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Theoretical investigation for optimization of FWM effects for 1Tb/s ultra-band DWDM system

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This paper investigates the Four-Wave Mixing (FWM) issues in ultra-band dense wavelength division multiplexing (DWDM) system design using low input power, high optical gain, and modulation format with an optimized duty cycle. Bandwidth and high data rate are key considerations in fiber optic system design. Emerging 5G technologies, internet development demand higher bandwidth, and large data rates, leading to DWDM enhancement in fiber optic communication. This introduces more fiber nonlinear effects and limits DWDM system performance. Hence, the study of fiber nonlinearities using various design parametric analysis is necessary to improve the long-haul fiber-optic system design's data transmission capacity. In this paper, FWM nonlinear issue is studied, and factors that are accountable for deviations in WDM design are analyzed. Simulations are performed to understand system parameters such as modulation format, channel spacing, transmission power level, and optical gain over FWM. Performance of 1.28 Tbps and 2.56 Tbps systems are analyzed by observing BER, Q-factor, power products of FWM, and eye-diagram characteristics. The simulation result provides optimum results with parameters such as high optical gain, channel spacing, transmission power, and modulation format with a low duty cycle for ultra-band DWDM system.

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Keywords: DWDM, FWM, Channel spacing, Modulation format, Q-factor, Min.BER

1. Introduction

Ever-increasing internet and applications of 5G technologies require wider bandwidth and higher data rate, which leads to the development of Wavelength Division Multiplexing (WDM) in the lightwave system design [1]. Wavelength division multiplexing (WDM) provides flexible design in optical networks, transparency, scalability, dynamic provisioning and increases system transmission capacity with higher data rate used in fiber optic access and long-haul communication systems. Implementation of WDM in fiber optical system design achieves high quality of data transmission and shows better spectral efficiency, which helps to design future light path design [2]. Developments in the WDM system require more channel numbers, higher data rates, and optical input power levels, reducing channel spacing, and introducing more nonlinear issues in an optical system [3–5].

In WDM, fiber nonlinearities such as pulse dispersion, FWM, scattering effects, and Phase modulation effects are introduced, which has adverse effects and degrades the system design's performance. Fiber optic dispersion occurs at higher data that causes pulse broadening in the received signal, which introduces crosstalk [6]. Furthermore, pulse broadening leads to an increase in the bit error rate (BER) in long-distance communications. Erbium-doped fiber amplifier (EDFAs) improves the transmission distance from their extremity of its fiber loss in an optical system. Accumulation of amplified spontaneous emission (ASE) noise, Kerr nonlinearity and combined effects of group velocity dispersion leads to signal degradations in the WDM system [7]. Therefore, it is necessary to reduce the impact of pulse dispersion and other nonlinearities in WDM. Compared to any other phenomenon, FWM is a critical problem, limiting the performance of ultra-dense wavelength division multiplexing (UDWDM) systems. FWM can create several inter-channel crosstalks due to its power products, i.e. new generations of the signal frequency with its wavelength produced by FWM, which interferes with other channel wavelengths [8]. Therefore, it is necessary to investigate FWM impacts on access networks and to reduce its impacts over the long-haul WDM communication system.

Many researchers proposes various methods and algorithms for analyzing and suppressing the FWM effects in DWDM design. FWM suppression is done through utilization of different dispersion characteristics of fiber such as non-zero dispersion shifted fiber, Reverse dispersion fiber, dispersion flattened fiber and highly nonlinear ultra-flattened dispersion shifted fiber (HN-UFF) [9]. The dispersion characteristics based DWDM design is complex in terms of structure and leads to minimum utilization of bandwidth [10]. FWM suppress through single mode fiber (SMF) and results in high dispersion effects in the receiver [11]. Furthermore, dispersion compensation fiber (DCF) method reduces FWM, whereas the method introduces more link loss long haul fiber optic DWDM system [12]. The CFBG method suppresses the FWM and disadvantage of this method is the wavelength time delay [13]. Moreover, less number of channel, for a distance of 100 km and low average Q-factor of 10.69 with minimal CFBGs investigate with high capacity DWDM system for efficient analysis [14].

In order to meet the demand in fast-growing industrial base, DWDM system is used for existing fiber optic design, as it supports higher data rates. The DWDM technology will reshape the futuristic telecommunication network in many aspects through it’s extraordinary benefits such as large transmission capacity and low power optical design using high-speed routers, which supports large bandwidth and high-speed internet. Furthermore, DWDM system can be deployed in various applications such as sensor networks [15], data center interconnect [16], remote radar networks [17], video transport [18], FTTH (Fiber to the Home) [19], Tele-spectroscopic controlled process [20]. Moreover, by multiplexing ESCON (Enterprise Systems Connection) and FICON (Fibre Connection) over DWDM transport mechanism has the capability to expand their capacity and hence serve as backup bandwidth without using any new fiber. Thus reducing the complexity of optical system designs.

To improve on speed and transmission capacity, DWDM system needs more number of channels and higher data rates leading to low channel spacing, and requires boosting of the input power levels in the existing system [21]. However, the above requirements in DWDM faces certain challenges during design such as attenuation, dispersion and other non-linear effects such as Four Wave Mixing (FWM) [22]. Increasing bit rate requires more input power, which directly induces more FWM nonlinearity power products. Increasing more number of channels that reduces channel spacing and requires higher input power, which leads to more inter-channel interferences and leads to higher cross talk [23]. These factors will highly influence nonlinear effects such as FWM in applications of existing DWDM systems, which affects waveform quality, lowers network efficiency and performs data droop, resulting in data re-transmission. The DWDM system design in ESCON and FICON, which has FWM issues lowers the data rate performance, and affects the control unit, which is configured in an S/390 and z-Series environment. Furthermore, problems due to FWM in FTTH can affect logical paths and control units during data migrations. Data droop, which happens due to FWM, can be optimized with system factors such as bit rate, number of channels, input power, optical gain and other modulation factors. FWM in video transport using ultra-band DWDM system introduces more signal distortions, which lowers OSNR and affects the Q-factor with pulse broadening. Thus, FWM reduces the speed, effective utilization and increases the latency in video transport applications using ultra-band DWDM system network, requiring data re-transmission. Thus, heavy losses are introduced into the system due to FWM.

From literature, it is observed that FWM is a major problem for high quality data transfer. Therefore, it is necessary to identify the influencing optical parameters, which cause FWM during DWDM transmission. Moreover, the correlation of these optical parameters in DWDM and their relations with FWM has to be identified. This paper will be investing the design parameters of the DWDM system that induces FWM. Furthermore, extensive study is carried out for channel spacing, input power, modulation format, effective core fiber radius and duty cycle. In the proposed system DCF is integrated with the optical amplifier and the effects are compared in order to gain a better understanding of it’s impact in reducing FWM. This research paper is organized as follows, Section II. Discuss the theoretical analysis of FWM. Section III. Provides simulation and method implemented in this paper. Section IV. Presents simulation results and detailed discussions are carried out. Section V. presents the conclusion and future work.

2. Theoretical analysis of FWM

In DWDM systems, Combinations of three different optical signals, which are traveling through a single-mode fiber with frequencies λ_i, λ_j and λ_k, which causes the third-order susceptibility generating a new signal whose frequency can be calculated by using equation (1)

$$\lambda_{ijk} = \lambda_i + \lambda_j - \lambda_k \tag{1}$$

and λ_k is either equal to λ_i or λ_j new frequencies are generated under given condition.

The FWM signal power can be estimated by understanding their influencing simulation parameters and given by equation (2)

$$P_{FWM}(\lambda_{ijk}) = \frac{1024\pi^S}{n^4\lambda^2c^2}\frac{d_{ijk}xL_{eff}}{A_{eff}}P_iP_jP_ke^{-\alpha\Lambda_{ijk}} \tag{2}$$

where L_{eff} is the fiber effective length $P_iP_jP_k$ are the corresponding j, k and I channels input power. α is the attenuation coefficient, L is the fiber length, Λ_{ijk} is the FWM efficiency, η is the core refractive index of the fiber, λ is the wavelength and A_{eff} is the fiber core effective area [4].

The nonlinear coefficient is represented by

$$\text{as}\gamma = \frac{2\pi n_2}{\lambda A_{eff}} \tag{3}$$

Scalar factor can be written as

$$\chi = \frac{cn^2}{48\pi^2}n_2 \tag{4}$$

The nonlinear refractive index and power equation can be rewritten as equation (5)

$$P_{FWM}(\lambda_{ijk}) = (\frac{d_{ijk}\gamma L_{eff}}{3})^2\ P_iP_jP_je^{-\alpha L_{ijk}} \tag{5}$$

where the fiber effective length is computed with

$$L_{eff} = \frac{1-e^{-\alpha L}}{\alpha} \tag{6}$$

and the FWM efficiency is expressed as in equation (7)

$$\Lambda_{ijk} = \frac{\alpha^2}{\alpha^2+\Delta E^2 ik}[1+\frac{4e^{-\alpha L}}{(1-e^{-\alpha L})^2}]\sin^2(\frac{\Delta E_{ijk}L}{2}) \tag{7}$$

where $\Delta E_{ijk}$is the phase mismatching factor, which can be represented as in equation (8)

$$\Delta E_{ijk} = \frac{2\pi\lambda_k'}{\epsilon}(|f_i - f_k||f_i - f_k|)[D_c + \frac{\lambda_k'}{2c}\frac{d\theta_c}{a_k}(|f_i - f_k| + |f_i - f_k|)] \tag{8}$$

Hence, the total power generated in a specific channel due to FWM crosstalk is given as in equation (9)

$$P_{FWM}(f_c) = \sum_{f_k=f_i+f_j-f_c}\sum_{f_j}\sum_{f_i}P_{FWM}(\lambda_i + \lambda_j - \lambda_k) \tag{9}$$

For precision-based analysis, the total effects of FWM crosstalk on particular channels are given by computing the influencing parameters such as data line rate, Input power, channel spacing, optical gain, transmission lengths, and modulation formats in iterative simulations. In equal channel spacing, FWM falls accurately into defined channels and creates a high impact FWM crosstalk [9]. System performance degradation is a highly disturbing quality of data transmission in real field requirements. The signal-to-noise ratio is the most important factor in equal channel spacing and shows the impacts of FWM which affects the system performance due to its phase matching.

The Signal-to-noise ratio can be expressed as in equation (10)

$$SNR = 10\log_{10}\frac{P_{\text{out}}}{P_{FWM}} \tag{10}$$

where P_{out} is the channel's output power with frequency f_c, i.e. $P_{\text{out}} = P_c e^{-\alpha L}$and P_{FWM} is the total power generated due to FWM crosstalk.

FWM, which affects the signal performance and fiber length, is calculated from equation (11)

$$P_F(L) = \frac{1024\pi^6}{n^4\lambda^2c^2}(D_X)\frac{P_i(0)P_j(0)P_k(0)}{A_{eff}^2}e^{-\alpha L}\frac{(1-e^{-\alpha L})^2}{\alpha^2}\eta \tag{11}$$

where $P_iP_jP_k$ are corresponding i,j and k channels optical signals power. P_F is the signal power of the FWM signal. n^4 the fiber's refractive index, λ is the wavelength, c is the light velocity at free space, $A_{eff}$is the effective core area of the fiber, α is the attenuation coefficient, ʟ is the fiber's length, D is the factor of degradation and η mentions the FWM efficiency due to the mismatch of phase which represents as ΔE.

The phase mismatch coefficient ΔE can be described as in equation (12)

$$\Delta E = E(f_i) + E(f_j) - E(f_k) - E(f_F) \tag{12}$$

Based on these factors, we evaluated UDWDM system setup efficacy by acclimatizing of parameters such as input power, channel spacing, optical gain, modulation techniques, duty cycle and how it instigates FWM.

3. Simulation setup

In a long haul communications, the WDM design with more number of the transmitted signal requires high input power and travels a long distance to reach the receiver end. Moreover, high power transmitted signal has more issues over FWM in a multichannel WDM system. In this system setup, the transmitter channels' input power is considered as 0.1mw i.e. (-10 dBm). By choosing the above range of input power, the FWM signal loses its power products and is degraded. A super-channel WDM optical network is designed at the data line rate of 10Gbps and channel spacing of 100GHz. The simulation setup for the proposed setup is shown in Fig. 1.

The WDM transmitter has a pseudo-random data source generator, which produces data at the rate of10Gbps. The electrical pulse generator converts digital input signals into short electrical pulses, further processed into Mach-Zehnder modulator (MZM), modulating the information. The WDM multiplexer combines all the input signal from different channels and allows into the nonlinear-fiber optic medium.

This fiber optic medium consists of single-mode optical fiber with its own dispersion and attenuation characteristics. In addition, the signal from single-mode fiber is employed and dispersion compensation fiber (DCF), which attains its attenuation and dispersion effects to compensate dispersion pulse broadening, which is also considered the nonlinear characteristic of optical fiber and DCF actuated. A WDM demultiplexer is used to cleavage the received signals into their own channel's frequency at the receiver side. The demultiplexer's output is passed through PIN photodetector and reached into an electrical low pass Bessel filter. Finally, the spectral output characteristics are monitored through BER Analyzer. Minimum bit error rate (Min.BER), Eye-opening, and Q-Factor are the observing factors that evaluates the WDM system performance. Typical BER for optical fiber communication to achieve minimum eye-opening is 10^{-9} or lower at the receiver end. In this paper, an investigation is carried out to evaluate the high capacity WDM system's performance. Here, the proposed system is designed, and several parameters are investigated to diminish the effects of fiber FWM nonlinearity, and analysis are carried out to improve the effective data transmission distance. Furthermore, a comparative study is also performed to choose the optimized range of system parameters that degrade the system efficiency and channel capacity.

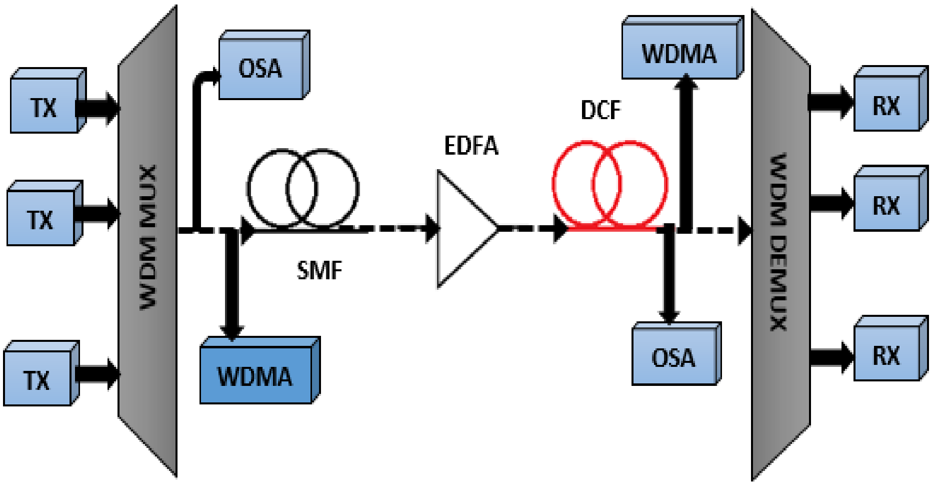


Fig. 1. Conceptual WDM optical network diagram (color online)

4. Results and discussion

In this section, simulation results for the proposed high capacity WDM system are analyzed to understand FWM fiber nonlinearities' variations. The varying number of channels, channel spacing, input power, varying modulation format, effective core radius of fiber, duty cycle and comparing effects of the proposed system with introducing DCF with optical amplifier are reported. Simulations are carried out for 1.28Tbps and 2.56Tbps at 150 km in the presence of fiber nonlinearities and results are observed.

4.1. Effects of Input power

The most investigated parameter to diminish the issues of FWM in the Long haul optical system is the input power, which is directly related to FWM. Considering other system design factors are constant and lowering transmitter input power, which diminishes FWM power products. Low input power shows a phenomenal reduction in Min.BER, eye height, and threshold values from eye diagrams characteristics. Moreover, lowering the Q factor is not negligible. From Fig. 2. During −10 dBm as an input power, it is noticed that for 2.56 Tbps data transmission system design has low OSNR decreases and obtains BER value as 7.91172e-145, with Maximum quality factor 25.5885. This phenomenon clearly shows that the significant changes are observed in dispersion and eye-height characteristics at −10 dBm input power.

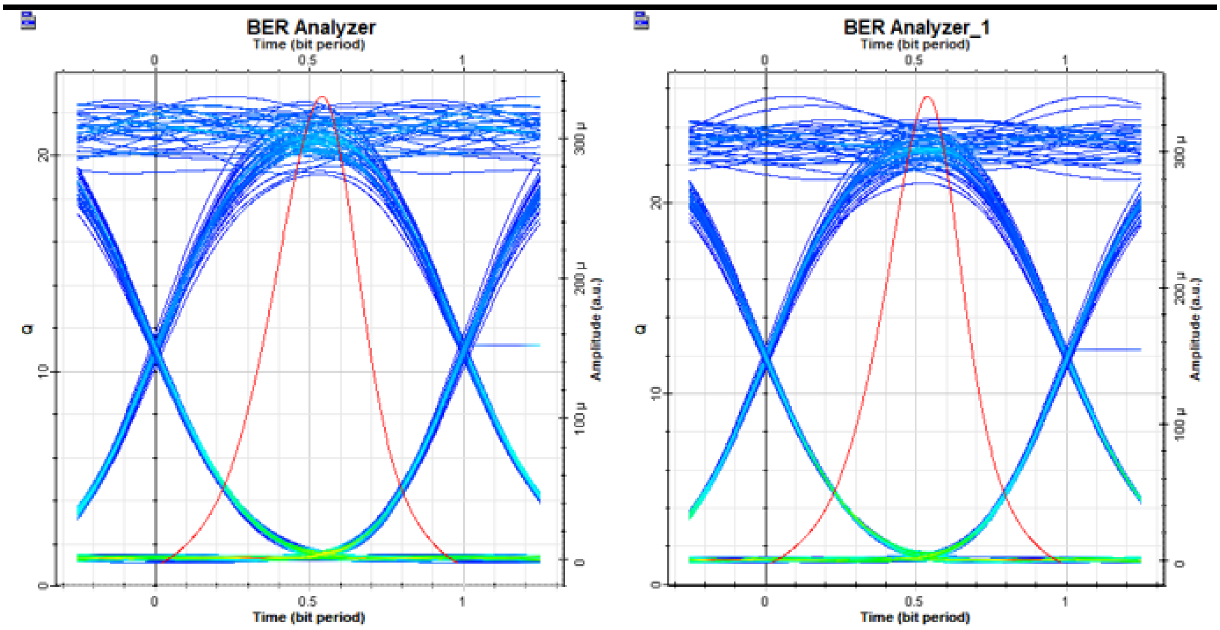
4.2. Effects of Channel spacing

Channel spacing is an extensively simulated parameter for mitigating FWM issues. For this setup, channel spacing varies from 100GHz to 110GHz. Channel spacing is nonlinearly related to the FWM effect. A phenomenal increase in channel spacing seems to lower the FWM products with nominal interference and spectrum protruding are observed as in [24]. From Fig. 3. Simulation results are shown that the system 1.28Tbps system has a very good utilization with designed fiber and amplifier. Besides, a 2.56Tbps system requires a hybrid amplifier combination to perform complete bandwidth utilization. After analyzing the results from 1.28Tb/s based system design, a min BER remains as 5.87197e-112, while other attributes are altered to minimal. Furthermore, it also diminishes signal quality factor into 22.443 and signals power that leads to increase OSNR.

4.3. Effects of Optical gain

In this Simulation setup, FWM and its impact over higher optical gain is discussed, and the rest of the design considerations are kept constant. Designing a ultra-band DWDM system with high optical gain leads to a higher power output spectrum with more power products of FWM [25]. FWM Power products and optical gain are linearly related factors, results in high FWM at 35dB optical gain. From Fig. 4. Simulation results are shown that both 1.28Tbps and 2.56Tbps perform better with high optical gain with a small improvement in BER 3.04548e-146 and a height characteristic of 0.00848055. Q-factor of 25.7125 is achieved. Further improvements in system considerations require a combination of hybrid amplifiers with different dispersion characteristics and other influencing devices such as Fiber Bragg grating (FBG).

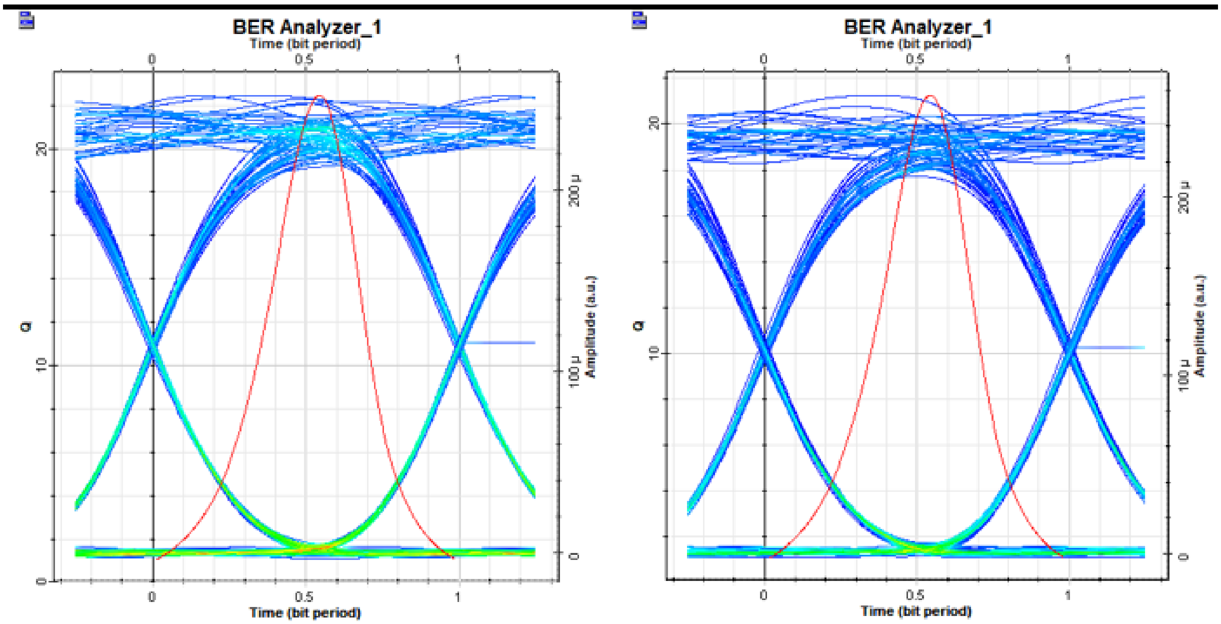
1.28Tbps	2.56Tbps



1.28Tbps	2.56Tbps
Max. Q Factor 22.7453	**Max. Q Factor 25.5885**
Min. BER 5.97643e-115	**Min. BER 7.91172e-145**
Eye Height 0.000258773	**Eye Height 0.000265331**
Threshold 4.33835e-005	**Threshold 4.90235e-005**
Decision Inst. 0.539063	**Decision Inst. 0.537109**

Fig. 2. Spectral characteristic for input power (color online)

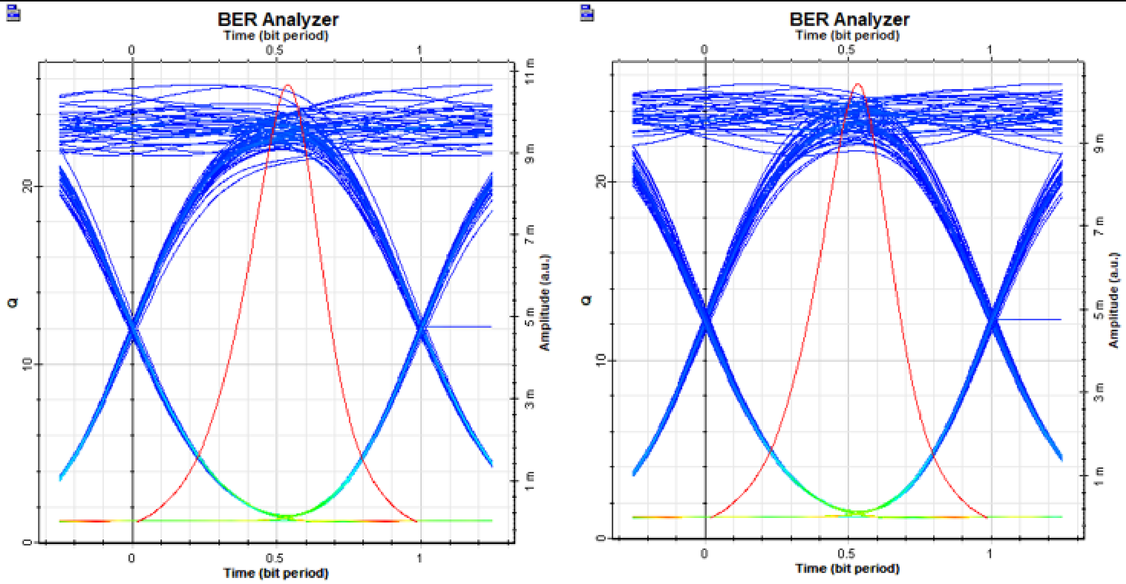
1.28 Tbps	2.56 Tbps



1.28 Tbps		2.56 Tbps	
Max. Q Factor	**22.443**	**Max. Q Factor**	**21.251**
Min. BER	**5.87197e-112**	**Min. BER**	**1.23355e-100**
Eye Height	**0.000197675**	**Eye Height**	**0.000194791**
Threshold	**4.04301e-005**	**Threshold**	**3.71202e-005**
Decision Inst.	**0.542969**	**Decision Inst.**	**0.542969**

Fig. 3. Spectral characteristic for channel spacing (color online)

1.28 Tbps	2.56 Tbps



Max. Q Factor	**25.7125**	**Max. Q Factor**	**25.5151**
Min. BER	**3.04548e-146**	**Min. BER**	**4.78284e-144**
Eye Height	**0.00837037**	**Eye Height**	**0.00837009**
Threshold	**0.00128686**	**Threshold**	**0.00125713**
Decision Inst.	**0.539063**	**Decision Inst.**	**0.533203**

Fig. 4. Spectral characteristic for optical gain (color online)

4.4. Effective Core Radius of Optical Fiber

The effective area of core size influences FWM in a way that increase in core size proportionally reduces effective core area and results in diminished FWM. In this simulation, the effective core radius is increased from 80 μm to 150 μm. Simulation results represent the graphical FWM power with effective variation in core radius of the optical fiber is shown in Fig. 5. Data rate for 2.56 Tbps are very high when compared to other setup. The occurrence of FWM issues are also high probable in 2.56 Tbps DWDM simulation setup hence the performance of this channel getting worse compared to 128 channels DWDM setup. This is clearly listed in simulation results in Fig. 5. From this, it is understood that as increases in effective core radius of the optical fiber, the product power of FWM generation is decreased which shows improved system performance. FWM power lowers a little due to increase in the effective core area (Aeff) which lowers intensity of light in inside fiber.

4.5. Effects of RZ modulation instead of NRZ

In long-haul UDWDM data transmission, RZ and NRZ have widely used modulation formats. RZ format is a key modulation method up to 2.56Tb/s since it possesses high OSNR, Peak Power, and low BER than other modulation formats. It also provides good immunity against nonlinear effects in the fiber optic system and lowers FWM [26]. Moreover, RZ modulation highly subjects in to pulse dispersion issues, which marginally lowers eye-opening height and quality factor and min BER debris identical. RZ modulation format is low susceptible to inter-symbol interference (ISI), and procures improved performance than NRZ. From Fig. 6. Simulation results are validated that the RZ modulation format behaves better, which shows higher variation and provides ample BER and Q factor modifications. Min BER is placed with a higher possibility of data communication, eye height and maximum Q factor reaching too high for 2.56Tbps, since it has a high data rate transmission. Higher-order modulation formats are also used when the system design involves with FBG and hybrid amplifiers for long-distance data transmission.

4.6. Effects of Duty cycle

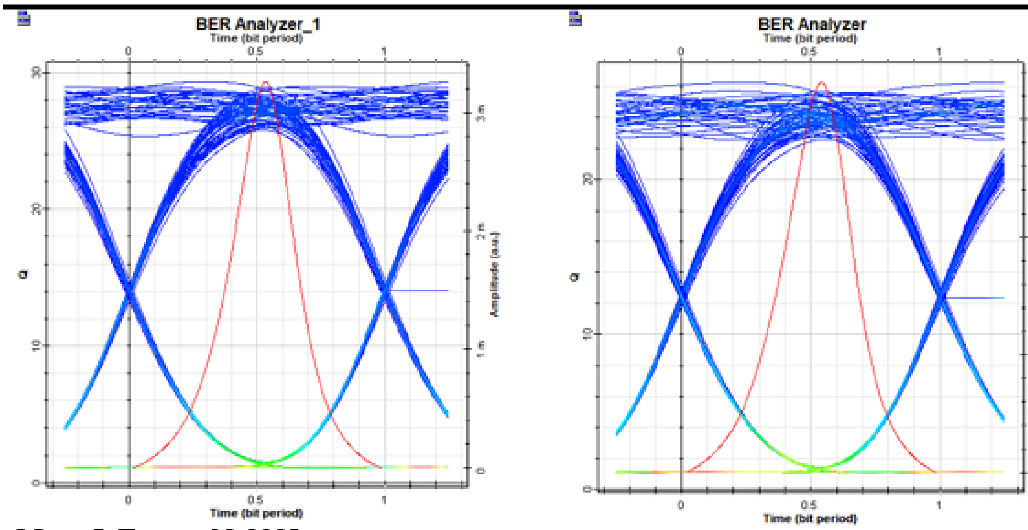
The duty cycle, which determines the signal, is in the active period. Designing RZ modulation with 25% of the duty cycle yields more pulse broadening that lower eye height characteristic, resulting in more FWM in the original spectrum. From Fig. 7. Simulation results are shown that 1.28 Tbps show a more pulse-broadened system. In addition, the proposed method has obtained better results in terms of min BER, OSNR, Q factor, and signal power.

4.7. Effects of OA in DCF place

An optical amplifier (OA) is a system that amplifies an optical signal, which is like to be a laser with cavity-suppressed feedback. Convincing results were observed in

BER analyzer by interchanging the position of OA and DCF. It results from small attritions in FWM, OSNR and signals power as observed in [27]. Fig. 8 shows the better eye opening characteristics and narrowed pulse which results better Q factor and BER for 1.28Tbps and 2.56 Tbps DWDM simulation setup. For 128 channels Max. Q Factor of 26.5773 and Min. BER 4.55213e-156 is achieved. Whereas Max. Q Factor 31.1189and Min. BER 5.3684e-213 was obtained for 2.56 Tbps DWDM setup.

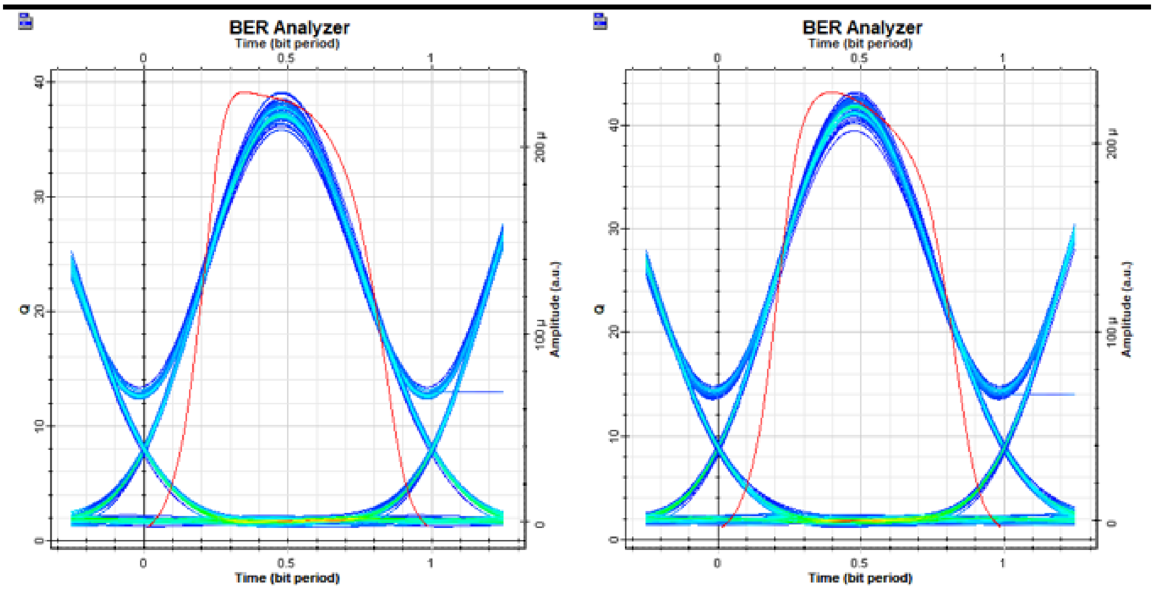
1.28 Tbps	2.56 Tbps



1.28 Tbps		2.56 Tbps	
Max. Q Factor	29.3331	Max. Q Factor	26.2825
Min. BER	1.47291e-189	Min. BER	1.1162e-152
Eye Height	0.0026926	Eye Height	0.00266155
Threshold	0.000459988	Threshold	0.000424027
Decision Inst.	0.533203	Decision Inst.	0.541016

Fig. 5. Spectral characteristic for core radius (color online)

1.28 Tbps	2.56 Tbps



1.28 Tbps		2.56 Tbps	
Max. Q Factor	39.0923	Max. Q Factor	43.1774
Min. BER	0	Min. BER	0
Eye Height	0.00020186	Eye Height	0.000203714
Threshold	4.4704e-005	Threshold	4.8824e-005
Decision Inst.	0.306641	Decision Inst.	0.501953

Fig. 6. Spectral characteristic for RZ modulation scheme (color online)

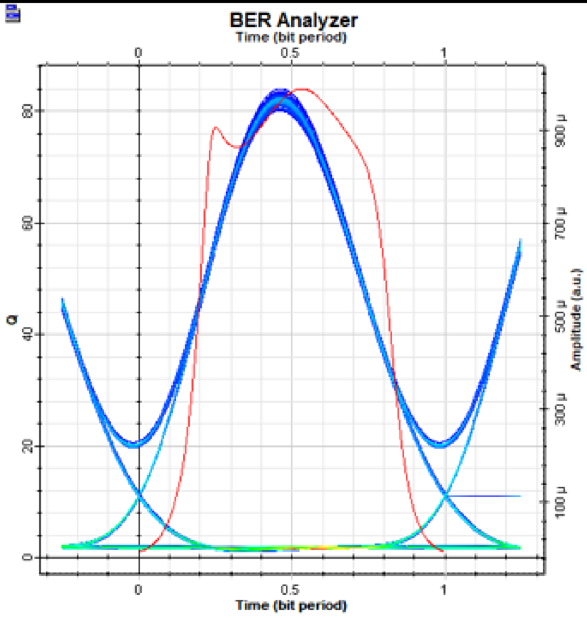
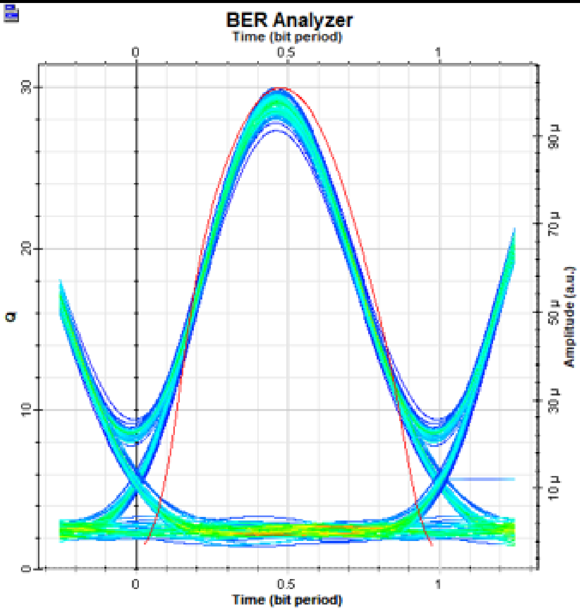
1.28 Tbps	2.56 Tbps
	
Max. Q Factor 84.0057	**Max. Q Factor** 29.9833
Min. BER 0	**Min. BER** 7.82384e-198
Eye Height 0.000925974	**Eye Height** 8.69545e-005
Threshold 6.16613e-005	**Threshold** 3.53991e-005
Decision Inst. 0.501953	**Decision Inst.** 0.476563

Fig. 7. Spectral characteristic for duty cycle (color online)

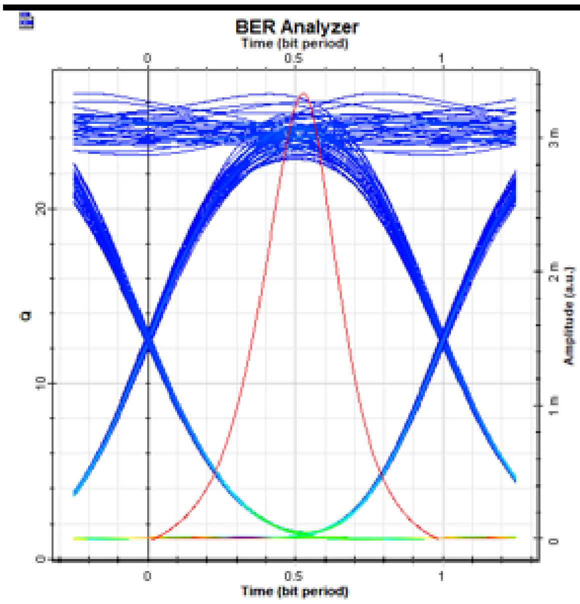
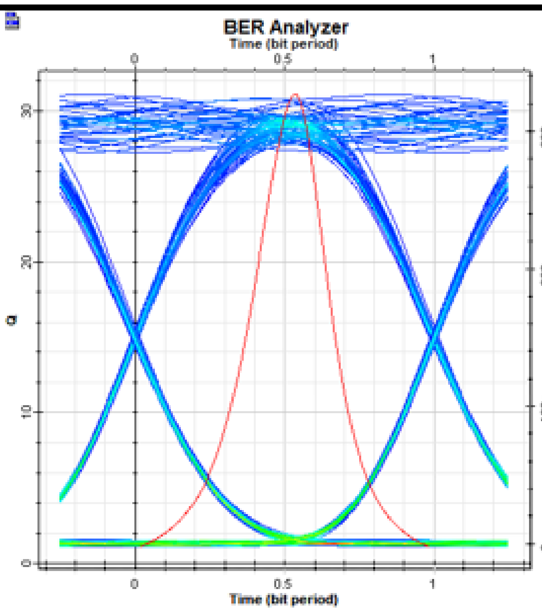
1.28 Tbps	2.56 Tbps
	
Max. Q Factor 26.5773	**Max. Q Factor** 31.1189
Min. BER 4.55213e-156	**Min. BER** 5.3684e-213
Eye Height 0.0026711	**Eye Height** 0.000271791
Threshold 0.000421586	**Threshold** 5.86807e-005
Decision Inst. 0.525391	**Decision Inst.** 0.535156

Fig. 8. Spectral characteristic for interchanging the place of DCF and OA (color online)

5. Conclusion

In this paper, the ultra-band DWDM system's performance is analyzed under design considerations such as transmission input power levels, high optical gain, modulation format with optimized duty cycle, optical gain, and channel spacing to overcome the issues of nonlinearities. This work has emphasized the FWM impact on a higher data rate of 1.28Tbps and 2.56Tbps in the optical WDM network. System design with 1.28Tbps of data transmission has shown efficient results in Q-factor, BER, eye-diagram characteristics, and FWM power products. Increasing transmission power broadens the power spectrum and improves FWM power products that introduce high interference and more channels. RZ modulation scheme with a low duty cycle shows better performance and reduces FWM over long transmission distance. 100 GHz channel spacing, which lowers FWM and leads to ultra-band DWDM design, using hybrid amplifiers to meet channel capacity requirements. High optical gain will enhance the power level of the original spectrum and improves the FWM nonlinearities. Furthermore, the proposed method can provide a better understanding of FWM in the high capacity WDM design. This work can be extended into implementing adaptive modulation formats using external modulation for future optical networks.

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