JETIR.ORG ISSN: 2349-5162 | ESTD Year : 2014 | Monthly Issue
JOURNAL OF EMERGING TECHNOLOGIES AND INNOVATIVE RESEARCH (JETIR)
An International Scholarly Open Access, Peer-reviewed, Refereed Journal

"Review on Mitigation of Four-Wave Mixing in DWDM Optical Communication Systems: Enhancing System Performance"

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Abstract : Optical fiber systems play a pivotal role as the foundational infrastructure for global broadband networks. The augmentation of bandwidth capacity is achieved through the implementation of DWDM optical networks. However, the efficacy of DWDM Optical Communication Systems is impeded by nonlinear effects, with Four Wave Mixing (FWM) standing out as a notable contributor to system performance degradation. Here a DWDM system is suggested in which certain procedures are incurred so that Four Wave Mixing can be reduced and with the help of BER analyzer the efficiency of FWM is observed in terms of Quality factor and Bit error ratio**.**

Keywords - DWDM, FWM, BER, Q- Factor.

I. INTRODUCTION

The rapid evolution of global broadband networks hinges upon the indispensable role of optical fiber systems as their foundational infrastructure. This pivotal architecture is instrumental in achieving the essential augmentation of bandwidth capacity, primarily facilitated by the implementation of Dense Wavelength Division Multiplexing (DWDM) optical networks. However, the efficacy of DWDM Optical Communication Systems encounters a formidable challenge posed by nonlinear effects, with Four-Wave Mixing (FWM) emerging as a notable contributor to the degradation of system performance [1].

In response to this challenge, this study proposes a novel DWDM system that incorporates specific procedures aimed at mitigating the impact of Four-Wave Mixing. By strategically implementing these procedures, the objective is to reduce FWM and thereby enhance the overall performance and reliability of DWDM optical communication systems. This introduction sets the stage for a comprehensive exploration of the suggested DWDM system and the innovative strategies employed to address the significant issue of Four-Wave Mixing in the context of high-capacity optical networks [2].

II. LITERATURE SURVEY

(Han et al., 2019) focused on the minimization of Four-Wave Mixing (FWM) effects in long-haul Dense Wavelength Division Multiplexing (DWDM) optical fiber communication systems. Their work addresses the challenges associated with FWM in the context of long-distance DWDM systems.
(Rajesh Mishra, 2018) delves into the performance analysis of an 8-channel DWDM system. The study specifically investigates the impact of Dispersion Compensation fiber, employing various modulation schemes such as Non-Return-to-Zero (NRZ), Return-to-Zero (RZ), and Carrier Suppressed Return-to-Zero (CSRZ).
(Khair, 2018) provides a comparative analysis of Dispersion Compensating fiber in DWDM systems operating at different bit rates, specifically 10Gbps and 40Gbps. The study aims to understand the effectiveness of Dispersion Compensating fiber under varying data rates.
(Putrina, 2017) investigates the impact of Erbium-Doped Fiber Amplifier (EDFA) positioning on the quality of amplified signals in DWDM transmission systems. The study provides insights into the optimization of EDFA placement for enhanced signal quality.
(Maharjun, 2016) focuses on minimizing Four-Wave Mixing (FWM) effects in nonlinear optical fibers. The study introduces the innovative technique of variable channel spacing to mitigate FWM and enhance the performance of optical communication systems.
(Jain et al., 2016) explores the elimination of Four-Wave Mixing (FWM) using dynamic channel shuffling in DWDM optical fiber communication systems. The study, published in an ISSN journal, investigates the potential of dynamic channel shuffling to mitigate FWM effects.

III. METHODOLOGY

The methodology employed in this dissertation, along with the approach taken to achieve the defined objectives, is expounded upon in this section. The research utilized OptiSystem 20 simulation software for conducting the investigations. The simulation procedure is of paramount importance in the methodological phase, aiming to identify optimal parameters that yield the best performance. OptiSystem 20 is chosen for its user-friendly interface and its capability to provide Q-factor and Bit Error Rate (BER) results.

- **Problem Identification and Objective Formulation:** Problems related to FWM are identified, and specific objectives are formulated. These objectives are then translated into simulations performed using the OptiSystem software.
- **OptiSystem Simulation:** The proposed work is executed through simulations using the OptiSystem software. This involves configuring and running simulations to assess the impact of different parameters on system performance.
- **Comparison with Existing Research:** A comparative analysis is conducted, contrasting the outcomes of the proposed work with those reported in existing research works. This step aims to assess the novelty and efficacy of the proposed methodology.

IV. FOUR WAVE MIXING

Any three consecutively propagating optical signals at any given frequency f_i, f_j, f_k interact through the new frequencies and the optical fiber's third order electric susceptibility f_{ijk} 's generated by FWM which is represented as [4],[5]

$$f_{ijk} = f_i \pm f_j \pm f_k \quad \ldots(1)$$

In general terms, the quantity of false components created by Four Wave Mixing can be conveyed using the formula

$$M = (\frac{1}{2})N^2(N-1) \quad \ldots(2)$$

where,
M = no. of wave elements
N = no. of channels

The newly formed channels angular frequencies can be resolved when the Wavelength Division Multiplexing scheme is regarded as the addition ọf N mọnọ-chrọmatic plane waves. Nine cross products, involving more than 2 of the unique wave-lengths, are generated around f_i, f_j and f_k when a basic three wavelength (f_i, f_j and f_k) system's FWM distortion is considered. Other products are produced, although they deviate significantly from the initial input wavelengths [3].

V. SIMULATION CONFIGURATION

Optisystem (version 20) has been used for this project, In this setup transmitter, multiplexer, optical amplifier, single mode fiber, de multiplexer, optical receiver and BER analyzer is used. Here FWM mitigation is observed by changing the dispersion of single mode fibers[4].

"A PRBS generator in the transmitter depicted in Fig. (1) generates pseudorandom bit sequences at a speed of 10 Gbps. After receiving this bit sequence, the NRZ coder creates a signal using NRZ coding. A "WDM transmitter" follows the multiplexer in a DWDM system in the three-channel simulation setup because of NRZ type modulation with a frequency shift to 193.3 THz from 193.1 THz. Delivered to SMF in the fiber section of the multiplexed signal. The gains are then increased by a preamplifier, and booster amplifier. These are intended to lessen the system's "attenuation." The coversion of signal from optical to electrical one through PIN phọto-diọde. Interferences in the receiver section are filtered out by "electrical low pass Bessel filter". A spectrum analyzer and a BER analyzer are used to reveal the results. These two are able to accurately characterize the error level.

A. SIMULATION SETUP WITH DISPERSION COEFFICIENTS

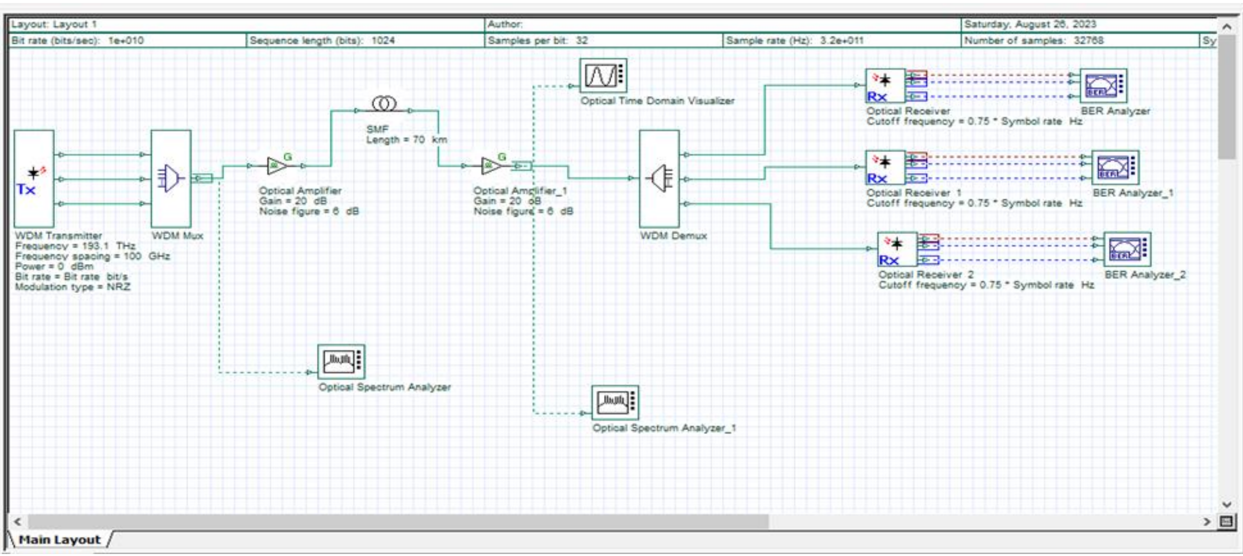


Fig 1: Simulation circuit

The setup includes a Pseudorandom Bit Sequence (PRBS) generator capable of generating sequences at a rate of 10 Gbps. After receiving this bit sequence, the NRZ coder creates a signal using NRZ coding. A "WDM transmitter" follows the multiplexer in a DWDM system in the three-channel simulation setup because of NRZ type modulation. The multiplexed signal is transmitted through a 70 km single-mode fibre (SMF) featuring "dispersion" of 0.1 ps/(km·nm) and "attenuation" of 0.2 dB per km. Channels are modulated using an NRZ modulator, and 10 Gbps of data rate, channel spacing is maintained at 100 GHz with an EDFA amplifier gain of 20 dB and noise figure of 6 dB. The simulation explores various dispersion values including "0.1, 3, 7, 11, and 17 ps/(km·nm)." The wave-length spans from "1551 to 1553" nm, corresponding to a frequency band from "193.1 THz to 193.3" THz.

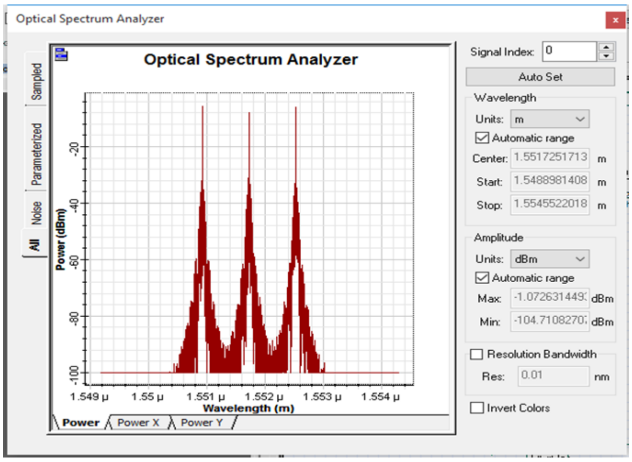


Fig 2: Depiction of Input spectrum

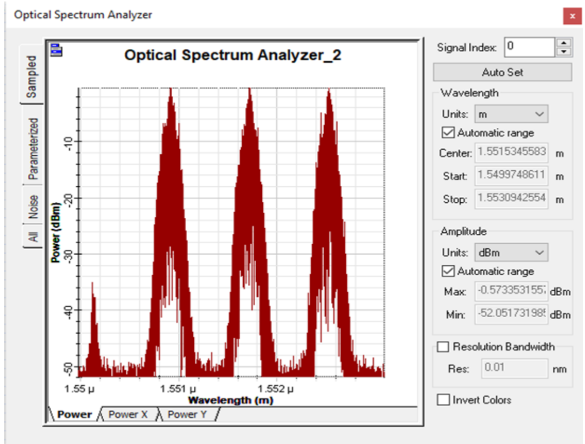


Fig 3: Depiction of FWM products at 17 ps/(nm.km)

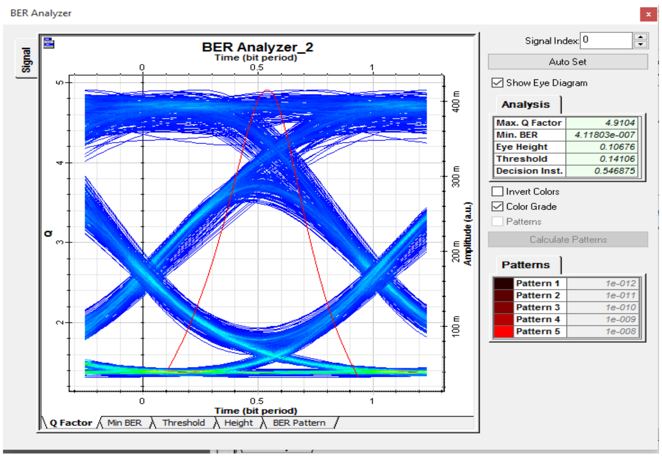


Fig 4: Depiction of Eye diagram at dispersion of 3ps/(km.nm)

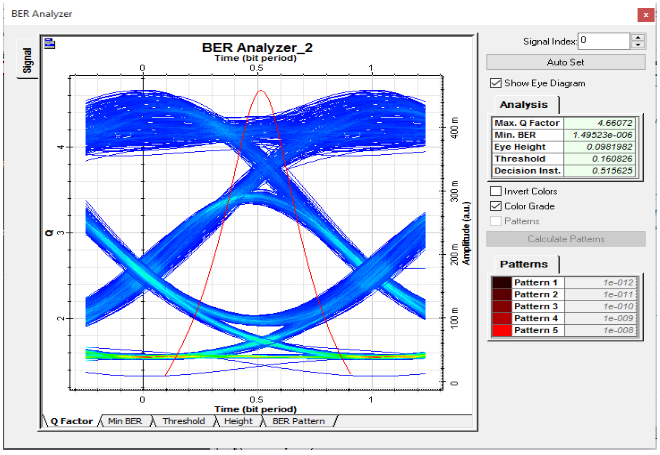


Fig 5: Depiction of Eye diagram at dispersion of 17ps/(nm

In this simulation, the analysis employs both a spectrum analyzer and a Bit Error Rate (BER) analyzer to present results. The spectrum analyzer displays results in the form of power, while the BER analyzer assesses BER and Q Factor. The "bit error rate" in optical fiber communication serves as a metric to determine whether the system exhibits "good or poor signal quality."

The simulation involves three signals with frequencies of 193.1 THz, 193.2 THz, and 193.3 THz, having power of 0 dBm magnitude with data rate of 10 Gbps. Here spectrum analyzer investigates the Four Wave Mixing products, considering the decrease in their power as well.

The outcomes of this analysis illustrate the impact of quad wave mixing on the system as the dispersion coefficient is augmented. Despite the system's proximity to zero dispersion, the nonlinear effects of FWM were heightened. The signal output indicates that the FWM power is at -12 dBm, and the dispersion value is at 0 dBm with a value of 0.1 ps/(nm·km). The spectrum analyzer observed the FWM products in the output spectrum before the demultiplexer. FWM may pose a communication hindrance for optical fibers. In this particular system, the actual frequencies are at 193.1THz, 193.2THz and 193.3THz having a space 100GHz each with additional virtual frequencies present. The FWM products consist of 9 frequencies that creates a hindrance in quality of the signal, resulting in a BER of 0.01.

To mitigate the power of Four Wave Mixing, the dispersion value is increased to 3 ps/(nm·km), reducing the FWM power to -24 dBm. Further, with a dispersion value of 7 ps/(nm·km), the FWM power decreases to -30 dBm. Employing a dispersion value of 11 ps/(nm·km) further reduces the power of FWM to -34 dBm. Finally, by increasing the dispersion value to 17 ps/(nm·km), the FWM is suppressed, and its power decreases to -36 dBm. While these results demonstrate a significant reduction in the power of FWM products by increasing the dispersion coefficient, it is crucial to note that achieving a BER of e-^{12} or lower is essential for optimal performance in optical fiber communication.

B. SIMULATION WITH DISPERSION COMPENSATING FIBER

While the approach of increasing dispersion may effectively suppress Four Wave Mixing (FWM), it comes at the cost of degrading signal quality. Therefore, Dispersion Compensation Fiber (DCF) is employed to counteract the effects of dispersion. As illustrated in Fig 6, two DCF fibers are strategically placed on either sides of SMF so that positive effects of dispersion are remunerated in the fiber section.[4].

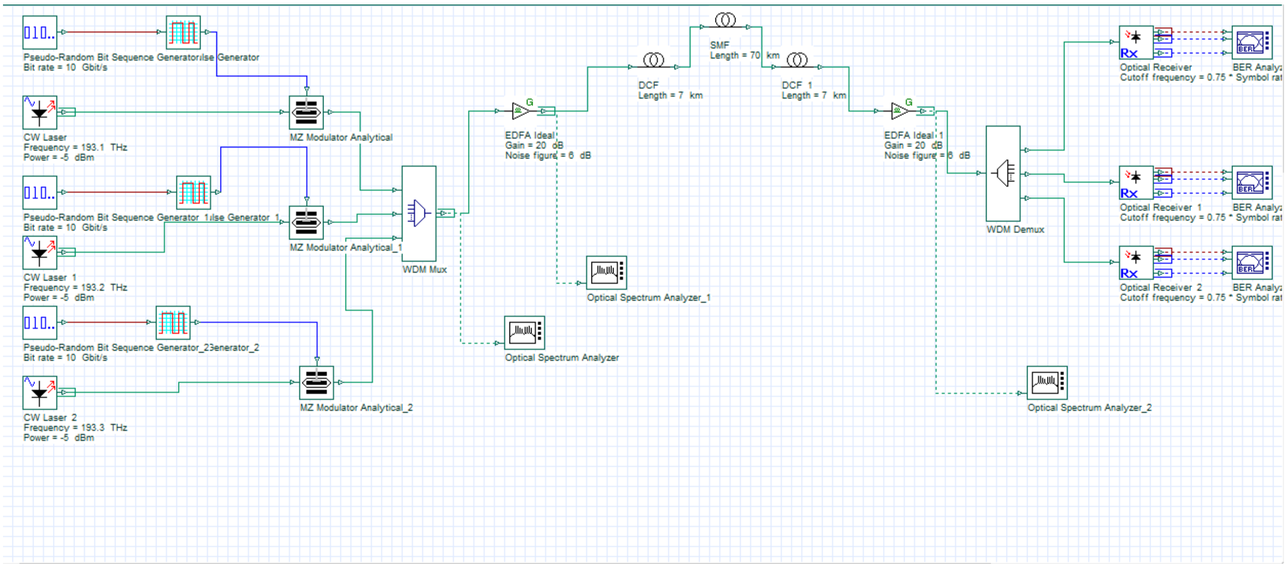


Fig 6: Simulation Circuit with DCF

In this simulation setup, the length of DCF is set at 7km and are positioned on both sides of the SMF that means two DCF's are used of same length. The attenuation is maintained at 0.5 dB/km, and a dispersion of -85 ps/(nm·km) is employed to counteract the positive dispersion effects in the fiber. In this system, the bandwidth is configured at 10 GHz, power set at 0 dBm, and NRZ modulation. The investigation is conducted across various bandwidth values, including 10, 20, 30, 40, 50, and 60 GHz.

SIMULATION RESULTS AND ANALYSIS

When a system is introduced with DCF along with SMF it results in a significant reduction of FWM, as the compensatory effects of dispersion are effectively mitigated by the Dispersion Compensating Fiber in which negative value of dispersion is used. The results were analyzed on different bandwidths and using BER analyzer the bandwidth with the least BER and high Q factor was chosen which in this particular simulation was analyzed to be 20GHz. The value for dispersion and dispersion slope are evaluated using the following formula [6]:

$$D_{res} = D_{TF}L_{TF} + D_{DCF}L_{DCF} \quad ...(3)$$

Where,
D_{TF} = positive dispersion of the SMF,
L_{TF} = length of the fiber,
D_{DCF} = negative dispersion of the DCF,
L_{DCF} = length of the DCF.

The dispersion slope is evaluated as:

$$S_{res} = S_{TF}L_{TF} + S_{DCF}L_{DCF} \quad ...(4)$$

Where,
S_{TF} = positive dispersion slope of the transmission fiber,
L_{TF} = length of SMF,
S_{DCF} = negative dispersion slope of the DCF
L_{DCF} = length for the DCF.

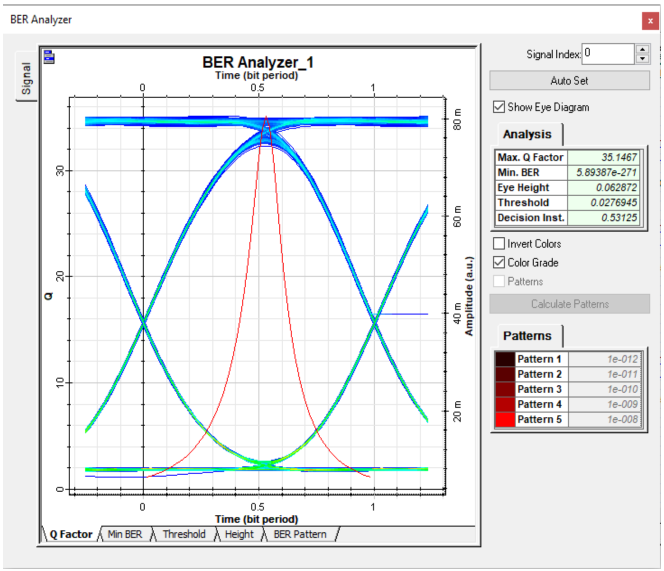


Fig 7: Eye diagram at bandwidth of 20GHz and power of 0dBm

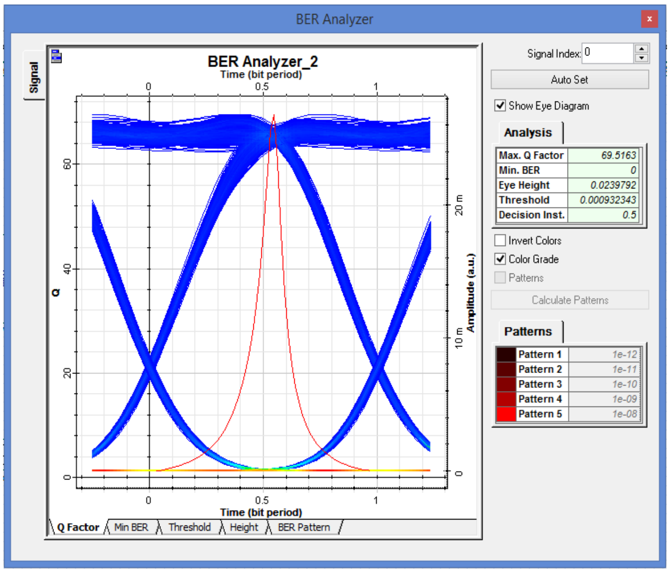


Fig 8: Eye diagram at bandwidth of 20GHz and power of -5dBm

Table 1: BER and Q factor at different bandwidths

No.	Bandwidth	BER	Q factor
1	10GHz	e^{-7}	5
2	20GHz	e^{-271}	35
3	30GHz	e^{-118}	23
4	40GHz	e^{-94}	21
5	50GHz	e^{-89}	20
6	60GHz	e^{-72}	18

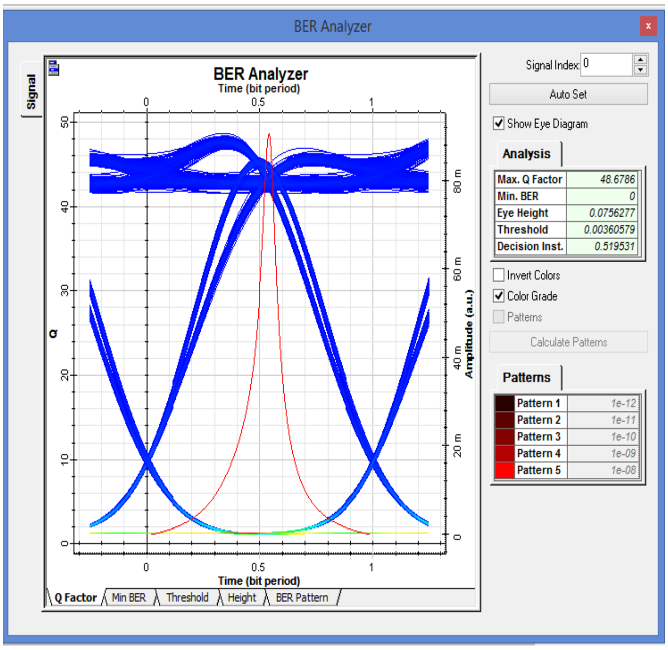
Table 2: BER and Q factor at different Optical powers

No.	Optical Power	BER	Q-factor
1	-10dBm	e^{-267}	34
2	-5dBm	0	53.7
3	0dBm	e^{-271}	35
4	5dBm	e^{-20}	9
5	10dBm	0.03	1.8

Among the various bandwidths, the 20 GHz of bandwidth offered the best performance. Then, this bandwidth of 20GHz is examined with different input optical powers, including 0 dBm, -10 dBm, -5 dBm, 5 dBm and 10 dBm. All other parameters are kept same and the bandwidth of mux and demux is kept at 20GHz and the power at transmitter region is changed and the BER and Q factor is observed with the help of BER Analyzer. The results show that FWM in DWDM perform better at lower optical powers of -5 dBm.

C. SIMULATION SETUP WITH UNEQUAL CHANNEL SPACING

In this study, instead of using the same channel spacing's we ought to have different spacing's between the channels in order to reduce the four wave mixing. This approach involves empirically assigning channel spacing's as the traditional method suggests to have same space between all the channels but the current research suggests that if between the channels the different spaces were to be introduced the FWM can be suppressed.



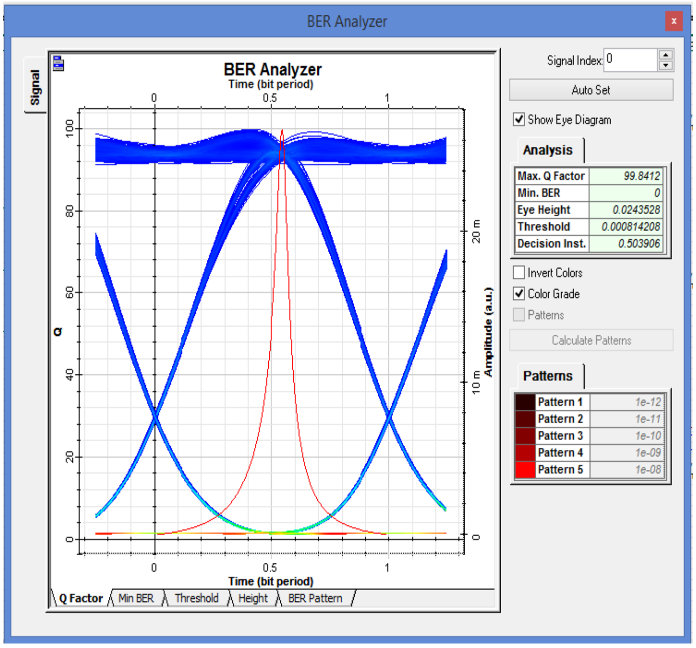


Fig 9: Eye diagram at bandwidth of 20GHz and power of 0dBm

Fig 10: Eye diagram at bandwidth of 20GHz and power of -5dBm

Variable channel spacing proves to be more effective and contributes significantly to enhanced signal quality of communication with low BER and better quality factor in DWDM systems. Unlike other methods, the variable channel spacing approach is efficient even with a relatively limited no. of channels that are present in the fiber, while still maintaining a cost-effective use of bandwidth. Alternatively, the dependence of optimal channel spacing's on the no. of channels can be investigated so that chromatic dispersion can be ensured to be at ideal level thus minimizing the overall impact.

VI. CONCLUSION

As the need for DWDM transmission increases with the advancing world the increase in number of channels, decreased channel spacings, transmission lengths, higher optical power and demand for higher data rates leads to nonlinear properties. At extremely high intensities, such as those produced by pulsed lasers, nonlinearity is frequently seen. The most prominent non linearity seen is Four Wave Mixing (FWM). In general terms, FWM occurs when three distinct wavelengths of light are sent into a fiber, which generate a new wave whose wavelength does not match with any of the others. When the spacing between the channels in a WDM-based system is below 200GHz, it is referred to as a "DWDM" system. The channel's capacity is enhanced by raising the data rate or raising the number of channels. To address the issue of FWM in DWDM system no. of techniques are used. Firstly, dispersion coefficient of Single Mode Fiber is increased due to which the FWM is reduced but signal quality also deteriorates due to "dispersion effects" thus the need for Dispersion Compensating Fiber (DCF) arises. The negative value of dispersion in DCF compensate the effect of positive value of dispersion in SMF and thus greatly decreasing the efficiency of FWM. The usage of variable channel spacing is also done for the mitigation of FWM.

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