Experimental study of EDFA Gain-Block for Booster Amplifier at C-band regime

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ABSTRACT

Erbium-doped fibre amplifiers (EDFA's) are realized to apply in a wide range of applications like metro-DWDM and CATV networks. These applications require the EDFA to provide maximum output power level by accepting input power at near saturation level. To get such an ideal amplifier among several parameters, erbium concentration in the composite core glass, optimum length of fibre, pump saturation and input signal SNR are to be critically studied and addressed. In an attempt few EDFA gain-blocks for power amplifier in laboratory scale have been designed and experimented with good power conversion efficiency (PCF) and better noise figure (NF). Experiments in different pump configurations, like co-, counter and bidirectional in varying concentrations of erbium doped fibres (EDF) have been performed after optimizing the fibre-length. It was observed that output power is high both in counter and bidirectional pumping scheme than that of co-directional pumping. But the output SNR is high, i.e., noise figure (NF) is low in co-directional pumping compared to other two directions. The gain characteristics in WDM system for different input signal powers have been studied. Some critical inherent fibre-parameters at near saturated input power level and in different configurations have been optimized in order to get better device performances.

Keywords: Booster Amplifier, Power Conversion Efficiency, Saturation Output Power, EDFA, CATV, WDM

1. INTRODUCTION

The erbium (Er)-doped fibre amplifier (EDFA) with a flattened gain at C-band (1530–1565 nm) is a key device for wavelength division multiplexing (WDM) systems in modern optical networks[1,2]. The development of erbium doped fibres with improved optical characteristics such as flat gain in the C band region initiated modification and improvement of the optical modelled fabrication methods. The main parameters in designing an EDFA include the fibre characteristics, optimization of length, pump source characteristics, and other passive components[3,4]. While designing an Er-doped fibre, the glass composition, waveguide characteristics, erbium concentration and its distribution are the important issues to be studied for translating into real efficient fibre. Among different applications of EDFAs, power amplifier or booster amplifier with high output for multiple splitting in CATV and long distance repeater-less WDM network is now getting modified due to the emergence of broadband application. A good booster amplifier should have high power conversion efficiency, high saturated output power and low noise figure. The important parameters affecting these are the spatial mode overlapping of the pump and signal light with the distribution of the erbium ions in the fiber core. Small modal field facilitates the pump light for efficient coupling with the narrow profile of Er-distribution into the core.

Erbium implantation into the core of the fibre is not an easy task as we optimized different rare earth doping processes by various means which have been described elsewhere[5,6,7]. Besides, stimulated emission that creates gain, the gain medium participates in amplified spontaneous emission (ASE) and up-conversion processes[8] by depleting pump energy in different Stark manifolds of higher energy levels. To counter these problems EDF has been modeled critically and then synthesized into good quality fibre.

In the next part of this presentation, performances of different EDFA configurations in high power multiwavelength environment pumped by strong 980 nm wavelength stabilized laser lights have been experimentally studied of selected EDF samples for its ultimate device application.

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2. MODELING:

Typically the spatial models are used to design the waveguide and doping parameters of the fibre, while the spectral models are used to characterize the amplifier performance[3].

2.1 Spatial-Mode Modeling:

Here we have examined our fiber design using Optiwave Fiber-CAD design software where a step approximation to the core-index profile and a weakly guided approximation for the optical-mode distribution has been considered. Since, for efficient functioning of EDFA, fiber design should be such that it always supports the propagation of fundamental LP_{01} mode both for pump and signal light. In our design software, we have taken the pump source at 980 nm and signal source at 1550 nm. In the figure-1, the refractive-index profile of an erbium-doped fibre (EDF) has been shown. Also in the figure-2a and 2b, the normalized intensity distributions of the fundamental mode (LP_{01}) both for pump and signal in the fibre core has been shown. Then the overlapping factor of the optical modes with the erbium ion distribution had been calculated. The portion of the optical mode which overlaps with the erbium ion distribution will stimulate absorption or emission from the Er^{3+} transitions. The entire mode, however, will experience gain or attenuation as a result of this interaction. Therefore, it will be advantageous to dope the erbium only in the very centre of the fibre core because the erbium ions will only see the very high intensity portion of the optical mode and the pump will more easily invert the maximum number of Er^{3+} ions resulting more power conversion efficiency.

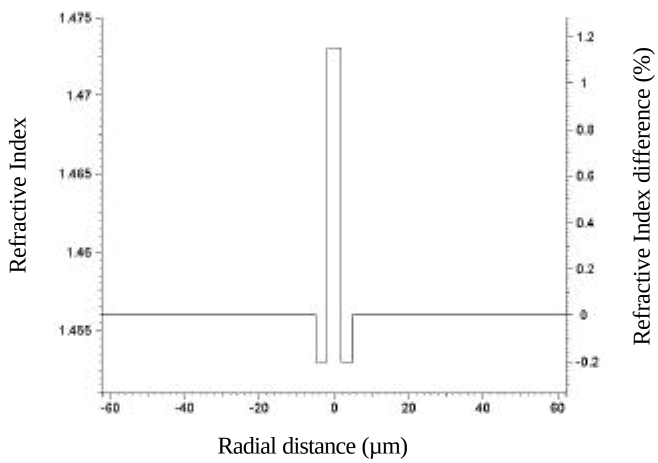

Figure 1: Refractive Index profile Profile of an EDF

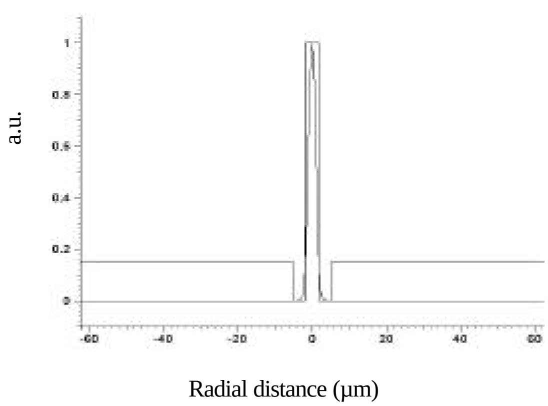

Figure 2a: Confinement of 980 nm pump light

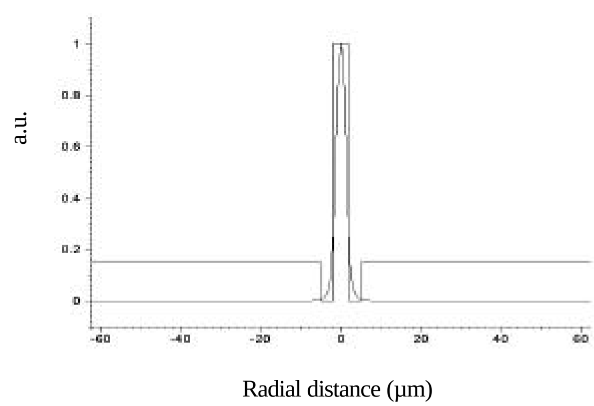

Figure 2b: Confinement of 1550 nm signal light

2.2 Spectral Modeling:

The absorption and emission spectra of the Er^{3+} ion are signatures of the energy states of its 4f inner electrons. In a glass host, these energy states are modified by local electric fields that causes Stark-splitting and by dynamical perturbation, i.e., thermal or homogeneous broadening. Inhomogeneous broadening results from the structural disorder of the glass. Other dopants added to the glass may alter these effects. Rare-earth ions in silicate glasses are too large to occupy interstitial sites and are more easily incorporated into the glass structure by adding a network modifier such as aluminium (Al), to produce non-bridging oxygen to which the rare earth attaches. The fibres mentioned in the Table-1 contain oxides of germanium and Al in the core. Adding Al in the core improves the solubility of Er^{3+} in glass structure and also broadens the amplifier gain spectrum. Two main fibre characteristics are loss spectrum $a(\lambda)$ and gain spectrum $g^*(\lambda)$ which are given by $a(\lambda) = s_a(\lambda)\ ?(\lambda)\ n_t$ and $g^*(\lambda) = s_e(\lambda)\ ?(\lambda)\ n_t$, where $?(\lambda)$ is the overlap integral between the optical mode and the erbium ions distribution and n_t is the concentration of erbium ions. The absorption and emission cross sections are $s_a(\lambda)$ and $s_e(\lambda)$ respectively. The loss spectra are measured using a white light source and monochromator (Bentham) which is shown in the figure. The gain spectra are measured (Agilent Lightwave Measurement System) with a high pump power at 980 nm to fully invert the Er^{3+} population to the metastable state $^4I_{13/2}$. The maximum gain that can be achieved in an EDF of length L and peak Er-ion concentration ρ_0 is given by $G_{max} = \exp(\rho_0\ \Gamma_s \sigma_{es} L)$, corresponding to regime of complete and uniform medium inversion level[11]. Γ_s is overlap factor and σ_{es} emission cross-section of the signal. For maximum signal gain, the fibre length has been optimized through simulation by taking the values of input pump power, signal power, Er-ion concentrations, overlapping factors and fibre waveguide parameters. Attempt has been made to measure the absorption and emission cross sections of discrete wavelengths and to relate the characteristics with the measured gains at optimized fibre length and pump power.

3. EXPERIMENTAL:

3.1 MCVD and Solution doping:

We have fabricated erbium doped fibre[5] by MCVD process where matched or depressed cladded structure has been formed inside a silica glass substrate tube followed by deposition of porous silica soot layer containing dopants such as GeO_2, P_2O_5 for formation of the core. The soot layer was deposited both by forward and backward deposition methods[6,7]. The preform cores composed of GeO_2 / P_2O_5 / SiO_2 glasses with GeO_2 level in the range of 3 to 15 mol% and P_2O_5 up to 5 mol%. The deposited soot layer was soaked in alcoholic / aqueous solution of the erbium salts containing codopants such as $AlCl_3$ in definite proportion. Further processing involved oxidation, dehydration and sintering of the RE containing porous deposit followed by collapsing at a high temperature to produce the preform. All the above steps required rigid control of process parameters to avoid evaporation of dopants including the RE chlorides. A particular temperature sequence was followed depending on the host glass composition and the proportion of Er/Al concentration to minimize change in composition during sintering. Additional $GeCl_4$ was supplied during collapsing stage inside the deposited substrate tube to neutralize the evaporation of GeO_2 from the core and to avoid the refractive-index dip at the center. With appropriate overcladding of the perform, fibre drawing was accomplished in 9.5 metre high fibre drawing (Heathway) tower applying soft and hard buffer coating to get suitable core-clad dimensions and geometry.

3.2 Measurement of waveguide parameters and erbium concentration:

The Refractive index (RI) profile shown in figure-3a of an erbium doped perform was measured by Preform Analyzer (Model: Photon Kinetics, PKL 2600) and that of erbium doped fibre was measured by Fibre Analyzer (Model: EXFO, NR-9200) as shown in figure-3b.

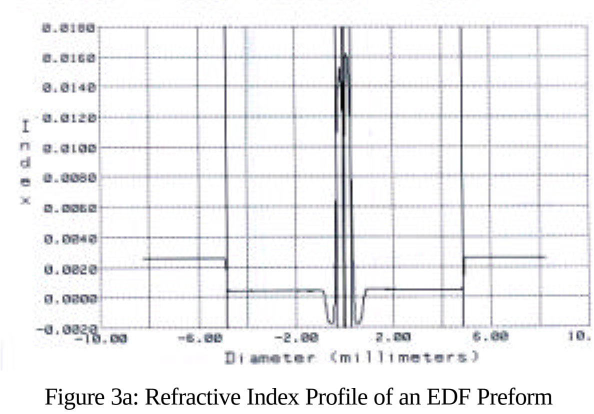

Figure 3a: Refractive Index Profile of an EDF Preform

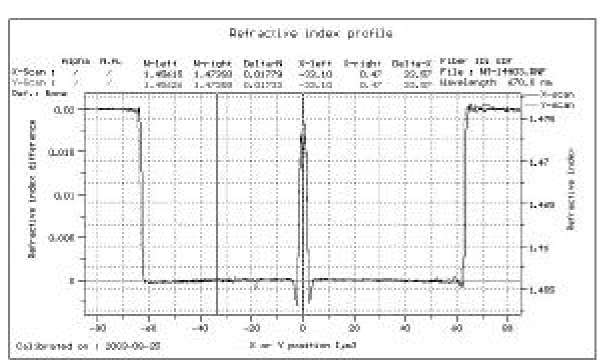

Figure 3b: Refractive Index Profile of an EDF

The measured parameters helped in fabricating the desired fibre configuration like core-clad geometry, mode field diameters etc. with high accuracy.

In order to pump EDF fibre at its characteristics absorption peak at 980 nm for optical amplification, cut off wavelength of the fibre should be near 980 nm. Er distribution profile as shown in figure 4a of an EDF was done by a fluorescence confocal spectroscopy. The spectral attenuation characteristics of Er doped fibres shown in figure with varied erbium concentration in the core were studied from the spectral range of 800 nm to 1600 nm (Model: Bentham) by Cut-back method. Er-ion concentration of the fibres were estimated from its characteristics absorption peaks at 980 nm and 1530 nm by comparing with standard fibre as well as measured through confocal microscopy.

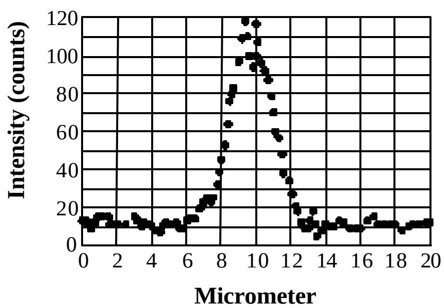

Figure 4a: Fluorescence of an EDF

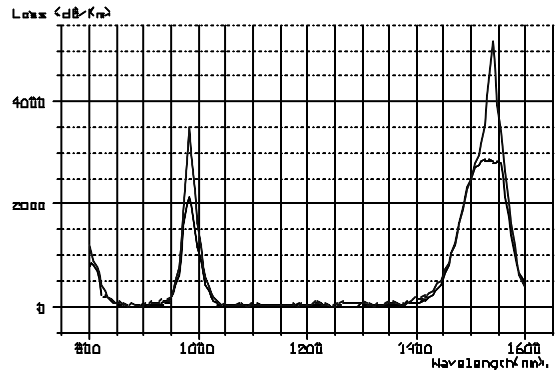

Figure 4b: Spectral attenuation curves of EDFs (F1 & F3) of different Er^{3+} concentrations

The waveguide parameters and erbium concentrations of some of the fibres are shown in Table-1:

Table-1: Waveguide parameters and erbium concentrations in different fibres

Fibre Sample	Core/Clad ratio	NA	Measured Cut-off wavelength (λ_c), nm	Overlapping factor for pump & signal (?$_p$) (?s)	Er^{3+} Conc.
F1	3.10 ± 0.05/125	0.22	815	0.77 0.49	~750 ppm
F2	3.55 ± 0.05/125	0.20	820	0.79 0.52	~750 ppm
F3	3.20 ± 0.05 /125	0.23	930	0.80 0.55	~450 ppm

3.3 Fluorescence life time measurement:

The fluorescence life time τ of the $^4I_{13/2}$ level was measured by pulsed excitation from a pump source as shown in figure-5. The pulse was generated by chopping a CW pump laser. The fluorescence pulse can be monitored in the longitudinal direction through a high density pump-blocking filter. To ensure that no stimulated emission or spurious

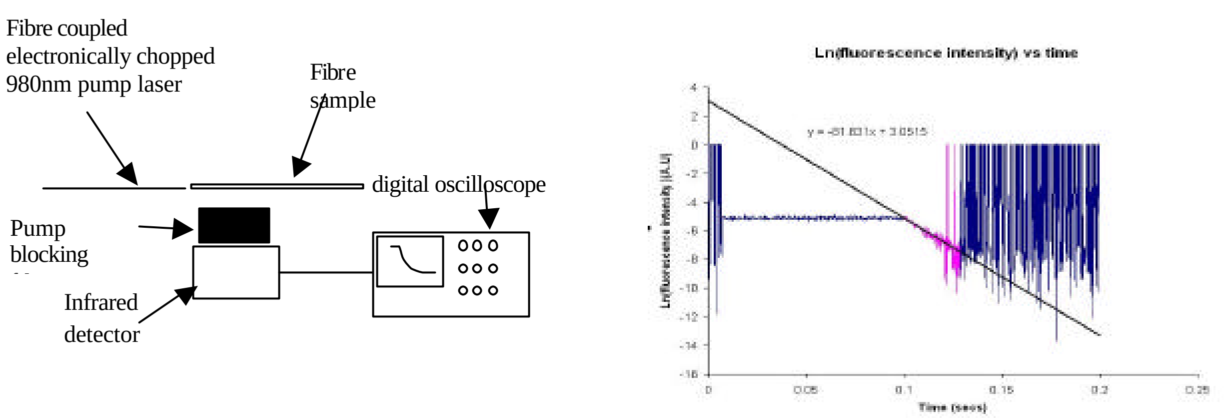

Figure 5: Life time measurement of F1

lasing effects occur, the 1/e characteristics delay time τ should be independent of pump power, past a certain level. In our fibre sample F-1, the measured life time is 12.2 ms which is good enough to get efficient gain characteristics. This enables us to measure the absorption and emission cross sections for comparing the calculated data.

4. RESULTS and DISCUSSION:

4.1 Choice of Fiber Length and Direction of Pumping Issues:

The effects of fibre length and the pumping configuration were investigated for 980 nm pumped EDFA as shown in figure-6. For a given pump power, to obtain the maximum gain / output saturation power for a given erbium concentration in the fibre core, the fibre length should be optimized. The optimum fibre length (Lopt) for maximum output power at saturated regime was calculated both from the spatial model and experimentally. We observed that the optimum fibre length increases with pump power and decreases with the signal power[9].

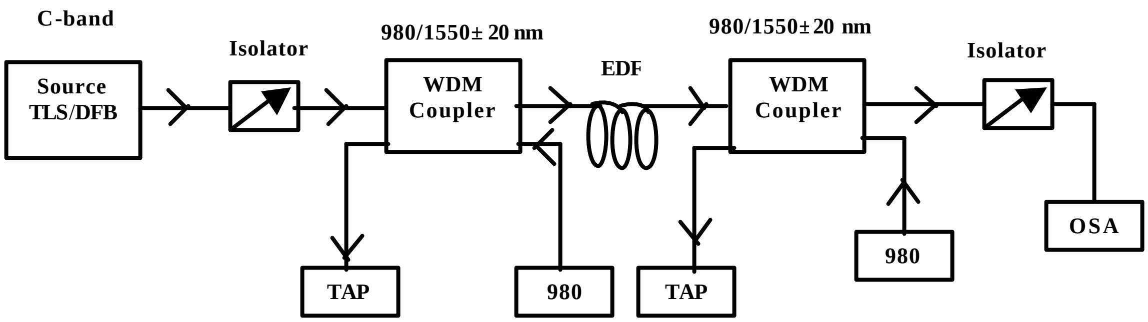

Figure 6: Schematic diagram of an EDFA Gain-Block

Three different pump configurations were used for pumping a length of erbium-doped fibre: co directional, counterdirectional and bidirectional pumping. It was observed that output power is high both in counter and bidirectional pumping scheme than that of co-directional pumping. But the output SNR is high, i.e., noise figure (NF) is low in co-directional pumping compared to other two directions. One such experimental result of fibre F3 is shown in Table-2:

Table 2: Output signal power and NF of EDF F3 at different pump directions:

I/P signal wavelength = 1550 nm, I/P signal power = + 0 dBm, Pump wavelength = 980 nm, Pump power = 60 mW		
Pumping direction	O/P signal power (dBm)	Noise Figure (dB)
Co-directional	13.3	4.8
Counter-directional	14.4	8.5
Bi-directional	14.0	5.4

4.2 Measurements of basic parameters of EDFA:

A useful parameter for the booster EDFA is saturation output power P^{out}_{sat} , defined conventionally as the output power for which the EDFA gain has dropped by 3 dB below its unsaturated gain value[10,11]. It was observed from the figure-7 that the values of P^{out}_{sat} varied due to the waveguide parameters of the fibre. Another important parameter is the EDFA saturated output power, generally referred to as the maximum output signal power that can be achieved under given experimental conditions. The saturated output power increases with the input signal and pump power as shown in the figure-8.

It is expected that the maximum output power can be, at most, as high as the input pump power when complete power conversion between pump and signal occurs. The value of P^{out}_{sat} is more relevant to characterizing the EDFA, since it represents a threshold value for the transition between linear and non-linear gain regimes of the amplifier. The saturation output power and gain can vary significantly from one fibre type to the other for fixed pump power[12]. For a given pump power level, the maximum gains or saturation powers are observed to depend on fibre designs and glass types. The measured gain and noise figure of an EDF (F3) of length 20 meter at pump power 70 mw @ 980nm by varying the signal power from -30 dBm to +5 dBm at 1550 nm are shown in figure-9.

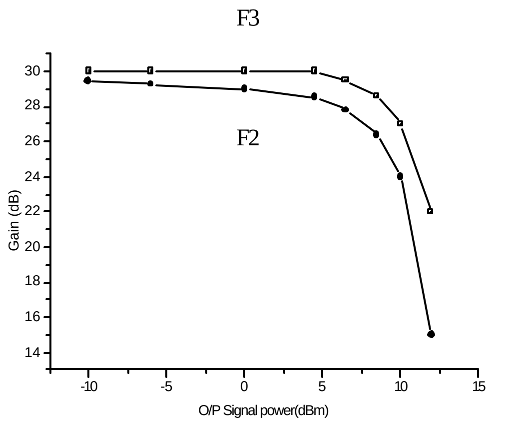

Figure 7: Gain v/s O/P signal for two different EDFs at const. pump power

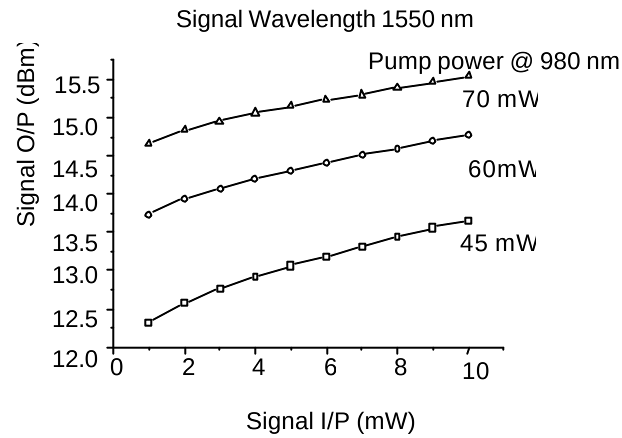

Figure 8: O/P signal v/s I/P signal at different pump power for EDF F1

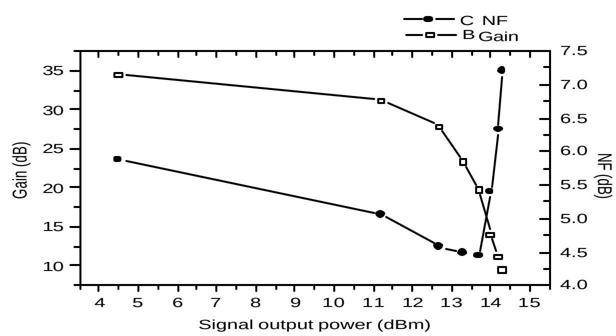

Figure 9: Gain & NF at different O/P signal power of EDF- F3

Another parameter of booster EDFA that is operated in the saturation regime in order to yield a maximized output signal power is power conversion efficiency (PCE) which is defined as[10]:

$$PCE = (P^{out}_{s} - P^{in}_{s}) / P^{in}_{p}$$

It is observed that PCE depends on fibre length and pumping configurations. We obtained 50% PCE corresponds to 79% quantum conversion efficiency at 980 nm pump wavelength. Efficient power amplifier should consume optimum pump power to make it cost effective.

As an example in CATV optical transmission network, an EDFA with output power of 16 dBm (40 mW) is required before splitting it into channels for onward transmission over several kilometers of each single mode fibre. In one of our experiments, we obtained saturated output power + 21 dBm (126 mW) for + 0 dBm (1mW) input signal at 1550 nm wavelength by putting 250 mW pump power at 980 nm wavelength in bi-directional pumping configuration. The high input launch power, particularly for CATV application, degrades the system performance by causing stimulated Brillouin scattering (SBS). Closely spaced time-varying electric fields while propagating through a fibre interact with the acoustic vibrational modes of core materials resulting scattering of incident light. Larger the input threshold, more light would be backscattered. The onset of SBS process depends on number of parameters including wavelength and line width of the optical pulse. As a result discrete output power in the range 13 to 23 dBm is being designed with the input power varying from +0 to 10 dBm for CATV network system.

To realize flat gain over a selective input WDM channels several experiments have been carried out. The measured gain shown in figure-10 from 1530 to 1560 nm by swiping the input signal from a tunable laser source (Model: 8164B, 81689B, Agilent) corresponds to 19.5 ± 0.5 dB intrinsic flat gain at -10 dBm input signal power level.

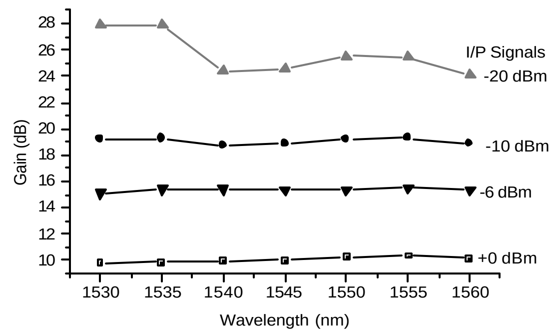

Figure 10: Spectral variation of Gain at C-band at swept mode foe EDF F1

The shape of a single erbium-doped fibre amplifier gain profile may appear more flat when the amplifier is in saturation, from the point of view of a single wavelength being swept across the gain spectrum. This does not however, imply that the amplifier gain is flat over that wavelength range with respect to multiple signal inputs present simultaneously shown in figure-11 because, the EDFA gain spectrum depends on the particular absorption and emission cross-section line shapes of the EDF, and the gain medium inversion along the fibre length. In WDM, amplification of each channel depends on the number of input channels present and also the channel spacing[9]. We measured the gain at different pump powers shown in figure-12 and at different input signal powers shown in figure-13 for 8-channels WDM system (DWDM Test-Bed, EXFO) at fixed fibre length of EDF F2. It was observed that the spectral flatness of the gain at C-

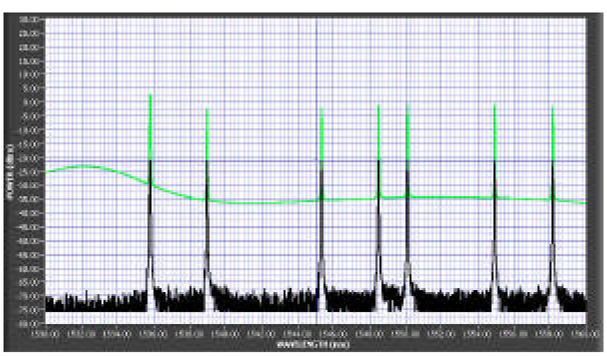

Figure 11: I/P & O/P power of 8-channels WDM system for EDF F2

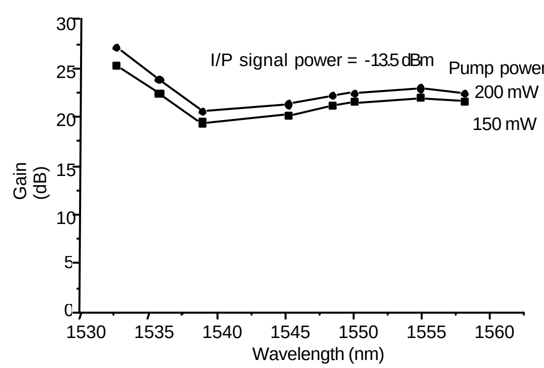

Figure 12: Gain curve of 8-channels WDM system at different pump power for EDF F2

band depends on the input signal level. When the EDFA operated at saturated input signal, the gain is high at red side of C-band and gradually increased to blue side of C-band as input signal level decreased. Small signal gain is high at 1530 nm regime due to its higher emission cross-sections than 1550 nm regime but at the same time more medium inversion is required at 1530 nm than that of 1550 nm.

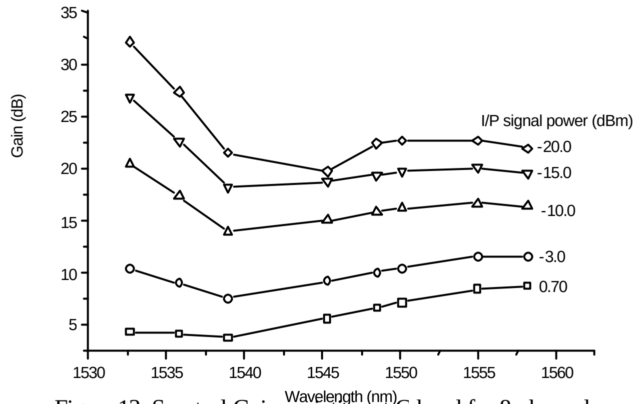

Figure 13: Spectral Gain variation at C-band for 8-channels WDM system of EDF F2

Therefore fibre length should be chosen in such a fashion that optimized flat gain is obtained in WDM application. Also, to achieve the gain flatness in WDM system at C-band, gain flattening filter (GFF) should be used. However as reported earlier[2] higher concentration of Al plays a significant role for obtaining suitable gain flattened regime independent of GFF. At CGCRI we are pursuing this work to develop commercial module for various applications.

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REFERENCES:

1. ‘Amplifiers for the masses: EDFA, EDWA, and SOA amplets for metro and access applications’, D.R. Zimmerman and H.S. Spiekmann, Journal of Lightwave Technology, **Vol. 22 (1)**, p. 63, 2004.
2. ‘Development of rare-earth doped fibres for amplifiers in WDM systems’- S.K.Bhadra et. al, IEE Proc. – Circuits, Devices and Systems, **Vol. 150(6)**, December 2003.
3. ‘Modeling erbium-doped fiber amplifiers’, RANDY C. GILES AND DESURVIRE E., *Journal of Lightwave Technology*, **Vol. 9(2)**, p. 271, 1991.
4. ‘Design considerations for an Er^{3+} -doped fiber amplifier’, M. Ohashi, Journal of Lightwave Technology, **Vol. 9 (9),** p. 1099, 1991.
5. ‘*Solution*-doping technique for fabrication of rare-earth-doped optical fibre’, TOWNSEND J.E., POOLE S.B., AND PAYNE D.N., *Electronics Letters*, **Vol. 23**, p-329, 1987.
6. ‘A method for fabricating rare earth doped optical fibre’, Ranjan Sen, Tarun Bandyopadhyay, Shyamal kumar Bhadra, Kamal Dasgupta, Mukul Chandra Paul, **PCT WO 02/060830 A1**
7. ‘A method of fabricating rare earth doped optical fibre’, Ranjan Sen, Mrinmay Pal, Mukul Chandra Paul, Shyamal Kumar Bhadra, Somesh Chatterjee, Kamal Dasgupta, **PCT WO 03/082756 A1**
8. ‘Effects of concentration on the performance of erbium-doped fiber amplifiers’, MYSLINSKI, P., NGUYEN, D., AND CHROSTOWSKI, J.: *Journal of Lightwave Technology*, **Vol. 15(1)**, p. 112, 1997.
9. ‘Multichannel amplification in strongly pumped EDFAs’, Inna Nusinsky, Amos A. Hardy, Journal of Lightwave Technology, **Vol. 22 (8)**, p. 1946, 2004.
10. DESURVIRE E.: ‘Erbium Doped Fiber Amplifiers -Principles and Applications’, John Wiley & Sons, USA, p. 306, 1994.
11. BECKER, P.C., OLSSON, N.A. AND SIMPSON, J.R.: ‘Erbium doped fiber amplifiers - fundamentals and technology’, Academic Press, USA, 1999.
12. ‘An investigation of the noise figure and conversion efficiency of 0.98 µm pumped erbium-doped fiber amplifiers under saturated conditions’, R.G.Smart, J.L. Zyskind, J.W. Sulhoff and D.J. DiGiovanni, IEEE Photonics Technology Letters, **Vol. 4(11),** p. 1261, 1992