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Study of Power Conversion Efficiency of a Novel Hybrid L-Band Erbium Doped Fiber Amplifier

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ABSTRACT
High gain and low noise figure are desired features of any erbium doped fiber amplifier (EDFA) based configuration. However, in L band region, low power and quantum conversion efficiencies have restricted EDFA based systems. The paper presents simulation studies of a novel EDFA based high L-band gain configuration which implements two different EDF's in bi-directionally pumped manner. The system shows a non-flattened high gain of 36.6dB for an optimized net EDF of length 30m, pump power of 120mW at 25^0C. It also presented a high power and quantum conversion efficiencies of 37.8% and 57.0%, variations of which are also studied with input signal and pump powers.

Keywords
Erbium Doped Fiber Amplifier, Gain, Noise Figure, Power and Quantum Conversion Efficiency, L Band.

1. INTRODUCTION
Since the fabrication of erbium doped fiber in 1987 [1], a great deal of effort has been made to introduce newer high gain, low noise, high power conversion efficient and low cost configurations. L band optical communication using EDF based configurations along with dense wavelength division multiplexing (DWDM) has increased the capacity immensely. Today commercialized C and L band EDFA are available which can amplify 160 channels. However, low power and quantum conversion efficiencies (PCE and QCE) in L band have challenged researchers to report newer and better configurations. Compressions of backward output ASE power for gain tilt control, and gain enhancement are some of the methods [2, 3]. Others include inclusion of inline fiber grating laser for gain flatness and gain clamping. The gain spectrum of EDFA shows a non-linear, abrupt behavior in the C and L band [4, 5, 6]. The non-linear gain variation of an EDF has also encouraged gain flattening schemes such as Mach-Zehnder filter [7], long period fiber grating [8] and side polished fiber based filter [9].
In this paper, a thorough investigation of PCE and QCE of an L-band hybrid configuration with different parameters has been reported.

As observed form figure 1, the system uses two different erbium doped fibers, EDF-II in between two EDF-I. The fiber amplifiers are pumped in a bidirectional manner by using 980nm and 1480nm laser pumps. An isolator implemented after the source, restrict the reflected power to affect the optical oscillator.

2. EDFA MODELING
According to Giles model [10], it was assumed that only homogeneous broadening occurs and ion-ion interaction is absent in an EDFA. It was further assumed that excited state absorption (ESA), pair induced quenching (PIQ) and Rayleigh backscattering (RBS) of the EDFA are negligible. The rate equations for forward (+) and backward (-) propagation for such a model is given by:

$$\pm\frac{dP_k^{\pm}}{dz}=(\alpha_k + g_k^*)\frac{n_2|av}{n_t|_{av}}P_k^{\pm}+g_k^*\frac{n_2|av}{n_t|_{av}}\, mhf_k\Delta f_k(\alpha_k + l_k)P_k^{\pm} \quad (1)$$

The steady state population inversion equation will be given by:

$$\frac{n_2|_{av}}{n_t|_{av}}=\frac{\sum_k\frac{P_k(z)\alpha_k}{hf_k\zeta}}{1+\sum_k\frac{P_k(z)\left(\alpha_k+g_k^*\right)}{hf_k\zeta}} \quad (2)$$

Where, α_k and g_k^* are the absorption and gain coefficient of the erbium doped fiber. ζ and l_k are the saturation parameter and background loss respectively. $P_k^{\pm}$ is the forward and backward propagating power of the k^{th} spectral component. Whereas $n_t|_{av}$ and $n_2|_{av}$ are the total average Er^{3+} ion concentration and that in the upper level. h and f_k are the Planck's constant and frequency of k^{th} spectral component.
The configuration shown in figure 1 employs DWDM, separated by 50GHz channel spacing. The power/channel is varied for three different values to analyze its effects on power and quantum conversion efficiency. The isolators used have an insertion loss of 0.3dB, isolation of 20dB, input return loss of 60dB and output return loss of 55dB. Two 980nm pumps are used in a bidirectional manner for better noise figure advantage [11].

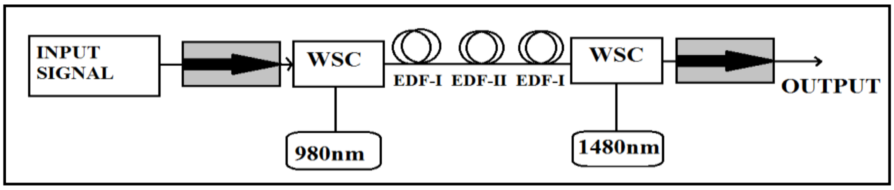

Fig 1: A novel L-band Hybrid EDFA configuration

Bidirectional pumping provides an added advantage in terms of population inversion; small signal gain and provides prolonged uniformity compared to co-directional and counter-directional pumping. The wavelength selective couplers (WSC) have signal and pump insertion losses of 0.2dB; pump and signal isolation of 20dB and 30dB; signal and pump return losses of 50dB and directivity of 55dB respectively. Two different EDF's, EDF-I and EDF-II have saturation parameters (ζ) of 1.6050 x10^{16}/ms and 3.091 x 10^{15}/ms, with input and output splice losses of 0.3dB. EDF-I and EDF-II have absorption peaks of 3.5 and 23-27µm at 980nm. The absorption and emission spectrum of both the fibers are shown in figure 2.

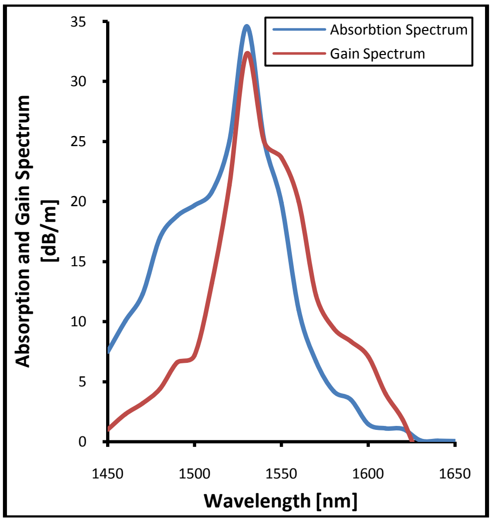

Fig 2: Absorption and Emission Spectra of EDF Type-I

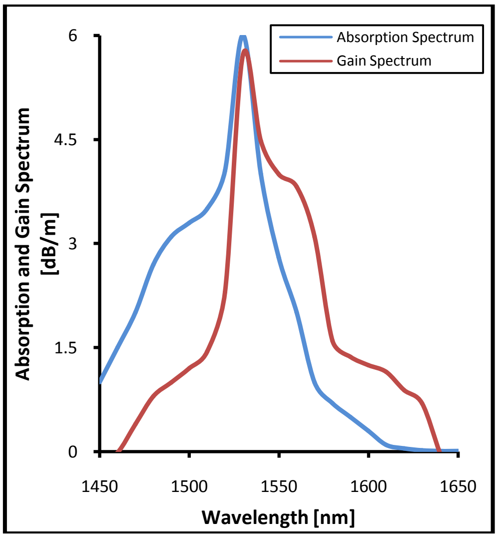

Fig 3: Absorption and Emission Spectra of EDF Type-II

3. RESULTS AND DISCUSSIONS

Booster amplifiers placed just after the input source needs to generate high output power to enhance the launched signal power. To obtain such a high output power, it is essential that large percentage of input light is converted into signal light. Power conversion efficiency is measure of pump power converted to signal power for amplification, a measure of system efficiency in terms of power, and is given by [12]:

$$\text{Power Conversion Efficiency (PCE)} = \frac{(P_{signal\ \ out} - P_{signal\ \ in})}{P_{pump}} \quad (3)$$

The PCE reduces considerably in the L band region. Many newer and better configurations have been proposed, such as dual-band EDFA covering both C and L band [13]. The quantum conversion efficiency (QCE) on the other hand, is more direct measure of efficiency in terms of photon transfer from pump to signal is given by:

$$\text{Quantum Conversion Efficiency (QCE)} = \text{PCE x } \frac{\lambda_{signal}}{\lambda_{signal}} \quad (4)$$

Also, the non-uniformity of gain is another factor which limits the number of channel a system can transmit. A gain over 20dB and noise figure below 5dB is considered ideal for optical communication. Such a gain increases optical signal to noise ratio (OSNR) and reduces bit-error-rate (BER), which is appropriate for receiver. Hence, for systems feasibility, these are important parameters to be analyzed.

3.1 Gain, PCE and QCE versus wavelength for Different pump powers

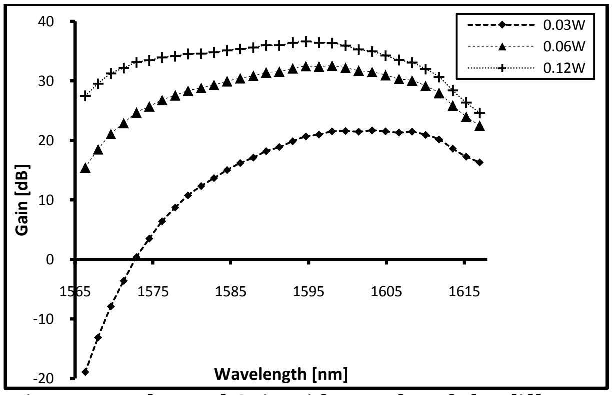

Fig 4: Dependence of Gain with Wavelength for different pump powers of pumps-I and II

Simulation studies of gain variation for pumps-I and II with three different pump powers for both the 980nm pumps: 30mW, 60mW and 120mW (As shown in figure 4) have been discussed. At 30mW pump powers, average gain obtained was at 18.23dB, with a maximum at 21.68dB a poor gain tilt of 29.4dB. The power and quantum conversion efficiency was as low as 3.38% and 5.54%. On doubling the pump power to 60mW, PCE and QCE increased by 7 times to 23.03% and 37.63%. The maximum gain too showed a sharp rise, to 32.52dB with a gain tilt and net average gain of 6.3dB and 29.5dB respectively. When compared to 60mW, at 120mW, PCE and QCE increased approximately 1.5 times to reach 33.28% and 54.26%, respectively and an average gain of 34.10dB with a gain tilt of -1.771dB was obtained. The figure 5 shows the variation of PCE and QCE for different values of pump powers. The PCE and QCE show an exponential rise up to 60mW, which then attains saturation for higher pump powers. PCE and QCE reach values as high as 32.45% and 52.95%. At such a condition, EDFA can operate as power amplifiers without signal distortion and cross-talk.

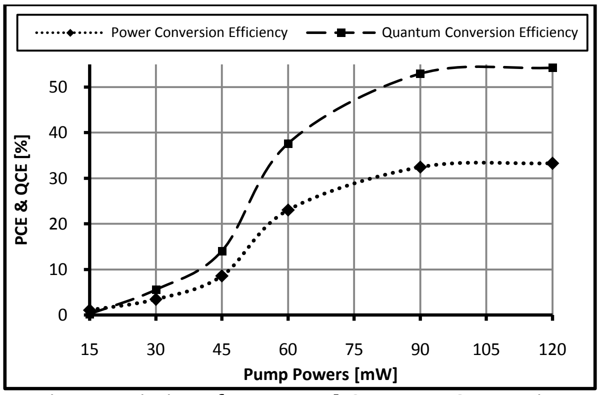

Fig 5: Variation of Power and Quantum Conversion Efficiency variation with pump powers

3.2 Gain and N.F versus Wavelength for Different Input Signal Power

Figure 6, shows the gain curve with varying signal power/ channel for different signal wavelengths. At lower ends of L band region, there is a steep fall of EDFA gain, but at higher wavelength region the gain fall is gradual. With increase in signal power, inversion is depleted, this reduces the gain considerably and increases noise figure (N.F), as shown in figure 7. As the signal output values exceed saturation values noise figure rises sharply. At higher input power signal, depletion of inversion occurs which can no longer be compensated by the pump. The signal robs gain from the backward amplified spontaneous emission (ASE), reducing gain and increasing N.F. And at even higher input signal power level, the noise figure attains a near constant value.

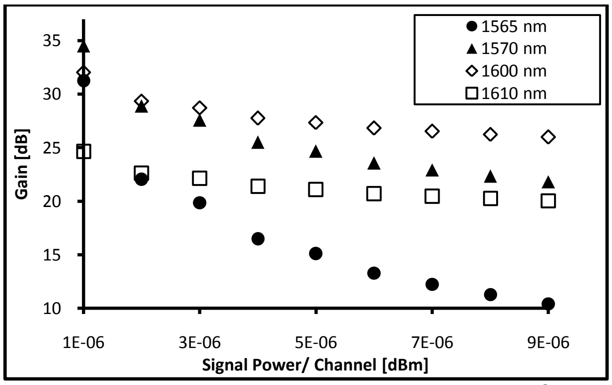

Fig 6: Gain variation with Signal power/Channel for different signal wavelengths

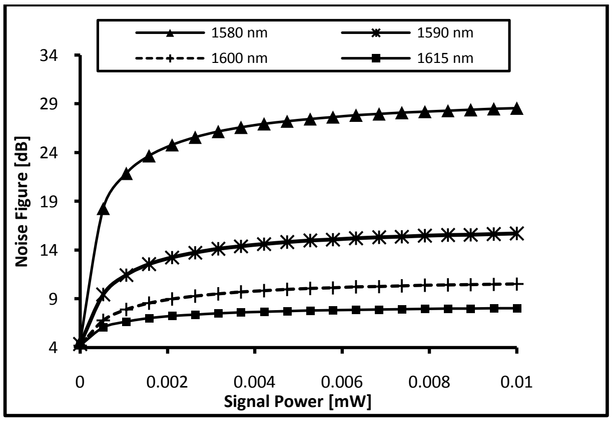

Fig 7: Noise Figure Variation with input signal powers for different signal wavelengths

3.3 Power and Quantum Conversion Efficiency for variable Amplifier Lengths

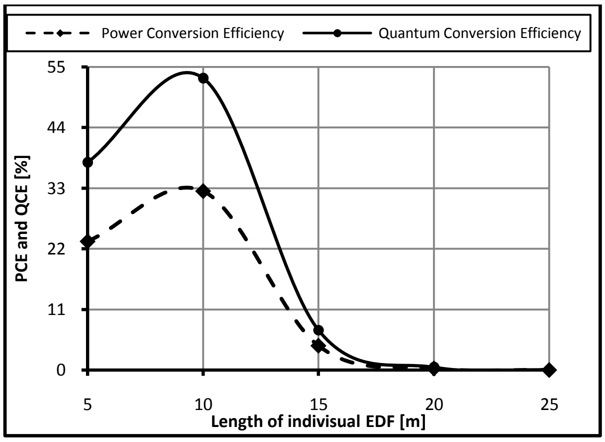

Fig 8: Variation of Power and Quantum Conversion Efficiency with amplifier length

As shown in figure 8, both power and quantum conversion efficiencies show a sharp increase with increase in length of individual erbium doped fibers (EDF's). For individual EDF lengths of 5m (15m in total), PCE and QCE values are 23.40% and 37.68%, which increased to a maximum of 32.70% and 52.95% for 10m EDF lengths, respectively. Such an increase in PCE and QCE is extremely encouraging, since it provides better inversion ratio and output gain. However, as the EDF length is increased further, PCE and QCE falls off monotonically to 4.43% and 7.27% at 15m individual EDF lengths and continues to decrease, eventually reaching near zero values at 20m EDF length. As evident from the figure, at 10m, the fiber reaches maximum inversion and any further increase above the optimum EDF length with constant pump power introduces ASE noise, without any considerable increase in gain. High power conversion efficiency in 65-80% has been reported in C band region [14]. Considerable increase in Aluminum doping and optimizing numerical apertures accordingly can result in further improvement as [15]. However increasing Er^{3+} ion concentration results in quenching effects and hence, reduces power and quantum conversion efficiencies.

3.4 Power and Quantum Conversion Efficiency for variable Input Signal Powers

With constant EDF lengths and pump powers of 10m and 120mW respectively, the power and quantum conversion efficiencies with input signal powers has been plotted in figure 9. It may be observed from the figure that as signal power increases, initially more and more pump power is transformed to amplify the signal wavelength, hence both PCE and QCE at -40dBm increase gradually from 9.36% and 1.18% respectively to a steady value of 36.63% and 56.93% at -20dBm. With further increase in the signal power, saturation occurs and inversion is reduced, resulting in a constant PCE and QCE, as output. However, above 0dbm, the PCE and QCE start to fall; this is so because the erbium ions now undergo absorption instead of emission. Hence there is a point beyond which any increase in input signal power will not be efficient in terms of power and gain.

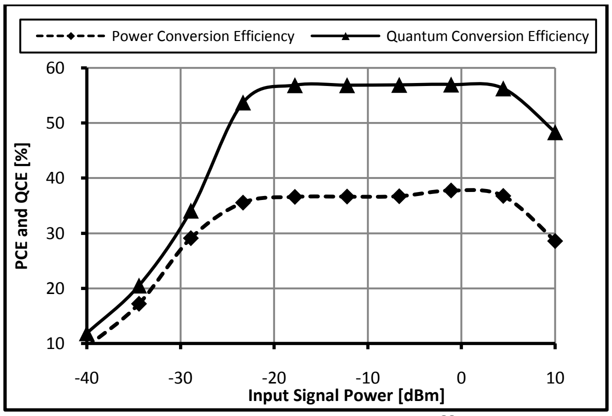

Fig 9: Power and Quantum Conversion Efficiencies with varying input signal power

4. CONCLUSIONS

An attempt has been made in this paper to investigate the power and quantum conversion efficiencies of a novel L band EDFA, which implements two EDF's having different saturation, absorption and emission spectra. As evident from the figures, the configuration provides a high gain of 34.01dB at 120mW pump powers. The system also depicts an improved power and quantum conversion efficiencies, reaching as high as 32.70% and 52.95% from 10m amplifier length. The paper also discusses the saturation effects of the system in terms of PCE and QCE with input signal power, where it remained constant at 36.63% and 56.93%. It has always been a challenge to increase the PCE at L band optical communication with EDFA. Further improvement in PCE and QCE is possible with rightful use of Aluminum (Al) concentration and host composition.

Table 1. Power Conversion and Quantum Conversion Efficiencies with input signal power

Input Signal Power (dBm)	PCE (%)	QCE (%)
-40.0	9.36	11.8
-34.45	17.23	20.5
-28.89	2.91	34.1
-12.23	36.6	56.94
-1.11	37.8	57.0
10	28.6	48.3

Table 2. Power Conversion and Quantum Conversion Efficiencies with pump power

Pump Power (mW)	PCE (%)	QCE (%)
15	0.99	0.164
30	3.382	5.548
45	8.556	14.011
60	23.031	37.632
90	32.456	52.948
120	33.285	54.26

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