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Gain and Noise Penalty for Detuned 980-nm Pumping of Erbium-Doped Fiber Power Amplifiers

B. Pedersen, J. Chirravuri, and W. J. Miniscalco

Abstract—**The impact of altering the fiber length and pump wavelength on the gain and noise performance of erbium-doped fiber power amplifiers pumped in the 980-nm band is examined. A gain penalty of < 0.5 dB was experimentally observed over a 18-nm pump wavelength range. Theoretical analysis indicates that increasing the NA from 0.15 to 0.25 significantly improves the tolerance for a given gain penalty but has little effect upon noise figure. For a given fiber length, the noise figure increases by 0.1 dB for each 3 nm the pump wavelength deviates from 979 nm.**

Introduction

THE very efficient [1]–[3] but relatively narrow 980-nm absorption band of erbium (FWHM ≈ 16 nm for Al/Er and ≈ 11 nm for Ge/Er silica) poses a serious problem for the manufacturers of semiconductor pump sources for erbium-doped fiber amplifiers (EDFA's). The low yield for devices within a few nanometers of the peak significantly increases their cost, and relaxing the wavelength tolerances for these lasers would significantly reduce the cost of 980-nm pumped EDFA's. We have performed a detailed experimental and theoretical investigation of power amplifiers pumped between 960 and 1000 nm. This has enabled us to determine the quantitative relationship between pump detuning and the penalty for both gain and noise figure, as well as the dependence of these penalties on pump power, fiber length, and waveguide design. The experiments indicate that pumping away from the peak of the absorption band leads to a gain penalty that decreases with pump power and fiber length. Using an accurate numerical model we show how a broad pump window around 980 nm can be obtained for power amplifiers by appropriate choice of fiber length and design, albeit with a degradation of noise figure.

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Experimental

The experimental setup has been described in [3]. A Ti:sapphire laser provided codirectional pumping at wavelengths ranging from 960 to 1000 nm. The pump and 1551-nm signal were combined by a WDM fiber-coupler, and the pump power launched into the doped fiber was monitored for each pump wavelength in the experiment.

Fig. 1 displays the signal output power as a function of pump wavelength for a Ge/Al/P/Er-doped silica fiber with an NA of 0.18 and a cutoff wavelength of 940 nm. The signal launched into the erbium-doped fiber was −1.4 dBm. The experimental results are indicated by marks for three different fiber lengths each pumped with 40 and 80 mW. The solid curves are computer simulations of the experiment obtained using a numerical model described previously [4]. All basic parameters used by the model were determined experimentally and the calculated values are seen to be in good agreement with experiment. Also indicated in Fig. 1 is the ground-state absorption (GSA) cross section spectrum which peaks at 979 nm. As expected, signal output and quantum conversion efficiency increase with pump power, reaching 16.3 dBm and 0.83, respectively, for the 16 m fiber pumped with 80 mW at 979 nm. This compares to 12.7 dBm and 0.71 for a 12 m fiber pumped with 40 mW. Note also that the output is less sensitivity to fiber length for higher pump powers: for 80 mW and this fiber design the gain penalty is < 0.1 dB for an uncertainty of ±25% around the optimum fiber length. Fig. 1 also reveals that the magnitude of the gain penalty for pump wavelengths away from 979 nm is significantly reduced at high pump powers. At 80 mW the penalty is < 0.5 dB for a pump wavelength range of ±9 nm about

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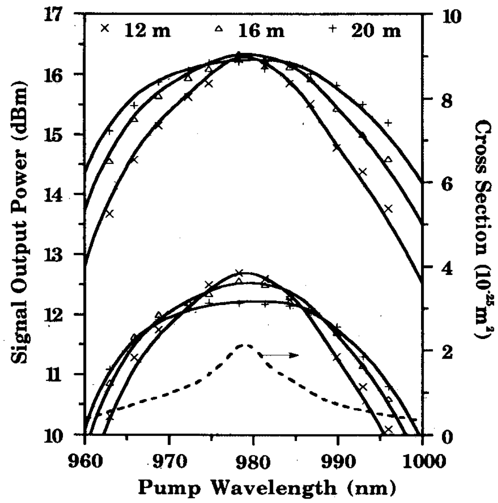

Fig. 1. Signal output power versus pump wavelength for three different fiber length pumped by 40 and 80 mW, the higher pump power resulting in the higher output. The 1551-nm signal input is −1.4 dBm. The experimental data are indicated by marks and the curves are numerical simulations.

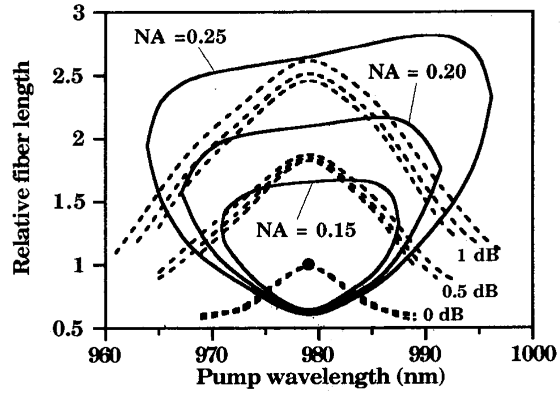

Fig. 2. Gain and noise figure penalties versus relative fiber length and pump wavelength. The solid curves are contours for a degradation of 0.5 dB in the gain from the maximum gain at the reference point (979 nm, 1.0) indicated by a solid circle. The dashed curves shows where the noise figure has increased by 0, 0.5, and 1.0 dB from the noise figure at the reference point. For a given noise penalty, higher NA's correspond to longer relative lengths. The pump power is 50 mW.

the peak if one does not alter the fiber length from the optimum for 979 nm (16 m). The corresponding range for 40 mW is only ±5 nm. Detuning the pump wavelength decreases the absorption coefficient; increasing the fiber length partially compensates for this and reduces the gain penalty. This has been observed for small-signal amplifiers [5]–[7].

Gain and Noise Figure

The fiber amplifier model was used to extend the above results and systematically examine the effects of fiber length and numerical aperture (NA) on power amplifiers pumped away from 979 nm. Fig. 2 plots the relative fiber length versus pump wavelength for step-index fibers with different NA's and a cutoff wavelength of 850 nm. The launched pump power is 50 mW and the signal input power is 1 mW at 1551 nm. The relative fiber length is the actual length divided by the length of the fiber giving the maximum gain at 979 nm. The latter is represented by the solid circle at (979 nm, 1.0) in the figure. With the pump power and waveguide design used here, the maximum small-signal gain for 979-nm pumping would be 31.4, 32.7, and 33.7 dB for the NA's of 0.15, 0.2, and 0.25, respectively. However, the 1-mW signal input almost completely saturates the quantum conversion efficiency and the hereby the signal output power which at the reference point in Fig. 2 is 14.1, 14.5, and 14.6 dBm, respectively. The noise figure at the fiber length that gives the highest gain is almost independent of the NA [3]. At the reference point in Fig. 2, the noise figure is ≈ 3.7 dB. The solid curves are contours for a degradation in the gain of 0.5 dB compared to the optimum point, and thus enclose regions of pump wavelength and fiber length that keep the penalty to less than this value. The dashed curves bound regions with less than a specified penalty in noise figure, F. For example, a curve labeled 1 dB means an increase in F of 1 dB over that at the reference point (979 nm, 1.0). As observed, the gain penalty contours are very sensitive to NA: an increase in NA from 0.15 to 0.25 doubles the bandwidth of the 0.5-dB contour from 16 to 32 nm. In contrast, the noise penalty curves are insensitive to NA.

Plots such as Fig. 2 are useful as design guides since they contain most of the information necessary to quantify the tradeoffs between pump wavelength, amplifier gain, and noise figure. This is illustrated by Fig. 3 which contains this information in greater detail for a given fiber NA (0.2), pump power (50 mW), and signal input (1 mW at 1551 nm). The solid curves are contours for progressively larger gain-penalties ranging from 0 to 1.0 dB in steps of 0.2 dB. The dashed curves are for different noise figure penalties, also increasing in steps of 0.2 dB. Both penalties are relative to the optimum operating point (979 nm, 1.0) for which the gain is 14.5 dB and F is 3.7 dB. With Fig. 3 it is possible to establish not only the fiber length which maximizes the pump wavelength tolerance but also the gain and F at any pump wavelength and fiber length. If the pump wavelength is 985.5 nm, for example, the fiber length that gives the highest gain is ≈ 50% longer than the optimum for 979 nm. This can be seen from Fig. 3 where 985.5 nm is the longest pump wavelength on the contour for a 0.2 dB gain penalty, the point being indicated by an open circle. Consequently, the maximum gain at 985.5 nm for the pump power used for Fig. 3 is 14.3 dB, 0.2 dB lower than at 979 nm and the F is 4.2 dB, 0.5 dB higher than at the reference point. Diagrams such as Fig. 3 are particularly useful if one wishes to design a power amplifier with a specified minimum gain and maximum F and needs to determine the tolerances on the pump wavelength and fiber length. One begins by locating the curves in Fig. 3 corresponding to the performance specifications, e.g., a gain penalty of 0.4 dB and F penalty of 0.6 dB. The permissible values of pump wavelength and fiber length occupy the area enclosed by the gain and F penalty curves where the boundary is always the curve lying closest to the reference point.

Several general conclusions can be drawn from Fig. 3. The

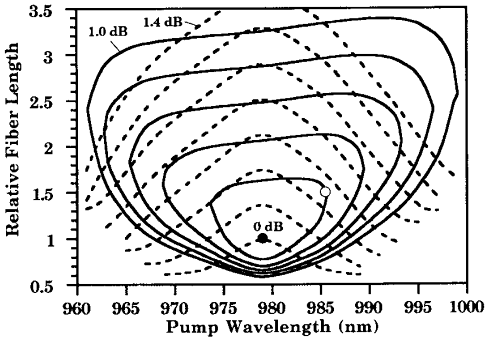

Fig. 3. Gain and noise figure penalties versus relative fiber length and pump wavelength. The NA is 0.2 and all other conditions are the same as in Fig. 2. The solid curves are for different gain penalties ranging from 0 to 1 dB in steps of 0.2 dB. The dashed curves are noise figure penalties ranging from 0 to 1.4, also in steps of 0.2.

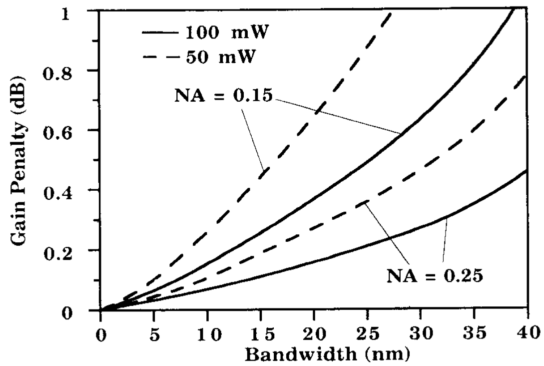

Fig. 4. Gain penalty versus pump bandwidth. Curves are shown for NA's of 0.15 and 0.25, and for pump powers of 50 and 100 mW.

fiber length that gives the maximum gain has a minimum with respect to pump wavelength at 979 nm, the wavelength which also provides the lowest F for any fiber length. Considering only gain, it is better to use too long a fiber length than too short, e.g., for 979 nm the same gain penalty of 0.2 dB is obtained for relative fiber lengths of 0.8 and 1.6. The penalty in F is ≈ 0.1 dB for each 3 nm the pump wavelength differs from 979 nm and for each 0.2 increment in the fiber relative length.

From Figs. 2 and 3 it is seen that while the positions of the gain penalty contours are sensitive to the NA, they all have the same characteristic shape for power amplifiers and are nearly symmetrical around 979 nm. If noise figure is not a consideration, one may replace a contour by its projection onto the x-axis (bandwidth) where fiber length is assumed to be adjusted as necessary. Fig. 4 plots the gain penalty as a function of bandwidth for step-index fibers with NA's of 0.15 and 0.25 pumped codirectional by 50 mW (dashed curves) and 100 mW (solid curves). It is apparent that NA is more critical to increasing pump wavelength tolerance than pump power. For users and manufacturers of 980-nm LD's the bandwidth in Fig. 4 translates into the specification on the eission wavelength. If the LD is specified to emit at 979 ± 5 nm, the bandwidth is 10 nm and the signal output power will be only slightly degraded from that achieved pumping exactly at 979 nm since the gain penalty is < 0.3 dB for the NA's and pump powers considered. However, if the uncertainty is ±20 nm the penalty is seen to be very sensitive to both pump power and NA. For 100 mW of pump power the penalty is < 0.5 dB for NA of 0.25, whereas it is > 1 dB for an NA of 0.15. For pump powers less than 50 mW, NA's lower than 0.15 are not practical if the uncertainty in the pump wavelength is ±20 nm.

Conclusion

We have performed a detailed experimental and theoretical investigation of the tolerances on pump wavelength and fiber length for power EDFA's pumped in the 980-nm band. Although fiber length and pump power play an important role, higher fiber NA was found to be the dominant consideration. The higher NA, the less sensitive the gain is to length and the wider the range of pump wavelengths that can be tolerated for a given length. Although noise figure is not directly affected by NA, for a given pump wavelength increasing the NA permits the desired gain to be obtained with a shorter fiber. This, in turn, improves the noise figure.

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