted from Eye Patterns that the Eye Diagrams generated from systems utilizing FBG are more explicit and wider; this means less noise and better performance, thus best quality for the transmitted signal and most efficient system. Furthermore, it is observed that the Eye Diagrams of systems using the proposed method are achieve proper eye-opening with high Q-factor values and Min.BER above 10^{-9} , which is more suitable for the quality of data transmission.

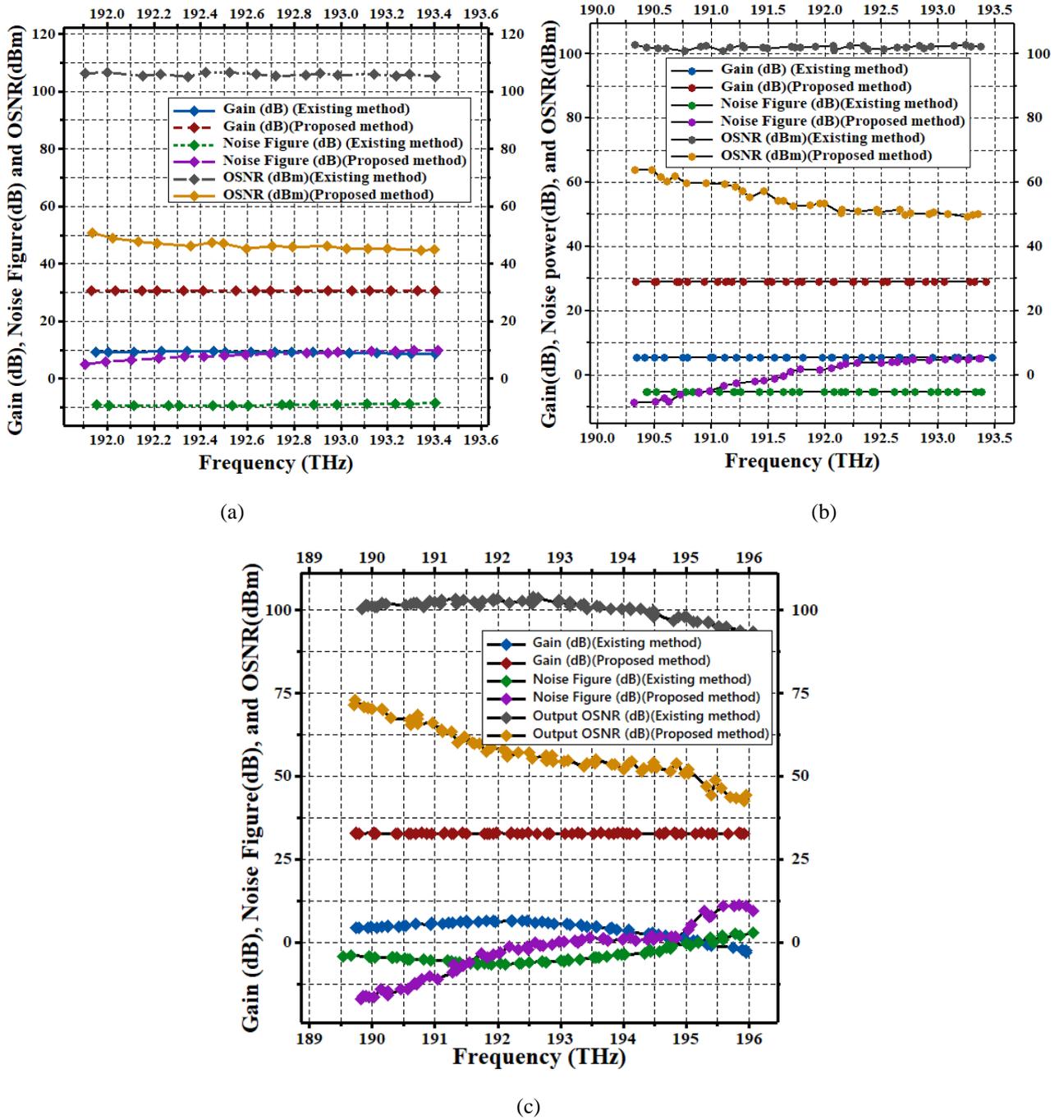


Fig. 5. Existing and Proposed method comparison of Gain, Noise Figure and OSNR for (a) 16- channel, (b) 32-channel, and (c) 64-channel configurations (color online)

5. Conclusion

To summarize, an EDFA and optimized reflectivity-based CFBG design are experimented to achieve high gain, Max Q-factor, and Min.BER using short period cascaded FBGs with optimized reflectivity values. The proposed system can equalize the gain up to a 64-channel DWDM system. Furthermore, it tunes the reflectivity of the CFBG and achieves an optimized range to effectively

reduce the presence of side lobes, thereby improving the system performance. In addition, simulations are carried out up to a 64-channel DWDM system after embedding the cascaded FBGs with EDFA. The optimal BER of 10^{-9} and low input power of -10 dBm are identified for the reported DWDM architecture. This adept response is obtained in the system using a uniform CFBG with suitable reflectivity values. The above results depict a high-quality factor for 16, 32, and 64 channel DWDM

systems. The eye-opening obtained is high, and the bit error rate has reduced immensely. FBG as a proper filter reduces the sidelobes and offers better performance, resulting in a larger Q-factor better Q-factor of 21.1099, BER of 3.28×10^{-8} high gain of 37.74 dB, and achieves proper spectral eye-opening for longer transmission distance. In the future, this research work can be extended to varying the doping concentration of the EDFA and introducing new host material to doped along with EDFA.

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