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Analyzing EDFA Performance using different Pumping Techniques

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Abstract: Wavelength Division Multiplexing (WDM) technology utilizes a multiplexer at the transmitter end and a demultiplexer at the receiver end to split the channels apart. Utilization of Erbium Doped Fiber Amplifier (EDFA) enables us to minimize various problems like insertion loss and dispersion. The EDFA-WDM System performance mainly depends on pumping technique used. We have analyzed various pumping techniques for a WDM system with pump powers from 40-120mW over different lengths of Erbium doped fiber (EDF). The designed system is analyzed in terms of Q-Factor and received power for a wavelength ranging 1530nm-1550nm with 0.5nm spacing. The results of pumping techniques are compared qualitatively to find the efficient performance of EDFA-WDM system.

Keywords: EDFA, WDM, Pump power, Fiber length

I. INTRODUCTION

Optical amplifiers amplify the signal in optical domain using stimulated emission and are used for compensating signal-splitting losses in long distance point-to-point and multi-access networks[1][2][3].The two main optical amplifier types can be classified as: Semiconductor Optical Amplifiers (SOA's) and Doped Fiber Amplifiers (DFA's). EDFA is the most stable amplifier to amplify signals in C-band (1525 -1565 nm)and L-band (1568-1610 nm).The fiber bandwidth is not fully utilized because of some predicaments which can be corrected up to good extent by incorporating WDM system [4][5][6]. EDFA incorporates a number of channels using WDM. Rest of the paper is organized as follows: Section II. Provides analytical description of EDFA pumping techniques. Section III. Contains System Design along with Simulation parameters followed by Results in Section IV. And Conclusion in Section V.

II. PUMPING TECHNIQUES

In optical pumping photon energy is used to raise electrons into excited states in contrast to SOA's where external current injection excites electrons to higher energy levels [7]. Two pumping source are considered at 980nm and 1480nm.The optical pumping requires the use of three energy levels as shown in figure 1.

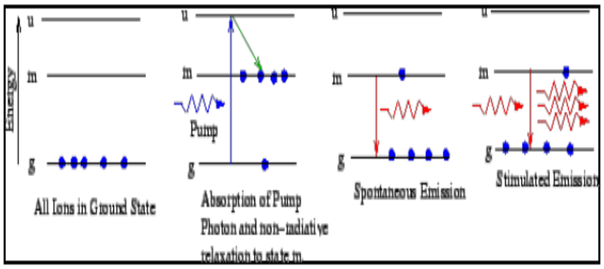


Figure 1: Energy level diagram of EDFA showing pumping and lasing

N_u, N_m and N_g denote the population of three energy states. The rate equations for EDFA can be represented as [8]:

$$\frac{dN_g}{dt} = \frac{N_m}{\tau_{mg}} + W_s(N_m - N_g) - W_p(N_g - N_u) \qquad (1)$$

$$\frac{dN_m}{dt} = \frac{N_u}{\tau_{um}} - W_s(N_m - N_g) \qquad (2)$$

$$\frac{dN_u}{dt} = -\frac{N_u}{\tau_{um}} + W_p(N_g - N_u) \qquad (3)$$

Where W_p is pumping rate; W_s is photon absorption rate;

τ_{ij} Is the spontaneous emission lifetime from i to j state

Population inversion indicates that $N_m > N_g$. The time derivatives disappear for steady state conditions. Since, the lifetime of intermediate state m is more than that of upper state u, the Boltzmann distribution gives a measure of population inversion.

$$N_u = N_m e^{-(E_u - E_m)/kT} = \beta N_m \qquad (4)$$

Where $\beta = e^{-(E_u - E_m)/kT}$

Under steady state conditions, rate equation can be written as

$$\frac{N_m}{\tau_{mg}} + W_s(N_m - N_g) - W_p(N_g - N_u) = 0 \qquad (5)$$

After further simplification equation (4) can be used for determining the inversion level n

$$n = \frac{N_m}{N_m - N_g} = \frac{(W_p + W_s)\tau}{W_p\tau(1-\beta) - 1} \qquad (6)$$

In 980nm, erbium ions are continuously moved from upper to lower level through intermediate stage while with1480nm the energy is slightly higher and ions are only moved in between intermediate stage to lower stage[9][10][11].
Using principle of energy conservation, the input and output powers of EDFA can be expressed as:

$$P_{s,out} \leq P_{s,in} + \frac{\lambda_p}{\lambda_s} P_{p,in} \qquad (7)$$

Where $P_{p,in}$ is the input pump power, and $\lambda_p$and λ_s are the pump and signal wavelengths, respectively. The major constraint while using EDFA is that the amount of extracted signal energy from an EDFA cannot exceed the pump energy [12]. In the above equation, inequality reflects the possibility of effects like the pump photons being lost due to various causes (interactions with impurities) or pump energy lost due to spontaneous emission.
From equation (5), it is clear that the ratio $\frac{\lambda_p}{\lambda_s}$ limits the maximum output signal power. For efficient pumping it is desirable to have $\lambda_p < \lambda_s$ and for appropriate gain $P_{s,in} \ll P_{p,in}$. Equation (8) represents the Power conversion efficiency (PCE).

$$PCE = \frac{P_{s,out} - P_{s,in}}{P_{p,in}} \approx \frac{P_{s,out}}{P_{s,in}} \leq \frac{\lambda_p}{\lambda_s} \leq 1 \qquad (8)$$

The pump power using forward pumping is expressed as:

$$P_p(z) = P_p(0)\exp(-\alpha_p L) \qquad (9)$$

In bidirectional pumping, the pump power is

$$P_p(z) = P_p(0)\exp(-\alpha_p(L - Z)) \qquad (10)$$

Where $P_p(0)$ is pumping power at z=0, L is the cavity length and α_p is the attenuation coefficient at pumping wavelength

The pumping techniques used in EDFA are:

(1) Co-Pumping
(2) Counter pumping
(3) Bidirectional Pumping

Co-Pumping (Forward Pumping): In this technique, the injected pump light and the signal flow have same directions and are combined using pump co-coupler or wavelength division multiplexer. The input signal gets energy through pumping along with amplification and at the output is coupled into the fiber. The optical isolators are used to prevent the back reflection of amplified signal and hence limit the noise.

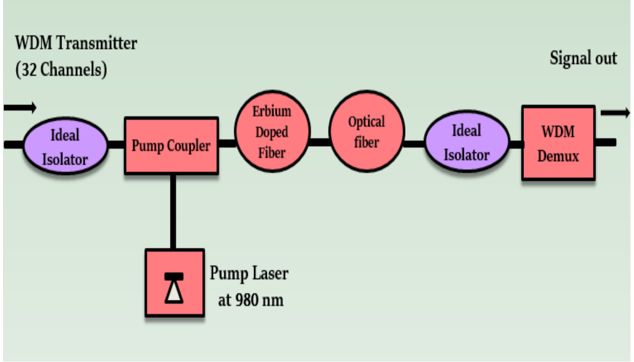


Figure 2. Block Diagram of Co-Pumping technique

Counter-Pumping (Backward Pumping):

In this technique, the injected pump light and signal flow have opposite directions. The signal direction is insignificant in this pumping for amplification. The optical isolators are used to prevent the back reflection of amplified signal.

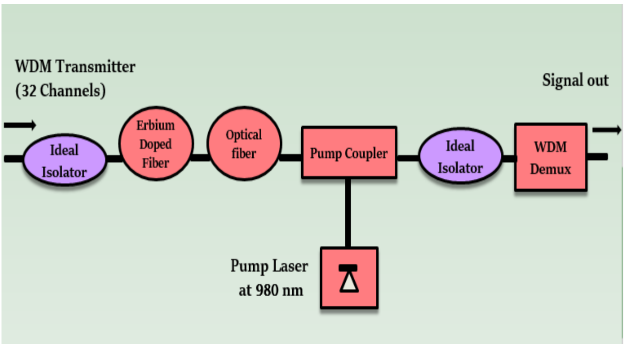


Figure 3. Block Diagram of Counter-Pumping technique

Bidirectional-Pumping:

In Bi-directional pumping, the input signal is propagated in forward direction.

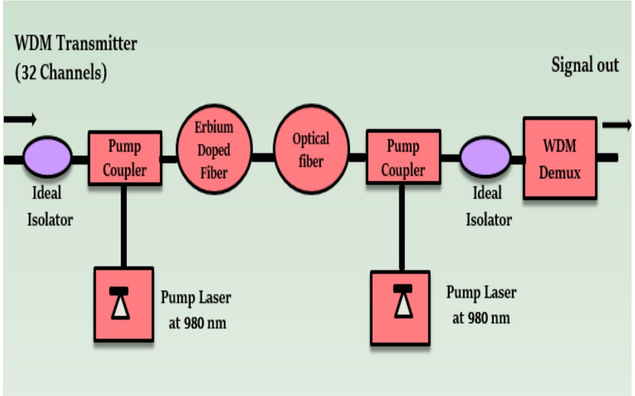


Figure 4. Block Diagram of Bidirectional Pumping Technique

Two pump sources are used in this technique to travel in both directions inside the fiber there by using both forward and backward pumping techniques simultaneously for optimum performance of EDF

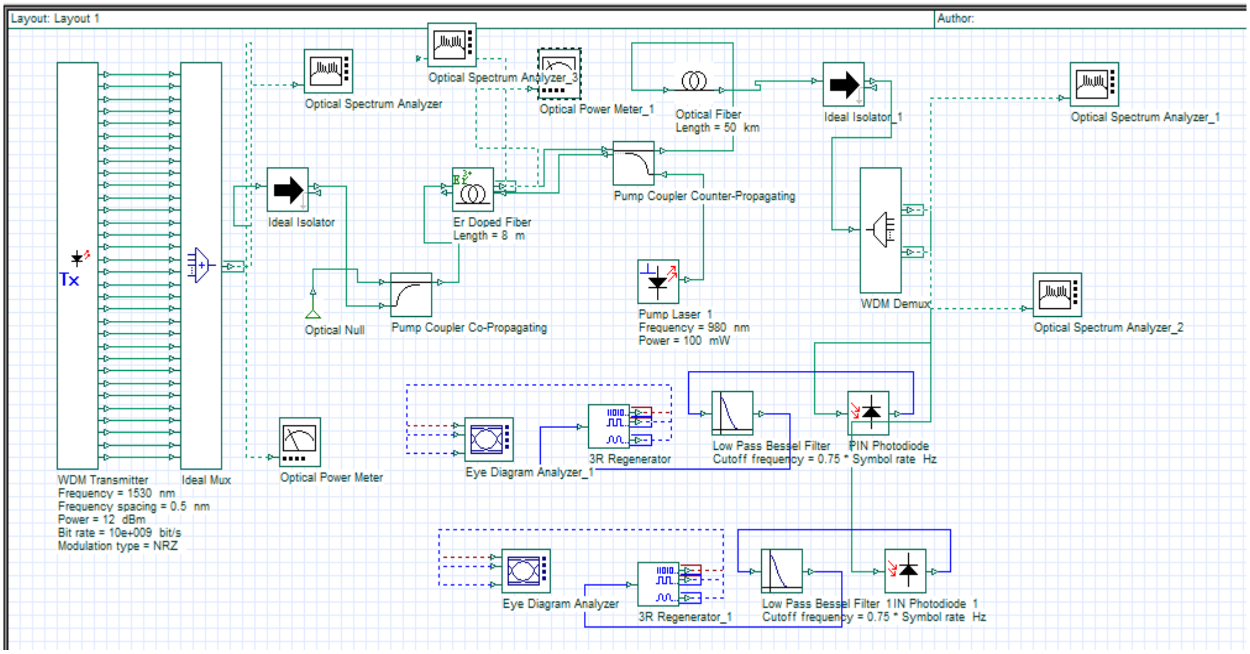
III. EDFA-WDM SYSTEM DESIGN

The 32-channel WDM system is designed in OPTISYS V14 and the performance of counter and bidirectional pumping techniques are analyzed over a range of 1530nm-1550nm with 0.5nm frequency spacing. The results are obtained for 50km length of optical fiber. The performance analysis of pumping techniques is done using various simulation parameters as shown in table 1.

Table 1. Parameters of simulation setup

Design Components	**Simulation parameters**	**Values**
WDM Transmitter	Channel power (dBm)	-26
	Modulation Type	NRZ
	Channel Spacing (nm)	0.5
	Bit Rate (Gbps)	10
Pump laser	Pumping power for EDFA (mW)	40,60,80,100,120
	Pumping wavelength (nm)	980,1480
EDF	Length of EDF (m)	4,6,8
	Er^{3+} ion density	10*1024 m-3
	Er^{3+} metastable lifetime (ms)	10
Optical fiber	Length (km)	50
Low pass Bessel filter	Cutoff frequency (Hz)	0.75*Bit rate
PIN diode	Responsivity (A/W)	1

The designed system layout for counter pumping is shown in figure5 below.



Frequency = 1530 nm
Frequency spacing = 0.5 nm
Power = 12 dBm
Bit rate = 10e+009 bit/s
Modulation type = NRZ

Length = 50 km

Length = 8 m

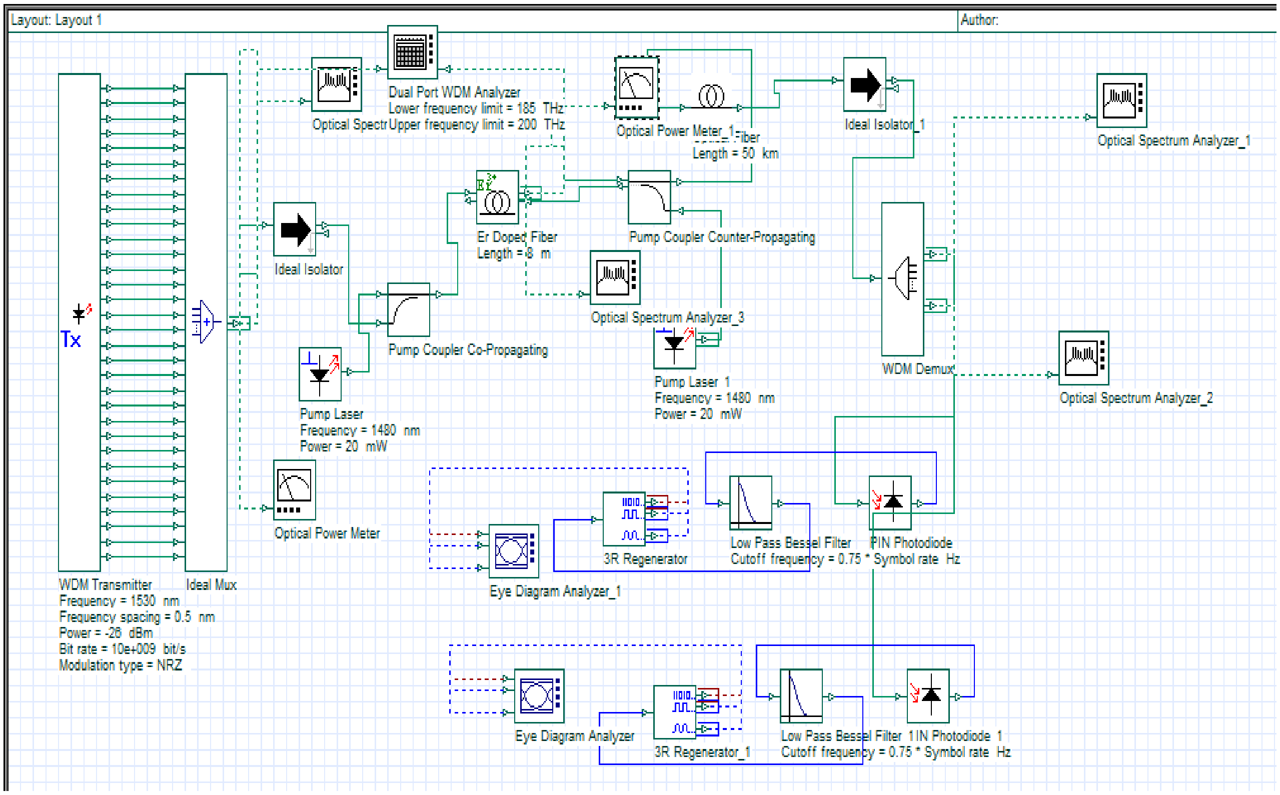
Frequency = 980 nm
Power = 100 mW

Cutoff frequency = 0.75 * Symbol rate Hz

Cutoff frequency = 0.75 * Symbol rate Hz

Figure 5. Designed System Layout for Counter pumping

The designed system layout for bidirectional pumping is shown in figure6 below.



Frequency = 1530 nm
Frequency spacing = 0.5 nm
Power = -26 dBm
Bit rate = 10e+009 bit/s
Modulation type = NRZ

Lower frequency limit = 185 THz
Upper frequency limit = 200 THz

Length = 50 km

Length = 8 m

Frequency = 1480 nm
Power = 20 mW

Frequency = 1480 nm
Power = 20 mW

Cutoff frequency = 0.75 * Symbol rate Hz

Cutoff frequency = 0.75 * Symbol rate Hz

Figure 6. Designed System Layout for Bidirectional pumping

IV. RESULT AND DISCUSSION

We have focused on the Q-factor of counter pumping and bidirectional pumping based on the results obtained after analyzing the variation of output power with input pump power for various lengths of EDF. For counter pumping, with increase in length of EDF the received power also increases but the transmission is acceptable up to 6m of EDF length as shown in figure 7 below.

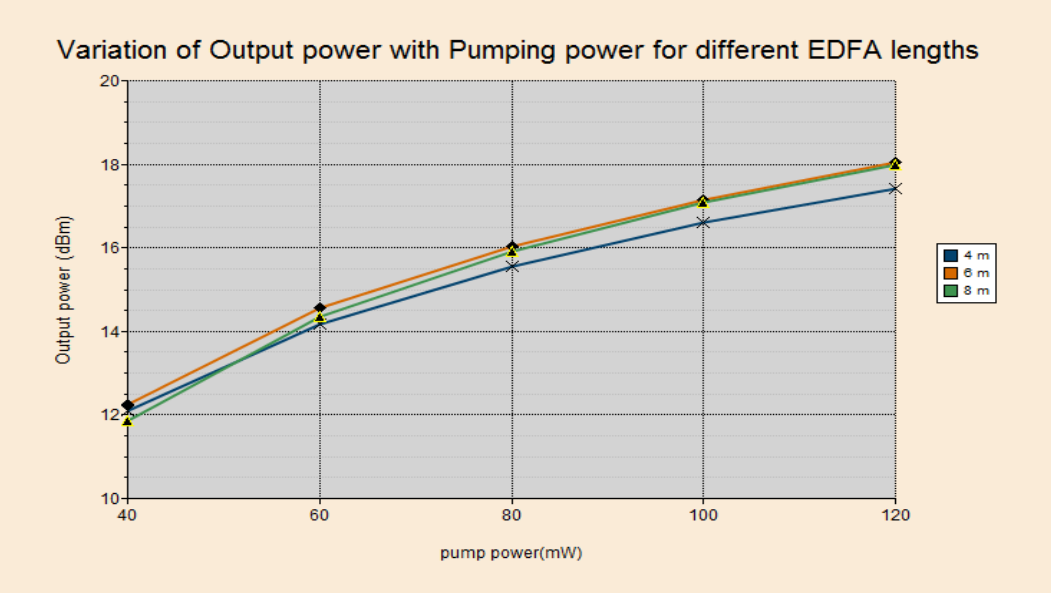


Figure 7. Variation of Output power with pump power for various EDF lengths in Counter pumping

The graphical results for Counter pumping are tabulated as below in table2.

Table 2. Power with varying Length of EDF for Counter Pumping Technique

Pumping power given to EDFA (mW)	**Input power (E-6)**	**Input power (dBm)**	**Counter Pumping**					
			Output power (E-3)			**Output power (dBm)**		
			4m	**6m**	**8m**	**4m**	**6m**	**8m**
40	43.865	-13.579	16.99	16.78	15.34	12.09	12.24	11.86
60	43.860	-13.579	26.20	28.55	27.17	14.18	14.55	14.34
80	43.850	-13.580	36.01	40.22	39.03	15.56	16.04	15.91
100	43.845	-13.581	45.71	51.94	50.98	16.60	17.15	17.07
120	43.831	-13.581	55.22	63.73	63.02	17.42	18.04	17.99

The output power variation with respect to pump power for bidirectional pumping is show n in the figure 8 below.

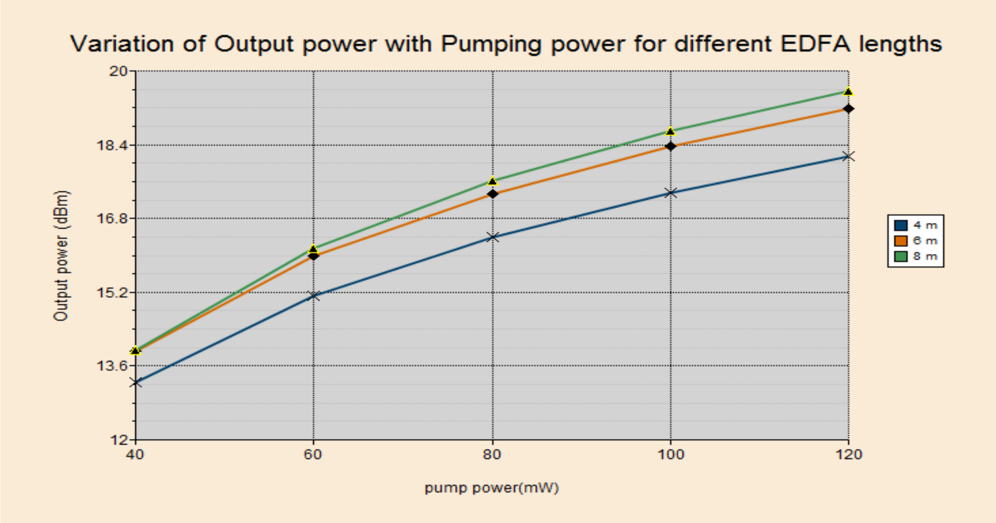


Figure 8. Variation of Output power with pump power for various EDF lengths in Bidirectional pumping

For bidirectional pumping, with increase in length of EDF it provides more power compared to the counter pumping in which for EDFA length greater than 6m, the power was decreasing. The graphical results are tabulated as below in table 3.

Table 3.Power with varying Length of EDF for Bidirectional Pumping Technique

Pumping power given to EDFA (mW)	Input power (E-6)	Input power (dBm)	Bidirectional Pumping					
			Output power (E-3)			Output power (dBm)		
			4m	6m	8m	4m	6m	8m
40	43.865	-13.579	21.14	24.70	27.74	13.25	13.92	13.93
60	43.860	-13.579	32.55	39.62	41.18	15.12	15.97	16.14
80	43.850	-13.580	43.64	54.22	57.67	16.39	17.34	17.61
100	43.845	-13.581	54.52	68.62	74.22	17.36	18.36	18.70
120	43.877	-13.578	65.24	82.84	90.51	18.14	19.18	19.56

Based on these results, comparative analysis of these two pumping techniques is carried out in terms of Q-factor with varying pump powers.

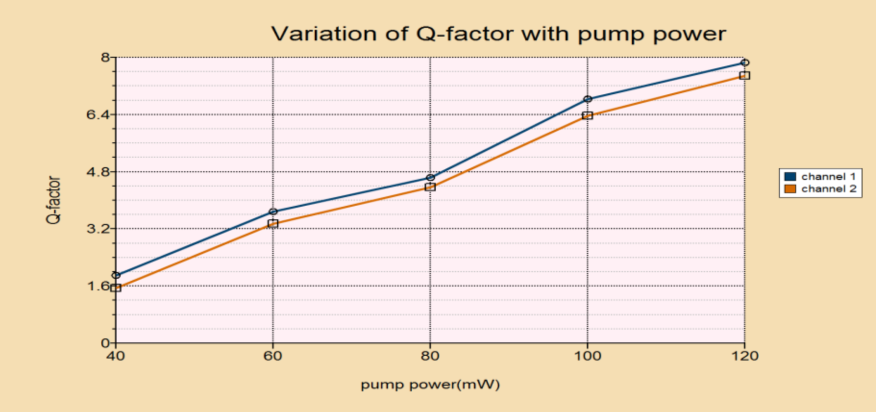


Figure 9. Q-factor analysis for counter pumping technique

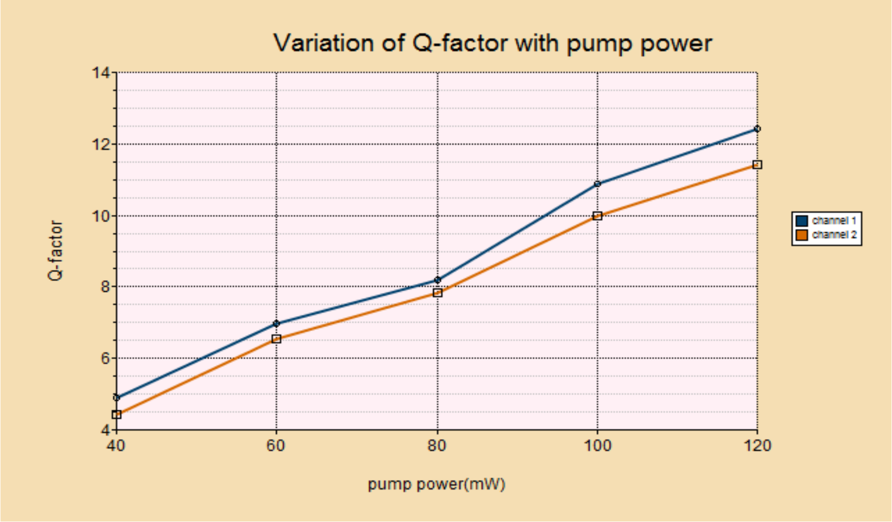


Figure 10. Q-factor analysis for bidirectional pumping technique

The graphical analysis of Q-factor shows that with increase in pump power, the Q-factor increases for both the pumping techniques but the increase is greater in bidirectional pumping. In counter pumping, since the transmission is acceptable up to 6m length of EDF, we have analyzed the Q-factor values at 6m EDF length and for bidirectional pumping the Q-factor values are analyzed at 8m of EDF length. The graphical values are tabulated as below in table 4.

Table 4. Q-Factor Variation with Pumping Power for Both Pumping Techniques

Pump power given to EDFA (in mW)	**Q-Factor**			
	Counter Pumping (EDFA length-6m)		**Bidirectional Pumping (EDFA length-8m)**	
	Channel 1	**Channel 2**	**Channel 1**	**Channel 2**
40	1.8942	1.543	4.884	4.432
60	3.693	3.348	6.983	6.542
80	4.642	4.364	8.130	7.822
100	6.841	6.403	10.873	9.987
120	7.863	7.492	12.413	11.432

V. CONCLUSION

In this paper, we have designed and evaluated the performance of EDFA using counter pumping and bidirectional pumping over a 32-channel WDM system based on Q-Factor and received output power with NRZ modulation format .We have evaluated the system for pumping power of 40,60,80,100 and 120mW at EDF length of 4,6and 8m. With increase in pump power, the Q-factor increases for both the pumping techniques but the increase is greater in bidirectional pumping. In counter pumping, since the transmission is acceptable up to 6m length of EDF, we have analyzed the values of Q-factor at 6m EDF length and for bidirectional pumping the values of Q-factor are analyzed at 8m of EDF length. The system depicts a considerable improvement and works optimally for bidirectional pumping with Q Factor of 12.413 and 11.432 at 8m of EDF at 120mW of pumping power.

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Authors Profile

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