SPECTRAL VARIATION OF EXCITED STATE ABSORPTION IN NEODYMIUM DOPED FIBRE LASERS

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The spectral variation of gain and excited state absorption have been measured for neodymium doped silica fibres co-doped with germania and alumina. The results show that an observed excited state absorption peak at 1300 nm is considerably reduced in the alumina co-doped fibre.

1. Introduction

Fibre lasers made from Nd^{3+} doped GeO_2 co-doped silica operate efficiently at 1088 nm and 938 nm, corresponding to the $^4F_{3/2}$–$^4I_{11/2}$, $^4I_{9/2}$ transitions in glass [1,2], but not on the $^4F_{3/2}$–$^4I_{13/2}$ transition which normally occurs at 1370 nm [3]. It has been supposed that this is due to excited-state absorption (ESA) in the fibre and pump induced loss has previously been observed at 1320 nm [4]. However, thus far no detailed measurements have been reported of the spectral variation of excited state absorption in Nd-silica and of the dependence on co-dopants. Co-dopants such as P_2O_5 and Al_2O_3 have been incorporated into Nd^{3+} doped silica glass in order to prevent detrimental clustering effects associated with Nd^{3+} dopant concentrations higher than a few hundred molar ppm Nd^{3+} [5]. We report here measurements of gain and excited state absorption over the wavelength range 900–1400 nm for a Nd^{3+}–GeO_2/SiO_2 fibre and 1000–1400 nm for a Nd^{3+}–Al_2O_3/SiO_2 fibre. The results confirm a pump-induced absorption centred at 1300 nm in both fibre types although the effect is seen to be considerably reduced in the case of Al_2O_3 co-doping.

2. Experiment

A 3.7 m length of silica fibre with 130 molar ppm Nd^{3+} and approx 10% molar GeO_2 doping was pumped through a beam splitter with a semiconductor laser operating at 827 nm (fig. 1). The fibre was characterised by an equivalent step index (ESI) NA of 0.21 and a second mode cutoff of 950 nm. The neodymium dopant concentration gave an optical density of 0.005 cm^{-1} at 827 nm and the total absorbed pump power measured using a cutback method was measured to be 2.2 mW. The induced gain and excited-state absorption under this pumping condition were measured using a spectrophotometer consisting of a counterpropagating white light signal and a monochromator. A germanium PIN detector was used to monitor the monochromator output. The total power in the 500 nm white light bandwidth was ~24 μW and at this low level gain saturation effects can be ignored.

The same measurements was made for an alumina co-doped silica fibre containing approximately 0.5% molar ppm Nd^{3+} and 4.5% Al_2O_3. This fibre was

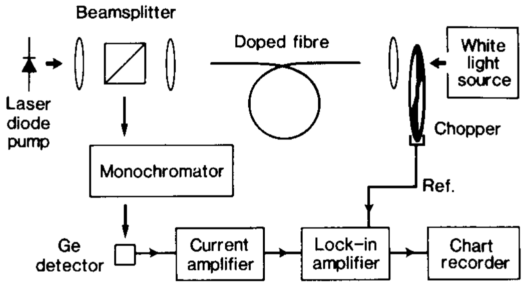

Fig. 1. Experimental setup.

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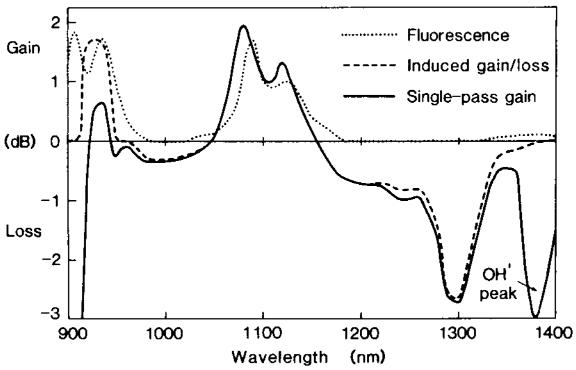

Fig. 2. Gain/ESA and fluorescence versus wavelength. Nd^{3+}–GeO_2/SiO_2 fibre. 2.2 mW 827 nm pump absorbed.

characterised by an ESI NA of 0.12 and second mode cutoff 820 nm. For convenience a 1 m length of the Al_2O_3 co-doped fibre was used although an optical density of 0.23 cm^{-1} at 827 nm indicates that the pump absorption takes place over a much shorter length. The launched pump power was estimated as 3 mW. The much higher dopant concentration of the alumina co-doped fibre prevented accurate measurements below 1000 nm due to the large absorption at 900 nm.

The results (figs. 2 and 3) show the effect of pumping the fibres. In fig. 2 the dashed curve shows the ratio of pumped and unpumped fibre output for the GeO_2 co-doped fibre and indicates the regions over which stimulated emission and excited-state absorption take place. Including the unpumped loss of the fibre gives the solid curve which therefore indicates the single pass gain or loss of the fibre as a function of wavelength. The dotted curve shows the

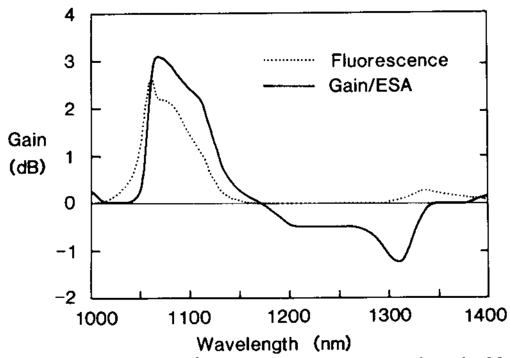

Fig. 3. Gain/ESA and fluorescence versus wavelength. Nd^{3+}–Al_2O_3/SiO_2 fibre. 3 mW 827 nm pump absorbed.

fluorescence output of the fibre under the same pumping conditions for comparison with the gain curve. In fig. 3, the solid curve can be taken to indicate both the single pass and the pump induced gain/ESA of the Al_2O_3 co-doped fibre due to the low fibre loss (<0.1 dB) in the region of interest. The fluorescence is again included as the dotted curve for comparison. It should be noted that the fluorescence has not been corrected for material re-absorption and excited state absorption in figs. 2 and 3. The effect of this will be to partially re-absorb the fluorescence at certain wavelengths. However the wavelengths where fluorescence is observed indicates spectral regions in which a finite stimulated cross section, and hence the potential for gain, exists. The peak gain is seen at 1088 and 938 nm in the GeO_2 co-doped fibre and at 1060 nm in the Al_2O_3 co-doped fibre which is consistent with the lasing properties of the fibres at these wavelengths [1,2,6].

At 1300 nm we see that a loss of 2.8 dB is induced by pumping the GeO_2 co-doped fibre, indicating that an excited state absorption exists. For a stimulated cross section of 1.5×10^{-20} cm^2 at 1088 nm [7] and including the variation in the spot size between the two wavelengths, this implies an ESA peak cross section of $\sim2.5\times10^{-20}$ cm^2 at 1300 nm. Although the $^4F_{3/2}$–$^4I_{13/2}$ fluorescence is seen to peak at around 1370 nm, no gain is seen at this wavelength. This implies that any stimulated emission is being counteracted by the ESA centred on 1300 nm. The Al_2O_3 co-doped fibre also shows an ESA peak at 1310 nm although smaller in magnitude than that of the GeO_2 co-doped fibre. For a similar stimulated cross section to the GeO_2 fibre of 1.5×10^{-20} cm^2 [5] the ESA cross section at 1310 nm is seen to be $\sim0.9\times10^{-20}$ cm^2.

It is also interesting to note that in the GeO_2 co-doped fibre the observed excited state absorption extends into the fluorescence regions at 1160, 1050 and 980 nm and thus limits the potential wavelength tuning ranges of lasers operating on the $^4F_{3/2}$–$^4I_{11/2}$, $^4I_{9/2}$ transitions [4,8]. Within the limits of experimental resolution the alumina co-doped fibre does not appear to show the same limitation of tuning range due to ESA although gain is observed over a 100 nm bandwidth on the $^4F_{3/2}$–$^4I_{11/2}$ transition similar to the GeO_2 co-doped fibre. Hence, although GeO_2 co-doped silica has a broader fluorescent bandwidth than

Al_2O_3 co-doped silica [5], the tuning ranges of these fibres around 1.1 μm are expected to be similar due to the effect of ESA in the GeO_2 co-doped fibre.

The exact mechanism of the reduction of ESA in the Al_2O_3 co-doped fibre over the GeO_2 co-doped fibre is not clear. However transition probabilities, and hence stimulated cross sections, are known to depend on the local ligand field experienced by neodymium ions in glass structures and this field is likely to be different for the two different co-dopants. GeO_2 co-doping is not expected to modify the structure of the silica significantly as it has a similar tetragonal structure to SiO_2. Al_2O_3 co-doping however is believed to modify the tetragonal glass structure due to the presence of a proportion of octahedral $AlO_{6/2}$ [5] and this is likely to alter the local ligand field.

3. Energy levels

Using measurements of the spectral absorption of the fibre at a number of temperatures, and by comparison with published energy levels of Nd in silicate laser glasses, we have been able to construct a partial Dieke diagram for the GeO_2 co-doped silica fibre (fig. 4). The intention here being to identify the energy levels responsible for the strong observed ESA in this fibre. Using this technique the presence of an absorption peak in the attenuation spectrum is deemed to indicate the presence of an energy level transition. By cooling the fibre to 77 K essentially only the true ground state is thermally populated and the wavelengths of absorption peaks indicate the position of energy levels. Conversely, heating the fibre to around 373 K populates more of the ground state Stark levels and the appearance of additional absorption peaks indicates the positions of the levels. It is of interest to note that a split level of the ground-state was measured to be around 600 cm^{-1} above true ground. This implies a thermal population at room temperature of <6% of the zero level resulting in quasi-4-level lasing operation at 938 nm [2]. The ESA centred on 1300 nm is attributed to excitation from the $^4F_{3/2}$ level to the $^2G_{9/2}$ and $^4G_{7/2}$ levels. These levels correspond to ground state absorption in the 500–550 nm band (18×10^3–20×10^3 cm^{-1}). Note that a drop in the ground state absorption between 530 nm and 550 nm (corresponding to a gap between the $^4G_{7/2}$ and the $^2G_{7/2}$ levels) in these fibres indicates the excited state absorption drops between 1.3 μm and 1.43 μm as observed in figs. 2 and 3. In the Al_2O_3 co-doped fibre the ESA is less and at ~1.38 μm it becomes matched by the stimulated emission occuring on the $^4F_{3/2}$–$^4I_{13/2}$ transition. Above this wavelength laser action is possible and has recently been reported in an Al_2O_3 co-doped silica fibre laser [6].

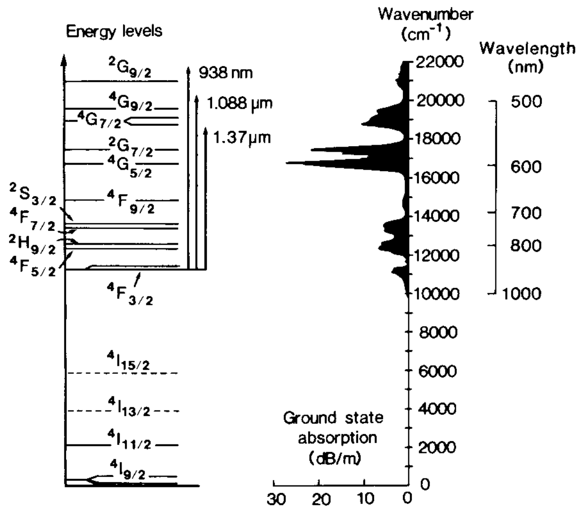

Fig. 4. Partial Dieke diagram for Nd^{3+} in GeO_2 doped silica. Solid lines represent measured levels.

4. Conclusions

It is seen that fibre lasers made from GeO_2 and Al_2O_3 co-doped silica both show an excited state absorption peak at 1300 nm which has the effect of reducing the efficiency of the $^4F_{3/2}$–$^4I_{13/2}$ stimulated transition. The spectral variation of excited state absorption appears similar in each case and follows the spectral variation of ground state absorption into the same energy levels. However the magnitude of excited state absorption is seen to be smaller in the Al_2O_3 co-doped fibre, such that it is overcome by gain within the fluorescent bandwidth on the $^4F_{3/2}$–$^4I_{13/2}$ transition. The only report of laser action on the $^4F_{3/2}$–$^4I_{13/2}$ transition in Nd^{3+} doped silica fibre lasers has been with this type of fibre.

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