Pump excited-state absorption in erbium-doped fibers

R. I. Laming, S. B. Poole, and E. J. Tarbox*

Optical Fibre Group, Department of Electronics and Computer Science, University of Southampton, Southampton S09 5NH, UK

Received July 18, 1988; accepted August 16, 1988

Ground-state and excited-state absorption spectra covering the wavelength range of 450–1050 nm are presented for erbium-doped silica fibers with four different core codopants: GeO_2, GeO_2/B_2O_3, GeO_2/P_2O_5, and Al_2O_3. It is shown that the host glass influences the excited-state absorption spectra and that P_2O_5- or Al_2O_3-codoped fibers are the preferred choice for 514.5-, 655-, or 807-nm pump wavelengths owing to reduced pump excited-state absorption. However, excited-state absorption is still significant at the 807-nm wavelength. Pump wavelengths of 524, 532, and 980 nm appear ideal because of the strong ground-state absorption and lack of excited-state absorption.

Erbium-doped fiber lasers and amplifiers have attracted much attention[1–5] for operation in the third telecommunications window at wavelengths near 1.5 μm. However, there are problems to be overcome to allow efficient operation at this wavelength, since erbium acts as a three-level laser system. Such systems require more ions to be in the excited, metastable state than in the ground state to create a population inversion. Significant unwanted absorption of pump energy may then occur, since ions can be further excited from the highly populated metastable level to higher energies if an appropriate energy transition exists. This effect, pump excited-state absorption (ESA), is detrimental because it depletes the metastable level and makes inefficient use of pump energy. A figure of merit indicating the significance of the ESA at a given wavelength is the ratio $\sigma_{ESA}/\sigma_{GSA}$, where σ_{ESA} and σ_{GSA} are the ESA and ground-state absorption (GSA) cross sections, respectively. Ideally, for a prospective pump absorption band, this ratio should be zero.

As shown in Fig. 1, it has been demonstrated that erbium can be pumped either directly[5] into the $^4I_{13/2}$ metastable level, which occurs at 1490 nm, or into higher-energy levels (e.g., $^4I_{9/2}$, $^4F_{9/2}$, and $^2H_{11/2}$), from which nonradiative decay occurs to the metastable level. In these cases, suitable pump wavelengths are 807, 660, and 514.5 nm, respectively.[1–3] ESA is anticipated in the region of these latter pump wavelengths. It may, therefore, be advantageous to modify the glass host since it is well known[7] that this can alter the absorption spectrum and thus may also shift the ESA band away from the pump band.

Previous observations of ESA in Er^{3+}-doped fibers[4] have been made using an F-center laser operating in the region of 1.5 μm to populate equally the $^4I_{13/2}$ and $^4I_{15/2}$ levels, i.e., the laser transition levels (see Fig. 1). Under these conditions the absorption from the ground-state $^4I_{15/2}$ level will be reduced, and absorptions from the $^4I_{13/2}$ metastable level to higher levels will occur that can be measured as a change in absorption spectrum. For this research we have used a dye laser operating at 665 nm to excite ions to the $^4F_{9/2}$ level. These rapidly decay nonradiatively to the metastable $^4I_{13/2}$ level, which has a relatively long lifetime. Consequently, nearly 100% of the ions can be inverted from the $^4I_{15/2}$ to the $^4I_{13/2}$ level at the power levels (100 mW) available from the dye laser.[2] The $^4I_{13/2}$ level then effectively becomes the ground state, and a full ESA spectrum can be measured.

In this Letter we present GSA and ESA spectra measured in a series of erbium-doped fibers with different core-glass compositions. The measurements span the range of 450–1050 nm and show that the host glass does have an effect on ESA as anticipated.

The experimental configuration is shown in Fig. 2. Chopped white light from a tungsten lamp was launched into one end of a short length of doped fiber, and the output was analyzed with a monochromator (FWHM ~2 nm). Counterpropagating pump light at 665 nm from a polarized Ar^+-pumped dye laser was coupled in through a polarizing beam splitter. The fiber throughput between 450 and 1050 nm was measured both pumped and unpumped to obtain the ESA, after which the fiber was cut back and remeasured to obtain a value for unpumped loss (GSA). Four erbium-doped silica fiber types were tested, containing GeO_2, GeO_2/B_2O_3, GeO_2/P_2O_5, and Al_2O_3, all prepared by the solution-doping technique[8]; their characteristics given in Table 1.

The GSA and change in absorption between 450 and

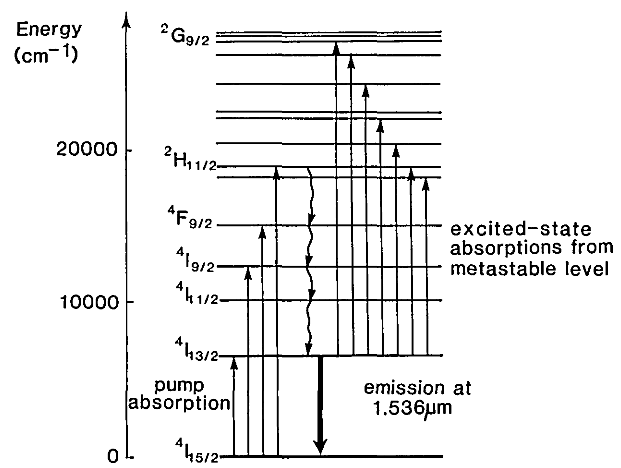

Fig. 1. Erbium energy-level diagram.[6]

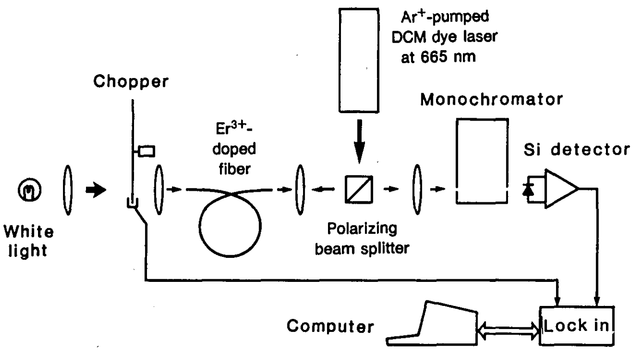

Fig. 2. Experimental layout.

Table 1. Fiber Characteristics

	Fiber Type			
	GeO_2	Ge_2/B_2O_3	GeO_2/P_2O_5	Al_2O_3
Core constituents (wt./%)[a]	$Er_2O_3 \sim 0.1$ $GeO_2 \sim 15$	$Er_2O_3 \sim 0.1$ $GeO_2 \sim 23$ $B_2O_3 \sim 15$	$Er_2O_3 \sim 0.02$ $GeO_2 \sim 6.5$ $P_2O_5 \sim 3.5$	$Er_2O_3 \sim 0.2$ $Al_2O_3 \sim 6$

[a] The rest of the core material is SiO_2.

660 nm when pumped are shown in Figs. 3(a) and 3(b) for the GeO_2/B_2O_3- and Al_2O_3-codoped fibers, respectively. [The values for the GeO_2- and GeO_2/P_2O_5-codoped fibers are almost identical to those for the GeO_2/B_2O_3- and Al_2O_3-codoped fibers, respectively, and are shown only in the region near 650 nm (insets).] Negative changes in absorption indicate bleaching of the GSA, and if the negative change is equal in magnitude to the GSA, full bleaching of the transition has been achieved. Figure 3 can be more readily understood if we note that the $^4I_{13/2}$ metastable level is virtually fully populated when pumped and therefore behaves as though it is the ground state for absorptive transitions to higher levels. With this in mind we see that there is a large ESA between 460 and 490 nm corresponding to the $^4I_{13/2}$–$^2G_{9/2}$ transition, and this prevents successful pumping at 488 nm.

There is a strong ESA centered near 505 nm that renders pumping at 514.5 nm with an Ar^+ laser only moderately successful. However, the ESA is modified slightly in the Al_2O_3 fiber, making this the preferred type for this pump wavelength. On the other hand, in the heart of the 525-nm absorption band it appears that there is little or no ESA, from which we infer that 524 or 532 nm would be the ideal pump wavelength using either a frequency-doubled mini-YLF or YAG laser, respectively.

ESA can be seen to be significant at the short-wavelength end of the GSA centered at 650 nm. However, at longer wavelengths the ESA can be seen to decrease radically, which confirms that pump wavelengths between 655 and 675 nm are suitable.[2]

From these figures we can calculate the ratio of ESA to GSA strengths, $\alpha_{ESA}/\alpha_{GSA}$, at 655 nm; these are listed in Table 2. The ratio of excited-state to ground-state cross sections, $\sigma_{ESA}/\sigma_{GSA}$, will be similar since

$$\frac{\alpha_{ESA}}{\alpha_{GSA}} = \frac{\sigma_{ESA}}{\sigma_{GSA}} \frac{N_2\,(\text{pumped})}{N_1\,(\text{unpumped})},$$

where N_2 and N_1 are the upper-state and lower-state populations pumped and unpumped, respectively. Under strong pumping, N_2 (pumped) $\approx$ N_1 (unpumped). The ratios at 488 and 514.5 nm were measured with an attenuated Ar^+ laser replacing the white-light source as the probe beam for greater wavelength accuracy and are listed in Table 2. It can be seen from these results that the presence of Al_2O_3 or P_2O_5 in the fiber core is advantageous for either 514.5- or 655-nm pump wavelengths.

The GSA and ESA in the GeO_2-, GeO_2/P_2O_5-, and Al_2O_3-codoped fibers from 750 to 900 nm, which includes the important diode-pumpable $^4I_{15/2}$–$^4I_{9/2}$ transition occurring at approximately 807 nm, are shown in Figs. 4(a)–4(c), respectively. (The GeO_2/B_2O_3-codoped fiber is not shown, since it exhibited characteristics similar to those of the GeO_2-codoped fiber.) In the GeO_2-codoped fiber the ESA extends across the GSA, while the Al_2O_3- and GeO_2/P_2O_5-codoped fibers

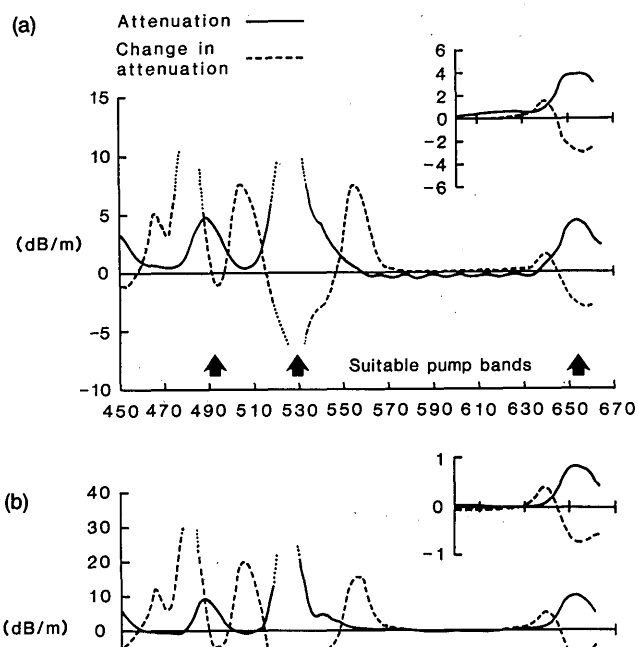

Fig. 3. Spectral plots of attenuation and change in attenuation for (a) GeO_2/B_2O_3- and GeO_2- (inset) codoped fibers and (b) Al_2O_3- and GeO_2/P_2O_5- (inset) codoped fibers.

Table 2. Ratio of ESA to GSA Strengths, $\alpha_{ESA}/\alpha_{GSA}$, as a Function of Wavelength

	Fiber Type			
Wavelength (nm)	GeO_2	GeO_2/B_2O_3	GeO_2/P_2O_5	Al_2O_3
488	2.9		1.86	1.74
514.5	0.95		0.55	0.5
655	0.28	0.25	0.13	0.14
810	2.0	2.0	1.0	1.0
980				0

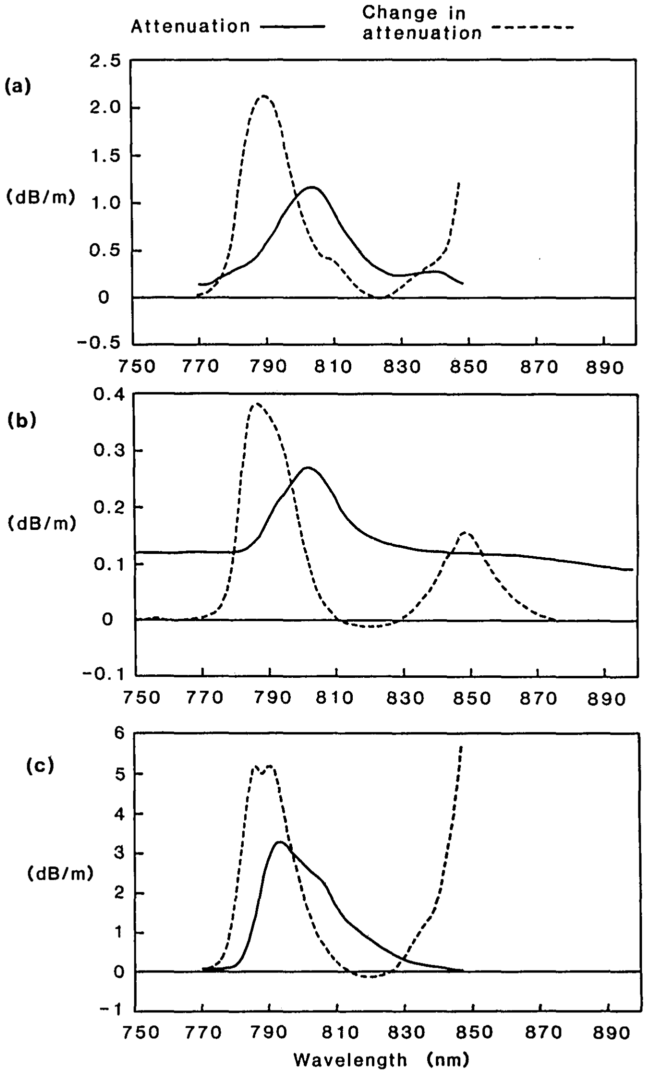

Fig. 4. Spectral plots of attenuation and change in attenuation for (a) GeO_2-, (b) GeO_2/P_2O_5-, and (c) Al_2O_3-codoped fibers.

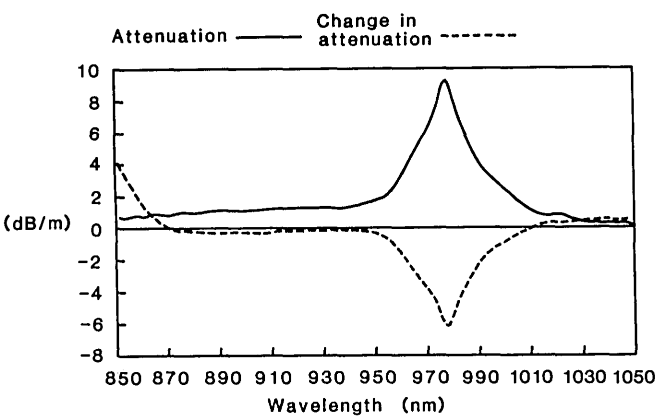

Fig. 5. Spectral plot of attenuation and change in attenuation for Al_2O_3-codoped fiber.

have reduced ESA within the absorption band, which may prove advantageous for diode pumping. There is, however, a broadening of the GSA in the Al_2O_3-codoped fiber at 800 nm that we have interpreted to be due to the enhancement of a further Stark transition. We also note a strong ESA near 850 nm that could be detrimental for Yb/Er-codoped fiber lasers or amplifiers pumped at semiconductor wavelengths.[5]

The $^4I_{15/2}$–$^4I_{11/2}$ transition, centered on 980 nm, was also investigated in an Al_2O_3-codoped fiber (Fig. 5). As can be seen, no ESA was observed, which agrees with the expected result from a study of energy-level diagrams. All four fiber types should behave identically. Thus 980 nm appears to be an ideal pump wavelength, particularly since the absorption cross section is comparable with that at 1.536 μm. In addition, the small Stokes shift between the pump and signal wavelengths gives more efficient use of the pump energy and improves the modal overlap between the pump and the signal in a single-mode fiber. The ratio of absorption strengths for all available pump wavelengths and the four fiber types is shown in Table 2.

Pump ESA has been measured in the range of 450–1050 nm for erbium-doped silica fibers with four different core codopants: GeO_2, GeO_2/B_2O_3, GeO_2/P_2O_5, and Al_2O_3. The latter two types have been found to have a lower ratio of ESA to GSA strengths at 488, 514.5, 665, and 810 nm, from which we infer that they are better choices if pumping on these bands is desired. However, the ESA is still significant at 488 and 810 nm, making these nonideal pump wavelengths. On the other hand, the ratio $\alpha_{ESA}/\alpha_{GSA}$ was found to be good at the 514.5- and 655-nm pump bands (~0.5 and ~0.15 for the latter two fiber types). Measurements show no ESA at the transition centered on 980 nm, where the GSA cross section is comparable with that at 1536 nm. This and the fact that fibers can be made single mode at both pump (980-nm) and signal (1.536-μm) wavelengths giving good pump and signal overlap make this an ideal pump wavelength.

The authors wish to thank D. N. Payne, M. C. Farries, and P. R. Morkel for helpful discussions and Pirelli General plc for financial support.

* Present address, Pirelli General plc, Leigh Road, Eastleigh, UK.

References

1. R. J. Mears, L. Reekie, S. B. Poole, and D. N. Payne, Electron. Lett. **22,** 159 (1986).
2. R. J. Mears, L. Reekie, I. M. Jauncey, and D. N. Payne, Electron. Lett. **23,** 1026 (1987).
3. E. Desurvire, J. R. Simpson, and P. C. Becker, Opt. Lett. **12,** 888 (1987).
4. J. R. Armitage, C. G. Atkins, R. Wyatt, B. Ainslie, and S. P. Craig, in *Digest of Topical Meeting on Tunable Solid-State Lasers* (Optical Society of America, Washington, D.C., 1987), paper WD3.
5. E. Snitzer, H. Po, F. Hakimi, R. Tumminelli, and B. C. McCollum, in *Digest of Conference on Optical Fiber Communication* (Optical Society of America, Washington, D.C., 1988), postdeadline paper 2.
6. G. H. Dieke, *Spectra and Energy Levels of Rare-Earth Ions in Crystals* (Interscience, New York, 1968).
7. K. Arai, H. Namikawa, K. Kumata, T. Honda, Y. Ishii, and T. Handa, J. Appl. Phys. **59,** 3430 (1986).
8. J. E. Townsend, S. B. Poole, and D. N. Payne, Electron. Lett. **23,** 329 (1987).