IJNRD.ORG ISSN : 2456-4184
INTERNATIONAL JOURNAL OF NOVEL RESEARCH AND DEVELOPMENT (IJNRD) | IJNRD.ORG
An International Open Access, Peer-reviewed, Refereed Journal

A Performance Analysis of EDFA-EYCDFA Hybrid Amplifier using pump power, input power, length of the fiber, Numerical aperture, and core radii in backward and forward pumping.

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Abstract: The performance of the EDFA-EYCDFA hybrid amplifier is examined in this study using parameters such as pump power, input signal power, fibre length, numerical aperture, and fibre core radii in both backward and forward pumping modes. Using the EYCDFA amplifier in series with a generic EDFA amplifier, all simulations were run in the Opti System 7.0. Every experiment that is run draws from the one before it. The input signal for the system has been adjusted to replicate a laser with a continuous frequency of 1552 nm. Any noise generation has been stopped using an optical isolator. The output from the EDFA and the pump were multiplexed together using an ideal multiplexer. After that, an EYCDFA is used to process the signal. The final output is examined on a WDM analyzer after being routed through an optical isolator. The technique described in the paper is just the first stage of amplification; numerous further stages can be used to increase the signal's gain. The outcomes demonstrate that a gain to noise ratio of over 10 has been attained. This study also intends to analyze how the EDFA-EYCDFA amplifier performs when the fibre characteristics are put to the test, giving engineers insight into how to employ these fibre parameters more effectively.

Index Terms - Hybrid fiber amplifier, Erbium doped Fiber amplifier, Erbium co-doped fiber amplifier, Fiber-Communication, input signal power, length of the fiber, Numerical aperture, core radii, backward pumping, forward pumping.

1. INTRODUCTION

Ytterbium (Yb)-co-doped erbium (Er)-doped fibre amplifiers (EDFAs) have subsequently shown high and broad gain, equivalent to the efficiency of traditional EDFAs. EYCDFAs can also provide significantly larger output powers at a significantly lower cost than traditional EDFAs because the Yb3+ ions absorb most of the pump power and cross-correlation Higher Er3+ concentrations are possible thanks to the addition of Yb3+ without experiencing significant quenching effects [3]. EDFA has evolved into a crucial component in communication systems because to its excellent qualities of high gain, good noise feature, and high transmission rate. It has been shown that the fibres have an ideal length, and if the length were to be raised past this length, the benefit would be greatly reduced. However, depending on how powerful the pump laser is used, this length might change [2]. We can achieve flat gains from EDFA fibers by manipulating the EDFA lengths and pump powers as a result, we can achieve high gains with low noise figures by controlling the length of the EDFA and pump powers with managed input power variation [3]. In our research, we have observed a significant impact on the variation of input signal power because input power is the initial signal powers of the source amplifiers that need to be amplified. The type of material the fibre is comprised of affects the numerical apertures. The fiber's refractive index varies depending on the substance. Therefore, a change in the numerical aperture of the fibre might affect the output signal's gain to noise ratio. As more dopant ions are concentrated close to the core and interact with the pump signal, decreasing the core radius while maintaining the doping radius might result in large gains for the input signals [5].

In this paper, we examined how the EDFA-EYCDFA hybrid amplifier was impacted by several extrinsic parameter modifications, including changes in the input signal strength, fibre length, numerical aperture, pump power, fibre core radius, and pumping techniques. In contrast to the EYCDFA, which is used as a post amplifier, the EDFA is utilized as a pre-amplifier. 20dBm has been chosen as the input signal power levels. Pumping with 85mW power has been done for both backward and forward configurations. The highest gain to noise ratios for each parameter variation result have been displayed.

Optical fibres have been used in the structure of many modern communication networks, mostly because of the benefits that the fibre may provide to the system, including large bandwidth, low loss, low distortion, security, and electromagnetic isolation. However, high-capacity transmission systems were not possible until the introduction of optical amplifiers employing rare-earth doped optical fibres [6].

WORKING PRINCIPLE.

On continuous pumping between 800 and 1100 nm produces the sole broadband laser transition for Yb3+ ions in silica fibre. Because there is a significant spectral overlap between the Yb3+ and Er3+ ions, the Yb3+ ions absorb the pump power.[7]. This method makes it possible to have a strong pump absorption without signal absorption because of the concentration of Er3+, which makes it possible to create highly powerful amplifiers and lasers [8]. Due to the great efficiency of fibre amplifiers, the output power for a strong input signal and the amplification coefficient for a weak input signal are nearly proportional to the power of the pump absorbed in the fibre. When compared to conventional single mode fibre designs, double-cladding fibres have a significantly lower potential cost for power scaling fibre lasers and amplifiers. Typically, an optical signal is sent through the inner core of a double-cladding fibre. For signal amplification purposes, the optical pumping energy must be connected directly into the core where it will be absorbed. However, this energy might be linked in the inner cladding, where it would then spread out in a multi reflective trajectory until it encounters the core. This pump energy will be absorbed when it comes in contact with the core [9]. As shown below. [2] where N_x is given by Populations.

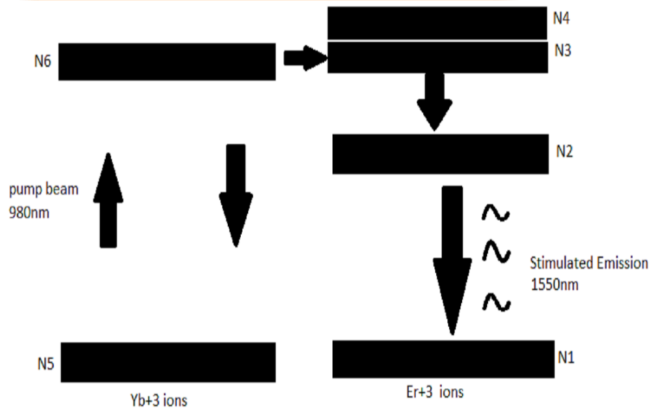

Figure 1 Energy Level Diagram of EDFA-EYCDFA

2. MATHEMATICAL MODEL

Gain saturation and the consequences of uneven gains must be taken into consideration while evaluating the cascaded amplifier system's constant signal output power after each amplifier. The total output power of all amplifiers is assumed to be constant as a standard assumption to treat gain saturation. The equation given below describes the signal power provided after amplification.

The gain of the amplifier is given by [10]

$$G = \frac{(Pin + 2\eta_{sp} + \hbar\nu B_0)}{(PinL + 2\eta_{sp} + \hbar\nu B_0)}$$

The Noise Figure is given by [10]

$$F_{sys} = F_1 + \frac{F_2}{G_1} + \cdots + \frac{F_n}{G_1 G_2 G_3 \ldots G_{n-1}}$$

The noise figure from the amplifier's first stage generates the most overpowering noise when compared to the subsequent stages, as can be seen from the equation above. Therefore, while constructing any multistage amplifier, noise reduction at the first stage is crucial. As a result, an amplifier that has a strong gain to noise ratio in the first stage will also have a good gain to noise ratio overall in subsequent stages.

Integrating across the amplifier length L yields the amplifying factor that a faint signal is amplified by. As EDFAs are made using short fibres (approximately 10 m), fibre losses are neglected, and the amplified rate is provided by

$$G(\omega) = exp\left[\int_0^L g_0(z,\omega)\,dz\right]$$

Where, $G(\omega)$ is the gain spectrum, L is the length of the fiber, $g_0(z,\omega)$, being the effective gain

The mode field diameter (MFD), a measurement of the size of the fibre's light-carrying core, can be impacted by the NA of the EDFA fibre as well. In the fibre, a bigger MFD can enhance the overlap between pump and signal light, resulting in better amplification and less noise. But a bigger MFD might also lead to more dispersion and less bandwidth. [12]

$$MFD = \frac{2 * \sqrt{NA} * \lambda}{\pi * NA}$$

Where, λ is the wavelength, NA is the numerical aperture of the fiber

The MFD of the fibre can also be affected by the core radii of the fibre by the given formula [13].

$$MFD = \sqrt{\frac{(2 * n1 * r)}{n2}}$$

3. SIMULATION, SPECIFICATIONS AND RESULTS.

All simulations have been performed using Opti System software version 7. We, first and foremost, have explored different avenues regarding an all-forward pumping plan for the EDFA-EYDFA setup.

The first amplifier's forward-pumped pump has a power of 70 mW and a wavelength of 980 nm. With 10mW and 980nm, the second amplifier is forward-pumped. The initial length of 14 meters is maintained for both amplifiers. Initially, the EDFA amplifier and the EYCDFA amplifier have core radii of 1.5um and 5um, respectively. The 1.5um and 1.2um doping radius of EDFA and EYCDFA, respectively. The EDFA amplifier's numerical aperture has been set to 0.67 because different kinds of materials have different refractive indexes. The double-cladded fiber known as the EYCDFA has a numerical aperture of 0.45. The wavelength of the input is 1552 nm with a power of -20 Dbm. In the EDFA amplifier, the Erbium ion density is set to 5 x 1024 m-3 . In the EYCDFA, the concentrations of Erbium ions and Ytterbium ions are set to 85 x 1024 m-3 and 13.5 x 1024 m-3, respectively. The Er metastable lifetime and the Yb meta stable lifetime have been set to 2.5 milliseconds, respectively. Losses at 1550 nm and 980 nm for the EDFA are set to 0.1 dB/m and 0.15 dB/m, respectively. Pump loss is set to 0.15 dB/m and signal loss is set to 0.1 dB/m for EYCDFA. The EYCDFA has a 50um2 effective area.

TABLE 1

INITIAL EXPERIMENT RESULTS FOR ALL FORWARD PUMPING

Frequency (THz)	193
Gain (dB)	30.85
Noise Figure (dB)	4.07
Input Signal (dBm)	-20
Input Noise (dBm)	-73
Input SNR (dB)	53.04
Input OSNR (dB)	55.12
Output Signal (dBm)	10.85
Output Noise (dBm)	-20.95
Output SNR (dB)	31.81
Output OSNR (dB)	33.85
Bit rate	1Gbps
Length of the fiber	14m

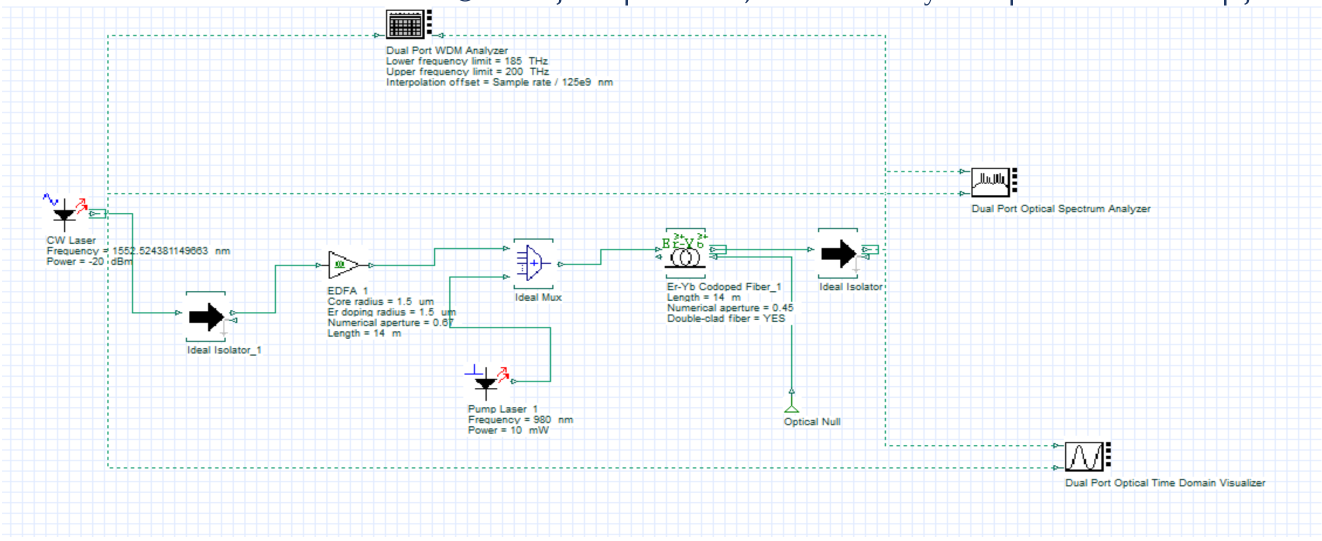

Figure 2 Forward Pumping Configuration

TABLE 2
INITIAL EXPERIMENT RESULTS FOR ALL BACKWARD PUMPING

Frequency (THz)	193.1
Gain (dB)	32.613052
Noise Figure (dB)	7.720318
Input Signal (dBm)	-20.001467
Input Noise (dBm)	-74.845469
Input SNR (dB)	54.844003
Input OSNR (dB)	56.885202
Output Signal (dBm)	12.611585
Output Noise (dBm)	-15.576955
Output SNR (dB)	28.18854
Output OSNR (dB)	30.22974
Bit rate	1Gbps
Length of the fiber	14m

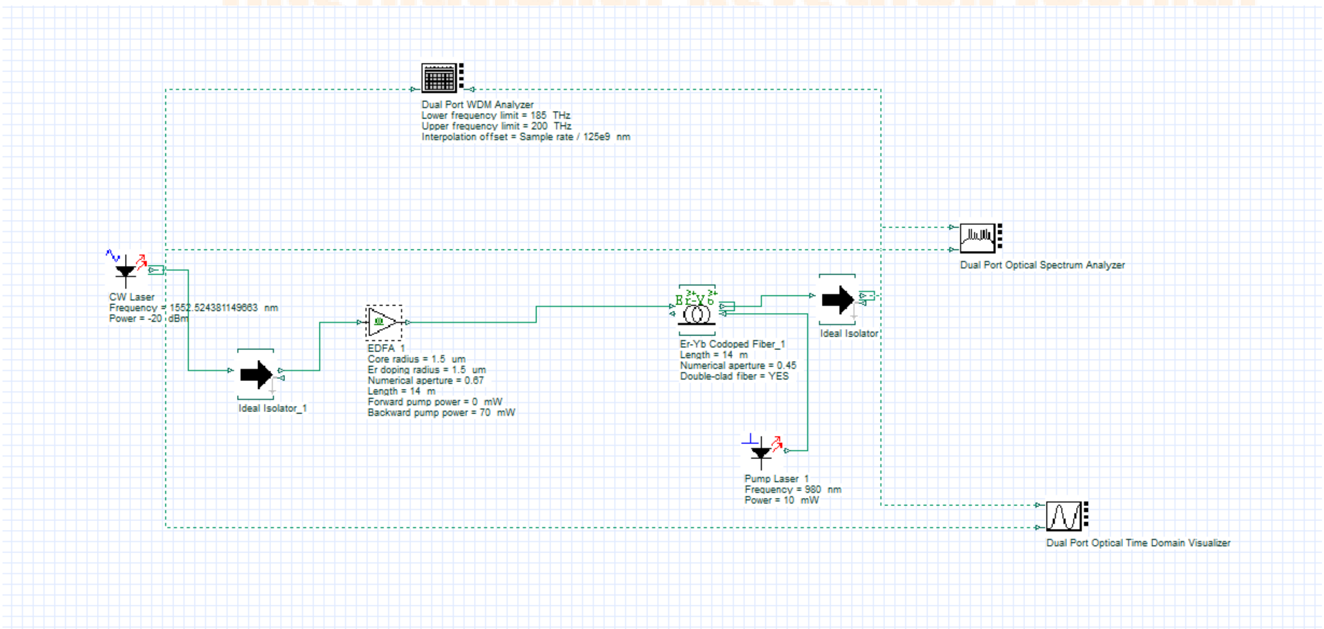

Figure 3 Backward Pumping Configuration

As you can see, when we use an all-forward pumping technique but increase the gain by 2dB, the noise figure is significantly enhanced. This suggests that while reverse pumping has a high noise figure, it can still produce a good gain.

Both an all-forward pumping arrangement and an all-backward pumping configuration have been tested. According to the findings, an all-forward pumping arrangement can deliver a reasonable noise figure at the expense of gain. Depending on how the amplifier's parameters change, this outcome might alter. Using a sweep condition, we adjusted several parameters and tracked each outcome. All the experiments performed inherit the parameters of their previous experiment.

Pump Power Variation

FORWARD PUMPING

Pump power is varied from 5mW~100mW in forward pumping configuration.

Varied Pump Power (mW)	EDFA pump varied and EYCDFA constant at 10mW (Gain-Noise Ratio)	EDFA pump constant at 90mW and EYCDFA varied (Gain-Noise Ratio)	Both pumps varied (Gain-Noise Ratio)
5	1.251929	7.786725	-0.9242
10	4.026667	7.523621	2.77367
15	5.072324	8.116965	5.307162
20	5.713892	7.730871	6.31565
25	6.382535	7.778095	6.845708
30	6.477682	7.688133	7.204724
35	6.741213	7.950623	7.422465
40	6.883622	7.960482	7.564767
45	6.930761	7.900973	7.74677
50	7.15916	8.030657	7.896907
55	7.194147	8.249098	8.025707
60	7.114461	8.210604	8.158568
65	7.282367	8.035096	8.252551
70	7.446937	8.026316	8.335878
75	7.437335	8.306748	8.406091
80	7.7603	8.3602	8.470886
85	7.658271	8.243832	8.527778
90	7.871801	8.298544	8.579345
95	7.821529	8.398585	8.649874
100	7.608711	8.221569	8.690955

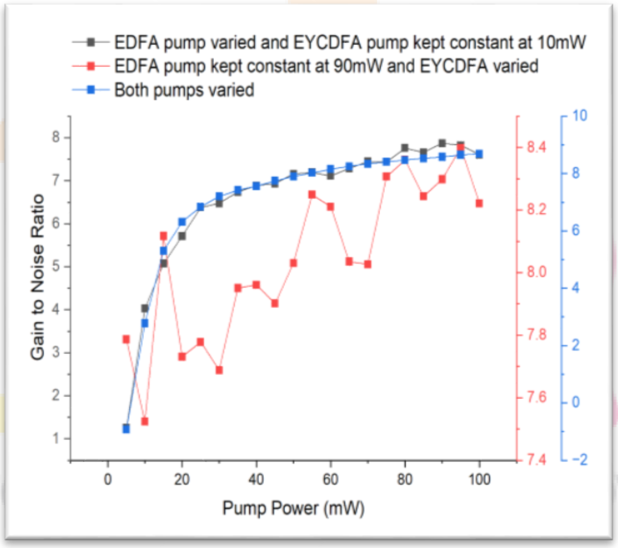

Figure 4 Gain to Noise Ratio Comparison (All forward)

From the findings, we can conclude that when the pumps for both amplifiers are set to 100mW, they deliver the highest gain to noise ratio as predicted, but we can also utilize pump powers of 85mW to locate a suitable power pump at a cheaper price. We can also observe that a gain to noise ratio greater than 8 is produced when both pump powers are adjusted at 55 mW to 100 mW.

BACKWARD PUMPING

In the backward pumping we have reduced the pump power variation from 85mW to 100mW. As these pump powers provided suitable results.

Pump Power (mW)	Gain to noise ratio when EYCDFA pump varied	Gain to noise ratio when EDFA pump varied
85	0.075286	0.075286
90	0.078846	0.157996
95	0.082372	0.246305
100	0.085753	0.338322

Pump Power (mW)	noise figure when EYCDFA pump varied (dB)	noise figure when EDFA pump varied (dB)
85	49.3385	49.3385
90	49.3391	45.8686
95	49.3398	42.6634
100	49.3404	39.7672

No significant difference was found when the gain to noise ratio of both the variations are compared to one another this linearity is present due to the balancing of both the gains providing an mostly similar gain to noise ratio however when we compare the noise figures obtained in the experiments, we see a significant difference.

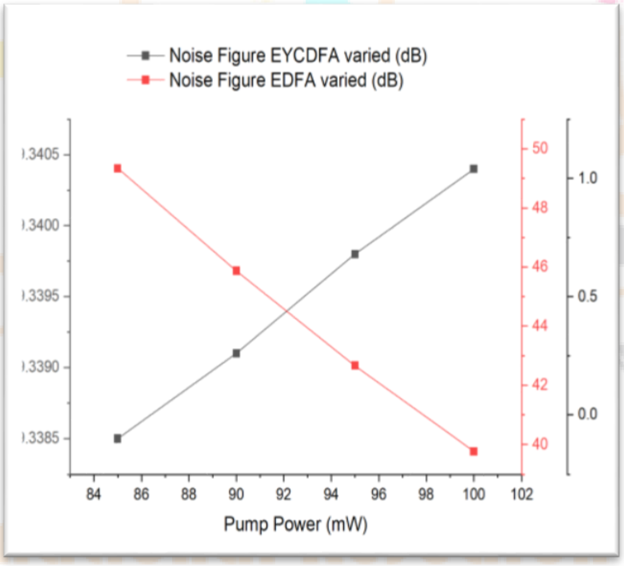

Figure 5 Variation in Noise Figure when Pump Power is varied

The gain to noise ratio of the backward pumping system is inferior to that of the all-forward pumping strategy, as can be seen from the results obtained above

Input Power Variation

FORWARD PUMPING

In this experiment pump power is kept constant at 85mW for all pumps of EDFA and EYCDFA. The input signal power was varied from -20dBm to 20dBm. Given below is the result of the experiment.

Input signal power (dBm)	**Gain (dB)**	**Noise (dB)**	**Gain to Noise Ratio**
-20	33.77	3.96	8.527778
-15	30.14	3.45	8.736232
-10	25.72	3.13	8.217252
-5	21.02	3.20	6.56875
0	16.16	3.82	4.230366
5	11.34	5.38	2.107807
10	6.79	7.92	0.857323
15	2.91	10.71	0.271709
20	-0.11	12.85	-0.008

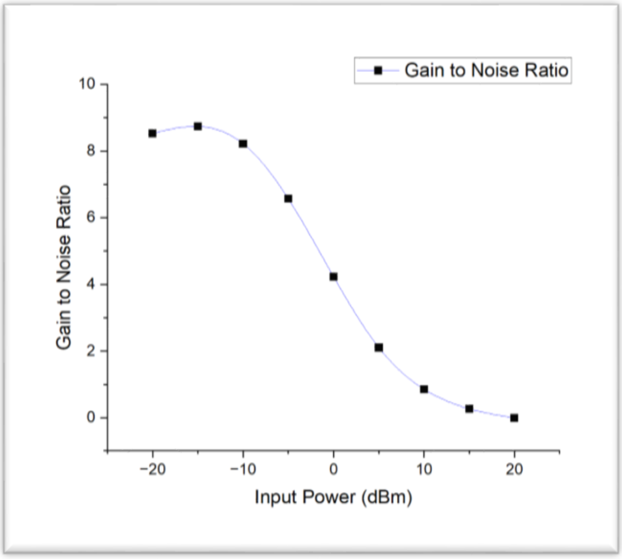

Figure 6 Pump powers set to 85mW; Input signal power varied

BACKWARD PUMPING

In this experiment pump power is kept constant at 85mW for all pumps of EDFA and EYCDFA. The input signal power was varied from 20dBm to 20dBm. Given below is the result of the experiment.

Input signal power (dBm)	Gain (dB)	Noise (dB)	Gain to Noise Ratio
-20	3.7144773	49.3385	0.075286
-15	3.9158924	49.1343	0.079698

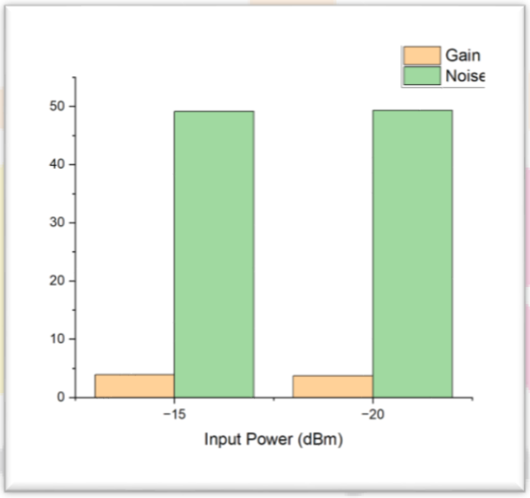

Figure 7 Pump powers set to 85mW; Input signal power varied in backward configuration

Variation In Length of The Fiber

FORWARD PUMPING

Both amplifiers' lengths were experimented with and modified. All the pump powers were set to 85mW, and tests were conducted at an input power level of -20dBm.

Length of the Fibre (m)	Gain to Noise Ratio on variation of EDFA length	Gain to Noise Ratio on variation of EYCDFA length	Gain to Noise Ratio on variation of both fibre length
5	9.624525	9.662688	9.529763
6	9.750984	9.917781	9.77409
7	9.891915	10.12249	10.0121
8	10.03475	10.28138	10.23661
9	10.17263	10.40015	10.46438
10	10.30032	10.48459	10.64552
11	10.41281	10.54018	10.79197
12	10.50429	10.57166	10.89455
13	10.56565	10.583	10.94049
14	10.57746	10.57746	10.9162

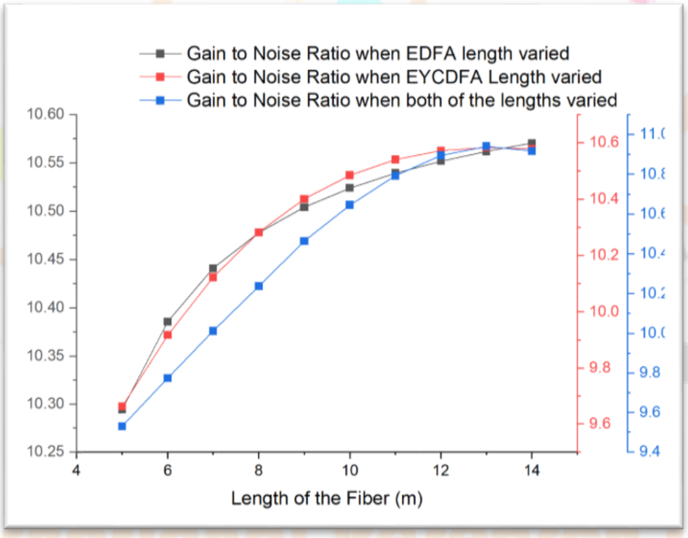

Figure 8 Gain to Noise Ratio vs Length of Fiber in Forward Pumping

BACKWARD PUMPING

Iteration	Length (m)	Gain (dB)	Noise (dB)	Gain to Noise Ratio
1	5	38.176483	4.33175	8.813178
2	6	39.026483	4.95175	8.45
3	7	39.425809	5.03857	7.824801
4	8	39.684787	5.58308	7.108046
5	9	39.750524	6.26563	6.344218
6	10	39.678392	7.10242	5.586602
7	11	39.490296	8.06603	4.895878
8	12	39.204027	9.09377	4.311086

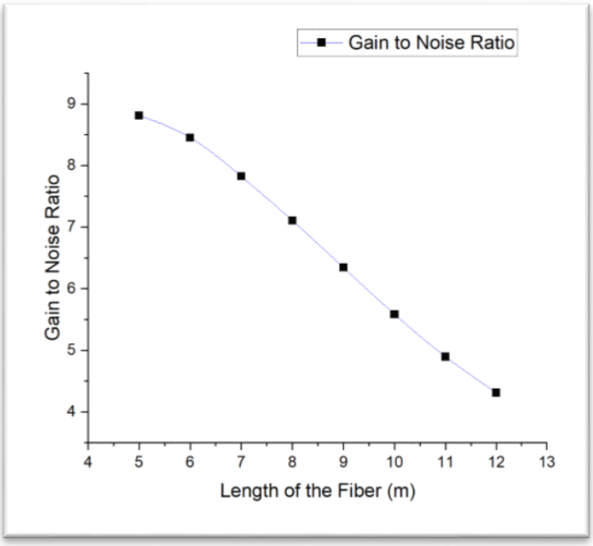

Figure 9 At input of -20dBm, Pump Power level set to 85mW, EDFA length varied from 5m to 12m, EYCDFA length kept constant at 12m.

Iteration	Length (m)	Gain (dB)	Noise (dB)	Gain to Noise Ratio
1	5	37.069796	4.38085	8.461782
2	6	37.482425	4.37431	8.568763
3	7	37.761736	4.36736	8.646353
4	8	37.949673	4.36024	8.703574
5	9	38.068622	4.35304	8.745296
6	10	38.13743	4.34585	8.775597
7	11	38.17001	4.33873	8.797508
8	12	38.176483	4.33175	8.813178

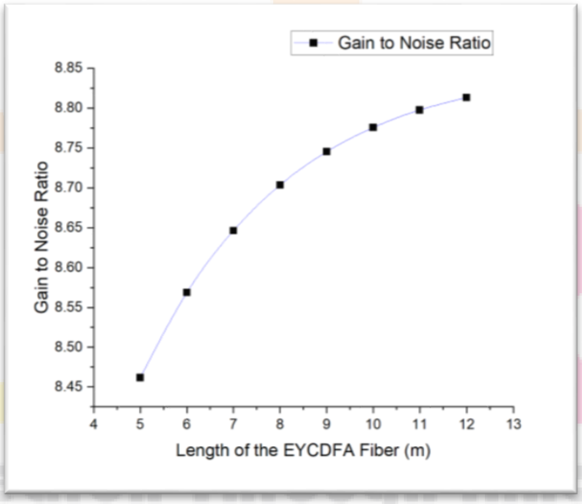

Figure 10 At input of -20dBm, Pump Power level set to 85mW, EYCDFA length varied from 5m to 12m, EDFA length kept constant at 5m.

Variation In Numerical Aperture

FORWARD PUMPING

The Numerical apertures of both EDFA and EYCDFA are varied, pump powers have been set to 85mW and tested at -20dBm.

	Gain to Noise Ratio	
Numerical Aperture	**N.A of EDFA varied**	**N.A of EYCDFA varied**
0.1	5.191402	9.917672
0.2	10.5708	10.60567
0.3	10.89024	10.75953
0.4	10.84363	10.82387

0.5	10.72108	10.85893
0.6	10.62254	10.88106
0.7	10.55359	10.89641
0.8	10.50686	10.90776
0.9	10.47494	10.91658

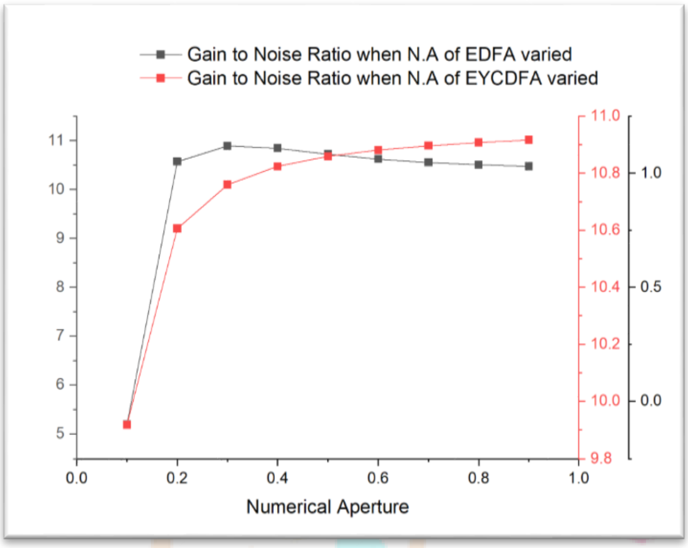

Figure 11 Gain to Noise Ratio observed in Variation of Numerical Apertures

Numerical Aperture	Gain to Noise Ratio when EDFA varied	Gain to Noise Ratio when EYCDFA varied
0.1	8.480344	7.822101
0.2	8.44386	7.46023
0.3	8.848297	7.88617
0.4	8.813178	7.961128
0.5	8.707782	7.931888
0.6	8.629816	7.898764
0.7	8.579102	7.898764
0.8	8.546378	7.857057
0.9	8.524625	7.845828

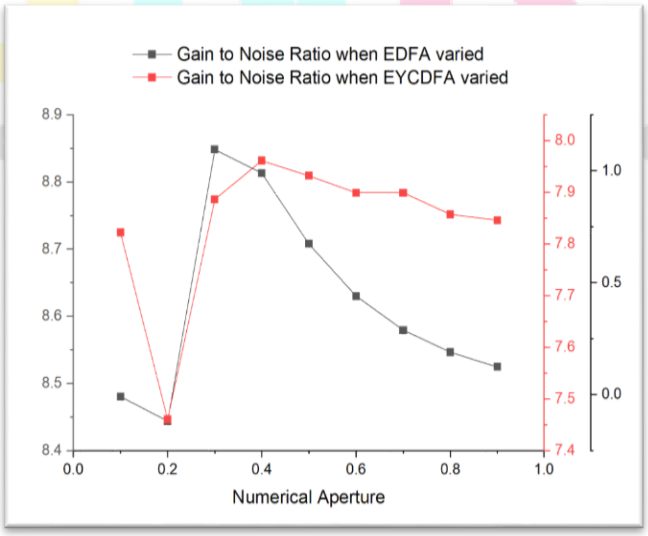

Figure 12 Variation in Numerical Aperture (Backward Configuration)

Variation In Core Radii

Core Radii (um)	Gain to Noise Ratio of (EDFA radii varied)	Gain to Noise Ratio of (EYCDFA radii varied)
1.5	10.91658	8.617101
2.375	10.58662	10.42968
3.25	10.19436	10.91759
4.125	9.997072	11.03326
5	9.974622	10.91658

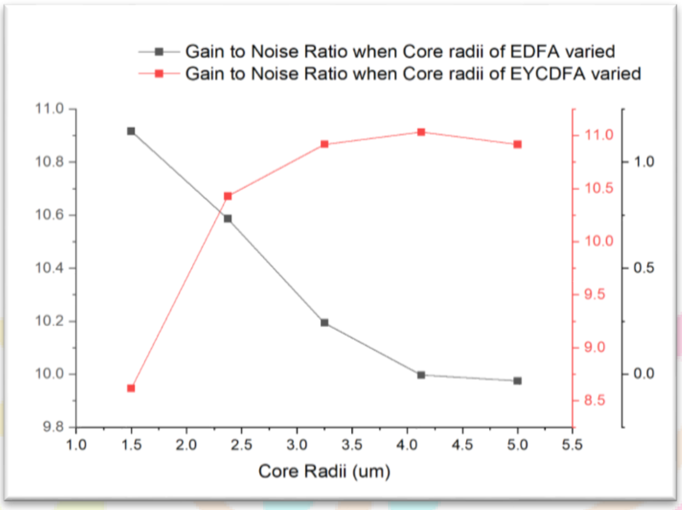

Figure 13 Gain to Noise Ratio observed in Variation of Core Radius

We will undertake the same parameter variation for the backward pumping scheme as we did for the forward pumping scheme because we have already conducted various trials with it. We will change the following parameters in the backward pumping scheme. Both fibers' core radii will be inherited from forward pumping techniques, which yield the highest gain-to-noise ratios at 5um for EYCDFA and 1.5um for EDFA.

4. CONCLUSION

This report provides an investigation on the extrinsic parameters associated to the EDFA-EYCDFA amplifier. It provides us with the helpful specficications for designing EDFA-EYCDFA hybrid amplfiiers. One key aspect of the extrinsic parameters associated with the EDFA-EYCDFA amplifier is the ability to customize and optimize the gain and noise figure of the amplifier for specific applications. By carefully selecting the input and output couplers, as well as the pump powers and wavelengths, it is possible to achieve highly efficient and effective amplification of the signal while minimizing any excess noise introduced by the amplifier. Additionally, the use of an EDFA-EYCDFA hybrid amplifier allows for the benefits of both types of amplifiers to be utilized, such as the wide gain bandwidth of the EDFA and the improved noise performance of the EYCDFA. Overall, understanding the extrinsic parameters of the EDFA-EYCDFA amplifier is essential for designing and implementing high-quality amplification systems in a variety of applications.

5. ACKNOWLEDGEMENT

I appreciate Prof. Santosh Jagtap, for assistance with the research and for reviewing the paper which really improved the manuscript. I am also grateful to Prof. Santosh Jagtap for his comments on an earlier draft of the manuscript, though any inaccuracies are our own and should not reflect poorly on these illustrious individuals.

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