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Lifetime Quenching in Yb Doped Fibres

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Abstract

We have discovered that in ytterbium-doped silica fibres the excited state lifetime of a fraction of the Yb ions can be quenched to a very small value, leading to a strong unbleachable loss. This unexpected behaviour seems to be caused by some, yet unidentified, impurity or structural defect. It is of considerable relevance for various Yb doped lasers and amplifiers including Er:Yb codoped fibres as used in telecommunication amplifiers although it should also be emphasized that fibres can be produced that are free from the quenching effect.

Introduction

Ytterbium doped silica fibres offer a wide range of applications as fibre lasers and amplifiers [1]. Gain is available between ~976nm and ~1200nm using pump wavelengths in the very wide range from ~800nm to at least 1064nm, as available e.g. from AlGaAs and InGaAs diode lasers and Nd:YAG lasers. Highly efficient wavelength conversion, high power operation in a cladding pumped scheme [2], and single-frequency lasing have all been demonstrated already with Yb doped fibres [1]. The simple level structure of ytterbium avoids problems like multiphonon decay, excited state absorption, and concentration quenching.

However, we have recently observed effects which seriously affect the performance in some Yb-doped fibres. For a list of the fibres see Tab. 1. The first observation was made when we tried to achieve lasing from the reflection of two bare fibre ends with various fibres, pumped with a Ti:sapphire laser with wavelengths between 940nm and 980nm.

A 3m piece of fibre 1 (1200 ppm Yb) showed lasing around 1035 nm with threshold powers around 40 mW launched into the fibre (as expected from a numerical model based on data in Ref. 1) when the pump wavelength was between 940nm and 960nm. However, as the pump wavelength approached the main absorption peak at 976 nm (see Fig. 1) the threshold increased rapidly while both the fluorescence output and the residual pump power at the fibre exit (for a given launched pump power) decreased dramatically; with a 976 nm pump no lasing, very little transmitted pump and very much reduced fluorescence were observed even at high pump powers (up to ~120mW). As essentially the whole pump power could be absorbed in this length of fibre, no significant wavelength dependence of the threshold power had been expected.

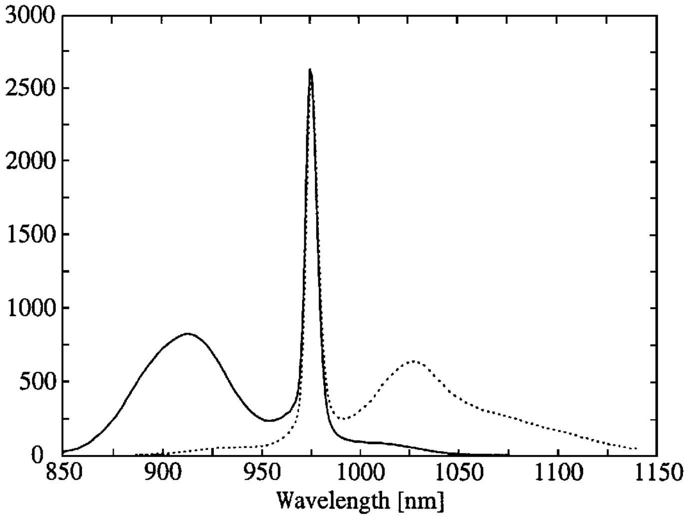

Fig. 1. Absorption (solid) and emission (dotted) cross-sections (in 10^{-27} m^2) of Yb^{3+} in germanosilicate glass.

In another experiment a 2 m piece of fibre 2 (4200 ppm Yb) was pumped by a Ti:sapphire laser between 850nm and 940nm. Lasing around 1035nm was achieved only for pump wavelengths between 855 nm and 890 nm, despite essentially total pump absorption for longer wavelengths.

Fibre 3 with still higher Yb concentration (10,000ppm) did not lase with any pump wavelength, using various lengths of fibre. The same applies to fibre 4 which has similar Yb concentration but an alumino-phospho-silicate host material (without germanium). Measurements of the decay of side-light fluorescence did not reveal any anomalies; simple exponential decays with time constants between 843 µs and 1350 µs were obtained (see table 1), with only small deviations caused by some inhomogeneity. The variations could be explained by the differences in host materials.

Table 1. Parameters of the fibres investigated.

no	Yb conc.	host	cut-off	NA	measured lifetime
1	1200 ppm	germano-silicate + boron	900 nm	0.15	945 µs
2	4200 ppm	germano-silicate	850 nm	0.3	900 µs [a]
3	10000 ppm	germano-silicate	1180 nm	0.2	843 µs
4	10000 ppm	alumino-phosphate-silicate	>1050 nm	0.21	1350 µs
5	3000 ppm	germano-silicate	930 nm	0.21	760 µs
6	2200 ppm	germano-silicate	700 nm	0.31	720 µs

[a] The weak fluorescence of fibre 2 showed significant non-exponential decay; for low excitation the decay constant was about 900 µs.

Due to the simple level structure of ytterbium we did not expect any concentration quenching to be present. So, to explain the observed behaviour, we first considered the possibility that there might be an induced loss mechanism similar to one which we had observed in Tm doped ZBLAN fibres [3]. We set up an experiment in which the pump beam from a Ti:sapphire laser was launched through a dielectric beam splitter into a 50 cm length of fibre 1, while chopped white light (probe) from a bulb was launched into the opposite end. A part of this probe light was extracted from the pump input end via the beam splitter and monitored using a monochromator, a silicon photodetector, and a lock-in amplifier. The fibre ends were angle cleaved in order to prevent reflections of pump light. The set-up allowed measurement of the transmission at various probe wavelengths with and without pump power, for various pump wavelengths. If a pump-induced absorption were the culprit then a decrease in transmission at the fluorescence (gain) wavelengths would be expected as the pump is tuned towards 976 nm. However, no such evidence was found.

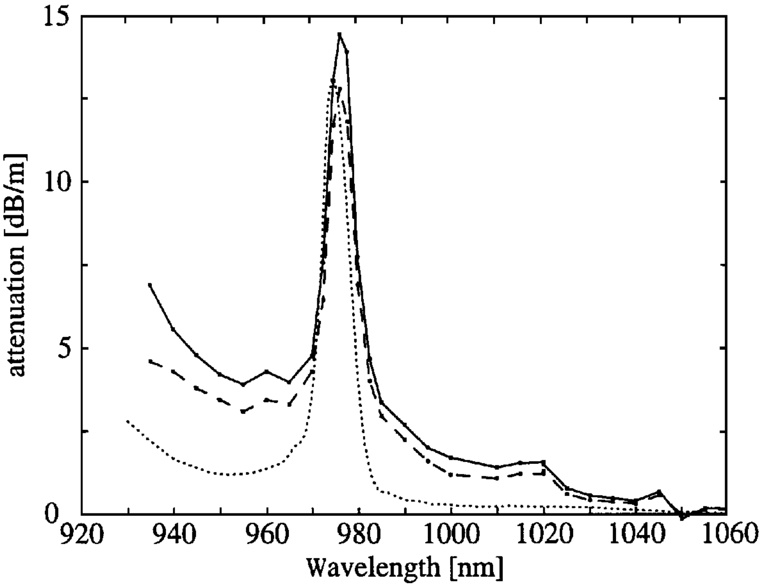

Fig. 2. Absorption spectra of fibre 1. Solid curve: absorption for maximum available power (e.g. 120mW at 976nm); dashed curve: unsaturable absorption, calculated by subtracting the expected absorption of the not quenched ytterbium; dotted curve: absorption of quenched ytterbium with an assumed concentration of 220 ppm, calculated from the cross-sections as used in the model.

We then carefully measured the absorption of the pump itself. The pump light was launched into one arm of a fibre coupler. Most of the pump light then entered a length of Yb-doped fibre which was fusion spliced to one output port of the fibre coupler while a germanium detector at the other output port was used to provide a measure of the launched pump power independent of any changes in launch efficiency. An angled cleave at the end of the doped fibre was used to avoid reflections and thereby suppress lasing; in addition it was necessary to use short fibre lengths to avoid significant gain at 976 nm.

First measurements on fibre 1 revealed that there is an unsaturable absorption which is especially strong around 976nm, the highest absorption peak of ytterbium: even for high input powers (100mW, i.e. much higher than the saturation power of 0.3mW) the pump transmission was significantly lower than at longer wavelengths (e.g. 1050nm). In order to obtain a spectrum of the unsaturable absorption we measured the power transmission for relatively high input powers (around 100mW) at various wavelengths and used a computer program (propagating the pump wave through the fibre) to determine the amount of unsaturable absorption which was needed to account for the measured transmitted pump power. The computer model used cross-sections as measured earlier for a similar Yb doped silica fibre; the actual cross-sections in the fibres used are expected to differ slightly from these values, but these deviations are not very significant as the correction for saturable absorption was in most cases small compared to the peak of the unsaturable absorption.

The spectrum of unsaturable absorption which we obtained in this way for fibre 1 is shown in Fig. 2 (dashed curve). The shape of this spectrum strongly suggests that the unsaturable absorption is caused by a part of the Yb population for which the upper state lifetime is reduced to a very

3small value. Fig. 2 also shows the calculated absorption of an assumed population of 220 ppm of quenched ytterbium (dotted curve). The spectral shape of the unsaturable absorption seems to differ slightly from typical ytterbium absorption spectra; some broad absorption background in addition to the typical ytterbium features seems to suggest additional absorption by some impurity or structural defect which may also be responsible for quenching of the ytterbium ions: excitation energy is transferred from an Yb ion to a defect centre and then dissipated non-radiatively by the latter one. Measurement errors as well as errors in the fibre parameters and cross-sections used in the model are not large enough to explain the discrepancy of the spectrum from the usual ytterbium absorption spectrum.

We conclude that in fibre 1 roughly 20% of the Yb ions (i.e. about 220 ppm of the total 1200 ppm) are quenched by some impurity or structural defect while the other 80 % of the ions are not affected at all (and display the normal fluorescence with a measured decay time of 945 µs). The lifetime of the quenched population can be at most a few microseconds, since we could not detect this fast decay with a time resolution of our fluorescence measurement of ~5 µs.

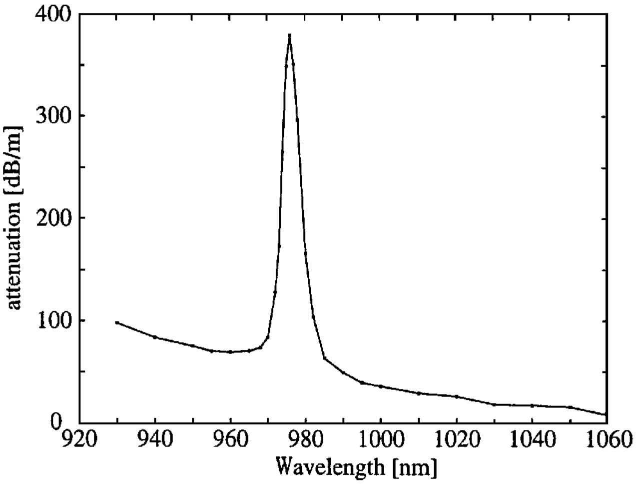

Fig. 3. Absorption spectrum of fibre 2, measured for maximum available power

Similar unsaturable absorption spectra were found for other fibres. Fig. 3 shows the spectrum for fibre 2 in which we calculate that roughly 90% of the Yb ions are quenched. In this case we did not subtract the saturable absorption because this correction is small. Again we see the ytterbium features appearing on a broad background rising towards shorter wavelengths. The strong quenching explains why lasing of this fibre could only be observed in a region of relatively small pump absorption cross-sections (see above): in regions of high absorption cross-sections, the useful absorption is saturated and the unsaturable absorption (which does not create significant excited state population and gain) dominates. Note that lasing around 1035 nm is possible despite the strong quenching effects because there is only low absorption at this wavelength.

Of the fibres tested only fibre 5 (the most recently fabricated) was found to have nearly no unsaturable absorption (only about 1% of the 3000 ppm Yb doping). This fibre showed lasing from bare ends for a broad range of pump wavelengths with thresholds around 40 mW launched as expected from calculation based on the usual Yb data [1]. The threshold power increases only by about 15% when the pump laser is tuned to the 976nm peak, and the absorption at 976nm can be bleached almost completely. Note that lasing with the reflections from bare ends and a 976 nm pump constitutes the case where the quenching has the strongest influence on performance.

The nature of the observed quenching process is still not fully understood although it seems likely that the problem is caused by some impurity or structural defect as mentioned above. Energy exchange between Yb ions can clearly not explain the effect since the simple level structure of Yb ions only allows energy migration but no lifetime shortening. Transfer of energy to other rare-earth impurities would be expected to result in fluorescence at other wavelengths, e.g. around 1.55 µm if it were erbium. However, no other fluorescence (besides the usual Yb emission) has been detected in the whole range from 400 nm to 1800 nm. (Only when a sample of fibre 6 was irradiated with 488nm light from an argon ion laser, some very weak broad-band fluorescence between about 575nm and 780nm has been observed; this may be caused by Ge-O defects [4].) At higher Yb concentrations (e.g. 10,000ppm), the rapid energy migration between Yb ions could result in most of the ions being quenched even for low defect (trap) concentrations. However, the fact that fibre 5 does not display any quenching points to the possibility of changes in the preform production process, i.e. either that some impurity in the chemicals used earlier was no longer present in later batches or that modifications in the process parameters have eliminated the creation of certain structural defects. We note that Ref. 5 reports about defects with a similar absorption spectrum in phosphate-silicate fibres which have been identified as colour centres.

Whatever the origin of the effect, the unwelcome consequences of the unsaturable absorption for Yb doped fibre lasers and amplifiers are obvious. Especially if the pump wavelength is close to the 976 nm peak (as required in some applications) the unsaturable absorption will cause a large loss of pump power. We also expect that fibres with Yb codoping - in particular the Er:Yb fibres as used in telecommunication amplifiers - could be adversely affected in a similar way. Indeed there has been a, hitherto unexplained, observation that maximum efficiency of some Er:Yb fibre amplifiers has required detuning of the pump slightly from the 976 nm absorption peak [6]. An even more severe problem will occur for lasers operating at the wavelength of the 976 nm peak (being pumped around 910 nm) where according to our computer model the slope efficiency can be significantly reduced if even only 1 % of the ytterbium is quenched; such lasers are being considered as powerful pump sources for erbium-doped amplifiers, and high efficiency is especially important in this case.

In conclusion, we have discovered that in various Yb doped fibres the excited state lifetime of a part of the Yb population is quenched by an, as yet unidentified, impurity or defect. This effect can severely affect the performance of Yb doped fibre lasers and amplifiers. However, it is also confirmed that fibres can be prepared in which this problem is much reduced, although the precautionary procedures required have not been explicitly identified.

Acknowledgments

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