DIRECT OBSERVATION OF COOPERATIVE UPCONVERSION MECHANISMS IN ERBIUM-DOPED FIBRE AMPLIFIERS

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Abstract
By examining upconversion fluorescence in Er^{3+}-doped fibres, ion-pair upconversion and uniform upconversion have been directly and separately observed. An upper limit for the ion-pair lifetime has been determined.

Introduction
A major unresolved issue in the operation of Er-doped fibre amplifiers (EDFAs) is concentration quenching due to Er^{3+} ion cooperative upconversion. The effect limits the erbium ion concentration (and thus the minimum amplifier length) to a very low level [1-5] if efficient operation is desired. For various reasons, such as packaging, cost, reduction of internal Rayleigh backscatter and for the development of compact fibre laser devices, it is desirable to use short fibres with higher Er^{3+} ion concentrations. In addition, the development of erbium-doped planar waveguide amplifiers, which must of necessity be short, is hampered by erbium concentration effects [6]. We are currently seeking a solution by studying in detail the mechanisms causing cooperative upconversion in Er^{3+}-doped fibres and glasses. Two different upconversion mechanisms have been proposed: (i) uniform upconversion [7] and (ii) ion-pair upconversion [8,9]. In the former case, upconversion due to interactions associated with the average separation of ions in a uniformly-dispersed ion distribution is assumed, whereas for ion-pair quenching a rapid upconversion process associated with a subset or cluster of the ions occurs. In practice, both mechanisms are present, their relative magnitudes depending on the glass chemistry and the Er^{3+} concentration.

In this work we have, for the first time, experimentally resolved both uniform upconversion and ion-pair upconversion in Er^{3+}-doped fibres. We have studied the effect of Er^{3+} ion concentration and host-glass composition and show that, although alumina is effective in reducing ion-pair upconversion, uniform upconversion degrades the efficiency for all of the glass types investigated at concentrations above $\approx$ 1000ppm. Since uniform upconversion depends only on inter-ion spacing, it is possible that this limit will prove universal and severely curtail efforts to produce an efficient Er^{3+} planar amplifier.

As shown in Fig 1, upconversion is an energy-transfer process between two excited erbium ions, resulting in one Er^{3+} ion (donor) decaying to the ground state, while another (acceptor) is excited to the $^4I_{9/2}$ state, from whence it decays to the $^4I_{11/2}$ level. Therefore one absorbed pump photon, at least, is lost in the process. In general, when an erbium-doped fibre is pumped at a wavelength of 1480nm, a degree of 980nm upconversion fluorescence from the $^4I_{11/2}$ level will be observed. When the pump is switched off, the decay characteristics of the fluorescence will depend on the mechanism by which the $^4I_{11/2}$ level is populated, ie whether it is by uniform or ion-pair upconversion. Ion-pair upconversion will give rise to a rapid decay component (μs), whereas uniform upconversion will give rise to a slow decay component of several ms. Examination of the 980nm fluorescence in the time domain thus allows these mechanisms to be resolved.

Analysis
It can be shown that for a general fibre having both uniform and ion-pair upconversion the decay of 980nm fluorescence power after the 1480nm pump light is extinguished is given by:

$$P_{980}(t) = P_s(0).exp\left(-\frac{2t}{\tau_f}\right) + P_f(0).\left|exp\left(-\frac{t}{\tau_p}\right) - \frac{\tau_3}{\tau_p}exp\left(-\frac{t}{\tau_3}\right)\right|$$

Here $P_s(0)$, $P_f(0)$ represent the initial powers of the slow and fast decay components respectively due to uniform and ion-pair upconversion, τ_f, τ_3 & τ_p represent the metastable level, 980nm band and ion-pair lifetimes respectively and it has been assumed that $\tau_p \neq \tau_3$ (a separate expression applies in this specific case). As the upconversion fluorescence has differing decay characteristics depending on the upconversion mechanism, we can examine the temporal decay of 980nm fluorescence to determine the relative magnitudes of the different upconversion mechanisms in the fibre.

Experimental

The experimental configuration is shown in Fig 2. The Er^{3+}- doped fibres were pumped with light from a chopped 1480nm laser diode, with a CW launched power of around 15mW in each case. Fluorescence at 980nm was selected and detected from the side of the fibre using a monochromator and a Hamamatsu 3236P Extended PMT with suitable amplification. Photon counts of the signal were recorded in various time slots using a two-channel Gated Photocounter. The overall time resolution of the set-up was 4μs. Seven fibre samples of varying Er^{3+} concentrations and differing core compositions were measured.

For each of the fibres, fast and slow decay components of various magnitudes were observed, corresponding to ion-pair and uniform upconversion. Fig 3 shows the 980nm fluorescence decay characteristic obtained for a fibre with a Ge/Si core. A large initial fast decay component is seen, followed by a comparatively-small slow decay component (magnified for clarity) with a lifetime of 4.3 ± 0.6ms. For an Al/Si host a slow-decay component of 4.2 ± 0.8ms was recorded, similar to the Ge/Si result and in agreement with the analysis which predicts that a slow-decay time-constant of $\tau_f/2$, ie half the usual $^4I_{13/2}$ lifetime. The fast decay components of the fibres were then measured at higher chopper frequencies to obtain the maximum temporal resolution. Fig 4 shows the fast- decay component for the same Ge/Si fibre indicated in Fig 3 and gives a lifetime of $7\pm5\mu$s. All of the fibres again showed similar fast-decay lifetimes and are probably determined by the 980nm band lifetime, which is known to be around this value. Hence we can say that the ion-pair lifetime $\tau_p \leq 7\mu$s.

We also compared the magnitude of the 980nm fluorescence emitted at the same pump level from each of the fibres by normalising the initial magnitudes of the fast and slow decay components to the total number of Er^{3+} ions present. Fig 5 shows the results of power vs. Er^{3+}-ion concentration for the different fibre types. By examining the effect at low Er^{3+} ion concentrations, we confirmed that residual pump ESA at 1480nm had negligible effect on the results. We can see clearly from Fig 5 that ion-pair upconversion in Al/Ge/Si or Al/Si hosts increases far less with increasing concentration than in a Ge/Si host, while for a given Er^{3+} concentration, there is no significant difference in uniform upconversion between them. This can be explained if we postulate that uniform upconversion depends only on the average distance between well-dispersed erbium ions, whereas ion-pair upconversion depends on the population of erbium ion pairs present in the glass. It is well known that adding trivalent Al^{3+} ions reduces the proportion of erbium ion-pairs by creating better Er^{3+} solubility, but Al^{3+} is not expected to change the average distance between the erbium ions.

Summary

By analyzing and measuring the 980nm fluorescence of erbium-doped fibres pumped at a wavelength of 1480nm, we have directly observed and separated the two upconversion processes in Er^{3+}-doped silica fibres for the first time. We have determined that the upper limit to the Er^{3+} ion-pair lifetime is a few microseconds and this explains why ion-pair upconversion has little effect on the 1.5μm fluorescence decay lifetime. Despite its frequent use, this lifetime is in fact a poor measure of ion-clustering in the glass. The commonly-observed non-exponential decay of the 1.5μm emission at very high Er^{3+} concentrations results from uniform upconversion. Ion-pair upconversion in Al^{3+}-containing

hosts is effectively suppressed, although there is no significant difference between hosts for the Er^{3+} concentration at which the onset of uniform upconversion occurs (~ 1000ppm Er^{3+} ions). Above this concentration the amplifier efficiency will drop substantially in all the hosts investigated and this sets a lower limit of a metre or two of fibre for efficient EDFAs, regardless of how well the ions are dispersed by appropriate choice of glass chemistry. The onset of uniform upconversion will also severely limit the development of planar amplifiers.

References

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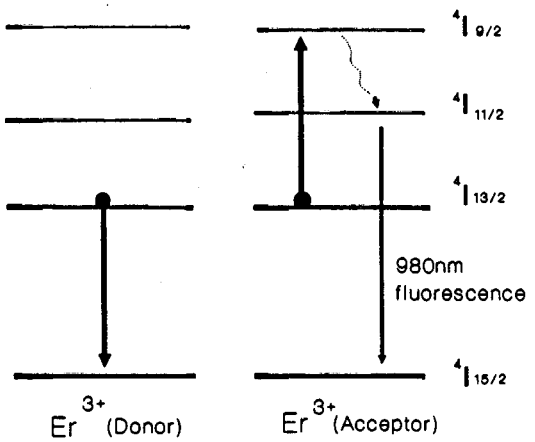

Fig 1 Erbium ion cooperative upconversion(ERCU)

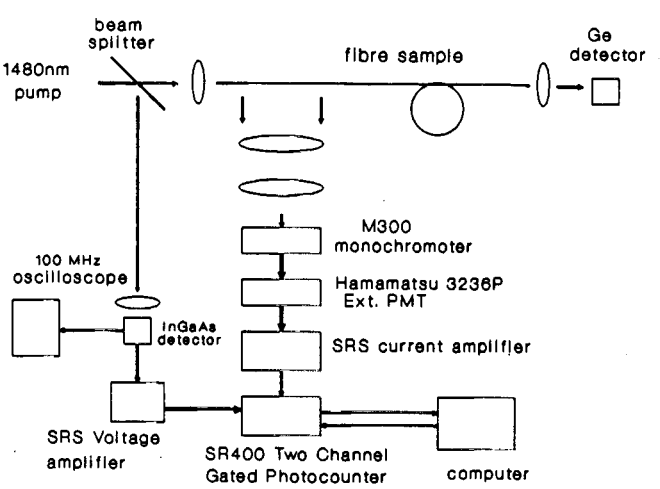

Fig 2 Experimental set up

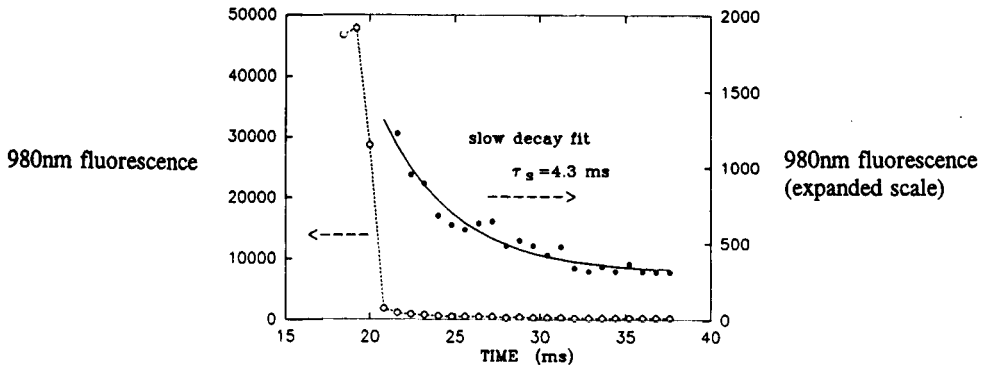

Fig 3 Slow decay component of 980nm fluorescence for Ge/Si fibre containing 1560ppm Er^{3+}

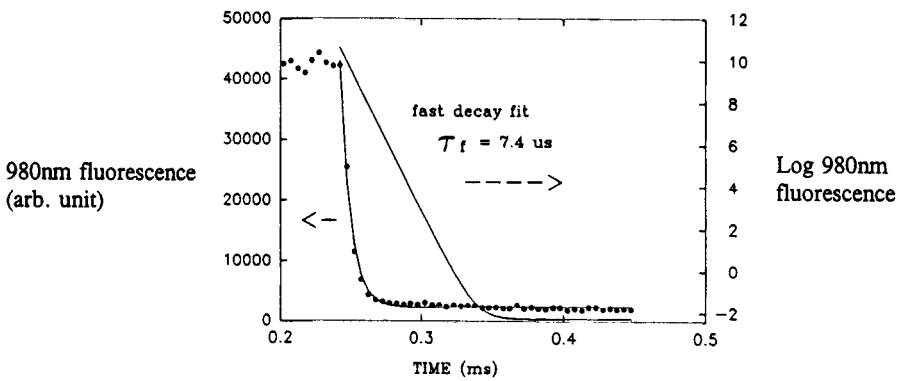

Fig 4 Fast decay component of 980nm fluorescence for Ge/Si fibre containing 1560ppm of Er^{3+}

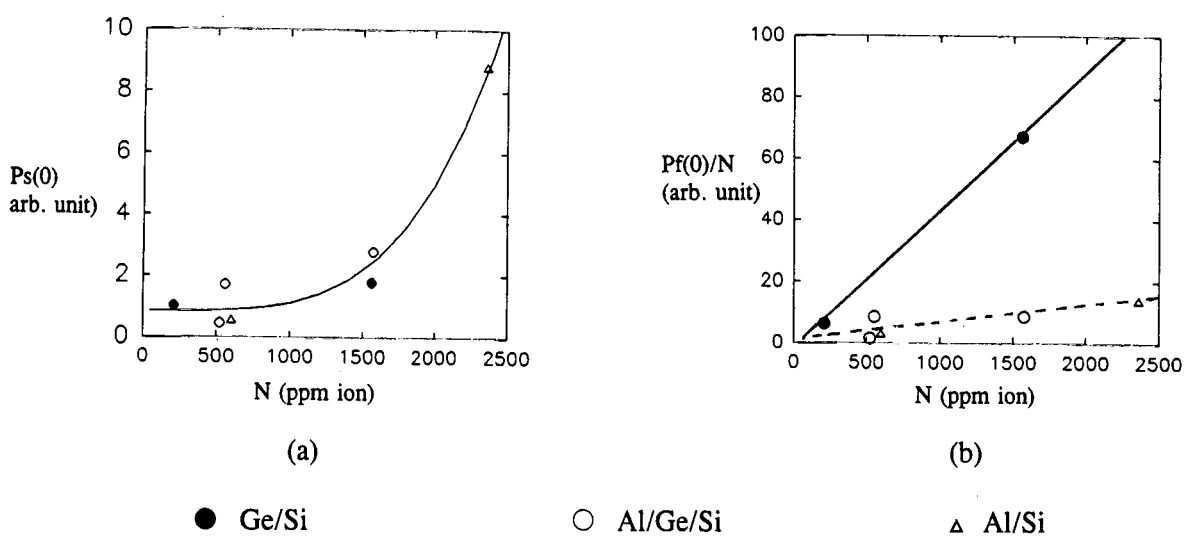

Fig 5 (a) Initial value of slow component of 980nm fluorescence Ps(0) and (b) initial value of fast component Pf(0) normalised to the Er^{3+} concentration N, plotted for various glasses as a function of Er^{3+} concentration N