Er-doped sapphire fibre temperature sensors using upconversion emission

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Abstract::
We report the production of Er:Al_2O_3 and Er:Yb:Al_2O_3 fibres using the LHPG method for application as fibre temperature sensors. Intense upconversion emission in the blue, green and red was observed from these fibres when pumped with a laser diode at 965nm. The lifetime and the integrated intensity of the upconversion signal was characterised as function of laser power and temperature. Results indicate the ratiometric analysis of the integrated intensities provides a suitable transduction mechanism for temperatures up to 1000K.

Introduction

The development of optical-fibre sensors for operation at extremely high temperatures (>1300K) has, until recently, been problematic. A number of applications such as monitoring of combustion parameters, particularly temperature, in turbines would benefit from the inherent advantages of optical fibre technologies such as minimal weight, electrical passivity, etc. Over recent years, to address this problem, there has been increasing interest in the use of single-crystal fibres to develop optical-fibre sensors for use in extreme environments. To date this has almost exclusively meant operation at elevated temperatures for measurement of strain or thermometry.

A number of approaches have been examined. Pyrometric sensors using black-body cavities fixed to the end of sapphire fibres have been undergoing development for a number of years[1, 2, 3]. Interferometric sensors using both intrinsic and extrinsic Fabry-Perot cavities, also in sapphire fibres, have been reported [4, 5]. The use of doped fibres and the behaviours of fluorescence emission, in particular the fluorescence lifetime, have been successfully used in development of temperature sensors. Materials examined to date include ruby[6, 7] and Er:YAG[8, 9]. The latter work was of interest in that doping levels of fibres was necessarily kept low as were pump powers in order to avoid upconversion processes. Upconversion was considered detrimental since, being such a strongly non-linear process, it greatly complicates analysis of the characteristic decay lifetime shape thus making estimation of the decay lifetime more difficult.

Upconversion in Er^{3+} doped glasses has been demonstrated as a transduction mechanism for measurement of moderate temperatures both in fibres and in bulk[10, 11]. In this work a ratiometric approach was employed between two phonon coupled upconversion emission lines. Since higher doping levels would then be desirable to facilitate efficient upconversion, materials with a high rare earth solubility may offer improved performance. Al_2O_3 has just such a high solubility, with the formation of the self-activated garnet $Er_3Al_5O_{12}$ in the limit. This work reports the use of upconversion in Er-doped sapphire fibres for the measurement of temperatures up to 1000K.

Fibre growth

Er-doped and co-doped fibres were grown from pure sapphire fibres with initial diameters of approximately 325μm. These fibres were coated using a slurry of oxide powders (e.g. Er_2O_3) and then heat treated to fix the coating on the fibre surface. Generally, three such coatings were applied to achieve the desired doping levels. These coated fibres were then used as source rods from which the final fibres were grown using the laser-heated pedestal growth method. Fibres as long as 300mm and with diameters in the range of 80 - 150μm were grown. Both Er:Al_2O_3 and Er:Yb:Al_2O_3 fibres have been grown.

Fibres could also be end-doped rather than doped along their entire length for better spatial resolution by coating only the tips of the source rod; the end of these fibres were then melt-

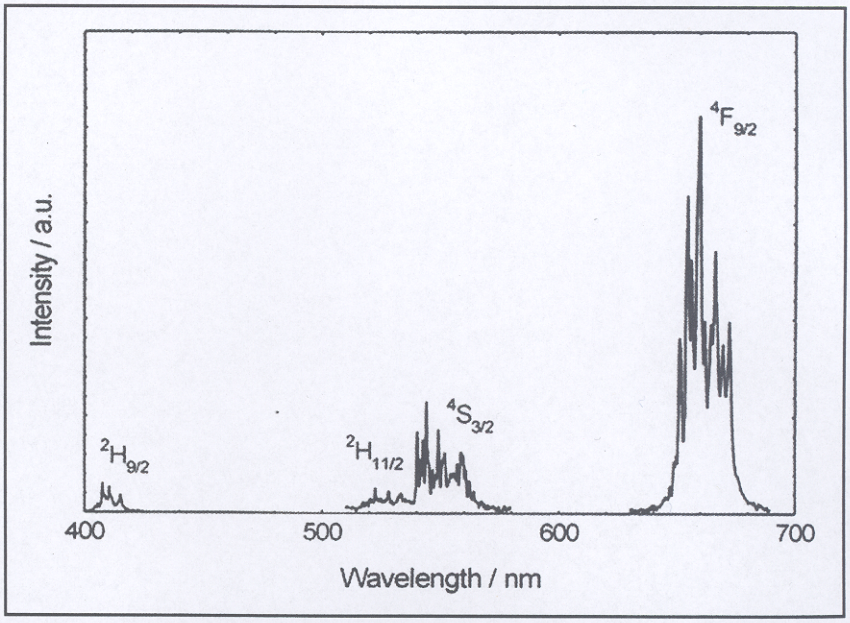

Figure 1 : Upconversion spectrum from Er:Yb:Al2O3 fibre pumped at 965nm.

ed using laser heating to incorporate the dopant. This process was repeated to produce very highly doped crystalline tips at the end of the sapphire fibres. Electron microprobe analysis showed that doping levels as high as 12at% Er could be achieved.

Results

The upconversion emission spectrum of an Er:Yb co-doped sapphire fibre when pumped at 965nm is shown in *Figure 1*. Intense red and green upconverted light was clearly visible from these fibres even when pumped at powers of a few mW. The efficiency of the upconversion process, although not quantified, is estimated to be relatively high due to the high doping levels and efficient energy transfer from the Yb^{3+} to Er^{3+} ions.

The lifetime of the green upconversion signal is shown in *Figure 2* for a range of pump power levels (measured using a monitoring photodiode). It is seen that the emission lifetime is dependent on laser power. Since the nature of the curve is not a simple single or double exponential as is conventionally used in fluorescence lifetime based thermometric measurements, there was some difficulty in estimating the characteristic lifetime using conventional curve-fitting techniques and models.

Upconversion emission spectra were measured from room temperature up to 1000K. The integrated signals within each of the red and green transitions were estimated and are plotted in *Figure 3*. Of note is the thermal population of the $^2H_{11/2}$ level from the $^4S_{3/2}$ level with increasing temperature up to approximately 550K, after which the population of both levels begins to fall with thermal quenching. The phonon coupling between these states is similar to the processes observed in the work of dos Santos *et al*[11] in chalcogenide glasses.

The absolute as well as the relative intensities were found to be dependent on pump power as one would expect from a strongly non-linear process such as upconversion. Further analysis is currently in progress to examine the upconversion mechanisms which occur during emission. It is expected that co-operative energy transfer as well as excited state absorption occur

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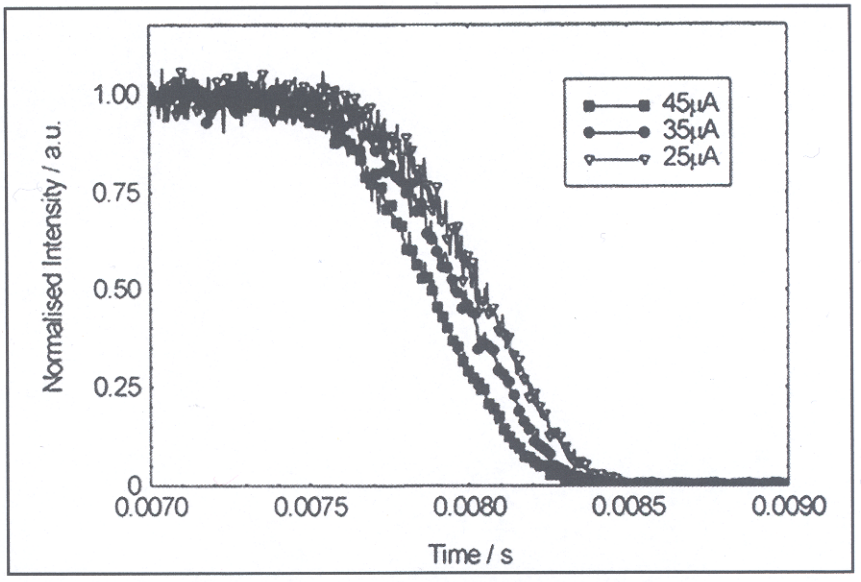

Figure 2 : Upconversion emission decay at 542nm.

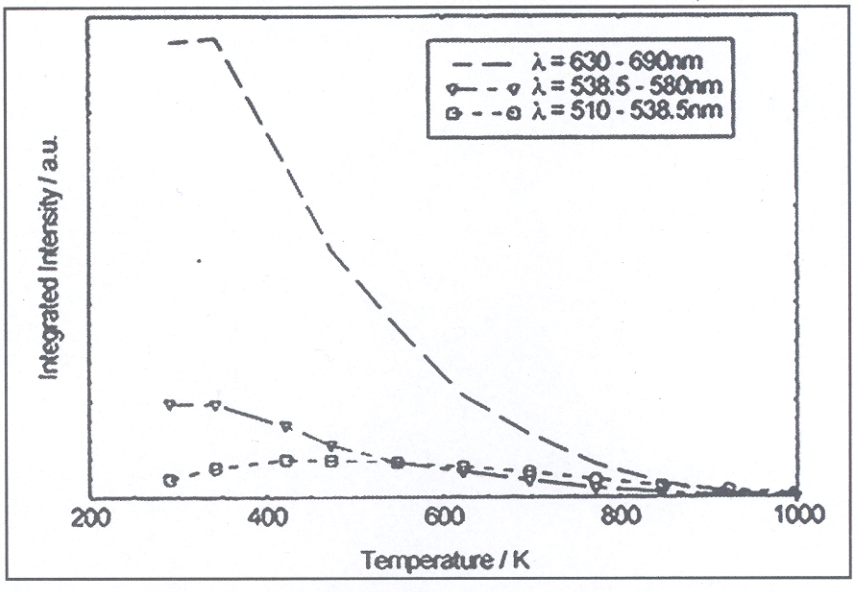

Figure 3 : Integrated upconversion intensities for red and green transitions.

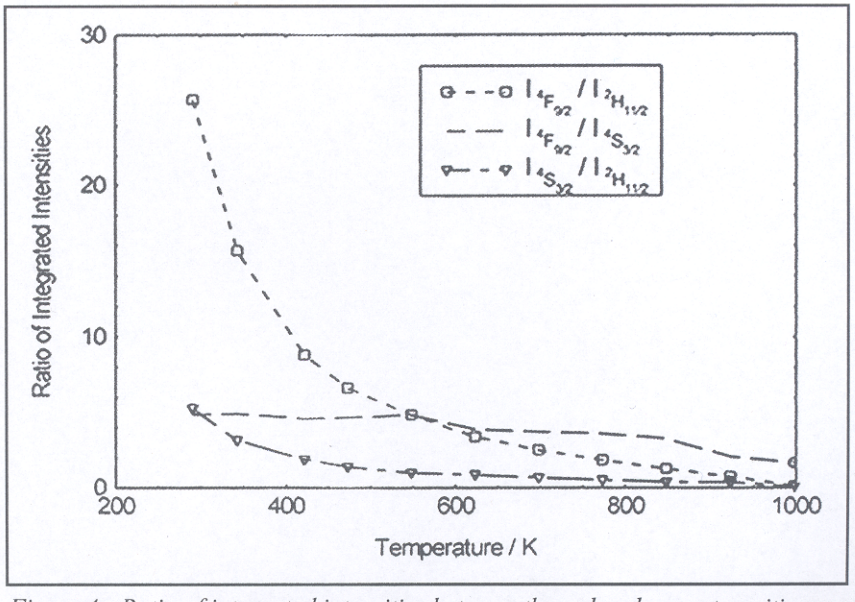

Figure 4 : Ratio of integrated intensities between the red and green transitions.