Experimental Evidence of Differences in the Absorption Spectra of Clustered and Isolated Ions in Erbium Doped Fibers

B. N. Samson, W. H. Loh* and J. P. de Sandro+

Optoelectronics Research Centre
University of Southampton
Southampton SO17 1BJ
United Kingdom
Email: BNS@ORC.SOTON.AC.UK

Tel: +44 01703 594523
Fax: +44 01703 593142

Abstract

The absorption spectra of clustered and isolated ions in erbium-doped germanosilicate fibers have been experimentally studied. The ground state absorption spectra broaden as the degree of erbium-ion clustering increases, indicating that the absorption spectra of clustered ions is significantly different from that of the homogeneous ions. This is confirmed by comparing the broadened absorption spectra with the fibre unbleachable loss spectrum; a direct measurement of the clustered ions. This is the first experimental evidence indicating different absorption cross-sections for the two species of ions in germanosilicate glass, an assumption used in the theoretical description of self-pulsing in erbium doped fiber lasers, but in direct contradiction to the pair-induced quenching model widely used to characterise EDFAs.

Erbium ion clustering is a serious issue in erbium doped fiber amplifiers (EDFAs) and lasers as it adversely impacts on the device performance, giving rise to unbleachable losses that compromise the device efficiency[1-3]. The unbleachable loss is attributed to ion-ion interactions within a cluster giving rise to a co-operative upconversion process between two neighbouring excited state ions. The net result of this upconversion process is one ion in the ground state whilst the other quickly returns to the metastable level via multiphonon relaxation. Since the intra-cluster transfer rate is high (typically microsecs) the saturation power required to excite the two neighbouring/clustered ions into the metastable level is large; of the order of watts[4]. Hence for intermediate powers (around 100mW) there exists an "unbleachable" loss, that is related to the number of clustered ions. Previous work on EDFAs have attempted to characterise the fraction of clustered ions by using the pair-induced quenching model[3,5]; however, an assumption implicit in these calculations is that the absorption characteristics of the clustered ions are basically the same as that of homogeneous or isolated ions. Indeed all calculations of the clustered ion fraction found in the literature are based on an equal absorption cross section for the clustered ions and the homogeneous ions[4,6,7]. In addition to degrading the efficiency of EDFAs, it has been pointed out that high ion concentration effects are linked to the phenomenon of sustained self-pulsations observed in many Er-fiber lasers[8,9]. To account for this, a theoretical model including energy transfer between ion pairs has been put forward, capable of predicting the self-pulsations. However, a key assumption necessary for this model is that the absorption cross-section of ion pairs should be substantially different (smaller) from that of isolated ions[8]. To our knowledge, there is very little experimental evidence to support this theoretical assumption, indeed it is contrary to the assumption implicit in the pair-induced quenching model widely used to characterise EDFAs. If indeed the

absorption cross section for clustered ions is less than that for the isolated it would appear that the fractions of clustered ions have been previously underestimated quite considerably.

Unfortunately, the determination of the absolute value of the absorption cross-section of ion pairs/clusters, σ^c_{abs}, is by no means an easy task. However, it is reasonable to expect that if σ^c_{abs} is indeed significantly different from that for isolated ions, then the absorption spectra of the two species would be dissimilar. In this paper, then, we concentrate on characterising any observable differences between the absorption spectra of ion clusters and isolated ions by two different approaches, as a means towards clarifying this issue.

The small signal absorption characteristics for the four Er-doped germanosilicate (no alumina) fibers used in these experiments are listed in table 1. The fibers all have similar NA and cut-off wavelengths around 900nm. We choose to study alumina-free fibres for two reasons; clustering is far more severe in pure germanosilicate fibers[4] and more importantly any variation in alumina concentration between fibres would give an additional broadening mechanism which would mask any contributions from the clustered ions. Also listed in this table is the large signal or unbleachable loss for each fibre obtained from cut-back measurements using around 100mW of 980nm radiation. Typically we used fiber lengths with around 10-15dB of small signal absorption for these measurements being careful to avoid any affects from ASE. Finally we have also tabulated the unbleachable loss expressed as percentage of the small signal absorption, a value directly related to the amount of clustering in the fiber.

Regarding table 1, we see that with higher erbium ion concentrations the degree of clustering

correspondingly increases, a trend well documented in the literature[4-7]. Hence, we might expect any significant differences between the absorption spectrum of isolated and clustered ions should be increasingly noticeable in these four fibers. In Fig. 1(a), the normalised 980 nm absorption spectra of the four fibers clearly show an increase in the short wavelength side of the spectrum with increasing erbium ion concentration and hence clustering. These spectra were taken at 77 K. Fig. 1(b) shows the room temperature normalised 1530 nm absorption spectra, which again displays a similar broadening trend with increasing erbium concentration. Given that the glass composition is the same in all fibres, these results indicate that the absorption spectrum for the fibres is at least dependant on the erbium ion concentration, however not necessarily directly related to the clustering. In order to investigate this further we have compared the unbleachable loss spectra for the various fibres with the small signal absorption spectrum for the heavily doped (clustered) fibre. Since the unbleachable loss spectrum is a direct measure of the clustered ion lineshape, we might expect some similarities between this spectrum and the small signal absorption spectrum for the heavily doped (clustered) fiber.

In this experiment, the large signal 980 nm absorption (unbleachable loss) spectra of the various fibers was obtained by tuning a high power ($>$100mW) Ti:sapphire around 980nm and measuring the fibre loss. At these powers the isolated erbium ions are all in the metastable level having a saturation power less than 1mW when pumped at the peak of the 980nm absorption band. Since the residual loss is attributed to the clustered ions, the large signal absorption spectrum may be considered to be the absorption spectrum for the clustered ions. Fig. 2 shows that the large signal absorption spectrum is indeed different from the small signal

absorption spectrum, with considerable broadening on the short wavelength side, similar to the broadened small signal absorption spectra obtained on the clustered fibers (figure 1).

Finally, in figure 3, we have compared the small signal ground state absorption spectrum for fibre 4, which is almost entirely clustered, with the large signal (unbleachable loss) spectra of fibers 2 and 3. The similarity in this set of spectra is striking, indicating that the broadening of the small signal absorption spectra seen in the heavily doped fibres is indeed very similar to the broadened large signal or unbleachable loss spectrum. Hence we believe that the broadening of the spectra seen in figure 1 is indeed due to the increase in erbium ion clustering and that the absorption spectrum for fibre 4 is essentially that of clustered erbium ions. Note that although fibre 4 has 69% unbleachable loss, the percentage of ions within a clustered environment is higher than this, since some clustered ions are bleachable[5,6]. Hence, the implication is that the clustered erbium ions have a significantly different spectral lineshape and hence cross-section when compared with that of the isolated ions (fiber 1).

In summary, we have provided two sets of experimental results that indicate the absorption spectra of clustered ions in germanosilicate glass is significantly broader than that of the homogenous or isolated erbium ions in this glass. Firstly, measurement of the unbleachable loss spectrum in moderately clustered fibres is broader than the small signal absorption spectrum of the same fibre. This result alone is not enough evidence, since this measurement may be affected by the presence of 980nm excited state absorption[7,10] (ESA) and may not solely represent the absorption spectrum of the unbleachable or clustered ions. However the similarity of this spectrum with the broadened small signal absorption spectrum found in

heavily clustered fibres indicates that the contribution from ESA in this measured spectrum is negligible under the present experimental conditions. Finally, the small signal absorption spectra for both the 980nm and 1550nm transitions clearly broaden as the erbium ion concentration and hence clustering increases indicating a fundamental change in the erbium ion spectrum. We rule out changes in the glass composition as the explanation for the measured changes in absorption spectra since the addition of a co-dopant, say alumina, to the fibres would dramatically decrease degree of clustering at the levels required to broaden the spectra.

The above results strongly suggest that the absorption spectum of erbium ion clusters in EDFAs is substantially different from that of isolated ions. These findings could have implications for both the design/assessment of EDFAs as well as Er-fiber lasers, in particular the choice of pump wavelength for these devices, since we would expect some inhomogeneous contribution to the gain profile. Indeed recent measurements[11] on the pump wavelength dependence of the gain profile in EDFA's have indicated a larger than expected degree of inhomgeneous gain in EDFA's. Although since most EDFA's use germano-aluminosilicate fibers we might expect the difference in spectra between isolated and clustered to be less dramatic than we measure in germanosilicate. Finally, we believe this is the first direct experimental verification that the clustered ions in silica glass have a different cross section from isolated ions, an essential assumption in the theoretical description of self-pulsing in erbium doped fiber lasers.

Acknowledgements

The authors are grateful to Pirelli and Fibercore for some fibers used in these measurements. This work was supported in part by the EC ACTS project PHOTOS. The Optoelectronics Research Centre is an EPSRC-funded Interdisciplinary Research Centre.

* Present address: QPS Technology Inc., 2270 St-Francois Rd, Dorval, H9P 1K2, Canada.

+ Present address: Corning S.A., Centre Europeen de Recherche de Fontainebleau, 7bis Avenue de Valvins, F-77210 Avon, France.

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Figure Captions

Figure 1. (a) Small signal 980nm absorption spectra of fibres 1-4 measured at 77K.

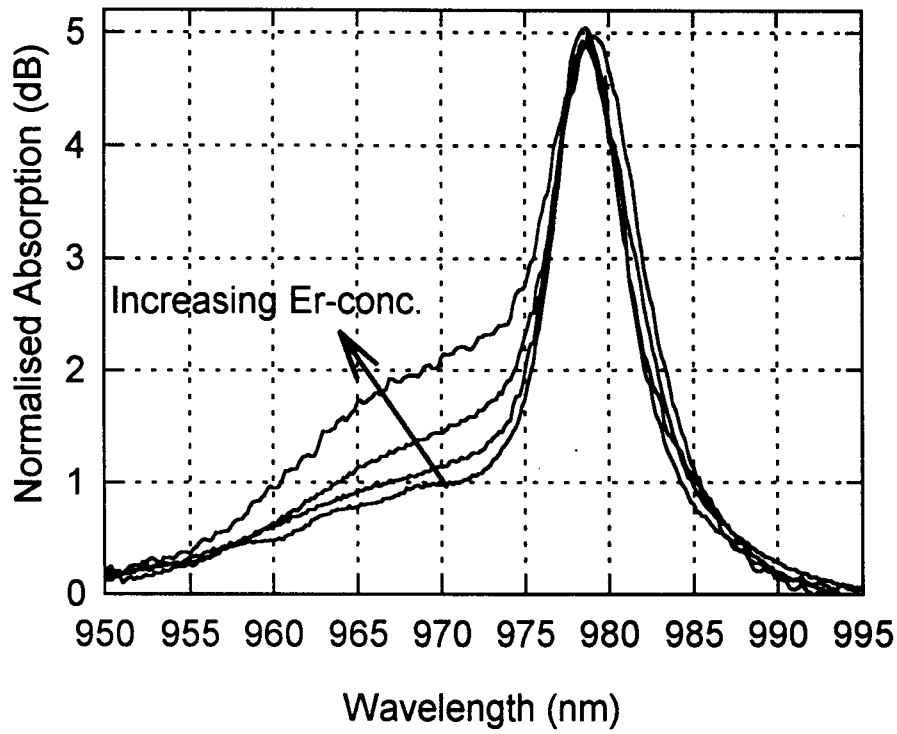
(b) Small signal 1550nm absorption spectra of fibres 1,2 and 4 measured at room temperature.

Figure 2. Comparison of small signal (—) and large signal (•) absorption spectra for fibre 3. The large signal spectrum has been normalised. All data is taken at room temperature

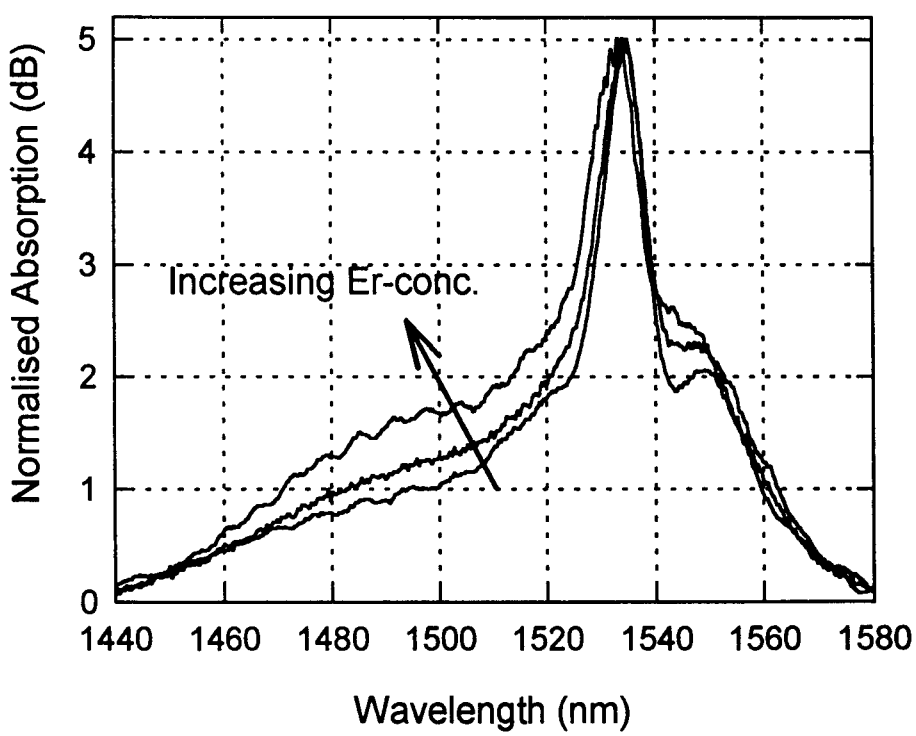
Figure 3. Small signal absorption spectrum of highly clustered fibre 4 (—) with large signal absorption spectra for fibres 2 (□) and 3 (•). All data is taken at room temperature.

Table 1 Absorption Characteristics of Erbium-Doped Germanosilicate Fibres

Fibre Number	980 nm small signal absorption (dB/m)	980 nm large signal (unbleachable) absorption (dB/m)	Unbleachable loss as a percentage of small signal absorption
1	1.8	negligible	negligible
2	4	0.4	10%
3	8	1.6	20%
4	18	12.4	69%


Normalised Absorption (dB)
0
1
2
3
4
5
Increasing Er-conc.
950 955 960 965 970 975 980 985 990 995
Wavelength (nm)

(a)


Normalised Absorption (dB)
0
1
2
3
4
5
Increasing Er-conc.
1440 1460 1480 1500 1520 1540 1560 1580
Wavelength (nm)

(b)

Fig 1

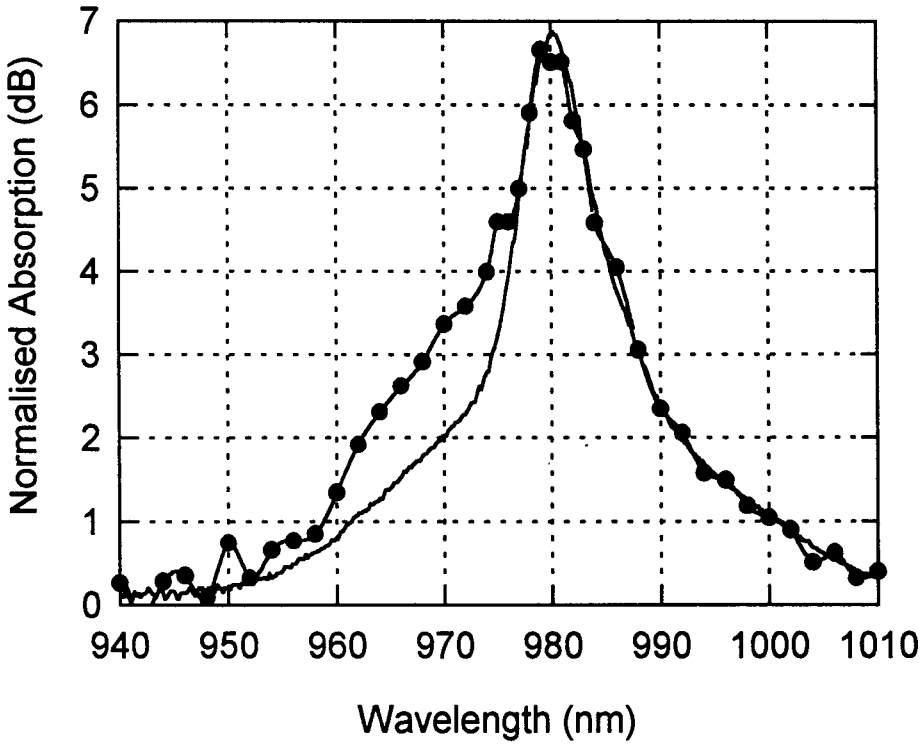

Normalised Absorption (dB)
0
1
2
3
4
5
6
7
940
950
960
970
980
990
1000
1010
Wavelength (nm)

Fig 2

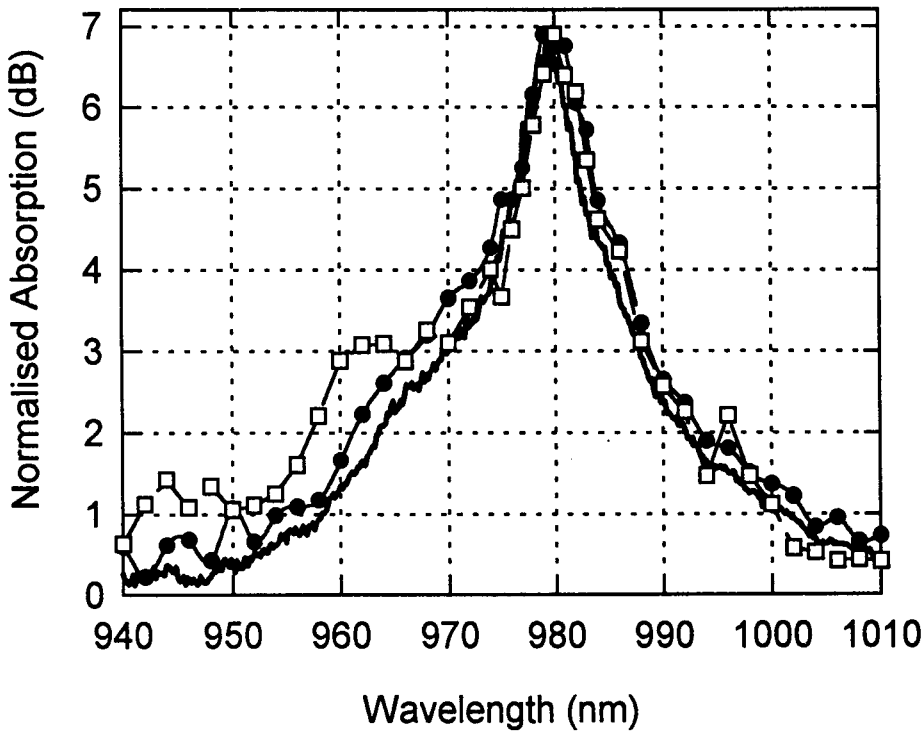

Normalised Absorption (dB)
0
1
2
3
4
5
6
7
940
950
960
970
980
990
1000
1010
Wavelength (nm)

Fig 3