PERFORMANCE ANALYSIS OF DWDM BASED ADVANCED OPTICAL NETWORK SYSTEM FOR DIFFERENT OPTICAL AMPLIFIERS AND CHANNEL CONFIGURATIONS

BY

SYED ZAHIDUR RASHID
ID: 123-25-265

This Thesis Presented in Partial Fulfillment of the Requirements for the Degree of Master of Science in Computer Science and Engineering

Supervised By

Dr. Touhid Bhuiyan
Professor and Head
Department of CSE
Daffodil International University

DAFFODIL INTERNATIONAL UNIVERSITY

DHAKA, BANGLADESH

JUNE 2021

APPROVAL

This thesis titled "**PERFORMANCE ANALYSIS OF DWDM BASED ADVANCED OPTICAL NETWORK SYSTEM FOR DIFFERENT OPTICAL AMPLIFIERS AND CHANNEL CONFIGURATIONS**", submitted by **Syed Zahidur Rashid**, ID: **123-25-265** to the Department of Computer Science and Engineering, Daffodil International University, has been accepted as satisfactory for the partial fulfillment of the requirements for the degree of M.Sc. in Computer Science and Engineering and approved as to its style and contents. The presentation has been held on 3rd June, 2021.

BOARD OF EXAMINERS

______________________ **Chairman**

Dr. Touhid Bhuiyan
Professor and Head
Department of Computer Science and Engineering
Faculty of Science & Information Technology
Daffodil International University

______________________ **Internal Examiner**

Dr. Md. Ismail Jabiullah
Professor
Department of Computer Science and Engineering
Faculty of Science & Information Technology
Daffodil International University

______________________ **Internal Examiner**

Dr. Sheak Rashed Haider Noori
Associate Professor and Associate Head
Department of Computer Science and Engineering
Faculty of Science & Information Technology
Daffodil International University

______________________ **External Examiner**

Dr. Shamim H Ripon
Professor
Department of Computer Science and Engineering
East West University

DECLARATION

I hereby declare that, this thesis has been done by me under the supervision of **Dr. Touhid Bhuiyan, Professor and Head, Department of Computer Science and Engineering, Daffodil International University**. I also declare that neither this thesis nor any part of this thesis has been submitted elsewhere for award of any degree or diploma.

Supervised by:

____

Dr. Touhid Bhuiyan
Professor and Head
Department of Computer Science and Engineering
Faculty of Science & Information Technology
Daffodil International University

Submitted by:

____

Syed Zahidur Rashid
ID: 123-25-265
Department of Computer Science and Engineering
Faculty of Science & Information Technology
Daffodil International University

ACKNOWLEDGEMENT

My sincere thanks goes to the **Daffodil International University** for providing me the chance to meet the very inspiring and motivating personalities as my teachers and mentors.

I am extremely grateful and indebt to my honorable supervisor **Dr. Touhid Bhuiyan, Professor and Head, Department of Computer Science and Engineering, Daffodil International University** for his heartfelt direction, care, impulse and reinforcement throughout the completion of this work in a proper scientific methodology.

I would also like to extend my appreciation to my family members who always reinvigorated and supported me in doing this thesis work.

Lastly, I would also express my gratitude to all the faculty members of the department of Computer Science and Engineering who have been very co-operative while doing this research work.

ABSTRACT

The main aim of this thesis is to design and do performance analysis of 32, 64 and 128 channels DWDM system for three different amplifier configurations which are EDFA, Raman and OA amplifiers where each channel having 10 Gbps data rate multiplexed with frequency spacing of 100 GHz. Dispersion is an important factor to be considered while designing a DWDM system. Dispersion affects the penalties due to various types of fiber nonlinearities. Single mode fiber is preferred for long distance communication over Multimode fiber. In this proposed work Optisystem 16.0 commercial optical simulator is used to analyze the performance of 32, 64 and 128 channels DWDM system for three different amplifier configurations which are EDFA, Raman and OA amplifiers. The system performance is enhanced by using Dispersion compensation fiber to reimburse for the dispersion formed by single mode fiber. The system performance is imperfect due to the dispersion. In order to recompense this, we have used Dispersion Compensation Fiber (DCF). Between amplifier spans standard single-mode fiber is used, but at each amplifier position, dispersion compensating fiber having a negative chromatic dispersion is presented. By using this we have effectively designed a DWDM system with 32/64/128 channels each having 10 Gbps data rate multiplexed with frequency spacing of 100 GHz. It is apprehended that, in coming future, DWDM can appear as an auspicious technique to escalate the capacity and meet the bandwidth constraint. This work can further be stretched to more number of channels i.e. 256 channels or more with different frequency spacing.

TABLE OF CONTENTS

CONTENTS	PAGE

Board of Examiners	i
Declaration	ii
Acknowledgements	iii
Abstract	iv
Table of Contents	v
List of Figures	viii
List of Tables	xvii
CHAPTER	
CHAPTER 1: INTRODUCTION	**1-3**
1.1 Motivation	1
1.2 Problem Statement	1
1.3 Aim and Contribution of the Thesis	2
1.4 Structure of the Thesis	3
CHAPTER 2: LITERATURE REVIEW	**4-8**
CHAPTER 3: SYSTEM DESCRIPTION	**9-19**
3.1 DWDM System	9
3.2 Single Mode Fiber (SMF)	10
3.3 Dispersion Compensation Fiber (DCF)	11
3.4 Raman amplifier-average power model	11

3.5 Erbium doped fiber amplifier (EDFA) 14

3.6 OA amplifier 14

3.7 The Pin Photodetector 18

3.8 Q-factor 19

3.9 Bit Error Rate 19

CHAPTER 4: SIMULATIONS, RESULTS AND DISCUSSION **20-92**

4.1 Configurations in Optisystem for 32 channels DWDM system e Mode 22

4.1.1 Settings for EDFA amplifier 29

4.1.2 Settings for Raman amplifier 31

4.1.3 Settings for OA amplifier 33

4.2 Configurations in Optisystem for 64 channels DWDM system 35

4.2.1 Settings for EDFA amplifier 42

4.2.2 Settings for Raman amplifier 44

4.2.3 Settings for OA amplifier 46

4.3 Configurations in Optisystem for 128 channels DWDM system 48

4.3.1 Settings for EDFA amplifier 55

4.3.2 Settings for Raman amplifier 57

4.3.3 Settings for OA amplifier 59

4.4 Outputs of 32 channels DWDM system 61

4.4.1 Outputs of 32 channels DWDM system for EDFA amplifier 61

4.4.2 Outputs of 32 channels DWDM system for Raman amplifier 63

4.4.3 Outputs of 32 channels DWDM system for OA amplifier	66
4.5 Outputs of 64 channels DWDM system	69
4.5.1 Outputs of 64 channels DWDM system for EDFA amplifier	69
4.5.2 Outputs for 64 channels DWDM system for Raman amplifier	71
4.5.3 Outputs for 64 channels DWDM system for OA amplifier	74
4.6 Outputs for 128 channels DWDM system	77
4.6.1 Outputs for 128 channels DWDM system for EDFA amplifier	77
4.6.2 Outputs for 128 channels DWDM system for Raman amplifier	79
4.6.3 Outputs of 128 channels DWDM system for OA amplifier	82
4.7 Combined outputs graphs for 32 channels DWDM system	84
4.8 Combined outputs graphs for 64 channels DWDM system	86
4.9 Combined outputs graphs for 128 channels DWDM system	88
4.10 Comparison among all combinations of the simulation designs (EDFA, Raman and OA amplifiers for 32, 64 and 128 channels)	90
4.11 Validation and final comparison among related previous works	91
CHAPTER 5: CONCLUSION	**93-93**
REFERENCES	**94-98**

LIST OF FIGURES

FIGURES	PAGE NO
Figure 3.1: Block diagram of the DWDM based advanced optical network system	10
Figure 4.1: Simulation testbed for 32 channels DWDM system using Raman amplifier (Also same configuration is used for EDFA and OA amplifiers)	20
Figure 4.2: Simulation testbed for 64 channels DWDM system using EDFA (Also same configuration is used for Raman and OA amplifiers)	21
Figure 4.3: Simulation testbed for 128 channels DWDM system using OA amplifier (Also same configuration is used for EDFA and Raman amplifiers)	21
Figure 4.1.1: System layout settings	22
Figure 4.1.2: Settings for optical fiber	22
Figure 4.1.3: Settings for optical fiber dispersion	23
Figure 4.1.4: Settings for noise in optical fiber	23
Figure 4.1.5: Settings for Dispersion Compensation Fiber (DCF)	24
Figure 4.1.6: Settings for dispersion in Dispersion Compensation Fiber (DCF)	24
Figure 4.1.7: Settings for Polarization Mode Dispersion (PMD) in Dispersion Compensation Fiber (DCF)	25
Figure 4.1.8: Settings for noise in Dispersion Compensation Fiber (DCF)	25
Figure 4.1.9: Settings for WDM demultiplexer	26
Figure 4.1.10: Settings for optical receiver	26
Figure 4.1.11: Settings for optical receiver (Low Pass Filter)	27
Figure 4.1.12: Settings for WDM transmitter	27
Figure 4.1.13: Settings for WDM transmitter (Modulation type)	28

Figure 4.1.14: Settings for WDM multiplexer 28

Figure 4.1.15: Settings for noise in WDM multiplexer 29

Figure 4.1.1.1: Settings for Erbium Doped Fiber 29

Figure 4.1.1.2: Settings for Erbium Doped Fiber 30

Figure 4.1.1.3: Settings for noise in Erbium Doped Fiber 30

Figure 4.1.2.1: Settings for Raman amplifier 31

Figure 4.1.2.2: Settings for Raman amplifier (average power model) 31

Figure 4.1.2.3: Settings for Raman amplifier 32

Figure 4.1.2.4: Settings for noise in Raman amplifier 32

Figure 4.1.3.1: Settings for OA amplifier 33

Figure 4.1.3.2: Settings for noise in OA amplifier 33

Figure 4.1.3.3: Simulation processing view for 32 channels in DWDM System 34

Figure 4.2.1: Settings for layout of 64 channels 35

Figure 4.2.2: Settings for Optical fiber 35

Figure 4.2.3: Settings for dispersion in optical fiber 36

Figure 4.2.4: Settings for noise in optical fiber 36

Figure 4.2.5: Settings for Dispersion Compensation Fiber 37

Figure 4.2.6: Settings for Dispersion Compensation Fiber (DCF) 37

Figure 4.2.7: Settings for Polarization Mode Dispersion (PMD) 38

Figure 4.2.8: Settings for noise in DCF 38

Figure 4.2.9: Settings for WDM demultiplexer 39

Figure 4.2.10: Settings for optical receiver 39

Figure 4.2.11: Settings for LPF of optical receiver 40

Figure 4.2.12: Settings for WDM transmitter 40

Figure 4.2.13: Settings for modulation in WDM transmitter 41

Figure 4.2.14: Settings for WDM multiplexer 41

Figure 4.2.15: Settings for noise in WDM multiplexer 42

Figure 4.2.1.1: Settings for Erbium Doped Fiber 42

Figure 4.2.1.2: Settings for Erbium Doped Fiber 43

Figure 4.2.1.3: Settings for noise in Erbium Doped Fiber 43

Figure 4.2.2.1: Settings for Raman amplifier 44

Figure 4.2.2.2: Settings for Raman amplifier (average power model) 44

Figure 4.2.2.3: Settings for Raman amplifier 45

Figure 4.2.2.4: Settings for Raman amplifier 45

Figure 4.2.3.1: Settings for OA amplifier 46

Figure 4.2.3.2: Settings for OA amplifier 46

Figure 4.2.3.3: Simulation running view for 64 channels DWDM system 47

Figure 4.3.1: Settings for optical fiber 48

Figure 4.3.2: Settings for dispersion in optical fiber 48

Figure 4.3.3: Settings for noise in optical fiber 49

Figure 4.3.4: Settings for Dispersion Compensation Fiber 49

Figure 4.3.5: Settings for Dispersion in DCF 50

Figure 4.3.6: Settings for PMD in DCF 50

Figure 4.3.7: Settings for DCF 51

Figure 4.3.8: Settings for WDM demultiplexer 51

Figure 4.3.9: Settings for optical receiver 52

Figure 4.3.10: Settings for LPF in optical receiver 52

Figure 4.3.11: Settings for WDM transmitter 53

Figure 4.3.12: Settings for WDM transmitter 53

Figure 4.3.13: Settings for WDM multiplexer 54

Figure 4.3.14: Settings for noise in WDM multiplexer 54

Figure 4.3.1.1: Settings for Erbium Doped Fiber 55

Figure 4.3.1.2: Settings for Erbium Doped Fiber 55

Figure 4.3.1.3: Settings for Erbium Doped Fiber 56

Figure 4.3.2.1: Settings for Raman amplifier 57

Figure 4.3.2.2: Settings for Raman amplifier 57

Figure 4.3.2.3: Settings for Raman amplifier 58

Figure 4.3.2.4: Settings for noise in Raman amplifier 58

Figure 4.3.3.1: Settings for OA amplifier 59

Figure 4.3.3.2: Settings for OA amplifier 59

Figure 4.3.3.3: Simulation processing view for 128 channels DWDM system. 60

Figure 4.3.3.4: Simulation processing completed view for 128 channels DWDM system. 60

Figure 4.4.1.1: 32 channels input signal in OSA before entering to the optical link for EDFA 61

Figure 4.4.1.2: 32 channels output signal in OSA after entering to the optical link for EDFA (at loop control), signal power versus noise power where red color indicates the signal power and green color represents the noise power 61

Figure 4.4.1.3: 32 channels output signal in OSA after entering to the optical link for EDFA (at loop control), noise power 62

Figure 4.4.1.4: 32 channels output signal in OSA after entering to the optical link for EDFA (at loop control), signal power with side lobes (FWM) 62

Figure 4.4.1.5: Output of eye diagram from BER analyzer for EDFA 63

Figure 4.4.2.1: 32 channels input signal in OSA before entering to the optical link for Raman 63

Figure 4.4.2.2: 32 channels output signal in OSA after entering to the optical link for Raman (at loop control), signal power versus noise power where red color indicates the signal power and green color represents the noise power 64

Figure 4.4.2.3: 32 channels output signal in OSA after entering to the optical link for Raman (at loop control), noise power 64

Figure 4.4.2.4: 32 channels output signal in OSA after entering to the optical link for Raman (at loop control), signal power with side lobes (FWM) 65

Figure 4.4.2.5: Output of eye diagram from BER analyzer for Raman amplifier 65

Figure 4.4.3.1: 32 channels input signal in OSA before entering to the optical link for OA amplifier 66

Figure 4.4.3.2: 32 channels output signal in OSA after entering to the optical link for OA amplifier (at loop control), signal power versus noise power where red color indicates the signal power and green color represents the noise power 66

Figure 4.4.3.3: 32 channels output signal in OSA after entering to the optical link for OA amplifier (at loop control), noise power 67

Figure 4.4.3.4: 32 channels output signal in OSA after entering to the optical link for OA amplifier (at loop control), signal power with side lobes (FWM) 67

Figure 4.4.3.5: Output eye diagram from BER analyzer for OA amplifier 68

Figure 4.5.1.1: 64 channels input signal in OSA before entering to the optical link for EDFA 69

Figure 4.5.1.2: 64 channels output signal in OSA after entering to the optical link for EDFA (at loop control), signal power versus noise power where red color indicates the signal power and green color represents the noise power 69

Figure 4.5.1.3: 64 channels output signal in OSA after entering to the optical link for EDFA (at loop control), noise power 70

Figure 4.5.1.4: 64 channels output signal in OSA after entering to the optical link for EDFA (at loop control), signal power with side lobes (FWM) 70

Figure 4.5.1.5: Output of eye diagram from BER analyzer for EDFA amplifier 71

Figure 4.5.2.1: 64 channels input signal in OSA before entering to the optical link for Raman 71

Figure 4.5.2.2: 64 channels output signal in OSA after entering to the optical link for Raman (at loop control), signal power versus noise power where red color indicates the signal power and green color represents the noise power 72

Figure 4.5.2.3: 64 channels output signal in OSA after entering to the optical link for Raman (at loop control), noise power 72

Figure 4.5.2.4: 64 channels output signal in OSA after entering to the optical link for Raman (at loop control), signal power with side lobes (FWM) 73

Figure 4.5.2.5: Output eye diagram from BER analyzer for Raman amplifier 73

Figure 4.5.3.1: 64 channels input signal in OSA before entering to the optical link for OA amplifier 74

Figure 4.5.3.2: 64 channels output signal in OSA after entering to the optical link for OA amplifier (at loop control), signal power versus noise power where red color indicates the signal power and green color represents the noise power 74

Figure 4.5.3.3: 64 channels output signal in OSA after entering to the optical link for OA amplifier (at loop control), noise power 75

Figure 4.5.3.4: 64 channels output signal in OSA after entering to the optical link for OA amplifier (at loop control), signal power with side lobes (FWM) 75

Figure 4.5.3.5: Output eye diagram from BER analyzer for OA amplifier 76

Figure 4.6.1.1: 128 channels input signal in OSA before entering to the optical link for EDFA 77

Figure 4.6.1.2: 128 channels output signal in OSA after entering to the optical link for EDFA (at loop control), signal power versus noise power where red color indicates the signal power and green color represents the noise power 77

Figure 4.6.1.3: 128 channels output signal in OSA after entering to the optical link for EDFA (at loop control), noise power 78

Figure 4.6.1.4: 128 channels output signal in OSA after entering to the optical link for EDFA (at loop control), signal power with side lobes (FWM) 78

Figure 4.6.1.5: Output eye diagram from BER analyzer EDFA amplifier 79

Figure 4.6.2.1: 128 channels input signal in OSA before entering to the optical link for Raman amplifier 79

Figure 4.6.2.2: 128 channels output signal in OSA after entering to the optical link for Raman (at loop control), signal power versus noise power where red color indicates the signal power and green color represents the noise power 80

Figure 4.6.2.3: 128 channels output signal in OSA after entering to the optical link for Raman (at loop control), noise power 80

Figure 4.6.2.4: 128 channels output signal in OSA after entering to the optical link for Raman (at loop control), signal power with side lobes (FWM) 81

Figure 4.6.2.5: Output eye diagram from BER analyzer for Raman amplifier 81

Figure 4.6.3.1: 128 channels input signal in OSA before entering to the optical link for OA amplifier 82

Figure 4.6.3.2: 128 channels output signal in OSA after entering to the optical link for OA amplifier (at loop control), signal power versus noise power where red color indicates the signal power and green color represents the noise power 82

Figure 4.6.3.3: 128 channels output signal in OSA after entering to the optical link for OA amplifier (at loop control), noise power 83

Figure 4.6.3.4: 128 channels output signal in OSA after entering to the optical link for OA amplifier (at loop control), signal power with side lobes (FWM) 83

Figure 4.6.3.5: Output eye diagram from BER analyzer for OA amplifier 84

Figure 4.7.1: Channel Input Power (dBm) versus Signal Quality (dB) for 32 channels DWDM system 84

Figure 4.7.2: Input Channel Power (dBm) versus Max. eye Opening Factor (%) for 32 channels DWDM system 85

Figure 4.7.3: Input Channel Power (dBm) versus Min log of BER for 32 channels DWDM system 85

Figure 4.8.1: Input Channel Power (dBm) versus Signal Quality (dB) for 64 channels DWDM system 86

Figure 4.8.2: Input Channel Power (dBm) versus Min log of BER for 64 channels DWDM system 86

Figure 4.8.3: Input Channel Power (dBm) versus Max. eye Opening Factor (%) for 64 channels DWDM system 87

Figure 4.9.1: Channel Input Power (dBm) versus Min log of BER for 128 channels DWDM system 88

Figure 4.9.2: Channel Input Power (dBm) versus Signal Quality (dB) for 128 channels DWDM system 88

Figure 4.9.3: Channel Input Power (dBm) versus Max. eye Opening Factor (%) for 128 channels DWDM system 89

Figure 4.11.1: Comparison graph for Signal Quality (dB) of different amplifiers with existing works 92

LIST OF TABLES

TABLES	PAGE NO
Table 4.10.1: Comparison table for all combinations of the simulation designs (EDFA, Raman and OA amplifiers for 32, 64 and 128 channels)	90
Table 4.11.1: Comparison table of current investigation with related previous works	91

CHAPTER 1
Introduction

1.1 Motivation

Increasing demand for higher transmission bandwidth has directed to the astonishing growth in internet traffic due to which we can notice increasing deployment of broadband networks. In this era of real-time interactive multimedia communications massive data rate is a necessity for which it is mandatory to improve channel capacity, improved diversity and diverse functionality of communication networks. Nowadays people wants to communicate in real-time without any kind of delays in the networks. Besides the network must be secured, bandwidth efficient, reliable and fault tolerant.

A total communication system contains a transmitter, a channel and a receiver. It contains various types of nodes through the backbone network by which it establishes communication among various parties.

In the setup of complete communication system an engineer can use various types of technologies for the overall communication network. To meet the rising demand of higher and higher data rate optical communication is the most feasible option as it can provide an incredible rate of transmission, to satisfy demand of faster and faster communication networks. Optical networks can provide lowest signal alteration, reduced device cost as compared to outcome, massive bandwidth, lesser power constraint, reduced signal attenuation, and slighter operation expenses. Also by using coherent optical transmission system (COTS) channel capacity can be increased by using multilevel modulation format and thereby gaining better spectral efficiency [1].

1.2 Problem Statement

While dealing with long distance advanced optical communication networks two main restraints that effects the performance of the system are nonlinearities due to dispersion and Amplified Spontaneous Emission (ASE). To mitigate both restricting factors while achieving higher date rates, DWDM system with different types of amplifiers can be useful for different number of channel configurations [2]. Signals which are at different frequencies are modulated at the receiver side and sent over the fiber and then at the receiver side they are demodulated and brought back to their original frequencies. But in case of long haul optical communication networks signal attenuation is a great detrimental factors for which using of repeater comes as a recovery agent in the scenario. But these are highly inclined to noise, nonlinearity and signal diminution. In every cases of system design, it is obligatory to maintain the required level of satisfactory outcome from system for a long haul optical communication network [3].

1.3 Aim and Contribution of the Thesis

By using different types of amplifiers which are specialized for optical fiber communication only such as EDFA, Raman and OA amplifiers these factors can be mitigated at different levels [4]. They do not rely on the conversion to electrical domain. They directly enhance the signal power in the optical domain. Although these amplifiers has also their distinctive merits and demerits. By using proper pump configuration setup and by choosing appropriate wavelength the outcome from Raman amplifier can be optimized. Here different signal wavelength and pump wavelengths are used for optimum performance [5]. On the contrary, Raman amplifier works better with greater pump power and greater pump laser. OA amplifier works better from 1310nm to 1550nm and the maximum data rate with which it can work fine is 10 Gbps. For EDFA amplifier, greater amplification is achieved at 1550nm. The benefits of EDFA amplifier is that it can handover high pump power for the signal with high dynamic range and with low noise figure. It is also suitable for long haul optical communication networks [5], [6]. In some cases, Hybrid Optical Amplifiers (HOA) are used for increasing the capacity of the long haul communication link with DWDM system. They have used various hybrid amplifier configurations for examining the performance of the system [2], [7]. But here main aim of this thesis is to design and do performance analysis of 32, 64 and 128 channels DWDM system for three different amplifier configurations which are EDFA, Raman and OA amplifiers where each channel having 10 Gbps data rate multiplexed with frequency spacing of 100 GHz. The system performance is enhanced by using Dispersion compensation fiber to reimburse for the dispersion formed by single mode fiber. The system performance is imperfect due to the dispersion. In order to recompense this, we have used Dispersion compensation fiber. Between amplifier spans standard single-mode fiber is used, but at each amplifier position, dispersion compensating fiber having a negative chromatic dispersion is presented. By using this we have effectively designed a DWDM system with 32/64/128 channels each having 10 Gbps data rate multiplexed with frequency spacing of 100 GHz and performed it's performance analysis for different amplifiers (EDFA/Raman/OA).

1.4 Structure of the Thesis

The substantial part of this thesis is based on the research work conducted by the author on the design of a DWDM system with 32/64/128 channels each having 10 Gbps data rate multiplexed with frequency spacing of 100 GHz and performed its performance analysis for different amplifiers (EDFA/Raman/OA). This research work comprises merely the fundamental mathematical expressions to make the research work as comprehensible as possible.

The thesis is structured in eight chapters as given below:

• Chapter 1 – Introduction: in this chapter, the fundamental research problems are stated and then the goal and contribution of the thesis are listed.

• Chapter 2 – Literature Review is presented.

• Chapter 3 – System Description is presented in this chapter.

• Chapter 4 – Simulations, Results and Discussion are discussed here.

• Chapter 5 – Conclusion is presented in this chapter.

CHAPTER 2

Literature Review

In [1], the authors examined the output for DP-32QAM (symbol rate 10 Gsymbol/s), DP-64QAM (symbol rate 8.33 Gsymbol/s) and DP-128QAM (symbol rate 7.142 Gsymbol/s) levels with different CW laser input power for Coherent Optical Transmission System (COTS) with 100Gbps data rate. In [2], a DWDM system with 128x10 channels with 100 GHz channel spacing was investigated and main target was to optimize the signal quality. They used three distinct Hybrid Optical Amplifiers (HOA) to evaluate signal quality, min log BER, highest eye opening factor. They have produced a trend line for predicting the performance of the DWDM system for long distance optical network. They reported that H3 (EDFA-Raman-OA setting can perform better with 128 channels where optimum channel input power was -5 dBm for17.11 dB signal quality. In [3], optical amplifiers SOA, EDFA, Raman and hybrid amplifiers (SOA-EDFA, EDFA-EDFA, Raman-EDFA) were used where frequency spacing was 50 GHz and they used a DWDM system model of 8 channels and 10 Gbps data rate. They measured Q-factor, eye opening, output power and BER for a changing distance of 20 to 200 km. At maximum output power was found at 100 km distance for SOA-EDFA with reasonable Q-factor, minimum BER and highest eye opening. In [4], optical amplifiers of two distinct types were investigated for 16×10 Gbps WDM system where the transmission length was 10 to 200 km and they have reported the dispersion as 16.75 ps/nm/km. They have measured the factors such as total gain, QF and BER. They reported that EDFA performed 64% better than Raman, 57.5% for amplification gain and 26.7% for maximum quality factor. In [5], the authors worked with a WDM PON system with 10 Gbps rate by using single and hybrid amplifiers (EDFA, Raman, SOA, EDFA-Raman, EDFA-SOA, Raman-Raman and EDFA-EDFA). Output Power, Q-factor and minimum bit error rate were considered for 40 to 200 km and it was found that EDFA-EDFA gives better result at dispersion of 2ps/nm/km. In [6], the researchers validated a WDM 40 Gbps system for L band and U band for a DSF. At 225 km distance for a WDM system with distributed Raman amplifiers (DRAs) and L-band erbium-doped fiber amplifiers (EDFAs) in L band and U band they reported a speed of

54x42.7 Gbps (2.2 Tbps). In [7], authors investigated a DWDM system for HOA (Raman-EDFA, Raman-EDFA-Raman, Raman-SOA and Raman-SOA-Raman) in C+L band where they reported that Raman-EDFA givers most usable output for signal quality (>21 dB), high output power (10 dBm) and greater eye opening factor with channel spacing 0.15nm. It was perceived that Hybrid and Conventional amplifier with NRZ performs at satisfactory level. Optical amplifiers enhances signal power directly without any transformation from optical to electrical domain. They amplify the signal as well as maintain the proper bandwidth and system outcome at the same time. They are perfectly suitable for long haul optical communication networks [8]. There are various types of optical amplifiers among which EDFA, Raman and OA are significant. Stimulated Raman Scattering is the technique used in Raman amplifier for amplification purpose. It can have variations by varying pump power and also by varying pump wavelength as shown in [8]. It works with upper pump power and upper level of pump laser. On the other hand, OA amplifier provides amplification at 1310nm-1550nm frequency range with 10Gbps data rate which is polarization reliant with larger noise figure and cross talk. EDFA which is suitable for long haul optical communication network links shows better promise at 1550 nm by serving high pump power with larger dynamic range and low noise figure. Some used hybrid optical amplifiers for boosting the bandwidth and enhancing the length of the communication link [9], [10]. For a link having a length of 50 km, amplifier (Raman-EDFA hybrid configuration) gain flatness of 90.5 nm was achieved at 90.5nm in [11]. In article [12], EDFA, Raman and OA amplifiers were used in parallelism or in sequence and then signal can be de-multiplexed with help of a coupler after which it can be amplified and then multiplexed by a coupler again. But the detrimental factor here is that because of the guard band of the coupler there will be inoperative bandwidth in this structure and it also reduces amplifier noise figure. Different configurations of hybrid optical amplifier (such as post, pre and symmetric) were researched in [12]. The work in [13] discovered multiple types of WDM structures and determined that SOA gives improved outcome at dispersion D = 2 ps/nm/km in fewer number of channels and fall in system outcome or performance when the number of channels are increased. But EDFA works better than SOA when larger number of channels are used with higher dispersion. Raman-EDFA amplifier configuration at dispersion D = 2 ps/nm/km at 160 km shows maximum output power which is 20.18 dBm by using various modulation techniques on HOA and attained acceptable Q factor (13.88 dB) with fewer eye closure (2.609 dB) in [14]. A 64 × 10 Gbps DWDM system were studied for various HOA and it was seen that EDFA-EDFA-EDFA contributes maximum output power whereas better Q-value 26.22 dB at 50 km for NRZ was given by EDFA-EDFA-Raman in [15]. In [16], multiple Terabit transmission rate was elucidated by using HOA by a paper where main target was to make the most of the span length and decrease the nonlinearities. It provided a flat gain of 20 dB and less than 7 dB noise figure [16]. In [17], WDM systems with EDFA, SOA and Raman amplifier was examined and from dispersion and distance point of view their performance was analyzed. For fewer number of channels and lower dispersion SOA performed better. But for improved number of channels and dispersion, EDFA outperformed SOA. As compared to other amplifiers, Raman provided better results and low output power for L band range 17]. In the research work of [18] a single wavelength pump was used in S+C band for amplification by designing a hybrid optical amplifier. In case of L band amplification, Raman amplifier was utilized and for C band amplification EDFA was utilized. This configuration was applicable for 100km and that provided 5 dB noise figure and 1 dB of gain [18]. Optical amplifiers for diverse dispersion and transmission distance were optimized in [19]. The measuring parameters for evaluation were BER metric, eye diagram, eye opening factor and Q factor. They have measured the outcome of EDFA and SOA from eye diagram and power point of view [19]. In article [20], an OTDM system of data rate of 160 Gbps with all channel modulation and all channel synchronized demultiplexing was simulated. The Mach-Zehnder Interferometer (MZI) uphold the delay setting for adjacent channels and deliver stability at higher temperature which is the prominent feature of an OTDM system. A single in-line SOA and Raman amplifier system were used in [21]. Results extended the distance to 112 km from 69km. Major effective factors were discussed in proposed systems. EDFA in SOA jointly were used in [22] to form a distributed Raman Amplifier which resulted in less distortions. In [23], Raman-EDFA, Raman-SOA, SOA-EDFA, EDFA-Raman EDFA amplifier configurations were considered for 16 and 32 channels having 10Gbps data rate. BER, Signal Quality, eye opening factor and power at the system output were analyzed for varying number of channels. 16, 32, and 64 channels based system with 10Gbps data rate and different hybrid amplifiers were studied in [24] where BER, quality factor, eye opening factors and signal jitter were evaluated and they documented that SOA-EDFA provides best quality factor for 64 channels at 260km distance [24]. Authors in [25] analyzed optical network system performance for 64 channels based 10 Gbps data rate system where backward multi-pump Raman amplifier were used for lessening difference in gain to avoid the usage of practical methods of gain flattening by using four pumps only. They documented noise figure higher than 8 dB and highest gain of 8.6 dB. In [26], the authors established a long- haul transmission system where they have used cascaded Raman amplifier and linear optical amplifier with single mode fiber of length of 1040km and 16 channels with 10Gbps data rate. It achieved a Q factor which is higher after 1040km distance (12.7-14.5 dB). They demonstrated that hybrid optical amplifiers can be a practical solution for long distance optical communication network. In [27], the authors examined long distance WDM system link with Raman-EDFA amplifier. It was found that for distances of 650km and 530km Raman-EDFA as inline amplifier can be a reasonable solution. Satisfactory Q-factor, power, eye opening factor and BER was achieved before 530 km and 650 km. In [28], performance evaluation of a WDM system for 16x10Gbps, 32x10Gbps and 64x10Gbps was conducted with EDFA, Raman and SOA amplifiers separately. They provided the performance comparison from transmission range and dispersion (considering and not consider nonlinearities) point of view. EDFA outperforms SOA for increased dispersion from output power and BER point of view. But Raman shows better commitment for L band intensification. In [29]-[31], the authors have shown that for WDM system the transmission capacity can be significantly improved by expanding the optical bandwidth for inline amplifiers. Besides, in [32], it was seen that with homogeneous dispersion values for nonzero dispersion-shifted fibers (NZDSFs).And dispersion shifted fibers (DSFs) the passband in optical domain is restricted to the L bands and C bands. This is due to the fact that the transmission performance is worsen with the introduction of fiber nonlinearity (for DSF case, in the C band and for NZDSF case, in the S band). Consequently, the usage of elongated wavelengths (U band) becomes a necessity for commercial systems [32]. In [33], authors reported that U band provides better signal quality than L band also for the stretched signal wavelength. They reported almost same noise figure for L-band DRAs and U-band DRAs. Also, L-band DRAs have higher pump loss U-band DRAs. In [34], the authors observed the working of RZ, NRZ and CSRZ. They found that in presence of complete dispersion RZ face less nonlinearities than NRZ [34]. It was found that HOA provides better performance than EDFA in [35]. In [36], HOA sowed low noise figure and high output power and it was seen that in S+C+L bands with 105nm bandwidth for silica fiber the transmission capacity was improved by HOA. While comparing NRZ and RZ in [37] for long haul optical network with single channel dispersion model, the authors described that signal waveform distortion and linear amplified spontaneous emission (ASE) accumulation because of group velocity dispersion (GVD) and self-phase modulation (SPM) governs the performance. In [38], authors reported that for WDM system with 40Gbps data rate RZ is more prone to dispersion than NRZ. They reported that high modulation bandwidth was the reason behind this behavior. In [39], at 40Gbps NRZ, RZ and CSRZ were used for ultra-dense wavelength-division multiplexing (UDWDM) system and they discovered that orthogonal polarization launch of adjacent channels helps NRZ modulation to perform better. Although RZ and CSRZ performed better as compared to NRZ. The researchers in [40] explored HOA system with Raman-EDFA for DWDM system consisting of 60 channels with 200 GHz lodging a bandwidth of 98nm.

CHAPTER 3

System Description

3.1 DWDM System

WDM system with 100 GHz spacing (0.8nm) among neighboring channels is called Dense WDM (DWDM) system where the regular operation range is from 1530 nm-1565nm. This range is also the area where EDFA performs better. There is another type of WDM which is known as coarse WDM (or CWDM). In CWDM the channels situated at 1310 nm and 1550 nm with 20nm channel spacing. But in case of DWDM, huge number of channels can be lodged together for a high capacity long haul optical communication network system by which it can also evade water peak wavelength of the fiber which is responsible for the vibration of the oxygen-hydrogen bond in the regular silica optical fiber. For this positive characteristic DWDM is a dominant backbone system for long haul high capacity optical fiber network system [41], [42].

The DWDM transmission system encompasses numerous crucial subsystems and apparatus. The transmitter covers optical source, modulator and modulation circuitry to enforce the high-speed data onto the laser beam. Characteristically the optical source is distributed feedback (DFB) laser with continuous wave (CW) production, and LiNbO3 modulator is used to modulate the intensity or phase of the laser output with the data. Non-return-to-zero on-off-keying (NRZ OOK) is applied in standard 10 Gbps transmission. Although multilevel phase modulation schemes such as QPSK, OFDM and various multiplexing techniques (such as polarization multiplexing) can be used for higher data rate transmission which also results in complex system management for controlling noise figure and maintaining proper gain. Optical multiplexer is used for combing multiple channels (channel spacing 100 GHz) inside a single optical fiber which is classically an arrayed waveguide grating (AWG)-based passive optical device which provides multiplexing with standard ITU (International Telecom Union) formats. The Loop Control permits multiple times signal propagation in the components that are connected between the Loop Control input and output ports. Loop Control is applied to calculate the system performance based on the number of fibers and EDFA spans [41], [42].

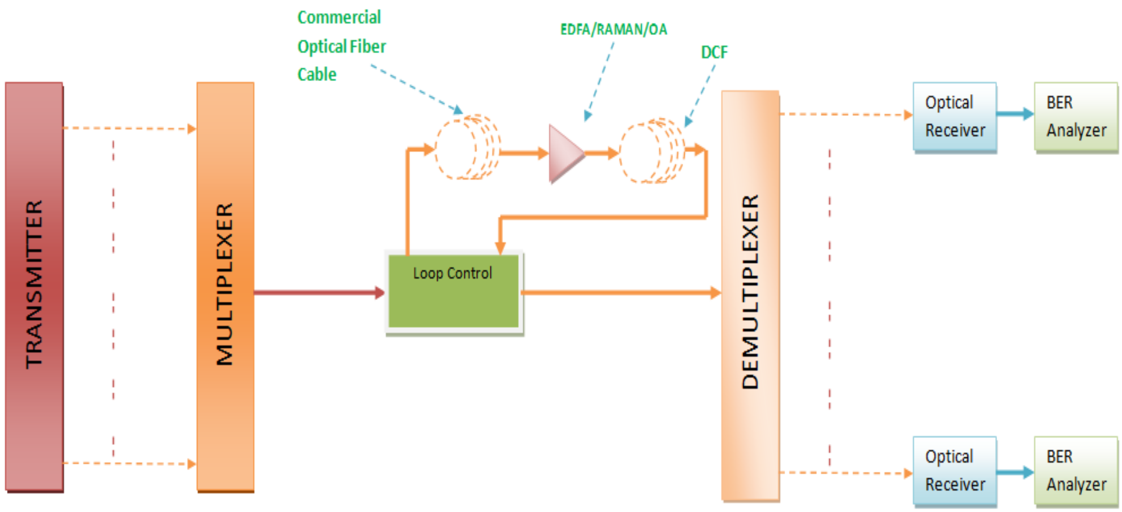


Figure 3.1: Block diagram of the DWDM based advanced optical network system

3.2 Single Mode Fiber (SMF)

In single-mode optical fiber (SMF) a single mode of light is conveyed which known as the transverse mode. Modes are attained by coalescing Maxwell's equations and the boundary conditions which are solutions of Helmholtz equation for waves.

These modes describe the mechanism the wave trips through space, i.e. how the wave is dispersed in space. Waves having the same mode can have diverse frequencies. Single-mode fibers can have waves with diverse frequencies which are in same mode which indicates that they are dispersed in space in the identical way and thereby produce a single ray of light. As its electromagnetic fluctuations happen perpendicular (transverse) to the length of the fiber so it is named as transverse mode.

The primarily used and the first commercially used single mode fiber type is NDSF or Non-DSF (Non-Dispersion-Shifted Fiber). NDSF was enhanced for operation at 1310 nm, the wavelength of choice at that time but after that 1550 nm systems were presented. NDSF at 1550 nm presents high dispersion, restrictive data rate and transmission range. DSF was designed for better performance at 1550 nm. DSF functioned better with a single wavelength at 1550 nm, but revealed nonlinearities when manifold, closely-spaced wavelengths (in 1550 nm band) were transmitted, as in DWDM systems. For solving this issue, different types of DSF fiber were designed which are recognized as NZ-DSF (non-zero dispersion-shifted fiber). Single mode fiber covers a superior distance than multimode fiber even with the benefit of low attenuation and have better bandwidth efficiency. For example, single mode fiber can cover a long distance such as 200 km where a multimode fiber can reach a few hundred meters only.

3.3 Dispersion Compensation Fiber (DCF)

Dispersion Compensation Fiber (DCF) is to overcome the contribution from chromatic dispersion which brings intersymbol interference (ISI) in the scenario. Pulse broadening is dependent on distance as well as dispersion parameter D. The dispersion parameter is specified in ps/nm/km and fluctuates depending on the fiber. It is also a function of wavelength. D is typically about 17 ps/nm/km in the 1.55 μm wavelength range for a standard single mode fiber (SMF). It is at an extreme of 3.3 ps/nm/km in the similar window for a dispersion-shifted fiber (DSF). Nonzero dispersion fiber (NDF) has a chromatic dispersion in the middle of 1 and 6 ps/nm/km or -1 and -6 ps/nm/km [41], [42]. For outwardly modulated sources, transmission distance restricted by chromatic dispersion is [41]

$$L < \frac{2\pi c}{16|D|\lambda^2 B^2}$$

When D=16 ps/(km-nm) and at 2.5 Gbps, L ≈ 500km, whereas it drops to 30 km at 10 Gbps bit rate.

3.4 Raman amplifier-average power model

Raman amplifiers (Raman) have emerged as one of the most promising technologies for the succeeding cluster of fiber amplifiers, typically because of their options in bandwidth design [43]. Nonetheless, the simulation methods that are frequently applied for Raman amplifiers, have necessitated extensive computational period, due to the use of direct incorporation of the coupled differential equations that designate the Raman amplifier's behavior [44], [45]. The coupled differential equations have the nature perceived in (1). A comparable set of equations, unfolding the backward propagation, is resolved at the same time we explain the forward equations inscribed down [46]-[48]. Further details on equation (1) with the physical properties engaged into consideration for this amplifier can be seen in [4], [47],

$$\frac{dP_f(z,v)}{dz} = \alpha(v)P_f(z,v) + \gamma(v)P_b(z,v) + P_f(z,v)\sum_{v<\zeta} \frac{g_r(v-\zeta)}{K_{eff}A_{eff}}[P_f(z,\zeta) +$$

$$P_b(z,\zeta)]h\Delta v\sum_{v<\zeta} \frac{g_r(v-\zeta)}{A_{eff}}[P_f + P_b]\left[1+\exp\left(\left[\frac{h(\zeta-v))}{kT}\right]1\right)^{-1}\right] -$$

$$P_f(z,v)\sum_{v<\zeta} \frac{g_r(v-\zeta)}{K_{eff}A_{eff}}\frac{v}{\zeta}[P_f(z,\zeta)+P_b(z,\zeta)] -$$

$$2hv\Delta v P_f(z,v)\sum_{v<\zeta} \frac{g_r(v-\zeta)}{A_{eff}}\left[1+\exp\left(\left[\frac{h(v-\zeta))}{kT}\right]1\right)^{-1}\right] \quad (1)$$

The impression behindhand this technique is primarily to divide the amplifier into a sequence of trivial sections, and then to apply the trivial signal wave result in each section in (3). For excluding the dependency in a trivial section length, average powers in each section are familiarized in (4). Actually we reorganized some terms of the original in (1) and moderated the equations to a naivest form, appropriate for investigation, may be inscribed as [4], [49]:

$$\frac{dP_f(z,v)}{dz} = A(z,v)P_f(z,v) + B(z,v) \quad (2)$$

Here

$$A(z,v) = -\alpha(v) + \sum_{v<\zeta} \frac{g_r(v-\zeta)}{K_{eff}A_{eff}}[P_f(z,\zeta)+P_b(z,\zeta)]\sum_{v<\zeta}\frac{v}{\zeta}\frac{g_r(v-\zeta)}{K_{eff}A_{eff}}[P_f(z,\zeta) +$$

$$P_b(z,\zeta) - 2hv\Delta v\sum_{v<\zeta} \frac{g_r(v-\zeta)}{A_{eff}}\left[1+\frac{1}{\exp\left(\left[\frac{h(v-\zeta))}{kT}\right]-1\right)^{-1}}\right] \quad (2a)$$

$$B(z,v) = \gamma(v) P_b(z,v) + hv\Delta v \sum_{v<\zeta} \frac{g_r(v-\zeta)}{A_{eff}} [P_f(z,\zeta) +$$

$$P_b(z,\zeta)] \left[1 + \frac{1}{\exp\left(\left[\frac{h(v-\zeta)}{kT} \right] - 1 \right)^{-1}} \right] \qquad (2b)$$

Replacing $P_f(z,\zeta)$, $P_b(z,\zeta)]$ in equation (2a) and in equation (2b) in to each lump by average powers in the lump, factors $A(z,v)$, $B(z,v)$ are independent of z elucidation for (2) can be inscribed as [4], [49]:

$$P_f(z_0 + H, v) = P_f(z_0, v) \exp(A(v)H) + \frac{B(v)}{A(v)} [\exp((A(v)H) - 1)] \qquad (3)$$

Here H is the size of the lumps.

Inside each lump, powers $P_f(z,\zeta)$, $P_b(z,\zeta)$ necessarily to be substituted by average powers [4], [49],

$$\left\langle P_{f,b}(v) \right\rangle = P_{f,b}^{in} \frac{G-1}{\ln G} + \frac{B(v)}{A(v)} \left[\frac{G-1}{\ln G} - 1 \right] \qquad (4)$$

Here $P_{f,b}^{in}$ are input powers to the lump for backward and forward propagation, and the gain is specified by: $G = \exp(A(v)H)$. The system designer should be accountable to guarantee that the term $A(v)$ should not turn into zero.

3.5 Erbium doped fiber amplifier (EDFA)

EDFA amplifier is engaged to strengthen the optical signals. Pump is the main difference between EFDA and Raman amplifiers. The EDFA procedures are mathematically resolved underneath stationary circumstances [4], [50], these are the following equations:

$$\frac{\partial N_2(z,t)}{\partial t} = \frac{N_2(z,t)}{\tau}\frac{1}{A_{eff}}\sum_{n=1}^{M}\left\{\Gamma_n[(\sigma_n^e + \sigma_n^a)N_2(z,t) - \sigma_n^a]\right\}[P_n^+(z,t) + P_n^-(z,t)] \tag{5}$$

$$N_1 + N_2 = 1 \tag{6}$$

$$\frac{\partial P_n^{\pm}(z,t)}{\partial z} = u_n\{\rho\Gamma_n[(\sigma_n^e + \sigma_n^a)N_2(z,t) - \sigma_n^a - \alpha]\}P_n^{\pm}(z,t) + 2\rho\Delta v N_2 \Gamma_n \sigma_n^e \tag{7}$$

The confinement factor Γ_n is specified by [4], [50]:

$$\Gamma_n(v) = \frac{\int_0^b |E(r,v)|^2 rdr}{\int_0^\infty |E(r,v)|^2 rdr} \tag{8}$$

Resolving (5-7) under stationary circumstances facilitate engineers to determine the features of the amplifier performance. The optical fiber factors such as core of the fiber and E_r doping radius of the fiber, E_r metastable state lifetime, the fiber's numerical aperture, E_r ion density, forfeiture at 980 nm and 1550 nm, and the length of the optical fiber are the prerequisite as input factors [4], [50].

3.6 OA amplifier

OA amplifiers applies second-order nonlinearity to handover energy from a static frequency pump pulse to a inconstant frequency signal pulse, and signify an informal way of tuning over a extensive range the frequency of an otherwise stable laser system. OAs can also perform as broadband amplifiers, transmitting energy from a narrowband pump to a broadband signal and hence substantially shortening the period of the pump pulse [51].

Let us assume an optical field, comprising of the superposition of three homochromatic waves, at frequencies ω_1, ω_2 and ω_3 [51]:

$$E(z,t) = \frac{1}{2}\left\{A_1(z)\exp\left[i(\omega_1 t - k_1 z\right] + A_2(z)\exp\left[i(\omega_2 t - k_2 z\right] + A_3(z)\exp\left[i(\omega_3 t - k_3 z\right] + c.c.\right\} \quad (9)$$

satiating the circumstance $\omega_1 + \omega_2 = \omega_3$, encroaching on a non-centrosymmetric medium producing a second order nonlinear polarization:

$$P_{NL}(z,t) = \varepsilon_0 \chi^{(2)} E^2(z,t) \quad (10)$$

Such a condition is acknowledged as "nonlinear second-order parametric interaction" and resembles to an interchange of energy amongst the three fields interceded by the second order nonlinearity. The nonlinear polarization comprises three constituents at frequencies ω_1, ω_2 and ω_3, given by [51]

$$P_{1NL}(z,t) = \frac{\varepsilon_0 \chi^{(2)}}{2} A_2^* A_3 \exp\left\{i\left[\omega_1 t - (k_3 - k_2)z\right]\right\} + c.c \quad (11a)$$

$$P_{2NL}(z,t) = \frac{\varepsilon_0 \chi^{(2)}}{2} A_1^* A_3 \exp\left\{i\left[\omega_2 t - (k_3 - k_1)z\right]\right\} + c.c \quad (11b)$$

$$P_{3NL}(z,t) = \frac{\varepsilon_0 \chi^{(2)}}{2} A_1 A_2 \exp\left\{i\left[\omega_3 t - (k_1 + k_2)z\right]\right\} + c.c \quad (11c)$$

Clearly there are other expressions on P_{NL} at diverse frequencies, such as, for instance, $2\omega_1$, $2\omega_2$, $\omega_1 - \omega_2$ ..... At this point we consider merely the terms at ω_1, ω_2 and ω_3 since we adopt that simply the collaboration amongst these three fields is efficient, owing to the phase-matching condition [51].

The nonlinear polarization at frequency ω_j can consequently be inscribed as:

$$P_{NLj}(z,t) = \frac{1}{2}\rho_{NLj}(z)\exp\left\{i\left[\omega_j t - k_{pj} z\right]\right\} + c.c \quad (12)$$

Here we accentuate that the wave vector of the polarization k_{pj} is in general different from that of the analogous field. The propagation equation for each field in the nonlinear medium may be inscribed, in the monochromatic limit, as [51]:

$$\frac{\partial A_j}{\partial z} = -i\frac{\mu_0 \omega_j c}{2n_j}\rho_{NLj}\exp\left[-i\Delta k_j z\right] \quad (13)$$

where $\Delta k_j = k_{pj} - k_j$ is the "wave-vector mismatch" amid the nonlinear polarization and the field. By injecting Eq. (11) into Eq. (13), we can derive the following three equations for the fields at ω_1, ω_2 and ω_3 [51], [52]:

$$\frac{\partial A_1}{\partial z} = -ik_1 A_2^* A_3 \exp\left[-i\Delta kz\right] \qquad (14a)$$

$$\frac{\partial A_2}{\partial z} = -ik_2 A_1^* A_3 \exp\left[-i\Delta kz\right] \qquad (14b)$$

$$\frac{\partial A_3}{\partial z} = -ik_3 A_1 A_2 \exp\left[i\Delta kz\right] \qquad (14c)$$

where the nonlinear coupling coefficients: $k_i = \frac{\omega_i \chi^{(2)}}{4cn_i}$ and the "wave-vector mismatch" as: $\Delta k = k_3 - k_1 - k_2$. Remind that the first two equations are properly matching, demonstrating that the fields at ω_1 and ω_2 show the same role. Conferring to the boundary initial environments $A_i(0)$ $(i = 1, 2, 3)$, two main nonlinear processes can ascend: sum frequency generation (SFG) and difference frequency generation (DFG). In SFG the input fields are $A_1(0)$) and $A_2(0)$ at ω_1 and ω_2; their interaction produces the field A_3 at frequency $\omega_3 = \omega_1 + \omega_2$. Second harmonic generation (SHG) is just a specific case of SFG in which $\omega_1 = \omega_2$. In DFG, the input fields are $A_3(0)$ at ω_3 and $A_1(0)$ at ω_1; the field A_3 drops energy in favor of A_1 and of the anew generated field A_2 at $\omega_2 = \omega_3 - \omega_1$. The OA is a technique alike to DFG, excluding for the strength of the intermingling fields: DFG ascends when the fields at ω_3 and ω_1 have analogous concentrations, while for an OA the field at ω_1 is much scrawnier. In the OA process, consequently, a strong beam at ω_3 (the pump) handovers energy to the beam at ω_1 (the signal), thereby intensifying it, and produces light at ω_2 (the idler). Note that the DFG/OA processes also happen opening from the fields $A_3(0)$ at ω_3 and $A_2(0)$ at ω_2; in this scenario the anew generated field is at ω_1. This indicates that the signal and idler play an transposable part in the OA process [51], [52].

Eq. (14) can be resolved by building the supposition that the pump field is not depleted during the dealings ($A_3 \approx$ const.), and that there is no initial idler beam ($A_{20} = 0$). Subsequently proper manipulation, the signal development along the nonlinear medium can be inscribed as [51]:

$$\frac{d^2 A_1}{dz^2} = -i\Delta k \frac{dA_1}{dz} + \Gamma^2 A_1 \tag{15}$$

where $\Gamma^2 = \frac{2 d_{eff}{}^2 \omega_1 \omega_2}{c_0{}^3 \varepsilon_0 n_1 n_2 n_3} I_3$ and $I_3 = \frac{1}{2} n_3 c \varepsilon_0 \left| A_3 \right|^2$ is the pump beam strength. Γ is recognized as the small signal gain of the OA and $d_{eff} = \frac{\chi^{(2)}}{2}$ is the part of the $\chi^{(2)}$ tensor that retains trace of the polarization of the beams and propagation directions inside the nonlinear crystal lattice.

In the postulate of an initial signal field amplitude $A_1(0) = A_{10}$ (the "seed beam") and no early idler $(A_2(0) = 0)$, the solutions of Eq. (15) are:

$$I_1(z) = I_{10} \left\{ 1 + \left[\frac{\Gamma}{g} senh(gz) \right]^2 \right\} \tag{16a}$$

$$I_2(z) = I_{10} \frac{\omega_2}{\omega_1} \left[\frac{\Gamma}{g} senh(gz) \right]^2 \tag{16b}$$

here $g = \sqrt{\Gamma^2 - \left(\frac{\Delta k}{2} \right)^2}$. For the scenario of enormous gain $\left(gz \gg 1 \right)$ Eq. (16) more abridge to:

$$I_1(z) = \frac{I_{10}}{4} \left(\frac{\Gamma}{g} \right)^2 \exp(2gz) \tag{17a}$$

$$I_2(z) = \frac{\omega_2}{\omega_1} I_1(z) \tag{17b}$$

showing an exponential progress of both signal and idler strengths with crystal length, typical feature of an optical amplifier. It ought to be illustrated, that, in the huge gain limit, Eq. (17b) can be modified as:

$$\frac{I_2(z)}{\hbar\omega_2} = \frac{I_1(z)}{\hbar\omega_1} \tag{18}$$

which signifies that, in the great gain limit, signal and idler strengths are interrelated by energy preservation, since for each annihilated pump photon a signal and an idler photon are concurrently created [51].

The parametric gain for the signal beam, in the outsized gain limit, can be inscribed as:

$$G = \frac{I_1(z)}{I_{s0}} = \frac{1}{4}\left(\frac{\Gamma}{g}\right)^2 \exp(2gz) \tag{19}$$

which, for seamless phase equivalence $\left(\Delta k = 0\right)$ develops to:

$$G = \frac{1}{4}\exp(2\Gamma z) \tag{20}$$

The exponential development of the gain with propagation distance is qualitatively dissimilar from the quadratic development that arises in other second-order processes like SFG and SHG and displays that the OA performs as a genuine amplifier [51].

3.7 The Pin Photodetector:

Photo detectors are devices applied to transform the optical signal into electrical signal. They are produced from semiconductor material. When the light falls on the light detector a current is formed in the external circuit proportional to the concentration of the incident light. The Pin Photodetector comprises of p and n semiconductor regions disjointed by a very lightly n-doped intrinsic (i) region. A reverse-bias voltage is applied across the device. Incident photon which contains energy superior than or equal to the band gap energy of the semiconductor material, releases its energy and excite an electron from the valence band to the conduction band.

3.8 Q-factor

Q-factor describes the quality of the signal with respect to SNR (Signal to Noise Ratio). It contains all physical weakening factors demeaning the signal and instigating BER. A superior value of Q-factor provides a inferior BER. Q-factor is defined by the following [53]:

$$Q = \frac{I_1 - I_0}{\sigma_1 - \sigma_0}$$

here I_1 characterizes the logical level "1," I_0 characterizes logical level "0," σ_1 signifies standard variance of logical level "1," and σ_0 signifies standard variance of logical level "0."

3.9 Bit Error Rate

BER means Bit Error Rate. It is the ratio of imperfectly received bits bE to the complete number of received bits p in time t:

$$BER = \frac{bE}{vp.t}$$

BER is an important factor to determine the quality of the optical transmission. In practical scenario the nonzero likelihood of error decision or sample value is characterized by the value of logical "0" or logical "1". For a physical application case, the BER ought to be approximately 10^{-12}. The BER design taking into attention the Q- factor is well-defined as [53]:

$$BER = \frac{1}{2} erfc\left(\frac{Q}{\sqrt{2}}\right) \approx \frac{\exp\left(-Q^2 / 2\right)}{Q.\sqrt{2\pi}}$$

CHAPTER 4

Simulations, Results and Discussion

The aim of this work is to design and do performance analysis of 32, 64 and 128 channels DWDM system for three different amplifier configurations which are EDFA, Raman and OA amplifiers where each channel having 10 Gbps data rate multiplexed with frequency spacing of 100 GHz. In this proposed work Optisystem 16.0 commercial optical simulator is used to analyze the performance of 32, 64 and 128 channels DWDM system for three different amplifier configurations which are EDFA, Raman and OA amplifiers. The system performance is enhanced by using Dispersion compensation fiber to reimburse for the dispersion formed by single mode fiber. The system performance is imperfect due to the dispersion. In order to recompense this, we have used Dispersion compensation fiber. Between amplifier spans standard single-mode fiber is used, but at each amplifier position, dispersion compensating fiber having a negative chromatic dispersion is presented. By using this we have effectively designed a DWDM system with 32/64/128 channels each having 10 Gbps data rate multiplexed with frequency spacing of 100 GHz. The DWDM system designs for various channels and amplifiers configurations and their results are registered below in the following sections:

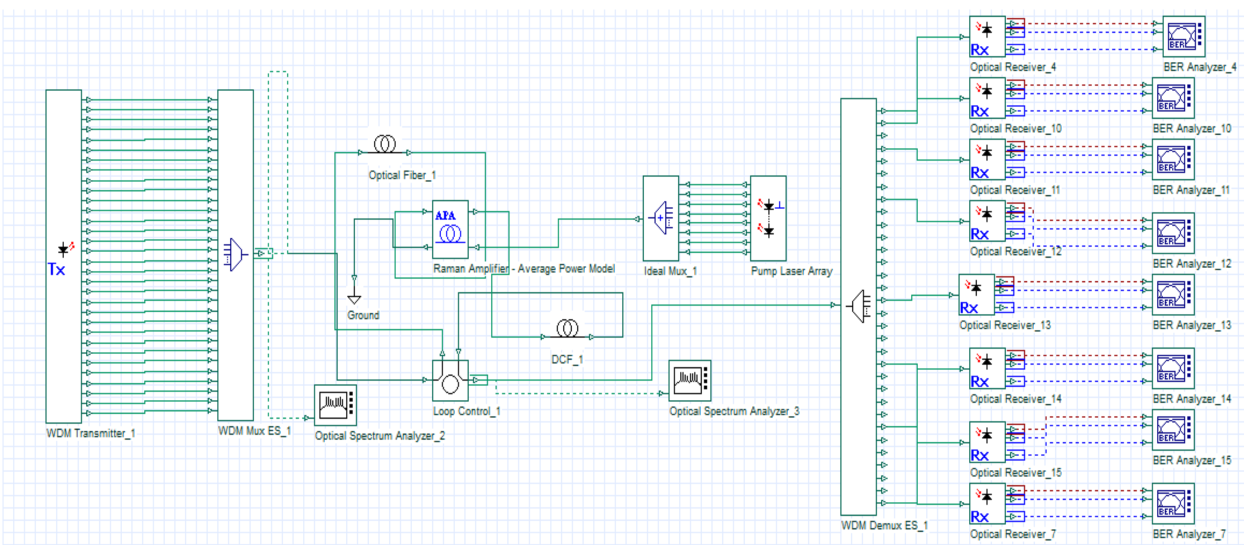


Figure 4.1: Simulation testbed for 32 channels DWDM system using Raman amplifier (Also same configuration is used for EDFA and OA amplifiers)

The above figure depicts the simulation setup for the 32 channels DWDM system using Raman amplifier. The same simulation setup is also used for simulating the system using EDFA and OA amplifiers.

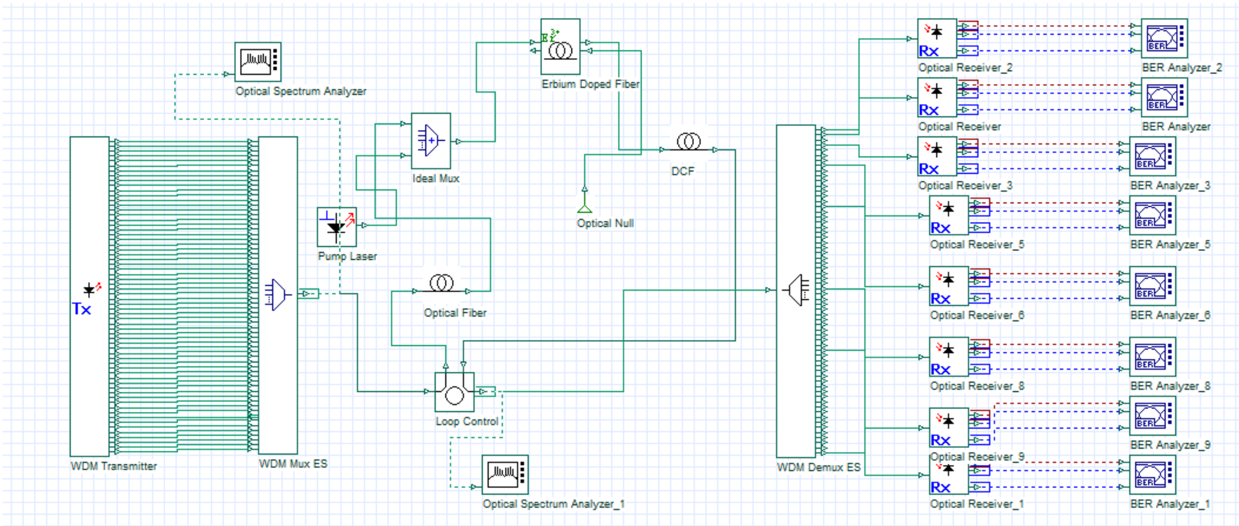


Figure 4.2: Simulation testbed for 64 channels DWDM system using EDFA (Also same configuration is used for Raman and OA amplifiers)

The above figure shows the simulation setup for the 64 channels DWDM system using EDFA (Also same configuration is used for Raman and OA amplifiers).

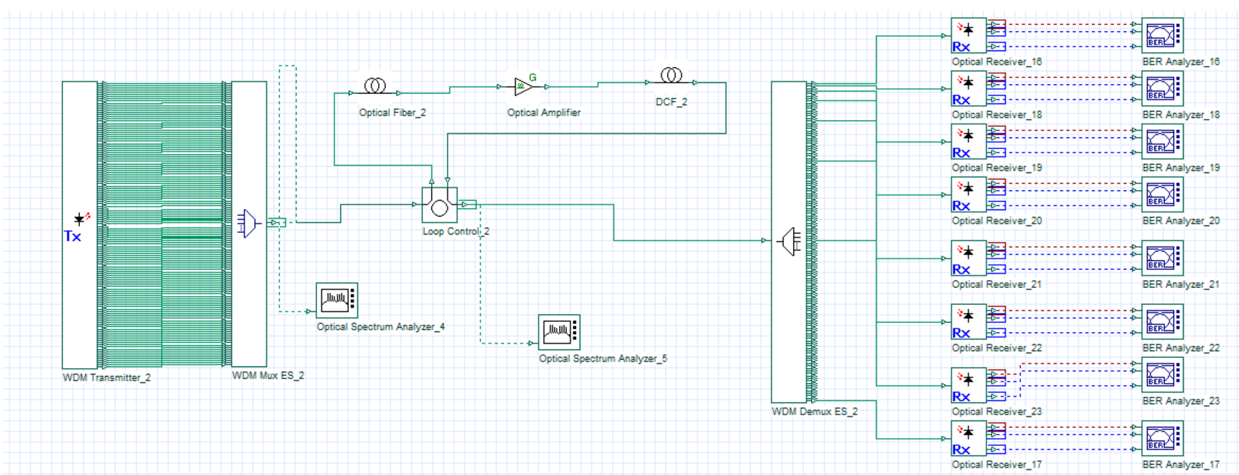


Figure 4.3: Simulation testbed for 128 channels DWDM system using OA amplifier (Also same configuration is used for EDFA and Raman amplifiers)

The above figure shows the simulation setup for the 128 channels DWDM system using EDFA (Also same configuration is used for Raman and OA amplifiers).

4.1 Configurations in Optisystem for 32 channels DWDM system

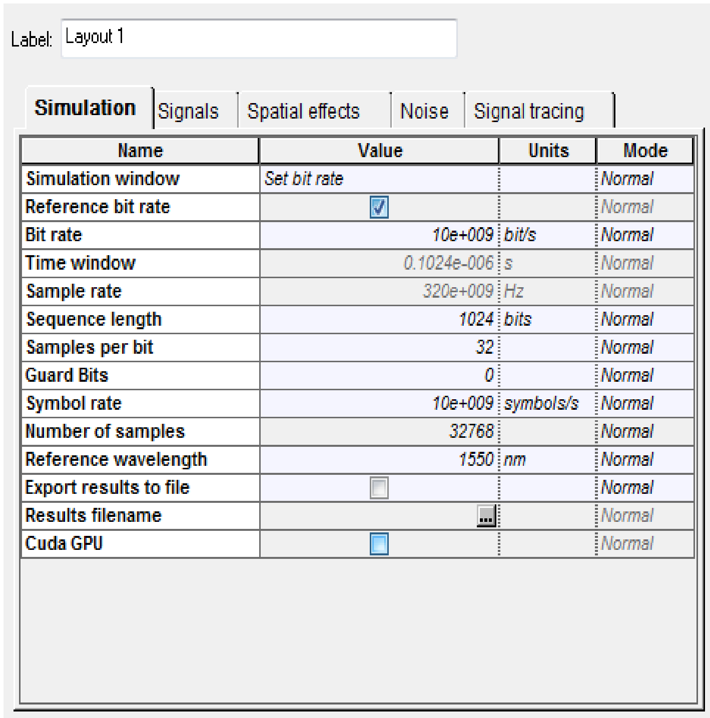


Figure 4.1.1: System layout settings

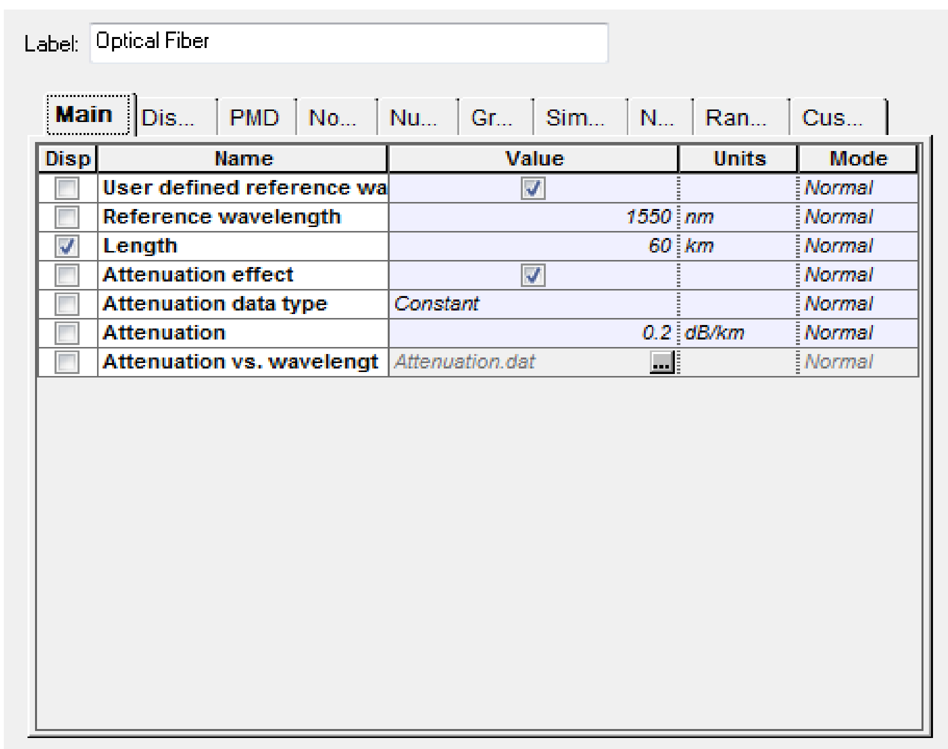


Figure 4.1.2: Settings for optical fiber

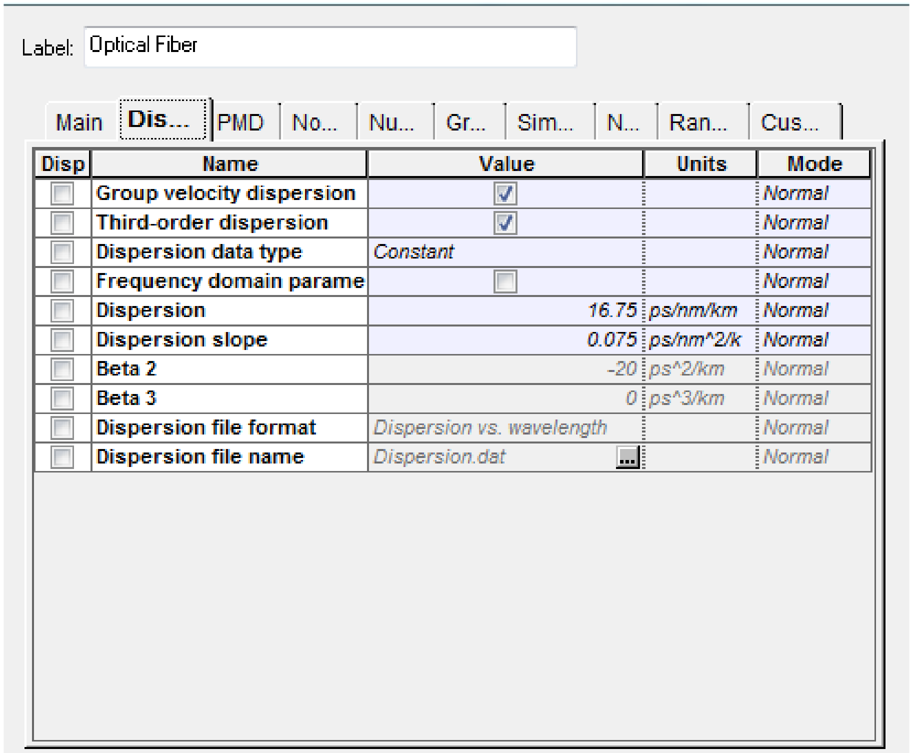


Figure 4.1.3: Settings for optical fiber dispersion

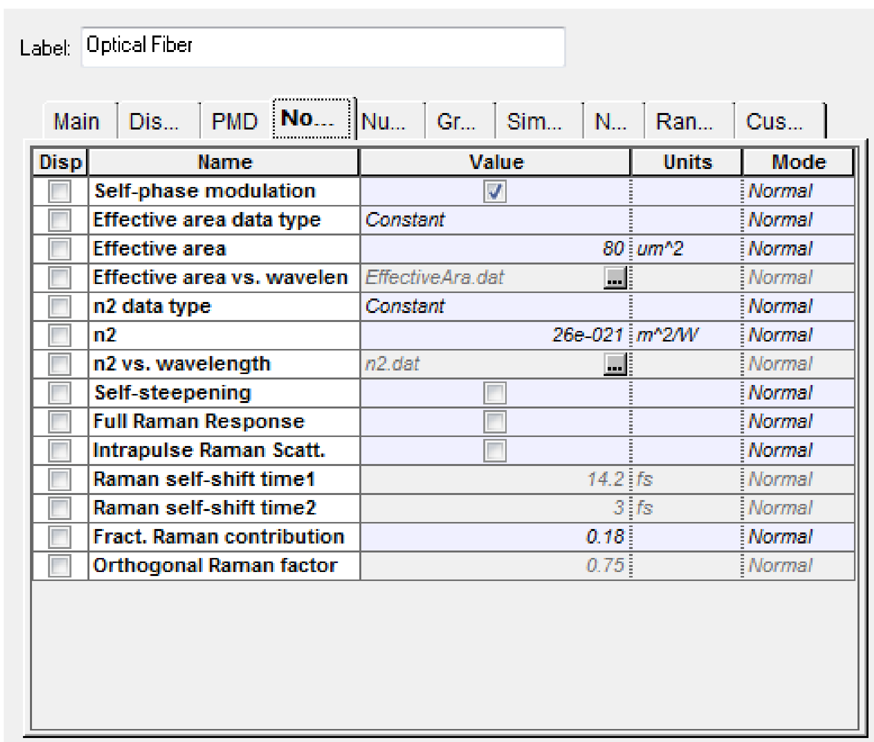
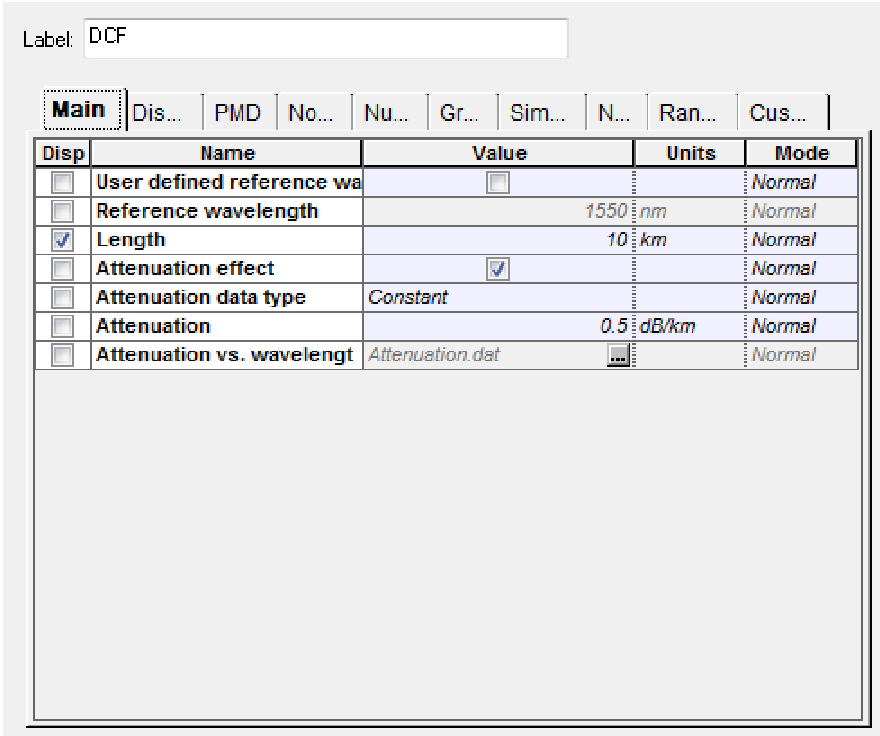


Figure 4.1.4: Settings for noise in optical fiber

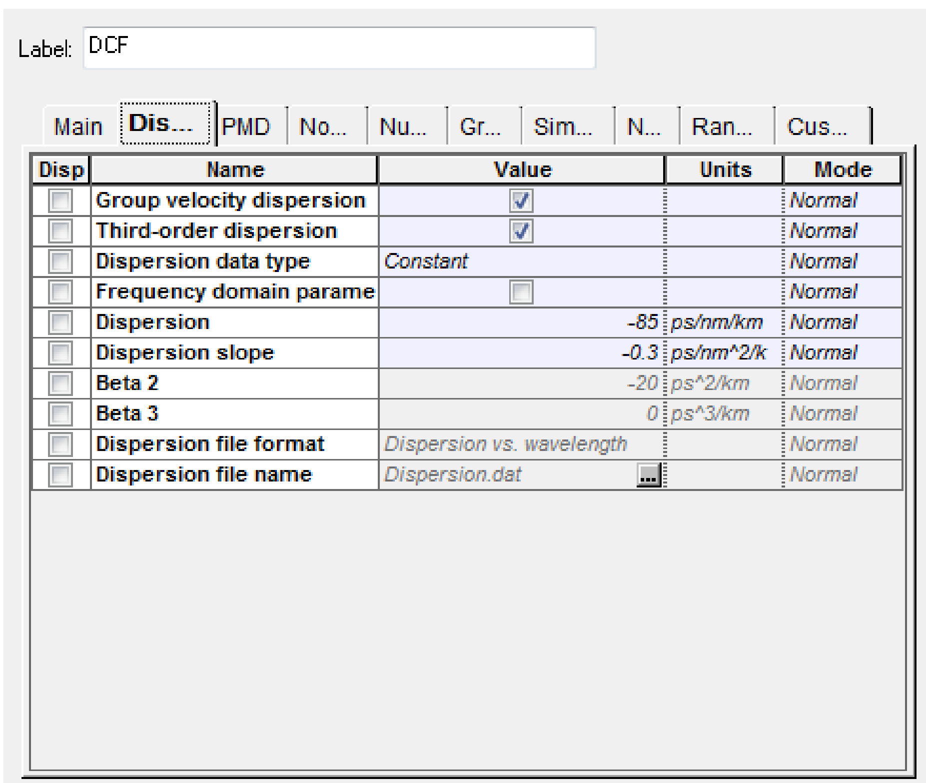


Label: DCF

Main | Dis... | PMD | No... | Nu... | Gr... | Sim... | N... | Ran... | Cus...

Disp	Name	Value	Units	Mode
☐	User defined reference wa	☐		Normal
☐	Reference wavelength	1550	nm	Normal
☑	Length	10	km	Normal
☐	Attenuation effect	☑		Normal
☐	Attenuation data type	Constant		Normal
☐	Attenuation	0.5	dB/km	Normal
☐	Attenuation vs. wavelengt	Attenuation.dat ...		Normal

Figure 4.1.5: Settings for Dispersion Compensation Fiber (DCF)



Label: DCF

Main | Dis... | PMD | No... | Nu... | Gr... | Sim... | N... | Ran... | Cus...

Disp	Name	Value	Units	Mode
☐	Group velocity dispersion	☑		Normal
☐	Third-order dispersion	☑		Normal
☐	Dispersion data type	Constant		Normal
☐	Frequency domain parame	☐		Normal
☐	Dispersion	-85	ps/nm/km	Normal
☐	Dispersion slope	-0.3	ps/nm^2/k	Normal
☐	Beta 2	-20	ps^2/km	Normal
☐	Beta 3	0	ps^3/km	Normal
☐	Dispersion file format	Dispersion vs. wavelength		Normal
☐	Dispersion file name	Dispersion.dat ...		Normal

Figure 4.1.6: Settings for dispersion in Dispersion Compensation Fiber (DCF)

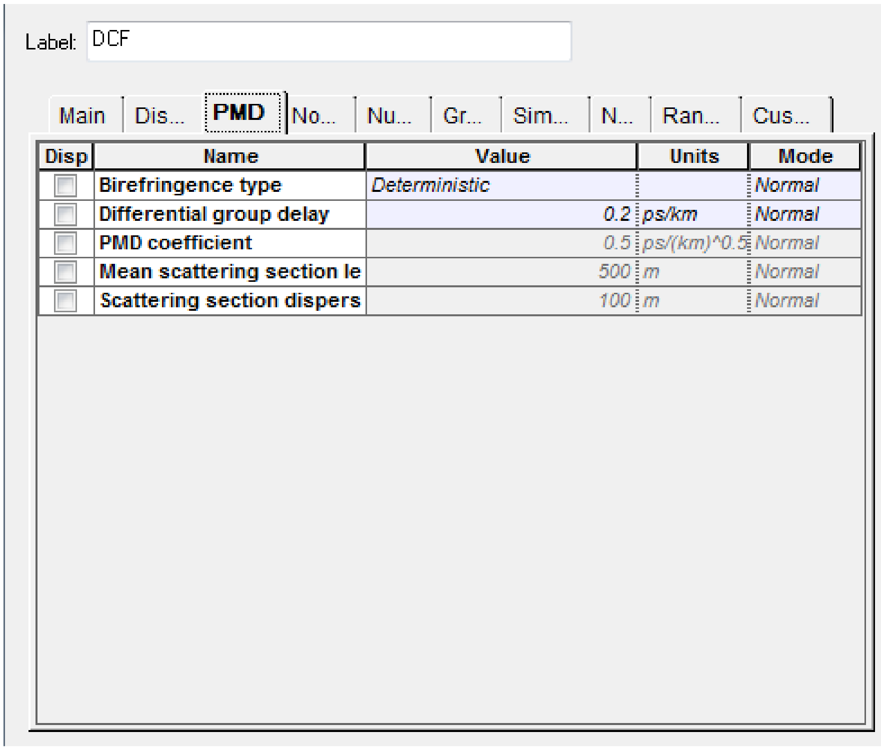


Figure 4.1.7: Settings for Polarization Mode Dispersion (PMD) in Dispersion Compensation Fiber (DCF)

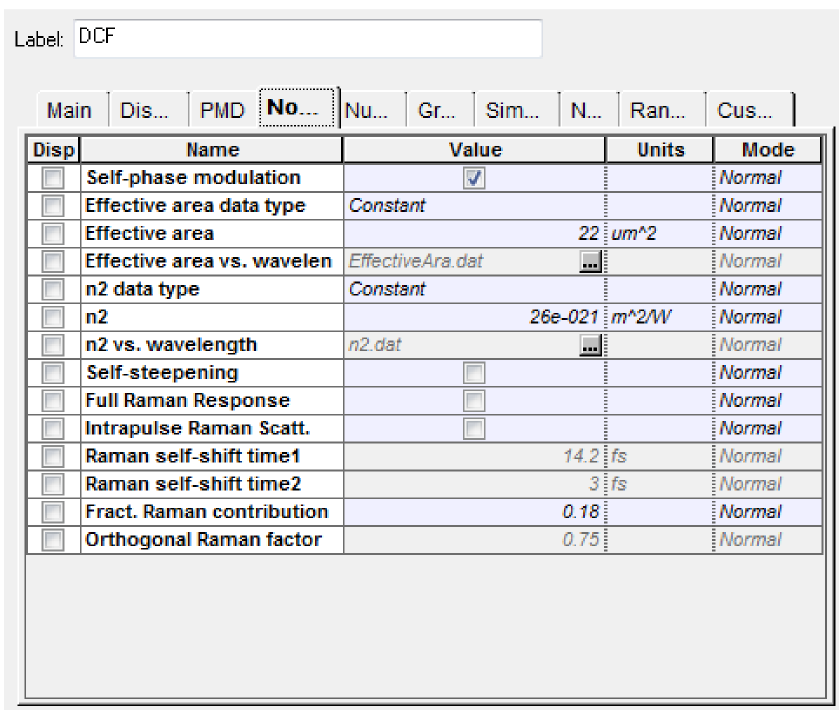


Figure 4.1.8: Settings for noise in Dispersion Compensation Fiber (DCF)

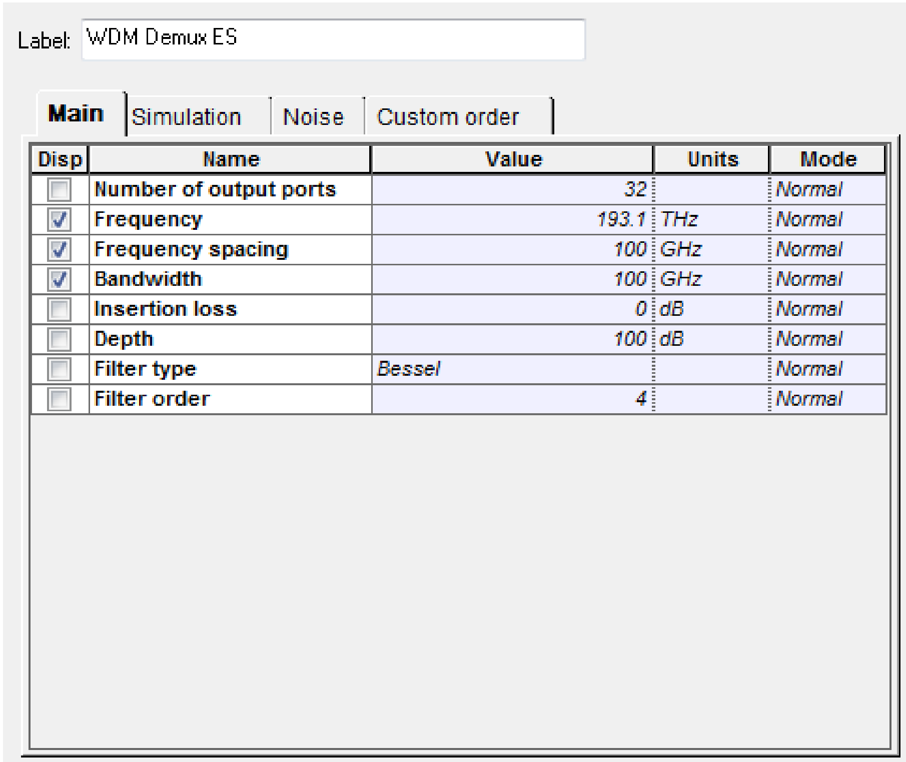


Figure 4.1.9: Settings for WDM demultiplexer

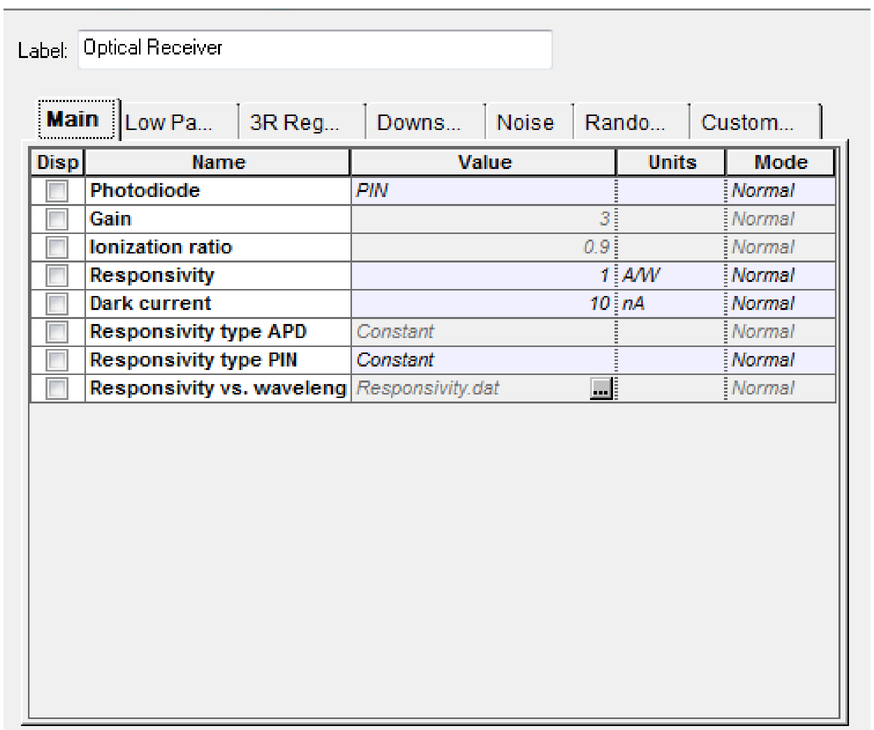


Figure 4.1.10: Settings for optical receiver

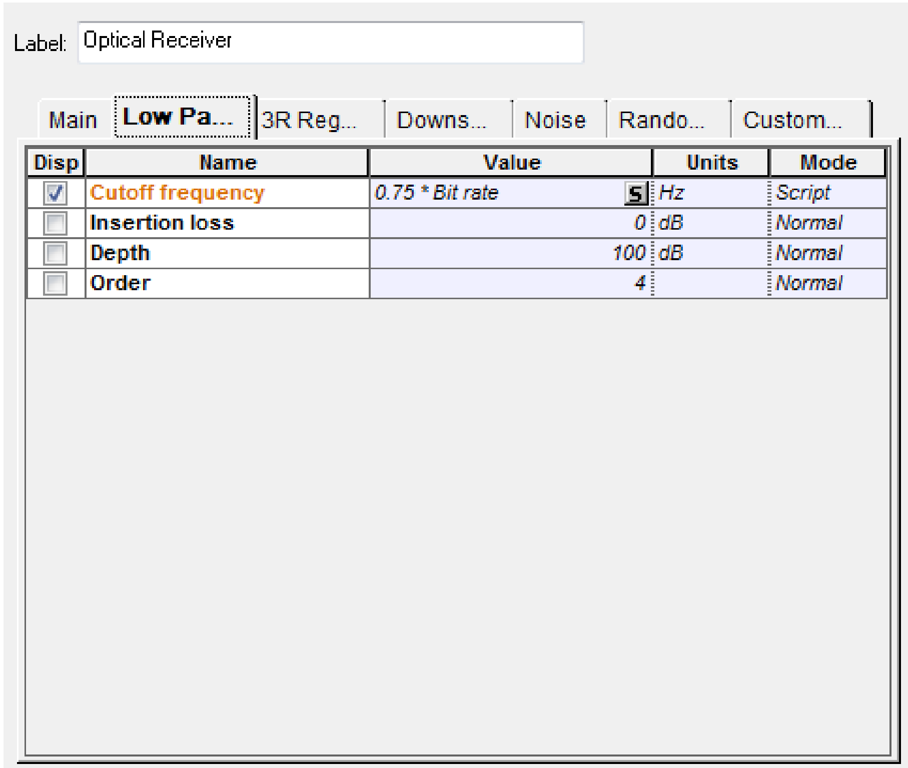


Figure 4.1.11: Settings for optical receiver (Low Pass Filter)

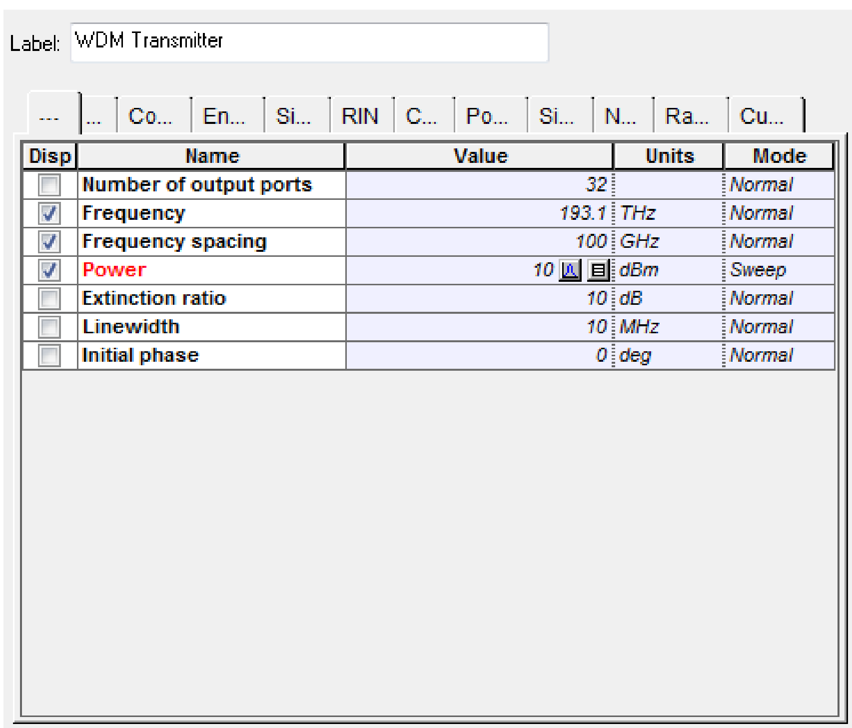
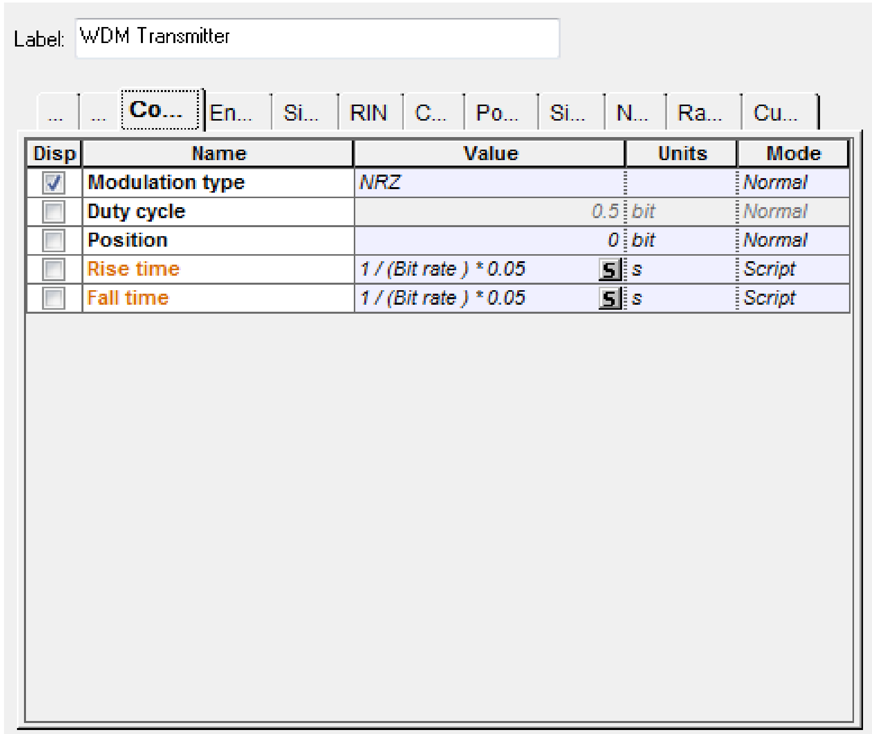


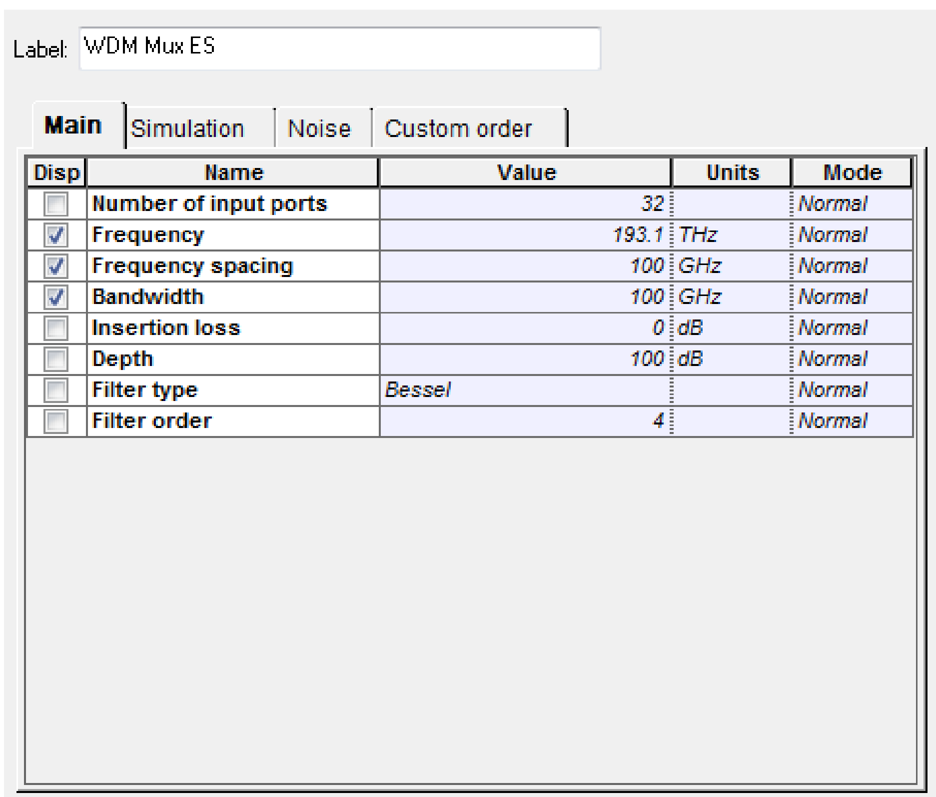
Figure 4.1.12: Settings for WDM transmitter


Label: WDM Transmitter

... | ... | Co... | En... | Si... | RIN | C... | Po... | Si... | N... | Ra... | Cu...

Disp	Name	Value	Units	Mode
☑	Modulation type	NRZ		Normal
☐	Duty cycle	0.5	bit	Normal
☐	Position	0	bit	Normal
☐	Rise time	1 / (Bit rate) * 0.05	s	Script
☐	Fall time	1 / (Bit rate) * 0.05	s	Script

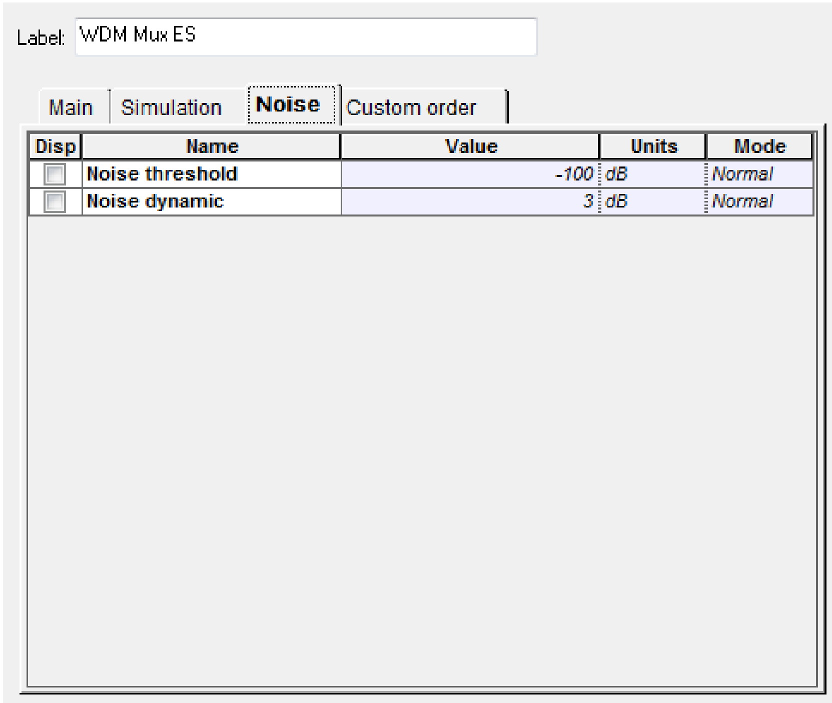
Figure 4.1.13: Settings for WDM transmitter (Modulation type)


Label: WDM Mux ES

Main | Simulation | Noise | Custom order

Disp	Name	Value	Units	Mode
☐	Number of input ports	32		Normal
☑	Frequency	193.1	THz	Normal
☑	Frequency spacing	100	GHz	Normal
☑	Bandwidth	100	GHz	Normal
☐	Insertion loss	0	dB	Normal
☐	Depth	100	dB	Normal
☐	Filter type	Bessel		Normal
☐	Filter order	4		Normal

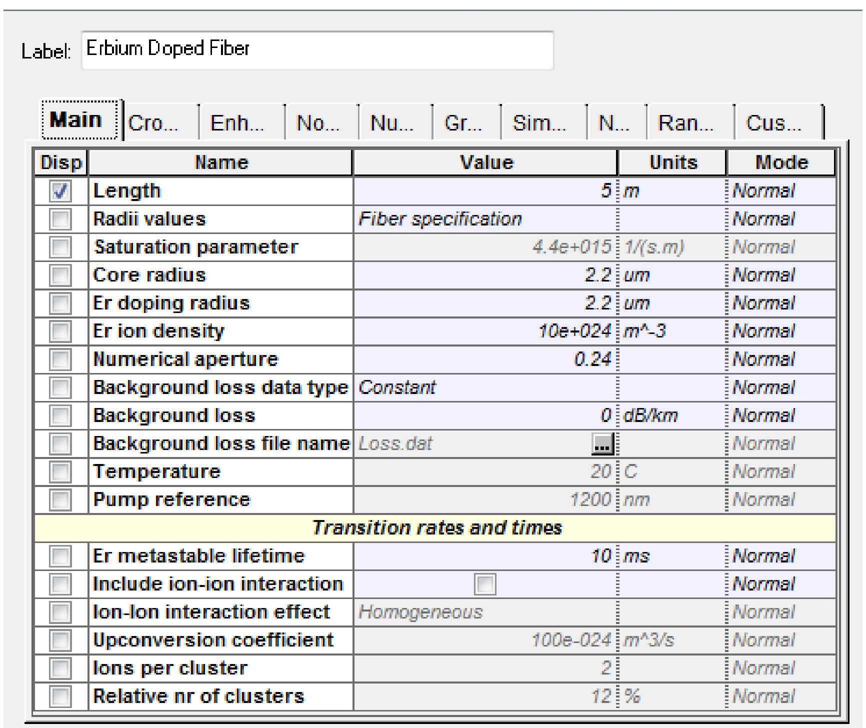
Figure 4.1.14: Settings for WDM multiplexer



Disp	Name	Value	Units	Mode
	Noise threshold	-100	dB	Normal
	Noise dynamic	3	dB	Normal

Figure 4.1.15: Settings for noise in WDM multiplexer

4.1.1 Settings for EDFA amplifier



Disp	Name	Value	Units	Mode
✓	Length	5	m	Normal
	Radii values	Fiber specification		Normal
	Saturation parameter	4.4e+015	1/(s.m)	Normal
	Core radius	2.2	um	Normal
	Er doping radius	2.2	um	Normal
	Er ion density	10e+024	m^-3	Normal
	Numerical aperture	0.24		Normal
	Background loss data type	Constant		Normal
	Background loss	0	dB/km	Normal
	Background loss file name	Loss.dat		Normal
	Temperature	20	C	Normal
	Pump reference	1200	nm	Normal
	Transition rates and times			
	Er metastable lifetime	10	ms	Normal
	Include ion-ion interaction			Normal
	Ion-Ion interaction effect	Homogeneous		Normal
	Upconversion coefficient	100e-024	m^3/s	Normal
	Ions per cluster	2		Normal
	Relative nr of clusters	12	%	Normal

Figure 4.1.1.1: Settings for Erbium Doped Fiber

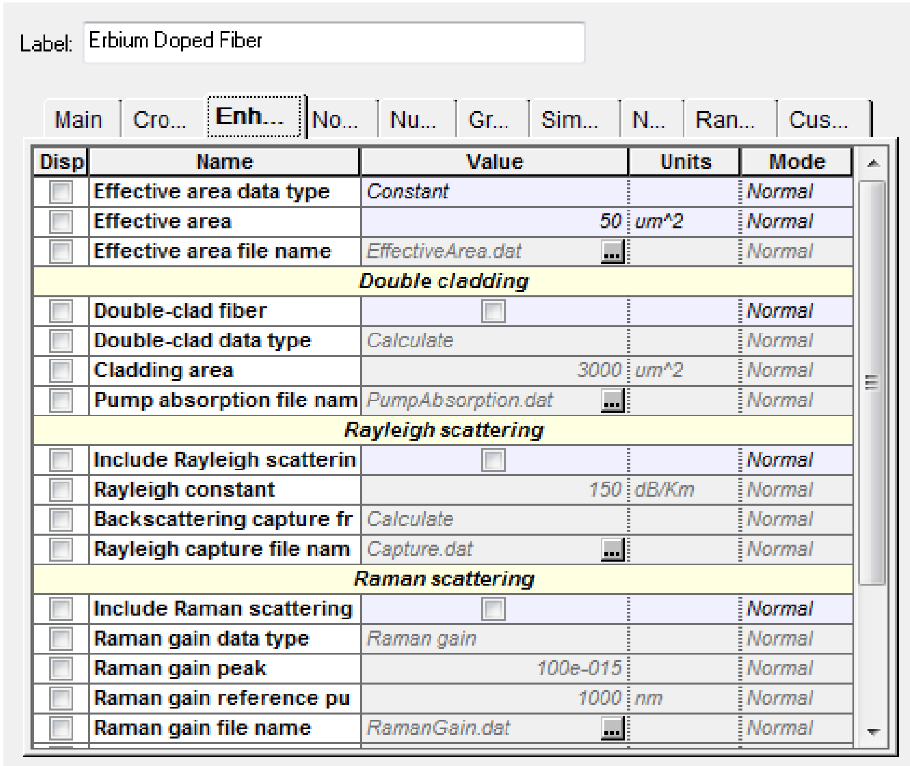


Figure 4.1.1.2: Settings for Erbium Doped Fiber

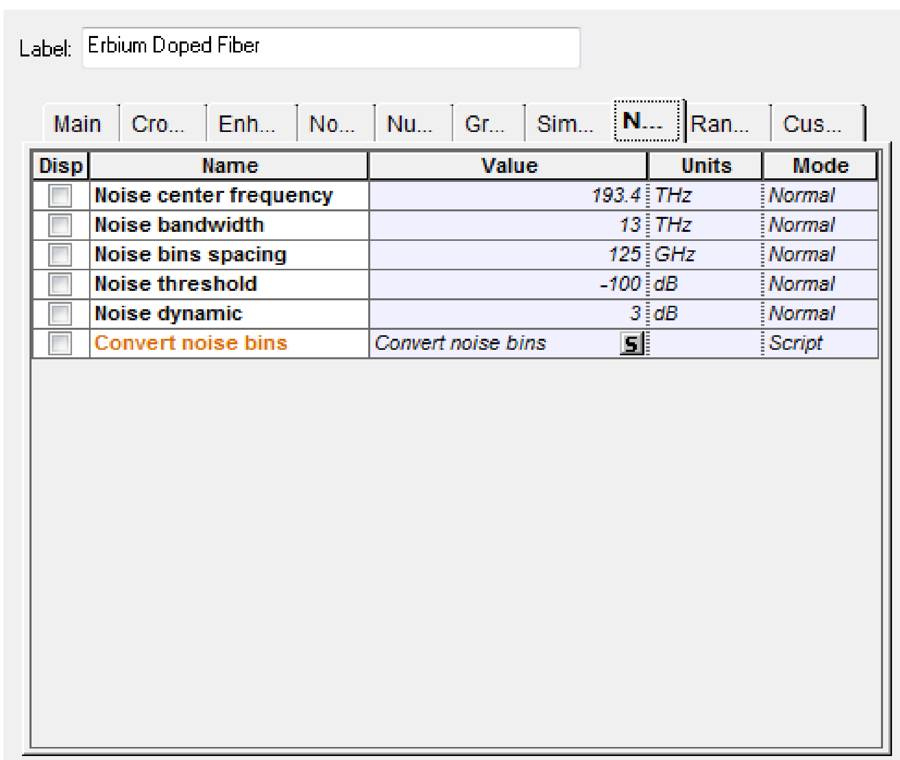


Figure 4.1.1.3: Settings for noise in Erbium Doped Fiber

4.1.2 Settings for Raman amplifier

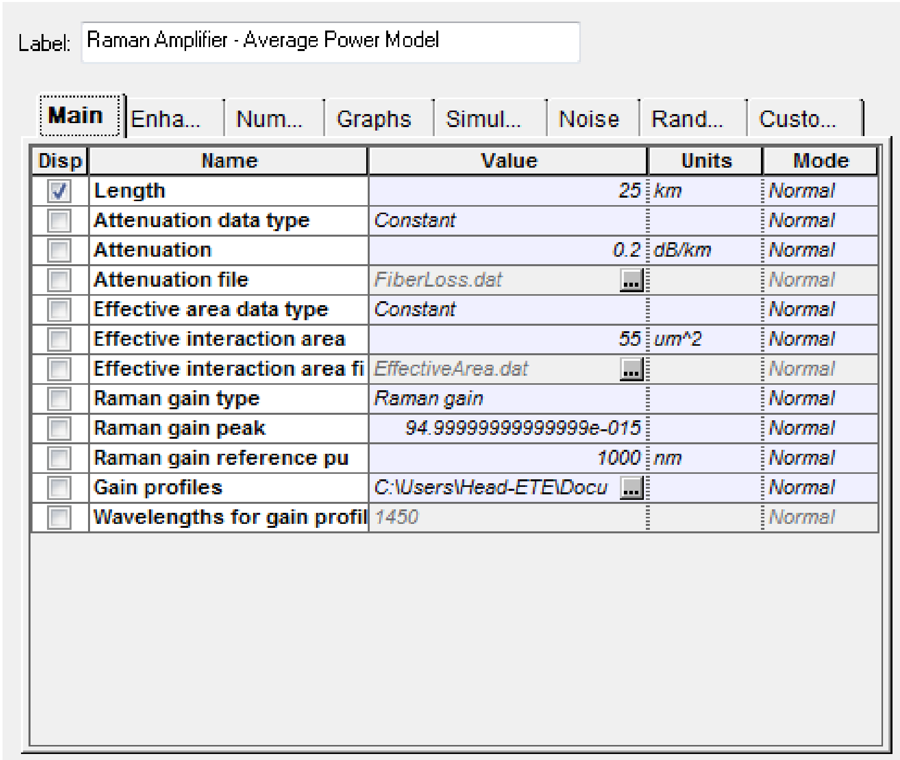


Figure 4.1.2.1: Settings for Raman amplifier

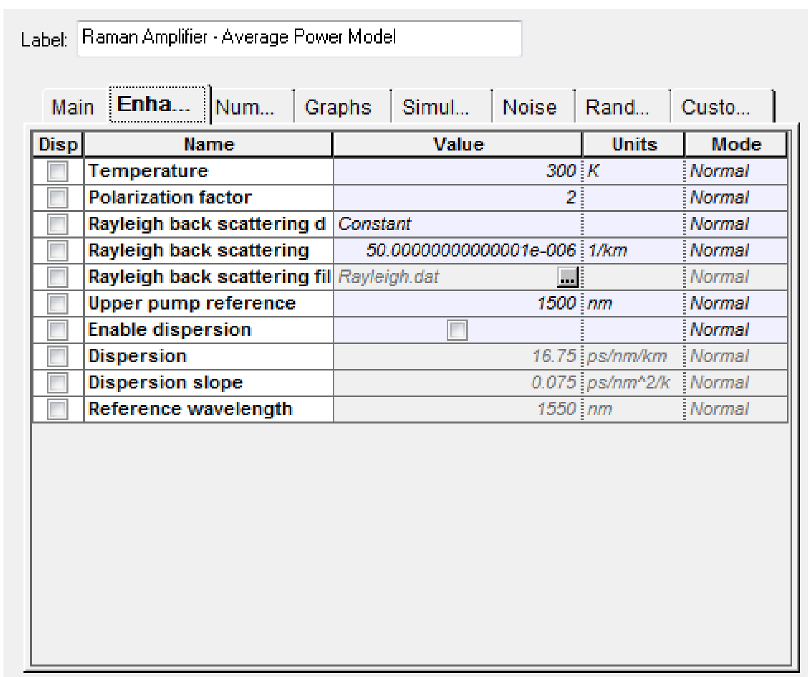


Figure 4.1.2.2: Settings for Raman amplifier (average power model)

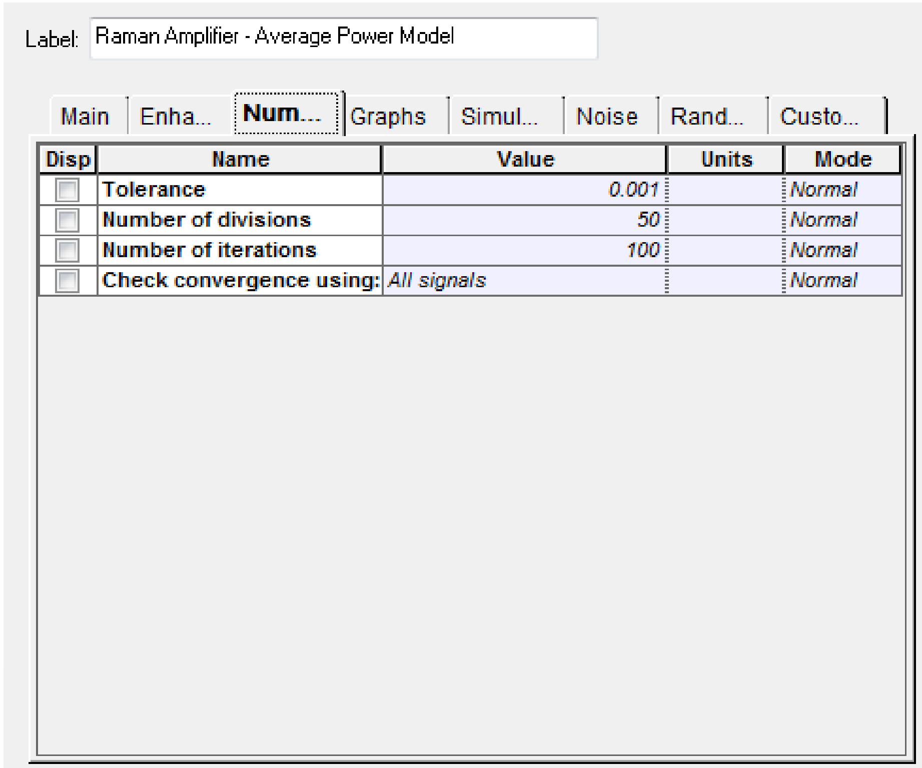


Figure 4.1.2.3: Settings for Raman amplifier

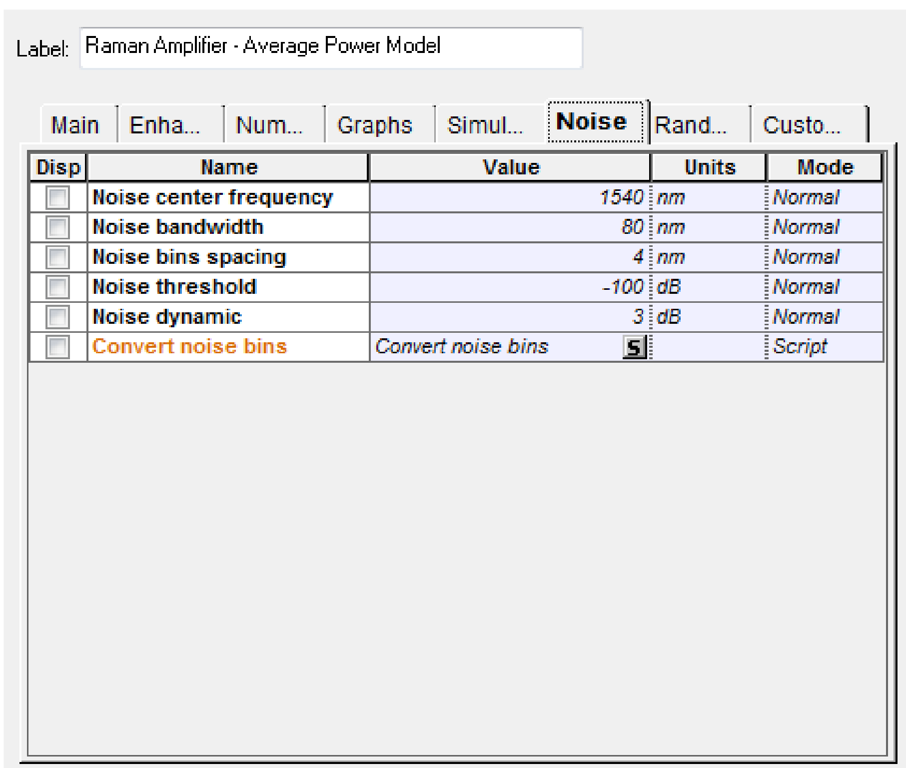


Figure 4.1.2.4: Settings for noise in Raman amplifier

4.1.3 Settings for OA amplifier

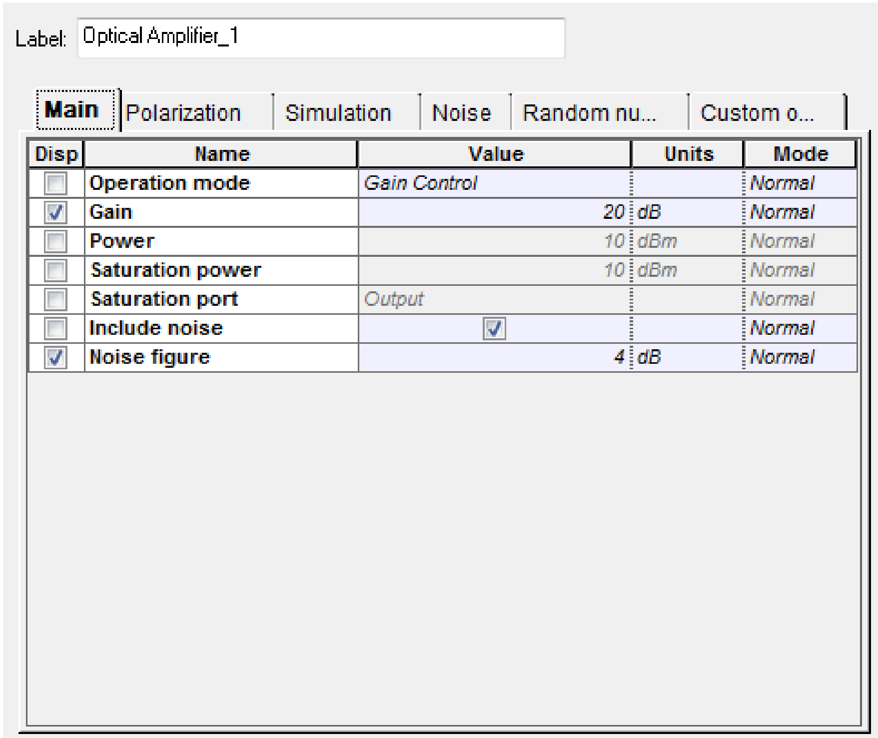


Figure 4.1.3.1: Settings for OA amplifier

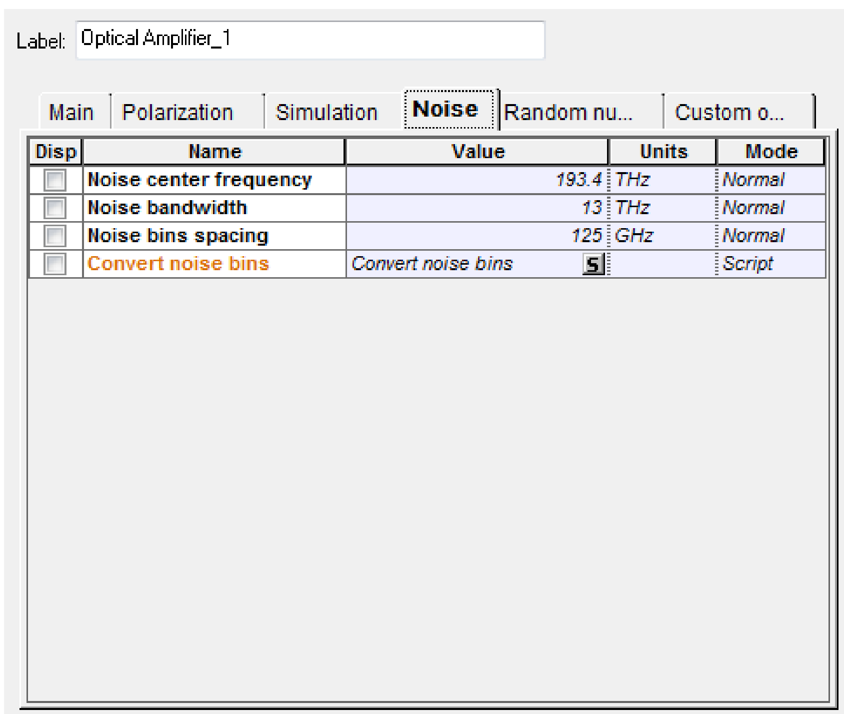


Figure 4.1.3.2: Settings for noise in OA amplifier

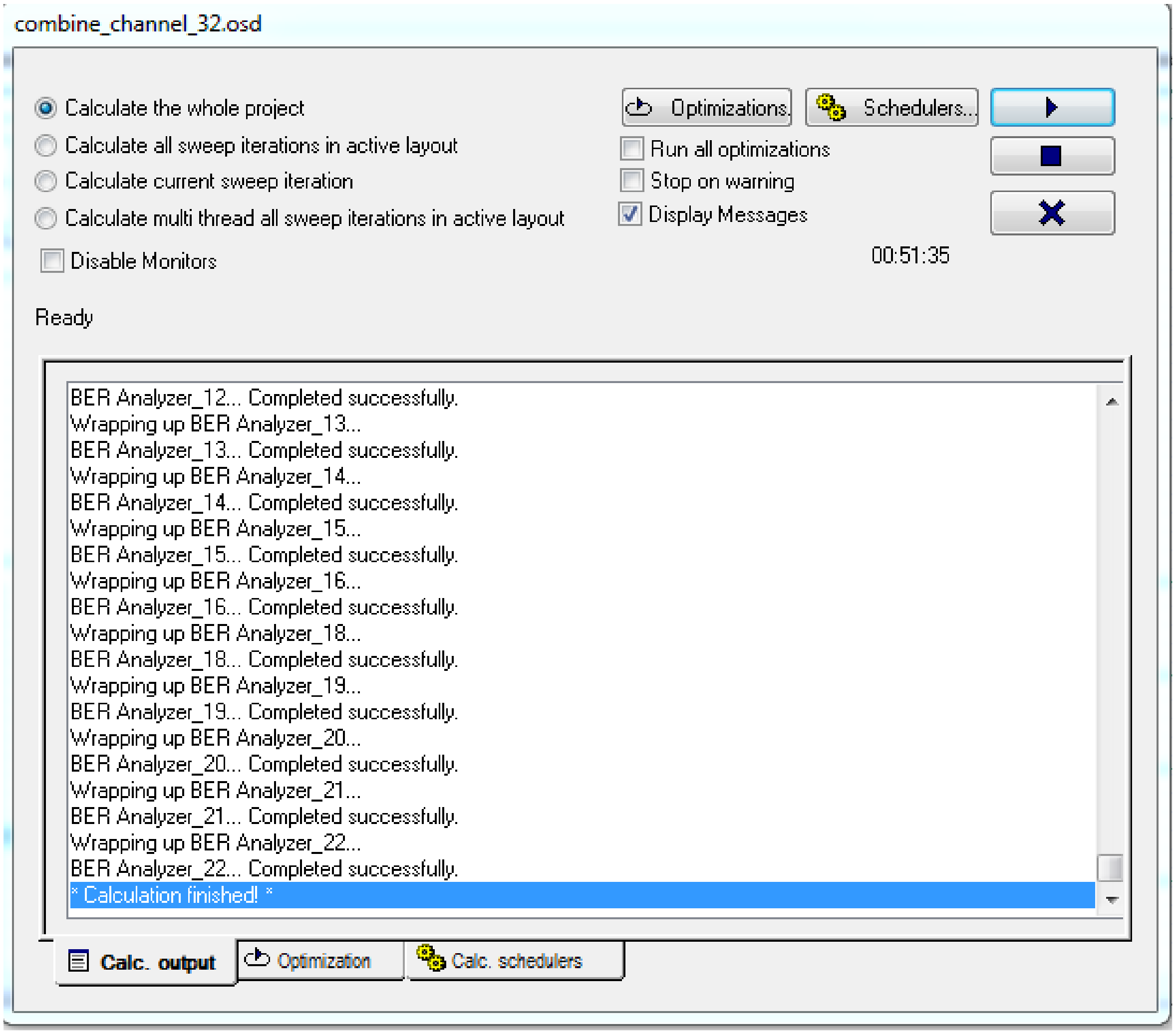
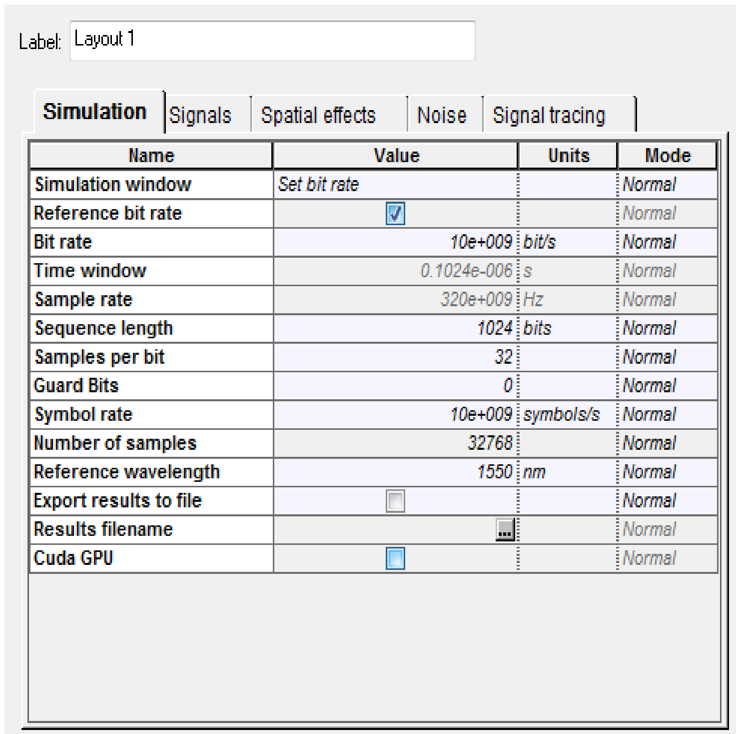


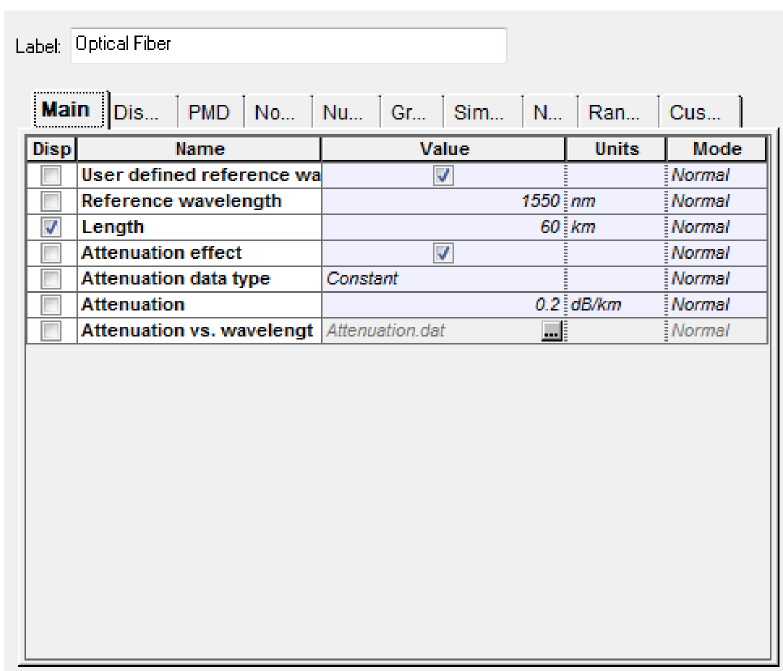
Figure 4.1.3.3: Simulation processing view for 32 channels in DWDM System

4.2 Configurations in Optisystem for 64 channels DWDM system



Name	Value	Units	Mode
Simulation window	Set bit rate		Normal
Reference bit rate	☑		Normal
Bit rate	10e+009	bit/s	Normal
Time window	0.1024e-006	s	Normal
Sample rate	320e+009	Hz	Normal
Sequence length	1024	bits	Normal
Samples per bit	32		Normal
Guard Bits	0		Normal
Symbol rate	10e+009	symbols/s	Normal
Number of samples	32768		Normal
Reference wavelength	1550	nm	Normal
Export results to file	☐		Normal
Results filename	...		Normal
Cuda GPU	☐		Normal

Figure 4.2.1: Settings for layout of 64 channels



Disp	Name	Value	Units	Mode
☐	User defined reference wa	☑		Normal
☐	Reference wavelength	1550	nm	Normal
☑	Length	60	km	Normal
☐	Attenuation effect	☑		Normal
☐	Attenuation data type	Constant		Normal
☐	Attenuation	0.2	dB/km	Normal
☐	Attenuation vs. wavelengt	Attenuation.dat ...		Normal

Figure 4.2.2: Settings for Optical fiber

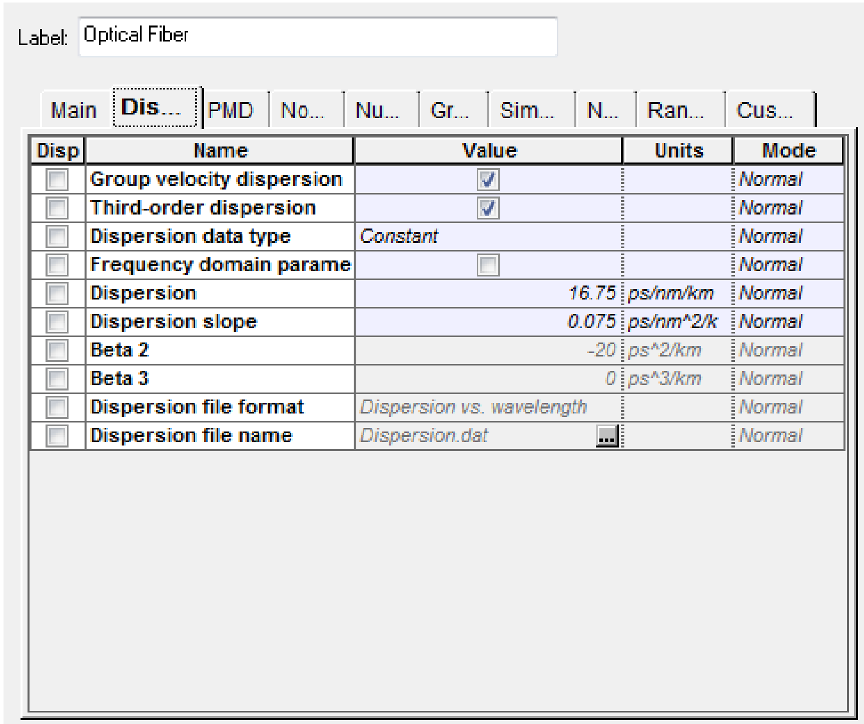


Figure 4.2.3: Settings for dispersion in optical fiber

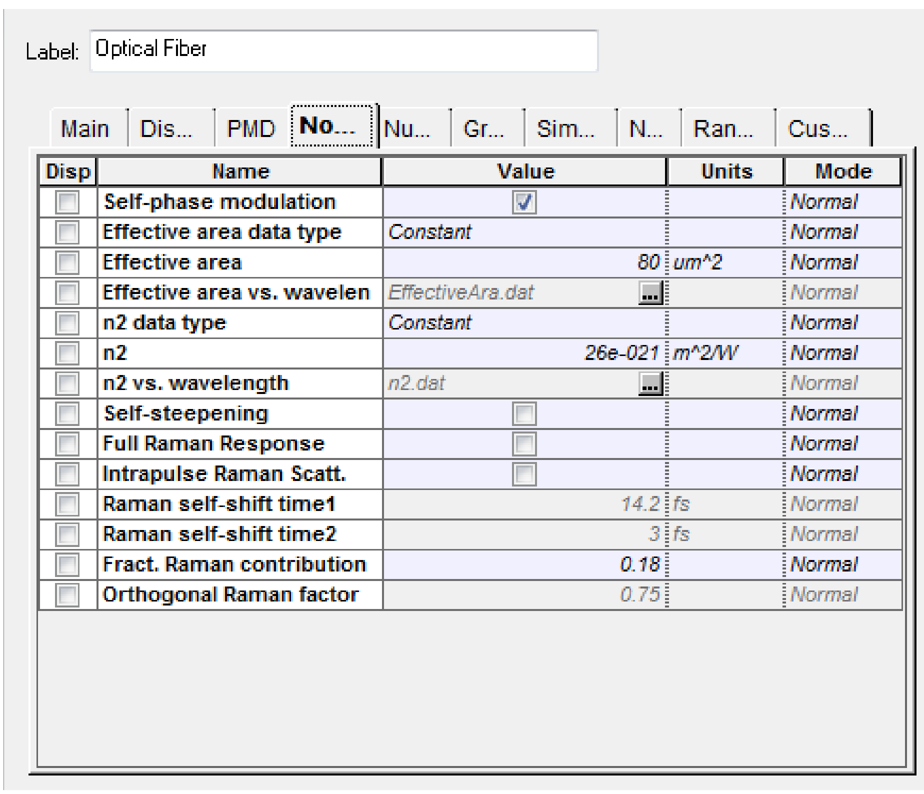


Figure 4.2.4: Settings for noise in optical fiber

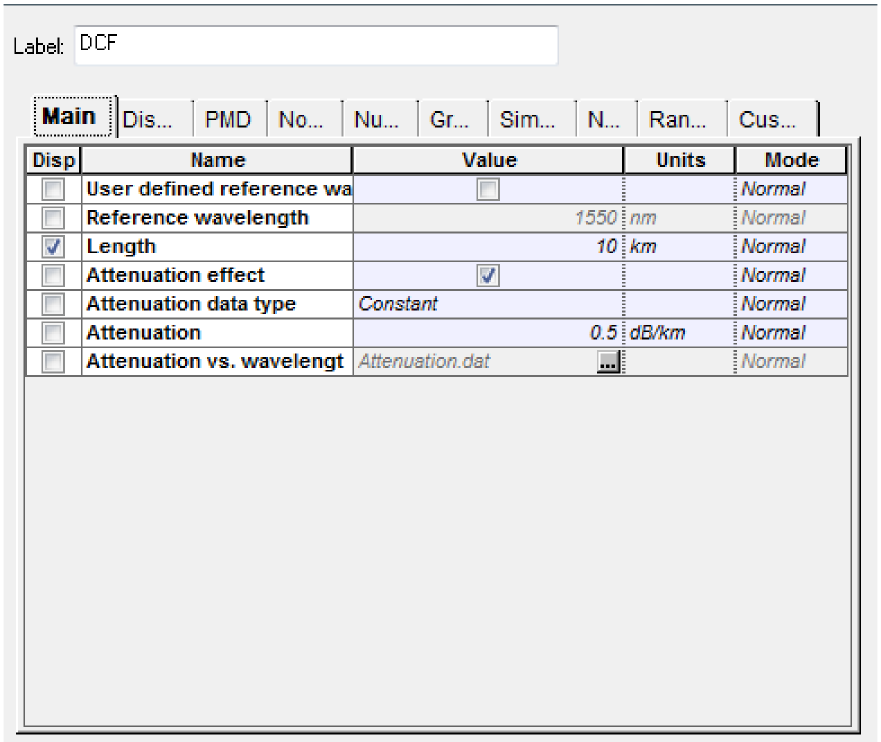


Figure 4.2.5: Settings for Dispersion Compensation Fiber

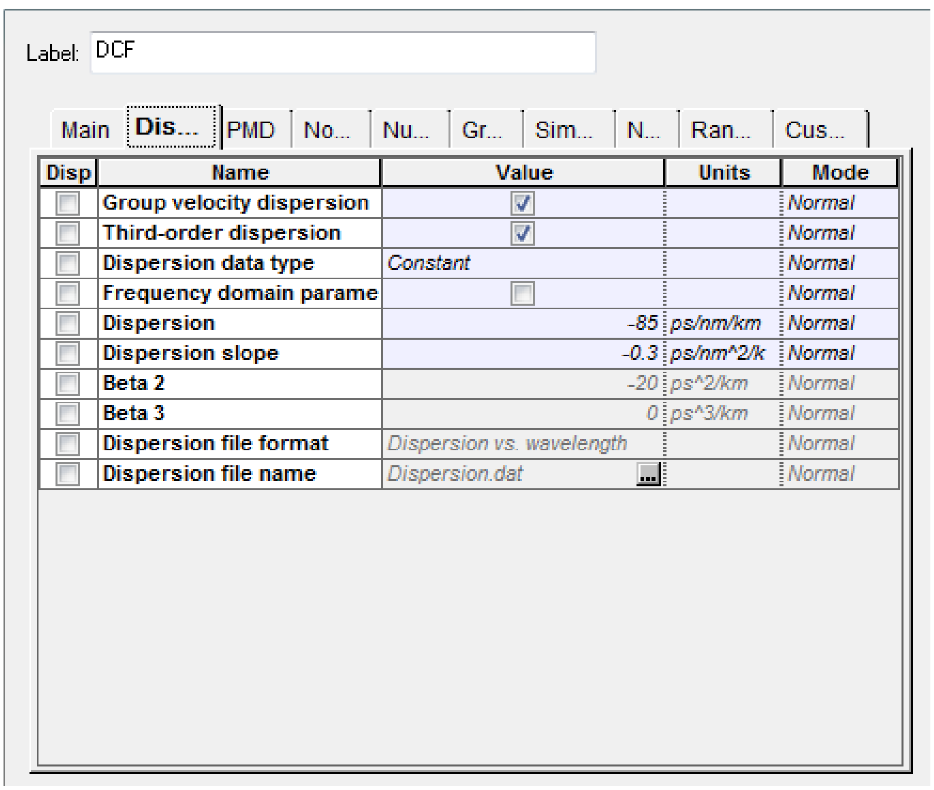
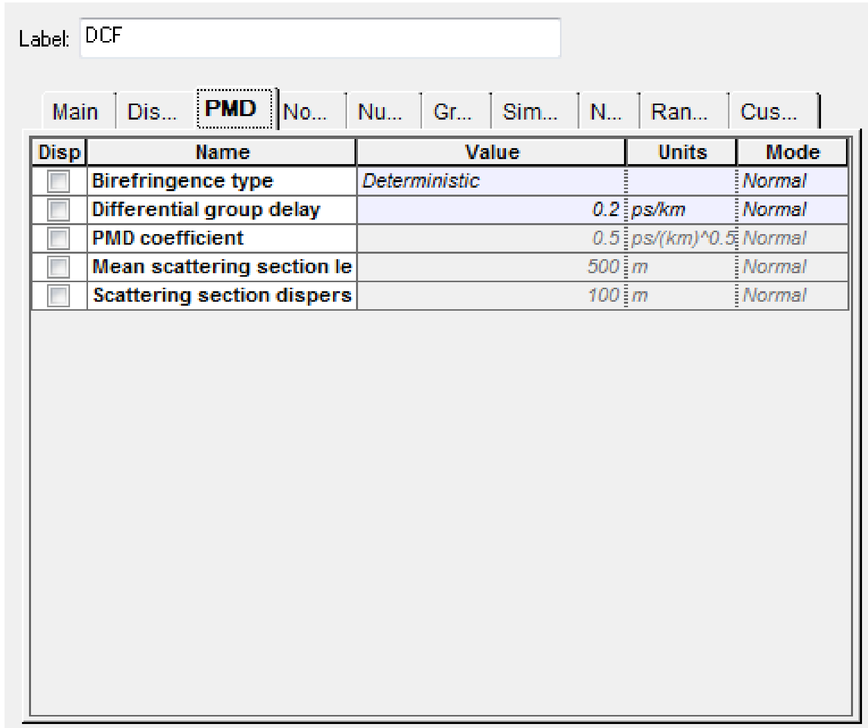


Figure 4.2.6: Settings for Dispersion Compensation Fiber (DCF)

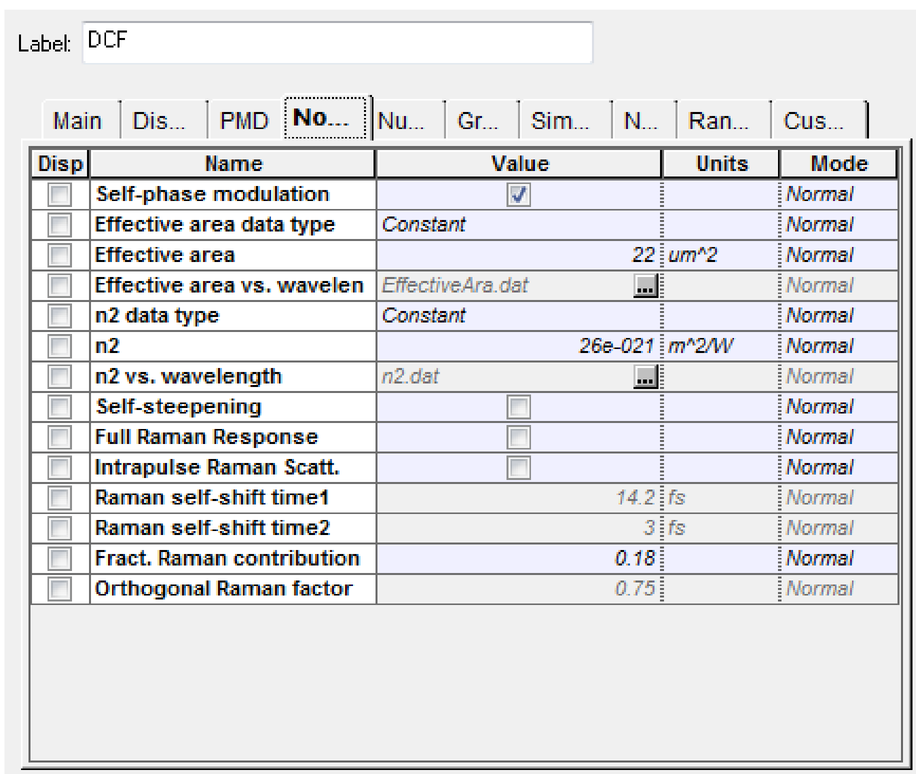


Label: DCF

Main | Dis... | PMD | No... | Nu... | Gr... | Sim... | N... | Ran... | Cus...

Disp	Name	Value	Units	Mode
☐	Birefringence type	Deterministic		Normal
☐	Differential group delay	0.2	ps/km	Normal
☐	PMD coefficient	0.5	ps/(km)^0.5	Normal
☐	Mean scattering section le	500	m	Normal
☐	Scattering section dispers	100	m	Normal

Figure 4.2.7: Settings for Polarization Mode Dispersion (PMD)

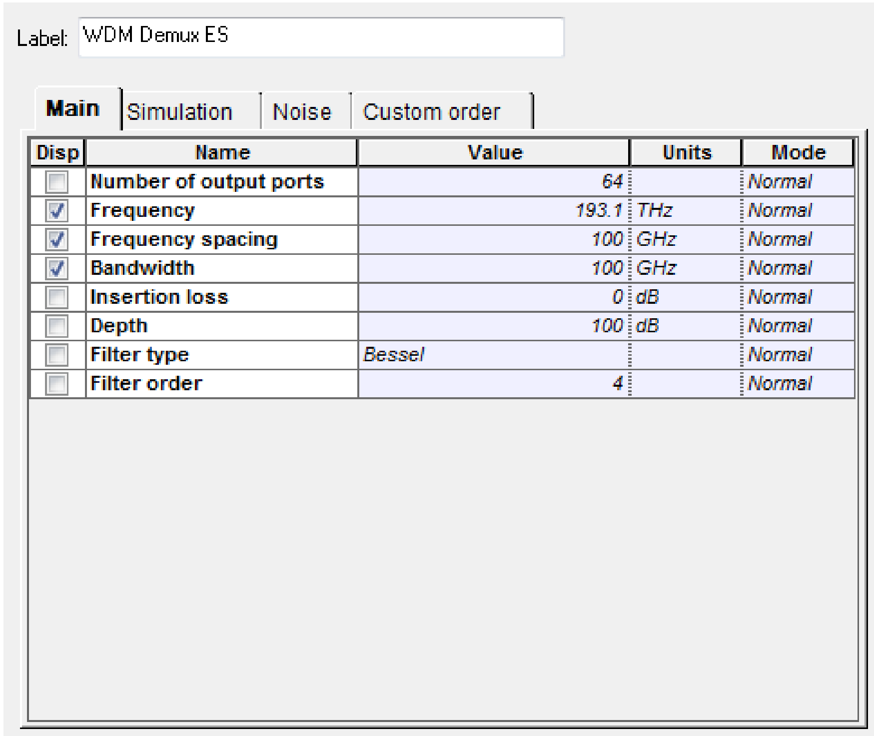


Label: DCF

Main | Dis... | PMD | No... | Nu... | Gr... | Sim... | N... | Ran... | Cus...

Disp	Name	Value	Units	Mode
☐	Self-phase modulation	☑		Normal
☐	Effective area data type	Constant		Normal
☐	Effective area	22	um^2	Normal
☐	Effective area vs. wavelen	EffectiveAra.dat ...		Normal
☐	n2 data type	Constant		Normal
☐	n2	26e-021	m^2/W	Normal
☐	n2 vs. wavelength	n2.dat ...		Normal
☐	Self-steepening	☐		Normal
☐	Full Raman Response	☐		Normal
☐	Intrapulse Raman Scatt.	☐		Normal
☐	Raman self-shift time1	14.2	fs	Normal
☐	Raman self-shift time2	3	fs	Normal
☐	Fract. Raman contribution	0.18		Normal
☐	Orthogonal Raman factor	0.75		Normal

Figure 4.2.8: Settings for noise in DCF

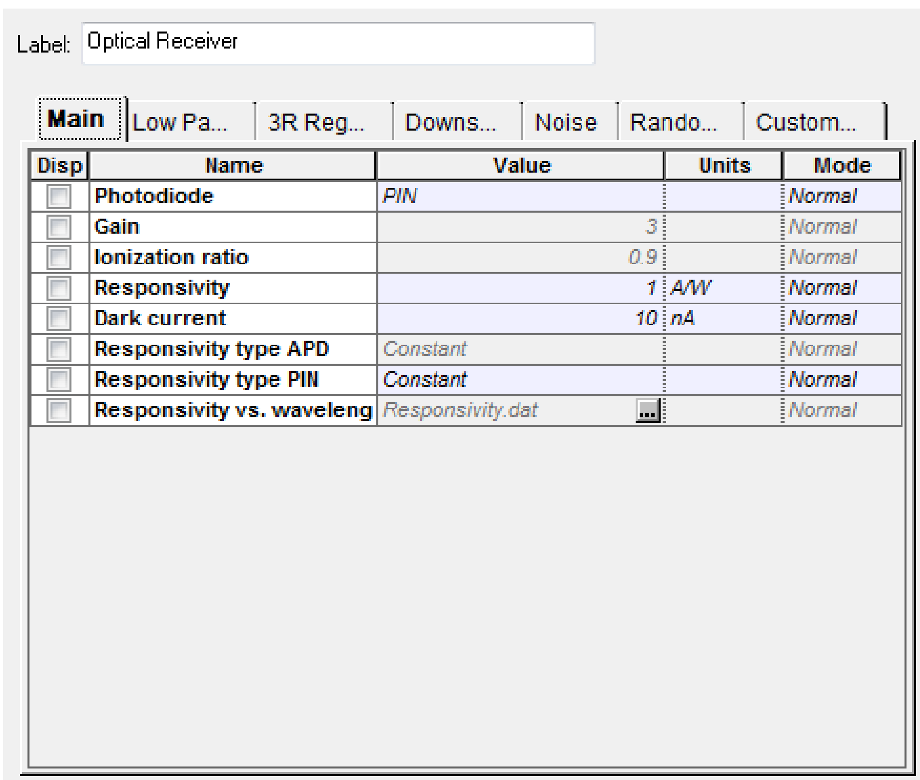


Label: WDM Demux ES

Main | Simulation | Noise | Custom order

Disp	Name	Value	Units	Mode
☐	Number of output ports	64		Normal
☑	Frequency	193.1	THz	Normal
☑	Frequency spacing	100	GHz	Normal
☑	Bandwidth	100	GHz	Normal
☐	Insertion loss	0	dB	Normal
☐	Depth	100	dB	Normal
☐	Filter type	Bessel		Normal
☐	Filter order	4		Normal

Figure 4.2.9: Settings for WDM demultiplexer



Label: Optical Receiver

Main | Low Pa... | 3R Reg... | Downs... | Noise | Rando... | Custom...

Disp	Name	Value	Units	Mode
☐	Photodiode	PIN		Normal
☐	Gain	3		Normal
☐	Ionization ratio	0.9		Normal
☐	Responsivity	1	A/W	Normal
☐	Dark current	10	nA	Normal
☐	Responsivity type APD	Constant		Normal
☐	Responsivity type PIN	Constant		Normal
☐	Responsivity vs. waveleng	Responsivity.dat ...		Normal

Figure 4.2.10: Settings for optical receiver

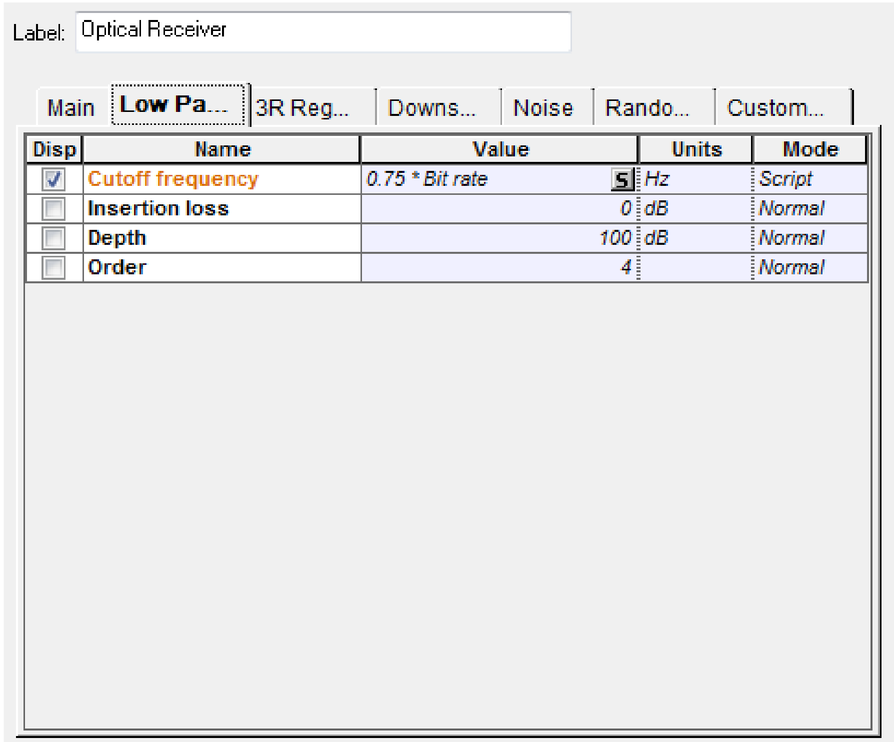


Figure 4.2.11: Settings for LPF of optical receiver

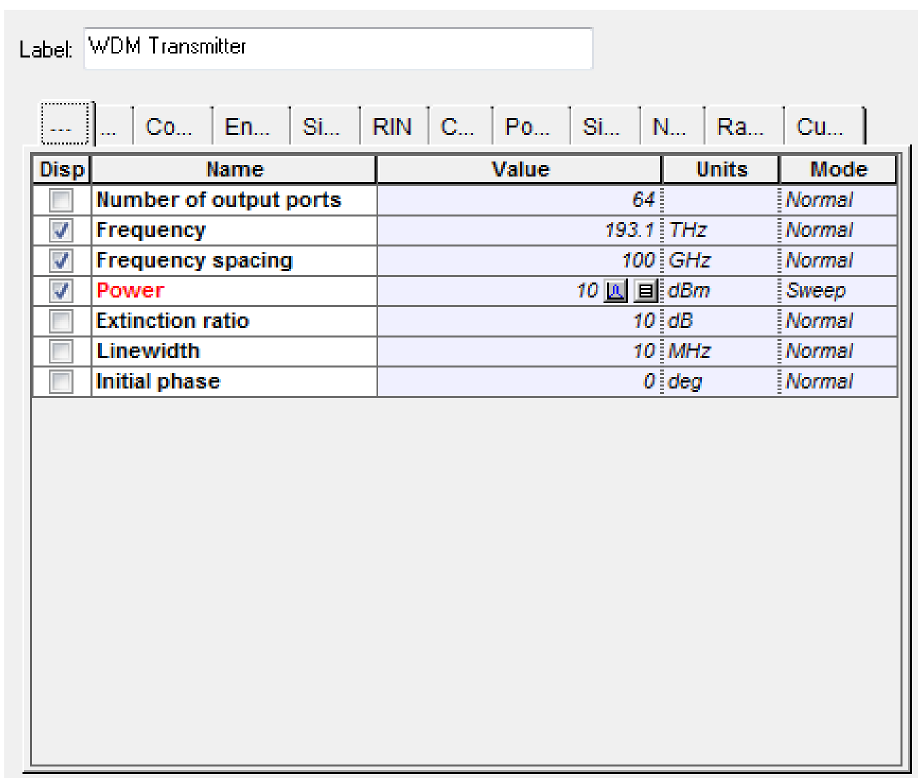


Figure 4.2.12: Settings for WDM transmitter

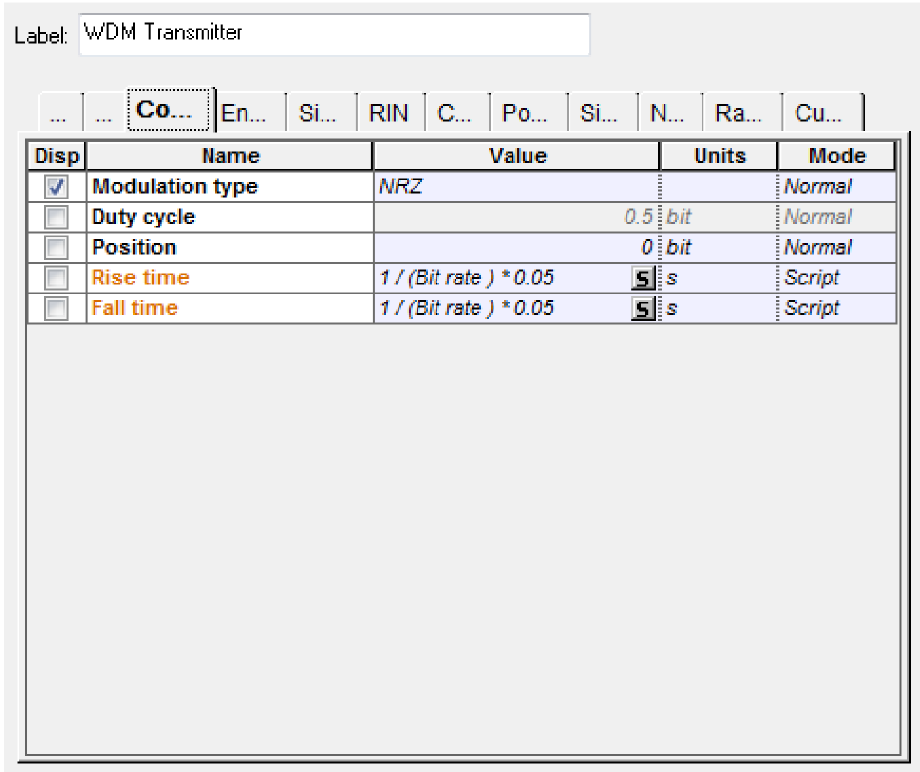


Figure 4.2.13: Settings for modulation in WDM transmitter

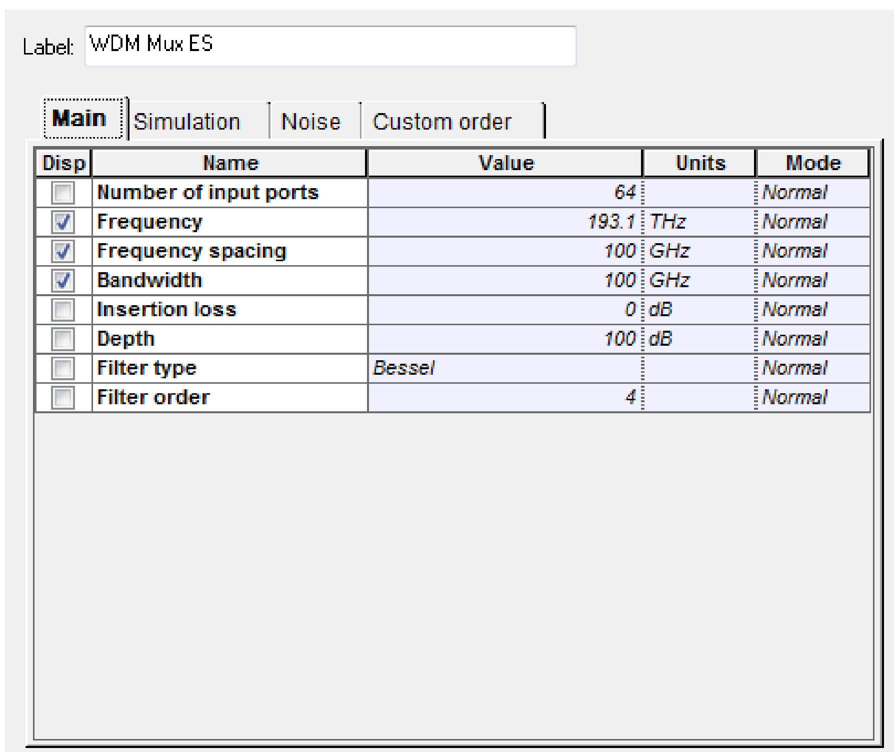
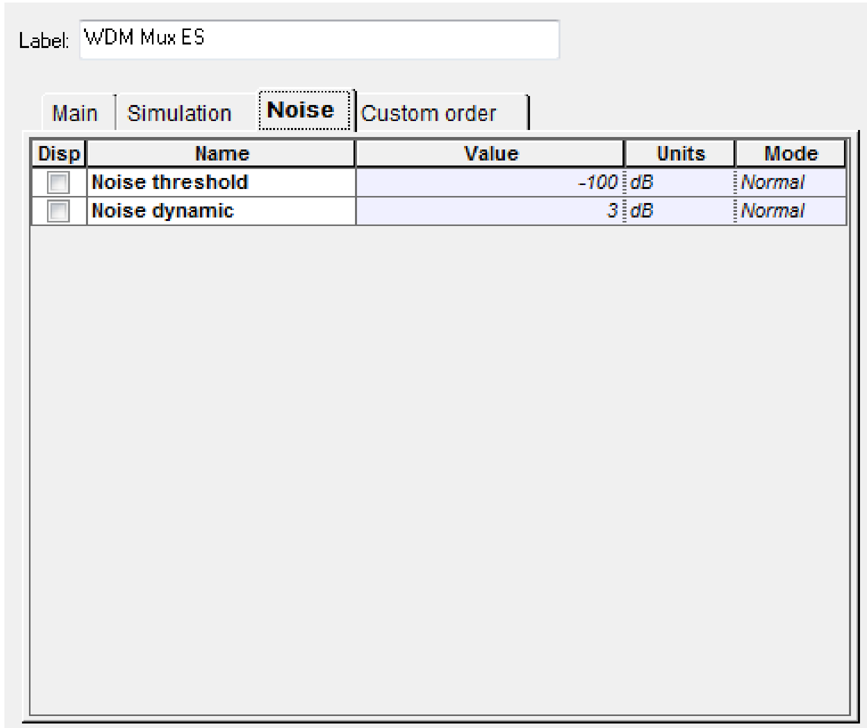


Figure 4.2.14: Settings for WDM multiplexer



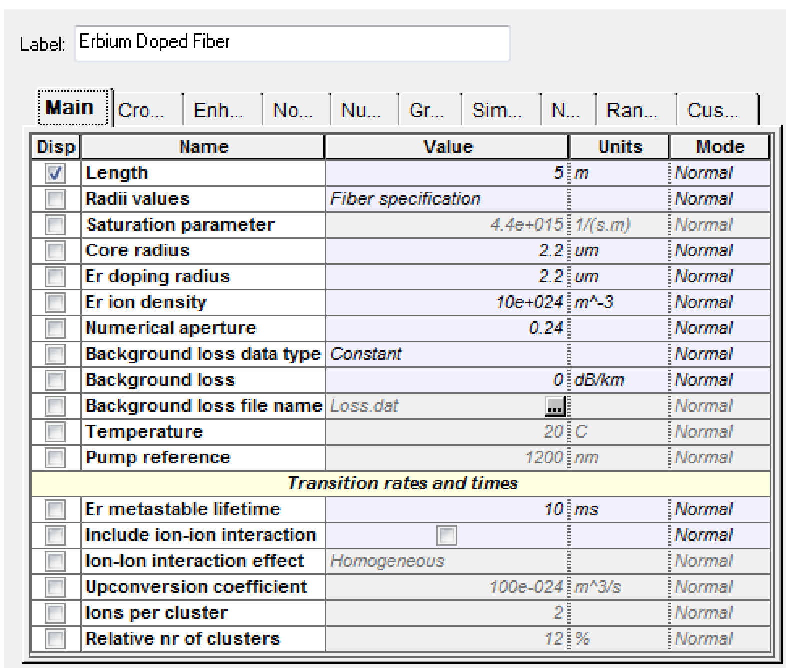
Label: WDM Mux ES

Main | Simulation | **Noise** | Custom order

Disp	Name	Value	Units	Mode
☐	Noise threshold	-100	dB	Normal
☐	Noise dynamic	3	dB	Normal

Figure 4.2.15: Settings for noise in WDM multiplexer

4.2.1 Settings for EDFA amplifier



Label: Erbium Doped Fiber

Main | Cro... | Enh... | No... | Nu... | Gr... | Sim... | N... | Ran... | Cus...

Disp	Name	Value	Units	Mode
☑	Length	5	m	Normal
☐	Radii values	Fiber specification		Normal
☐	Saturation parameter	4.4e+015	1/(s.m)	Normal
☐	Core radius	2.2	um	Normal
☐	Er doping radius	2.2	um	Normal
☐	Er ion density	10e+024	m^-3	Normal
☐	Numerical aperture	0.24		Normal
☐	Background loss data type	Constant		Normal
☐	Background loss	0	dB/km	Normal
☐	Background loss file name	Loss.dat		Normal
☐	Temperature	20	C	Normal
☐	Pump reference	1200	nm	Normal
	Transition rates and times			
☐	Er metastable lifetime	10	ms	Normal
☐	Include ion-ion interaction	☐		Normal
☐	Ion-Ion interaction effect	Homogeneous		Normal
☐	Upconversion coefficient	100e-024	m^3/s	Normal
☐	Ions per cluster	2		Normal
☐	Relative nr of clusters	12	%	Normal

Figure 4.2.1.1: Settings for Erbium Doped Fiber

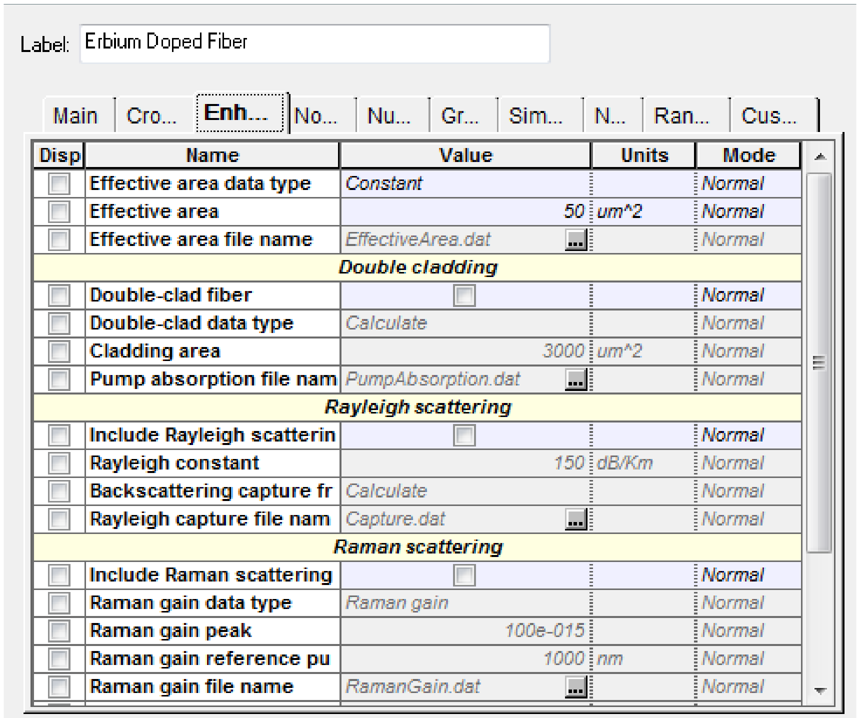


Figure 4.2.1.2: Settings for Erbium Doped Fiber

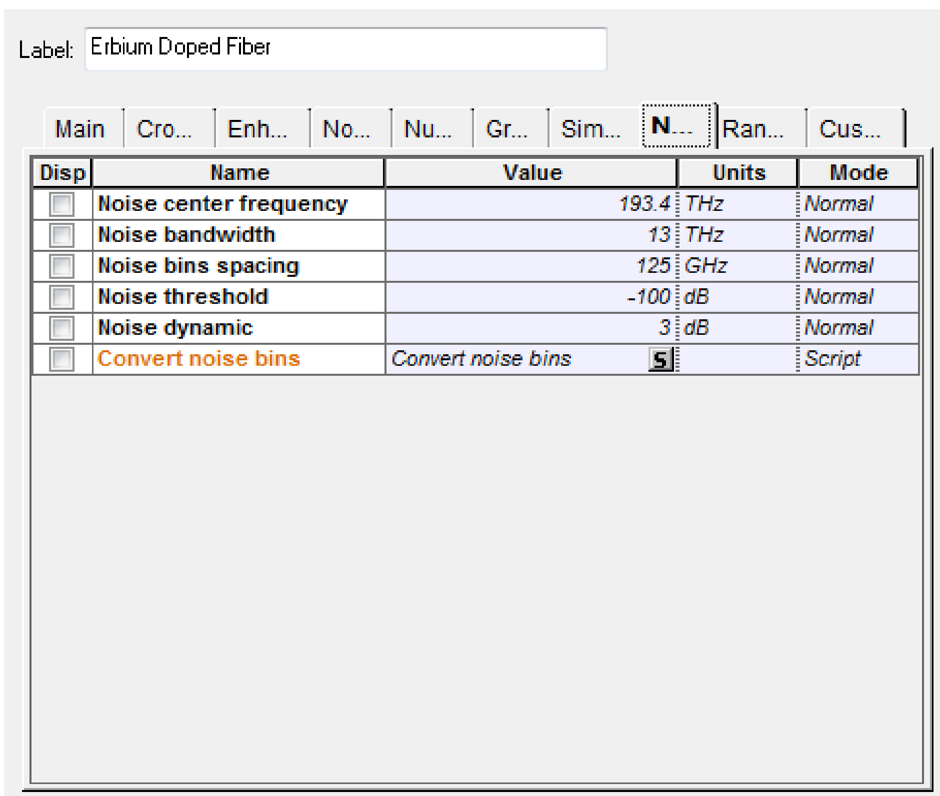
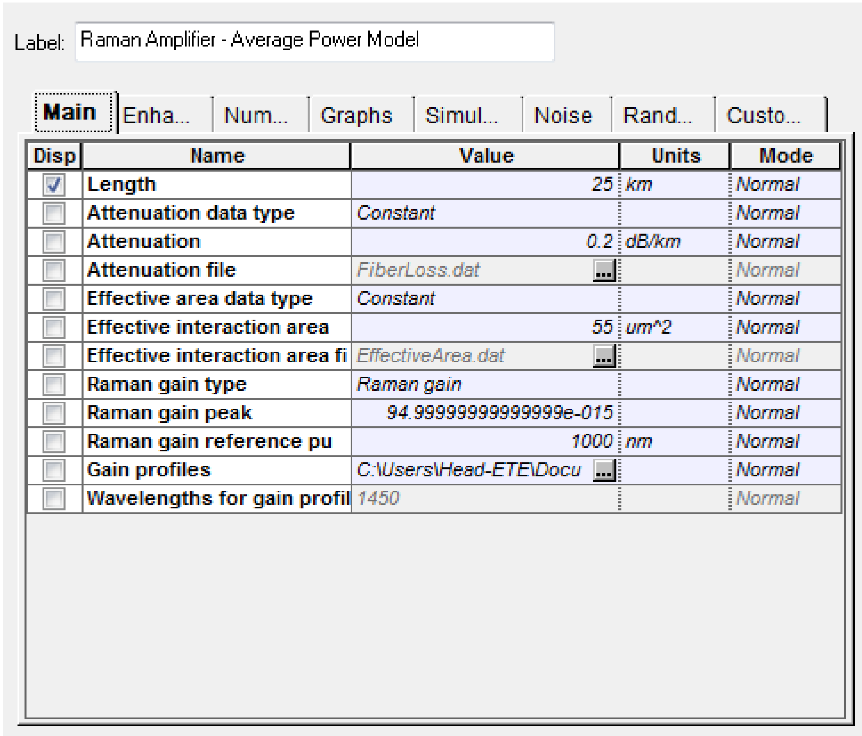


Figure 4.2.1.3: Settings for noise in Erbium Doped Fiber

4.2.2 Settings for Raman amplifier

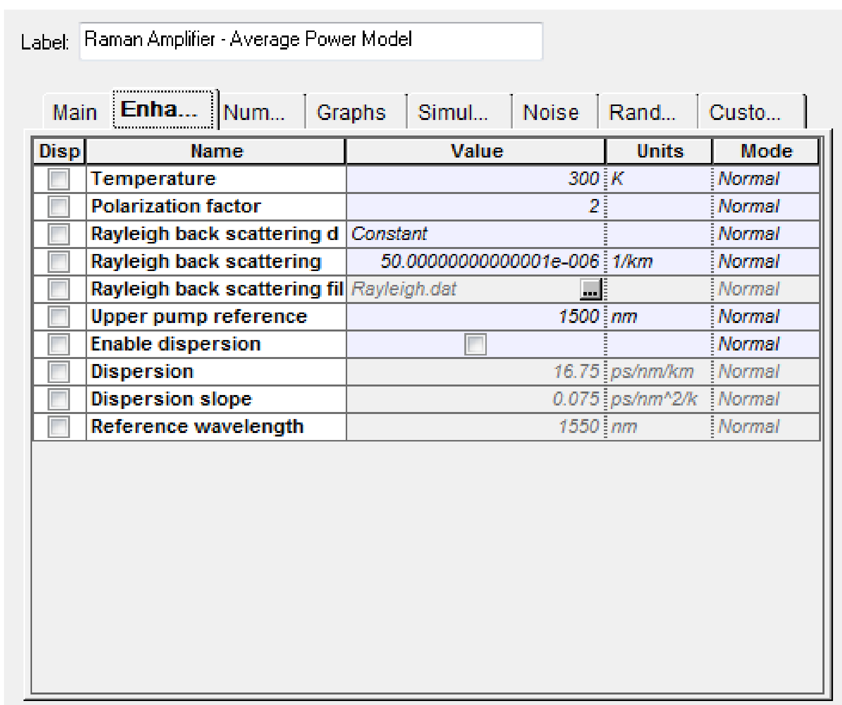


Label: Raman Amplifier - Average Power Model

Main | Enha... | Num... | Graphs | Simul... | Noise | Rand... | Custo...

Disp	Name	Value	Units	Mode
☑	Length	25	km	Normal
☐	Attenuation data type	Constant		Normal
☐	Attenuation	0.2	dB/km	Normal
☐	Attenuation file	FiberLoss.dat		Normal
☐	Effective area data type	Constant		Normal
☐	Effective interaction area	55	um^2	Normal
☐	Effective interaction area fi	EffectiveArea.dat		Normal
☐	Raman gain type	Raman gain		Normal
☐	Raman gain peak	94.99999999999999e-015		Normal
☐	Raman gain reference pu	1000	nm	Normal
☐	Gain profiles	C:\Users\Head-ETE\Docu		Normal
☐	Wavelengths for gain profil	1450		Normal

Figure 4.2.2.1: Settings for Raman amplifier



Label: Raman Amplifier - Average Power Model

Main | Enha... | Num... | Graphs | Simul... | Noise | Rand... | Custo...

Disp	Name	Value	Units	Mode
☐	Temperature	300	K	Normal
☐	Polarization factor	2		Normal
☐	Rayleigh back scattering d	Constant		Normal
☐	Rayleigh back scattering	50.00000000000001e-006	1/km	Normal
☐	Rayleigh back scattering fil	Rayleigh.dat		Normal
☐	Upper pump reference	1500	nm	Normal
☐	Enable dispersion	☐		Normal
☐	Dispersion	16.75	ps/nm/km	Normal
☐	Dispersion slope	0.075	ps/nm^2/k	Normal
☐	Reference wavelength	1550	nm	Normal

Figure 4.2.2.2: Settings for Raman amplifier (average power model)

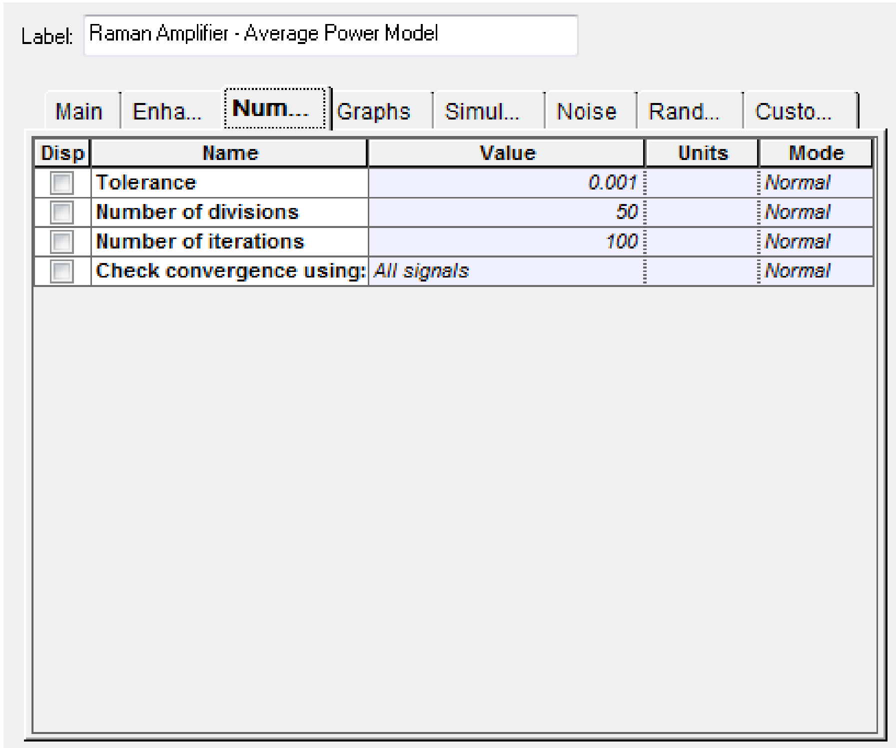


Figure 4.2.2.3: Settings for Raman amplifier

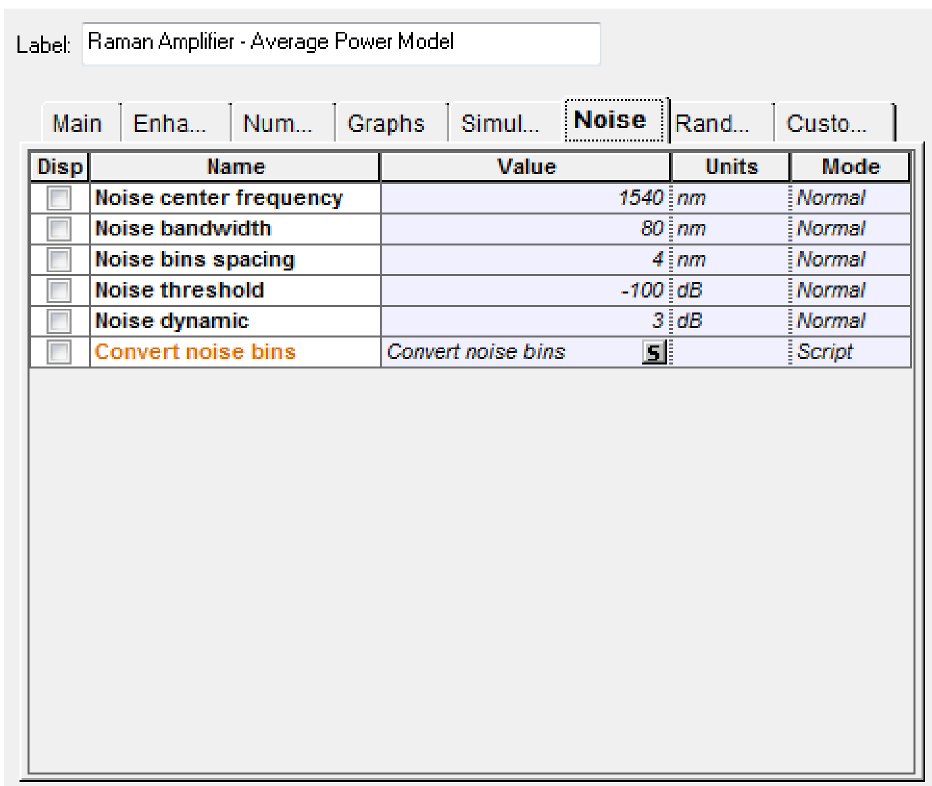


Figure 4.2.2.4: Settings for Raman amplifier

4.2.3 Settings for OA amplifier

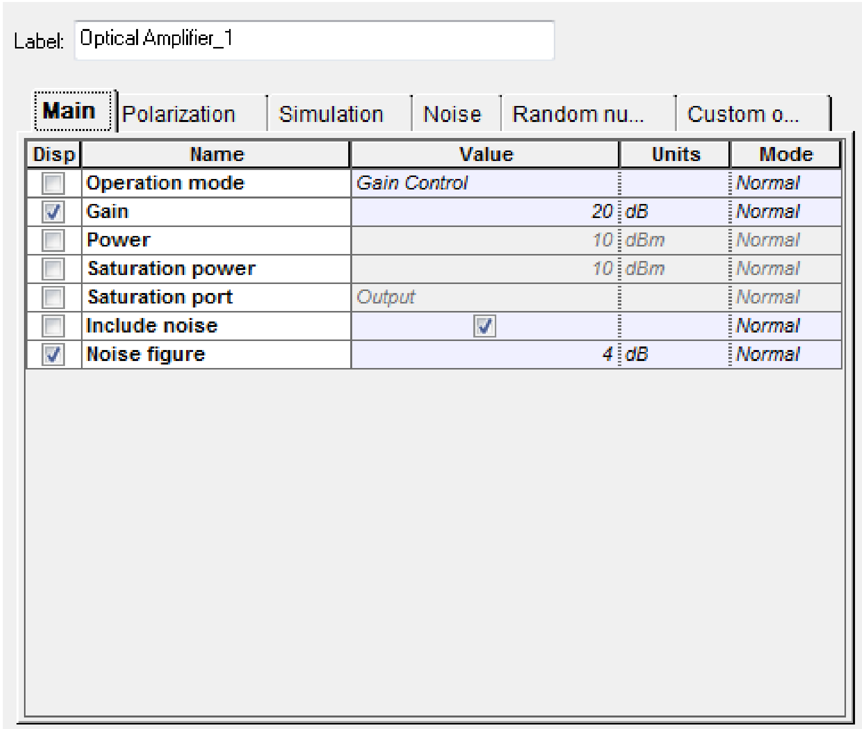


Figure 4.2.3.1: Settings for OA amplifier

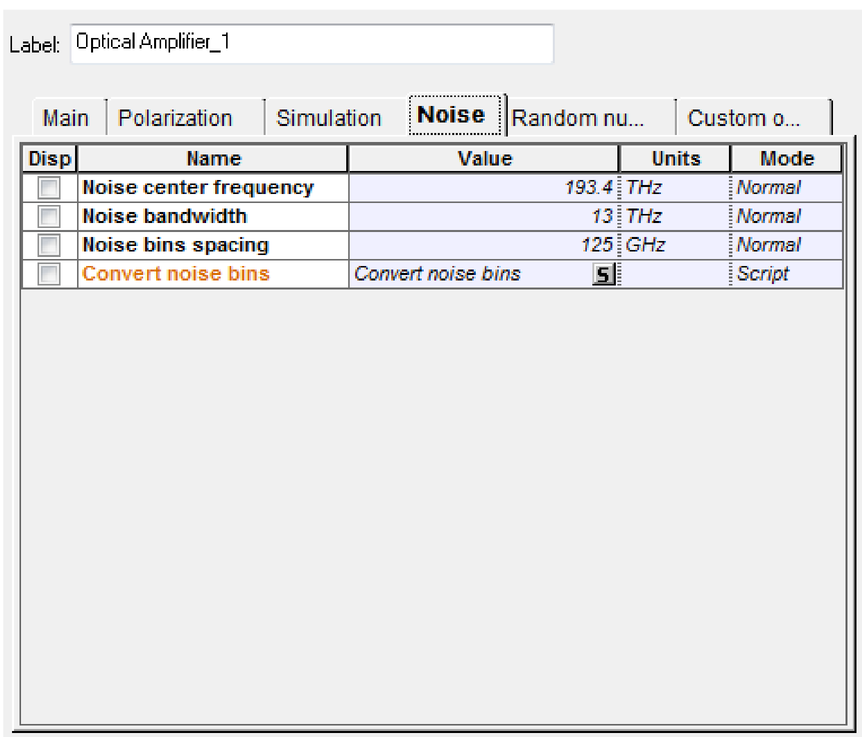


Figure 4.2.3.2: Settings for OA amplifier

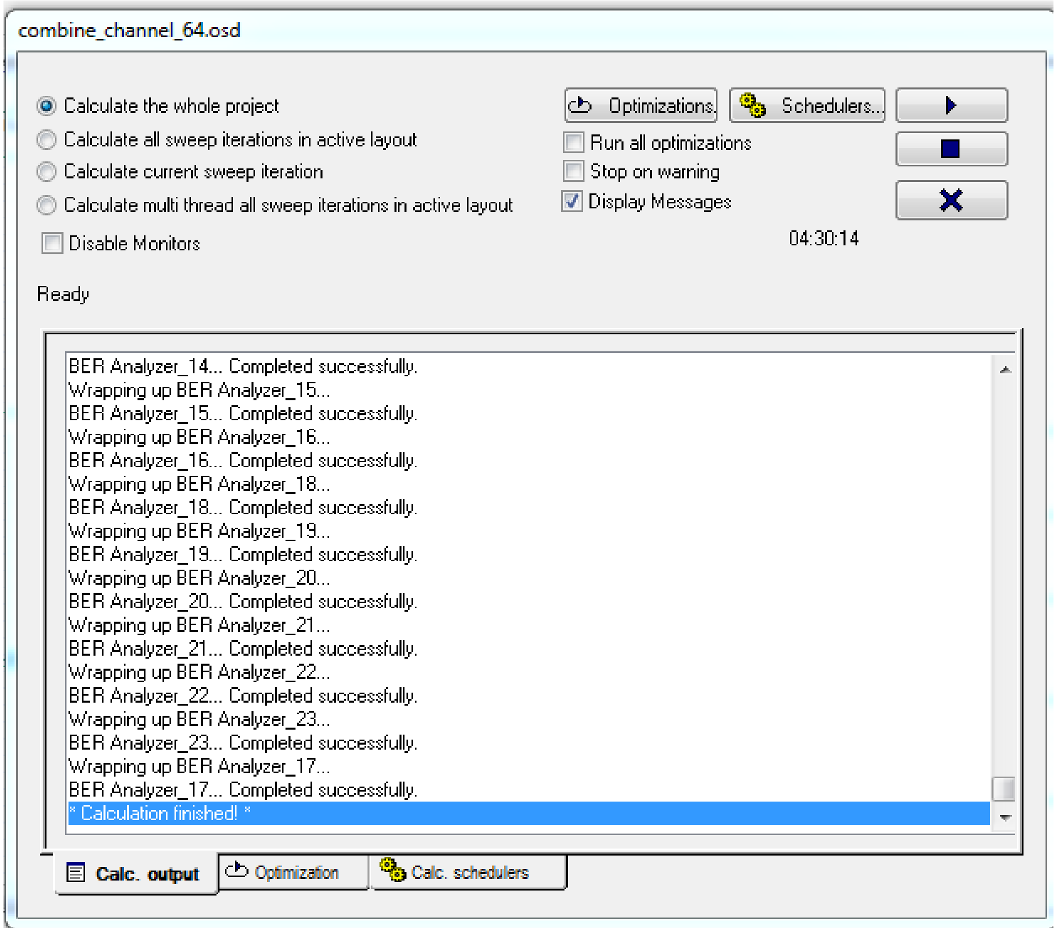
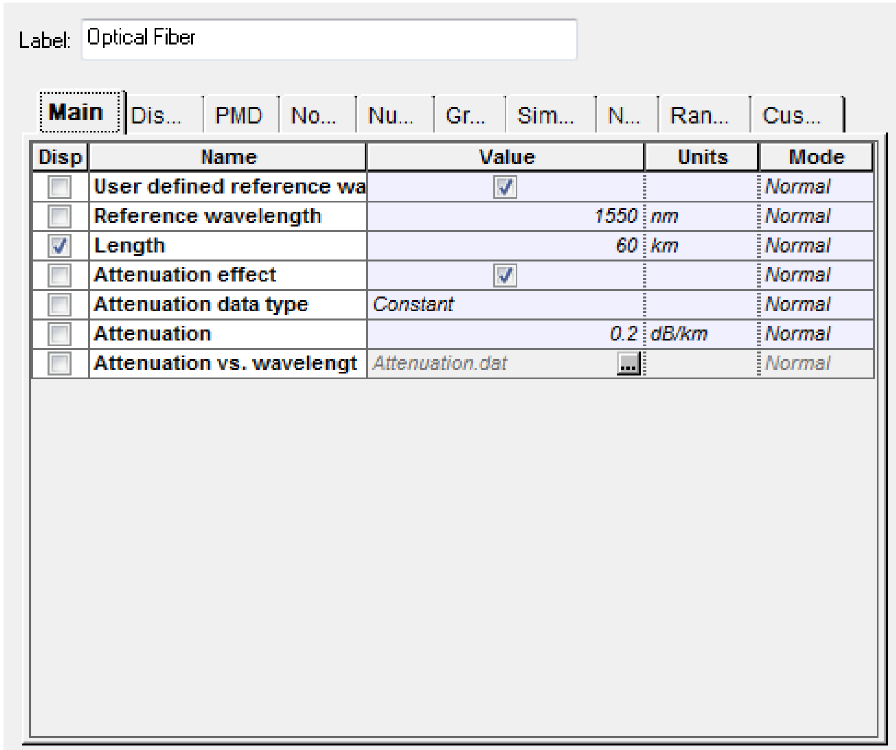


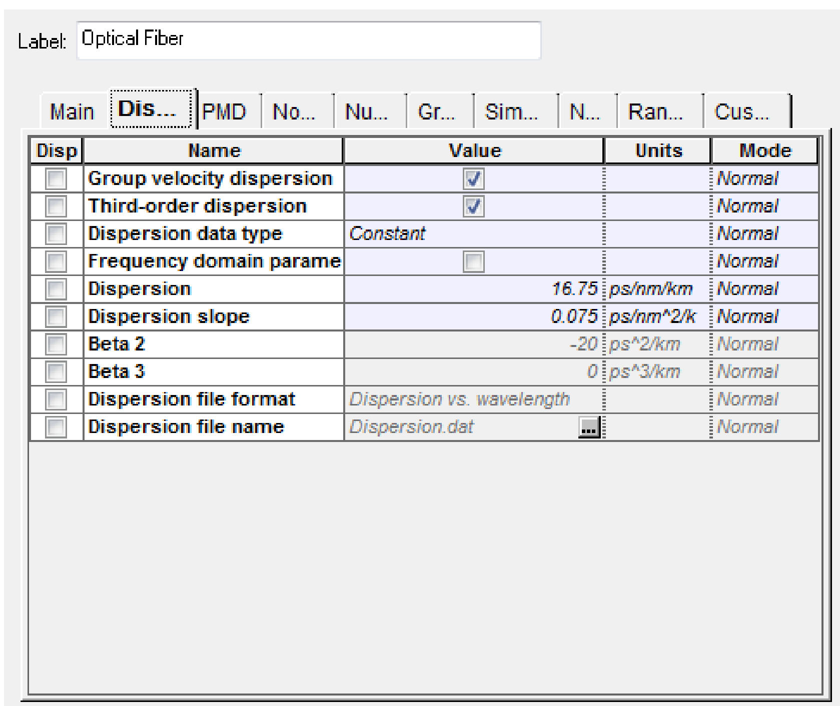
Figure 4.2.3.3: Simulation running view for 64 channels DWDM system

4.3 Configurations in Optisystem for 128 channels DWDM system



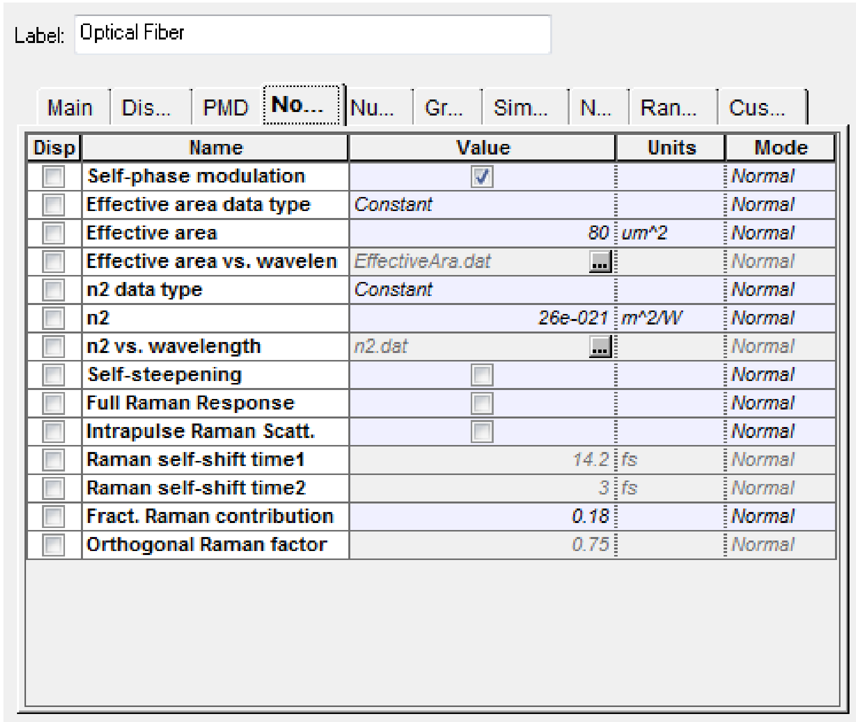
Disp	Name	Value	Units	Mode
☐	User defined reference wa	☑		Normal
☐	Reference wavelength	1550	nm	Normal
☑	Length	60	km	Normal
☐	Attenuation effect	☑		Normal
☐	Attenuation data type	Constant		Normal
☐	Attenuation	0.2	dB/km	Normal
☐	Attenuation vs. wavelengt	Attenuation.dat		Normal

Figure 4.3.1: Settings for optical fiber



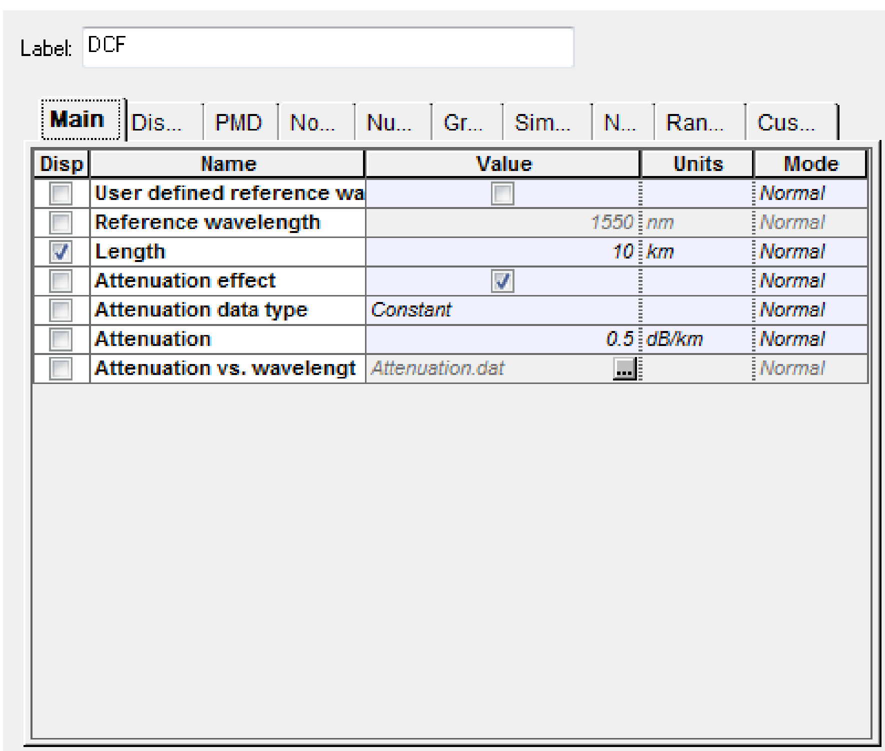
Disp	Name	Value	Units	Mode
☐	Group velocity dispersion	☑		Normal
☐	Third-order dispersion	☑		Normal
☐	Dispersion data type	Constant		Normal
☐	Frequency domain parame	☐		Normal
☐	Dispersion	16.75	ps/nm/km	Normal
☐	Dispersion slope	0.075	ps/nm^2/k	Normal
☐	Beta 2	-20	ps^2/km	Normal
☐	Beta 3	0	ps^3/km	Normal
☐	Dispersion file format	Dispersion vs. wavelength		Normal
☐	Dispersion file name	Dispersion.dat		Normal

Figure 4.3.2: Settings for dispersion in optical fiber



Disp	Name	Value	Units	Mode
☐	Self-phase modulation	☑		Normal
☐	Effective area data type	Constant		Normal
☐	Effective area	80	um^2	Normal
☐	Effective area vs. wavelen	EffectiveAra.dat		Normal
☐	n2 data type	Constant		Normal
☐	n2	26e-021	m^2/W	Normal
☐	n2 vs. wavelength	n2.dat		Normal
☐	Self-steepening	☐		Normal
☐	Full Raman Response	☐		Normal
☐	Intrapulse Raman Scatt.	☐		Normal
☐	Raman self-shift time1	14.2	fs	Normal
☐	Raman self-shift time2	3	fs	Normal
☐	Fract. Raman contribution	0.18		Normal
☐	Orthogonal Raman factor	0.75		Normal

Figure 4.3.3: Settings for noise in optical fiber



Disp	Name	Value	Units	Mode
☐	User defined reference wa	☐		Normal
☐	Reference wavelength	1550	nm	Normal
☑	Length	10	km	Normal
☐	Attenuation effect	☑		Normal
☐	Attenuation data type	Constant		Normal
☐	Attenuation	0.5	dB/km	Normal
☐	Attenuation vs. wavelengt	Attenuation.dat		Normal

Figure 4.3.4: Settings for Dispersion Compensation Fiber

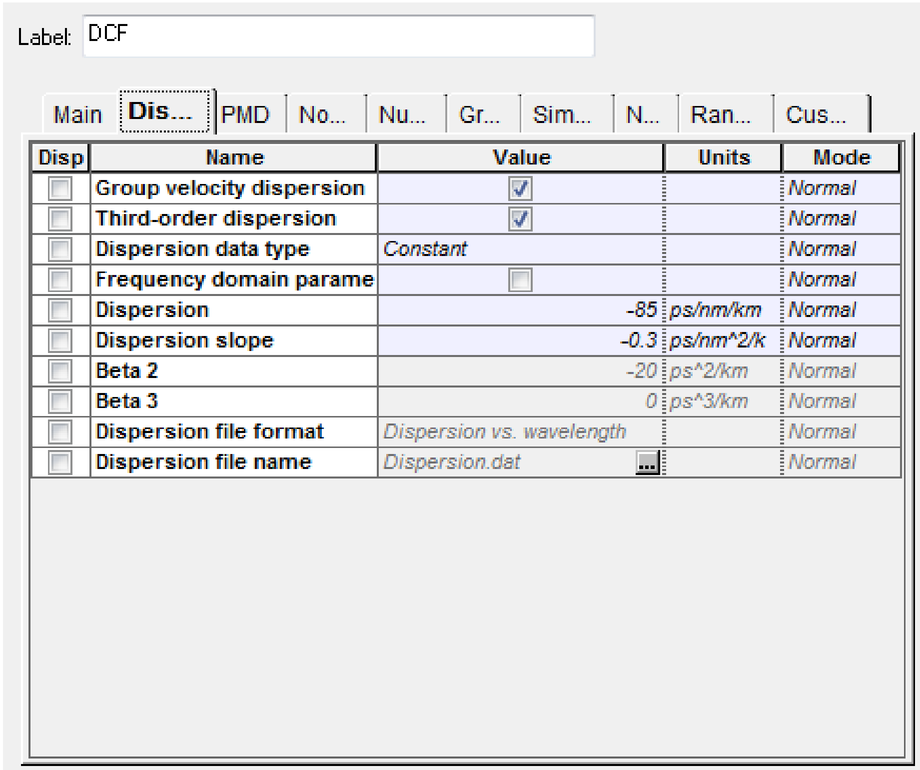


Figure 4.3.5: Settings for Dispersion in DCF

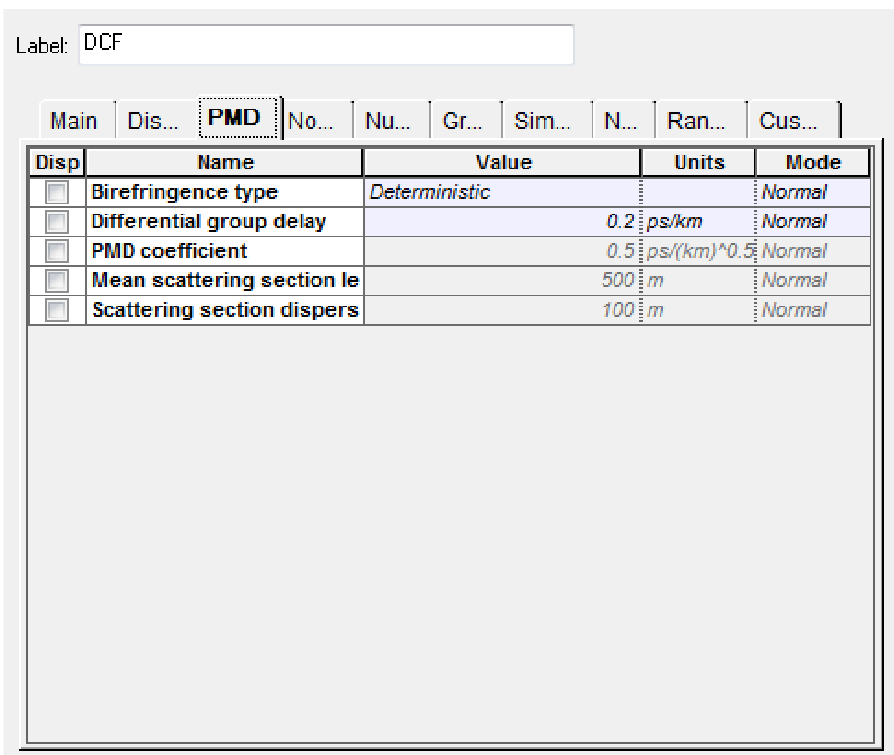
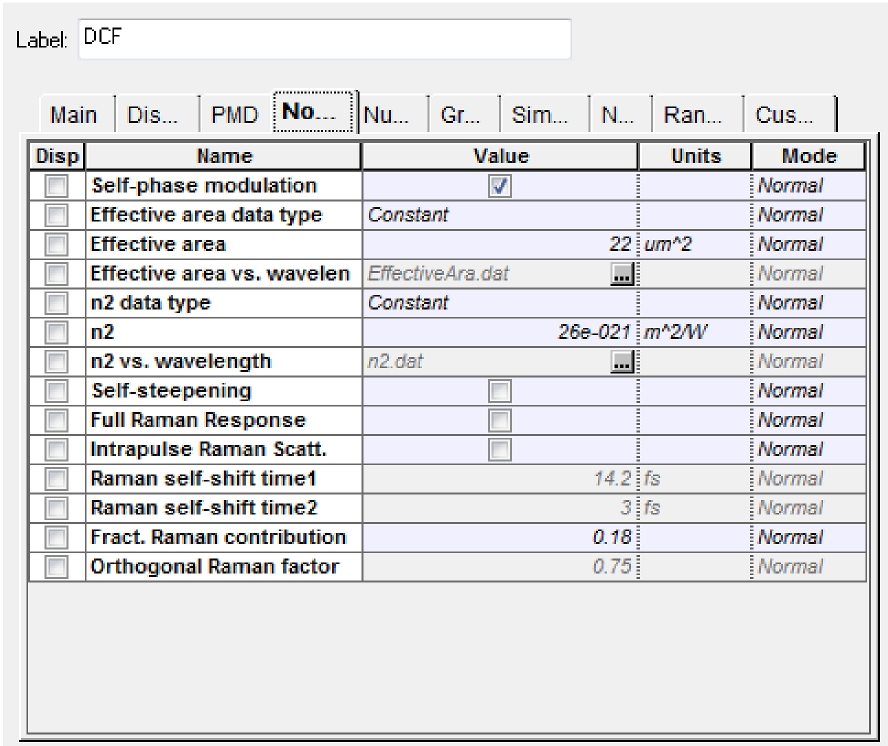


Figure 4.3.6: Settings for PMD in DCF

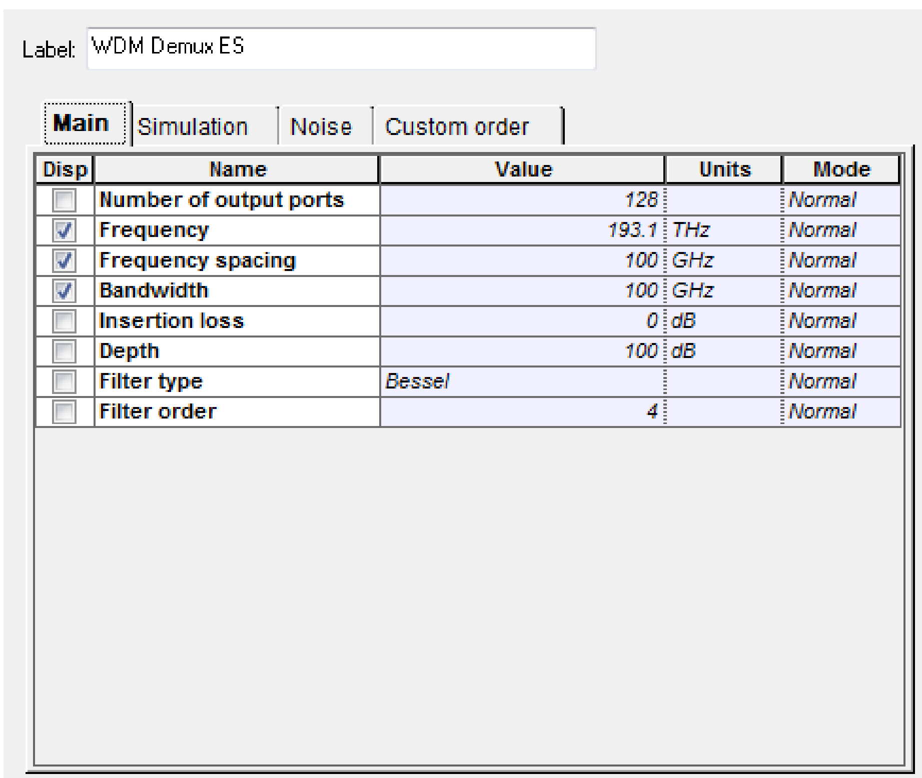


Label: DCF

Main | Dis... | PMD | No... | Nu... | Gr... | Sim... | N... | Ran... | Cus...

Disp	Name	Value	Units	Mode
☐	Self-phase modulation	☑		Normal
☐	Effective area data type	Constant		Normal
☐	Effective area	22	um^2	Normal
☐	Effective area vs. wavelen	EffectiveAra.dat		Normal
☐	n2 data type	Constant		Normal
☐	n2	26e-021	m^2/W	Normal
☐	n2 vs. wavelength	n2.dat		Normal
☐	Self-steepening	☐		Normal
☐	Full Raman Response	☐		Normal
☐	Intrapulse Raman Scatt.	☐		Normal
☐	Raman self-shift time1	14.2	fs	Normal
☐	Raman self-shift time2	3	fs	Normal
☐	Fract. Raman contribution	0.18		Normal
☐	Orthogonal Raman factor	0.75		Normal

Figure 4.3.7: Settings for DCF



Label: WDM Demux ES

Main | Simulation | Noise | Custom order

Disp	Name	Value	Units	Mode
☐	Number of output ports	128		Normal
☑	Frequency	193.1	THz	Normal
☑	Frequency spacing	100	GHz	Normal
☑	Bandwidth	100	GHz	Normal
☐	Insertion loss	0	dB	Normal
☐	Depth	100	dB	Normal
☐	Filter type	Bessel		Normal
☐	Filter order	4		Normal

Figure 4.3.8: Settings for WDM demultiplexer

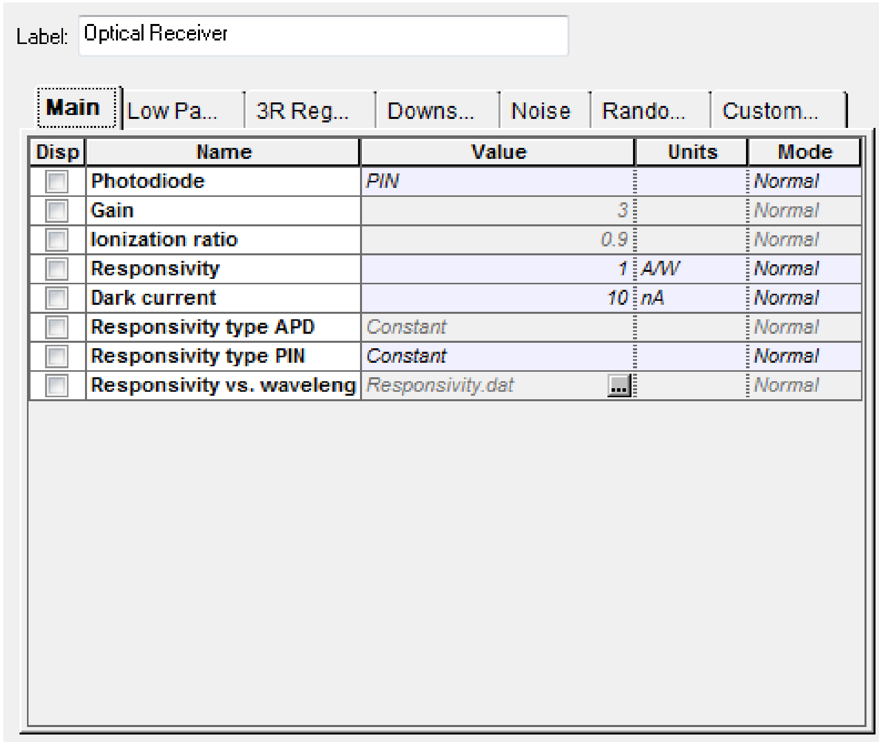


Figure 4.3.9: Settings for optical receiver

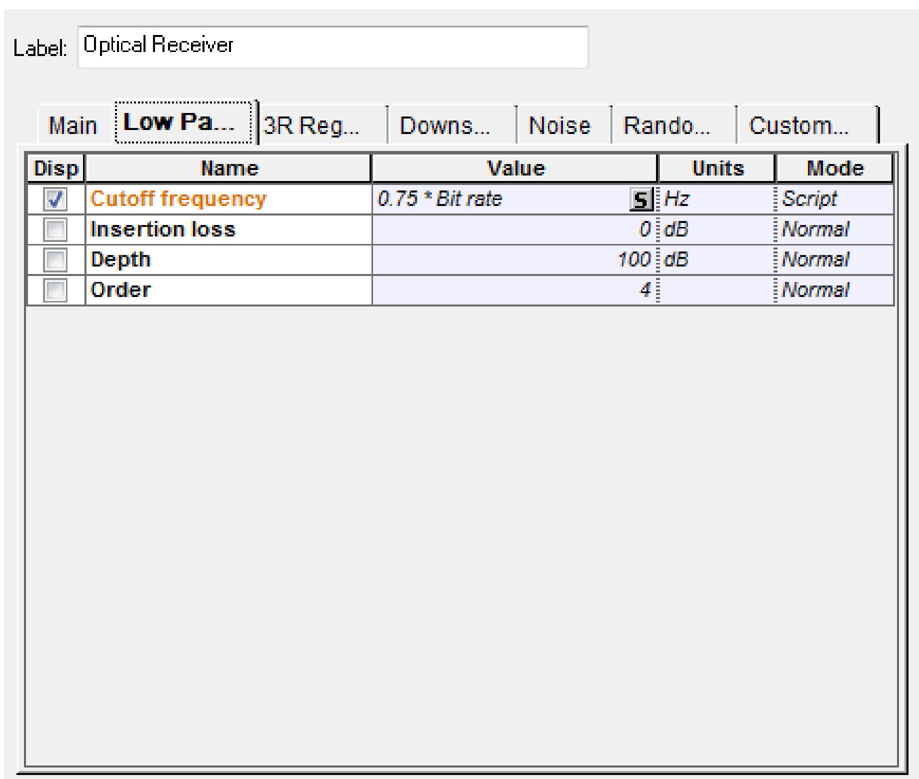


Figure 4.3.10: Settings for LPF in optical receiver

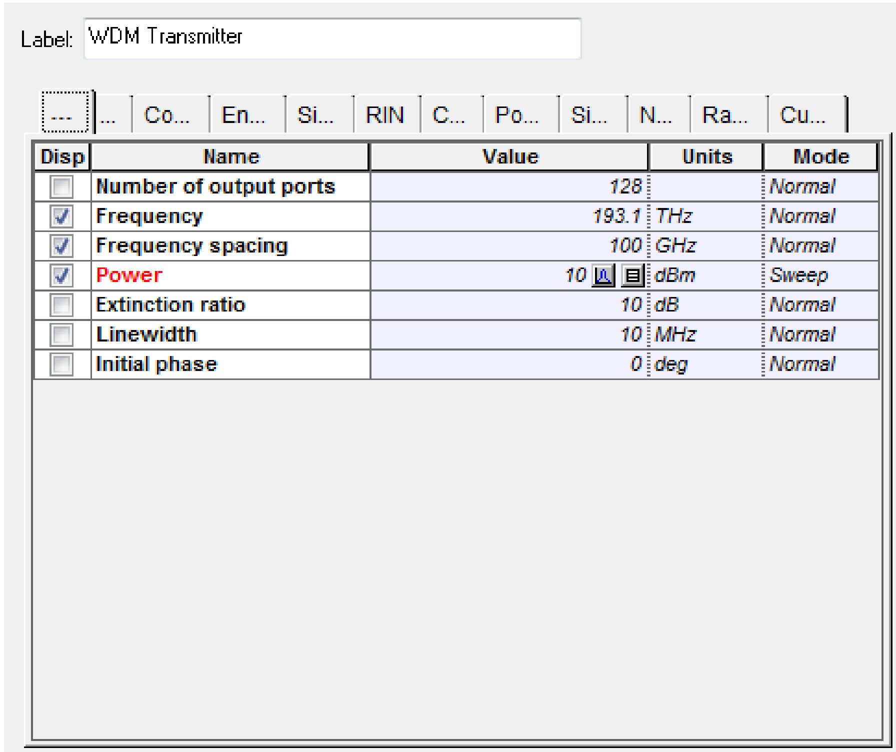


Figure 4.3.11: Settings for WDM transmitter

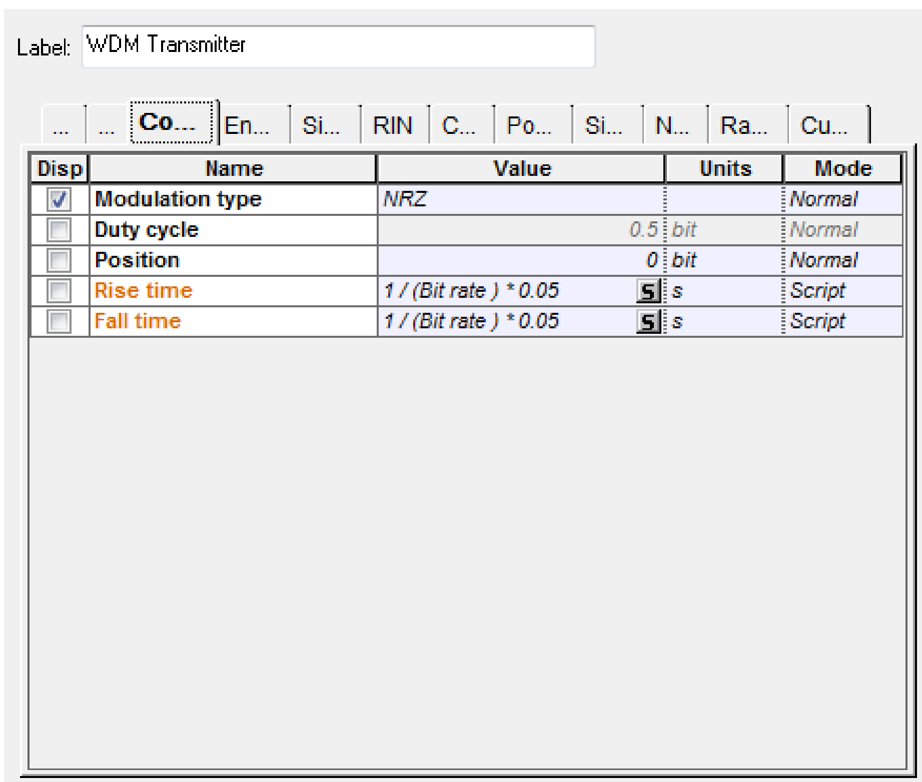
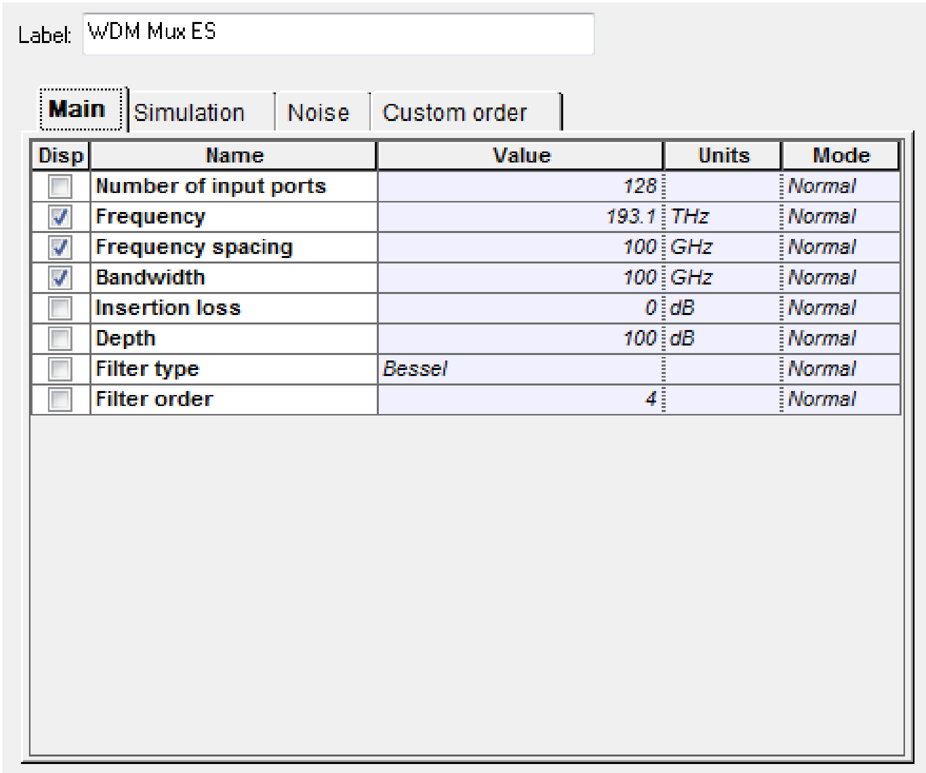


Figure 4.3.12: Settings for WDM transmitter

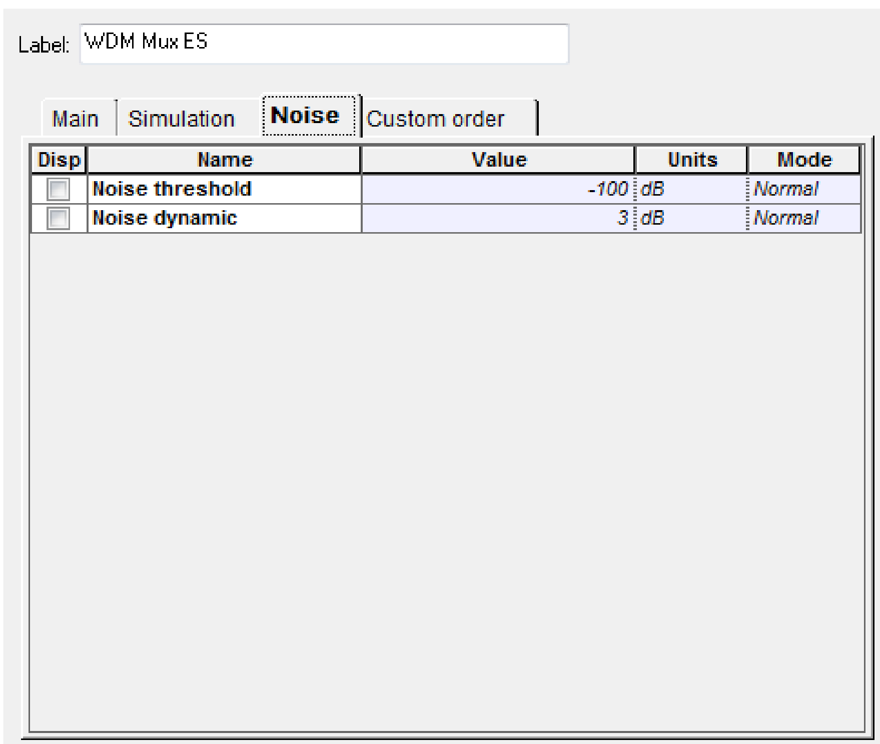


Label: WDM Mux ES

Main | Simulation | Noise | Custom order

Disp	Name	Value	Units	Mode
☐	Number of input ports	128		Normal
☑	Frequency	193.1	THz	Normal
☑	Frequency spacing	100	GHz	Normal
☑	Bandwidth	100	GHz	Normal
☐	Insertion loss	0	dB	Normal
☐	Depth	100	dB	Normal
☐	Filter type	Bessel		Normal
☐	Filter order	4		Normal

Figure 4.3.13: Settings for WDM multiplexer



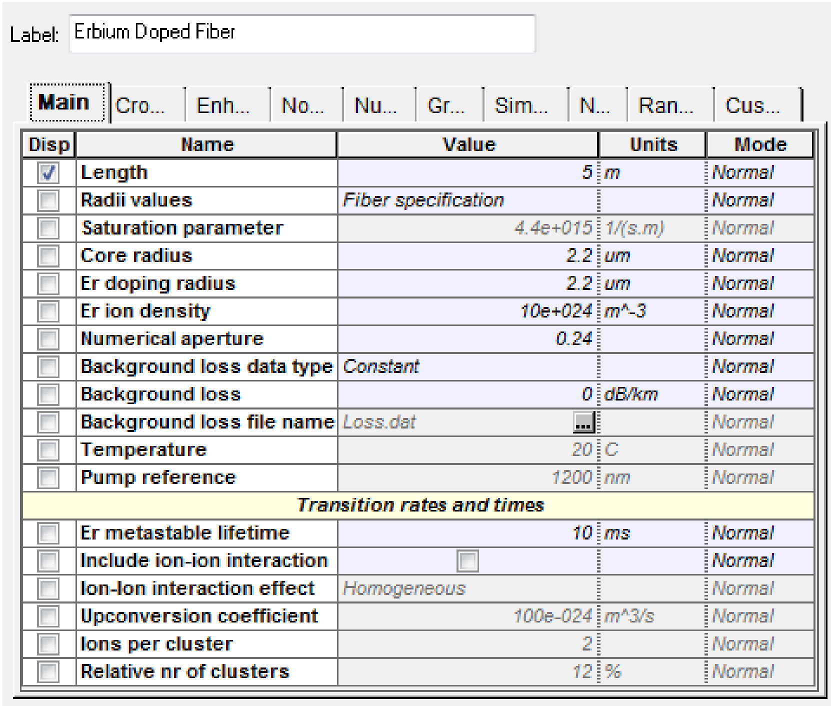
Label: WDM Mux ES

Main | Simulation | Noise | Custom order

Disp	Name	Value	Units	Mode
☐	Noise threshold	-100	dB	Normal
☐	Noise dynamic	3	dB	Normal

Figure 4.3.14: Settings for noise in WDM multiplexer

4.3.1 Settings for EDFA amplifier

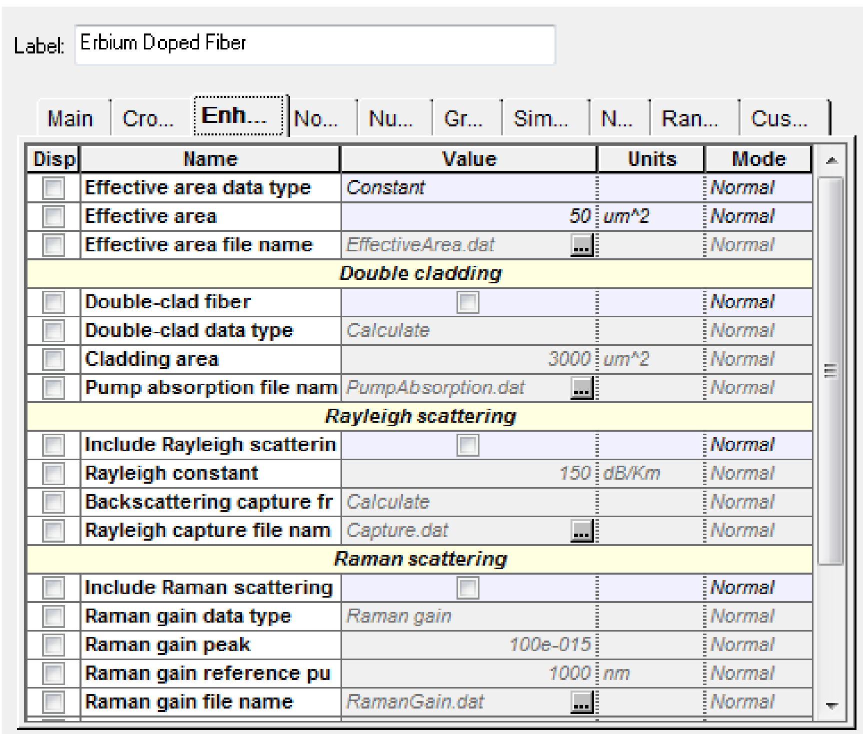


Label: Erbium Doped Fiber

Main | Cro... | Enh... | No... | Nu... | Gr... | Sim... | N... | Ran... | Cus...

Disp	Name	Value	Units	Mode
☑	Length	5	m	Normal
☐	Radii values	Fiber specification		Normal
☐	Saturation parameter	4.4e+015	1/(s.m)	Normal
☐	Core radius	2.2	um	Normal
☐	Er doping radius	2.2	um	Normal
☐	Er ion density	10e+024	m^-3	Normal
☐	Numerical aperture	0.24		Normal
☐	Background loss data type	Constant		Normal
☐	Background loss	0	dB/km	Normal
☐	Background loss file name	Loss.dat		Normal
☐	Temperature	20	C	Normal
☐	Pump reference	1200	nm	Normal
	Transition rates and times			
☐	Er metastable lifetime	10	ms	Normal
☐	Include ion-ion interaction	☐		Normal
☐	Ion-Ion interaction effect	Homogeneous		Normal
☐	Upconversion coefficient	100e-024	m^3/s	Normal
☐	Ions per cluster	2		Normal
☐	Relative nr of clusters	12	%	Normal

Figure 4.3.1.1: Settings for Erbium Doped Fiber



Label: Erbium Doped Fiber

Main | Cro... | Enh... | No... | Nu... | Gr... | Sim... | N... | Ran... | Cus...

Disp	Name	Value	Units	Mode
☐	Effective area data type	Constant		Normal
☐	Effective area	50	um^2	Normal
☐	Effective area file name	EffectiveArea.dat		Normal
	Double cladding			
☐	Double-clad fiber	☐		Normal
☐	Double-clad data type	Calculate		Normal
☐	Cladding area	3000	um^2	Normal
☐	Pump absorption file nam	PumpAbsorption.dat		Normal
	Rayleigh scattering			
☐	Include Rayleigh scatterin	☐		Normal
☐	Rayleigh constant	150	dB/Km	Normal
☐	Backscattering capture fr	Calculate		Normal
☐	Rayleigh capture file nam	Capture.dat		Normal
	Raman scattering			
☐	Include Raman scattering	☐		Normal
☐	Raman gain data type	Raman gain		Normal
☐	Raman gain peak	100e-015		Normal
☐	Raman gain reference pu	1000	nm	Normal
☐	Raman gain file name	RamanGain.dat		Normal

Figure 4.3.1.2: Settings for Erbium Doped Fiber

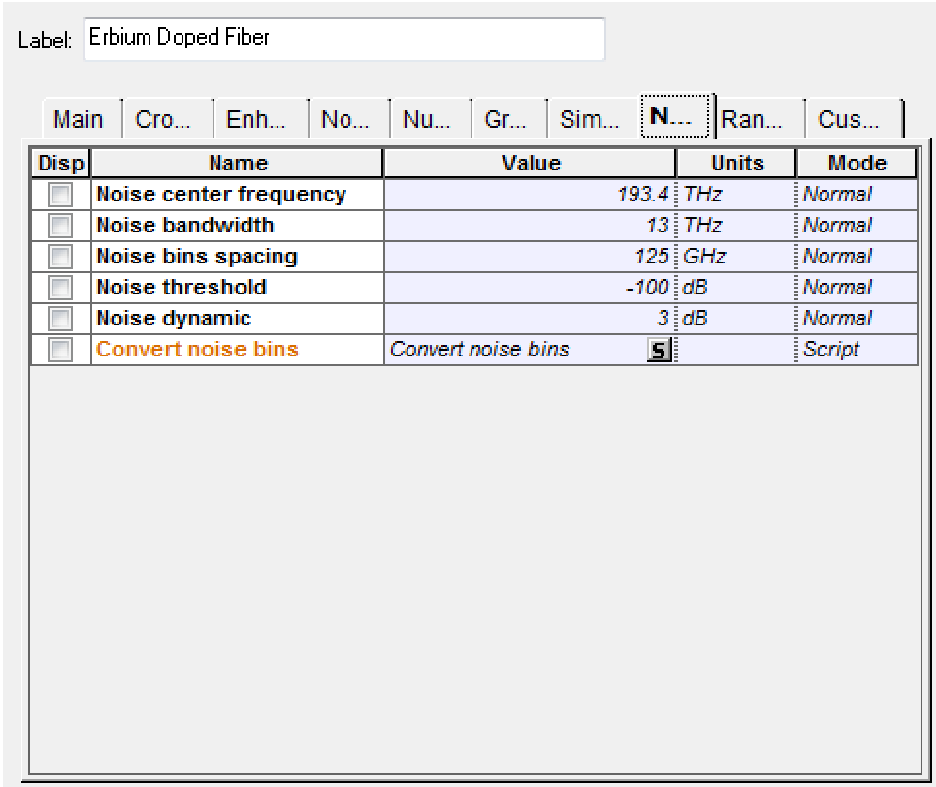
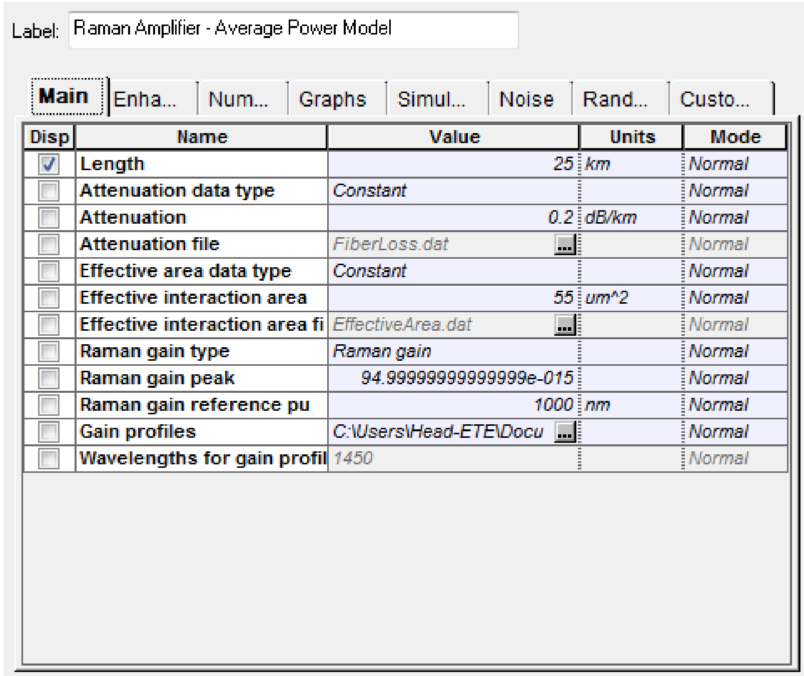


Figure 4.3.1.3: Settings for Erbium Doped Fiber

4.3.2 Settings for Raman amplifier

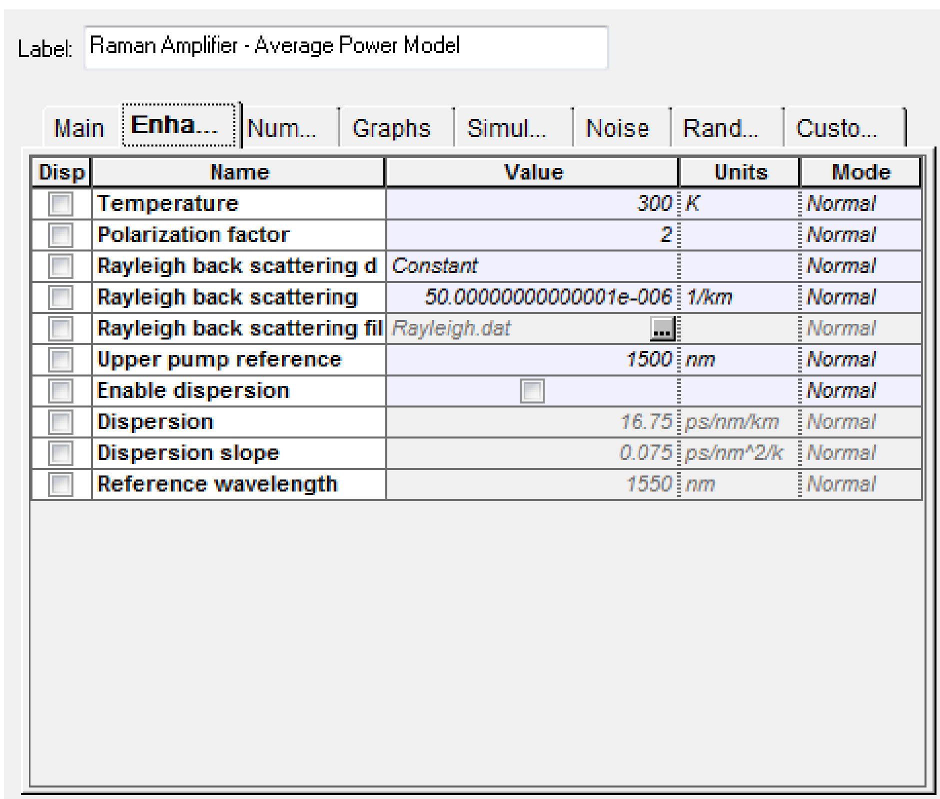


Label: Raman Amplifier - Average Power Model

Main | Enha... | Num... | Graphs | Simul... | Noise | Rand... | Custo...

Disp	Name	Value	Units	Mode
☑	Length	25	km	Normal
☐	Attenuation data type	Constant		Normal
☐	Attenuation	0.2	dB/km	Normal
☐	Attenuation file	FiberLoss.dat		Normal
☐	Effective area data type	Constant		Normal
☐	Effective interaction area	55	um^2	Normal
☐	Effective interaction area fi	EffectiveArea.dat		Normal
☐	Raman gain type	Raman gain		Normal
☐	Raman gain peak	94.99999999999999e-015		Normal
☐	Raman gain reference pu	1000	nm	Normal
☐	Gain profiles	C:\Users\Head-ETE\Docu		Normal
☐	Wavelengths for gain profil	1450		Normal

Figure 4.3.2.1: Settings for Raman amplifier



Label: Raman Amplifier - Average Power Model

Main | Enha... | Num... | Graphs | Simul... | Noise | Rand... | Custo...

Disp	Name	Value	Units	Mode
☐	Temperature	300	K	Normal
☐	Polarization factor	2		Normal
☐	Rayleigh back scattering d	Constant		Normal
☐	Rayleigh back scattering	50.00000000000001e-006	1/km	Normal
☐	Rayleigh back scattering fil	Rayleigh.dat		Normal
☐	Upper pump reference	1500	nm	Normal
☐	Enable dispersion	☐		Normal
☐	Dispersion	16.75	ps/nm/km	Normal
☐	Dispersion slope	0.075	ps/nm^2/k	Normal
☐	Reference wavelength	1550	nm	Normal

Figure 4.3.2.2: Settings for Raman amplifier

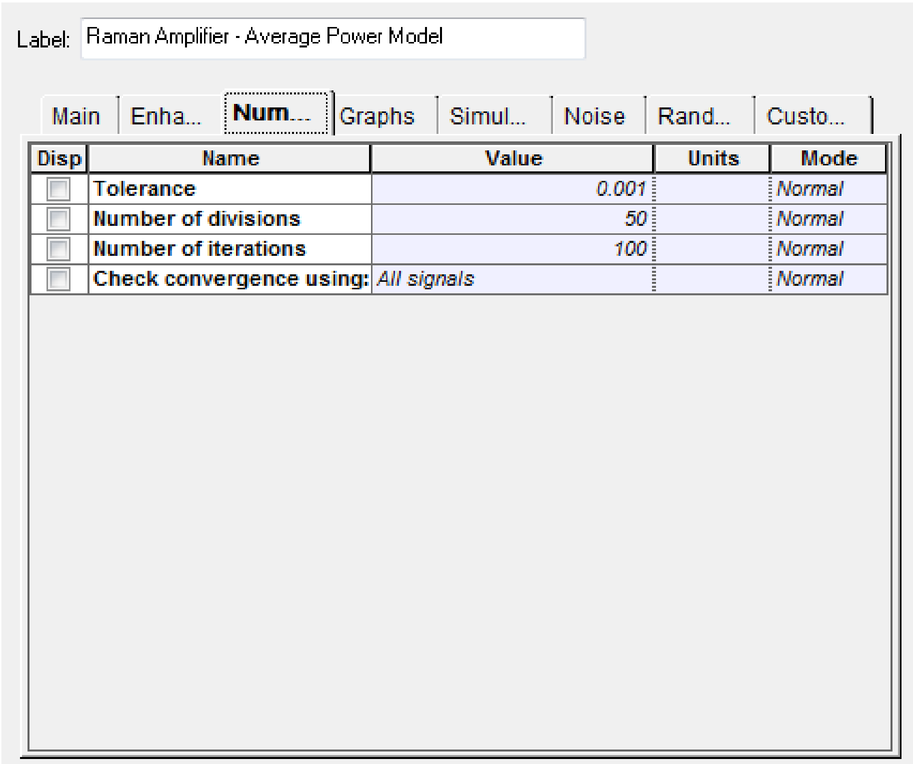


Figure 4.3.2.3: Settings for Raman amplifier

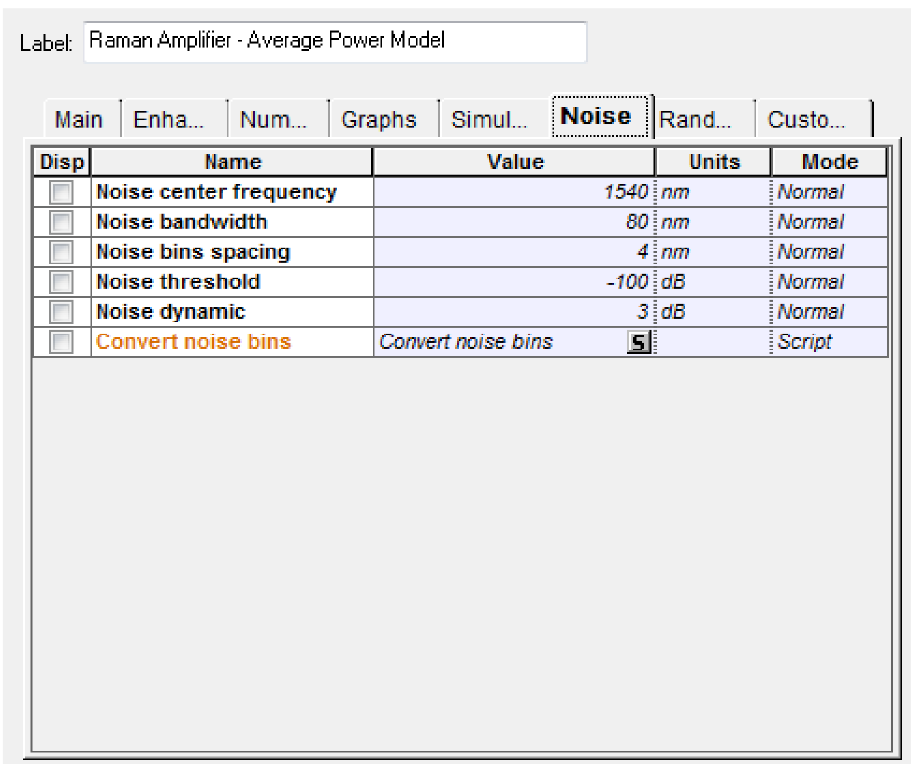
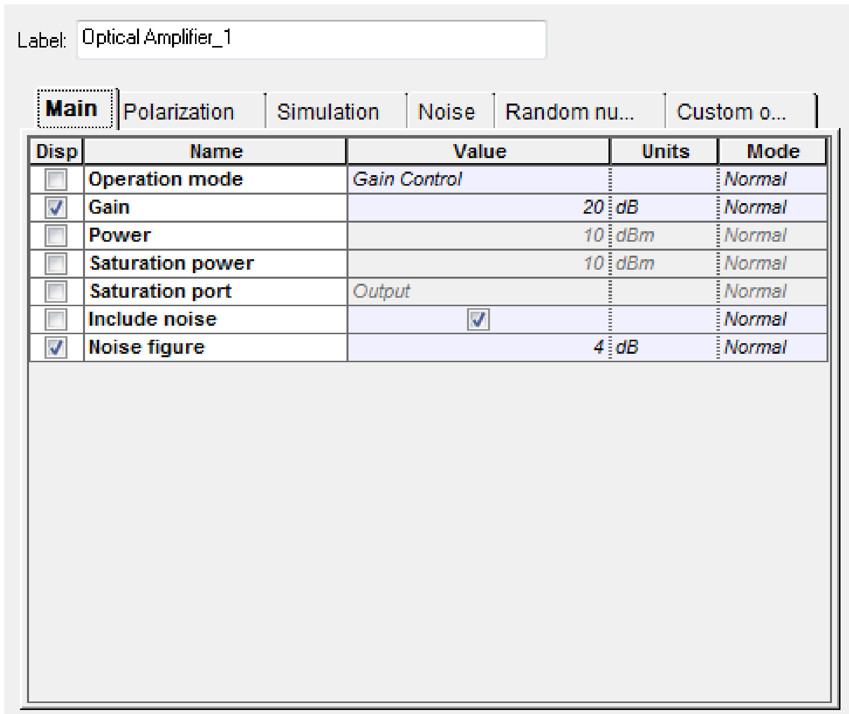


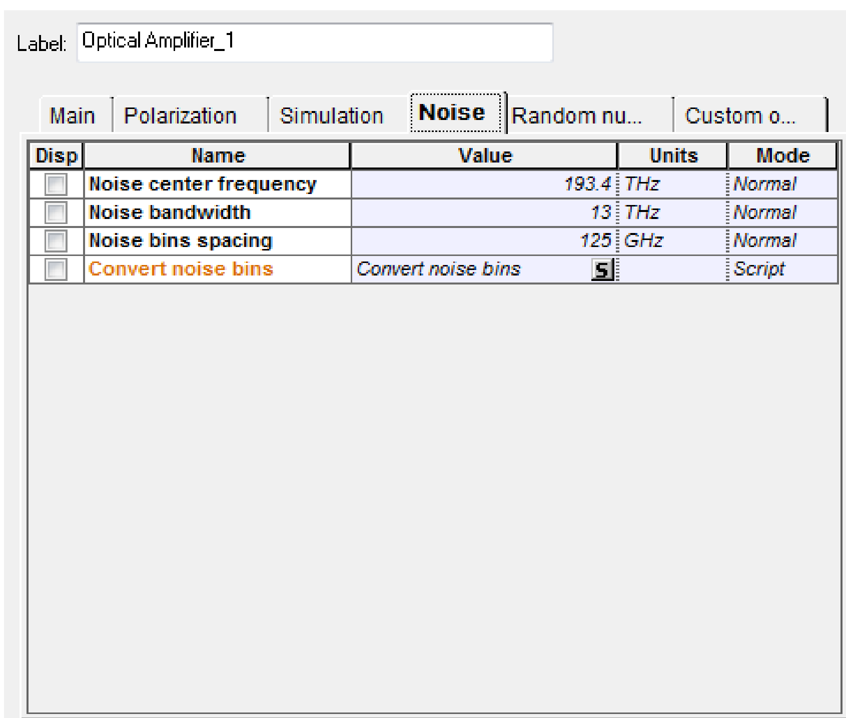
Figure 4.3.2.4: Settings for noise in Raman amplifier

4.3.3 Settings for OA amplifier



Disp	Name	Value	Units	Mode
☐	Operation mode	Gain Control		Normal
☑	Gain	20	dB	Normal
☐	Power	10	dBm	Normal
☐	Saturation power	10	dBm	Normal
☐	Saturation port	Output		Normal
☐	Include noise	☑		Normal
☑	Noise figure	4	dB	Normal

Figure 4.3.3.1: Settings for OA amplifier



Disp	Name	Value	Units	Mode
☐	Noise center frequency	193.4	THz	Normal
☐	Noise bandwidth	13	THz	Normal
☐	Noise bins spacing	125	GHz	Normal
☐	Convert noise bins	Convert noise bins S		Script

Figure 4.3.3.2: Settings for OA amplifier

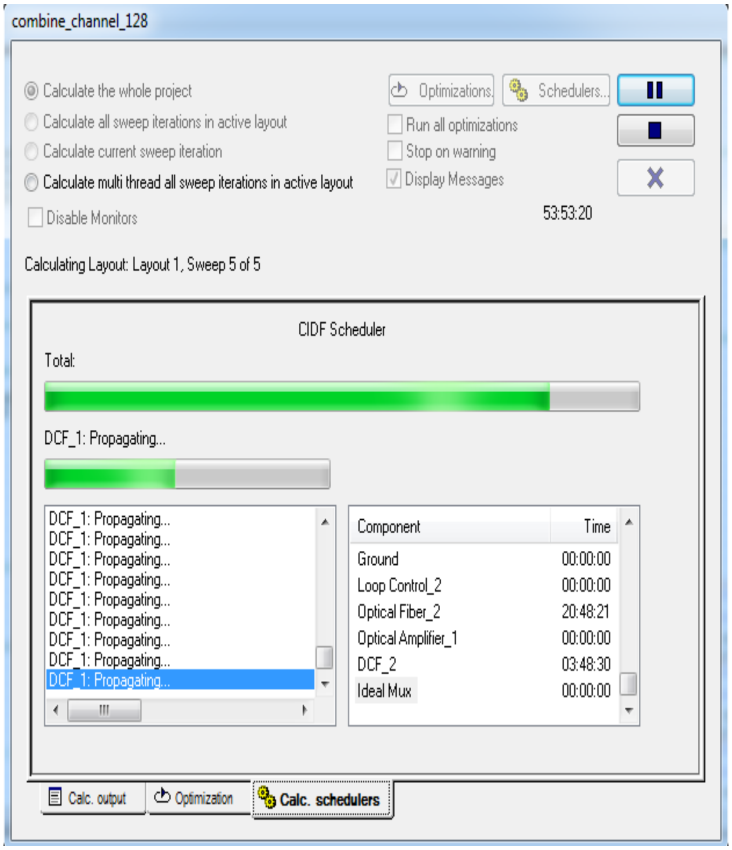


Figure 4.3.3.3: Simulation processing view for 128 channels DWDM system

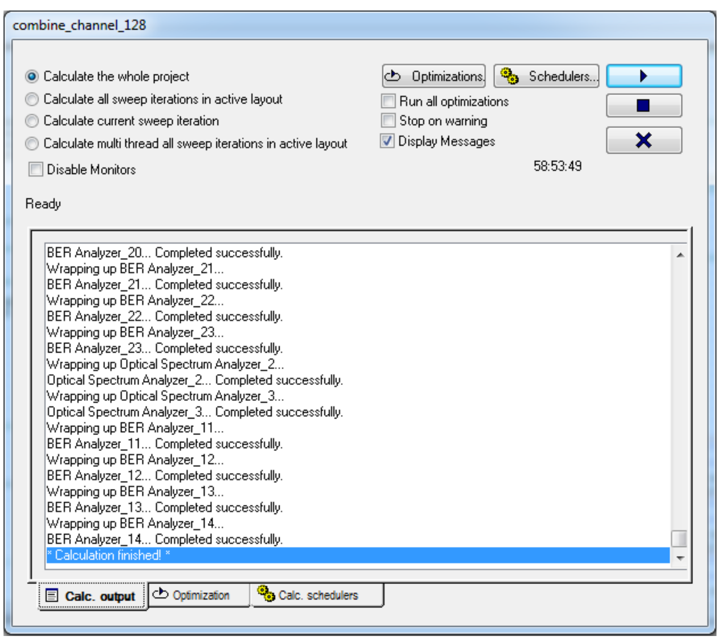


Figure 4.3.3.4: Simulation processing completed view for 128 channels DWDM system

4.4 Outputs of 32 channels DWDM system

4.4.1 Outputs of 32 channels DWDM system for EDFA amplifier

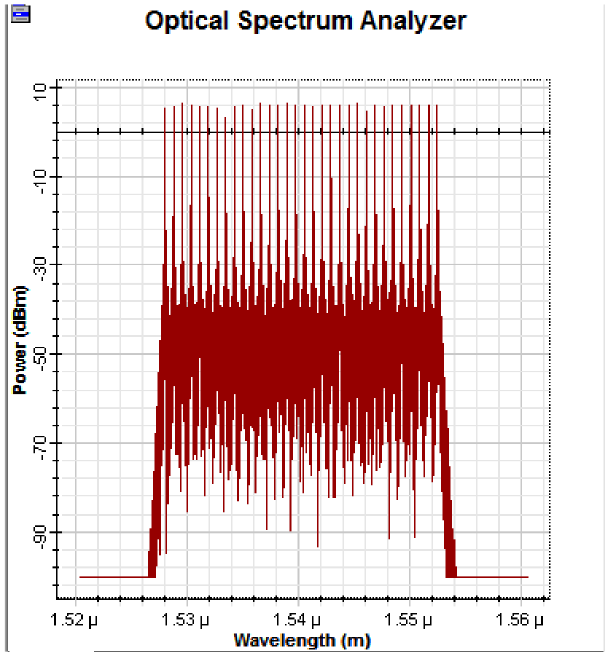


Figure 4.4.1.1: 32 channels input signal in OSA before entering to the optical link for EDFA

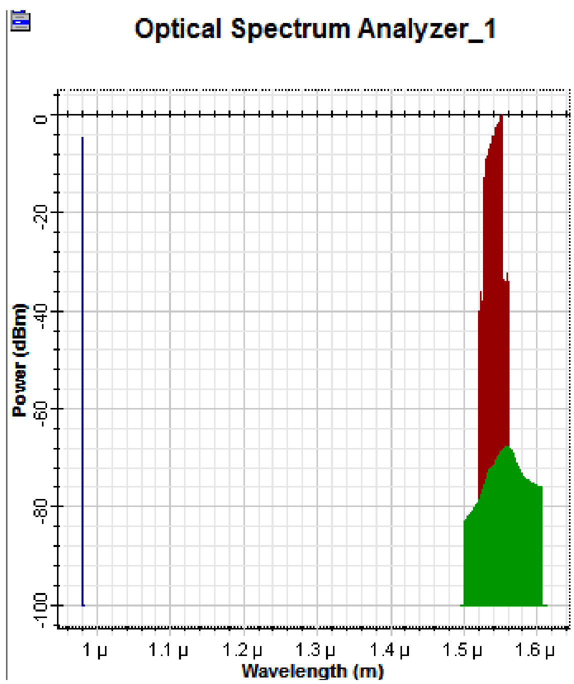


Figure 4.4.1.2: 32 channels output signal in OSA after entering to the optical link for EDFA (at loop control), signal power versus noise power where red color indicates the signal power and green color represents the noise power

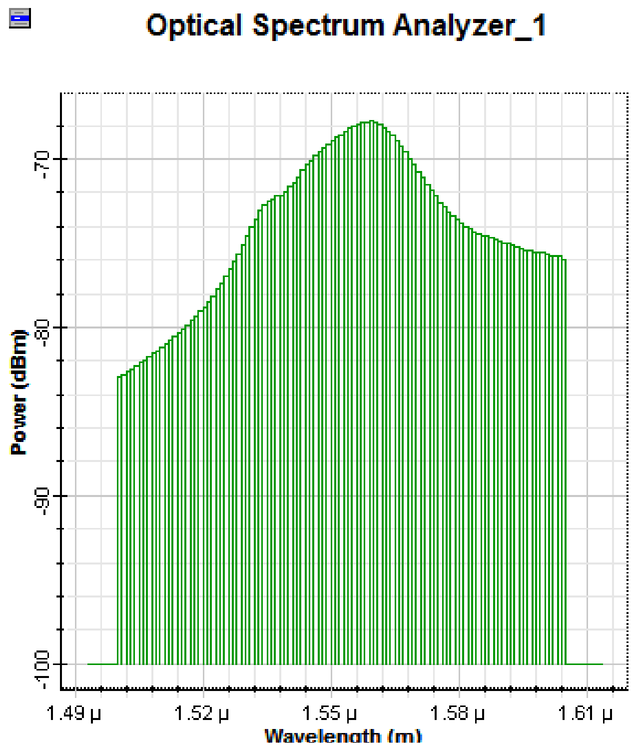


Figure 4.4.1.3: 32 channels output signal in OSA after entering to the optical link for EDFA (at loop control), noise power

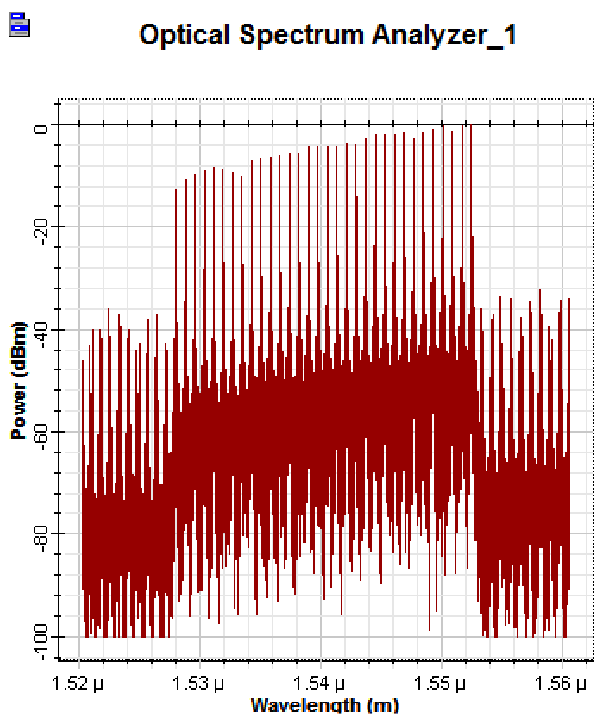


Figure 4.4.1.4: 32 channels output signal in OSA after entering to the optical link for EDFA (at loop control), signal power with side lobes (FWM)

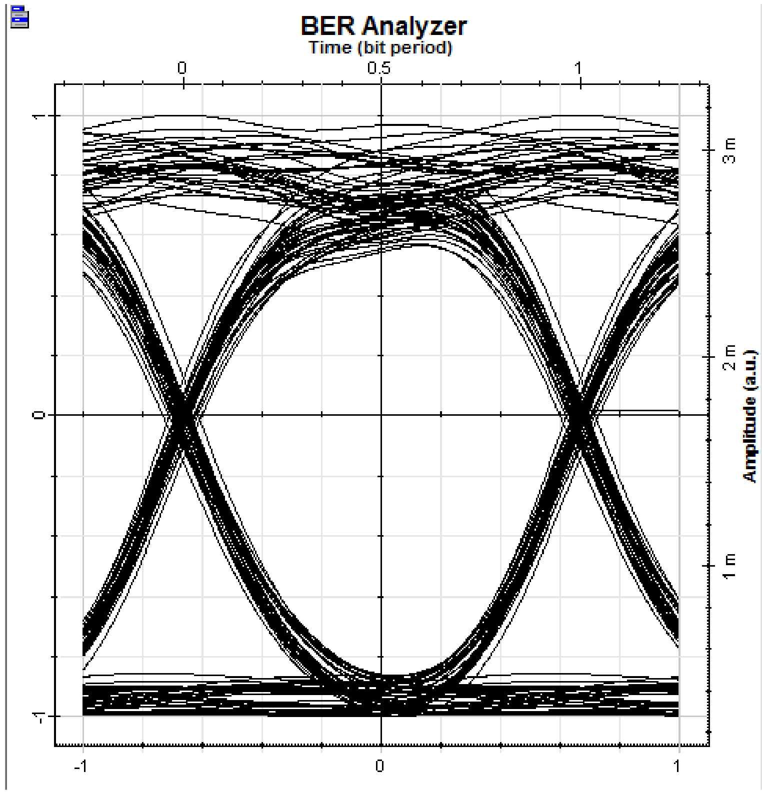


Figure 4.4.1.5: Output of eye diagram from BER analyzer for EDFA

4.4.2 Outputs of 32 channels DWDM system for Raman amplifier

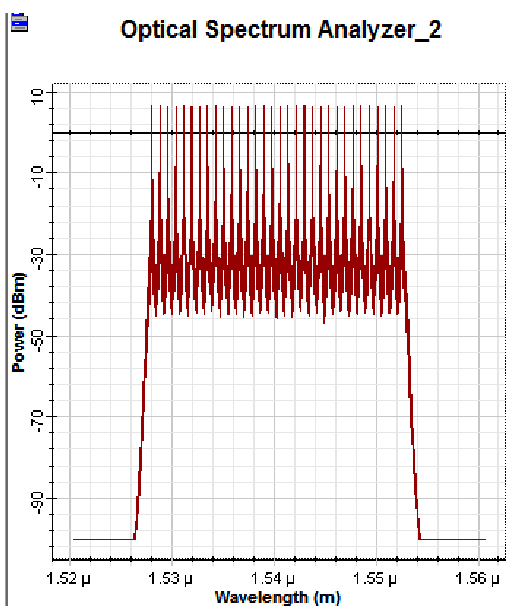


Figure 4.4.2.1: 32 channels input signal in OSA before entering to the optical link for Raman

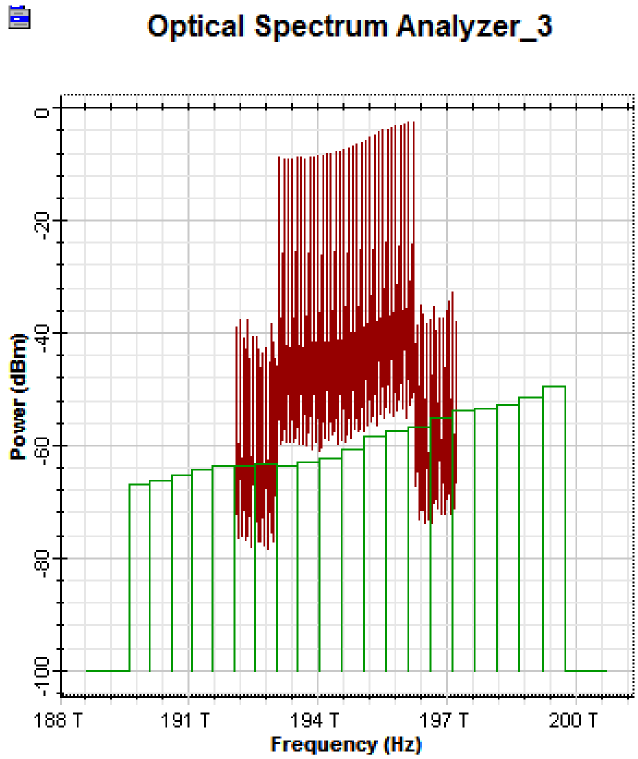


Figure 4.4.2.2: 32 channels output signal in OSA after entering to the optical link for Raman (at loop control), signal power versus noise power where red color indicates the signal power and green color represents the noise power

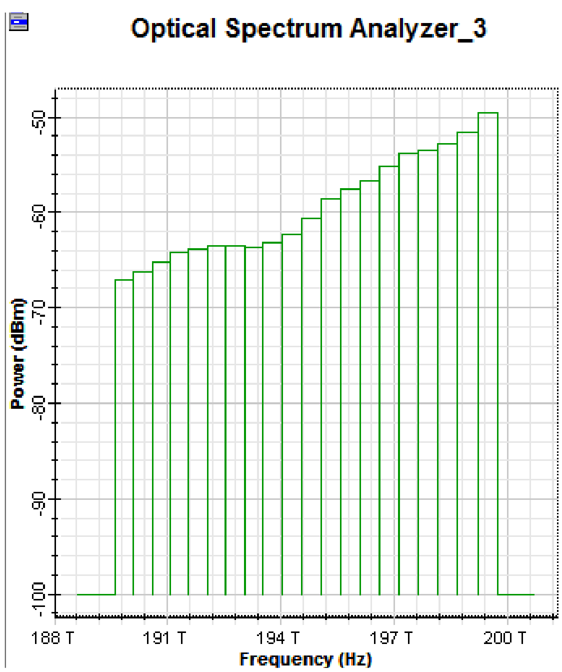


Figure 4.4.2.3: 32 channels output signal in OSA after entering to the optical link for Raman (at loop control), noise power

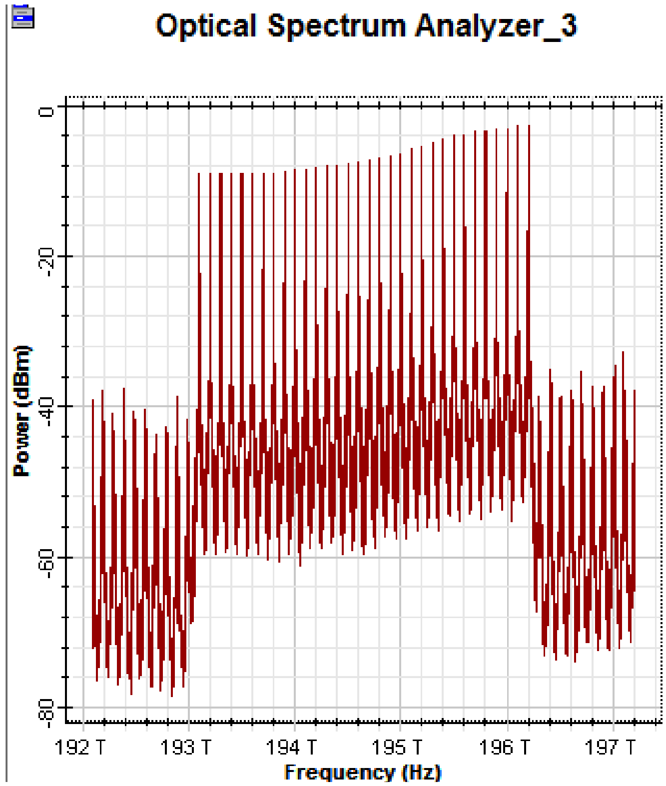


Figure 4.4.2.4: 32 channels output signal in OSA after entering to the optical link for Raman (at loop control), signal power with side lobes (FWM)

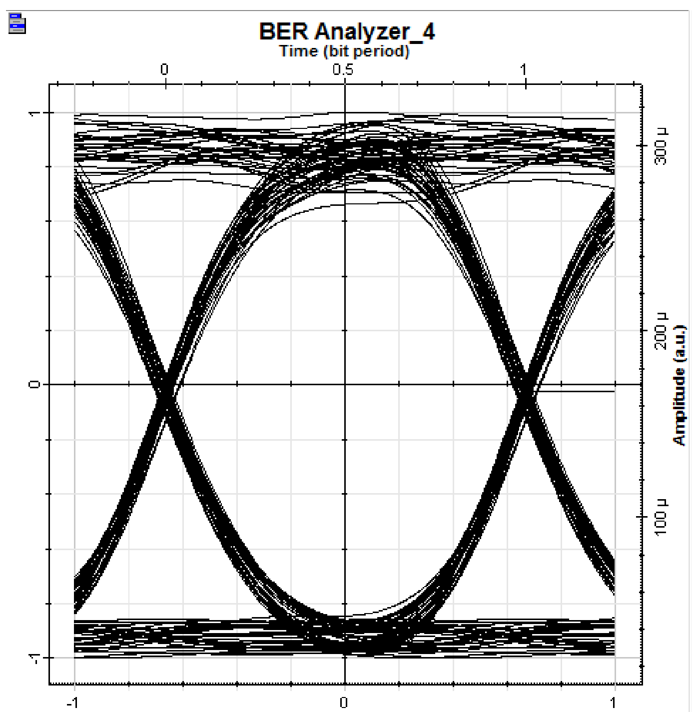


Figure 4.4.2.5: Output of eye diagram from BER analyzer for Raman amplifier

4.4.3 Outputs of 32 channels DWDM system for OA amplifier

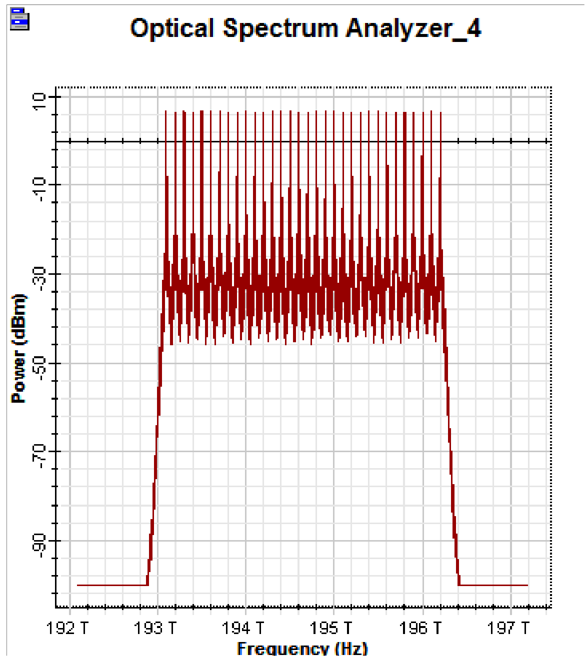


Figure 4.4.3.1: 32 channels input signal in OSA before entering to the optical link for OA amplifier

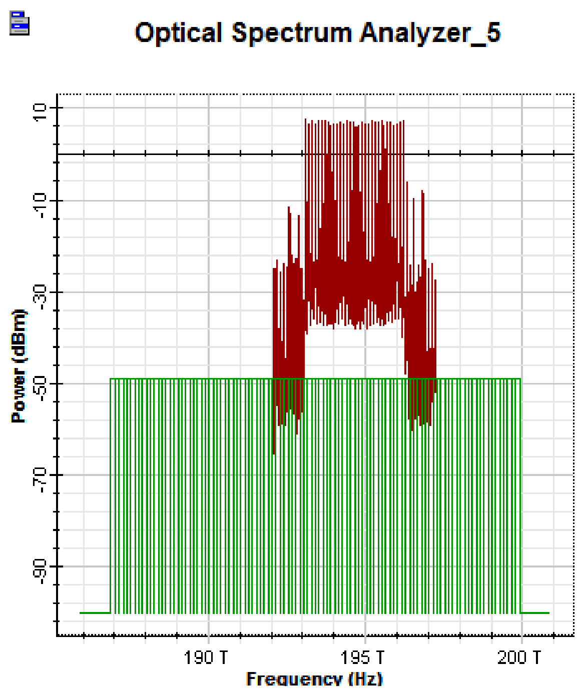


Figure 4.4.3.2: 32 channels output signal in OSA after entering to the optical link for OA amplifier (at loop control), signal power versus noise power where red color indicates the signal power and green color represents the noise power

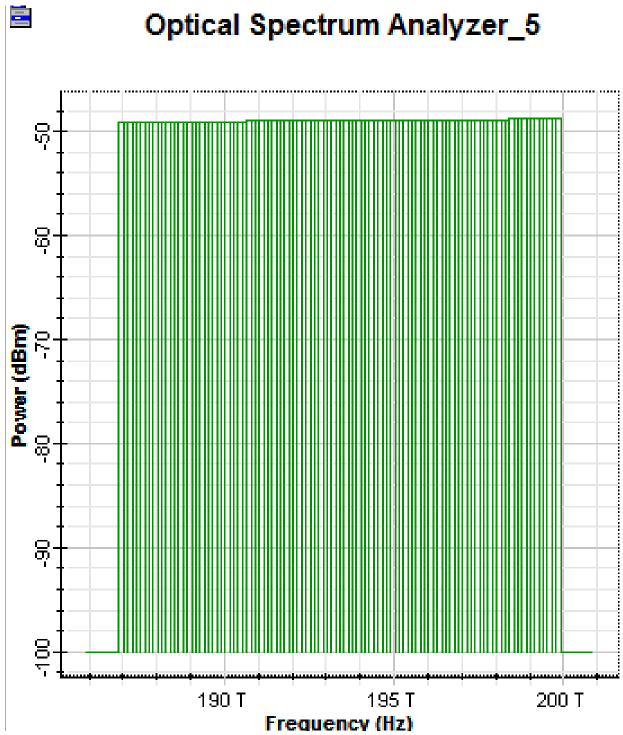


Figure 4.4.3.3: 32 channels output signal in OSA after entering to the optical link for OA amplifier (at loop control), noise power

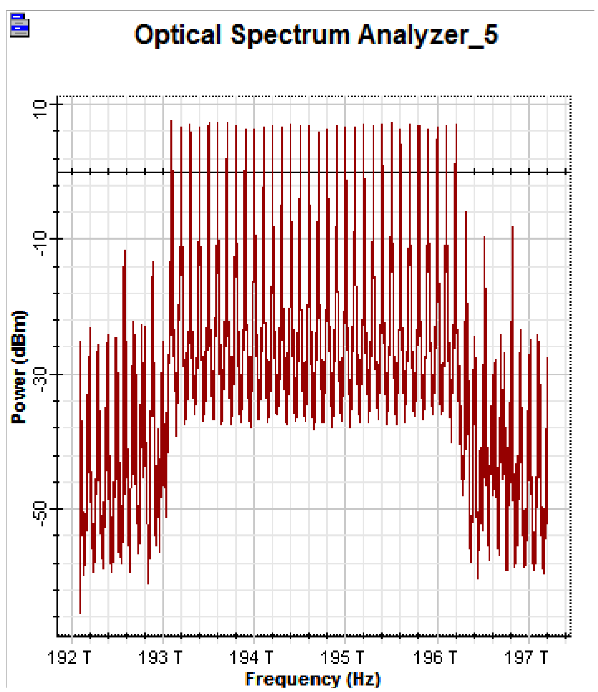


Figure 4.4.3.4: 32 channels output signal in OSA after entering to the optical link for OA amplifier (at loop control), signal power with side lobes (FWM)

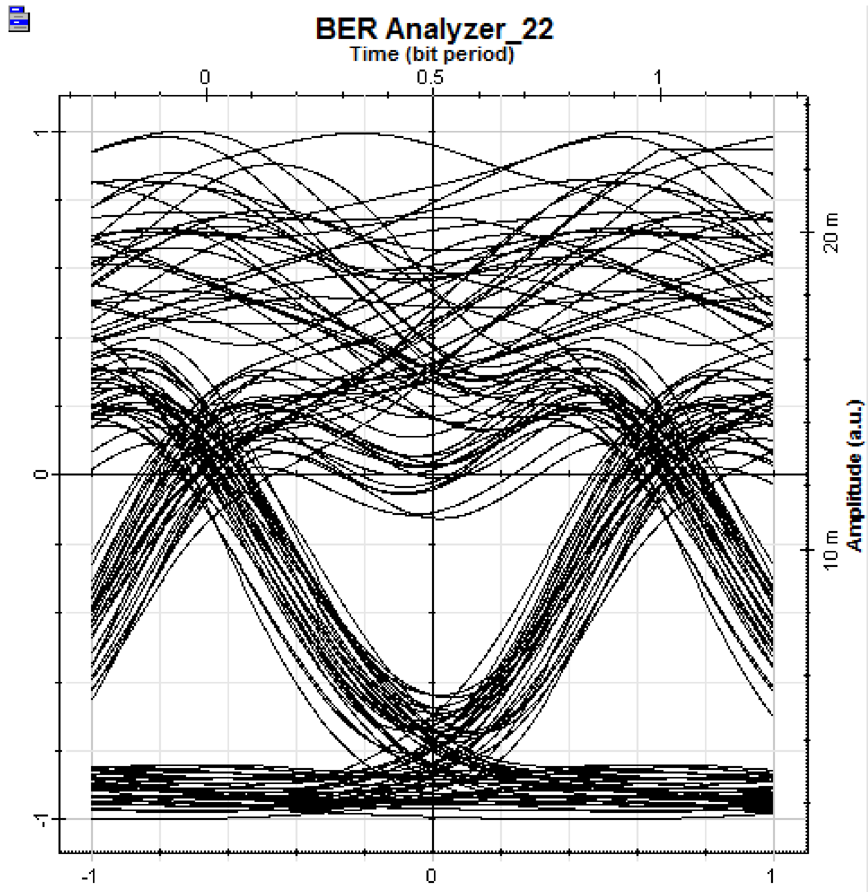


Figure 4.4.3.5: Output eye diagram from BER analyzer for OA amplifier

4.5 Outputs of 64 channels DWDM system

4.5.1 Outputs of 64 channels DWDM system for EDFA amplifier

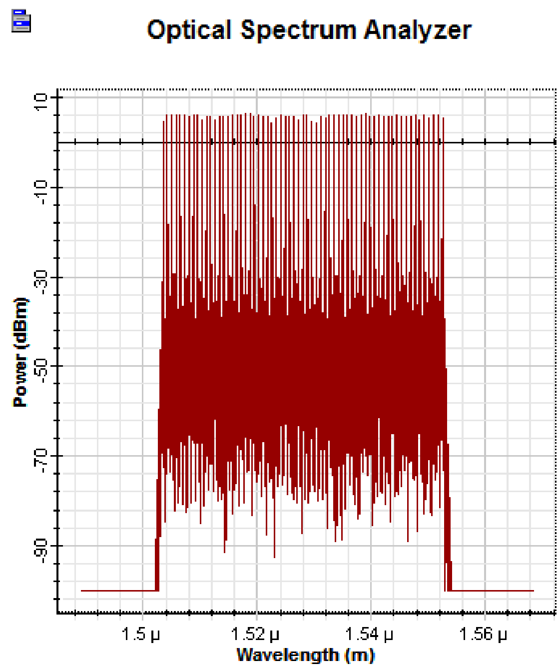


Figure 4.5.1.1: 64 channels input signal in OSA before entering to the optical link for EDFA

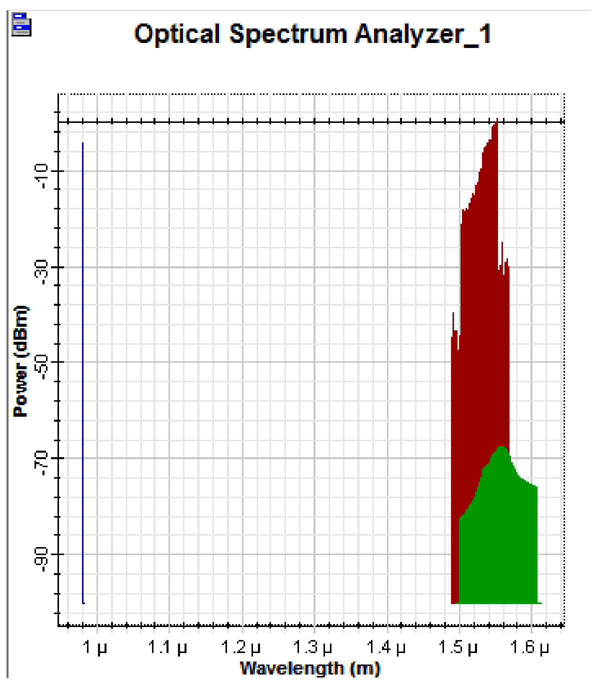


Figure 4.5.1.2: 64 channels output signal in OSA after entering to the optical link for EDFA (at loop control), signal power versus noise power where red color indicates the signal power and green color represents the noise power

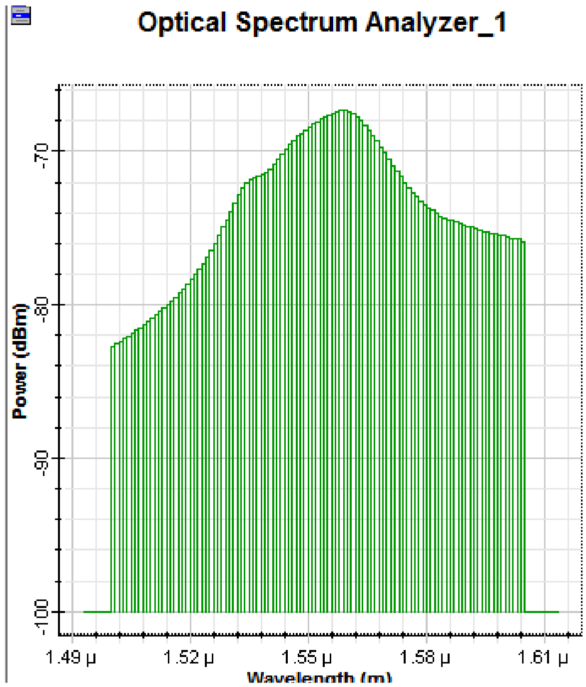


Figure 4.5.1.3: 64 channels output signal in OSA after entering to the optical link for EDFA (at loop control), noise power

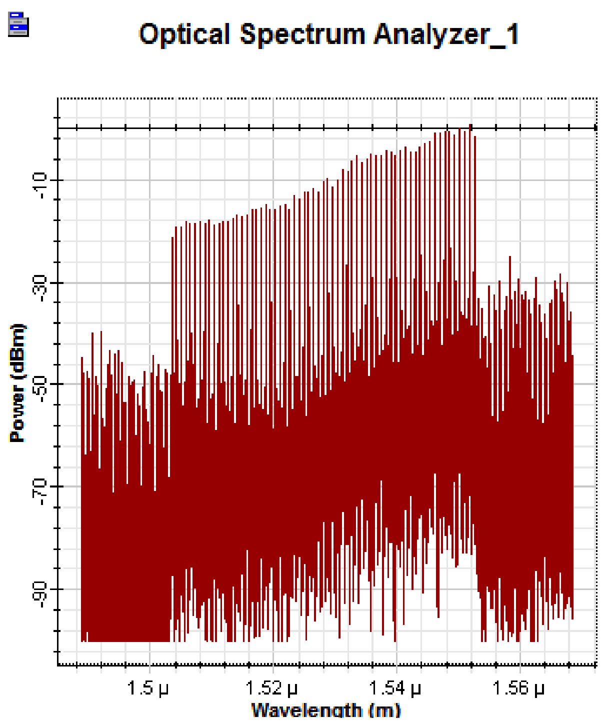


Figure 4.5.1.4: 64 channels output signal in OSA after entering to the optical link for EDFA (at loop control), signal power with side lobes (FWM)

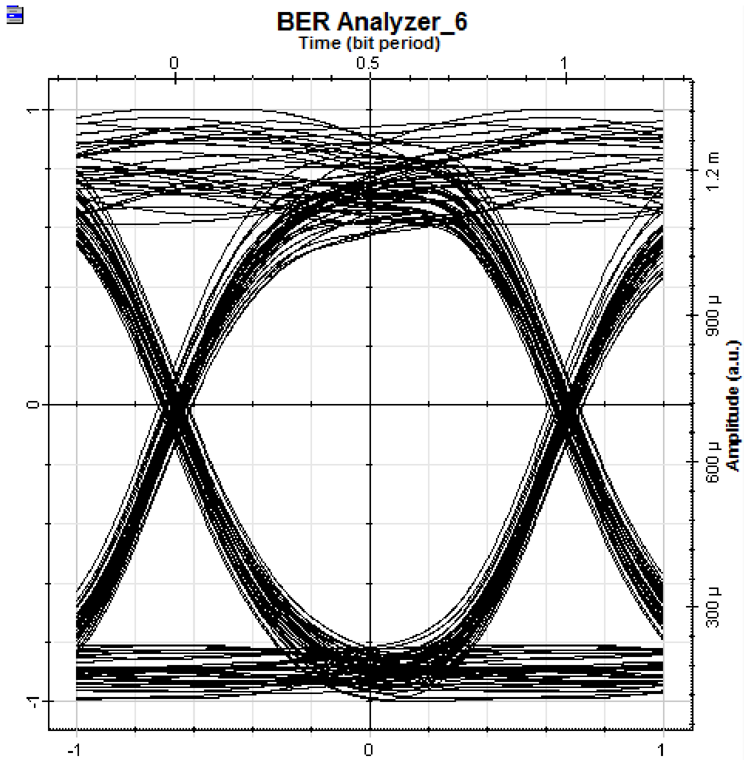


Figure 4.5.1.5: Output of eye diagram from BER analyzer for EDFA amplifier

4.5.2 Outputs for 64 channels DWDM system for Raman amplifier

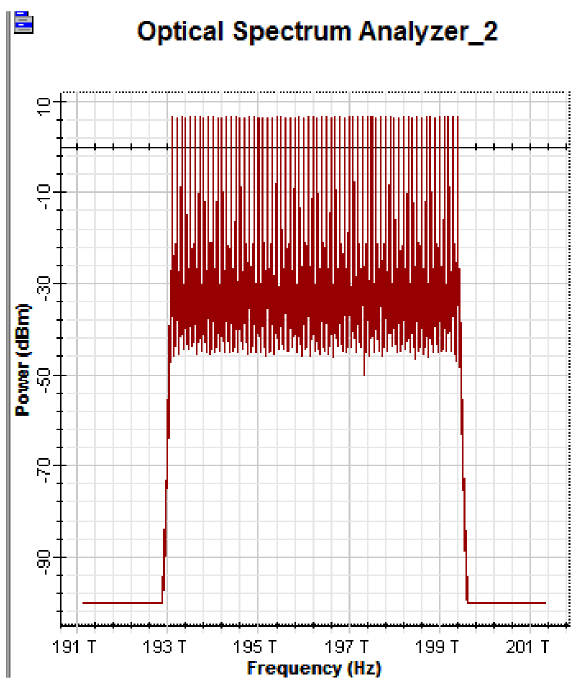


Figure 4.5.2.1: 64 channels input signal in OSA before entering to the optical link for Raman

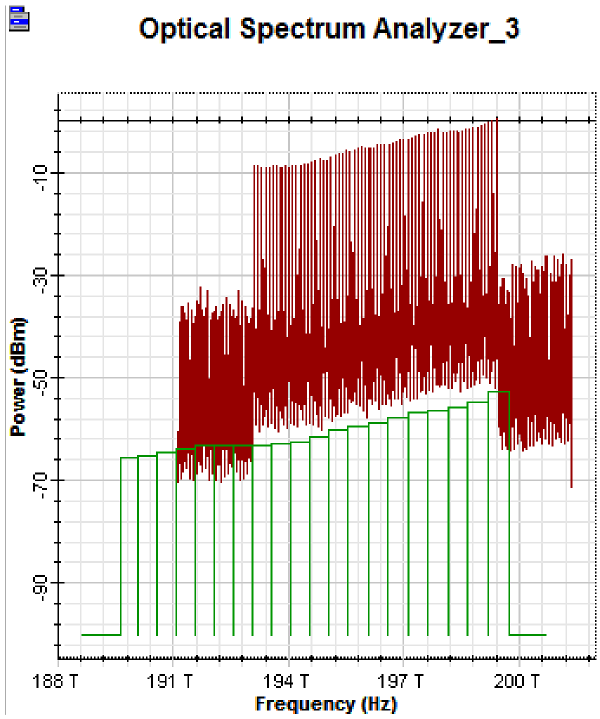


Figure 4.5.2.2: 64 channels output signal in OSA after entering to the optical link for Raman (at loop control), signal power versus noise power where red color indicates the signal power and green color represents the noise power

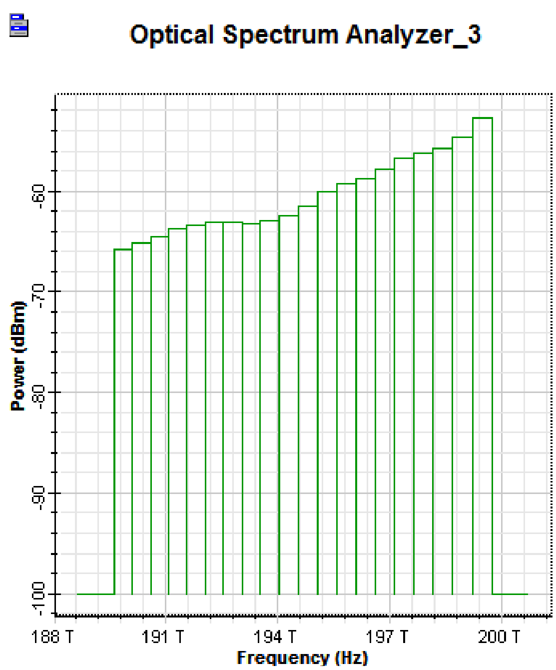


Figure 4.5.2.3: 64 channels output signal in OSA after entering to the optical link for Raman (at loop control), noise power

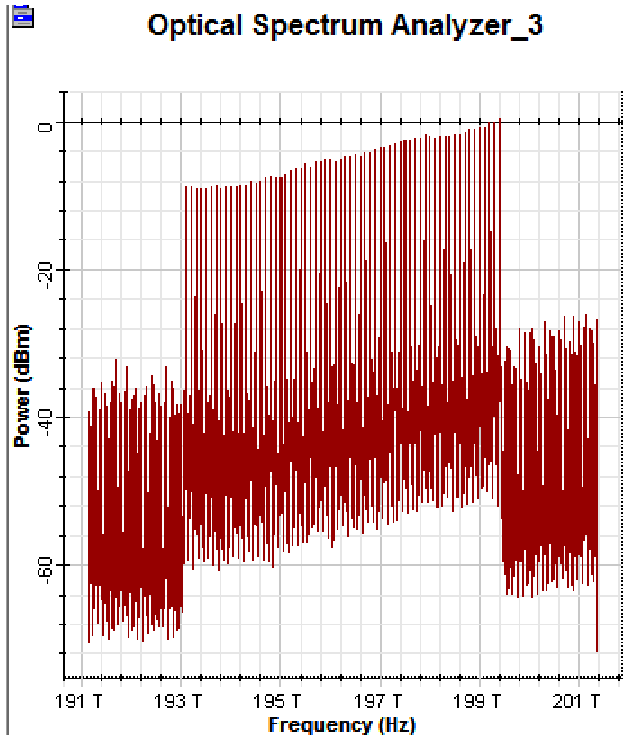


Figure 4.5.2.4: 64 channels output signal in OSA after entering to the optical link for Raman (at loop control), signal power with side lobes (FWM)

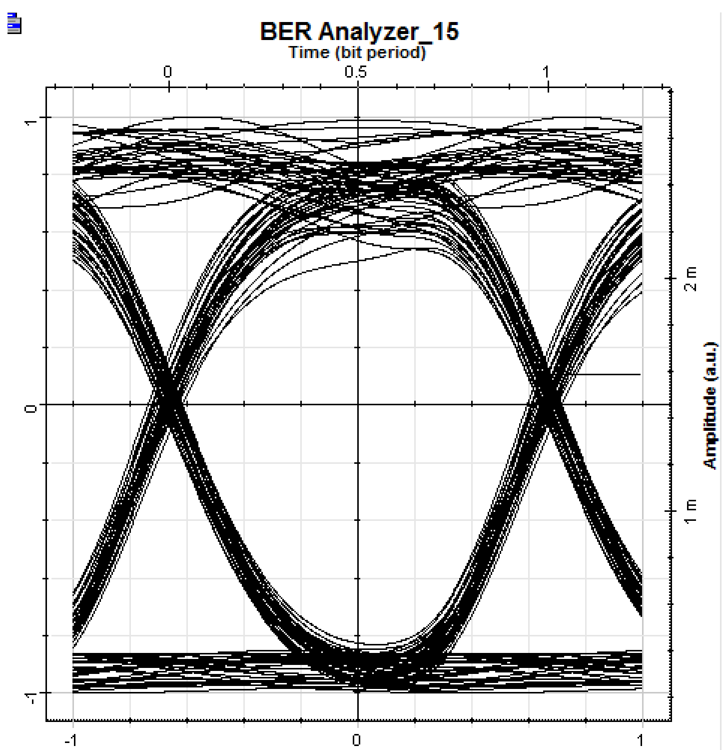


Figure 4.5.2.5: Output eye diagram from BER analyzer for Raman amplifier

4.5.3 Outputs for 64 channels DWDM system for OA amplifier

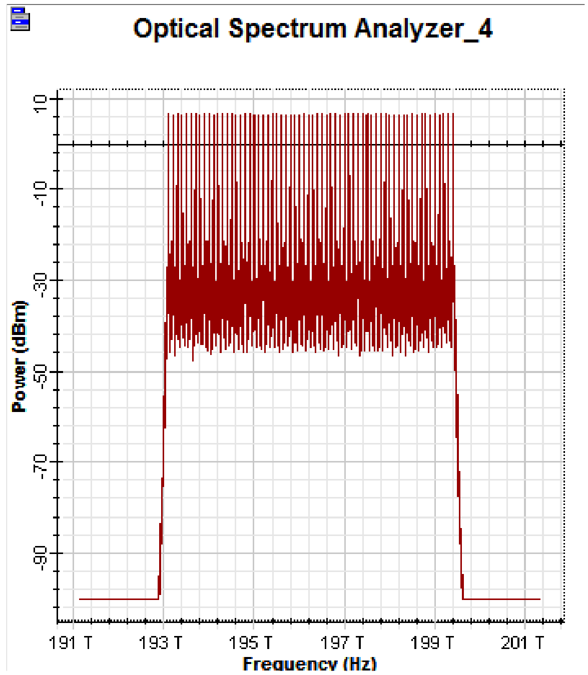


Figure 4.5.3.1: 64 channels input signal in OSA before entering to the optical link for OA amplifier

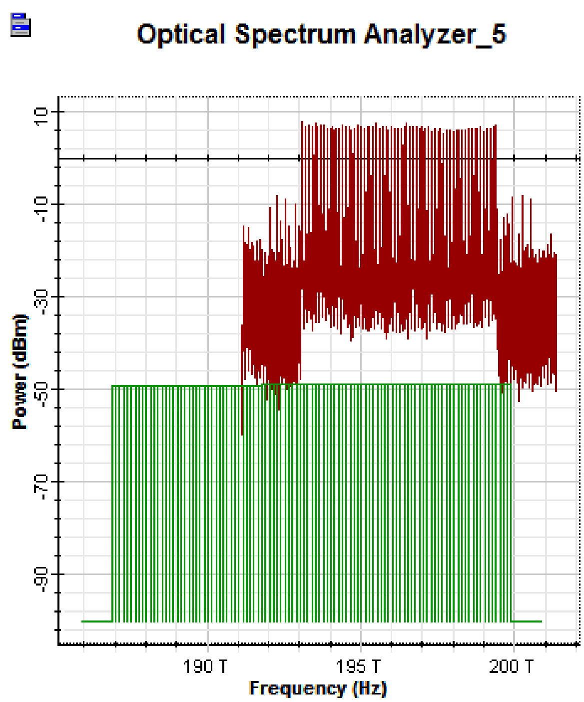


Figure 4.5.3.2: 64 channels output signal in OSA after entering to the optical link for OA amplifier (at loop control), signal power versus noise power where red color indicates the signal power and green color represents the noise power

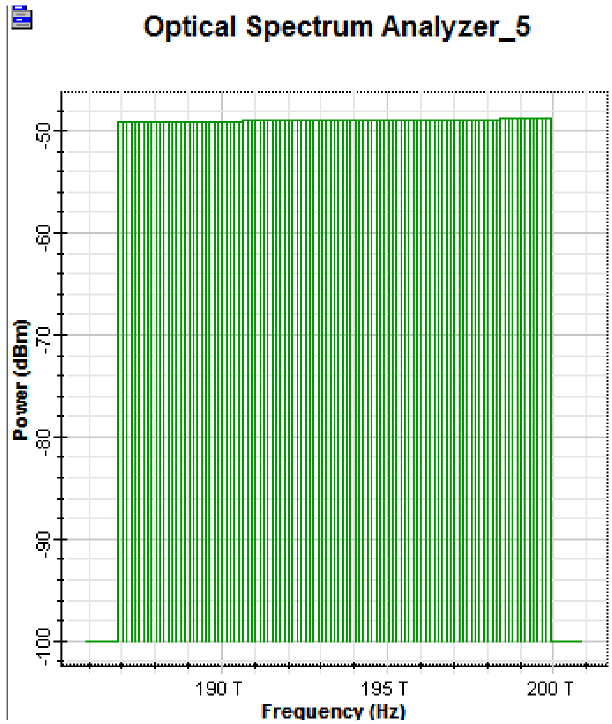


Figure 4.5.3.3: 64 channels output signal in OSA after entering to the optical link for OA amplifier (at loop control), noise power

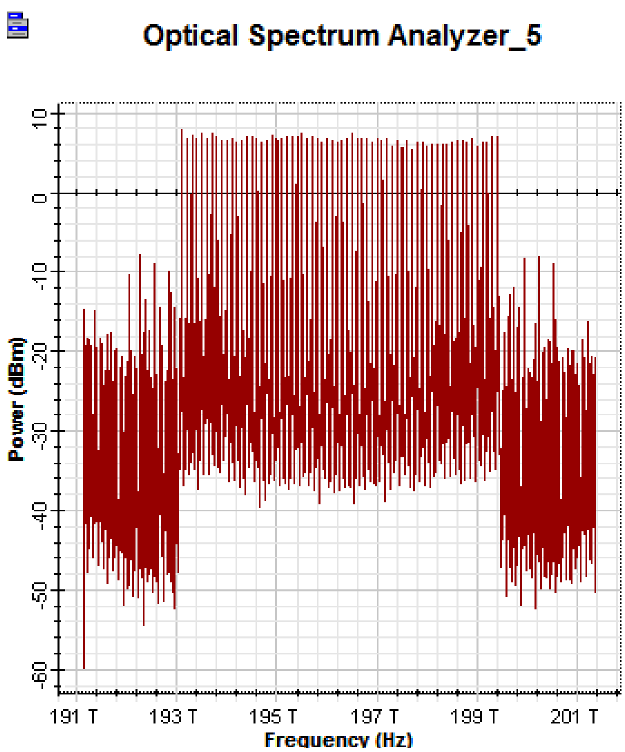


Figure 4.5.3.4: 64 channels output signal in OSA after entering to the optical link for OA amplifier (at loop control), signal power with side lobes (FWM)

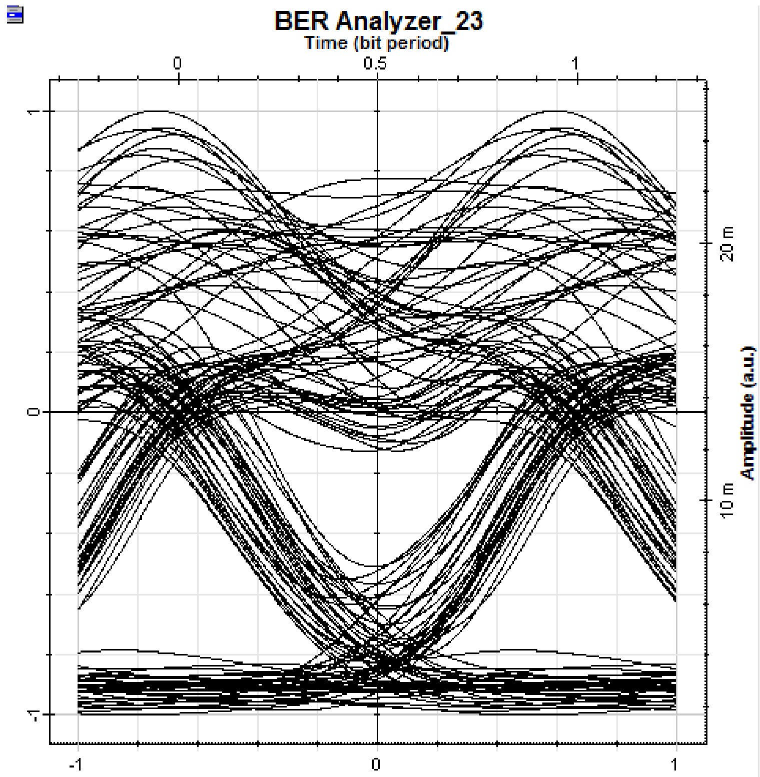


Figure 4.5.3.5: Output eye diagram from BER analyzer for OA amplifier

4.6 Outputs for 128 channels DWDM system

4.6.1 Outputs for 128 channels DWDM system for EDFA amplifier

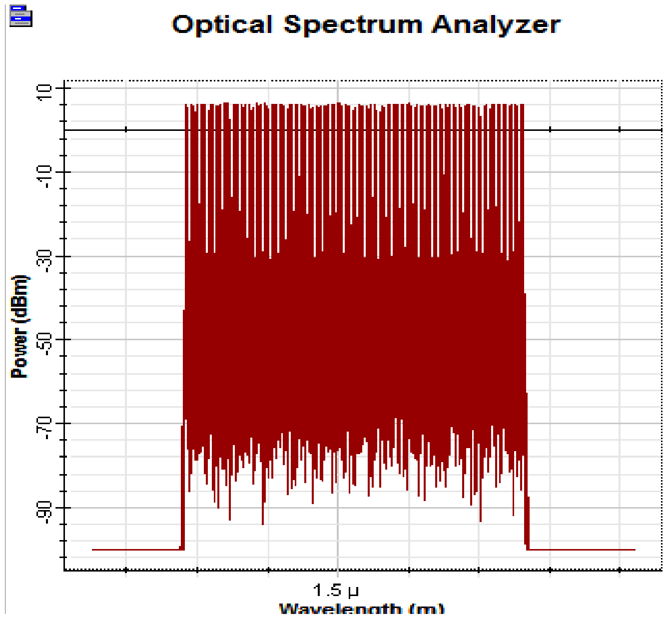


Figure 4.6.1.1: 128 channels input signal in OSA before entering to the optical link for EDFA

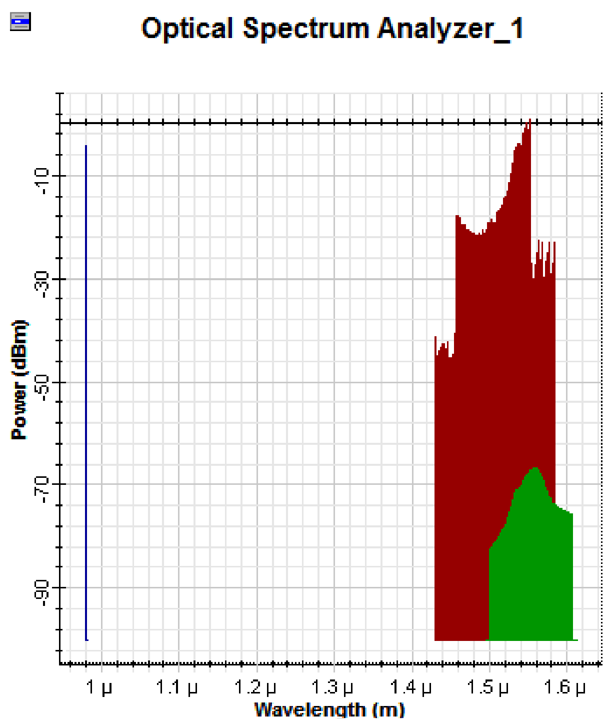


Figure 4.6.1.2: 128 channels output signal in OSA after entering to the optical link for EDFA (at loop control), signal power versus noise power where red color indicates the signal power and green color represents the noise power

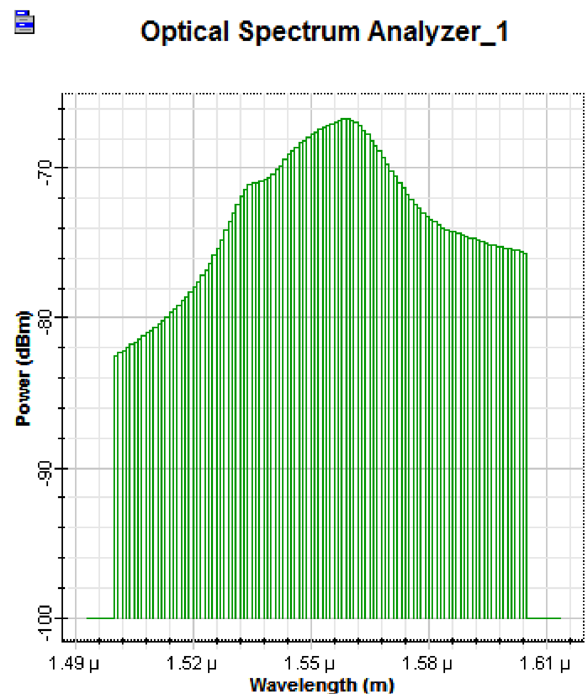


Figure 4.6.1.3: 128 channels output signal in OSA after entering to the optical link for EDFA (at loop control), noise power

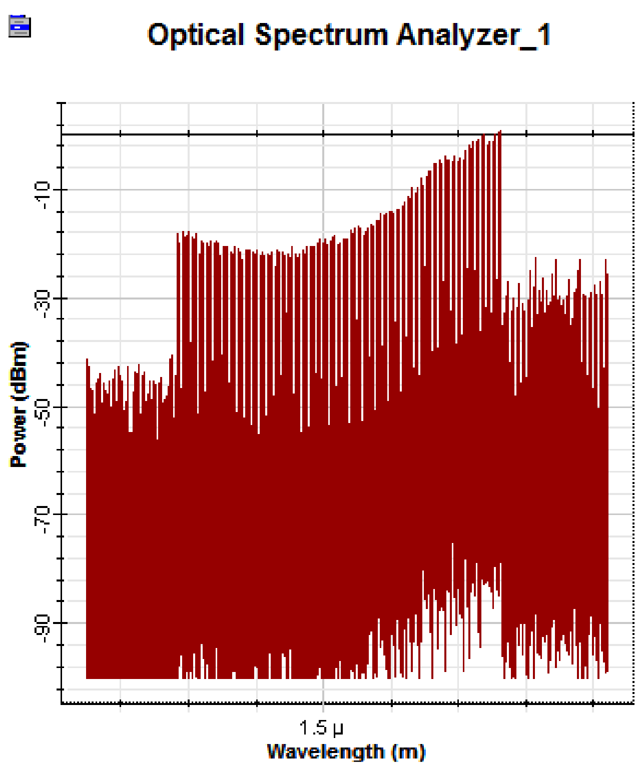


Figure 4.6.1.4: 128 channels output signal in OSA after entering to the optical link for EDFA (at loop control), signal power with side lobes (FWM)

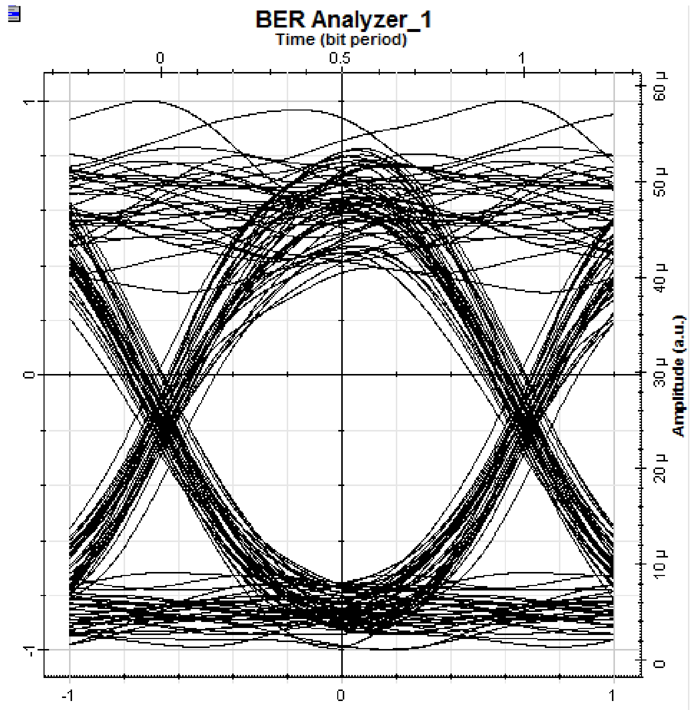


Figure 4.6.1.5: Output eye diagram from BER analyzer EDFA amplifier

4.6.2 Outputs for 128 channels DWDM system for Raman amplifier

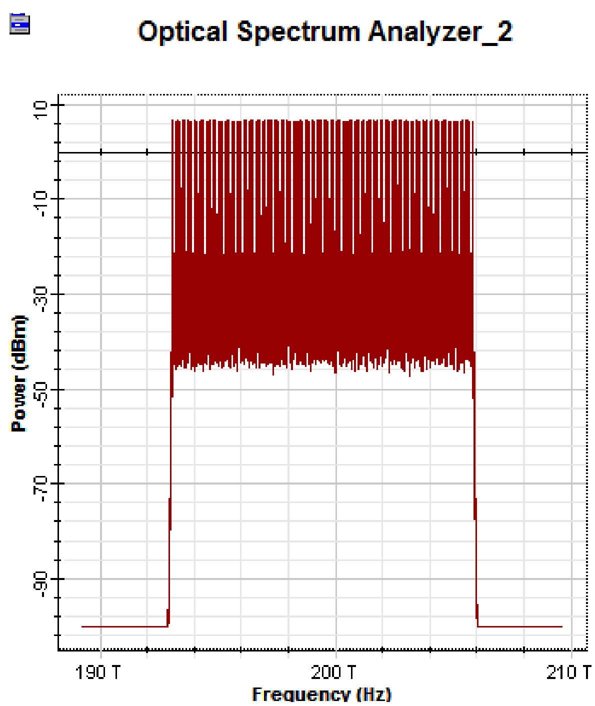


Figure 4.6.2.1: 128 channels input signal in OSA before entering to the optical link for Raman amplifier

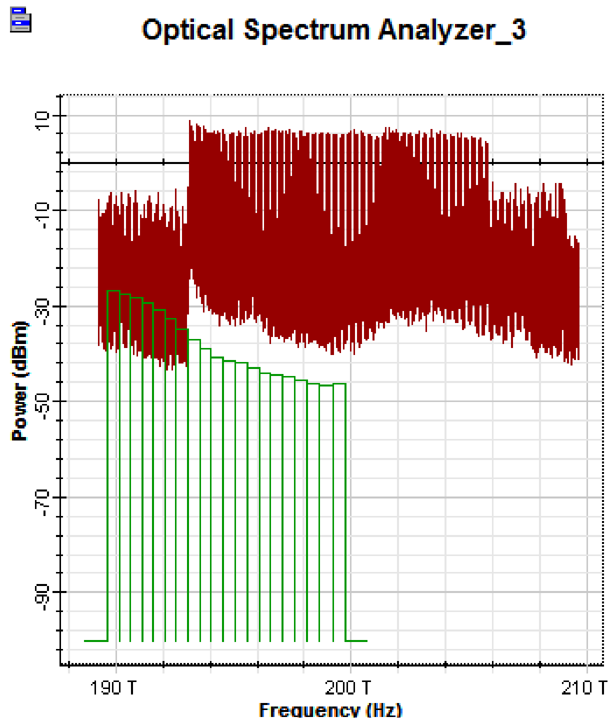


Figure 4.6.2.2: 128 channels output signal in OSA after entering to the optical link for Raman (at loop control), signal power versus noise power where red color indicates the signal power and green color represents the noise power

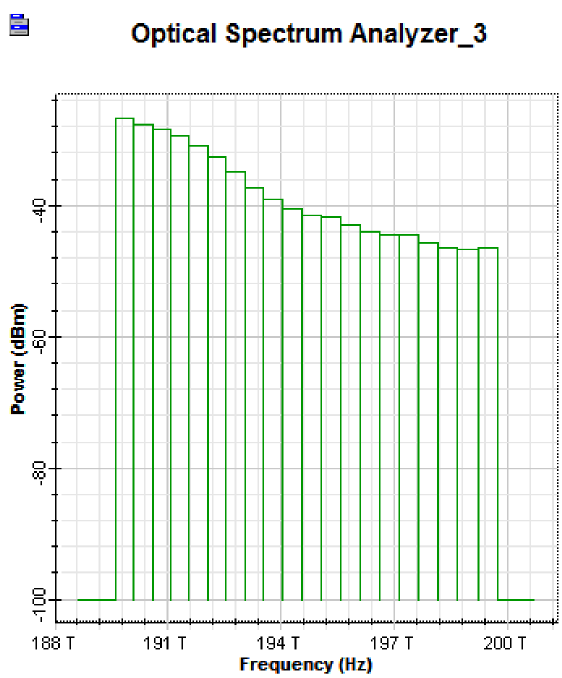


Figure 4.6.2.3: 128 channels output signal in OSA after entering to the optical link for Raman (at loop control), noise power

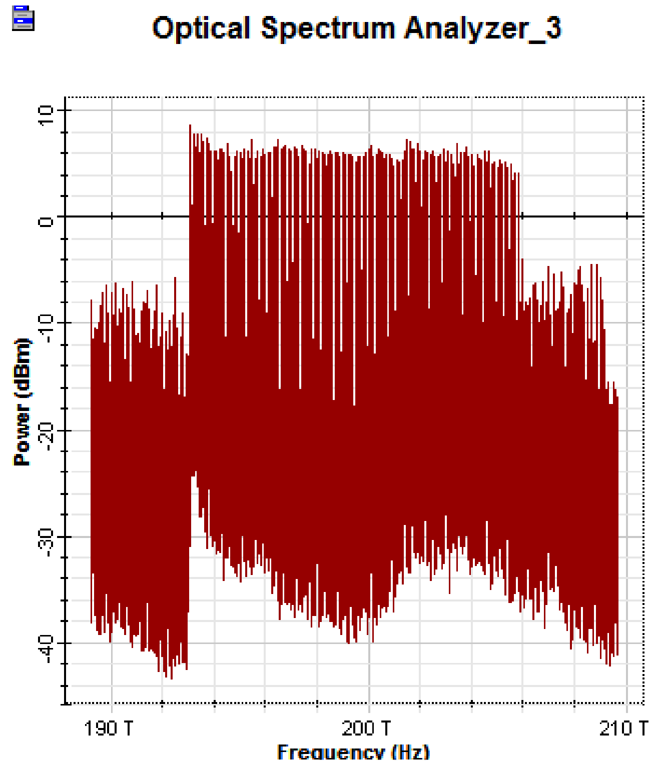


Figure 4.6.2.4: 128 channels output signal in OSA after entering to the optical link for Raman (at loop control), signal power with side lobes (FWM)

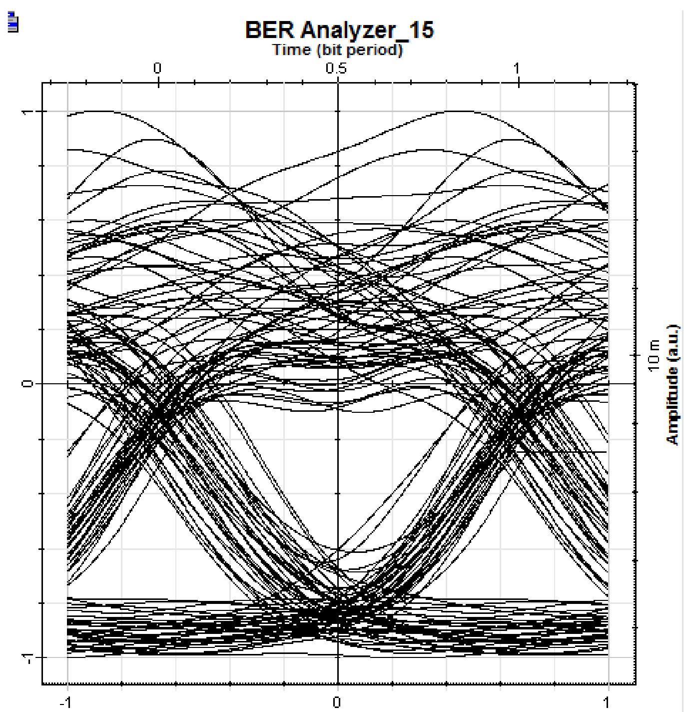


Figure 4.6.2.5: Output eye diagram from BER analyzer for Raman amplifier

4.6.3 Outputs of 128 channels DWDM system for OA amplifier

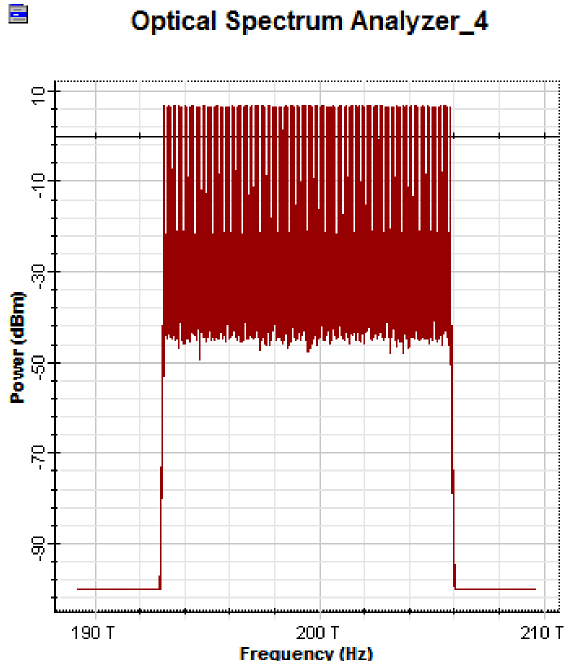


Figure 4.6.3.1: 128 channels input signal in OSA before entering to the optical link for OA amplifier

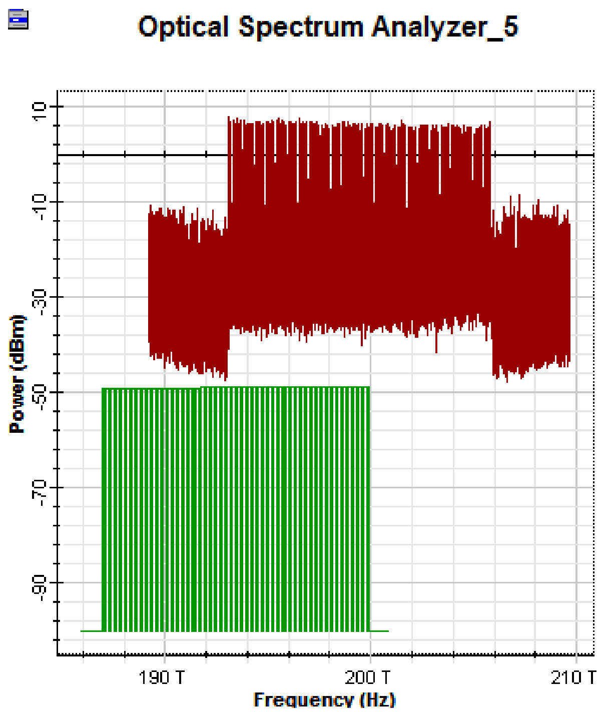


Figure 4.6.3.2: 128 channels output signal in OSA after entering to the optical link for OA amplifier (at loop control), signal power versus noise power where red color indicates the signal power and green color represents the noise power

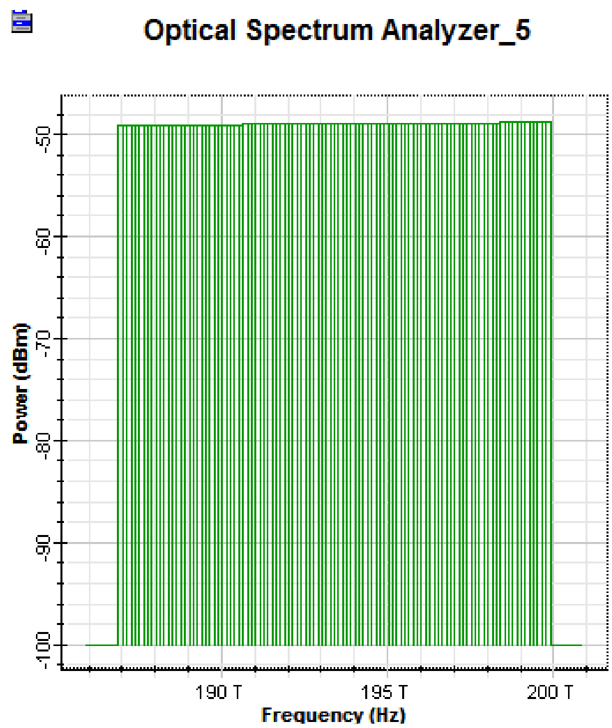


Figure 4.6.3.3: 128 channels output signal in OSA after entering to the optical link for OA amplifier (at loop control), noise power

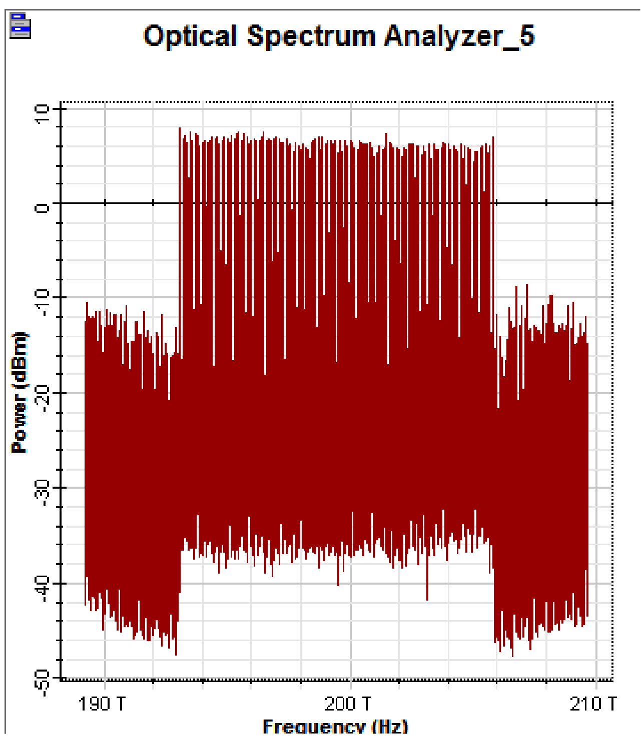


Figure 4.6.3.4: 128 channels output signal in OSA after entering to the optical link for OA amplifier (at loop control), signal power with side lobes (FWM)

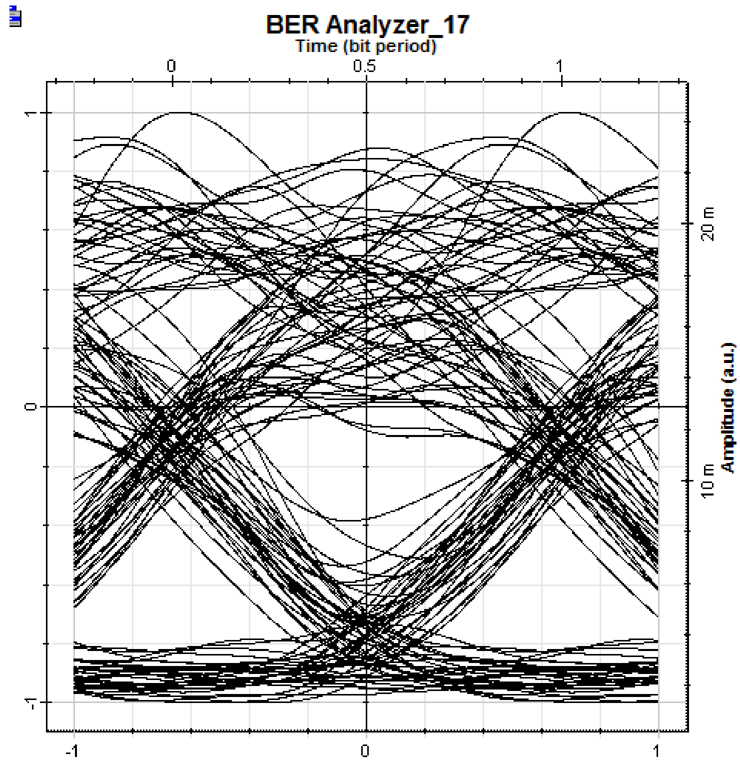


Figure 4.6.3.5: Output eye diagram from BER analyzer for OA amplifier

4.7 Combined outputs graphs for 32 channels DWDM system

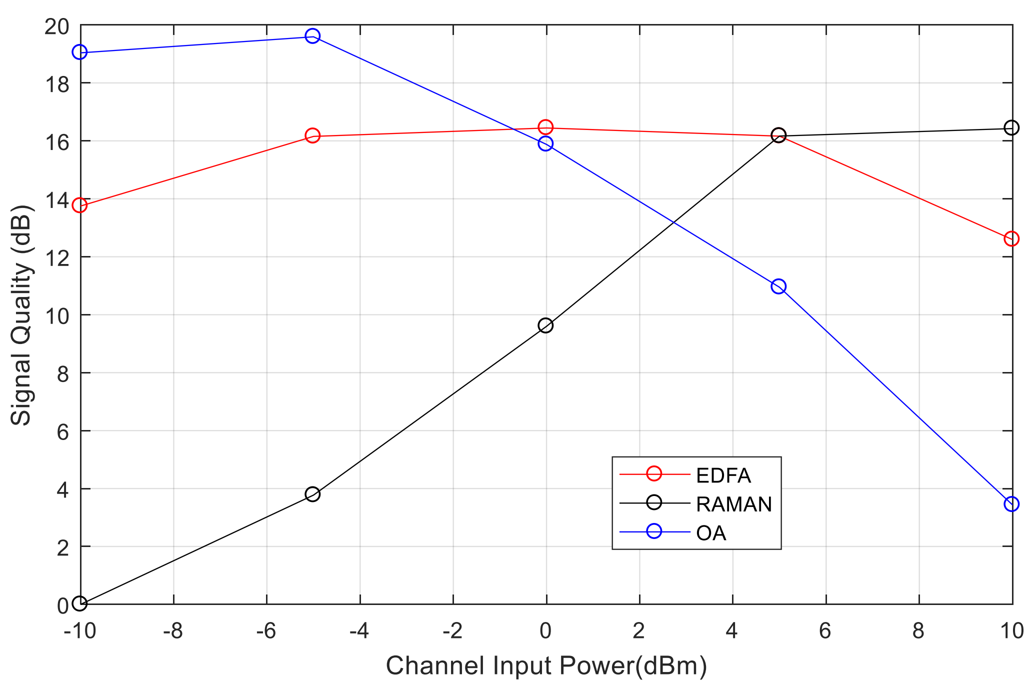


Figure 4.7.1: Channel Input Power (dBm) versus Signal Quality (dB) for 32 channels DWDM system

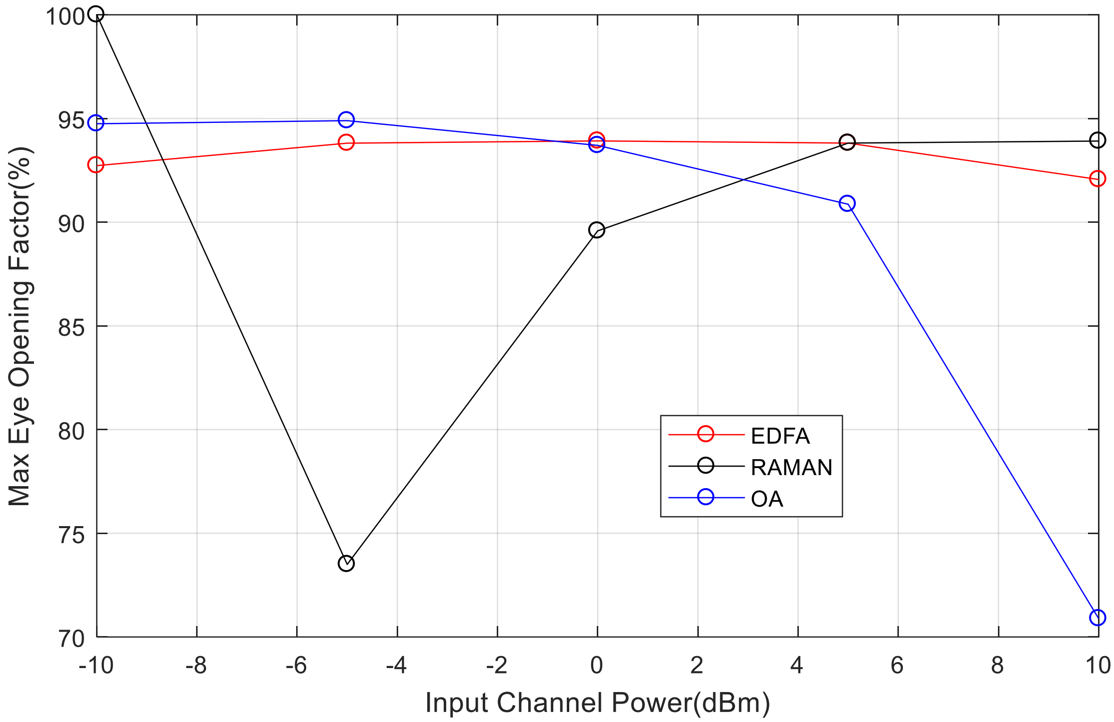


Figure 4.7.2: Input Channel Power (dBm) versus Max. eye Opening Factor (%) for 32 channels DWDM system

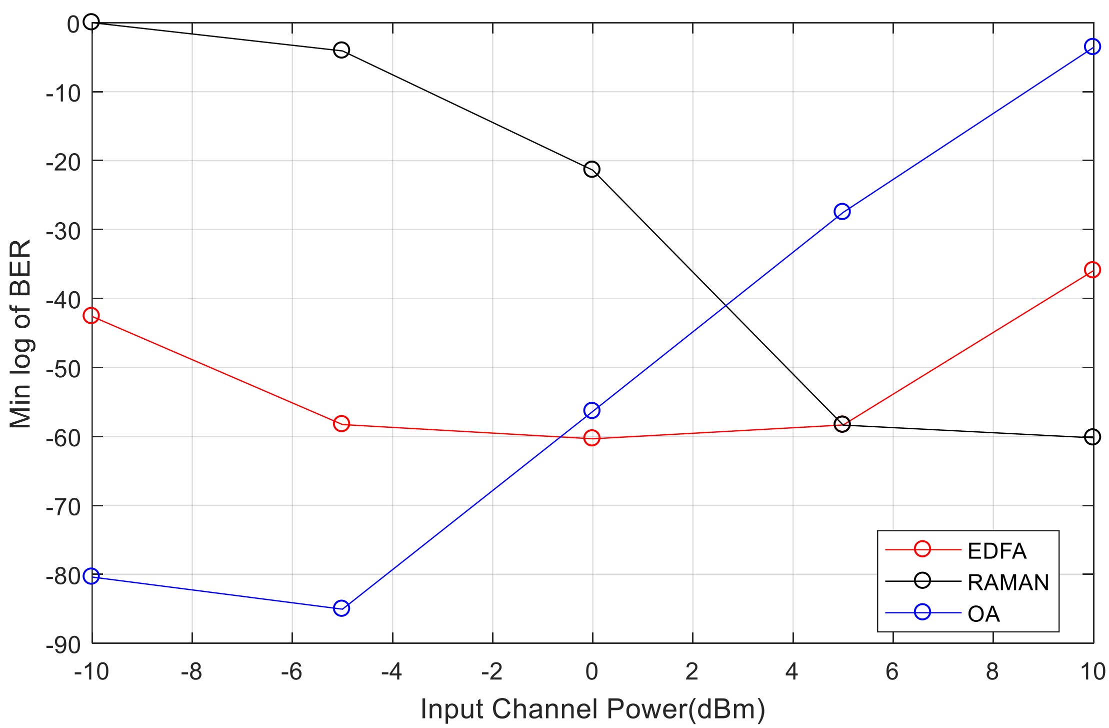


Figure 4.7.3: Input Channel Power (dBm) versus Min log of BER for 32 channels DWDM system

4.8 Combined outputs graphs for 64 channels DWDM system

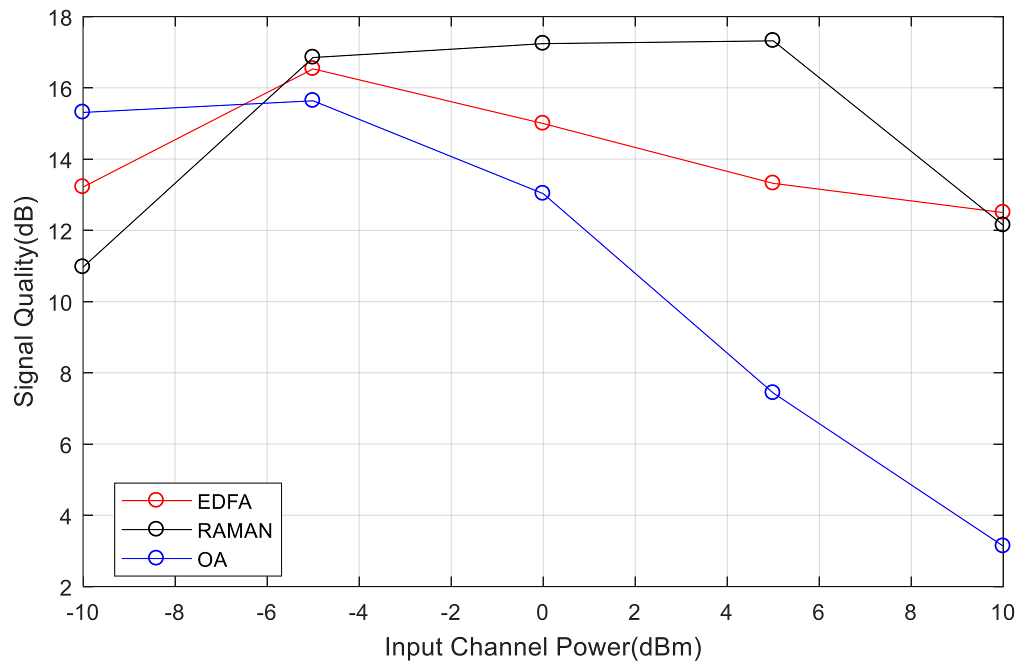


Figure 4.8.1: Input Channel Power (dBm) versus Signal Quality (dB) for 64 channels DWDM system

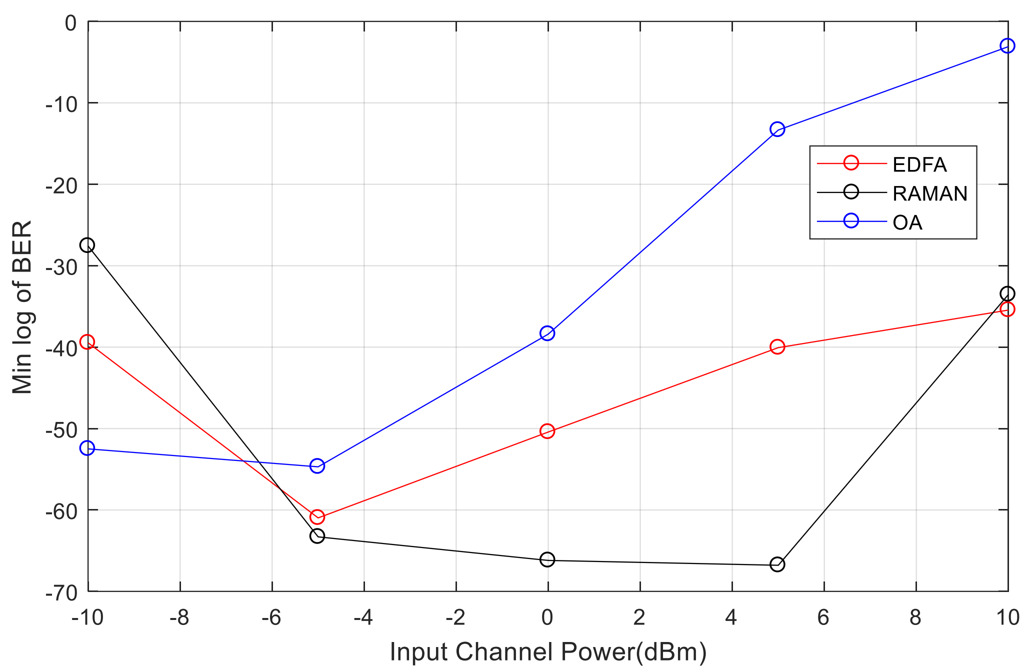


Figure 4.8.2: Input Channel Power (dBm) versus Min log of BER for 64 channels DWDM system

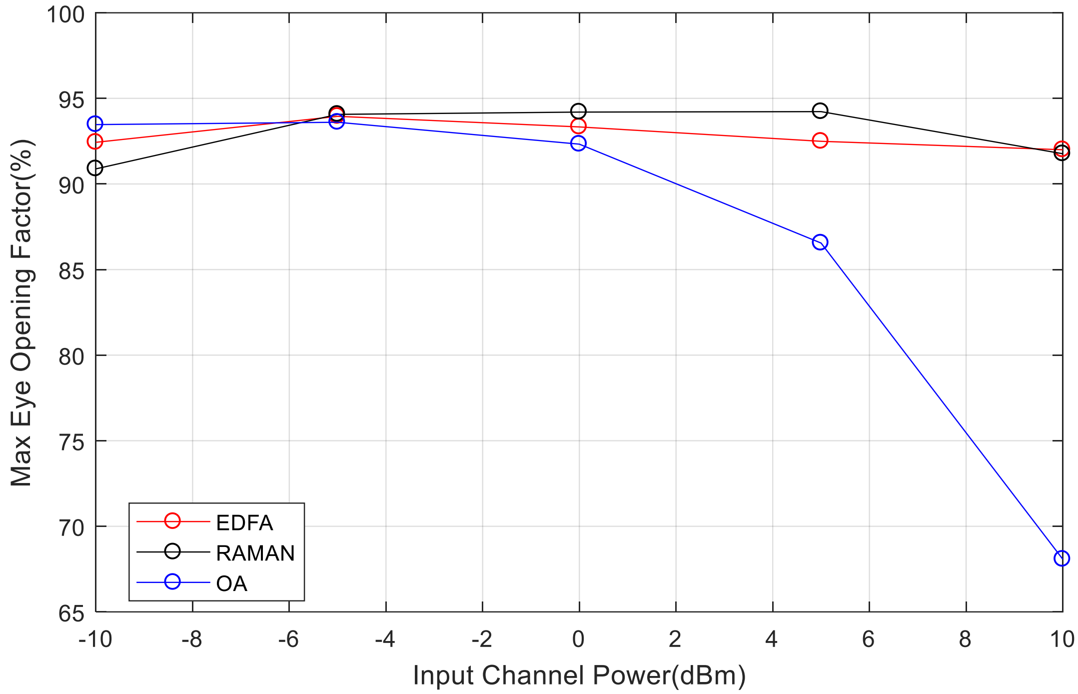


Figure 4.8.3: Input Channel Power (dBm) versus Max. eye Opening Factor (%) for 64 channels DWDM system

4.9 Combined outputs graphs for 128 channels DWDM system

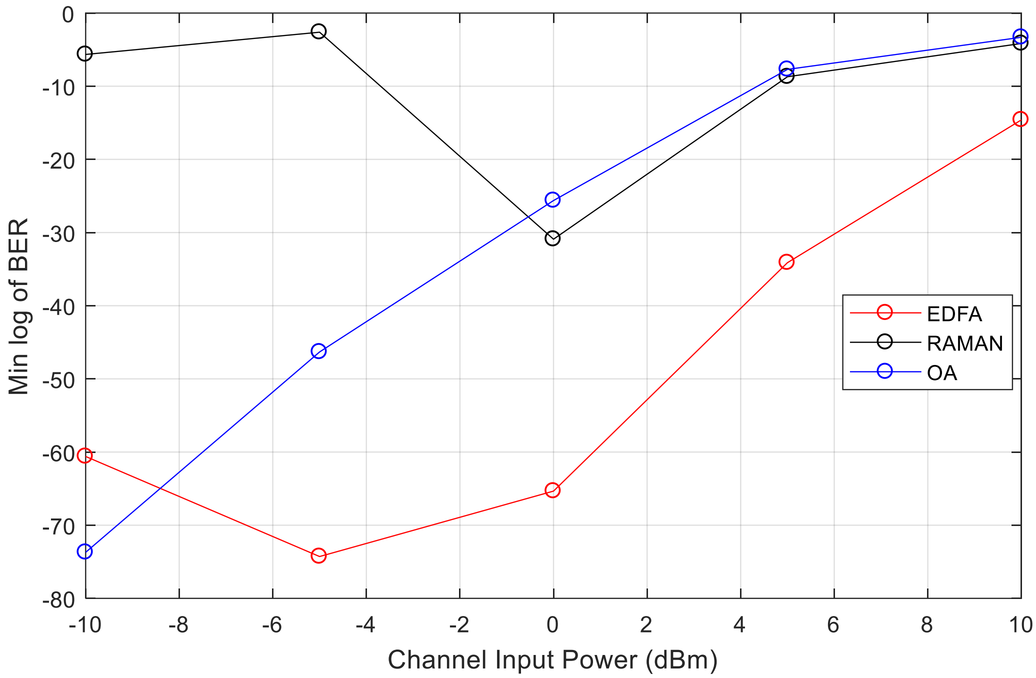


Figure 4.9.1: Channel Input Power (dBm) versus Min log of BER for 128 channels DWDM system

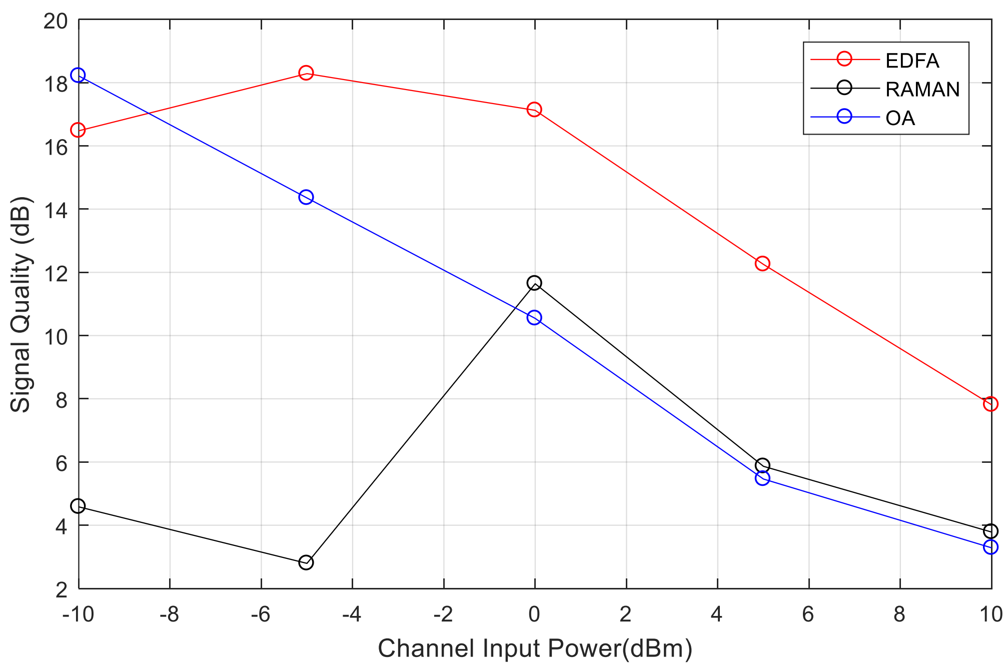


Figure 4.9.2: Channel Input Power (dBm) versus Signal Quality (dB) for 128 channels DWDM system

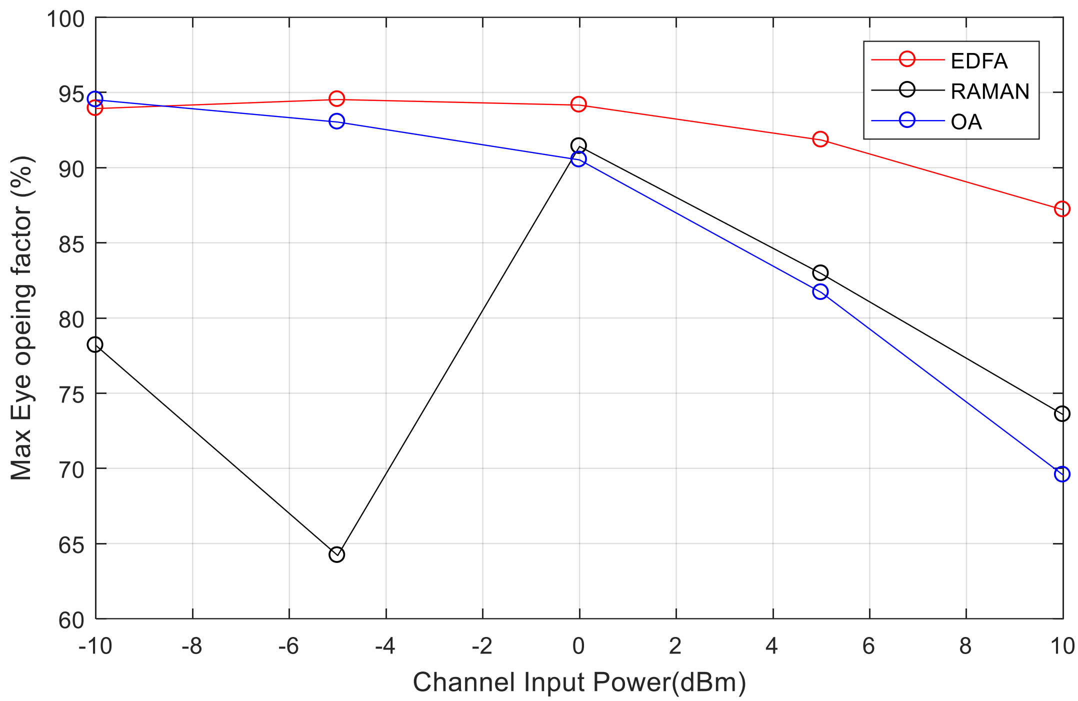


Figure 4.9.3: Channel Input Power (dBm) versus Max. eye Opening Factor (%) for 128 channels DWDM system

4.10 Comparison among all combinations of the simulation designs (EDFA, Raman and OA amplifiers for 32, 64 and 128 channels)

TABLE 4.10.1: COMPARISON TABLE FOR ALL COMBINATIONS OF THE SIMULATION DESIGNS (EDFA, RAMAN AND OA AMPLIFIERS FOR 32, 64 AND 128 CHANNELS)

Number of Channels	Amplifier Type	Maximum Q factor (Signal Quality) (dB)	Minimum log of BER	Maximum Eye Opening Factor (%)
32	EDFA	16.1	-60	94
	Raman	16.2	-59.9	99.8
	OA	19.7	-85	94.9
64	EDFA	16.8	-59.8	94
	Raman	17.5	-68	94.3
	OA	15.8	-54	93
128	EDFA	18.2	-74.3	94.8
	Raman	11.9	-30	91
	OA	18.1	-74	94.6

Table 4.10.1 shows the comparison table for all combinations of simulation designs. Here, it is evident that in case of 32 channels configurations OA amplifier performs best as it provides the maximum Q factor which is 19.7 dB with minimum log of BER of -85. On the other hand, for 64 channels configurations, it is clear that Raman amplifier provides the maximum Q factor of 17.5 dB and also gives minimum log of BER of -68. Moreover, for 128 channels configurations EDFA amplifier shows improved maximum Q factor than

Raman amplifier and OA amplifier where EDFA amplifier gives the maximum Q factor of 18.2 dB and minimum log of BER of -74.3.

4.11 Validation and final comparison among related previous works

TABLE 4.11.1: COMPARISON TABLE OF CURRENT INVESTIGATION WITH RELATED PREVIOUS WORKS

Factors	**Ref[3]**	**Ref[4]**	**Ref[5]**	**Ref[6]**	**Ref[7]**	**Current Investigation**
Multiplexing Type	WDM	WDM	WDM	WDM	DWDM	DWDM
Modulation Format	NRZ	NRZ	NRZ	NRZ	NRZ	NRZ
Data Rate Per Channel (Gbps)	10	10	10	42.7	2.5	10
Channel Spacing	50 GHz	100 GHz	20 GHz	100 GHz	25 GHz	100 GHz
Number of Channels	8	16	32, 64	54	160	32, 64, 128
Amplifier Type	EDFA, Raman	EDFA, Raman	EDFA, Raman	EDFA, Raman	EDFA, Raman	EDFA, Raman, OA
Maximum Q factor (Signal Quality) (dB)	E=22(8), R=26(8)	E=18.8(16) R=15.2(16)	E=12(64) R=11.8(32)	E=15.4(54) R=11.5(54)	E=19.3(160) R=11.2(160)	E=18.2(128) R=17.5(64) O=19.7(32)
Channel Input Power (dBm)	----	----	10	-2, -4	-10	-10 to +10
Span length (km)	20-200	10-200	40-200	75	15	70
Dispersion (ps/nm/km)	2	16.75	2	20.65	2.15	16.75

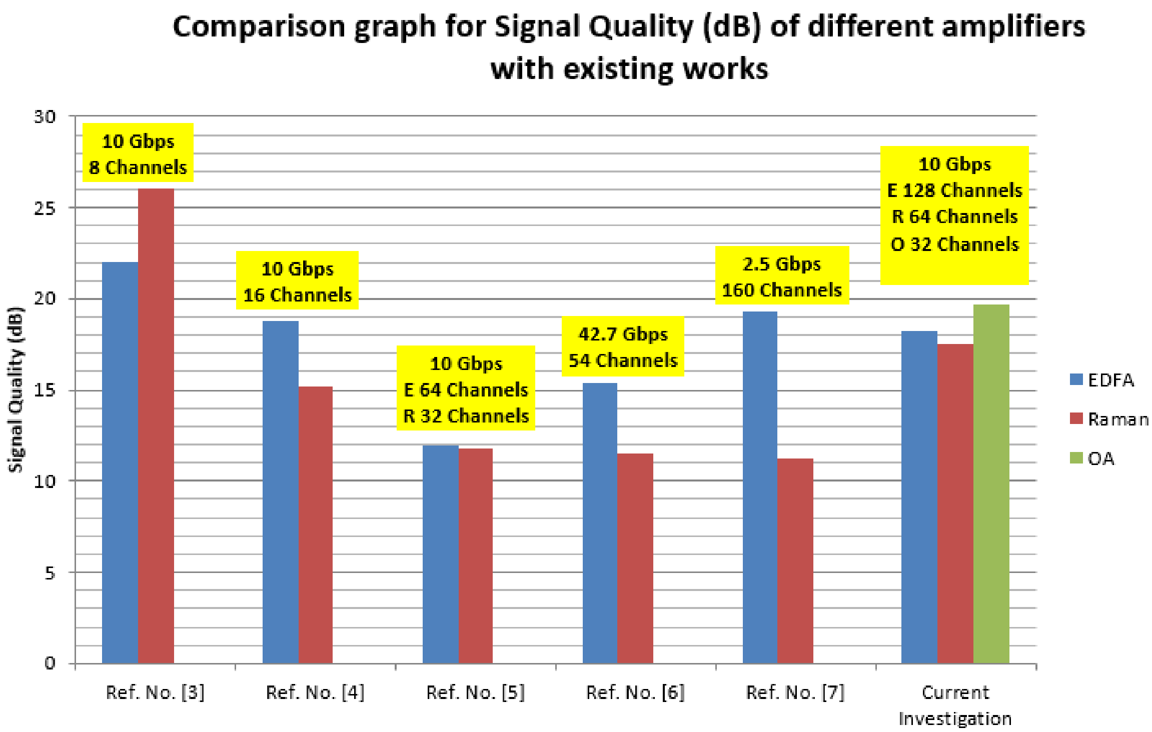


Figure 4.11.1: Comparison graph for Signal Quality (dB) of different amplifiers with existing works

Table 4.11.1 represents the comparison of current investigation with related previous works. It shows the validation of this work by comparing it with related previous works. Figure 4.11.1 shows the comparison graph for signal quality (dB) of different amplifiers with existing works. Although it is evident that other related works performed better either for lower number of channels or for lower data rates, but in current investigation this DWDM system performs better even for a very high capacity optical link having higher number of channels (128 channels for EDFA amplifier with a maximum signal quality of 18.2 dB) with a high data rate of 10 Gbps per channel. Same statement is also true for 64 channels Raman amplifier based DWDM system with 17.5 dB maximum signal quality with a high data rate of 10 Gbps per channel. In addition to that, this design also included OA amplifier based DWDM system with a high data rate of 10 Gbps per channel with the maximum signal quality of 19.7 dB for 32 channels which is not present in previous works.

CHAPTER 5

Conclusion

From the very beginning engineers and scientists concentrated on increasing the capacity of the optical communication network links as well as they are working relentlessly for supporting more and more users simultaneously over the existing optical network links.

In this thesis, design and performance analysis of 32, 64 and 128 channels DWDM system for three different amplifier configurations, which are EDFA, Raman and OA amplifiers, were conducted where each channel having 10 Gbps data rate multiplexed with frequency spacing of 100 GHz. In this work, Optisystem 16.0 commercial optical simulator is used to analyze the performance of 32, 64 and 128 channels DWDM system for EDFA, Raman and OA amplifier configurations. Dispersion compensation fiber is used to reimburse for the dispersion formed by single mode fiber. Between amplifier spans standard single-mode fiber is used, but at each amplifier position, dispersion compensating fiber having a negative chromatic dispersion is presented. By using this we have effectively designed a DWDM system with 32/64/128 channels each having 10 Gbps data rate multiplexed with frequency spacing of 100 GHz. From simulation results, it is evident that in case of 32 channels configurations OA amplifier performs best as it provides the maximum Q factor which is 19.7 dB with minimum log of BER of -85. On the other hand, for 64 channels configurations it is clear that Raman amplifier provides the maximum Q factor of 17.5 dB and also gives minimum log of BER of -68. Moreover, for 128 channels configurations EDFA amplifier shows improved maximum Q factor than Raman amplifier and OA amplifier where EDFA amplifier gives the maximum Q factor of 18.2 dB and minimum log of BER is -74.3. This work can further be stretched to more number of channels i.e. 256 channels or more with different frequency spacing.

References

[1] Abdul Gafur, M.S. Islam, Syed Zahidur Rashid, “Comparison of Coherent Optical Transmission Systems Performance by DP-QAM Levels,” *International Journal of Electrical and Computer Engineering (IJECE)*, Vol. 10, No. 3, November 2019.

[2] Abdul Gafur, M.S. Islam and Syed Zahidur Rashid, “Quality Optimization Based Trend Line for Hybrid Optical Amplifier Configurations in DWDM Transmission Systems,” *International Journal of Microwave and Optical Technology* Vol.14, no.5, September 2019.

[3] D. Malik, K. Pahwa, and A. Wason, “Performance optimization of SOA, EDFA, Raman and hybrid optical amplifiers in WDM Network with reduced channel spacing of 50 GHz,” *Optik*, vol. 127, no. 23, pp. 11131–11137, 2016.

[4] K. Mohammed and B. Younis, “Comparative performance of optical amplifiers: Raman and EDFA,” *TELKOMNIKA (Telecommunication Computing Electronics and Control)*, vol. 18, no. 4, p. 1701, 2020.

[5] B. Chandru, J. Helina Rajini and S. TamilSelvi, “Performance analysis of downstream transmission of 10Gbps WDM PON using single and hybrid optical amplifiers,” *2014 IEEE International Conference on Advanced Communications, Control and Computing Technologies*, 2014.

[6] T. Matsuda, T. Kotanigawa, T. Kataoka and A. Naka, “54×42.7 Gbit⁄s L- and U-band WDM signal transmission experiments with in-line hybrid optical amplifiers,” *Electronics Letters*, vol. 40, no. 6, p. 380, 2004.

[7] Y. Malhotra, “Performance evaluation and comparison of hybrid and conventional optical amplifiers in DWDM system at narrow channel spacing using various modulation formats,” *Optik*, vol. 145, pp. 218-224, 2017.

[8] D. Malik, G. Kaushik and A. Wason, “Performance Evaluation of Optical Amplifiers for High-Speed Optical Networks,” *Journal of Optical Communications*, vol. 41, no. 1, pp. 15-21, 2018. Available: 10.1515/joc-2017-0133.

[9] Rashmi, Anurag Sharma, Vikrant Sharma, “Performance Evaluation of Different Hybrid Optical Amplifiers for 64×10, 96×10 and 128×10Gbps DWDM transmission system,” *International Journal of Computer Science and Information Technologies*, Vol. 5 , pp.7199-7203, December 2014.

[10] Deepak Malik, Kuldip Pahwa, Amit Wason, “Performance optimization of SOA, EDFA, Raman and hybrid optical amplifiers in WDM network with reduced channel spacing of 50 GHz,” *Optik-International Journal for light and Electron Optics* Vol. 127, no. 23, pp.11131–11137, December 2016.

[11] S.Z.M. Hasan, V. Kalavally, R. Parthiban, T. Win, M. Premaratne , “Economic and system impact of hybrid Raman–EDFA amplification in a 40 x 40 Gbps optical transmission network with DPSK modulation,” *Optical Fiber Technology*, Vol. 19, no. 1, pp.10-15, January 2013.

[12] Lukasz Krzczanowicz, Ian Phillips, Md. Asif Iqbal, Mingming Tan, Paul Harper, and Wladek Forysiak, “Hybrid Discrete Raman/EDFA Design for Broadband Optical Amplification in Metro WDM Systems,” *International Conference on Transparent Optical Networks*, July 2017.

[13] João Pedro and Nelson Costa, “Optimized Hybrid Raman/EDFA Amplifier Placement for DWDM Mesh Networks,” *Journal of Light wave Technology*, Vol. 36, no. 9, May 2018.

[14] Seung Kwan Kim, Sun Hyok Chang, Jin Soo Han, and Moo Jung Chu, “Design of Hybrid Optical Amplifiers for High Capacity Optical Transmission,” *ETRI Journal*, Vol. 24, no. 2, April 2002.

[15] N. Md. Yusoff, A. H. Sulaiman, Sumiaty Ambran, Azura Hamzah, M. A. Mahdi, “Performance Improvement for Hybrid L-band Remote Erbium Doped Fiber Amplifier/Raman using Phase Modulator,” *International Journal of Electrical and Computer Engineering*, Vol. 8, no. 1, February 2018.

[16] Ramandeep Kaur, Rajneesh Randhawa, R.S. Kaler, “Performance evaluation of optical amplifier for 16 ×10, 32 ×10 and 64 × 10 Gbps WDM system,” *Optik- International Journal for light and Electron Optics*, Vol.124, pp.693– 700, April 2013.

[17] Vjaceslavs Bobrovs, Sergejs Olonkins, Sandis Spolitis, Jurgis Porins and Girts Ivanovs, “Evaluation of Parametric and Hybrid Amplifier Applications in WDM Transmission Systems,” *Optical Fiber and Wireless Communications*, Intechopen, Chapter 10, June 2017.

[18] Yugnanda Malhotra, R.S. Kaler, Enakshi Khular Sharma, “Performance of Hybrid Optical Amplifier and Conventional Optical Amplifier in the Scenario of Long Haul Ultra-Dense Wavelength Division Multiplexed System,” *Proceedings of the World Congress on Engineering*, Vol. I, July 2015.

[19] H. Bhagwan, T. Gulati and B. Rawat, “Evaluation of Optical Amplifiers,” *International Journal of Engineering Research and Applications (IJERA)*, vol, 2, no. 1, pp. 663-667, 2012.

[20] S. Kumar, I. Bala, and A. Singhal, “Optical Fiber Communication System Performance Using MZI Switching,” *International Journal of Soft Computing & Engineering (IJSCE)*, vol. 2, no. 3, pp. 98-107, 2012.

[21] S. Olonkins, et. al, “Comparison of Semiconductor Optical Amplifier and Discrete Raman Amplifier Performance in DWDM Systems,” *Electronics and Electrical Engineering*, vol. 7, no. 123, pp. 133-136, 2012.

[22] V. Bobrovs, et. al, “Comparative performance of Raman-SOA and Raman- EDFA hybrid optical amplifiers in DWDM transmission systems,” *Indian Journal of Pharmaceutical Sciences*, vol. 8, no. 39, pp. 1898-1906, 2013.

[23] P. Jain, B. Koushal, and S. Jain, “Performance analysis of different Hybrid optical amplifier due to varying Transmission distance at 10 Gbps,” *International Journal of Emerging Technologies in Computational and Applied Sciences*, pp. 246-250, 2013.

[24] S. Bhaskar, M.and R. Kaur, “Performance Comparison of different hybrid amplifiers for different numbers of channels,” *International Journal of Advanced Computer Science and Applications*, pp. 19-25, 2011.

[25] Dipika D. Pradhan and Abhilash Mandloi, “Performance Analysis of Flat Gain Wideband Raman Amplifier for S+C and C+L Band DWDM System,” *Hindawi Advances in OptoElectronics*, vol. 2018, pp. 1-7, 2018.

[26] H. Chung, J. Han, S. Chang and K. Kim, “A Raman plus linear optical amplifier as an inline amplifier in a long-haul transmission of 16 channels×10 Gbit/s over single-mode fiber of 1040 km,” *Optics Communications*, vol. 244, no. 1-6, pp. 141-145, 2005.

[27] S. Singh and R. Kaur, “32 x 10 and 64 × 10 Gb/s transmission using hybrid Raman-Erbium doped optical amplifiers,” *International Journal of Advanced Computer Science and Applications*, vol. 1, no. 2, 2011.

[28] Ramandeep Kaur, Rajneesh Randhawa, R.S. Kaler, “Performance evaluation of optical amplifier for 16 ×10, 32 ×10 and 64 × 10 Gbps WDM system,” *Optik- International Journal for light and Electron Optics*, Vol.124, pp.693– 700, April 2013.

[29] T. Matsuda, T. Kotanigawa, A. Naka and T. Imai, “62×42.7 Gbit⁄s (2.5 Tbit⁄s) WDM signal transmission over 2200 km with broadband distributed Raman amplification,” *Electronics Letters*, vol. 38, no. 15, p. 818, 2002.

[30] B. Zhu, L. Leng, L. E. Nelson, L. Gruner-Nielsen, Y. Qian, J. Bromage, S. Stulz, S. Kado, Y. Emori, S. Namiki, P. Gaarde, A. Judy, B. Palsdottir, and R. L. Lingle, “3.2Tb/s (80 × 42.7Gb/s) transmission over 20 × 100km of non-zero dispersion fiber with simultaneous C + L-band dispersion compensation,” in *Optical Fiber Communications Conference*, A. Sawchuk, ed., Vol. 70 of OSA Trends in Optics and Photonics (Optical Society of America, 2002), paper FC8.

[31] J. -. Cai, M. Nissov, C. R. Davidson, Y. Cai, A. N. Pilipctskii, H. Li, M. A. Mills, R. -. Mu, U. Feiste, L. Xu, A. J. Lucero, D. G. Foursa, and N. S. Bergano, “Transmission of Thirty-Eight 40 Gb/s Channels (>1.5 Tb/s) Over Transoceanic Distance,” in *Optical Fiber Communications Conference*, A. Sawchuk, ed., Vol. 70 of OSA Trends in Optics and Photonics (Optical Society of America, 2002), paper FC4.

[32] Masuda, H., Kawai, S., Suzuki, K., and Aida, K.: “1.65-mm band fiber Raman amplifier pumped by wavelength-tunable broad-linewidth light source,” *ECOC*’98, Madrid, Spain, 1998, PD, pp. 139–141

[33] Kotanigawa, T., Matsuda, T., and Kataoka, T.: “Applicable wavelength range of U-band signals in in-line amplifier WDM systems,” *Electron. Lett.*, 2003, 39, (13), pp. 999–1000

[34] A. Yina, Zhanga, “Analysis of modulation format in the 40 Gbit/s optical communication systems,” *Optik* 121 (2010) 1550-1557.

[35] S.H. Chang, J.S. Han, H.S. Chung, K. Kim, “Transmission Performance Comparison of Hybrid Optical Amplifiers,” *5th International Conference on Optical Internet*, Jeju- Korea, 2006, pp 274-276.

[36] H. Seo, W. Chung and J. Ahn, “A novel hybrid silica wide-band amplifier covering S+C+L bands with 105-nm bandwidth,” *IEEE Photonics Technology Letters*, vol. 17, no. 9, pp. 1830-1832, 2005.

[37] T. Matsuda, A. Naka, S. Saito, “Comparison between NRZ and RZ Signal Formats for In-Line Amplifier Transmission in the Zero-Dispersion Regime,” *IEEE Lightwave Technology* 16(3) (1998) 340-348.

[38] M. I. Hayee and A. E. Willner, “NRZ vs. RZ in 10-40 Gbit/s dispersion-managed WDM transmission systems,” in *Optical Fiber Communication Conference*, Vol. 2 of 1998 OSA Technical Digest Series (Optical Society of America, 1998), paper FE2.

[39] G. Bosco, A. Carena, V. Curri, R. Gaudino, and P. Poggiolini, “On the Use of NRZ, RZ, and CSRZ Modulation at 40 Gb/s With Narrow DWDM Channel Spacing,” *J. Lightwave Technol.* 20, 1694-1704 (2002).

[40] Afkhami, H., Mowla, A., Granpayeh, N. and Hormozi, A., “Wideband Gain Flattened Hybrid Erbium-doped Fiber Amplifier/Fiber Raman Amplifier,” *Journal of the Optical Society of Korea*, 14(4), pp.342-350, 2010.

[41] G. P. Agrawal, *Fiber Optic Communication Systems*, Wiley-Interscience, 1997.

[42] R. Ramaswami and K. N. Sivarajan, *Optical Networks: A practical Perspective*, Morgan Kaufmann, 1998.

[43] Mohammed N. Islam, *Raman Amplifiers for Telecommunications 1: Physical Principles*, Springer, USA, 2004.

[44] Vijay Rao Kumbhare, “Raman Amplifier Characteristics with Variation of Signal Power and Pump Power with and Without Amplified Spontaneous Emission,” *IJCA Proceedings on International Conference on Recent Trends & Advancements in Engineering Technology*, no. 2, 2015.

[45] Song Hu, Hanyi Zhang, and Yili Guo, “Stiffness analysis in the numerical solution of Raman amplifier propagation equations,” *Opt. Express* 12, 1656-1664 (2004).

[46] Desurvire, *Erbium-doped fiber amplifiers: principles and applications*, Wiley-Interscience, 1994.

[47] Xueming Liu and Byoungho Lee, "A fast and stable method for Raman amplifier propagation equations," *Opt. Express* 11, 2163-2176 (2003).

[48] C. Headley and G. P. Agrawal, *Raman Amplification in Fiber Optical Communication Systems*, Elsevier Academic Press, USA, 2005.

[49] B. Min, W. J. Lee, and N. Park, “Efficient Formulation of Raman Amplifier Propagation Equations with Average Power Analysis,” *IEEE Photonics Technology Letters*, vol. 12, no. 11, pp. 148-1488, 2000.

[50] C. R. Giles and E. Desurvire, “Modeling erbium-doped fiber amplifiers,” *Journal of Light-wave Technology*, vol. 9, no. 2, pp. 271-283, 1991.

[51] G. Cerullo, S. De Silvestri and C. Manzoni, “Optical Parametric Amplifiers”, *Encyclopedia of Modern Optics*, pp. 290-301, 2018. Available: 10.1016/b978-0-12-803581-8.09632-6.

[52] R. Boyd, *Nonlinear Optics*. London: Academic Press, 2020.

[53] T. Ivaniga and P. Ivaniga, “Comparison of the Optical Amplifiers EDFA and SOA Based on the BER and Q-Factor in C-Band,” *Advances in Optical Technologies*, vol. 2017, pp. 1-9, 2017. Available: 10.1155/2017/9053582.

Turnitin Originality Report

Processed on: 27-Apr-2021 18:17 +06
ID: 1571310328
Word Count: 14463
Submitted: 1

123-25-265 By Syed Zahidur Rashid

Similarity Index	Similarity by Source	
22%	Internet Sources:	13%
	Publications:	14%
	Student Papers:	6%

3% match (publications)
Giulio Cerullo, Sandro De Silvestri, Cristian Manzoni. "Optical Parametric Amplifiers", Elsevier BV, 2018

3% match (student papers from 28-Mar-2018)
Class: Article 2018
Assignment: Journal Article
Paper ID: 937594737

2% match (Internet from 12-Jun-2017)
http://www.i-scholar.in/index.php/indjst/article/view/135879/124173

1% match (Internet from 18-Jun-2017)
http://www.i-scholar.in/index.php/indjst/article/download/135879/124173

1% match (Internet from 04-Nov-2019)
https://dru5cjyjifvrg.cloudfront.net/wp-content/uploads/2015/03/OptiSystem_Tutorials_Volume_2.pdf

1% match (publications)
Deepak Malik, Kuldip Pahwa, Amit Wason. "Performance optimization of SOA, EDFA, Raman and hybrid optical amplifiers in WDM network with reduced channel spacing of 50 GHz", Optik, 2016

1% match (student papers from 29-Oct-2019)
Submitted to Manchester Metropolitan University on 2019-10-29

1% match (publications)
Giulio Cerullo, Daniele Brida. "Chapter 2 Ultra-Broadband Optical Parametric Amplifiers", Springer Science and Business Media LLC, 2013

1% match (student papers from 21-Jun-2013)
Submitted to NCC Education on 2013-06-21

1% match ()
Alatawi, Khaled. "High Data Rate Coherent Optical OFDM System for Long-Haul Transmission", Digital Commons @ DU, 2013

1% match (publications)
Cheng, Guanxiao, Ping Xu, Chunquan Hong, Yang Cao, Feng Zhu, Shuyang Feng, Ruibin Lin, Wolfgang Osten, and Armando Albertazzi. "Temperature sensing by modulating phase of optical fiber", Optical Measurement Systems for Industrial Inspection VIII, 2013.

1% match ()
Tomáš Ivaniga, Petr Ivaniga. "Comparison of the Optical Amplifiers EDFA and SOA Based on the BER and Q-Factor in C-Band", Hindawi Limited, 2017

1% match (publications)
Simranjit Singh, R.S. Kaler. "Performance evaluation of 64 × 10 Gbps and 96 × 10 Gbps DWDM system with hybrid optical amplifier for different modulation formats", Optik, 2012