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Evaluation of the 800-nm Pump Band for Erbium-Doped Fiber Amplifiers

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***Abstract*— Erbium-doped fiber amplifiers (EDFA's) can be excited around 800 nm where reliable and low-cost AlGaAs laser diodes can be obtained. We have performed a comprehensive experimental and theoretical investigation of methods to overcome the excited-state absorption (ESA), which is the main obstacle to efficient pumping at this wavelength. The effects of ESA on gain can be reduced at the cost of an additional noise penalty by adopting the bidirectional pumping scheme or by pumping in the long-wavelength tail of the ground-state absorption (GSA) band. The GSA and ESA cross-section spectra depend on the glass host material and the GSA/ESA ratio has been measured for different erbium-doped glasses. One of the most promising hosts, fluorophosphate, is compared to Al/P silica in a detailed analysis based on a quantitative numerical model. It is predicted that 2–3 dB less pump power is required to obtain similar performance for the fluorophosphate EDFA. For Al/P-silica EDFA's, the pump power requirements when exciting in the 800-nm band are compared to those for pumping at 980 and 1480 nm. It is found that ~7 dB higher power is required when pumping in the 800-nm band.**

I. Introduction

ERBIUM-DOPED fiber amplifiers (EDFA's) will play an important role in future lightwave communication systems. The erbium-doped silica fibers that EDFA's are based on are not considered to cause any problems as far as reliability is concerned since these fibers are produced from modifications of the OMCVD or VAD processes, techniques that are well established and used in very large scale to manufacture standard transmission fibers. The reliability as well as the price of an EDFA module will depend almost completely on the reliability and price of the light source used to excited the erbium ions. To be practical, these pump sources must be semiconductor laser diodes (LD's) and they must be capable of providing high output power. This limits the absorption bands that will be of interest for erbium to the 800- and 980-nm bands and to the signal band where inversion can be obtained by resonant pumping in the short wavelength tail of the absorption band around 1480 nm. Bands of 980 and 1480 nm have been demonstrated to be very efficient pump wavelengths for the EDFA, both when used as a small-signal amplifier [1], [2] and as a power booster [3], [4]. Although LD's emitting at these wavelengths can be obtained, it will still take some years before these LD's will be reduced in price to a competitive level, and it has not yet been established that 980-nm devices are reliable enough to be used in optical communication systems. In contrast, the well-known AlGaAs LD can be used as excitation source in the 800-nm pump band of erbium. These LD's are considered to be very reliable and can be obtained at relatively low costs. Unfortunately, the 800-nm absorption band for erbium is relatively weak and is dominated by an overlapping excited state absorption (ESA) transition.

In this paper, we investigate the 800-nm pump band for EDFA's and methods to overcome ESA, which is the main obstacle to efficient operation pumping in this band. The evaluation presented here is based on an accurate numerical model, described in Section II, and on a comprehensive experimental investigation. Section III focus on erbium-doped silica fibers pumped around 800 nm and it examines how the significance of the ESA can be reduced by pumping in the long wavelength tail of the ground state absorption (GSA) band [5], [6]. Another way to reduce the ESA is to incorporate erbium in a different glass host [7]. In Section IV the GSA/ESA ratio is measured for several different hosts and one, a fluorophosphate glass, is compared to the silica in a comprehensive analysis. It is predicted that the pump power required to obtain similar amplifier performance will be 2–3 dB less in an erbium-doped fluorophosphate fiber amplifier. Section IV also discuss how the significance of ESA can be reduced by adopting the bidirectional pumping scheme [8]. In Section V the 800-nm pump band is compared to pumping at 980 and 1480 nm. It is demonstrated that for silica fibers similar amplifier performance requires ≈7 dB higher power when pumping in the 800-nm band.

II. Numerical Model

Fig. 1 shows the energy level diagram for erbium, with the relevant transitions designated by vertical arrows. A detailed description of the model has previously [8], [9] been given and the model has been shown to accurately predict the performance of EDFA's [10]. The following differential equation for propagation of the pump along the fiber is used in the model taking into account both forward and backward pumping:

$$\frac{dP_p^{\pm}(z)}{dz} = \pm 2\pi \int_0^{\infty} \left[(\sigma_e(\nu_p) - \sigma_{\mathrm{esa}}(\nu_p))N_2(r,z) - \sigma_{\mathrm{gsa}}(\nu_p)N_1(r,z)\right] I_{01}^p(r)r\,dr \times P_p^{\pm}(z) \quad (1)$$

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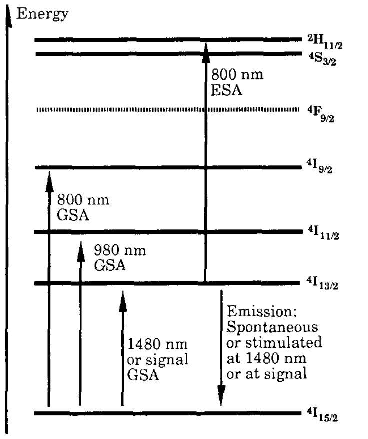

Fig. 1. Energy level diagram for erbium. Signal amplification is obtained by stimulating the transition from level $^4I_{13/2}$ to level $^4I_{15/2}$. Excited state absorption (ESA) occurs for wavelengths between 780 and 880 nm.

where $P_p^{\pm}(z)$ is the forward (+) and backward (−) pump power at position z along the fiber and $I_{01}^p(r)$ is the normalized radial (r) intensity distribution of the pump in the LP_{01} mode. $N_1(r,z)$ and $N_2(r,z)$ are the radial distribution of the population concentrations in the ground-state $^4I_{15/2}$ level and in the excited-state $^4I_{13/2}$ level, respectively, at position z [9]. $\sigma_{gsa}(\nu_p)$ is the GSA cross section at the pump frequency, ν_p. $\sigma_{esa}(\nu_p)$ and $\sigma_e(\nu_p)$ are the ESA and stimulated emission cross sections at ν_p, respectively. $\sigma_e(\nu_p)$ differs from zero only when pumping at 1480 nm. $\sigma_{esa}(\nu_p)$ is different from zero only when pumping in the 800-nm band. It is noted that the ESA transition does not appear in the steady-state rate equations for N_1 and N_2 (see [9]) since the ESA transition is assumed to be followed by fast relaxation back to the metastable state. In the model presented here and in the following analysis, only excitation in the fundamental pump mode will be considered since this is essential to an efficient use of the pump power. However, the model can easily be extended to include higher order modes. This can be done by writing the differential equation, similar to (1), for each pump mode considered. These equations and the signal differential equations should then be solved simultaneously with the power launched in each mode at the two fiber ends, $z = 0$ and $z = L$, as boundary conditions for the forward and the backward traveling pump, respectively.

III. Band of 800-nm Pumping of Erbium-Doped Silica Fibers

The 800-nm absorption band for erbium is potentially important because it matches the wavelength region in which AlGaAs laser diodes (LD's) can be obtained. Fig. 2 shows the GSA cross section spectrum for erbium-doped Al/P silica. The strength of the 800-nm GSA transition is seen to be very weak compared to that of the other important pump heads. Moreover, the 800-nm GSA band for erbium overlaps a relatively strong ESA transition. The latter occurs because photons at wavelengths between 780 and 880 nm can be absorbed in transitions from the $^4I_{13/2}$, level to the $^2H_{11/2}$ and $^4S_{3/2}$ levels.

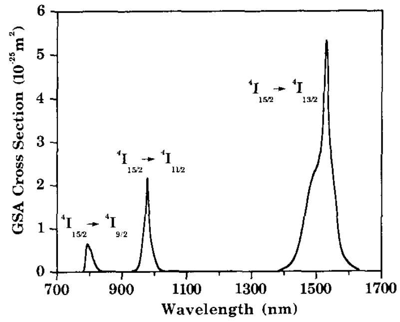

Fig. 2. Ground state absorption cross sections for erbium-doped Al/P silica.

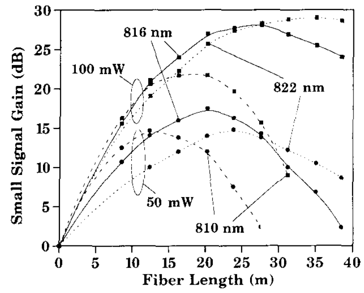

Fig. 3. Measured small-signal gain versus fiber length for different pump wavelengths. The erbium-doped Ge/Al/P-silical fiber has an NA of 0.18 and a cutoff wavelength of 940 nm. The signal wavelength is 1551 nm and the fiber is pumped codirectionally with 50 and 100 mW.

Both the GSA and the ESA cross sections are strong functions of the pump wavelength and high gains have been demonstrated [5], [6] by pumping in the long wavelength tail of the GSA band. In the present experiment a Ti: Sapphire laser was used for the pump and a 1551-nm DFB laser was used for the signal. The launch setup for the pump was single mode at 800 nm and inspection of the far-field intensity pattern of the residual pump from the doped fiber showed that excitation was predominantly in the fundamental pump mode. Fig. 3 plots the small-signal gain as function of fiber length for pumping codirectionally with 50 and 100 mW. Curves are shown when pumping at 810, 816, and 822 nm and were measured for an erbium-doped Ge/Al/P-silica fiber with an NA of 0.18 and a cutoff wavelength of 940 nm. As seen from Fig. 3 the fiber length that gives the highest gain increases with both the pump wavelength and the pump power. Fig. 3 also indicates that for a given pump power there is an optimum pump wavelength that provides the highest gain. For 100 mW of pump power the highest gain is obtained at 822 nm and for 50 mW it is obtained at 816 nm. This is further illustrated in Fig. 4, which shows the measured small-signal gain as function of pump wavelength for different pump powers. For each pump power and wavelength the fiber length has been optimized to give maximum gain. As can be seen, the optimum pump wavelength increases with the pump power.

In order to explore these effects further, the model was used to determine the optimum pump wavelength under different conditions. The analysis is based on measured cross sections,

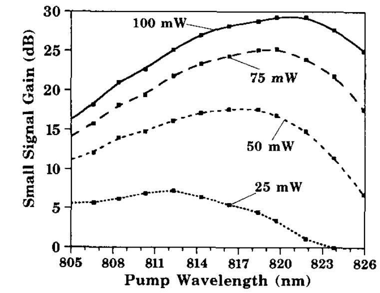

Fig. 4. Measured small-signal gain versus pump wavelength for different pump powers. Each point is for the fiber length that gave the highest gain.

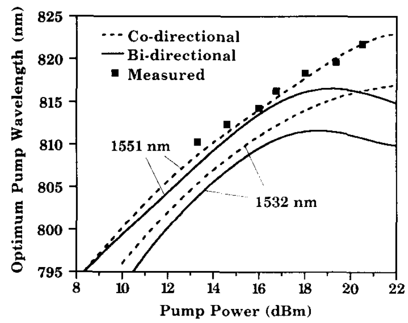

Fig. 5. Model predictions of optimum pump wavelength as function of pump power. Curves are shown for bi- and codirectional pumping and for signal wavelengths of 1532 and 1551 nm. The symbols are measured values.

including ESA cross sections, for an erbium-doped Al/P-silica fiber and will be valid for silica fibers in which aluminum dominates the spectral behavior of the erbium ions, i.e., Al/P- and Al-silica fibers and most Ge/Al/P- and Ge/Al-silica fibers. Fig. 5 displays the optimum pump wavelength versus the pump power when pumping codirectionally (dashed curves) and bidirectionally (solid curves). Results are shown for signal wavelengths of 1532 nm (emission peak) and 1551 nm. In the calculations are used the refractive index and the erbium-concentration profiles as determined for the Ga/Al/P-silica fiber used in the experiment. The experimental results for the 1551-nm signal in the codirectional pumping scheme are plotted in the figure as solid squares and agree very well with the upper dashed curve for this case. As seen from the figure the optimum pump wavelength is predicted to be shorter when the signal wavelength is centered at the peak of the emission, as previously demonstrated [11]. This is because the optimum fiber length is shorter due to the higher emission cross section at 1532 nm. When the fiber length is shorter, the significance of the ESA is less pronounced and the optimum pump wavelength approaches the peak of the GSA at 790 nm.

For bidirectional pumping, it is observed that for high pump powers the optimum pump wavelength decreases with increasing pump power. This is because the amplifier is saturated by amplified spontaneous emission (ASE). When the ASE power reaches levels where it starts to influence the population inversion, the pump rate [9] has to compete with the ASE rate. When the bidirectional pumping scheme is used,

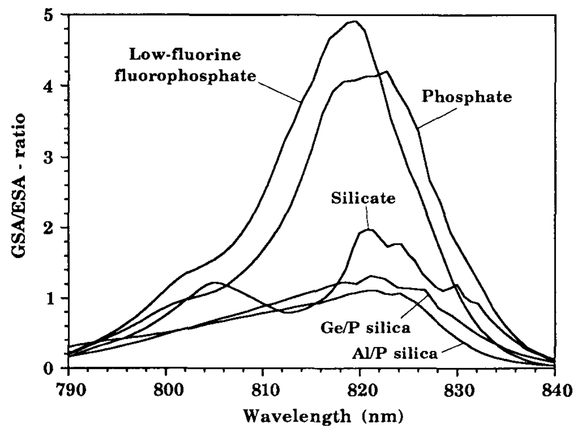

Fig. 6. The measured ratio between ground and excited state absorption cross sections as function of wavelength for different erbium-doped glasses.

the available pump power is cut in half and launched from both fiber ends. Thus, the pump rate is weaker at the fiber ends where the ASE rate is strongest. To enhance the pump rate the GSA cross section, to which the pump rate is proportional, can be increased by pumping at a shorter wavelength.

IV. Glass Host Dependency

As shown in the previous section the significance of ESA can be decreased by pumping in the long-wavelength tail of the GSA band. However, if the ESA could be decreased at the peak of the GSA, the efficiency of the amplifier would further improve because a higher GSA cross section means that less pump power is required to obtain a gain of one. The measured GSA to ESA cross section ratio [12] is plotted in Fig. 6 as a function of wavelength for erbium doped in different glasses. The importance of the ESA is strongly dependent on the host material and the GSA to ESA cross section ratio is seen to be significantly improved by using hosts other than silica. The measured ESA and GSA cross section spectra are shown in Fig. 7 for erbium-doped (a) Al/P silica and (b) fluorophosphate. The latter has a low fluorine content and is one of the most favorable compositions with respect to ESA. Fluorophosphate hosts with high fluorine content were also examined and found to have a lower GSA to ESA ratio in the spectral region of interest. As observed, the peak of the GSA for the fluorophosphate is located at a longer wavelength, around 802 nm, than the peak of the ESA, which is located around 790 nm. In contrast, for the Al/P silica both the GSA peak and the ESA peak are located at around 790 nm. For wavelength greater than 800 nm, the fluorophosphate has both a lower ESA and a higher GSA cross section than the Al/P silica, and consequently it is expected that amplifiers made from this fluorophosphate will be more efficient than those from Al/P silica. To quantify the expected improvements, the model was used to compare the performance of erbium-doped fluorophosphate and Al/P silica fiber amplifiers. The investigation used the emission and absorption cross sections for the signal band shown as inserts in Fig. 7.

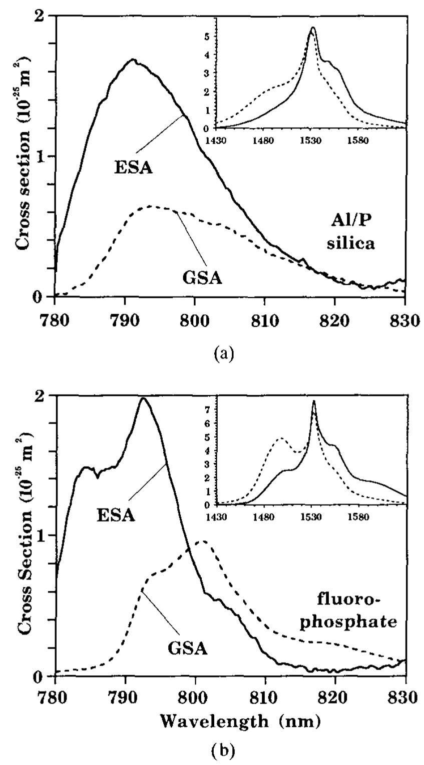

Fig. 7. Ground state and excited state absorption cross sections for erbium-doped (a) Al/P silica and (b) low-fluorine fluorophosphate. Inserts are absorption (dashed curves) and emission (solid curves) cross-section spectra for the signal band.

Fig. 8 displays the predicted gain coefficient as function of the cutoff wavelength for the LP_{11} mode in step-index fibers with different NA's. The gain coefficient is defined as the maximum of the ratio between the small-signal gain (in decibels) and total launched pump power (in milliwatts) for any value of pump power or fiber length. Results are shown for (a) Al/P silica pumped at 815 nm and (b) fluorophosphate pumped at 802 nm. The pumping schemes are codirectional (dashed curves) and bidirectional (solid curves). The signal wavelength is centered at the peak for the emission for each host. The pump wavelengths are the ones that give the highest gain coefficient for the respective hosts. Note that the optimum cut-off wavelength is ≈800 nm in all cases, and that the optimum pump wavelength for the fluorophosphate is located at the peak of the GSA band ≈802 nm, whereas the optimum pump wavelength for the Al/P silica is at a longer wavelength because the significance of the ESA is more pronounced in the latter host. The maximum gain coefficient for an NA of 0.4 is predicted to be 3.7 dB/mW for the fluorophosphate and 2.3 dB/mW for Al/P silica. This 60% improvement is also predicted for lower fiber-NA's.

For both hosts, further improvement can be obtained by confining the erbium doping to the central area of the core. Fig. 9 shows the gain coefficient plotted as function of the confinement factor, which is defined as the ratio between the erbium doping radius and the refractive index core radius.

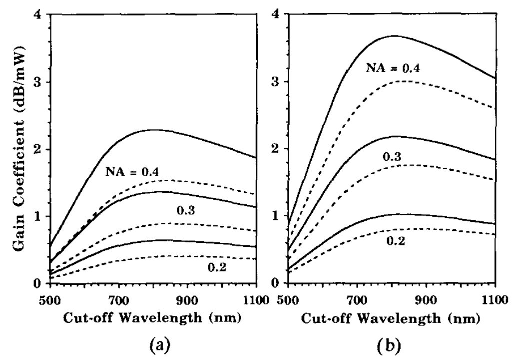

Fig. 8. Model predictions of gain coefficient as function of cutoff wavelength in step-index fibers with different NA's. The signal wavelength is 1532 nm and curves are shown for codirectional (dashed curves) and bidirectional (solid curves) pumping of erbium-doped (a) Al/P-silica fibers pumped at 815 nm and (b) fluorophosphate fibers pumped at 802 nm.

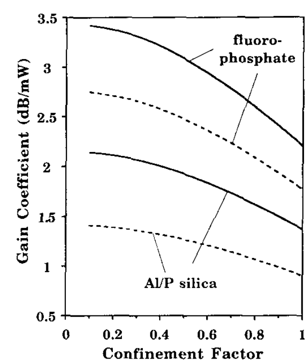

Fig. 9. Model predictions of gain coefficient as function of the erbium confinement factor for step-index fibers with an NA of 0.3. Curves are shown for codirectional (dashed curves) and bidirectional (solid curves) pumping of erbium-doped (a) Al/P-silica fibers pumped at 815 nm and (b) fluorophosphate fibers pumped at 802 nm.

The NA is 0.3 and curves are shown for codirectional (dashed curves) and bidirectional (solid curves) pumping of erbium-doped Al/P silica (815 nm pumping) and fluorophosphate (802 nm pumping). As seen, the gain coefficient can be improved ≈50% by decreasing the confinement factor from 1.0 to 0.1. This improvement can be shown to be almost (±5%) independent of the NA and the pump wavelength and yields more relaxed requirements when the erbium-doped fiber is spliced to standard transmission fibers [13].

Fig. 10 shows a plot of gain versus pump wavelength for (a) Al/P-silica and (b) fluorophosphate step-index fibers with an NA of 0.25, a cutoff wavelength of 800 nm, and a uniform erbium doping throughout the core. Curves are shown for codirectional (dashed curves) and bidirectional (solid curves) pumping with different powers. As can be seen, the advantage of pumping bidirectionally increases at shorter wavelength where the ESA is more significant. For the Al/P-silica fiber, pumped with 100 mW near the GSA peak, a 10-dB higher gain is predicted for the bidirectional pumping scheme. In contrast, when pumping in the tail of the GSA band the difference between bi- and codirectional pumping is

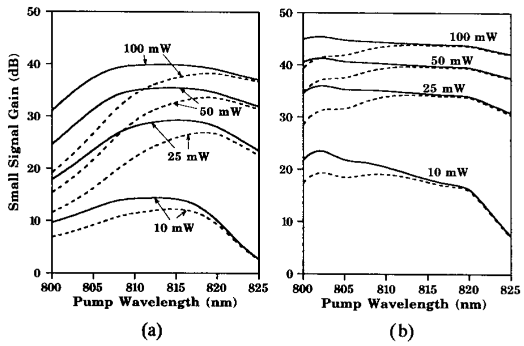

Fig. 10. Small-signal gain versus pump wavelength for codirectional (dashed curves) and bidirectional (solid curves) pumping with different pump powers. The NA is 0.25 and the cutoff wavelength is 800 nm. The signal wavelength is 1532 nm and the fiber lengths have been optimized to give maximum gain for each point on the curves. (a) Al/P silica. (b) Fluorophosphate.

insignificant. The fluorophosphate host provides higher gains and is less sensitive to the pump wavelength than the Al/P silica. The maximum gain for the fluorophosphate is predicted to be 47 dB, 6 dB higher than the maximum for Al/P silica. In particular, 100 mW of pump power is required to obtain 40 dB of small-signal gain in the silica host, whereas only 50 mW is required for the fluorophospate host. This represents a significant (3 dB) reduction in the requirements for the LD pump sources and leads to a reduction in the costs and an increase in the reliability of these sources.

For applications where low-noise amplifiers are of interest it should be emphasized that the noise figure F is also a function of the pump wavelength. This is illustrated in Fig. 11, where the small-signal gain and the noise figure are plotted as functions of the fiber length when pumping with 100 mW of total launched pump power at 1) 805 nm, and 2) 820 nm. Curves are shown for both co- and bidirectional pumping of an Al/P-silica fiber with an NA of 0.25 and a cutoff wavelength of 800 nm. The noise figure increases as a function of the fiber length. When pumping at 805 nm, however, there is a region around the length that gives maximum gain where F is almost constant, $F \approx 3.4$ dB for codirectional pumping, and $F \approx 4.8$ dB for bidirectional pumping. In contrast, when pumping at 820 nm F increases more rapidly (almost linearly) with the fiber length, and reaches higher values at the fiber length for maximum gain, $F \approx 5.8$ and 6.5 dB for co- and bidirectional pumping, respectively. This can be understood by noting that the GSA cross section is lower at the higher pump wavelength, leading to smaller average population inversion in the fiber.

To decide which pump wavelength and pumping scheme are optimum for low-noise amplifiers, the noise figure should be minimized for a specific gain. In Fig. 12 the noise figure is plotted as a function of the gain for the four cases treated in Fig. 11 with a total launched pump power is 100 mW. The gain has been adjusted by changing the fiber length. As seen from Fig. 12, codirectional pumping at 805 nm gives the lowest F for gains up to the maximum obtainable (≈ 29.5 dB) for that case. However, for gains <29.5 dB, bidirectional pumping at 820 nm, the worst case with respect to F, results in

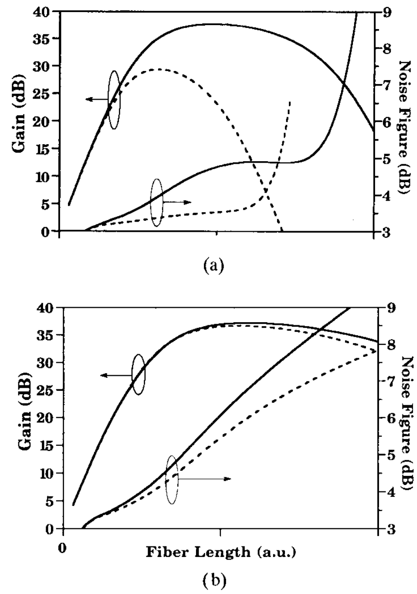

Fig. 11. Small-signal gain and noise figure as functions of fiber length for an erbium-doped Al/P-silica fiber with an NA of 0.25 and a cutoff wavelength of 800 nm. The signal wavelength is 1532 nm and curves are shown for codirectional (dashed curves) and bidirectional (solid curves) pumping at (a) 805 nm and (b) 820 nm.

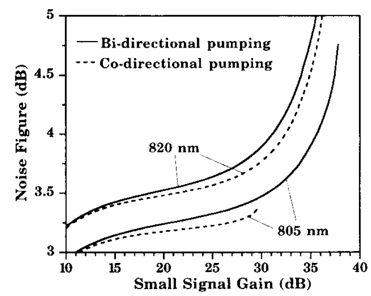

Fig. 12. Noise figure versus small-signal gain for codirectional (dashed curves) and bidirectional (solid curves) pumping at 805 and 820 nm. The total launched pump power is 100 mW and the gain is adjusted by changing the fiber length.

noise figures that are only 0.3 to 0.5 dB higher than for the best case. For gains higher than 30 dB, the best case is bidirectional pumping at 805 nm, which gives noise figures that are ≈ 1 dB lower than when pumping at 820 nm. A similar analysis was performed for the fluorophosphate leading to almost the same conclusions.

When the EDFA is used as a power booster, the signal power is so high that it has a significant influence on the population inversion. In the absence of ESA the saturated amplifier is operated close to the quantum limit [14], where all pump photons are converted to amplified signal photons. However, when ESA is present it is not possible to reach the quantum limit and the efficiency of the power booster will be limited by the ratio $\zeta = \sigma_{\rm gsa}/(\sigma_{\rm gsa} + \sigma_{\rm esa})$. The quantum conversion efficiency QCE is plotted in Fig. 13 as a function of the pump wavelength for bidirectional pumping with different

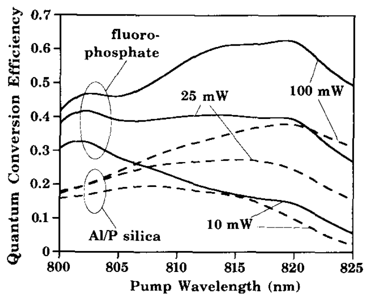

Fig. 13. Quantum conversion efficiency (QCE) as function of pump wavelength for step-index fibers with an NA of 0.3 and a cutoff wavelength of 800 nm. Curves are shown for bidirectional pumping with different pump powers. The signal wavelength is 1532 nm and the signal input power is 1 mW. All fiber lengths have been optimized with respect to maximum QCE.

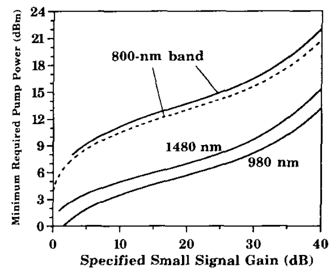

Fig. 14. Minimum required pump power as function of specified small-signal gain for an Al/P-silica EDFA with NA of 0.25. All fiber lengths are optimized. Curves are shown for codirectional (solid curves) pumping at 980 and 1480 nm and at the optimum wavelength in the 800-nm band, and for bidirectional (dashed curve) pumping at the optimum wavelength in the 800-nm band. The signal wavelength is 1532 nm.

powers. QCE is defined as the number of signal photons added to the signal divided by to total number of launched pump photons. The signal input power is 1 mW and all fiber lengths have been optimized to give maximum QCE. First, it is noted that QCE increases with the pump power and that the optimum pump wavelength is dependent on the pump power. For the highest pump power of 100 mW the optimum pump wavelength for both hosts are located in the long wavelength region ($\approx$820 nm) where ζ is highest. Since ζ is higher for the fluorophosphate host a higher QCE is reached, $\approx$0.63, compared to the maximum QCE of $\approx$0.38 for the Al/P-silica fiber. When used as a power booster this means that the same signal output power can be obtained with $\sim$2 dB less pump power if a fluorophosphate host is used instead of silica.

V. Pump Power Requirements

Although the AlGaAs LD is a mature technology, LD's emitting at 980 and 1480 nm have been developed and are now available in limited quantities. Compared to the AlGaAs LD, these new LD's are relatively expensive and unproven. Both the expense and the reliability of LD's are strong functions of the power level at which they are required to operate. It is therefore of interest to compare for these three bands the pump power required to achieve the same level of amplifier performance. The two sections that follow concentrate on this issue for small-signal amplifiers and power boosters.

A. Requirements for Small-Signal Amplifiers

Fig. 14 compares the minimum pump power required to obtain a specified small-signal gain for pumping an erbium-doped Al/P-silica fiber in the 800-nm band and at 980 and 1480 nm. The signal wavelength is 1532 nm, the Al/P-silica fiber has an NA of 0.25, and the fiber length as well as the cutoff wavelength are optimized to give the minimum required pump power for each point in the figure. Also, the optimum pump wavelengths are used for the 800-nm pumping cases. When pumping bidirectionally in the 800-nm band, $\sim$1 dB less pump power is required as compared to codirectional pumping. The most efficient pump band is at 980 nm. It requires $\sim$2 dB less pump power compared to 1480 nm pumping and $\sim$7–8 dB less pump power compared to the 800-nm band, in order to provide the same small-signal gain. The 980-nm pump band is more efficient than pumping at 1480 nm because, for the latter wavelength, resonant pumping directly into the metastable state reduces the maximum obtainable inversion to $\approx$0.7. This is a consequence of erbium having a significant stimulated emission cross section at 1480 nm. The model predicts a very significant reduction in the power requirement for 980 nm pumping compared to pumping in the 800-nm band.

To verify these predictions we experimentally investigated the power requirements for an erbium-doped Ge/Al/P-silica fiber (see Section III) pumped in the 800-nm band and at 980 nm. Fig. 15 shows the required pump power as function of the small-signal gain. The solid circles connected by thin curves are experimentally obtained and represent the best results, i.e., the fiber length is optimum with respect to gain, for 11 pump wavelengths spaced by $\approx$2 nm in the 800-nm band, one thin curve for each pump wavelength. The crosses connected by a thin curve are measured when pumping at 980 nm. The two thick curves are model calculations in which both the measured refractive index profile and the erbium profile are used as input parameters to the model ($\sigma_{\mathrm{gsa}}(980\ \mathrm{nm}) = 2.1 \times 10^{-25}\ \mathrm{m}^2$). As seen from the figure, the best-case measurements and the model predictions agree well and indicate that $\sim$7 dB less pump power is required for 980 nm pumping.

For some application, e.g., preamplifiers, it is important that the noise figure be kept as low as possible. For a fixed pump power, the noise figure is an increasing function of the fiber length whereas the gain has a maximum at approximately the length for which the pump power along the fiber (codirectional pumping) is decreased to the threshold value. If the noise figure can be ignored, one finds the minimum required pump power by plotting the gain versus fiber length for different pump powers and then choosing the pump power for which the specified gain is obtained at the optimum fiber length. This was done in Figs. 14 and 15. However, if the specified noise figure is less than the one at the fiber length for maximum gain, the fiber must be cut back and, in order to maintain the specified gain, the pump power must be increased. For 980 and 1480 nm this procedure is straightforward and the best pumping scheme will be the codirectional one because bidirectional pumping at these wavelengths has an insignificant effect on the gain

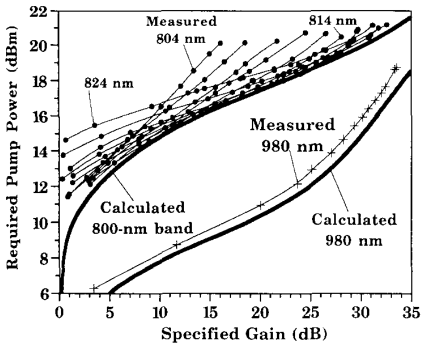

Fig. 15. Required pump power as function of small-signal gain for an erbium-doped Ge/Al/P-silica fiber. Solid circles connected by thin curves are measured when pumping codirectional in the 800-nm band at 11 different pump wavelengths spaced by ≈ 2 nm. The crosses connected by a thin curve are measured when pumping at 980 nm. The signal wavelength is 1551 nm and all fiber lengths were optimized throughout the measurements. The thick curves are calculated.

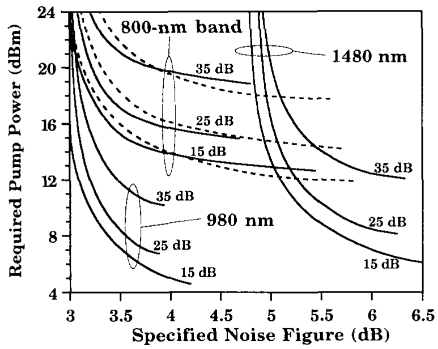

Fig. 16. Required pump power as function of specified noise figure for different specified small-signal gains of 15, 25, and 35 dB. Same cases are treated as in Fig. 13.

were as the noise figure will be higher because the average inversion is lower. When pumping in the 800-nm band one must always vary the pump wavelength to find the minimum pump power for a specification of both gain and noise figure. This procedure is, in principle, not complicated, but takes additional computation time. The required pump power is plotted in Fig. 16 as a function of the specified noise figure. The same cases are treated as in Fig. 14, and curves are shown for different specified small-signal gains of 15, 25, and 35 dB. Resonant pumping at 1480 nm leads to a minimum obtainable noise figure, $F_{\min} \approx 4.8$ dB for a signal wavelength of 1532 nm, and consequently noise figures <5 dB are not practical. In general $F_{\min}$ is given by [15]:

$$F_{\min} = \frac{2}{1 - \frac{\sigma_e(\nu_p)\sigma_{\text{gsa}}(\nu_s)}{\sigma_{\text{gsa}}(\nu_p)\sigma_e(\nu_s)}} \times \left(1 - \frac{1}{G}\right) + \frac{1}{G} \qquad (2)$$

where ν_s is the signal frequency and G is the gain.

For 1480 nm pumping, $F_{\min}$ decreases with increasing signal wavelength λ_s because the ratio $\sigma_{\text{gsa}}(\nu_s)/\sigma_e(\nu_s)$ decreases. For $\lambda_s \approx 1550$ nm, $F_{\min} \approx 4.2$ dB. With regard to excitation in the 800-nm band and at 980 nm, $F_{\min} = 3$ dB when $G >> 1$. From Fig. 16, it is observed that a significant improvement can be obtained by a slight increase in the pump power from the minimum required. For the 800-nm pump band it was found that, when the specified noise figure is less than ~ 4 dB, the best pumping scheme is the co-directional one and the optimum pump wavelength is 805 nm (± 3 nm). However, 980 nm is by far the best pump wavelength since 7–8 dB less power is required to obtain the same amplifier performance.

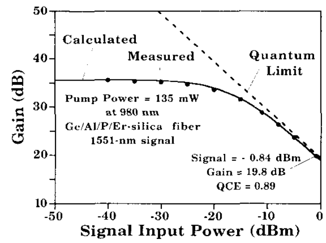

Fig. 17. Gain as function of signal input power for codirectional pumping at 980 nm. The solid circles are data points measured for an erbium-doped Ge/Al/P-silica fiber. The solid curve is calculated and the dashed curve is the quantum limit. The signal wavelength is 1551 nm.

B. Requirements for Power Boosters

The increasing interest in EDFA's used as power boosters is due to their excellent behavior under saturated conditions: immunity to distortion, low cross-talk [16] and high output powers [3], [4]. To provide a high signal output power, the launched pump power needs to be high as well because the EDFA is operated in the saturated region relatively close to the quantum limit. This is demonstrated in Fig. 17 where the gain is plotted versus the signal input power for an erbium-doped Ge/Al/P-silica fiber pumped codirectionally with 135 mW at 980 nm. The signal wavelength is 1551 nm. The measured values [17] are indicated by circles and the model predictions are shown as a solid curve. The dashed curve represents the quantum limit, i.e., the gain assuming all launched pump photons are converted into amplified signal photons. When the signal input is low, the gain is far from the quantum limit because the amplifier is saturated by amplified spontaneous emission (ASE). As the signal input increases, the ASE is suppressed and the gain approaches the quantum limit. The experiment demonstrated that 89% of the launched pump photons were converted into amplified signal photons, in excellent agreement with the calculated values. For 980- and 1480-nm pumping, the model predicts that the quantum limit can be approached either by increasing the signal or pump power or by improving the waveguide [9], [17].

As discussed in Section IV the efficiency of power fiber amplifiers is limited by ESA when pumping in the 800-nm band. The minimum required pump power is plotted in Fig. 18 as a function of specified output signal power for EDFA's with a signal input power of 1 mW at 1532 nm. The same cases as discussed in Fig. 14 are treated here. For a specified output power above 5 dBm, the pump power requirement is smallest for 1480-nm pumping, which requires up to 1.7 dB less pump power than at 980 nm due to the higher photon energy at the latter wavelength. However, since 980-nm LD's have been demonstrated [18] to be approximately twice as efficient as 1480-nm LD's, the overall efficiency will be highest for EDFA's based on 980-nm LD's. The power requirements for

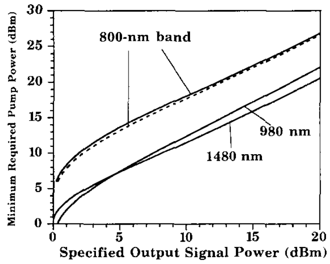

Fig. 18. Minimum required pump power as function of specified signal output power for an erbium-doped Al/P-silica fiber with an NA of 0.25 and with an 1-mW signal input at 1532 nm. Curves are shown for codirectional pumping (solid curves) in the 800-nm band, at 980 nm and at 1480 nm, and for bidirectional (dashed curve) pumping in the 800-nm band. All fiber lengths are optimized and the optimum wavelength within the 800-nm band has been used in all cases.

pumping in the 800-nm band is 6–7 dB higher than for the two other bands.

VI. Conclusion

We have examined in detail the characteristics of EDFA's pumped in the 800-nm band. The main obstacle to efficient performance is ESA, and its effects can be reduced by pumping in the long-wavelength tail of the band. The pump wavelength that gives the highest small-signal gain increases with increasing pump power. For erbium-doped silica fibers codoped with aluminum the optimum pump wavelengths, for codirectional pumping and small-signal gains higher than ~25 dB, are ~822 nm for a signal wavelength of $\lambda_s = 1551$ nm and ~817 nm for $\lambda_s = 1532$ nm. For bidirectional pumping the optimum pump wavelength is ≈3 nm shorter in each case. If a low-noise figure is required the optimum pump wavelength is 805 nm (±3 nm) and the best pumping scheme is the codirectional one.

The small-signal gain coefficient can be improved by ~60% if a fluorophosphate glass is used as the host instead of silica. For high-gain amplifiers the pump power required to obtain the same small-signal gain can be reduced by ≈3 dB through using the fluorophosphate hose. The fluorophosphate has ~60% higher quantum conversion efficiency than the silica, yielding a reduction of ≈2 dB in the pump power requirements for power boosters.

The pump power requirements for erbium-doped silica fibers pumped in the 800-nm band were also compared to those at 980 and 1480 nm. When pumping in the 800-nm band, ~7–8 dB higher pump power is required to obtain the same small-signal amplifier performance as when pumping at 980 nm. Low-noise preamplifiers should be pumped at 980 nm. For power fiber amplifiers the same specified signal output power requires 6–7 dB higher pump power for the 800-nm band. For silica fibers, the additional power required when pumping at 800 nm compared to 980 and 1480 nm is expected to offset the cost and reliability advantages of using AlGaAs laser diodes.

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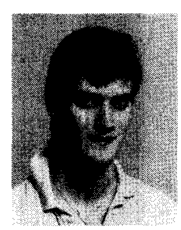

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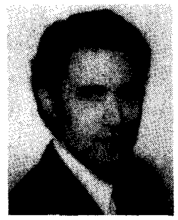

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