Highly-saturated Erbium-doped-fibre Power Amplifiers

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Introduction

It has not been generally appreciated that the erbium-doped fibre amplifier (EDFA) has both a saturation output power which increases with pump power, as well as an ability to operate deep in saturation without signal distortion and interchannel crosstalk. The latter is a consequence of its slow gain dynamics and is quite different from diode-amplifier behaviour. Most investigations of the gain-characteristics of EDFAs to date have concentrated on the small input signal regime and attempted to obtain high unsaturated gain for low-pump powers, an attribute which is required for an in-line amplifier. By contrast, in this paper we discuss the application of EDFAs as power (post) amplifiers where the input signal is large and the amplifier saturation behaviour outlined above can be exploited. In the highly-saturated regime we have obtained near-quantum-limited pump to signal conversion efficiencies, resulting in 55mW (17.4dBm) of amplified signal for only 100mW of pump power at 978nm. Operating in this mode EDFAs are attractive for application as power amplifiers to ease power budget restrictions in point-to-point digital links, video distribution networks and LANs.

Experiment

EDFA power amplifier performance was measured in both the counter- propagating and co-propagating pump and signal configurations. An LD was used to inject a large input signal, typically −3 to −2dBm, at a with wavelength matching the gain peak of the particular fibre under test. Pump light at 978–980nm was from a Ti:Sapphire laser and the amplified output signal power was measured as a function of pump power for several fibre lengths.

Figure 1 shows the results for an erbium-doped fibre with a germano-alumino-silicate core composition. Here the input signal was ∼−3dBm at a wavelength of 1533.3nm and the counter-propagating pump at a wavelength of 978nm. The fibre was characterised by an NA of 0.18, λ_{cutoff} of 900nm and attenuation at the pump and signal wavelengths of 6.5dBm and 10dBm respectively. Thus we estimate the dopant concentration to be 520ppm, (distributed uniformly across the fibre core). From the figure it is clear that for all fibre lengths there is a pump threshold below which no significant pump-to-signal conversion is obtained, but above which the output signal power increases approximately linearly with pump power. This pump threshold is the power required to bleach a given fibre length and, as expected, increases for longer fibres. For short fibre lengths (2.75m and 4.25m) there is poor pump/signal conversion efficiency and the amplified output signal departs from a linear dependence with pump power. This is because the fibre is too short for all the available pump power to be absorbed and a low gain results. For longer fibre lengths, both the pump threshold and differential efficiency increase and thus for a given pump power there exists an optimum length for maximum absolute power conversion efficiency.

Figure 1: Dependence of amplifier output power on pump power for different length counter-propagating amplifiers.

Figure 2(a) plots *absolute* efficiency against fibre length for pump powers of 50 and 100mW, whilst Figure 2(b) shows the differential efficiency. It can be seen that a maximum absolute conversion efficiency of 55% is obtained for a fibre length of 7m, although longer fibre lengths do not exhibit a marked decrease in efficiency. The horizontal offset in the data at short fibre lengths (∼1m) arose because the input signal power (−3dBm) was only comparable with the fibre saturation power (∼0dBm). Thus the signal is amplified exponentially in the first metre of fibre and does not therefore contribute significantly to the conversion efficiency. From Figure 2(b) it can be seen that the differential efficiency tends to the quantum limit with increasing fibre length, with a maximum efficiency of 63% being obtained for a fibre length of 9.5m.

Also shown on Figure 2(a) and (b) are similar data obtained for an EDFA operated in the co-propagating pump and signal configuration. Strikingly one notes the significant reduction in pump/signal conversion efficiency. A maximum absolute conversion efficiency of 37% is now obtained for a reduced optimum length of ∼5.5m. Similarly, a reduced slope efficiency of 42% is obtained. The reasons for this difference between the two configurations is not yet fully understood, but can be attributed to a a combination of fibre loss at the pump and signal wavelengths and excited-state absorption of pump photons from the pump-band $^4I_{11/2}$ to a higher level $^4I_{7/2}$ which may become significant for saturated amplifiers since the relative population of ions in the pump band increases. The counter-propagating configuration gives a higher efficiency since it maximises the pump power in the region of high signal intensity.

In further experiments the maximum absolute efficiency was measured as a function of erbium concentration and host-glass composition employing the counter-

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Figure 2: Absolute (a) and differential (b) conversion efficiencies for different fibre lengths and pumping configurations.

propagating configuration. The results are shown in Figure 3. Several erbium-doped germano-silicate fibre types were tested and fibres with concentrations around 100ppm were found to give the highest efficiency. Increasing the dopant concentration to ~350ppm resulted in a severe decrease in conversion efficiency. On the other hand, near quantum-limited conversion efficiencies were obtained for both germano-alumino-silicate and alumino-silicate fibre types with erbium concentrations up to 760ppm.

An additional advantage of EDFA power amplifiers operating in the highly-saturated regime is that they can exhibit nearly-flat, broadband spectral-gain. This is because their largely-homogeneous line-broadening allows gain across a large part of the spectrum to contribute to the signal output.

Figure 3: Dependence of conversion efficiency on erbium concentration.

Conclusions

Highly-saturated EDFAs have been shown to be efficient power amplifiers. Maximum absolute pump-to-signal power conversion efficiencies as high as 55% have been obtained, whilst the slope efficiency can be near quantum-limited at 63%. Low erbium concentrations (<100ppm) are required to obtain high efficiency when employing a germano-silicate host-glass, whereas germano-alumino-silicate and alumino-silicate host glasses allow for higher erbium concentrations. Power amplifiers operating in this mode have virtually flat spectral-gain characteristics.

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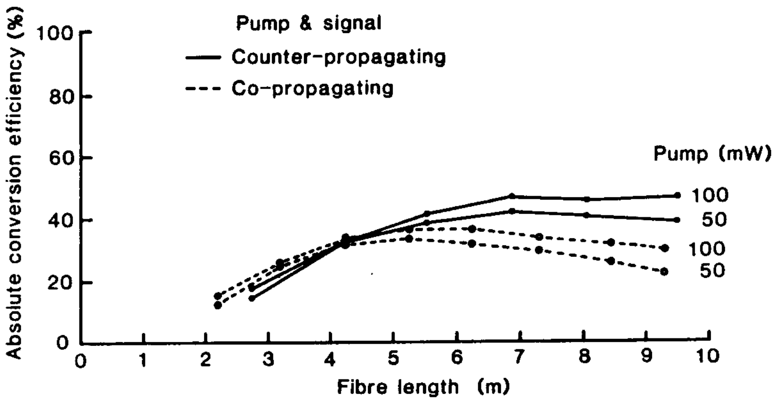


Figure 1: Dependence of amplifier output power on pump power for different length counter-propagating amplifiers.

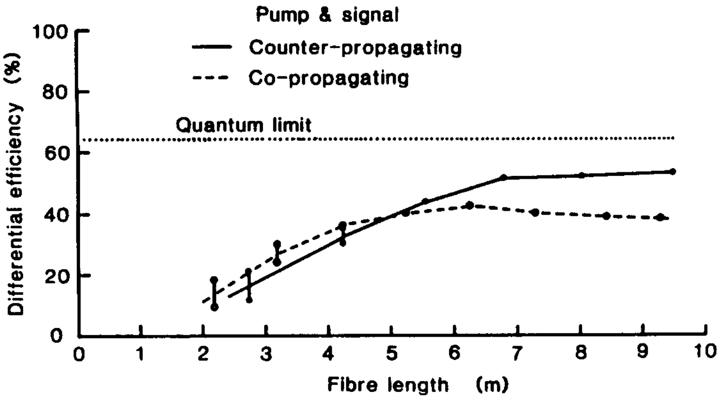


Figure 2. Absolute (a) and differential (b) conversion efficiencies for different fibre lengths and pumping configurations.

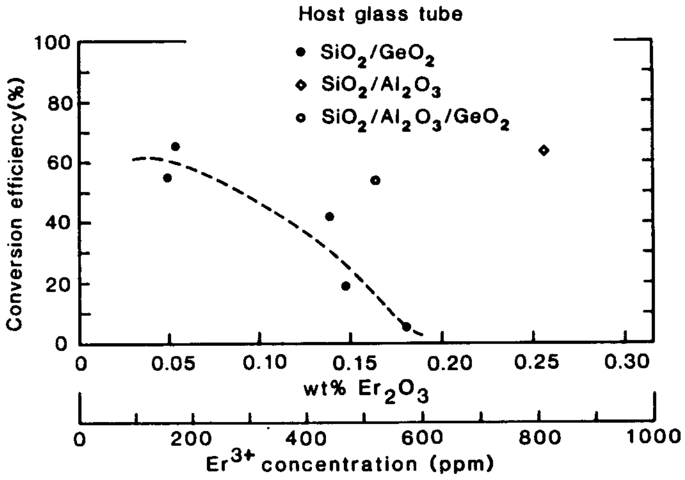
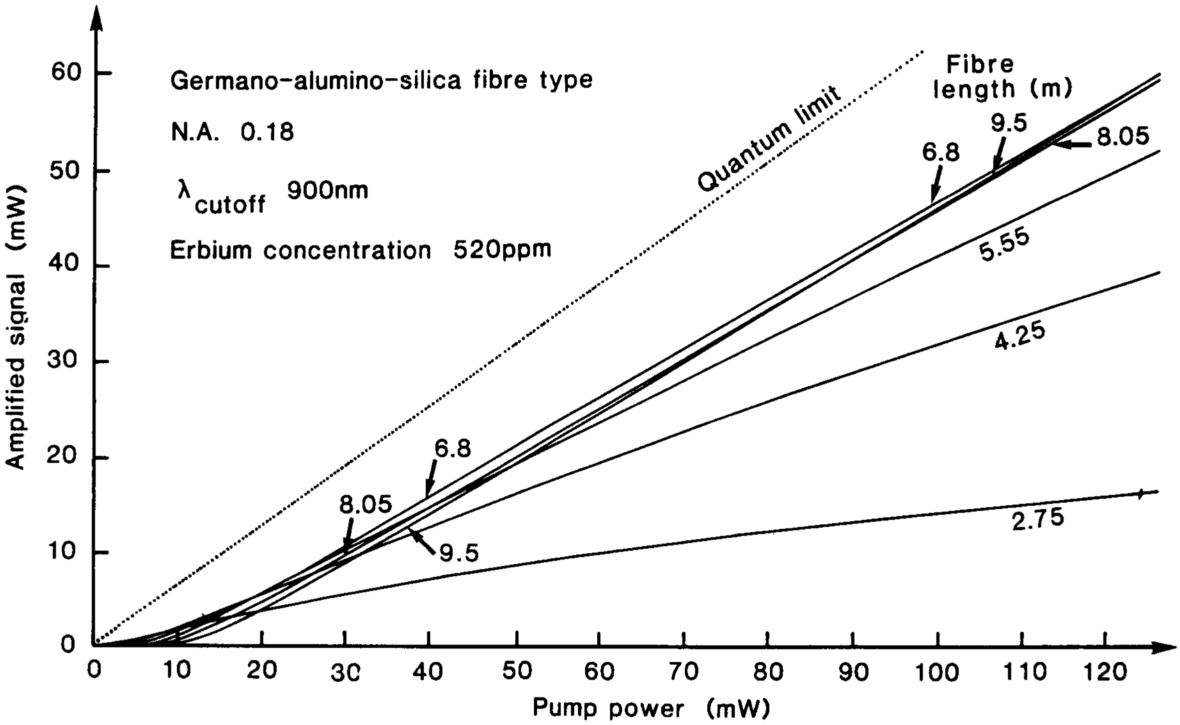


Figure 3. Dependence of conversion efficiency on erbium concentration.


Germano-alumino-silica fibre type
N.A. 0.18
λ_{cutoff} 900nm
Erbium concentration 520ppm
Quantum limit
Fibre length (m)
9.5
6.8
8.05
5.55
4.25
2.75
6.8
8.05
9.5
Amplified signal (mW)
0
10
20
30
40
50
60
Pump power (mW)
0
10
20
30
40
50
60
70
80
90
100
110
120