Excited-State Absorption Cross Sections in the 800-nm Band for Er-Doped, Al/P-Silica Fibers: Measurements and Amplifier Modeling

S. Zemon, B. Pedersen, G. Lambert, W. J. Miniscalco, L. J. Andrews, R. W. Davies, and T. Wei

Abstract—**Excited-state absorption (ESA) cross sections were determined for the 800-nm band of Er-doped, Al/P-silica fibers. The oscillator strength of the ESA transition exceeds that of the 800 nm, ground-state absorption (GSA) transition by a factor of ≈ 2.3, in reasonable agreement with a Judd–Ofelt calculation. The extended, long-wavelength tail of the GSA band leads to a region around 820 nm where the GSA cross section $\approx$ ESA cross section. The cross sections were incorporated into an amplifier model for pumping in the 800-nm band. Codirectional and the bidirectional pumping schemes were analyzed for excitation near the peak and in the long wavelength tail of the GSA band. Pumping in the tail for either pumping scheme or pumping near the peak for the bidirectional scheme are predicted to produce a significant improvement in the small-signal gain.**

I. Introduction

A CRITICAL factor in the utility of any optically pumped amplifier or laser is the availability of excitation sources and the efficiency with which pump photons produce gain. For Er^{3+}-doped fiber amplifiers excellent performance has been achieved pumping at 980 [1] and 1480 nm [2], but diode lasers at these wavelengths have relatively low powers and are quite expensive compared to AlGaAs lasers which can pump the absorption band at 800 nm. However, the latter pumping configuration does not lead to favorable amplifier characteristics because of the low ground-state absorption (GSA) cross section and an overlapping, intense excited-state absorption (ESA) transition. Some improvement has been realized by exciting the long-wavelength wing of GSA band. Gains up to 29 dB have been reported for Al/Ge-doped silica codirectionally pumped with 100 mW at 820 nm [3]. Using a high efficiency waveguide design, 39 dB has been achieved bidirectionally pumping Ge-doped silica with 50 mW at 827 nm [4]. However, this approach, requiring pumping the amplifiers at wavelengths for which the GSA cross section is substantially reduced from its already low peak value, is expected to degrade the amplifier noise figure. Comprehensive analyses of achievable efficiencies and noise figure penalties have been lacking, due largely to the unavailability of experimental ESA cross sections. Earlier measurements generally only provided the ratio of the ESA and GSA cross sections at specific wavelengths [5], [6]. We report here a measurement of the complete spectrum of the ESA cross section in the 800-nm region. Together with measurements of the excited-state lifetime and other relevant cross-section spectra, this result has been incorporated into an accurate amplifier model to assess the effects on performance of pumping near the peak or in the wing of the 800-nm band. Both codirectional and bidirectional pumping schemes have been treated.

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II. Experimental

The Al/P-doped silica fibers were drawn from modified-chemical-vapor-deposition preforms prepared by solution doping [7]. Fibers with core diameters of 6.7 μm (multimode at 800 nm) and 4 μm (singlemode at 800 nm) and lengths (L_0) of 120 and 10 cm were examined. The Er^{3+} concentration at the center of the core was 1.3×10^{19} cm^{-3}. The $^4I_{13/2}$ level, the only metastable state for Er^{3+}-doped silica, was populated by employing the 647.1-nm line from a krypton laser to excite from the $^4I_{15/2}$ ground state to the $^4F_{9/2}$ state. Significant populations were only generated in the metastable $^4I_{13/2}$ state since no ESA was observed for the upper excited states. For the 800-nm band the GSA transition corresponds to $^4I_{15/2} \rightarrow {}^4I_{9/2}$ (with cross section σ_{13}) while the ESA transition corresponds to $^4I_{13/2} \rightarrow {}^2H_{11/2}$ (with cross section σ_{24}).

The measurement consisted of determining the difference in transmission of a probe beam when the pump beam was turned on and off ($\Delta T = T_{off} - T_{on}$). To optimize the signal-to-noise ratio, a double modulation scheme was employed. The pump beam was chopped at 10 Hz (a frequency which is slow with respect to the ≈ 10 ms lifetime of the metastable $^4I_{13/2}$ state), reflected by a dichroic mirror, and focused onto one end of the fiber. Pump powers up to ≈ 0.5 W were used. The probe beam, an incoherent, 100-W lamp, was chopped at 400 Hz and focused onto the other end of the fiber. The cladding modes were stripped with index-matching fluid. The transmitted probe beam was collimated and focused into a spectrometer. The output was detected with a

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cooled, germanium, p-i-n photodiode and the signal was filtered with a 400-Hz lock-in. The 10-Hz modulated envelope was amplified by a second lock-in and the resultant data were recorded with a computer. To obtain ΔT from the raw data, a scaling factor (derived from accurate dc measurements) was used to correct for the averaging effect of the lock-in system. Finally, a scan was taken with the pump off to obtain T_{off}.

Saturation could be achieved with excitation powers as low as 0.2 W. The procedure for deriving the cross sections for these fibers from the saturated value of $\Delta T/T_{\text{off}}$ $[(\Delta T/T_{\text{off}})_{\text{sat.}}]$ is as follows. First, the attenuation α was evaluated using $\alpha = \{\ln[1 - (\Delta T/T_{\text{off}})_{\text{sat.}}]\}/L_0$. Then the α data for the 980-nm band were compared to the GSA cross-section data and a scaling constant C_0 was determined, i.e., $\sigma = C_0\alpha$. Thereupon, C_0 was used to translate the $(\alpha_{24} - \alpha_{13})$ data for the 800-nm band into the cross-section data $(\sigma_{24} - \sigma_{13})$ so that $\sigma_{24} = C_0(\alpha_{24} - \alpha_{13}) + \sigma_{13}$.

The procedure for determining the GSA cross sections from cut-back measurements and the Er^{3+} doping profile has been described previously [8]; in this investigation neutron activation analysis was used to provide a more accurate value of the Er^{3+} concentration [9]. Stimulated emission cross sections were determined from emission spectra and excited state lifetimes using established procedures [10].

III. Cross Sections

Fig. 1 shows the ESA and GSA cross sections over the wavelength range from 760 to 900 nm for the Al/P-doped silica. Essentially the same results were obtained for fibers that were single mode and multimode at 800 nm as well as for fiber lengths of ≈ 10 and 120 cm. The dashed curve corresponds to the GSA cross section. The solid curve represents the ESA cross section which includes two bands, one centered at ≈ 790 nm (due to $^4I_{13/2} \rightarrow {}^2H_{11/2}$) overlapping the 800-nm GSA band and the other centered ≈ 850 nm (due to $^4I_{13/2} \rightarrow {}^4S_{3/2}$). Although the oscillator strength of the ESA transition at 790 nm is significantly greater than that of the 800-nm GSA transition, the extended long-wavelength tail of the GSA band leads to a region around 820 nm where $\sigma_{13} \approx \sigma_{24}$. This is consistent with the improvement in Al/Ge-silica amplifiers realized by shifting the pump to longer wavelengths, as reported in [3].

The measured ratio of ESA to GSA oscillator strengths is ≈ 2.3 in reasonable agreement with a Judd–Ofelt calculation [11] which predicts the ratio of these transition strengths to be 2.8. The calculated oscillator strengths were obtained using the following Judd–Ofelt parameters: $\Omega_2 = 16.1 \times 10^{-20}$ cm^2, $\Omega_4 = 1.75 \times 10^{-20}$ cm^2, and $\Omega_6 = 0.90 \times 10^{-20}$ cm^2. These parameters were derived from the oscillator strengths of the three lowest energy GSA transitions at 1530, 975, and 800 nm [8], [9] and the 520-nm transition [12] which are 158.8×10^{-8}, 57.3×10^{-8}, 28.1×10^{-8}, and 2123×10^{-8}, respectively, where the oscillator strength is defined as $(mc/\pi e^2) \int \sigma(\upsilon) d\upsilon$ and υ is the frequency. It is important to include the 520-nm transition in deriving the Judd–Ofelt Ω parameters for the Er^{3+} ion in order to obtain an accurate value of Ω_2. The experimental oscillator strengths

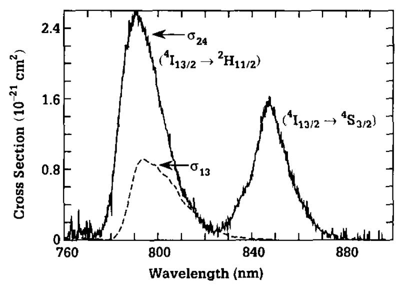

Fig. 1. The ground-state absorption cross section (dashed line) and excited-state absorption cross section (solid line) versus wavelength for an Er^{3+}-doped Al/P fiber.

were found to be 30.4×10^{-8}, 28.1×10^{-8}, and 65.9×10^{-8} for the 840-nm ESA band ($^4I_{13/2} \rightarrow {}^4S_{3/2}$), 800-nm GSA band ($^4I_{15/2} \rightarrow {}^4I_{9/2}$), and 790-nm ESA band ($^4I_{13/2} \rightarrow {}^2H_{9/2}$), respectively. The corresponding Judd–Ofelt oscillator strengths were calculated to be 36.9×10^{-8}, 31.7×10^{-8}, and 87.6×10^{-8}, respectively, where the latter value includes a magnetic-dipole contribution of 19.1×10^{-8}. The agreement between the experimental and calculated values is reasonably good.

IV. Amplifier Model

The measured GSA and ESA cross sections in the 800-nm pump band were incorporated into a qualitative amplifier model [13], [14] that uses the true LP_{01} modes for the signal and the pump. Additionally, it includes the spectrum of the absorption and emission cross sections at 1500 nm when calculating the amplified spontaneous emission (ASE). Both the forward and the backward ASE are considered by iteratively solving the differential equations for propagation in the forward and the backward direction. The solutions, which are obtained numerically, insure that the boundary conditions at both fiber ends are fulfilled. The model has previously been shown to predict gain and noise properties with a high degree of accuracy [14].

All the parameters used in the calculation were experimentally determined. The fiber parameters, chosen to be similar to those used by Kimura *et al.* [3] in their measurements on an Er^{3+}-doped Al/Ge-silica amplifier pumped in the 800-nm band, were as follows: core radius = 1.96 μm, NA = 0.229, and Er^{3+} concentration = 2.6×10^{18} cm^{-3}. λ_{p1}, which corresponds to pumping near the peak the GSA band, was taken to be 805.2 nm and λ_{p2}, which corresponds to pumping in the long-wavelength tail, was 819.2 nm. The relevant cross sections are $\sigma_{13}(\lambda_{p1}) = 6.90 \times 10^{-22}$ cm^2 with $\sigma_{24}/\sigma_{13} = 1.55$ and $\sigma_{13}(\lambda_{p2}) = 2.22 \times 10^{-22}$ cm^2 with $\sigma_{24}/\sigma_{13} = 0.653$. λ_s, the signal wavelength, was taken to be 1531.4 nm. $\sigma_{12}(\lambda_s)$, the GSA cross section for the $^4I_{13/2}$ state, was found to be 51.7×10^{-22} cm^2 and $\sigma_{21}(\lambda_s)$, the stimulated-emission cross section, was determined to be 55.5×10^{-22} cm^2. The radiative lifetime of the metastable $^4I_{13/2}$ state was measured to be 10.8 ms.

Fig. 2(a) and (b) show the small signal gain and the corresponding noise figure versus the fiber length for $\lambda_{p1} = 805.2$ nm and $\lambda_{p2} = 819.2$ nm, respectively. The dashed

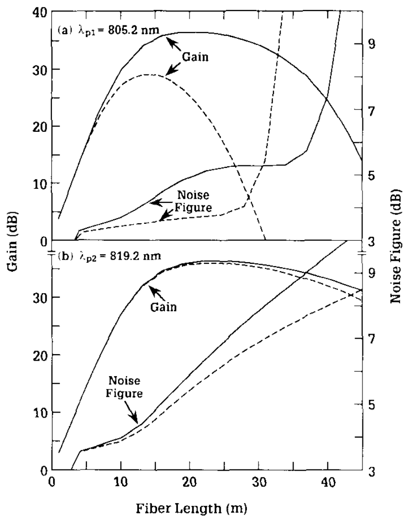

Fig. 2. Predicted gain and noise figure versus fiber length in an Er^{3+}-doped Al/P fiber when pumping at (a) 805.2 nm and (b) 819.2 nm. Results are shown for codirectional pumping (dashed curves) and for bidirectional pumping (solid curves).

curves represent pumping with 100 mW coupled into the same end as the signal (codirectional pumping) and the solid curves represent pumping with 50 mW coupled into each fiber end (bidirectional pumping) [15]. As seen from Fig. 2(a) for 805.2-nm pumping the bidirectional scheme has a maximum gain of 36.3 dB which is 7.3 dB higher than the maximum gain for the codirectional pumping scheme. The advantage of the former over the latter occurs because of excited-state absorption, essentially due to the fact that the pump is attenuated by ESA even when a complete inversion of the upper laser level is obtained. This means that when the pump power is high enough to approach inversion, part of any additional power is attenuated by ESA and will be of no use further on in the fiber. Thus, for 100-mW, codirectional excitation a larger percentage of the pump photons will be absorbed due to ESA than in the 50-mW, bidirectional pumping scheme [13]. In contrast, as seen from Fig. 2(b) for λ_{p2} = 819.2 nm, the difference between bi- and codirectional pumping is insignificant. This is because for 819.2-nm excitation the ESA cross section is relatively small (see Fig. 1) and, therefore, the two pumping schemes are almost equally efficient. Note that for the codirectional scheme there is a 7-dB increase in the maximum gain when pumping at λ_{p2} as compared to λ_{p1} but no increase for the bidirectional scheme, i.e., the advantage of pumping in the long-wavelength absorption tail present for codirectional pumping is predicted to vanish for bidirectional pumping.

The bidirectional pumping scheme is calculated to have a larger noise figure than the codirectional scheme. This is because the ASE counter-propagating with respect to the pump is larger than the ASE copropagating with the pump [13]. Furthermore, the noise figure for λ_{p2} = 819.2 nm is higher than that for λ_{p1} = 805.2 nm. This is due to the lower absorption cross section at 819.2 nm.

The results of the calculations compare reasonably well with those of the amplifier experiments of Kimura *et al.* [3] for Al/Ge-doped silica where a codirectional pumping configuration was used. Since Al/Ge- and Al/P-doped silica are spectroscopically similar, employing the cross sections for the latter to describe the former should be a good approximation. For 805.2-nm pumping the calculations give gains of 16 dB and 15 dB for fiber lengths of 5 and 26 m, respectively, as compared to the experimentally measured gains of 14 and 12.5 dB, respectively. For 819-nm pumping the calculated gains are 14.5 and 36 dB for 5 and 26 m, respectively, as compared to the measured gains of 11 and 29 dB, respectively.

In summary, ESA cross-section spectra have been measured for Al/P-doped silica in the 800-nm band. The oscillator strength of the ESA transition is $\approx 2.3 \times$ greater than that of the 800-nm GSA transition, in reasonable agreement with a Judd–Ofelt calculation. However, the extended, long-wavelength tail of GSA band leads to a region around 820 nm where the GSA and ESA cross sections are comparable. A full-scale, numerical model is used to analyze the gain and noise performance when pumping near the peak and in the tail of the GSA band. Based upon this analysis, either pumping in the GSA tail in the co- and bidirectional schemes or pumping near the peak in the latter scheme are expected to produce a significant improvement in the small-signal gain for excitation in the 800-nm band. However, the increased gain is obtained at the expense of a 2- to 3-dB increase in the noise figure as compared to the case of pumping near the peak in the codirectional scheme.

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References

[1] R. I. Laming, M. C. Farries, P. R. Morkel, L. Reekie, D. N. Payne, P. L. Scrivener, F. Fontana, and A. Righetti, "Efficient pump wavelengths of erbium-doped fiber optical amplifier," *Electron. Lett.*, vol. 25, no. 1, pp. 12–14, 1989.

[2] M. Nakazawa, Y. Kimura, and K. Suzuki, "Efficient Er^{3+}-doped optical fiber amplifier pumped by a 1.48-μm InGaAsP laser diode," *Appl. Phys. Lett.*, vol. 54, no. 4, pp. 295–297, 1989.

[3] Y. Kimura, K. Suzuki, and M. Nakazawa, "High gain erbium-doped fiber amplifier pumped in the 0.8 μm band," in *Proc. Eur. Conf. Optical Commun.*, Amsterdam, The Netherlands, vol. 1, 1990, pp. 103–106.

[4] M. Horiguchi, M. Shimizu, M. Yamada, K. Yoshino, and H. Hanafusa, "Highly efficient optical fiber amplifier pumped by a 0.8 μm band laser diode," *Electron. Lett.*, vol. 26, no. 21, pp. 1758–1759, 1990.

[5] C. G. Atkins, J. R. Armitage, R. Wyatt, B. J. Ainslie, and S. P. Craig-Ryan, "Pump excited state absorption in Er^{3+} doped optical fibers," *Opt. Commun.*, vol. 73, no. 3, pp. 217–222, 1989.

[6] R. I. Laming, S. B. Poole, and E. J. Tarbox, "Pump excited-state absorption in erbium-doped fibers," *Opt. Lett.*, vol. 13, no. 12, pp. 1084–1086, 1988.

[7] J. E. Townsend, S. B. Poole, and D. N. Payne, "Solution-doping technique for fabrication of rare-earth-doped optical fibers," *Electron. Lett.*, vol. 23, no. 7, pp. 329–331, 1987.

[8] M. P. Singh, D. W. Oblas, J. O. Reese, W. J. Miniscalco, and T. Wei, "Measurement of the spectral dependence of absorption cross section for erbium-doped single-mode optical fiber," *Symp. Opt. Fiber Measurements*, NIST Special Publication 792, 1990, pp. 93–96.

[9] M. P. Singh, private communication.

[10] W. J. Miniscalco and R. S. Quimby, "General procedure for the analysis of Er^{3+} cross sections," *Opt. Lett.*, vol. 16, pp. 258–260, 1991.

[11] L. J. Andrews, W. J. Miniscalco, and T. Wei, "Excited state absorption of rare earths in fiber amplifiers," in *Proc. First Int. School on Excited States of Transition Elements*, B. Jezowska-Trzebiatowska, Ed. Singapore: World Scientific, 1989, pp. 9–30.

[12] K. Dybdal, N. Bjerre, J. E. Pedersen, and C. C. Larsen, "Spectroscopic properties of Er-doped silica fibers and preforms," in *Fiber Laser Sources and Amplifiers*, M. J. F. Digonnet, Ed. Bellingham, WA: SPIE, vol. 1171, 1990, pp. 209–218.

[13] B. Pedersen, A. Bjarklev, H. Vendeltorp-Pommer, and J. H. Povlsen, "Erbium doped fiber amplifier: efficient pumping at 807 nm," *Opt. Commun.*, vol. 81, no. 1, 2, pp. 23–26, 1991.

[14] B. Pedersen, K. Dybdal, C. D. Hansen, A. Bjarklev, J. H. Povlsen, Vendeltorp-Pommer, and C. C. Larsen, "Detailed theoretical and experimental investigation of high-gain erbium doped fiber amplifier," *IEEE Photon. Technol. Lett.*, vol. 2, pp. 863–865, Dec. 1990.

[15] Amplifier-model calculations indicate that, for a given total pump power, the small-signal gain at the optimum fiber length for bidirectional pumping will always be a maximum if the pump power is divided equally.