High-Power Erbium-Doped-Fiber Amplifiers Operating in the Saturated Regime

R. I. Laming, J. E. Townsend, D. N. Payne, F. Meli, G. Grasso, and E. J. Tarbox

Abstract—**Highly saturated, erbium-doped fiber amplifiers can be employed as efficient power amplifiers. Differential pump-to-signal conversion efficiencies of 59%, (quantum-efficiency of 93%) can be obtained, resulting in 54 mW (+ 17.3 dBm) of amplified signal for only 100 mW of pump power at 978 nm. In addition, these amplifiers are shown to have virtually-flat spectral-gain characteristics with a 1 dB bandwidth in excess of 38 nm.**

INTRODUCTION

IT has not been generally appreciated that the erbium-doped fiber amplifier [1] (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 [2]. The latter is a consequence of its slow gain dynamics and is quite different from diode-amplifier behavior [3]. Most investigations of the gain-characteristics of EDFA's to date have concentrated on the small input-signal regime and attempted to obtain high unsaturated gain for low-pump powers [4], [5] an attribute which is required for an in-line amplifier. By contrast, in this letter we discuss the application of EDFA's as power (post) amplifiers where the input signal is large and the amplifier saturation behavior outlined above can be exploited [6]. In the highly-saturated regime we have obtained a differential pump-to-signal conversion efficiency of 59%, corresponding to a quantum-efficiency of 93%. This results in 54 mW (17.3 dBm) of amplified signal for only 100 mW of pump power at 978 nm. In addition, highly saturated EDFA's are shown to exhibit a flat gain spectrum with 1 dB bandwidth in excess of 38 nm. Operating in this mode, EDFA's are attractive for application as power amplifiers to ease power budget restrictions in point-to-point digital links, video distribution networks [7], and LAN's.

EXPERIMENT

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

Fig. 1 shows the results for an erbium-doped fiber with a germano-alumino-silicate core composition. Here the input signal was ~ −3 dBm at a wavelength of 1533.3 nm and the counter-propagating pump had a wavelength of 978 nm. The fiber was characterized by an NA of 0.2, λ_{cutoff} of 910 nm and attenuation at the signal wavelength of 2.9 dB/m. Thus, we estimate the dopant concentration to be 160 ppm (distributed uniformly across the fiber core). From the figure it is clear that for all fiber 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 fiber length and, as expected, increases for longer fibers. For short fiber lengths (9 and 15 m) there is poor pump/signal conversion efficiency and the amplified output signal departs from a linear dependence with pump power. This is because the fiber is too short for all the available pump power to be absorbed and a low gain results. For longer fiber 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.

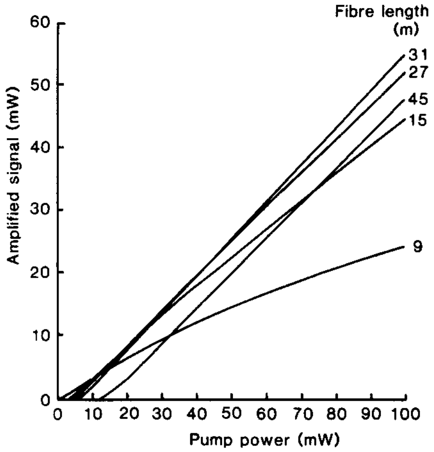

Fig. 1. Dependence of amplifier output power on pump power for different length counter-propagating amplifiers.

Fig. 2(a) plots absolute pump-to-signal power conversion efficiency against fiber length for pump powers of 50 and 100 mW, while Fig. 2(b) shows the differential conversion efficiency. It can be seen that a maximum absolute conversion efficiency of 54% is obtained for a fiber length of 31 m, although longer fiber lengths do not exhibit a marked decrease in efficiency. Similarly, from Fig. 2(b) it can be seen that the differential conversion efficiency approaches the quantum limit for fiber lengths around 30 m, with a maximum efficiency of 59% being obtained.

Also shown in Fig. 2(a) and (b) are similar data obtained for an EDFA operated in the copropagating pump and signal configuration. Strikingly, one notes the significant reduction in pump/signal conversion efficiency. A maximum absolute conversion efficiency of 48% is now obtained for a reduced opti-

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R. I. Laming, J. E. Townsend, and D. N . Payne are with the Optical Fiber Group, Department of Electronics and Computer Science, The University of Southampton, Hampshire SO9 5NH, United Kingdom.

F. Meli and G. Grasso are with Cavi Pirelli, Milano, Italy.

E. J. Tarbox is with Pirelli General plc., Hampshire S09 5YE, United Kingdom.

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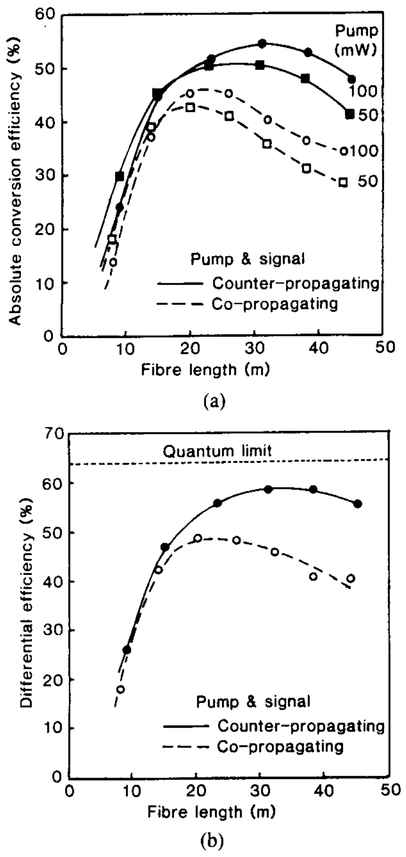

Fig. 2. Absolute (a) and differential (b) conversion efficiencies for different fiber lengths and pumping configurations.

mum length of 20 m. Similarly, a reduced slope efficiency of 48% is obtained. The reasons for this difference between the two configurations is not yet fully understood, but can be attributed to a combination of fiber loss at the pump and signal wavelengths [8], signal excited-state absorption [9], and clustering [9]. The counter-propagating configuration gives a higher efficiency since it maximizes the pump power in the region of high signal intensity.

An additional advantage of EDFA power amplifiers operating in the highly-saturated regime is that they can exhibit nearly-flat, broad-band 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. Thus, a near-constant output power is obtained for a wide range of signal wavelengths. The spectral characteristics of a saturated EDFA is shown in Fig. 3(a),(b). In this case 38 metres of fiber was employed in the counter-propagating configuration. Additionally, the input signal was maintained around −7 dBm while its wavelength was tuned from 1523 to 1574 nm. From Fig. 3(a) it is clear that differential pump-to-signal conversion efficiencies in excess of 50% can be obtained over a 37 nm bandwidth. As a result, a near constant gain spectrum is obtained, as shown in Fig. 3(b). In this case, for a pump power of only 50 mW a maximum output power of +13.6 dBm and 1 dB bandwidth of 38 nm are obtained. Extrapolating to a higher pump power of 100 mW indicates that amplified output powers greater than +16.5 dBm can be obtained over a 38 nm bandwidth.

Fig. 4 plots total-harmonic-distortion (THD) due to the power amplifier as a function of signal modulation frequency. Here the input signal was modulated sinusoidally with an 80% modulation depth and the THD measured at the amplifier output with an RF

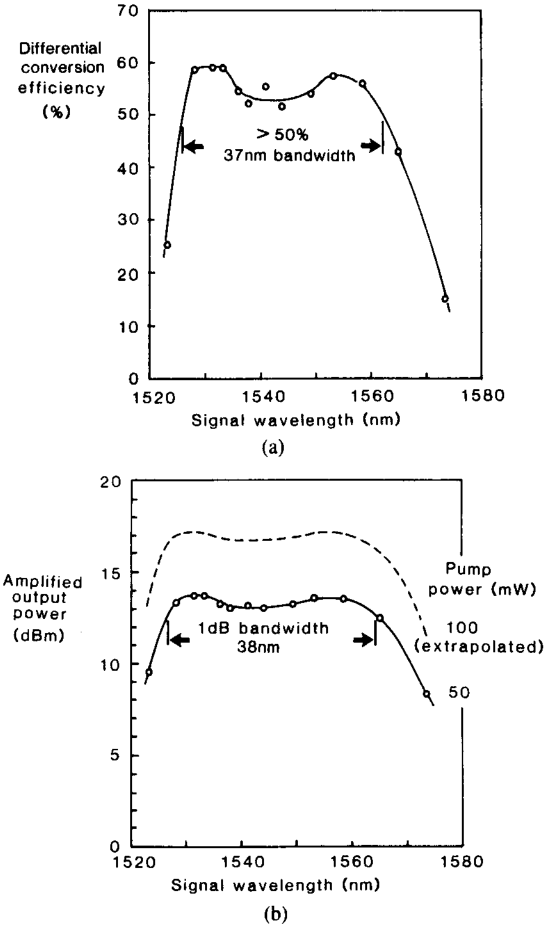

Fig. 3. Spectral characteristics of differential conversion efficiency (a) and output power (b) for a power amplifier.

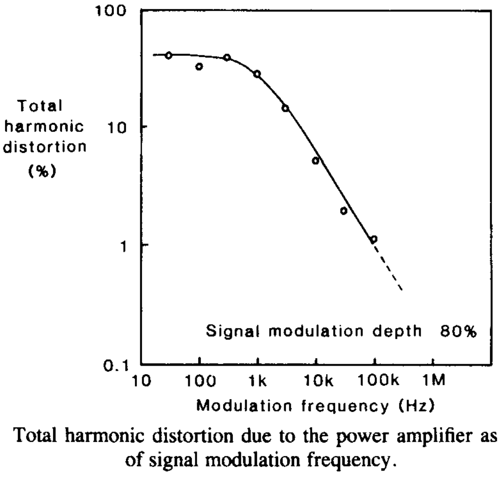

Fig. 4. Total harmonic distortion due to the power amplifier as a function of signal modulation frequency.

spectrum analyzer. The amplifier was operating deep in saturation with an output power in excess of 50 mW. THD is seen to decrease rapidly for modulation frequencies greater than ~ 1kHz, being less than 0.1% for modulation frequencies greater than 1 MHz. These results confirm the ability of the EDFA to operate deep in saturation without signal distortion.

In further experiments employing the counter-propagating configuration, the differential conversion efficiency was measured as a function of erbium concentration and host-glass composition employing the counter-propagating configuration. The results are shown in Fig. 5. Several erbium-doped ger-

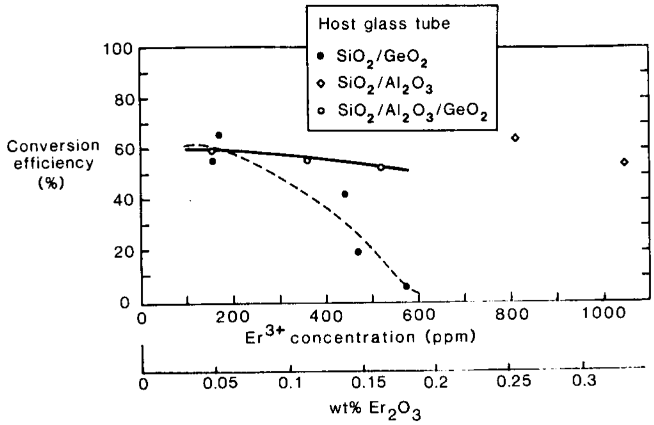

Fig. 5. Dependence of differential conversion efficiency on erbium concentration.

mano-silicate fiber types were tested and fibers with concentrations around 100 ppm were found to give the highest efficiency. Increasing the dopant concentration to ~350 ppm resulted in a severe decrease in conversion efficiency. On the other hand, germano-alumino-silicate and alumino-silicate fiber types exhibited a much less severe decrease in efficiency with increasing concentration. Thus, near quantum-limited conversion efficiencies were obtained for erbium concentrations up to ~1000 ppm in these fiber types.

CONCLUSIONS

Highly saturated EDFA's pumped at 980 nm have been shown to be efficient power amplifiers. Maximum absolute pump-to-signal power conversion efficiencies as high as 54% have been obtained, while the differential conversion efficiency can be as high as 59%, corresponding to a quantum-efficiency of 93%. Although this is a higher quantum-efficiency than obtained for 1.48 μm pumping [6] the absolute conversion efficiency is ~1.5 dB lower [6] owing to the increased Stokes shift between pump and signal wavelengths for 980 nm pumping. The overall efficiency of a practical EDFA is determined by pump diode efficiency as well as the efficiency of the fiber component. This complicates the selection of preferred pump wavelength for power amplifier applications.

Low erbium concentrations (~100 ppm) are required to obtain high efficiency when employing a germano-silicate host-glass, whereas germano-alumino-silicate and alumino-silicate host glasses allow higher erbium concentrations. Power amplifiers operating in this mode have virtually flat spectral-gain characteristics.

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