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Gain and Noise Properties of Small-Signal Erbium-Doped Fiber Amplifiers Pumped in the 980-nm Band

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

Abstract—We have experimentally and theoretically investigated the effects of detuning the pump wavelength on the gain and noise properties of small-signal, erbium-doped fiber amplifiers co-directionally pumped in the 980-nm band. While the pump wavelength can be varied over a wide range with little impact on the gain, a noise penalty is incurred. For amplifiers saturated by amplified spontaneous emission, it is possible to increase the gain by detuning the pump wavelength.

INTRODUCTION

THE 980-nm pump band is the most efficient for erbium-doped fiber amplifiers (EDFA's). It is relatively narrow, however, and the limits this imposes on pump laser wavelength is a source of concern [1], [2]. Recently, it has been demonstrated that the restrictions on pump wavelength are less severe than had been originally believed, and it is possible to obtain relatively constant gain over a broad-pump-wavelength range for both small-signal [3] and power [4] amplifiers. In this work, we examine in detail the effects of pump-wavelength detuning on small-signal EDFA's, including the first measurements of noise penalties. Theoretical and experimental investigations reveal relaxed pump-wavelength requirements with respect to gain, but also a noise figure penalty that increases 0.6 dB for each 10 nm of detuning. In addition, we report the observation that the performance of EDFA's saturated by amplified spontaneous emission (ASE) can actually be improved by pump-wavelength detuning. This results from a reduction of the amount of pump power that is lost to backward ASE. We conclude that for applications in which noise figure is not paramount it is not necessary to use pump lasers close to the peak of the absorption band.

SMALL-SIGNAL GAIN AND NOISE FIGURE

In the experiments pumping was provided by the output of a Ti:sapphire laser that was combined with the 1551-nm signal by a WDM coupler. The gain, G, was measured using a lock-in amplifier to separate the signal from the spontaneous emission. Determining the noise figure also requires a measurement of the ASE power. This was accomplished using a bandpass filter (FWHM $\approx$ 1.8 nm) centered on the signal wavelength. The transmitted power was measured with

the signal turned off and divided by the effective bandwidth of the filter to obtain the forward ASE power spectral density, $S_{\text{ASE}}(\nu_s)$, at the signal frequency, ν_s, exiting the EDFA. The noise figure was evaluated using the expression $F = [S_{\text{ASE}}(\nu_s)/h\nu_s + 1]/G$.

Fig. 1 plots (a) the small-signal gain and (b) the noise figure as functions of the launched pump power for different pump wavelengths. The Ge/Al/P/Er-doped fiber had an NA of 0.18 and cutoff of 940 nm. Signal powers were low enough not to affect the gain. The measured values are indicated by marks and the solid curves are simulations of the experiment performed using a comprehensive numerical model [5] for which all input parameters, including erbium- and refractive-index profiles, have been experimentally determined. The fiber length is 35 m, which is the optimum length for 120 mW of pump power at 979 nm, i.e., any change in the fiber length will decrease the gain. The gains for the other pump wavelengths, however, can still be improved by increasing the fiber length. A somewhat surprising result is that both theory and experiment indicate that the gain for 969 and 959 nm is higher than that for 979 nm, the wavelength with the highest absorption cross section. Lower gains were previously reported pumping at 979 nm, but in that instance it was attributed to using fiber lengths that were longer than optimum [3]. We have demonstrated here that it is possible to increase the gain by detuning the pump wavelength, even for amplifiers with optimum length. This effect results from the high level of ASE in the fiber and will be explored in the next section.

In contrast, Fig. 1(b) indicates that the noise figure can only be degraded by detuning, for these conditions increasing by $\approx$ 0.6 dB for each 10 nm the pump wavelength differs from 979 nm. In general, a good noise figure requires that a high inversion be maintained at the input end of the fiber over roughly the length required to provide the first 10–15 dB of signal gain. For a highly driven small-signal amplifier the major perturbation is the backward ASE, and obtaining a high inversion in this region requires that the pump rate be large compared to stimulated emission rate due to backward ASE. Since the pump rate is proportional to the pump absorption cross section, the best noise performance is always obtained at the peak of the absorption band.

IMPROVEMENT OF GAIN BY PUMP DETUNING

Fig. 2 plots the calculated small-signal gain as function of pump wavelength for three pump powers and the fiber used
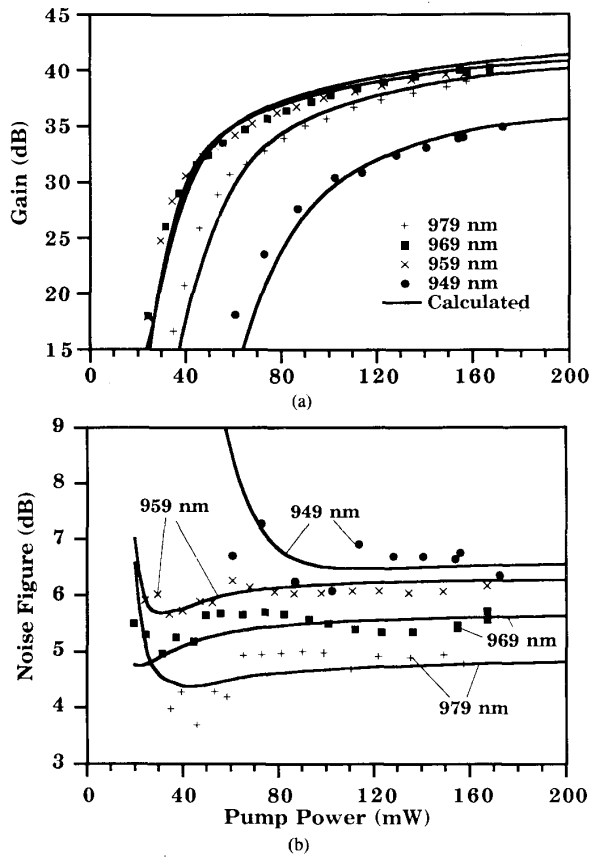
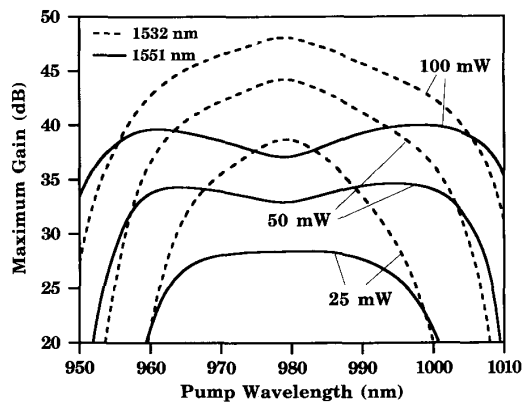Fig. 1.   (a) Gain and (b) noise figure as a function of pump power for the pump wavelengths indicated.

Fig. 2.   Maximum gain versus pump wavelength for the signal wavelengths and pump powers indicated. Fiber lengths have been adjusted to maximize gain.

in Fig. 1. The signal wavelengths are 1532 and 1551 nm, and the fiber lengths are those giving the highest gain. The gain is seen to be extremely tolerant to pump wavelength: for pump powers of 25, 50, and 100 mW, the 3-dB bandwidths are 16.5, 22.5, and 27 nm for a signal at 1532 nm, and 33, 47.5 and 56 nm for one at 1551 nm. The wider bandwidths for

1551 nm arise from a more favorable emission to absorption cross section ratio which permits gain with lower excited state populations. Fig. 2 indicates that for a signal at the peak of the stimulated-emission cross-section spectrum (1532 nm for the present fiber), the optimum pump wavelength will always be at the peak of the pump absorption (979 nm) as expected. For a signal in the shoulder of the emission spectrum (1551 nm), however, it is possible to obtain higher gain by detuning the pump wavelength ≈ 20 nm.

The explanation for this detuning enhancement is provided by Fig. 3 which plots the gain together with the pump, forward and backward ASE powers as functions of the location in the fiber for two pump wavelengths. The signal wavelength is 1551 nm, the pump power is 100 mW, and the fiber lengths are chosen for maximum gain: 32 m for 979 nm and 46 m for 999 nm. The fiber can be divided into three sections whose approximate boundaries are indicated in Fig. 3 by changes in slope for the gain and pump power. In the first section both the pump and the backward ASE are strong, and this combination leads to significant recycling of the erbium ions through stimulated emission and pump absorption. Consequently, there is a significant transfer of power from the pump to the backward ASE as indicated by the steep slopes for both curves. In the middle section both the forward and the backward ASE powers are low and the inversion is high since the only de-excitation process is spontaneous emission. In this region the gain increases most rapidly and the pump attenuation is lowest. In the final section the forward ASE has reached a level where stimulated emission has again become important but the low pump intensity is not sufficient to maintain inversion and the gain per unit length falls off.

Pumping at 999 nm provides higher gain than pumping at 979 nm because less pump power is lost to backward ASE in the first section of the fiber. This occurs since the lower absorption cross section at 999 nm reduces the rate at which erbium ions are re-excited and then de-excited by stimulated emission into the backward ASE. This can be seen by examining the point in Fig. 3 where the backward ASE is equal to 0 dBm, roughly the location of the boundary between the first and second region. Although the gain is the same for both the pump wavelengths, roughly twice as much pump power remains at 999 nm than at 979 nm. In effect, pump power is transferred to the second region of the fiber where it is more efficient at producing gain. This is consistent with the higher noise figure of the 999-nm-pumped amplifier: the lower pump rate which reduces loss to backward ASE also means a lower population inversion in the critical first section of the amplifier.

In addition to providing useful insights into the complex interactions occurring within an EDFA, the above investigations can provide information of practical importance. Since a major factor in the cost of diode pump lasers is the low yield for wavelengths near 979 nm, the relaxed tolerances seen in Fig. 2 could lead to a significant reduction in EDFA cost. It may also be possible to exploit the gain improvement due to detuning seen in Fig. 2. Fig. 4 plots (a) the maximum gain for 979 nm pumping, (b) the maximum gain improve-
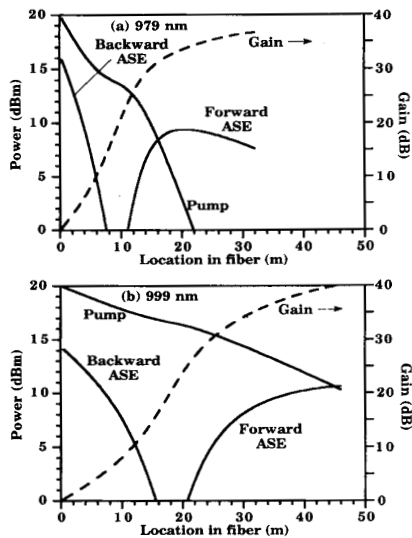
Fig. 3. Pump power, ASE power, and signal gain as a function of position within fiber for pump wavelengths of (a) 979 nm and (b) 999 nm.

ment from detuning, and (c) the optimum amount of detuning, all as functions of the pump power. Comparing Figs. 4(a) and (b) confirms that only for amplifiers saturated by ASE ($G > 25$ dB) is it possible to obtain a gain improvement by detuning the pump wavelength. Fig. 4(b) indicates that while the pump power at which the improvement first appears decreases with increasing NA, a greater benefit is obtained for fibers with low NA's. Fig. 4(c) shows that the amount of detuning for greatest improvement initially depends on pump power but eventually saturates at values in the 20–24 nm range. This detuning-induced gain enhancement can provide a significant improvement. For example, using an NA of 0.25 the maximum gain is 33.8 dB at 1551 nm when pumping with 50 mW at 979 nm. However, the same gain can be obtained with only 30 mW by detuning the pump wavelength ≈ 20 nm.

CONCLUSIONS

Experimental and theoretical investigations of 980-nm-pumped small-signal EDFA's have revealed significantly relaxed tolerances on pump wavelength if gain is the primary consideration. This is expected to have an important impact on the yield and cost of diode lasers for this pump band. A noise figure penalty of 0.6 dB per 10 nm of detuning is incurred, however, and must be considered in preamplifier applications. For ASE-saturated EDFA's near 1550 nm, it is possible to obtain a useful improvement in efficiency by detuning since this reduces the pump power lost to backward ASE.
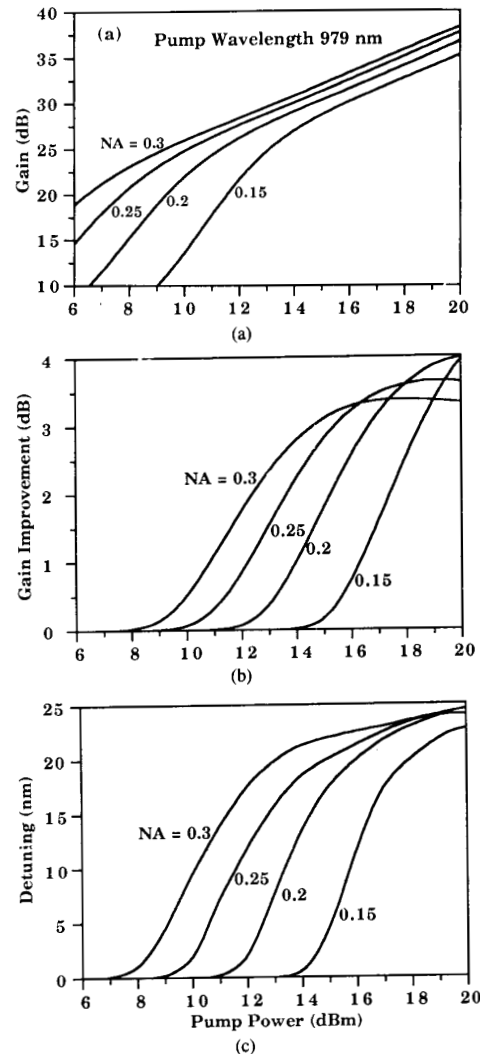
ACKNOWLEDGMENT

Fig. 4. (a) Gain for 979-nm pump wavelength, (b) gain improvement due to detuning, and (c) amount of detuning for maximum gain improvement. Calculations used step-index fibers with 850-nm cutoff wavelength. Lengths that maximized gain were used.

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