The design and fabrication of high performance Er^{3+} fibre devices

J.E.Townsend, M.N.Zervas and R.I.Laming
Optoelectronics Research Centre,
University of Southampton, SO9 5NH, UK

ABSTRACT

Optimisation of both fibre and device design is essential for maximum performance from erbium doped optical fibres as either line, pre- or power amplifiers, with optimum fibre composition and geometry being unique for each application. The field is extensive but selected examples are reviewed to indicate the range of device configurations and fibre structures available.

Key advances include, via fibre design the development of ultra high gain efficiency for reduced pump power requirements and hence increased reliability of practical systems. Further, use of a novel device configuration allows exploitation of high gain efficiencies without compromising noise levels for a pre- or line amplifier.

Power amplifiers demonstrating high output powers even at elevated signal levels are sought for many communications systems including local area networks. Both amplifier configuration and fibre composition have been investigated in the pursuit of output signals in excess of 20dBm. The relative merits of these systems are discussed and future direction indicated.

In summary, it is shown that optical fibre fabrication plays a key role in optimising performance whilst the versatility of fibre circuitry allows full exploitation of the fibre potential.

1. INTRODUCTION

In the six years following the first demonstration[1] of the Er^{3+} doped fibre amplifier (EDFA) the subject has been extensively investigated with considerable effort directed towards optimising the device. As a result, the performance of an EDFA has been found to be determined by a large number of factors.

Practical fibres for telecommunications applications are silica based with around 10-15mol% of index modifying material, although other glass hosts have been investigated[2]. These additional glasses have a significant effect on the Er^{3+} ion characteristics. GeO_2 gives a higher emission cross section[3] than the other widely employed component, Al_2O_3, but the gain spectrum is less flat and so Al_2O_3 might be preferable for wavelength division multiplexing applications. Various techniques[4,5] have been developed to overcome this problem and further flattening the gain spectrum, for example by the use of a fibre notch filter[5] integral to the EDFA.

The maximum dopant concentration and hence minimum device length is also host dependent. Rare-earth ions have limited solubility[6] in the tetrahedral GeO_2-SiO_2 lattice but are slightly more soluble in aluminosilicate structures. A maximum concentration around 100ppm (atomic) (7.5dB/m, assuming total mode/dopant overlap) is suggested[7] in GeO_2-SiO_2 core fibres before the onset of ion-ion interactions[8,9] due to clustering reduces emission efficiency. However the addition of alumina allows doping levels of up to ~1,000ppm (60dB/m in Al_2O_3, assuming total mode overlap) to be used.

Both hosts exhibit similar excited state absorption (ESA) spectra[10], leading to a limited choice of pump wavelength. In practice, the system is pumped at one of two wavelengths[11,12], 980nm or around 1,480nm. Of these, 980nm offers the potential for a quantum limited (3dB) noise figure[11] (NF) whilst in- band pumping near 1,480nm can offer a flatter gain spectrum and relaxed geometric constraints. Alternative pump wavelengths have been considered, for specialised applications, in particular in power amplifiers where high pump powers are required for high gains and large signal levels. To exploit the power available from sources such as Nd:YAG, which can not be used to pump directly the ion, Er^{3+} is sensitised with a codopant. The sensitiser, typically Yb^{3+} absorbs at the chosen pump wavelength but also efficiently transfers this pump energy to Er^{3+}, leading to 1.5μm emission.

The fibre geometry is defined in terms of the distribution of dopant in the core, second mode cutoff wavelength (λ_c) and numerical aperture (NA). Confinement of the dopant to the core centre[13], and/or use of a short cutoff wavelength, around 850nm for 980nm pumping give improved overlap between pump mode and dopant distribution, resulting in high pump efficiency.

Trade-offs[14] between high pump power density for high gain efficiency and low noise determine the optimum NA as well as confinement. Currently values of order 0.24 appear typical. However, the level of noise is partially determined by the EDFA pump configuration used[15]. In a counterpropagating scheme the NF is adversely affected by a low pump intensity at a point of low signal and low inversion thus, for line amplifiers the copropagating configuration is preferred.

The criteria outlined above need to be addressed for each device design and specific examples are given here to indicate the potential of and limits to the performance of optimised devices.

2. EXAMPLE DEVICES

2.1 High gain efficiency

The reliability of practical EDFAs is strongly dependent on that of the pump diode and can be improved by reducing the pump power requirements. Thus high gain efficiency fibres are sought. Gain performance is determined by the parameters outlined above and a theoretical analysis[16] indicated that, for a lossless GeO_2-SiO_2 host a numerical aperture of 0.4 and dopant confinement factor (radially) of 0.5 a gain efficiency in excess of 23dB/mW could be anticipated. However, it has subsequently been shown[17] that background losses are significant at these NAs and, in practice, the best reported result[18] of 11dB/mW corresponds to a NA of 0.28. The germanosilicate core fibre employed doped with 81ppm Er^{3+} was prepared by the VAD process[19].

Data are plotted in Figure 1 indicate the dependence of normalised gain efficiency on normalised pump loss for fibres of various NAs. The pump loss is normalised to the maximum signal absorption whilst the gain efficiency is normalised to that of lossless system. In this case, an increased NA is found to render the NA more tolerant to pump background loss as well as increasing absolute gain efficiency. However, base line loss shows a strong dependence on NA in GeO_2-SiO_2 core fibres[20] due to increased Rayleigh scatter. The minimum loss of 5dB/km at 980nm for 0.3NA increases to 16dB/km with 0.34 NA. This increased loss can not be compensated by reducing the device length with an increase Er^{3+} concentration due to the onset of ion-ion interactions around 100ppm so placing a practical constraint on the optimum NA and confinement factor. For example, assuming 100ppm Er^{3+} in a germanosilicate core fibre with optimum λ_c, 850nm, and a confinement factor of 0.5 with net signal absorption of 1.7dB/m (including modal overlap terms) a pump loss of 17dB/km (1%) is achieved for a NA of 0.34. With reference to Figure 1, this combination is seen to give rise to 90% of the ideal lossless efficiency[16] (17.6dB/mW), thus a gain efficiency of ~16dB/mW might be achievable.

However, this result is strongly fabrication process dependent. Er^{3+} doped germanosilicate core fibres prepared by the MCVD technique tend to exhibit a lower concentration at the core centre leading to reduced overlap efficiency. As a worst case, the effective overlap is reduced by a factor of two, thus, for the above design criteria but with no confinement possible, a maximum gain efficiency of only 11dB/mW might be achieved.

2.2 High gain low noise preamplifier

Gains in excess of 30dB and low noise (3dB) are required for high sensitivity optical pre-amplifiers to overcome the thermal noise of the electrical receiver. However, there is a trade-off between noise and gain efficiency[15], due primarily to amplified spontaneous emission (ASE). As described above high gain efficiencies are achieved with increased NAs this is at the expense of an increased noise figure. As a result it is not possible in a standard configuration with practical 980nm pump powers to achieve gain (>30dB) simultaneously with 3dB NF.

These limitations may be overcome by placing an isolator[21] in the system, as shown in Figure 2, to suppress backward ASE. Two WDM couplers allow the pump to bypass the isolator which is lossy at 980nm and typical signal losses are 2dB in the forward direction and 30dB in the reverse. The model indicates that no further benefit is gained by increasing the extinction ratio, for a single amplifier, although this may be beneficial in a system configuration.

Conventional optimised fibre is used in the configuration with 0.24NA, λ_c of 900nm and less than 100ppm Er^{3+} in GeO_2-SiO_2 being typical. Modelling[21] of the optimum position for the isolator shows that for gains greater than 30dB the isolator should be located ~30% along the fibre. With reference to Figure 3, it may be seen that an optimum range exists over which gain and noise remain virtually fully optimised. It should be noted that owing to the elimination of saturation by backwards ASE pump power absorption occurs over longer lengths and the optimum length is increased by ~80%.

The effectiveness of the isolator has been confirmed with a result of 51dB gain and 3dB NF achieved for only 45mW of 980nm pump power[22]. Further, insertion losses from the isolator do not adversely affect output powers and gains of 49dB have been demonstrated for signals as large as -39dBm. An additional is that, at high input signals (-25dBm), the device behaves as an optical limiter[23] an advantage in long haul systems.

2.3 Direct pumped power amplifier

High saturated output powers are sought to overcome splitting losses in communications networks. An optimised system allows high pump powers to be launched into the fibre so making increased energy available at 1.5μm. Semiconductor laser diodes are attractive pump sources but the power available from a single stripe diode is typically limited to less than 100mW. One approach to optimising available energy is to allow efficient use of several sources simultaneously[24]. Four laser diodes operating at 1,480nm and each emitting in excess of 100mW are employed and to maximise use of available power the insertion losses of passive components such as isolators, WDMs, couplers and the laser diode-to-fibre coupling losses must be minimised. Further, considerable care is required to maintain thermal stability of the high power laser diodes. Thus, a total of 345mW could be launched into the fibre from the four diodes each emitting just over 100mW.

A standard fibre comprising 1,000ppm Er^{3+} in an aluminosilicate core was employed with the optimised launch configuration to achieve the saturated output characteristics shown in Figure 4. With reference to the figure it may be seen that an amplifier output signal power of 22.3dBm (270mW) was obtained with net conversion efficiency of 69%

2.4 Indirectly pumped power amplifier

The diode pumped device described above is compact but device reliability will be relatively poor owing to the large number of high pump power diodes employed. An alternative approach is to modify the fibre structure to enable more reliable pump sources to be employed.

One route is to use diode pumped Nd^{3+} lasers (DPL) by sensitising Er^{3+} doped fibre, usually with Yb^{3+}.

The DPL is an efficient high brightness convertor giving high beam quality from high power reliable AlGaAs diode laser arrays and, unlike direct diode excitation this approach is directly power scalable.

A conventional amplifier configuration is employed but success[25] with this pumping scheme relies on efficient net energy transfer, shown schematically in Figure 5. This process is strongly dependent on glass host[26]. Modelling[27] suggests that a high ratio of Yb^{3+} to Er^{3+} is required with high total ion concentration (around 20,000ppm minimum) to ensure small ion-ion separation and efficient forward energy transfer to Er^{3+} from Yb^{3+}. However, to ensure high net energy transfer efficiency the back transfer must be minimal. This is achieved by rapid decay from $^4I_{11/2}$ to the metastable by use of a high phonon energy glass. However, the lattice vibration energy is constrained to an upper limit to ensure the metastable transition remains fully radiative and a phosphate structure is found to be optimum. This host is mimicked in a silica base glass to retain compatibility with standard fibres.

Despite the stringent fibre design criteria high performance is achieved as shown in Figure 6, showing the output power as a function of system gain. A maximum power of +24.6dBm (290mW) was obtained for a 4dBm signal at 1535nm under counterpropagation, 1W pump excitation at 1047nm (ND:YLF) and a maximum small signal gain of 51dB was obtained at 1535nm.

When power scaled with 1,500mW launched from two Nd lasers in a bidirectional configuration a maximum output power of 27dBm has been demonstrated. Further, the noise performance was evaluated in a system transmitting 40CATV channel frequencies, with an average noise of 3.5dB (which when corrected for coupling losses equate to a quantum limited 3dB).

This tandem pumped scheme, in which a diode array pumps an intermediate laser (e.g Nd:YAG) which in turn pumps the codoped fibre has given the highest output characteristics of any fibre system to date. However, the use of an intermediate laser reduces device compactness and a power amplifier in which the intermediate is eliminated by directly pumping a codoped cladding pumped[28] via a 1W 963nm diode array has been reported. The structure was not optimised and a maximum output power of only 17dBm was achieved however it clear that outputs in excess of 20dBm should be possible.

3. CONCLUSIONS

The Er^{3+} doped fibre amplifier is shown to be a highly versatile tool with optimisation of fibre host and structure as well as configurational design leading to high performance devices. High gain efficiencies, high gains, low noise and high saturation output power with low nose all having been demonstrated. EDFAs have evolved enormously from the early days but it is clear that further improvements are possible.

4. ACKNOWLEDGEMENTS

The Optoelectronics Research Centre is an SERC supported interdisciplinary research institute.

5. REFERENCES

1. R.J.Mears, L.Reekie, I.M.Jauncey and D.N.Payne, "High gain rare-earth doped fibre amplifier at 1.54μm", Proc. Optical fibre communications, pp.167, Reno, 1987
2. W.J.Miniscalco, "Erbium doped glasses for fibre amplifiers at 1500nm", J. Lightwave Technology, vol.9(2), pp.234-250, 1991
3. W.L.Barnes, R.I.Laming, E.J.Tarbox and P.R.Morkel, "Absorption and emission cross section of Er^{3+} doped silica fibres", IEEE J. Quantum Electronics, vol.27(4), pp.1004-1010, 1991
4. R.Welter, R.I.Laming, R.S.Vodhanel, W.Sessa, M.W.Maeda and R.E.Wagner, "Performance of erbium-doped fibre amplifier in a 16-channel coherent broadcast network", Proc. Conference on Lasers and Electro-optics, Paper PD22, Baltimore, 1989

5. M.Tachibana, R.I.Laming, P.R.Morkel and D.N.Payne, "Gain-shaped erbium-doped fibre amplifier (EDFA) with broad spectral bandwidth", Proc. Topical meeting on Optical Amplifiers and their Applications, vol.13, Paper WD3, Monterey, 1990
6. K.Arai, H.Namikawa, K.Kumata, Y.Ishii, H.Tanaka and I.Iida, "Fluorescence and its Nd^{3+} concentration dependence of ND^{3+} doped SiO_2 glasses prepared by plasma torch CVD", Japanese J. Applied Physics, vol.22(7), pp.L397-L399, 1983
7. R.I.Laming, D.N.Payne, F.Meli, G.Grasso and E.J.Tarbox, "Highly saturated erbium doped fibre power amplifiers", Proc. Optical amplifiers and their applications, vol.13, Paper WD3, Monterey, 1990
8. R.Wyatt, "Spectroscopy of rare-earth doped fibres", SPIE vol.1171 Fibre laser sources and amplifiers, pp.54-64, Boston, 1989
9. T.Georges, E.Delevaque, M.Monerie, P.Lamouler and J-F.Bayon, "Pair induced quenching in erbium doped silicate fibres", Proc. Topical meeting on Optical Amplifiers and their Applications, vol.17, Paper WE4, Santa Fe, 1992
10. R.I.Laming, S.B.Poole and E.J.Tarbox, "Pump excited-state absorption in erbium doped fibres", Optics Letters, vol.13, pp.1084-1086, 1988
11. M.Nakazawa, Y.Kimura and K.Suzuki, "Efficient Er^{3+} doped optical fibre amplifier pumped by a 1.48μm InGaAsP laser diode", Applied Physics Letters, vol.54(4), pp.295-297, 1989
12. R.I.Laming and D.N.Payne, "Noise characteristics of erbium doped fibre amplifier pumped at 980nm", IEEE Photonics Technology letters, vol.2(6), pp.418-421, 1990
13. B.J.Ainslie, J.R.Armitage, S.P.Craig and B.Wakefield, "Fabrication and optimisation of the erbium distribution in silica based doped fibres, Proc. European Conference on optical communications, Brighton, 1988
14. M.N.Zervas, R.I.Laming and D.N.Payne, "Trade-off between gain efficiency and noise figure in an optimised fibre amplifier", Proc. Optical Fibre Communications, Paper WK7, San Jose, 1992
15. A.Yariv, Optical Electronics, Saunders College Publishing, ISBN 0-03-047 444-2
16. M.N.Zervas, R.I.Laming, J.E.Townsend and D.N.Payne, "Design and fabrication of high gain-efficiency erbium-doped fibre amplifiers, Proc. SPIE OE/Fibres, Boston, 1992
17. M.N.Zervas and R.I.Laming, "Performance limits of erbium doped fibre amplifiers due to internal Rayleigh backscattering", To be presented at Conference on Optical fibre communications, Paper ThD3, San Jose, 1993
18. M.Shimizu, M.Yamada, M.Horiguchi, T.Takeshita and M.Okayasu, "Erbium doped fibre amplifiers with an extremely high gain coefficient of 11.0dB/mW", Electronics Letters, vol.26(20), pp.1641-1643, 1990
19. T.Izawa, S.Sudo and F.Hanawa, "Continuous fabrication process for high silica fibres", Trans IECE Japan, vol E-62, pp.779-785, 1979
20. S.T.Davey, D.L.Williams, D.M.Spirit and B.J.Ainslie, "The fabrication of low loss high NA silica fibres for Raman amplification", SPIE vol.1171, Fibre laser sources and amplifiers, pp.181-191, 1989
21. M.N.Zervas, R.I.Laming and D.N.Payne, "Efficient erbium-doped fibre amplifier with integral isolator", Proc. Optical amplifiers and their applications, Paper FB2-1, Santa Fe, 1992
22. R.I.Laming, M.N.Zervas and D.N.Payne, "54dB gain quantum limited erbium doped fibre amplifier", Proc. European Conference on optical communications, Paper MoA3.4, 1992
23. M.N.Zervas and R.I.Laming, "Erbium doped fibre optical limiting amplifier", Proc. European Conference on Optical Communications, Paper MoA3.1, Berlin, 1992
24. H.Takenaka, H.Okuno, M.Fujita, Y.Odagiri, Y.Sunohara and I.Mito, "Compact size and high power output power Er-doped fibre", Proc. Optical amplifiers and their applications, Snowmass, 1991
25. S.G.Grubb, P.A,Leilabady, K.L.Sweeney, W.H.Humer, R.S.Cannon, S.W.Vendetta, W.L.Barnes and J.E.Townsend, "High output power Er^{3+}/Yb^{3+} codoped optical amplifiers pumper by diode pumped Nd^{3+} lasers", Proc. Optical amplifiers and their applications, Paper FD1, Santa Fe, 1992

26. J.E.Townsend, W.L.Barnes and S.G.Grubb, "Yb^{3+} sensitised Er^{3+} doped silica based optical fibre with ultra high transfer efficiency", Materials Research Symposium, vol.244, Optical waveguide materials, pp.143-146, Boston, 1991

27. P.R.Morkel, "Modelling erbium/ytterbium doped fibre amplifiers", Proc. Optical Amplifiers and their applications, vol.17, Paper FD2, Santa Fe, 1992

28. J.D.Minelly, W.L.Barnes, R.I.Laming, P.R.Morkel, J.E.Townsend and S.G.Grubb, "Er^{3+}/Yb^{3+} codoped power amplifier pumped by a 1W diode array", Proc. Optical amplifiers and their applications, Paper PD2, Santa Fe, 1992

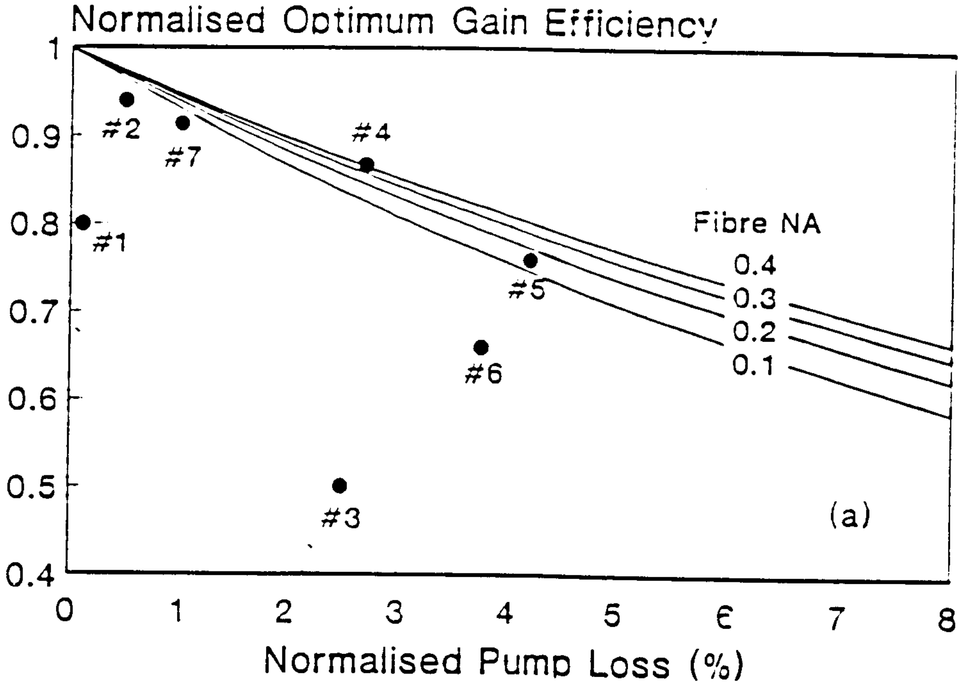

Figure 1 Effect of baseline loss on gain efficiency (ref. 16)

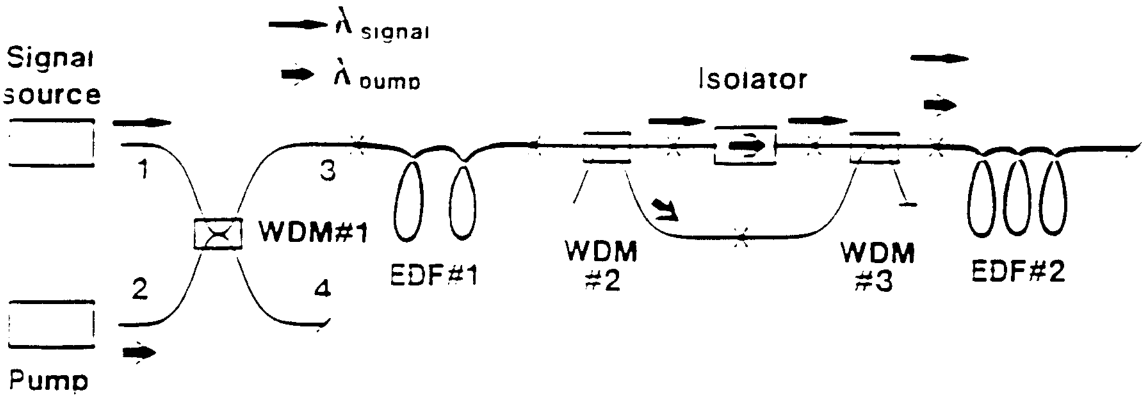

Figure 2 Schematic of EDFA with integral isolator (ref. 21)

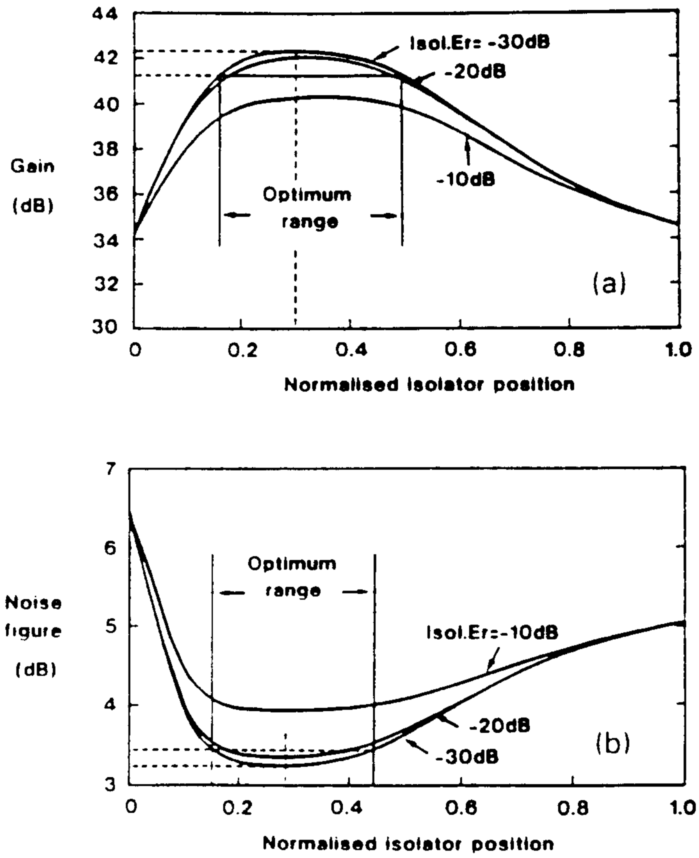

Figure 3 a) Gain and b) noise figure as a function of normalised isolator position (ref. 21)

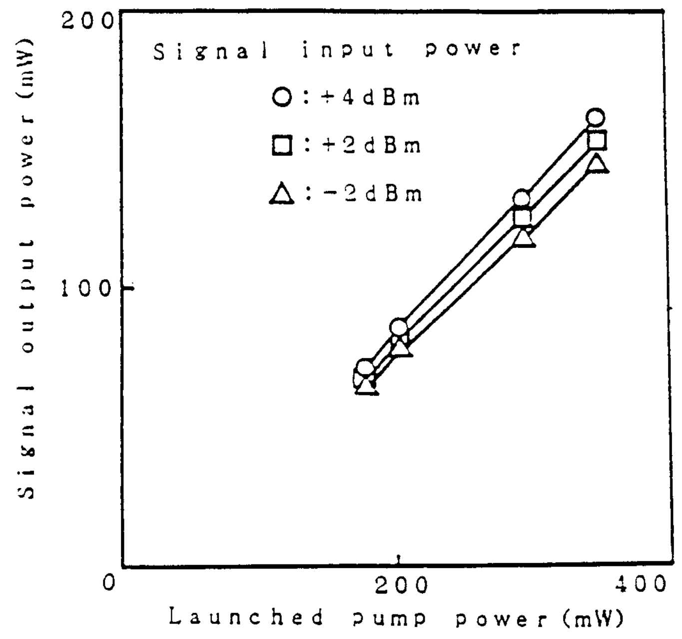

Figure 4 Saturated output characteristics of EDFA pumped simultaneously by four 1.48μm laser diodes (ref. 24)

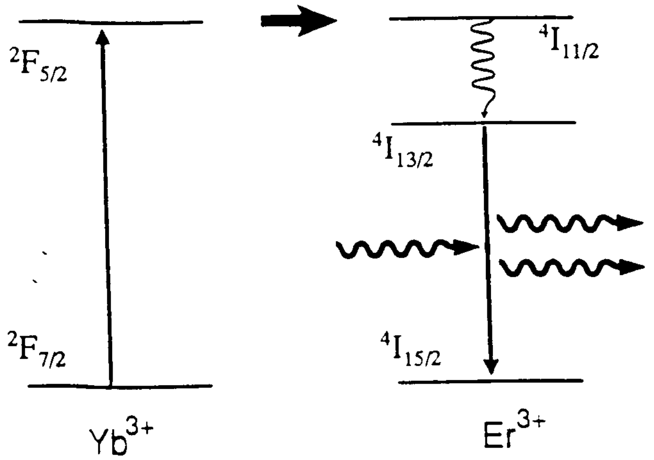

Figure 5 Schematic of energy transfer process from Yb^{3+} to Er^{3+}

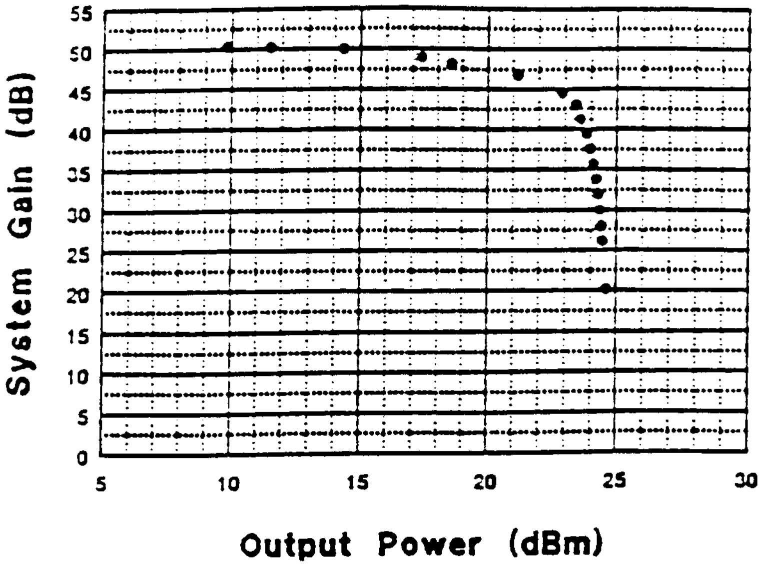

Figure 6 Output power as a function of gain for a single DPL pumped $Er^{3+}Yb^{3+}$ optical fibre amplifier (ref. 25)