# SIMULATION AND EXPERIMENTAL INVESTIGATION OF MITIGATION OF FWM EFFECTS IN FRONTHAUL TRANSMISSION SYSTEM

**THESIS REPORT**

*Submitted in partial fulfillment of the requirements for the award of the*
*Degree of Master of Technology in Electronics and Communication*
*Engineering with specialization in Communication Systems by the*
*A P J Abdul Kalam Technological University*

*by*

**ELSA CLEETUS**
Reg.No TKM21ECCS04

**DEPARTMENT OF ELECTRONICS AND COMMUNICATION ENGINEERING**

**TKM COLLEGE OF ENGINEERING**

**KOLLAM 691 005**

**MAY 2023**

# SIMULATION AND EXPERIMENTAL INVESTIGATION OF MITIGATION OF FWM EFFECTS IN FRONTHAUL TRANSMISSION SYSTEM

**THESIS REPORT**

*Submitted in partial fulfillment of the requirements for the award of the*
*Degree of Master of Technology in Electronics and Communication*
*Engineering with specialization in Communication Systems by the*
*A P J Abdul Kalam Technological University*

*by*

**ELSA CLEETUS**
**Reg.No TKM21ECCS04**

**DEPARTMENT OF ELECTRONICS AND COMMUNICATION ENGINEERING**

**TKM COLLEGE OF ENGINEERING**

**KOLLAM 691 005**

**MAY 2023**

**DEPARTMENT OF ELECTRONICS & COMMUNICATION ENGINEERING**

**TKM COLLEGE OF ENGINEERING**

**KOLLAM 691 005**

## CERTIFICATE

Certified that this Project report titled **” SIMULATION AND EXPERIMENTAL INVESTIGATION OF MITIGATION OF FWM EFFECTS IN FRONTHAUL TRANSMISSION SYSTEM”** is a bonafide record of the work done by **ELSA CLEETUS** (Reg.No.TKM21ECCS04) under my supervision, in partial fulfillment of the requirements for the award of the Degree of Master of Technology in Electronics and Communication Engineering with specialization in Communication Systems by the A P J Abdul Kalam Technological University.

**Guide**
**Prof. SANIYA AZEEM**
Assistant Professor
Dept. of ECE, TKMCE

**Coordinator**
**Dr. NISHANTH N**
Associate Professor
Dept. of ECE, TKMCE

**HOD**
**Prof. SHABEER S**
Head, Dept. of ECE
TKMCE

# Acknowledgements

At the outset, I consider it my duty to thank Almighty God for giving me the necessary wisdom to successfully complete this project presentation.

I thank **Prof. SHABEER S**, HOD, Department of Electronics and Communication, for his encouragement and support.

I express my sincere thanks to our PG coordinator, **Dr. NISHANTH N**, Professor, Department of Electronics and Communication Engineering, for the support and encouragement during the course of this presentation.

I take this opportunity to express my sincere gratitude and profound thanks to my guide, **Prof. SANIYA AZEEM**, Assistant Professor, Department of Electronics and Communication, for her advice, supervision and patience during the course of project preparation and presentation and for providing me guidance and critical inputs in the preparation and presentation of my project.

I would also like to express my sincere gratitude to all my teachers, friends and my family for their much needed support during the preparation and presentation of the project.

**ELSA CLEETUS**
TKM21ECCS03

# ABSTRACT

Over the recent years, the need for high capacity and high broadband wireless access were in demand and in order to satisfy it various technologies were introduced among which RoF came into existence which has low attenuation, immunity to electromagnetic interference and superior signal integrity. Therefore, it enables the transmission of signal over long distance and thus improves the capacity and mobility of the optical transmission system. In this review, we would concentrate on analyzing the effect of fiber nonlinearity such as Four wave mixing (FWM) effect in long haul transmission system. Basically, FWM is an impairment due to the interaction of field intensity with the fiber refractive index which results in signal broadening, undesirable signal modulation and attenuation and thereby limiting the transmission capability of long-haul system. A parametric analysis for reducing the power level of crosstalk generated by FWM by incorporating various optical components in the communication link is done and optimization based on channel spacing, input power, fiber length, bitrate, is performed.

This article discusses the nonlinear effect, four-wave mixing (FWM), which lowers the performance of optical communication systems. The concept of Linear polarization was introduced to reduce the effects of FWM. Here, orthogonal polarization is used with the modulation technique NRZ. Linear polarization was found to reduce the effect of FWM more than round polarization. Weaknesses of the four wavelength mixes were analyzed for various levels of input power. The capacity of a four-wave mixing product (FWM) is assessed by an optical spectrum analyzer. System performance is analyzed in terms of quality factors and BER.

*Keywords - FWM, WDM, RoF*

# Contents

# List of Figures

# Chapter 1

# Introduction

Data rates have significantly increased in recent years as a result of the steady rise in demand for wired and wireless networks [26]. The micro cellular system was developed to meet the rising need for high capacity and high-speed broadband wireless connectivity. This technology, which consists of numerous small cells, has garnered interest as a useful way to provide high-speed and high-capacity communication by optimizing frequency use. Nevertheless, due to the high cost of installing several Base Stations (BSs) to cover the entire service region, this method has some drawbacks. The investment is increased by the inevitable need for complex channel control methods among BSs for spectrum delivery and hand off operations. By adopting a system design in which complex operations are carried out at a Control Station (CS) rather than a Base Station (BS), this enormous increase in data traffic can be handled [27,28]. Radio over Fiber (RoF), which is a primary access network solution for high-speed communication systems, uses optical fibre to transmit radio signals [29]. Optical fibre with low attenuation, high signal integrity, and immunity to electromagnetic interference is used in RoF technology. As a result, it makes wireless networks more mobile and ubiquitous by allowing signal transmission over large distances.

RoF is a technology that uses radio waves to alter light. For wireless access, this light will be sent over optical fibre [30-31]. The key benefits of employing optical fibres for radio signal transmission include their large bandwidth, low transmission loss, and immunity to electromagnetic interference [32-33]. Using this architecture, a central station may generate optical and ultra-broadband radio transmissions. The base stations receive the modulated optical signals that have been transmitted across the optical fibre. The subscriber will receive the base station's demodulated millimetre wireless signals after they are broadcast through the antenna. The spectral efficiency of mobile services rises with every new network technology release. The mobile wireless industry has been growing, inventing, and expanding since the early 1970s. From 0G to 4G, mobile wireless technologies have seen four or five iterations of innovation [34-35]. The first generation of wireless networking technology, most frequently referred to as cell phones, is what the term ”first generation” refers to. Mobile radio telephones and other technologies like the Mobile Telephone System (MTS), Advanced Mobile Telephone, and 1G technology, which replaced 0G technology, In the 1970s and 1980s, Push to Talk (PTT), the Improved Mobile Telephone Service (IMTS), and the Advanced Mobile Telephone System (AMTS) were developed [36]. Unlike its replacement, 2G, 1G wireless networks used analogue radio signals. It has Low capacity, erratic handoff, poor voice connectivity, and lack of security due to audio communications being replayed in radio towers, making them susceptible to outside eavesdropping. Hence the proposed Model of 8/32 RoF-BF – Linear Polarizer System is used to mitigate the FWM effects which clearly shows the reduction of FWM side band power enhance the Q Factor in comparison with the normal DCF-EDFA 8/32 RoF-BF system.

# Chapter 2

# Literature Review

This section, presents an overview of some works related to the proposed approach.

[1] Is based on an improved 32 channel 256 Gbps DWDM-based RoF optical system with the ability to transmit data at 8 Gbps per channel and provide the best signal reception over distances of 60 km and 120 km, the integration of DCF and FBG as dispersion compensators has been examined. When used in 8 channel mode with a 4 Gbps per channel bit throughput, the suggested system achieved a very high Q factor of about 79 for 50 GHz channel spacing. The observed spectra also demonstrated a significant 6 dBm reduction in FWM side band power level. The transmission quality was shown to be significantly superior than the existing WDM-RoF systems for long distance traversal (120 km) and constrained channel spacing (50 GHz). Here they also do the comparative study with the existing two RoF systems. First off, the suggested technique produced a fantastic Q factor of roughly 79 for when used in 8 channel mode at 4 Gbps per channel bit rate and 50 GHz channel spacing, lowering FWM side band power level by an average of 6 dBm, as seen from the measured spectra. Second, the simulated 32/256 DWDM-RoF system achieved much higher values of Q factor and BER, especially for constrained channel spacing, when compared to another current 16 channel RoF system (50 GHz). Consequently, it can be concluded that compared to the current WDM-RoF systems, the proposed DWDM-RoF system is significantly more efficient for long-distance transmission at 50 GHz channel spacing.

In [2] All the necessary hardware for converting an electrical signal to an optical signal and vice versa is included in a RoF network. To enhance the number of wavelengths sent by a single fibre, WDM systems are used in optical links [47]. It has been noted that nonlinear deficiencies in the RoF system are caused by inelastic scattering and variations in the fibre core's refractive index with optical intensity [48]. Self-Phase Modulation (SPM), Cross-Phase Modulation (CPM), and Four-Wave Mixing (FWM) are examples of non-linear impairments caused by the interaction of the field intensity with the fibre refractive index. Brillouin (SBS) and Raman (SRS) are examples of non-linear impairments caused by stimulated scattering mechanisms. These flaws reduce the long-haul system's capacity to transmit by causing signal broadening [49], undesired signal modulation, and signal attenuation. Given that they produce an accumulated effect over a long distance, these non-linearities are extremely important for the deployment of the RoF system. When compared to a WDM system, the non-linear effects are seen to be less severe for a single optical channel. A statistical analysis [50] for lowering the power level of crosstalk produced by FWM has been described. To lessen the FWM effect for the deployment of RoF systems, an optimization technique based on performance factors (channel spacing, channel power, and fibre area) has been presented. FWM has a significant impact on WDM systems because it causes crosstalk, which lowers system performance. Moreover, channelling with irregular spacing was suggested for WDM systems to lessen the FWM effect. The FWM crosstalk power for three channel systems is calculated using an analytical model that is provided in this study. A 32Gbps simulation model for an 8-channel system is also suggested in order to mitigate the FWM effect by the use of the Bessel Filter. The reduction in FWM can be accomplished, it is decided, by lowering the input source power and increasing the quantity and spacing of input channels. Here FWM Sideband power is reduced by 4 dbm.

In [3] Data traffic over optical networks has increased as a result of the internet's tremendous growth in popularity today. Increase the optical bandwidth in the WDM system to handle the traffic load. It can provide the high baud rate data transmission requirements [51]. While data traffic on optical fibres increases, the number of wavelengths in a compressed wavelength division multiplexing (DWDM) system also rises [5,11,19]. The nonlinear effect will grow as the optical fibre's resistance rises, which might affect the signal's effectiveness and ultimately lower system performance [52]. To lessen the Four Wave Mixing (FWM) effect, an orthogonal polarisation technique is used in this research and is examined. When compared to the current circular polarisation method, the suggested orthogonal polarisation method reduces FWM products more effectively. It has been employed with a variety of modulation schemes, including NRZ, RZ, GAUSSIAN, and RAISED COSINE. Analysis of FWM reduction is done for different input powers. The use of RZ with orthogonal polarisation provides the best reduction in FWM among the four approaches.

According to [4] to minimise the nonlinear effects such as Four Wave Mixing (FWM) of dense wavelength division multiplexing (DWDM) for optical long-haul networks, chirped Fibre Bragg Grating (FBG) has been developed. Also, many chromatic dispersion levels have been used to investigate the proposed approach. While using Chirped FBG, optical amplification is necessary to both amplify the signal and counteract fibre loss. After demultiplexing, the Chirped FBG and EDFA would be applied to ensure fewer nonlinear effects in data receivers. Moreover, the FWM impact has been studied at various dispersion values. Opti system simulator has been used to mimic the suggested solution. Also, the study has concentrated on two optical communication scenarios, the first with low chromatic dispersion and the second with high dispersion, allowing evaluation of the impact of chromatic FBG on FWM minimization in both cases. Thus, the simulation results demonstrate that the suggested solution using Chirped FBG delivers low FWM nonlinear effects and high chromatic dispersion correction regardless of chromatic dispersion level, which enhances synchronisation and signal transmission in WDM long haul networks.

According to [5] reliable parameters that contribute to the formation and enhancement of FWM are examined, modelled, and based on extensive sets of results, a thorough analysis has been done to lower the FWM. The simulated results generated using Optisys simulator and nine crucial parameters reveal extremely insightful information for the elimination of nonlinear effects in WDM. Nine different parameters including input power, channel spacing, number of channels, core size of fibre, modulation technique, duty cycle of input, optical gain, and effect of placement of OA (Optical Amplifier) with DCF (Dispersion Compensating Fiber), have all been examined in detail. The results of these simulations have been thoroughly examined. These attributes metric analysis provides us with detailed insight into how various parameters might be traded off to lessen FWM. Also, by utilising their parametric analysis, they can optimise their systems without reducing bandwidth or adding any additional hardware. Based on the simulated results with the antecedental mentioned system characteristics, it is determined that a real trade-off needs to be made to best reduce FWM.

[6] is thought to be a 32-channel 40-Gbps system, the effects of FWM for different input power levels, effective fibre areas, channel spacings, and modulation styles are examined. With the Single Parameter Optimization (SPO) technique, an optimum DWDM system is created taking all of these factors into account. Here by changing the channel spacing, input power and various modulation format they have analysed the effect of these parameters on FWM. They concluded from their observations that the following conditions, such as the channel spacing should be as high as possible, input power should be as low as possible, the fibre cross-sectional area should be as high as possible, and preferably RZ modulation is to be used in comparison to NRZ modulation, can be maintained in order to minimise the detrimental FWM effect for higher data rates and long-haul communication systems.

In [7] Here they examined the effects of four-wave mixing (FWM) and cross-phase modulation (XPM) in this research. As a result of its precoded property, the results demonstrate that ODB performs better when it comes to reducing the FWM and XPM effects. The FWM-induced sensitivity penalty utilising ODB is decreased to 2 dB from the erratic sensitivity penalty based on NRZ and PAM4. Furthermore, using ODB reduces the XPM-induced sensitivity penalty by 1 dB, outperforming NRZ and PAM4 modulation formats by nearly 5 dB.

In this research, here use NRZ, PAM4, and ODB modulation formats to investigate the non-linear effects in WDM-PON based 5G fronthaul networks, including the XPM effect in C-band and the FWM impact in O-band. When compared to the unpredicted sensitivity penalty when utilising NRZ and PAM4, the FWM-induced sensitivity penalty is lowered by using ODB by up to 2 dB because of the precoded feature. Moreover, the ODB analysis performed by the XPM has a 1-dB sensitivity penalty, which is more than 5 dB better than the NRZ and PAM4 modulation formats.

The first step is to examine the sensitivity penalty caused by FWM in 5G fronthaul networks built on WDM-PON As can be observed, for 110-2 BER, when Channel 1 is transmitted after BtB, the acquired sensitivity is -22 dBm. However, a 2-dB sensitivity penalty is incurred when Channel 1 is transmitted after 20 km SSMF due to the -20 dBm achieved sensitivity. More significantly, Channel 6 experiences the most severe FWM impact because it is in the middle of the channels and its BER (using Low Density Parity Check (LDPC) coding) cannot even meet the BER criteria of 110-2, resulting in an erratic sensitivity penalty. Moreover, PAM4 gives comparable results, as seen in despite the unpredictable FWM-induced sensitivity cost of Channel 6. When Channel 6 is transmitted after BtB/20 km SSMF, it can be demonstrated using the ODB modulation scheme that the acquired sensitivity is -22 dBm/-20 dBm, leading in a 2-dB sensitivity penalty. Moreover, the FWM-induced sensitivity penalty can be mitigated by utilizing the pre-coded characteristics of ODB at the Tx side. In [53], the optical phase conjugators (OPCs) are used to mitigate the FWM effect and a 0.8-dB mitigation improvement is achieved. In [54], polarization mode dispersion (PMD) emulators are employed for eliminating the FWM effect, obtaining a 5-dB mitigation improvement. While, the use of additional devices in will undoubtedly increase the system cost. After comparison, it is clear that our work is showing structural simplicity and improved performance.

In [8], It emphasis that one of the main limiting phenomena for wavelength division multiplexed optical communication systems is four wave mixing (FWM). In optical communication over single mode fibre, this work analyses four wave mixing with sub-plank higher-order dispersion (HOD) parameters up to eighth order. For various channel powers, effective core areas, and channel spacing, the four wave mixing power with a mixture of dispersion parameters up to eighth-order dispersion has been examined and compared with the predominant second-order dispersion parameter. It has been found that the combined effects of dispersion parameters can reduce four-wave mixing by 10-15 dB and make it easier to infer the performance of four-wave mixing using HOD parameters. Hence, the results can offer greater guidance in selecting fibre characteristics for effective FWM control across a range of applications.

The impact of higher-order dispersion parameters on FWM has been thoroughly numerically analysed and is reported in this study. The existence of higher-order dispersion characteristics reduces the FWM power by 10-15 dB, as shown theoretically and analytically. The FWM power is suppressed by a combination of dispersion settings after 50 mW channel power. So, at higher pump outputs, the combinations of dispersion parameters lead to increased optical communication system performance. Our findings can help modern fibre optic systems choose the best fibre parameter choices and can be used to develop effective dispersion correction strategies for long-distance communication networks.

In [9], In this study, experimentation and modelling are used to investigate the influence of nonlinear effects on the WDM-PON system enabling 5G fronthaul. There are established 25 Gb/s NRZ multi-wavelength systems with a 200-GHz transmission channel spacing of 25 km SSMF. The experimental results demonstrate that even when the phase matching criterion is roughly satisfied in the O-band, the second channel of the 4-channel example cannot exceed the BER threshold of 1.0 x $10^3.Thefindingsindicatethat, whenthesystemreachesthepowerbudgetof30.9dB.$

The number of additional wavelengths greatly increases when the number of wavelengths is increased to 4. It demonstrates that when the channel spacing is raised to 400 GHz, the number and powers of new frequencies are decreased in the 4-channel situation. Because the signals are delivered in situations with high input power, tight channel spacing, and zero dispersion, the FWM effect is easily observed in studies. According to the experimental findings, when the transmitted wavelengths are in the zero-dispersion zone in the O-band, the second channel cannot surpass the BER threshold of 1.0 x $10^3inthe4 - channelsituation.$

Additionally, the 12-channel WDM system is simulated, and the results demonstrate that, in the worst case, only the first and last [55-56] channels in the O-band may meet the BER criterion when the power budget of 30.9 dB is met.

[10] Cross Phase Modulation (XPM), Stimulated Raman Scattering (SRS), and Four Wave Mixing are the nonlinearities that develop in WDM systems (FWM). Moreover, it is discovered that the channel spacing, input power, and dispersion all affect these nonlinearities. Two strategies to get rid of FWM and SRS effect have been put forth in this study. Initially, by increasing the input power, the fibre optic link has been studied. According to the analysis, increasing the input power causes the FWM impact to rise. However, for long-distance fibre optic links, the transmission power should be at its maximum. Before going via the fibre link, the circular polarizers are alternately placed in each transmitter to lessen the FWM effect. The best distribution of input power is another approach that has been suggested to get

rid of SRS. By distributing the transmitted power in a random manner, the undesirable power tilt caused by the SRS effect is reduced. The software used is OPTSIM and OPTISYSTEM to conduct the simulation investigations. The simulations were run for multichannel systems with uniform channel spacing. It was discovered that the system performance was also enhanced by the optimal power level allocation.

Several modulation approaches are used to lessen the nonlinear impairments [57]. As the system is used over greater distances, the launching power should be increased in order to achieve high data rates. On the other hand, if the transmission input power increases, nonlinearities also do [58]. The nonlinear effects like FWM and SRS were examined and mitigated here for varied input power levels. Circular polarizers also lessen the FWM effect, and BER analysis is used to determine how much input power should be used optimally. The transmitted power is distributed at random to reduce the SRS impact. By changing the input power level, the fibre optic link has been examined with 8, 32, and 64 channels. According to the analysis, the FWM effect can be reduced by adding alternate circular polarizers before transmission. When the input power level is between 0 and 4 dBm, the system performs better.

# Chapter 3

# Proposed Model

The goal of this article is to reduce the effect of four-wavelength mixing (FWM) by incorporating the concept of Linear polarization into WDM systems. It uses Linear polarization and NRZ modulation to reduce FWM. FWM impact strength is tested for various input power levels, such as 0 dBm, 10dBm and 20 dBm. An optical spectrum analyzer is used to analyze the FWM power. BER analyzers examine eye charts, Q and BER factors to analyze system performance. Fig. 3.1 represents the Transmitter-Receiver section of the proposed system. Fig. 3.2 represents and illustrates the concept of the 8/32 RoF-BF configuration incorporating DCF and EDFA to analyze the FWM effects and thereafter we bring forth in Fig. 3.3, the proposed 8/32 RoF-BF-Linear Polarizer system which is also shown clearly in parts and with the help of a block Diagram from Fig. 3.4-3.6 to distinguish the difference in increase in mitigation of FWM effects and thereby the increase of Q Factor for high data rate transmission systems.

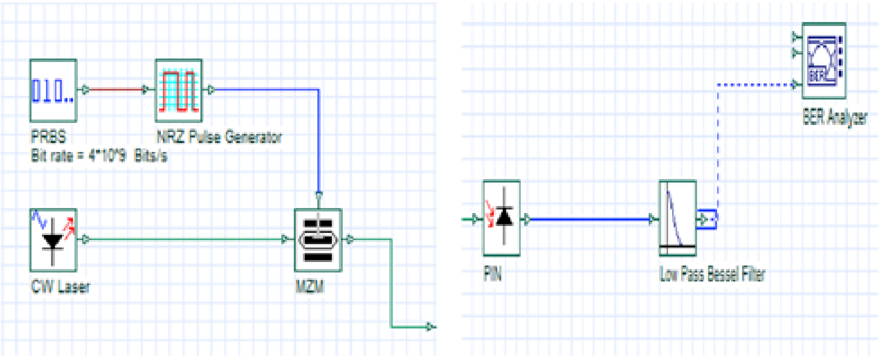


Figure 3.1: Transmitter-Receiver Section

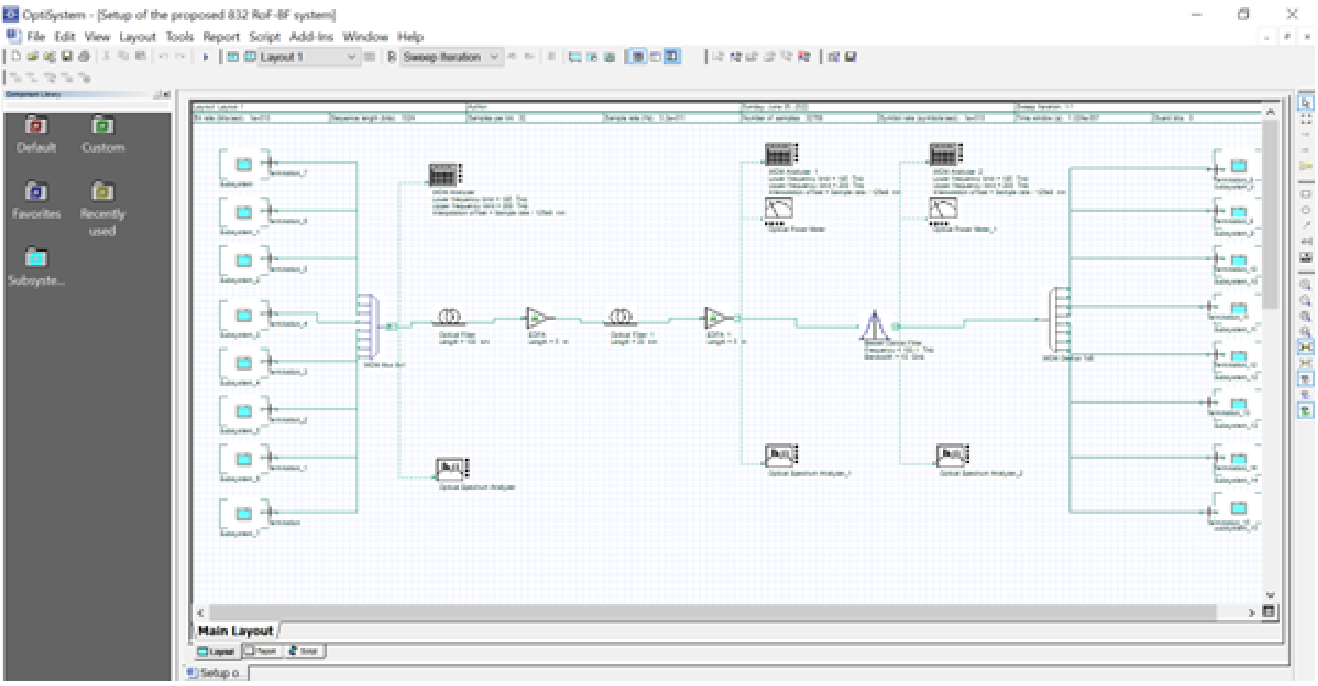


Figure 3.2: Setup of 8/32 RoF-BF System incorporating DCF and EDFA

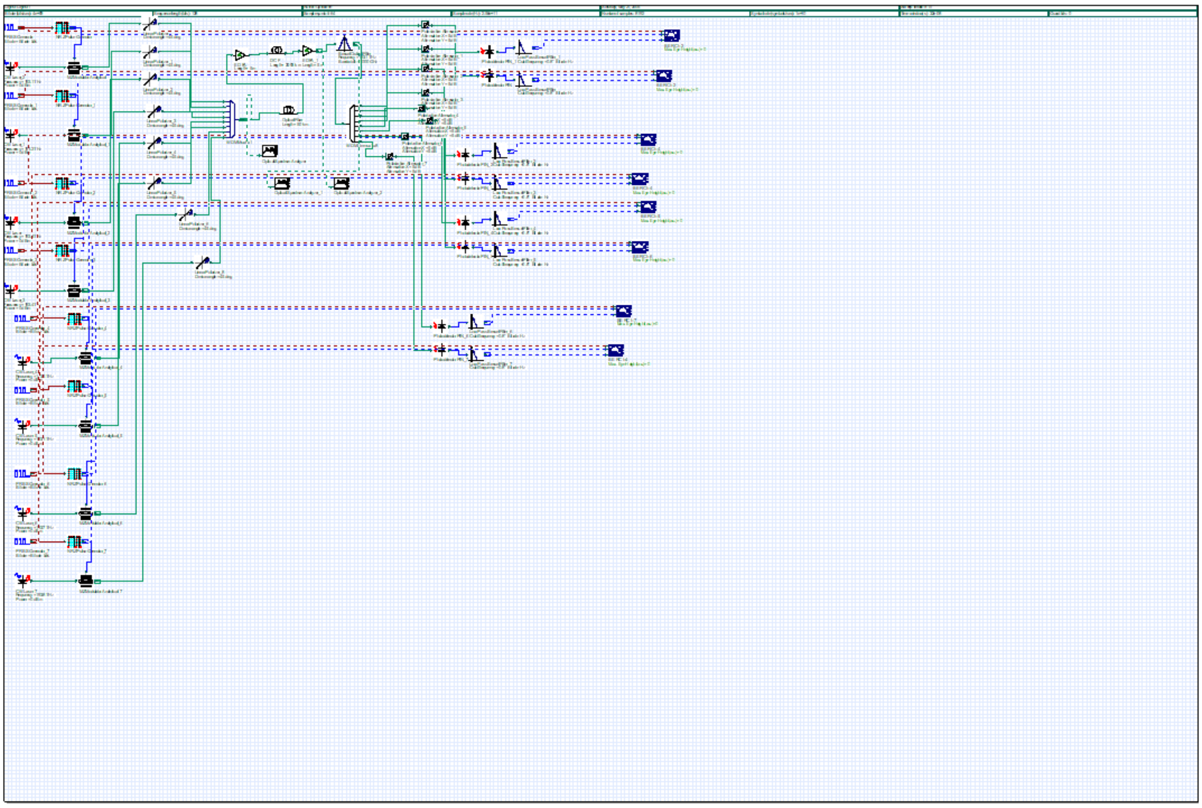


Figure 3.3: Setup of 8/32 RoF-BF System incorporating Linear Polarizer

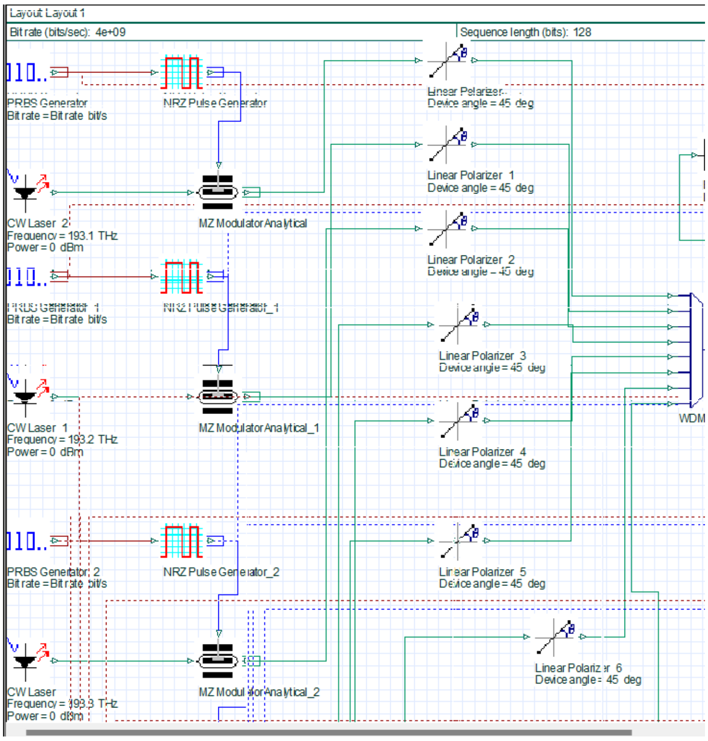


Figure 3.4: Setup of 8/32 RoF-BF System incorporating Linear Polarizer Part 1

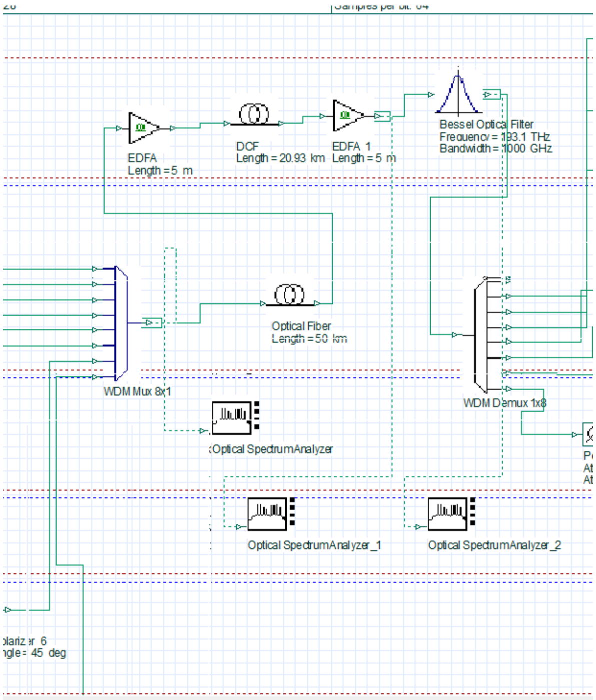


Figure 3.5: Setup of 8/32 RoF-BF System incorporating Linear Polarizer Part 2

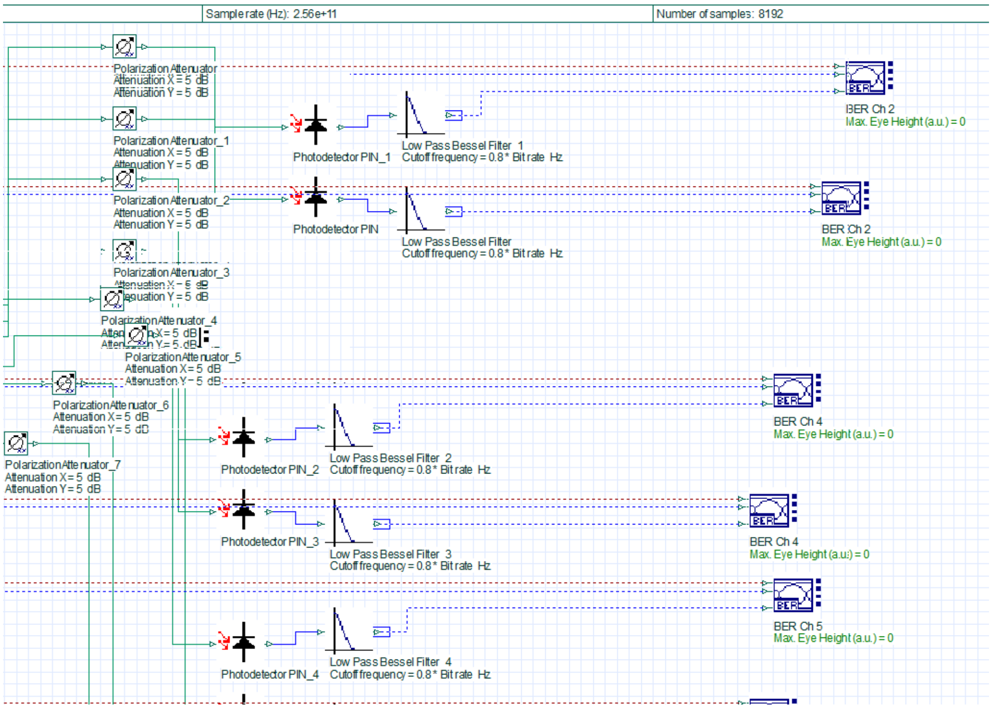


Figure 3.6: Setup of 8/32 RoF-BF System incorporating Linear Polarizer Part 3

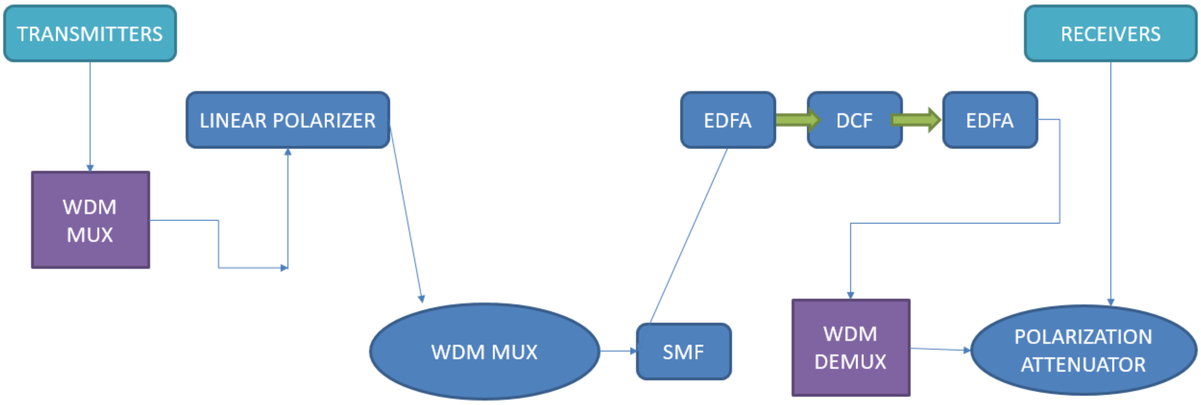


Figure 3.7: Setup of 8/32 RoF-BF System incorporating Linear Polarizer System in Block Diagram

Filter, amplifiers, a transmitter, a transmission medium, and a receiver make up the system. The Mach-Zehnder Modulator (MZM) and a light source, which produce continuous wave millimeter wave optical signals that transmit at various wavelengths, make up the driver circuit of the transmitter seen in Fig. 4(a). The driver circuit has line coding formats that convert the ON/OFF pulses produced by the PRBS generator, which has a bit rate of 4 Gbps, into Non-Return to Zero (NRZ) format. The NRZ coding scheme is used because it is simple to implement and has a small spectrum. The MZM superimposes this coded information signal onto a high frequency optical carrier. Long-distance communication is improved when the MZM and Erbium Doped Fiber Amplifier (EDFA) are used together because the MZM couples more optical output power into an optical fiber, supports faster transmission rates, and offers minimal chirp and excellent compatibility with the EDFA. A linear polarizer produces a beam of light whose electric vector is vibrating primarily in one direction with only a small component vibrating in the direction perpendicular to it thereby reducing the reflections. To boost system capacity, the WDM combines the modulated optical output from many laser transmitters operating at various wavelengths. Through Single-Mode Fiber (SMF), the multiplexed optical signal is transmitted. SMF transmits data at a high rate and travels farther than Multi-Mode Fiber (MMF), although the transmission distance is constrained by the dispersion and non-linearities caused by the fiber. To make up for the loss and dispersion, optical amplifiers and Dispersion Compensating Fiber (DCF) are used in a link. The first amplifier in this link serves as an in-line amplifier by boosting the incoming signal from a low level to a predetermined level. The design includes an EDFA because it offers the necessary optical amplification with the least amount of extra noise. The DCF receives the amplified signal and produces equal and opposite dispersion ranging from 70 ps/nm-km to 90 ps/nm-km to link dispersion, resulting in zero chromatic dispersion. A pre-amplifier needs to be added before the optical receiver to accommodate the demand for increased receiver sensitivity and SNR. As a result, the second EDFA serves as a pre-amplifier with high gain and low noise levels. Bessel Filter must be incorporated into the architecture of the optical fiber link in order to reduce the fiber nonlinearities caused by the specific FWM. Bessel filters are used in design because they have characteristics such a maximum flat group delay, slow cut-off and overshoot, and—most importantly—they maintain the wave shape of filtered signals in the pass band, which directly results in the optimum phase response. The receiver receives the filtered optical signal. The optical detector, filter, and bit error rate (BER) analyzer make up the receiver in Fig. 3.1. To reduce the noise produced by the link, the Positive Intrinsic Negative (PIN) photo detector turns the incident optical signal into an electrical signal. This signal is then filtered with the aid of a Low Pass Bessel Filter. The BER analyzer evaluates the receiver's performance in terms of the Eye Diagram and Q-Factor. Three visualization tools—the optical power meter, the WDM analyzer, and the optical spectrum analyzer—have been used to show the impact of nonlinearity in optical fiber.

# Chapter 4

# Simulation Results And Discussion

The simulation result of 8/32 RoF-BF system using NRZ pulse generator along with DCF and EDFA is analyzed for varying channel spacing and input power. A long-haul RoF system incorporates an optical Bessel Filter to lessen the non-linear effect, particularly FWM, because the evaluation of non-linear impairments using the Non-Linear Schrodinger Equation (NLSE) method requires complex calculations. In the suggested system, the FWM effect can be diminished by significantly increasing the channel spacing (50 GHz - 100 GHz) while concurrently lowering the channel input power (20 dBm to 0 dBm). The following simulation parameters are considered in order to assess the impact of channel spacing in the proposed RoF system: input power level (0 dBm), fiber length (100 km), and dispersion (16.75 ps/nm-km). Fig illustrates the impact of expanding channel spacing and varying input power at the output. The device uses a Bessel filter to cut down on sideband power produced by fiber nonlinearity. It is obvious that as channel spacing is increased, less power is produced at the filter's output. But because the SNR is determined by Q-Factor, this power will not lower the SNR. Additionally, Q-Factor is raised, but the 50 GHz channel spacing yields the best Q Factor results and reduce the sideband power by -40 dBm.

Now we bring forth the introduction of Linear Polarizer into the link and results of mitigation of FWM effects has been analyzed by varying channel spacing and input power. The results of the link has been analyzed by fixing the polarization degree of each channel at conditions of Zero degree and Forty Five polarization angles.Fig. 4.1-4.29 depicts the comparison of Q Factors in respective channels when the combination

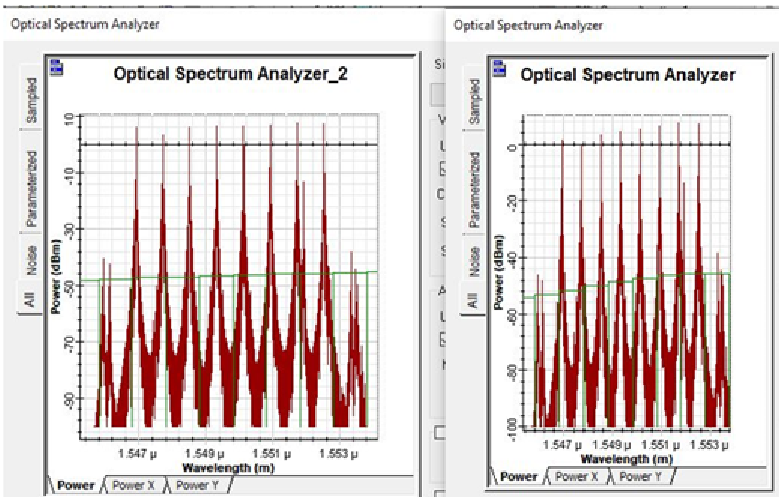


Figure 4.1: FWM side band power results using 50 GHZ Channel Spacing and 0dBm Power

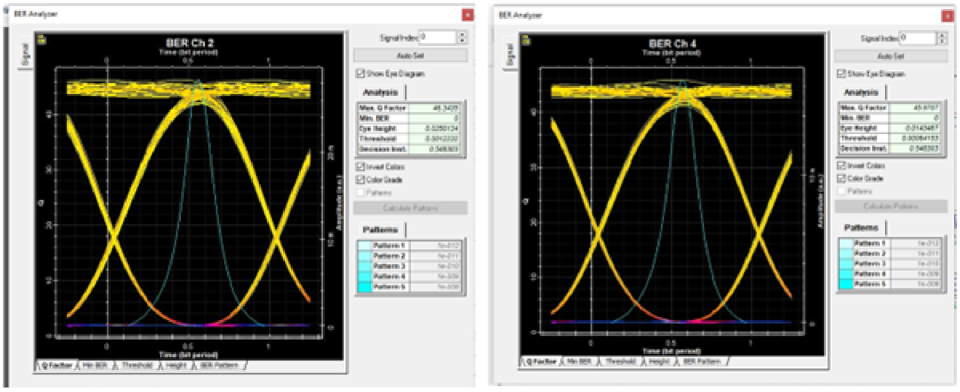


Figure 4.2: Q Factor results using 50 GHZ Channel Spacing and 0dBm Power

of DCF and EDFA is incorporated in the link and when Linear Polarizer is introduced in the link along with DCF and EDFA.Also we have done an analyzation study of incorporating Circular Polarizer in the link along with DCF and EDFA and from Fig. 4.27 , it is concluded that the use of Linear polarization gives better reduction in the power of FWM products while comparing with the use of circular polarization. Here, FWM is reduced by adjusting the polarization state of the adjacent channels.Fig. 4.14 represents the variation in Q Factors and BER of Linear Polarization at Zero Degree with the variation of channel spacing and input power and Fig. 4.20 represents the the variation in Q Factors and BER of Linear Polarization at Forty Degree with the variation of channel spacing and input power.

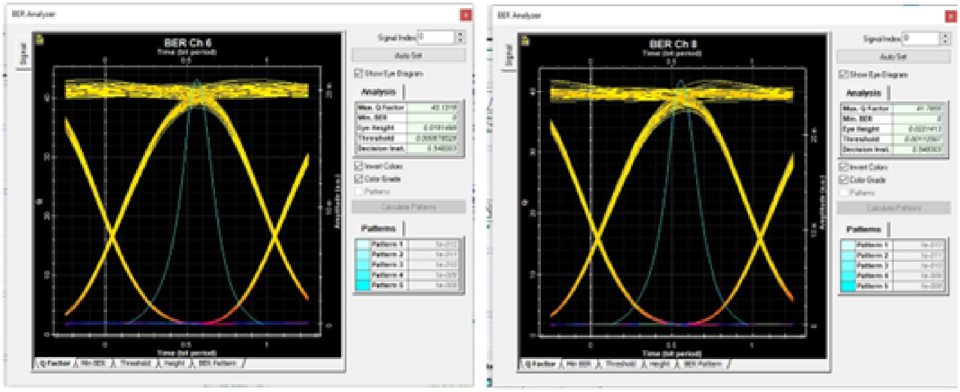


Figure 4.3: Q Factor results using 50 GHZ Channel Spacing and 0dBm Power

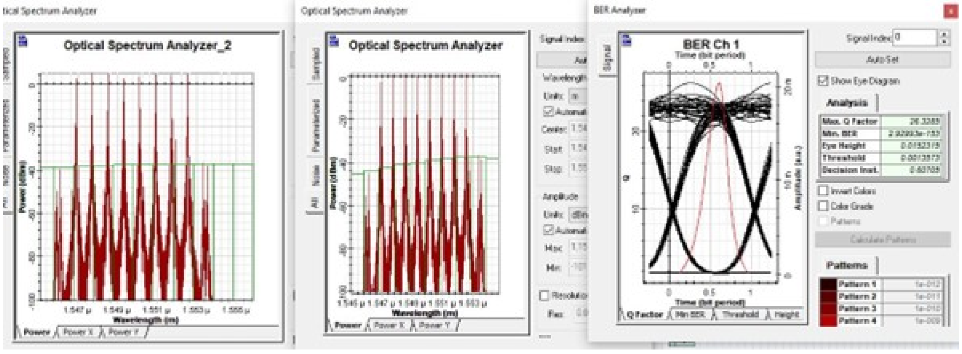


Figure 4.4: Q Factor results using 50 GHZ Channel Spacing and 10dBm Power

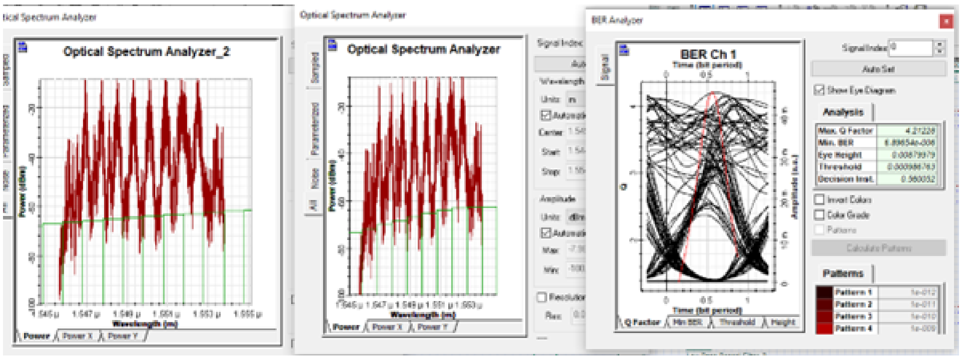


Figure 4.5: Q Factor results using 50 GHZ Channel Spacing and 20dBm Power

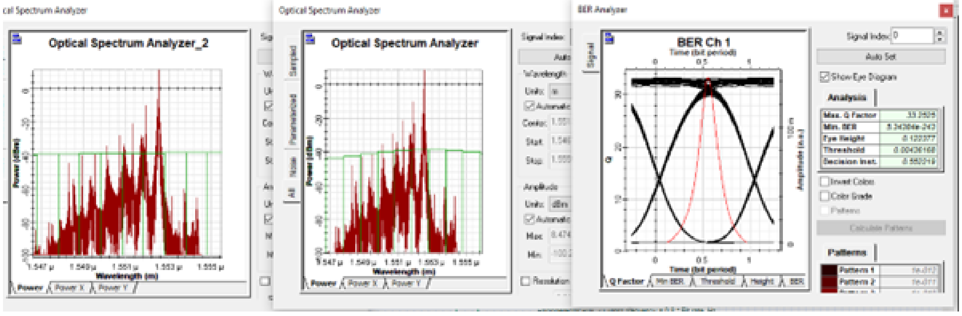


Figure 4.6: Q Factor results using 75 GHZ Channel Spacing and 0dBm Power

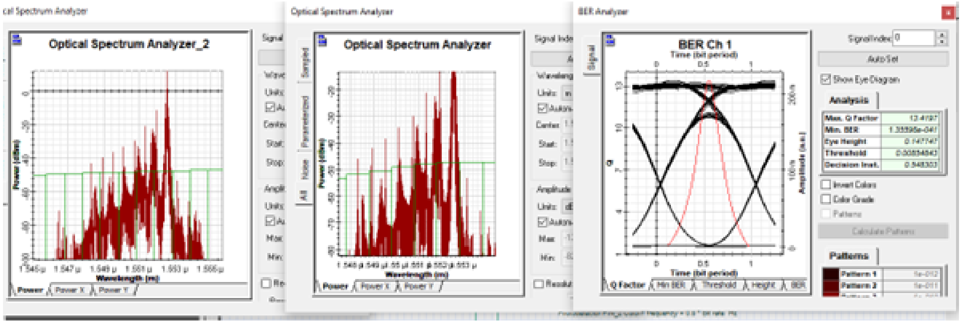


Figure 4.7: Q Factor results using 75 GHZ Channel Spacing and 10dBm Power

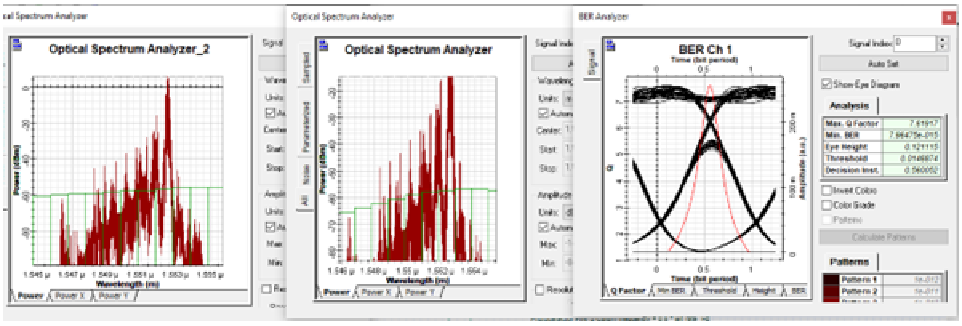


Figure 4.8: Q Factor results using 75 GHZ Channel Spacing and 20dBm Power

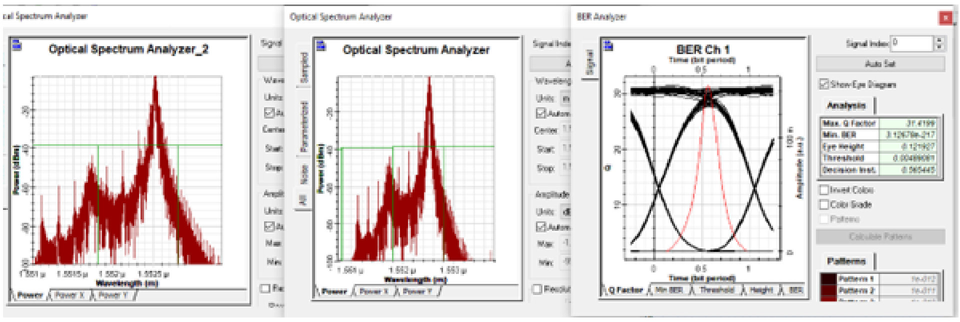


Figure 4.9: Q Factor results using 100 GHZ Channel Spacing and 0dBm Power

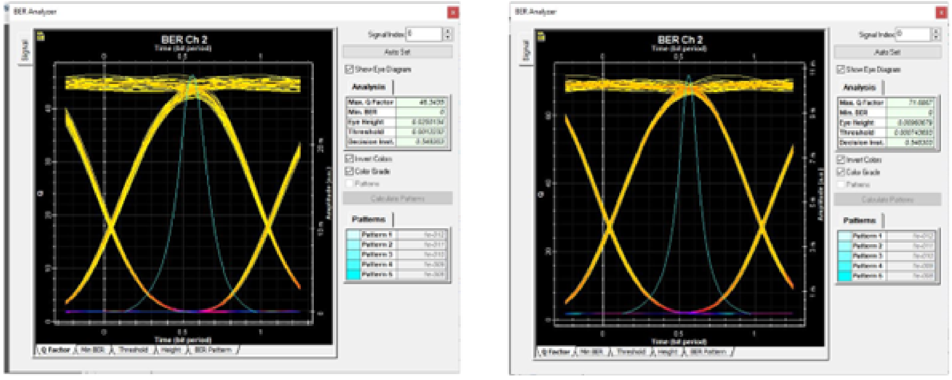


Figure 4.10: Q Factor results using 50 GHZ Channel Spacing and 0dBm Power using 0-degree polarization

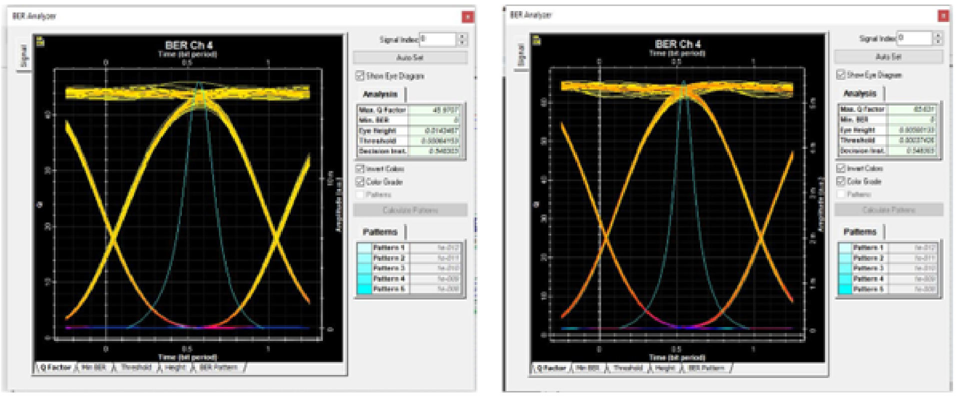


Figure 4.11: Q Factor results using 50 GHZ Channel Spacing and 0dBm Power using 0-degree polarization

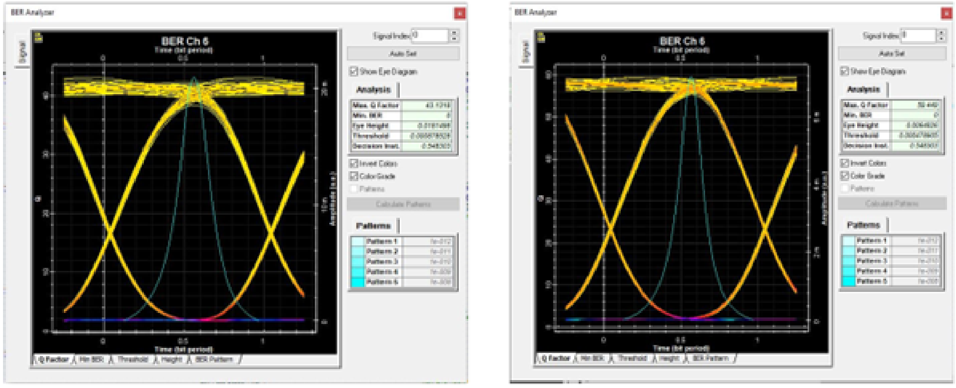


Figure 4.12: Q Factor results using 50 GHZ Channel Spacing and 0dBm Power using 0-degree polarization

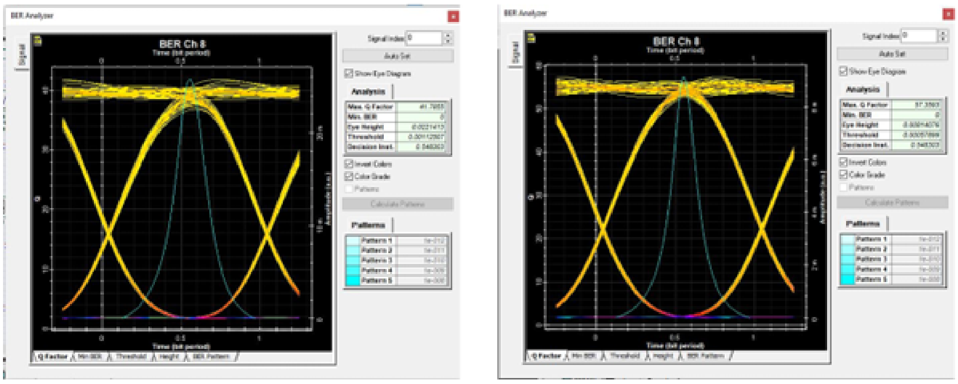
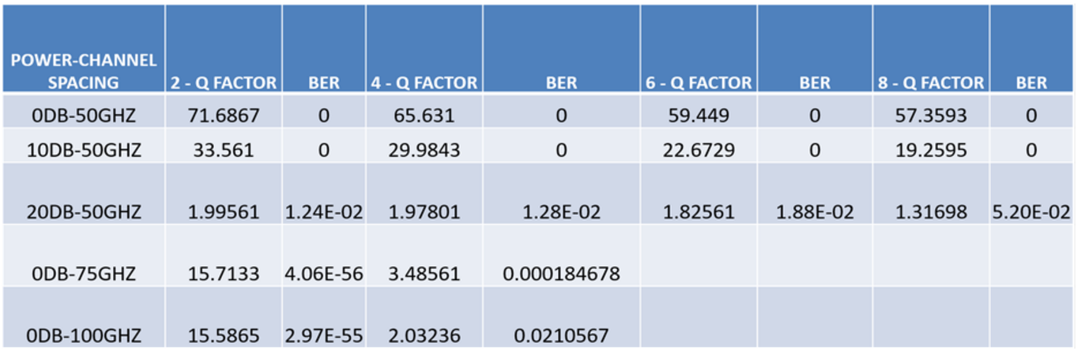
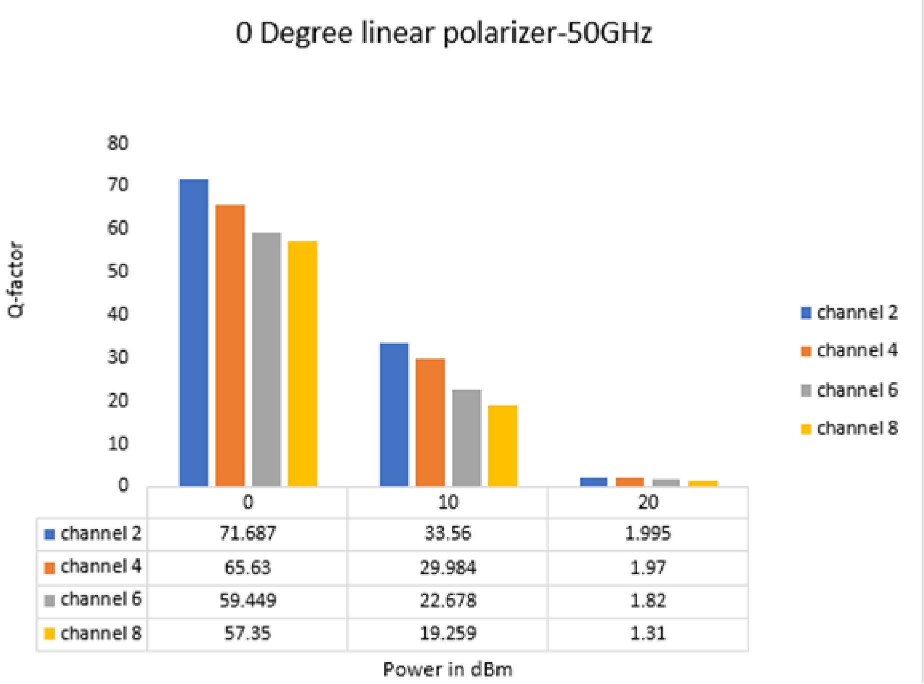


Figure 4.13: Q Factor results using 50 GHZ Channel Spacing and 0dBm Power using 0-degree polarization



| POWER-CHANNEL SPACING | 2 - Q FACTOR | BER | 4 - Q FACTOR | BER | 6 - Q FACTOR | BER | 8 - Q FACTOR | BER |
|---|---|---|---|---|---|---|---|---|
| 0DB-50GHZ | 71.6867 | 0 | 65.631 | 0 | 59.449 | 0 | 57.3593 | 0 |
| 10DB-50GHZ | 33.561 | 0 | 29.9843 | 0 | 22.6729 | 0 | 19.2595 | 0 |
| 20DB-50GHZ | 1.99561 | 1.24E-02 | 1.97801 | 1.28E-02 | 1.82561 | 1.88E-02 | 1.31698 | 5.20E-02 |
| 0DB-75GHZ | 15.7133 | 4.06E-56 | 3.48561 | 0.000184678 | | | | |
| 0DB-100GHZ | 15.5865 | 2.97E-55 | 2.03236 | 0.0210567 | | | | |

Figure 4.14: Tabular representation of results for zero degree polarization



| | 0 | 10 | 20 |
|---|---|---|---|
| 🟦 channel 2 | 71.687 | 33.56 | 1.995 |
| 🟧 channel 4 | 65.63 | 29.984 | 1.97 |
| ■ channel 6 | 59.449 | 22.678 | 1.82 |
| 🟨 channel 8 | 57.35 | 19.259 | 1.31 |

Figure 4.15: Bar Graph Representation of Q Factor using 0-degree polarization

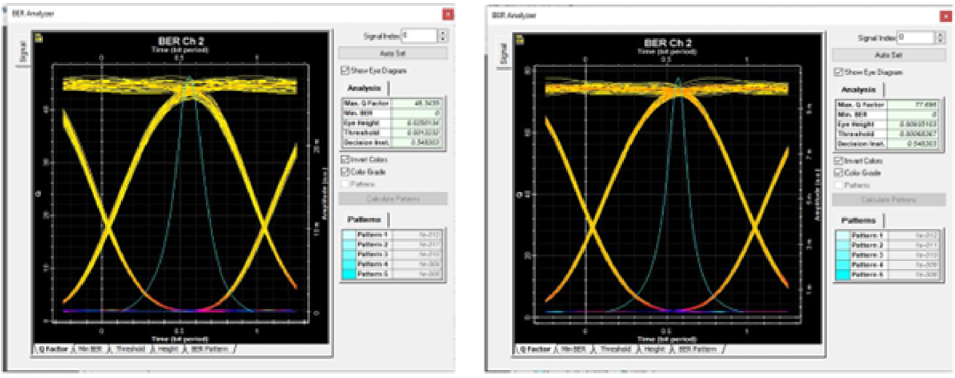


Figure 4.16: Q Factor results using 50 GHZ Channel Spacing and 0dBm Power using 45-degree polarization

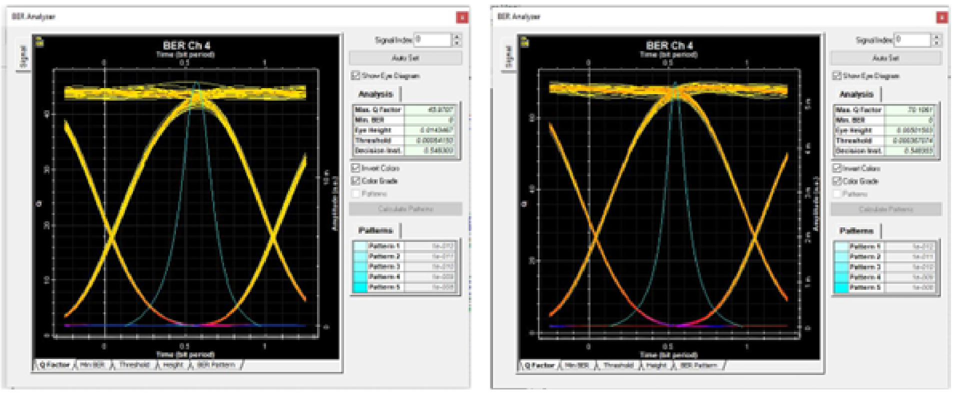


Figure 4.17: Q Factor results using 50 GHZ Channel Spacing and 0dBm Power using 45-degree polarization

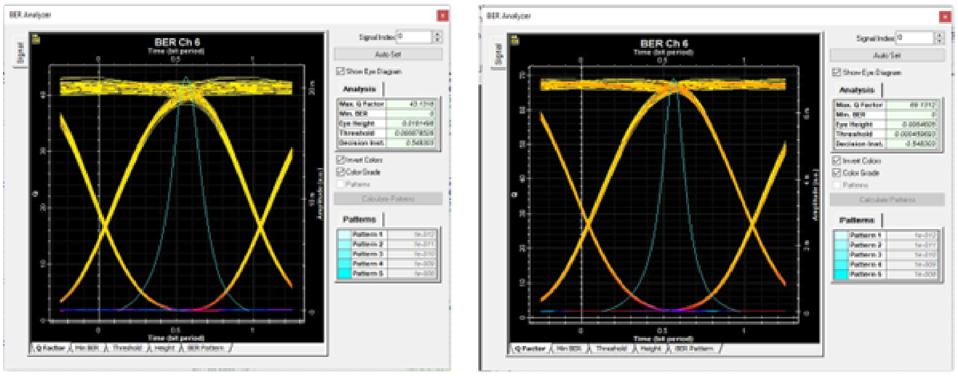


Figure 4.18: Q Factor results using 50 GHZ Channel Spacing and 0dBm Power using 45-degree polarization

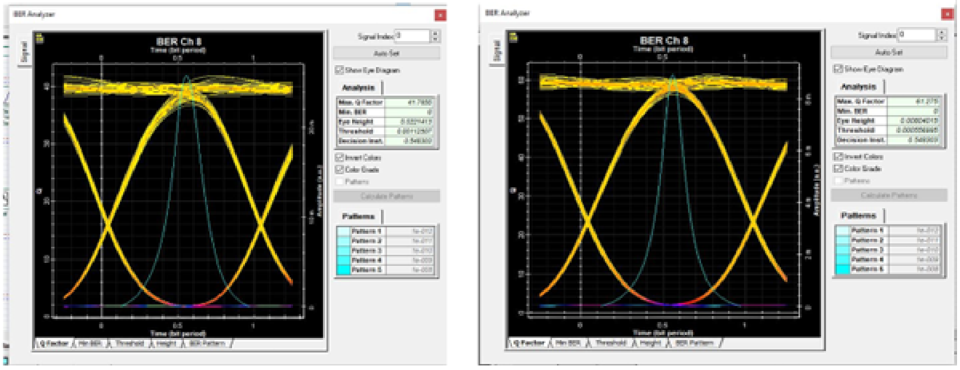
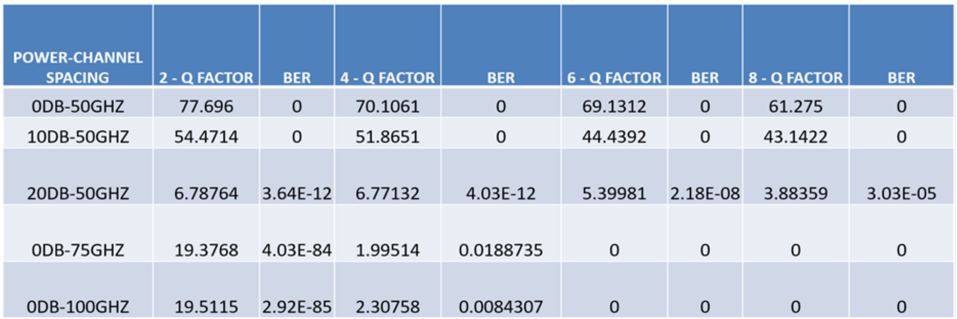


Figure 4.19: Q Factor results using 50 GHZ Channel Spacing and 0dBm Power using 45-degree polarization9



| POWER-CHANNEL SPACING | 2 - Q FACTOR | BER | 4 - Q FACTOR | BER | 6 - Q FACTOR | BER | 8 - Q FACTOR | BER |
|---|---|---|---|---|---|---|---|---|
| 0DB-50GHZ | 77.696 | 0 | 70.1061 | 0 | 69.1312 | 0 | 61.275 | 0 |
| 10DB-50GHZ | 54.4714 | 0 | 51.8651 | 0 | 44.4392 | 0 | 43.1422 | 0 |
| 20DB-50GHZ | 6.78764 | 3.64E-12 | 6.77132 | 4.03E-12 | 5.39981 | 2.18E-08 | 3.88359 | 3.03E-05 |
| 0DB-75GHZ | 19.3768 | 4.03E-84 | 1.99514 | 0.0188735 | 0 | 0 | 0 | 0 |
| 0DB-100GHZ | 19.5115 | 2.92E-85 | 2.30758 | 0.0084307 | 0 | 0 | 0 | 0 |

Figure 4.20: Tabular representation of results for Forty Five degree polarization

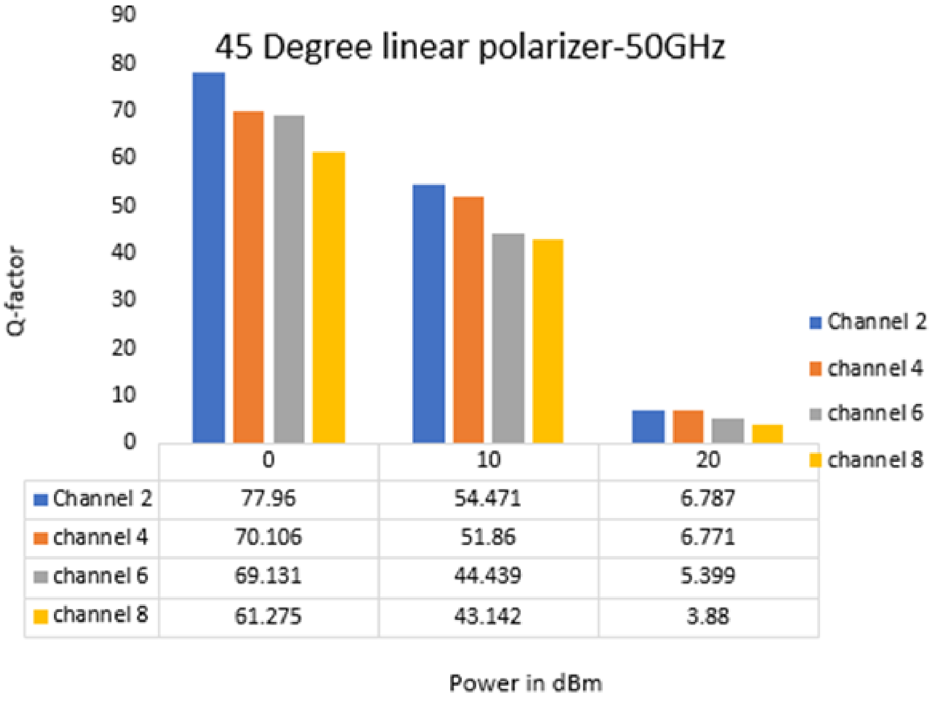


Figure 4.21: Bar Graph Representation of Q Factor using 45-degree polarization

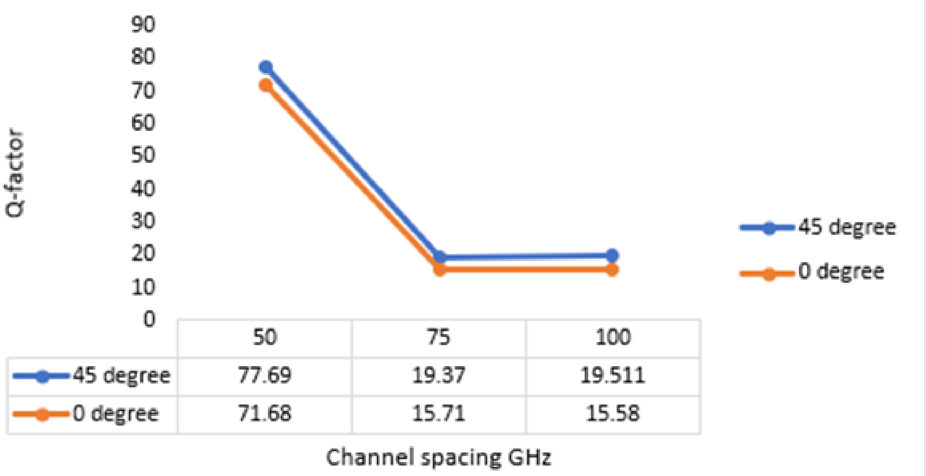
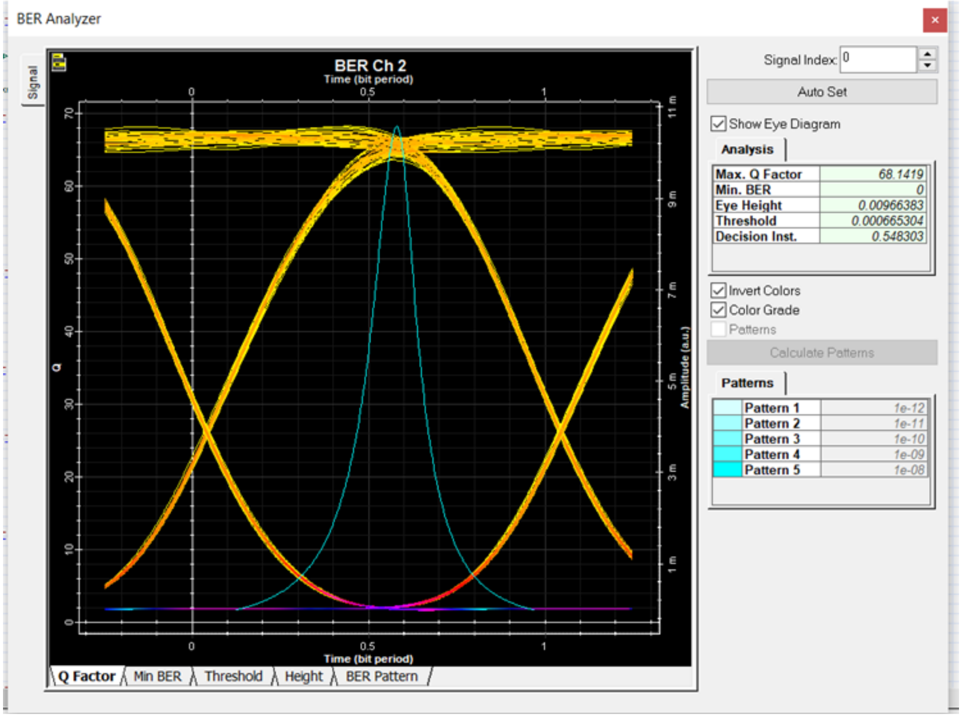


Figure 4.22: Bar Comparison of Zero Degree Polarization Vs 45 Degree Polarization @ 0 dBm



Signal Index: 0

☑ Show Eye Diagram

**Analysis**

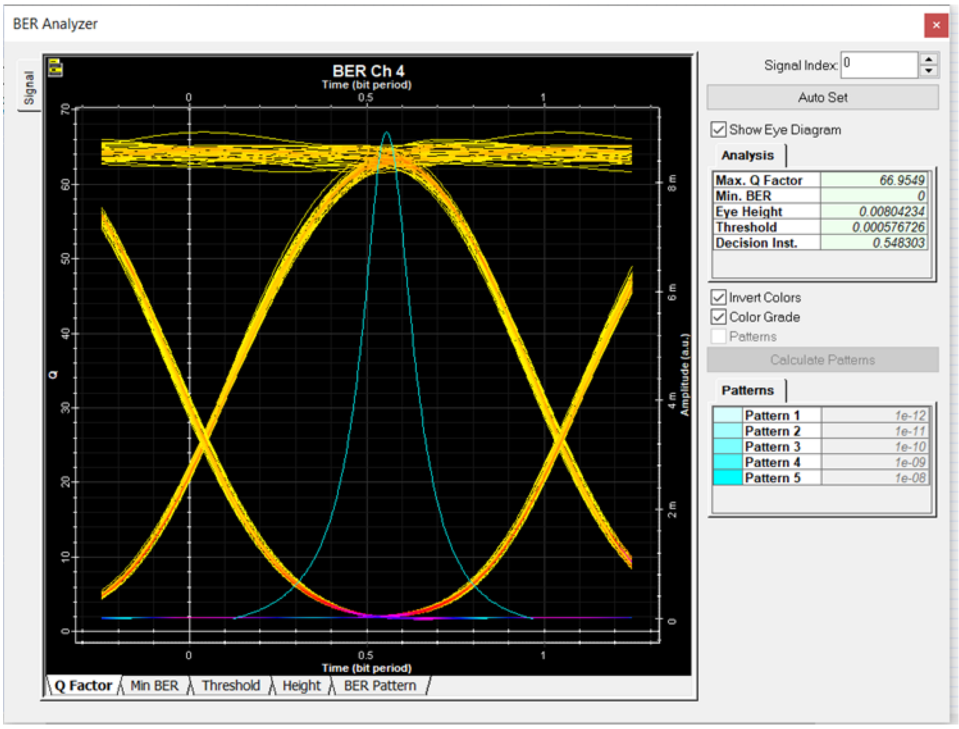
| | |
|---|---|
| Max. Q Factor | 68.1419 |
| Min. BER | 0 |
| Eye Height | 0.00966383 |
| Threshold | 0.000665304 |
| Decision Inst. | 0.548303 |

☑ Invert Colors
☑ Color Grade
☐ Patterns

**Patterns**

| | | |
|---|---|---|
| | Pattern 1 | 1e-12 |
| | Pattern 2 | 1e-11 |
| | Pattern 3 | 1e-10 |
| | Pattern 4 | 1e-09 |
| | Pattern 5 | 1e-08 |

Figure 4.23: Q Factor results using 50 GHZ Channel Spacing and 0dBm Power using circular polarization



Signal Index: 0

☑ Show Eye Diagram

**Analysis**

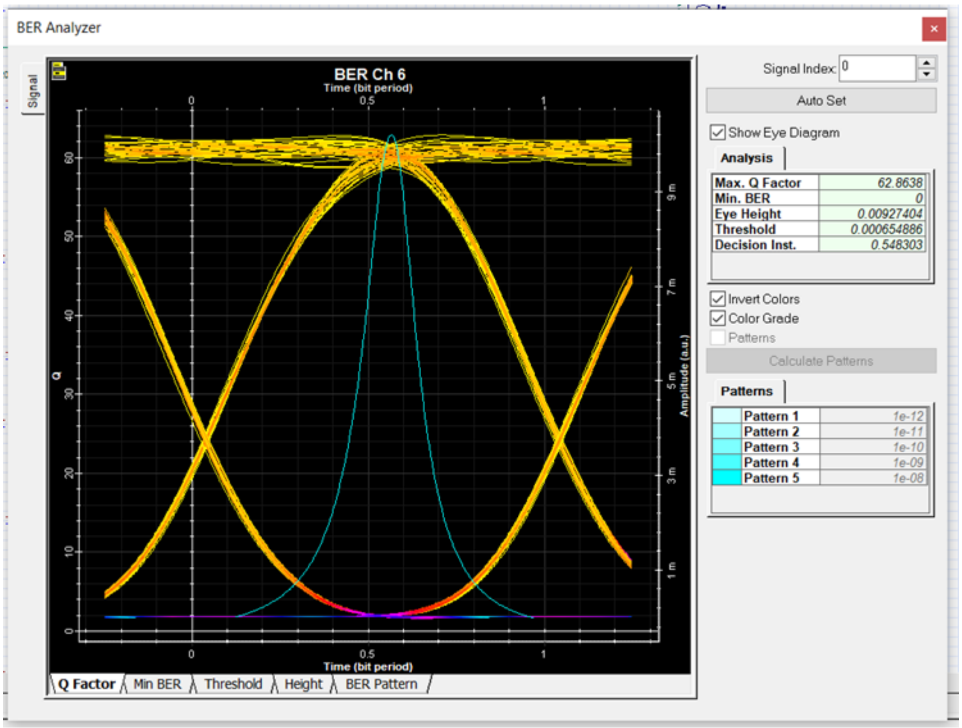
| | |
|---|---|
| Max. Q Factor | 66.9549 |
| Min. BER | 0 |
| Eye Height | 0.00804234 |
| Threshold | 0.000576726 |
| Decision Inst. | 0.548303 |

☑ Invert Colors
☑ Color Grade
☐ Patterns

**Patterns**

| | | |
|---|---|---|
| | Pattern 1 | 1e-12 |
| | Pattern 2 | 1e-11 |
| | Pattern 3 | 1e-10 |
| | Pattern 4 | 1e-09 |
| | Pattern 5 | 1e-08 |

Figure 4.24: Q Factor results using 50 GHZ Channel Spacing and 0dBm Power using circular polarization



Signal Index: 0

☑ Show Eye Diagram

**Analysis**

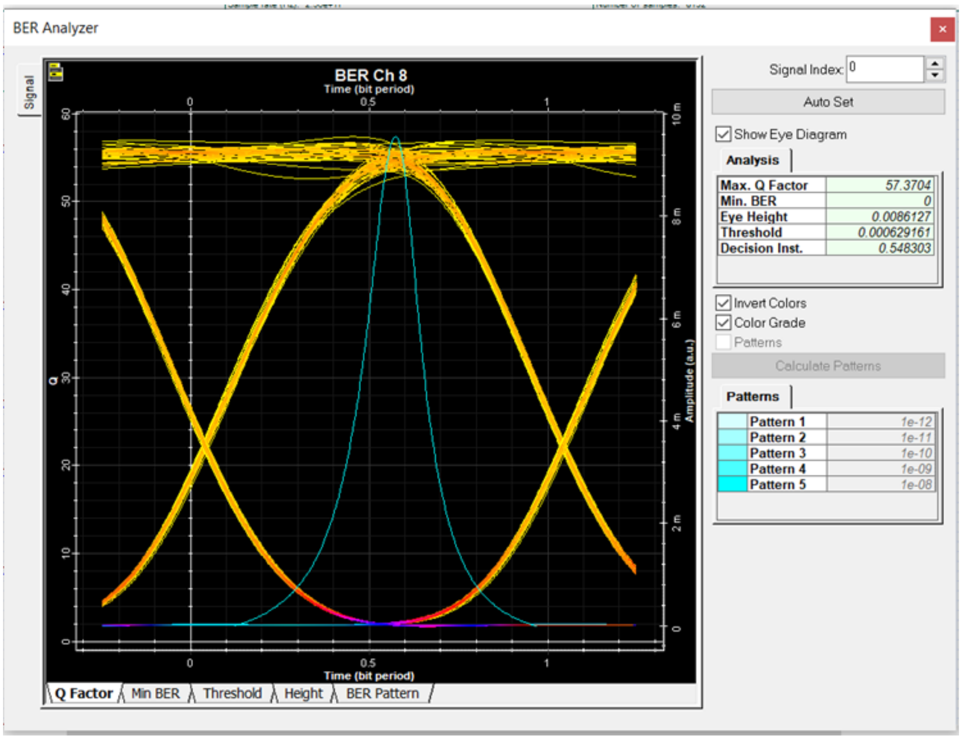
| | |
|---|---|
| **Max. Q Factor** | 62.8638 |
| **Min. BER** | 0 |
| **Eye Height** | 0.00927404 |
| **Threshold** | 0.000654886 |
| **Decision Inst.** | 0.548303 |

☑ Invert Colors
☑ Color Grade
☐ Patterns

**Patterns**

| | | |
|---|---|---|
| 🟦 | **Pattern 1** | 1e-12 |
| 🟦 | **Pattern 2** | 1e-11 |
| 🟦 | **Pattern 3** | 1e-10 |
| 🟦 | **Pattern 4** | 1e-09 |
| 🟦 | **Pattern 5** | 1e-08 |

Figure 4.25: Q Factor results using 50 GHZ Channel Spacing and 0dBm Power using circular polarization



Signal Index: 0

☑ Show Eye Diagram

**Analysis**

| | |
|---|---|
| **Max. Q Factor** | 57.3704 |
| **Min. BER** | 0 |
| **Eye Height** | 0.0086127 |
| **Threshold** | 0.000629161 |
| **Decision Inst.** | 0.548303 |

☑ Invert Colors
☑ Color Grade
☐ Patterns

**Patterns**

| | | |
|---|---|---|
| 🟦 | **Pattern 1** | 1e-12 |
| 🟦 | **Pattern 2** | 1e-11 |
| 🟦 | **Pattern 3** | 1e-10 |
| 🟦 | **Pattern 4** | 1e-09 |
| 🟦 | **Pattern 5** | 1e-08 |

Figure 4.26: Q Factor results using 50 GHZ Channel Spacing and 0dBm Power using circular polarization

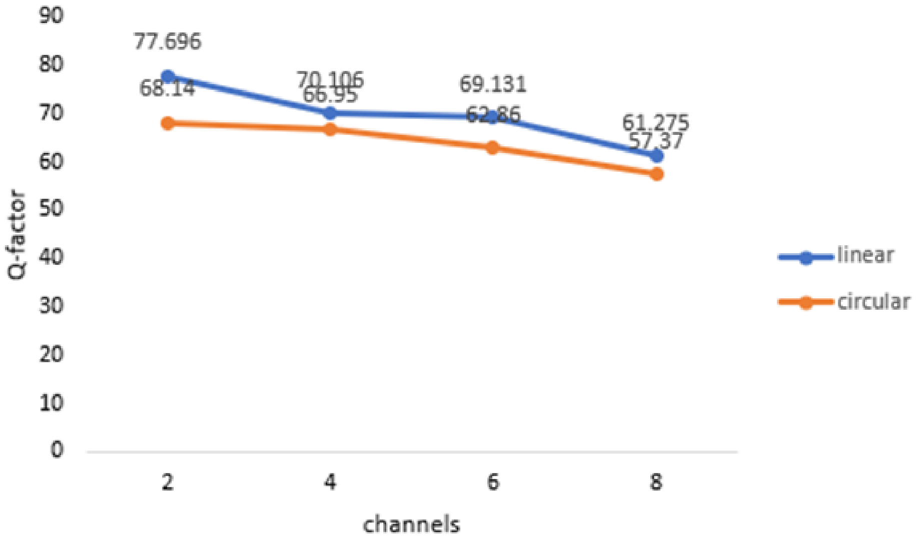


Figure 4.27: Comparison of Linear and circular polarization at 50GHZ 0dBm Power

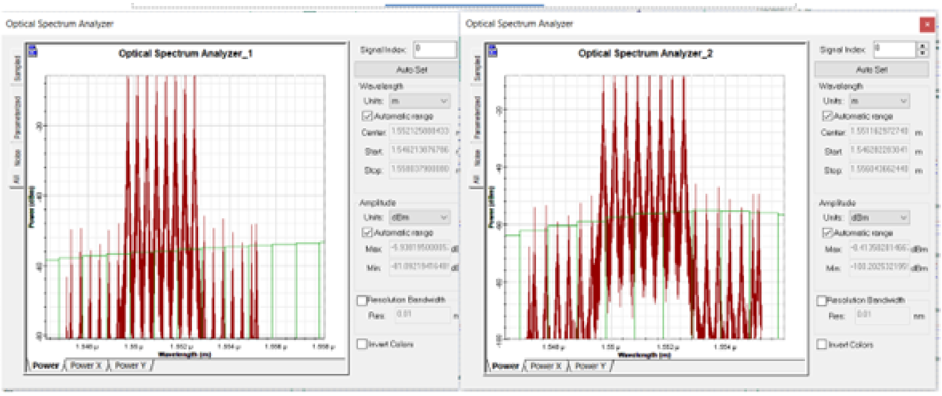


Figure 4.28: FWM SBP using 50 GHZ Channel Spacing 0dBm Power using 45-degree polarization

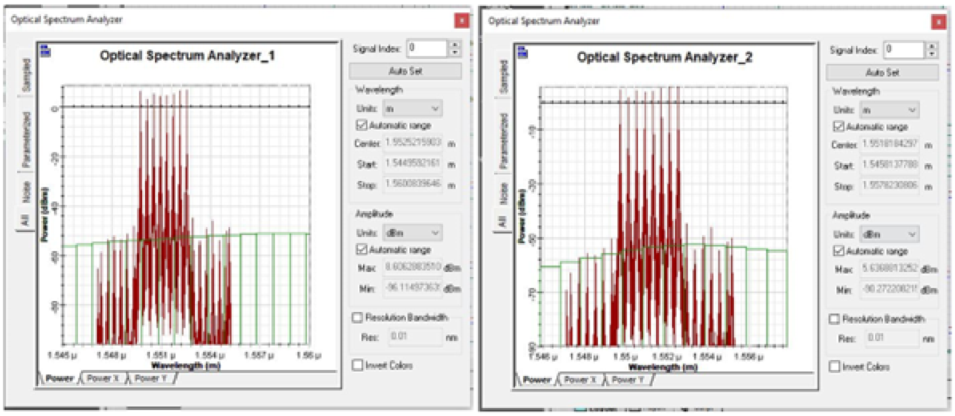


Figure 4.29: FWM SBP using 50 GHZ Channel Spacing and 0dBm Power using Zero-degree polarization

# Chapter 5

# Conclusion

Using the optisystem Version 20 simulator, a thorough and in-depth examination of significant contributing parameters was conducted to determine how these characteristics affect FWM.Analysis was done by 2 different methods in both (I) 8/32 RoF-DCF and EDFA incorporated system and (II) 8/32 RoF-BF DCF and EDFA-Linear/Circular Polarizer incorporated system:

-Varying channel spacing of various CW laser source (50 GHZ - 100 GHZ) -Varying transmitter power of signal source

Keeping the number of input channels to eight with a simultaneous reduction in channel input power (20 dBm to 0 dBm) in the proposed DCF and EDFA incorporated system. We can see that the simulated results for the system with the aforementioned requirements concludes that a real trade-off needs to be made to reduce FWM as much as possible. The 8/32 RoF-BF DCFA and EDFA system's viability has been examined and proven in this study. The operation of channel spacing, power level, and channel count has been examined to determine how well the system performs. Based on the findings, it has been found that the FWM effect diminishes as the channel spacing and signal source power are at 50GHZ and 0dBm respectively. According to the simulation results, keeping the channel spacing at 50 GHz and the input power level for the 8-channel system at 0 dBm will lessen the effects of the FWM effect.Bessel filter integration results in a significant reduction of the FWM sideband power by -40 dBm for system incorporated with DCF and EDFA for 50 GHZ Channel spacing. At the same time we can also see that Q Factor level rises to 46.34 for the same whereas for 75 GHZ and 100 GHZ channel spacing the Q Factor falls to 33.02 26.32

respectively.

Thereby when the system is additionally intergrated with Linear Polarizer and Circular Polarizer respectively it is noticed that with the channel spacing at 50 GHz and the input power level for the 8-channel system at 0 dBm will lessen the effects of the FWM sideband power. We can observe that the Linear polarizer at Zero Degree when incorporated in addition to DCF and EDFA 8/32 RoF-BF System and by consequently simulating by increasing the channel spacing and increasing the input power along with NRZ modulation, the FWM sideband power reduces by -90dBm for polarization at zero degree and -100dBm for polarization at forty five degree which is double the leap from the 8/32 RoF-BF system when incorporated with just DCF and EDFA.

We have also done an additional analyzation replacing the Linear Polarizer with Circular Polarizer and we can observe that the Q Factor ranges form 68 to 57 when compared to Q Factor range from 77 to 61 of Linear Polarizer with 45 degree polarization form and Q Factor range from 71 to 57 with zero degree polarization from which we can infer that Linear Polarization when incorporated in optical link performs better than circular polarization.

From all the different parameters and mitigation schemes analyses we have done throughout the simulation we can conclude that the Linear Polarizer incorporated system performa better than DCF and EDFA incorporated system as well as DCF and EDFA along with circular polarizer incorporated system at 50 GHZ channel spacing and 0dBm power.

# Chapter 6

# Future Scope

RoF-Bessel filter and Linear Polarizer integration results in a significant reduction of the FWM sideband power by -100 dBm. Additionally, the current research might help us comprehend non-linear effects in the RoF system better. When deploying the RoF system in future transport networks, the proposed system can be expanded to use adaptive modulation formats by utilizing external modulation. Also by Increasing the number of channels and incorporating DWDM system, we can contribute to increased availability to users maintaining effective data transmission rate and receiver sensitivity with least distortion in a cost effective way.

# References

[1] R. Bhattacharjee, P. Dey and A. Saha, “ Implementation of an enhanced 32 channel 256 Gbps DWDM based Radio over Fiber optical system for constricted channel spacing employing Fiber Bragg Grating ”in International Journal for Light and Electron Optics 253 (2022) 0030-4026.

[2] Namita Kathpal and AmiT KumaGar,”Analysis of Radio over Fiber system for mitigating four-wave mixing effect”, in Digital Communications and Networks 6 (2020) 115–12, 11 January 2019 2352- 8648.

[3] H R Suresh, V Vinitha, N Girinath and R Karthik,”Suppression of Four Wave Mixing Effect in DWDM Systems”, 2214-7853/ 2021 Elsevier Ltd.

[4] Fahd CHAOUI3*, Otman AGHZOUT1, IEEE Member, Ana Vazquez ALEJOS, IEEE Member, Francisco FALCONE, IEEE Senior Member, Mounia CHAKKOUR, Mounir EL YAKHLOUFI,”Reduction of Four Wave Mixing Effect in DWDM Long Haul Optical Networks”,2016 IEEE 5th International Conference on Multimedia Computing Systems (ICMCS).

[5] Jameel Ahmeda, Ashiq Hussainb, M.Y. Siyalc, Habibullah Manzoora, Abdullah Masoodaa,” Parametric Analysis of Four Wave Mixing in DWDM Systems”, 0030-4026.

[6] Bijayananda Patnaik and P.K.Sahu,”Optimization of FWM Effect in RoF for a 32 Channel 40 GBPS DWDM System”, 2010 IEEE, 78-0-7695-4294-2/10.

[7] Asad Saleem, Yan Xu,b, Shuai Wang, “ Investigation of fiber non-linear effects in WDM-PON based 5G fronthaul networks” 1068-5200.

[8] Richa Bhatia, Ajay K Sharma, Jyoti Saxena, “Improved analysis of four wave mixing with sub-plank higher-order dispersion parameters in optical communication systems” 2016.07.035 0030-4026.

[9] Li H, Wang G, Gao X, Liang J, Hou H, ”A Novel Metasurface for Dual Mode and Dual-Band Flat High- Gain Antenna Application,” IEEE Transactions on Antennas and Propagation, Vol. 66, pp. 3706-3711, July 2018.

[10] T. Sabapathi, R. Poovitha, “Mitigation of nonlinearities in fiber optic DWDM system” 0030-4026.

[11] Habib Ullah Manzoor, Tareq Manzoor, Ashiq Hussain, Moustafa H. Aly. “FWM Mitigation in DWDM Optical Networks” Journal of Physics: Conference Series.

[12] Noora Salim, Haider J. Abd, Ahmed N. Aljamal, and Alaaldin H. Jaber, “Four-Wave Mixing Suppression Method Based on Odd-Even Channels Arrangement Strategy” Progress In Electromagnetics Research M, Vol. 66, 163–172, 2018.

[13] S. Betti, M. Giaconi, and M. Nardini, “Effect of Four-Wave Mixing on WDM Optical Systems: A Statistical Analysis” 1041-1135.

[14] Gurmeet Kaura, M.L.Singhb, M.S.Patterha, “Effect of fibre nonlinearities in a WDM transmission system” 0030-4026.

[15] Vishal Sharma, Ramandeep Kaur. “Implementation of DWDM system in the presence of four wave mixing (FWM) under the impact of channel spacing” 0030-4026

[16] Warsha Balani, Manish Saxena, “Unique Filtering and Wavelength-Stabilization through FBG in WDM/DWDM Networks” International Journal of Computer Applications (0975 – 8887).

[17] M. Noshada, A. Rostamia,b,, “FWM minimization in WDM optical communication systems using the asymmetrical dispersion-managed fibers” 0030-4026.

[18] A.Panda1, D.P.Mishra2, “Nonlinear Effect of Four Wave Mixing for WDM in Radio-over-Fiber Systems” Quest Journals Journal of Electronics and Commu-

nication Engineering Research Volume 2 Issue 4 (2014) pp: 01-06 ISSN(Online) : 2321-5941.

[19] A.Selvamani, Mr.T.Sabapathi, "Suppression of Four Wave Mixing by Optical Phase Conjugation in DWDM Fiber Optic Link" 978-1-4577-2149-6/11.

[20] Fabrizio Forghieri, R. W. Tkach, A. R. Chraplyvy, and D. Marcuse, "Reduction of Four-Wave Mixing Crosstalk in WDM Systems Using Unequally Spaced Channels" IEEE PHOTONICS TECHNOLOGY LETTERS, VOL. 6, NO. 6, JUNE 1994.

[21] Habib Ullah Manzoor, Abaid Ullah Salfiy, Tayyab Mehmoodz and Tareq Manzoorx, "Reduction of Four Wave Mixing by Employing Circular Polarizers in DWDM Optical Networks" 978-1-4799-6369-0/15.

[22] Farman Ali1 · Fazal Muhammad2 · Usman Habib3 · Yousaf Khan4 · Muhammad Usman5, "Modeling and minimization of FWM effects in DWDM-based long-haul optical communication systems" Received: 26 September 2019.

[23] Antonella Bogoni and Luca Potì, Member, IEEE, "Effective Channel Allocation to Reduce Inband FWM Crosstalk in DWDM Transmission Systems" IEEE JOURNAL OF SELECTED TOPICS IN QUANTUM ELECTRONICS, VOL. 10, NO. 2, MARCH/APRIL 2004

[24] Iftikhar Rasheed, Muhammad Abdullah, Shahid Mehmood, Mahwish Chaudhary. "Analyzing the Non-linear Effects at various Power Levels and Channel Counts on the Performance of DWDM based Optical Fiber Communication System" 978-1-4673-4451-7/12

[25] Mehtab Singh, "Analyzing the Effect of Channel Spacing and Chromatic Dispersion Coefficient on FWM in Optical WDM System" International Journal of Signal Processing, Image Processing and Pattern Recognition.

[26] F. Laghezza, F. Scotti, P. Ghelfi, A. Bogoni, Photonics-assisted multiband rf transceiver for wireless communications, J. Lightwave Technol. 32 (16) (2014) 2896–2904..

[27] R. Llorente, M. Beltran, Radio-over-fibre techniques and performance, in: Frontiers in Guided Wave Optics and Optoelectronics, InTech, 2010.

[28] M. Bakaul, A. Nirmalathas, C. Lim, D. Novak, R. Waterhouse, Hybrid multiplexing of multiband optical access technologies towards an integrated dwdm network, IEEE Photon. Technol. Lett. 18 (21) (2006) 2311–2313.

[29] V.A. Thomas, S. Ghafoor, M. El-Hajjar, L. Hanzo, A full-duplex diversity-assisted hybrid analogue/digitized radio over fibre for optical/wireless integration, IEEE Commun. Lett. 17 (2) (2013) 409–412.

[30] Radio-Over-Fiber Technology: Present and Future Christina Lim, Senior Member, IEEE, and Ampalavanapillai Nirmalathas, Senior Member, IEEE

[31] Transmission Performance Analysis of WDM Radio over Fiber Technology for Next Generation Long-Haul Optical Networks Badiaa Ait Ahmed,1 Otman Aghzout,1 Mounia Chakkour,2 Fahd Chaoui,2 and Azzeddin Naghar.

[32] Suresh Kumar, S. Sharma, Sandeep Dahiya, WDM-Based 160 Gbps Radio Over fiber system with the application of dispersion compensation fiber and fiber Bragggrating,Front.Phys.9(2021),691387.

[33] Kaur, Rupinder, Mandeep Singh, 2016. “Dispersion Compensation in Optical Fiber Communication System Using WDM with DCF and FBG.” (2016).

[34] D. Perez-Galacho, D. Sartiano, and S. Sales, “Analog radio over fiber links for future 5G radio access networks,” in Proc. 21st Int. Conf. Transparent Opt. Netw. (ICTON), Angers, France, Jul. 2019, pp. 1–4.

[35] A. Delmade et al., “Performance analysis of analog IF over fiber fronthaul link with 4G and 5G coexistence,” IEEE/OSA J. Opt. Commun.Netw., vol. 10, no. 3, pp. 174–182, Mar. 2018.

[36] Application Note. Accessed: Oct. 25, 2020. [Online]. Available: https://www.fujitsu.com/us/Images/Centralized-Radio-Access-Network C-RAN-Transport-Application-Note.