Emission at 1.3μm from dysprosium-doped Ga:La:S glass

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Indexing terms: Fibre lasers, Chalcogenide glasses

The potential for optical amplification at 1.3μm is demonstrated in a dysprosium-doped gallium-lanthanum-sulphide based glass. Lifetimes of 59μs are observed for the $^6H_{9/2}$ - $^6H_{15/2}$ transition for which the emission peaks at 1.32μm. A radiative lifetime of 203μs is calculated by a Judd-Ofelt analysis, indicating a total radiative quantum efficiency of 29%. A pump absorption cross-section 20 times greater than Pr^{3+} suggests that shorter fibre devices may be possible.

Introduction: With the majority of the world's land-based fibre networks operating at a wavelength of 1.3μm, the need for an optical amplifier operating in this telecommunications window is well known. Following the success of the erbium-doped fibre amplifier [1], the quest for an efficient optical fibre amplifier for this application led first to neodymium-doped fibres [2]. However, the 1.3μm transition in this ion has a low branching ratio allowing the ASE from the 1.06μm transition to saturate the 1.3μm gain. More recently, the $^1G_4$ - $^3H_5$ transition in praseodymium-doped fluorozirconate-based optical fibres [3] has been exploited to provide amplification at 1.32μm with a typical small-signal gain coefficient of up to 0.20dB/mW. Practical devices however, require pump powers of hundreds of milliwatts at 1.01μm. Improved efficiency is predicted through the use of low-phonon-energy glasses such as mixed halides and sulphides, although the realisation of low-loss singlemode fibres in these materials remains a major challenge [4].

We show here the potential of dysprosium-doped low phonon energy glasses to provide an attractive alternative to neodymium and praseodymium. Through calculation of the radiative properties and measurement of the fluorescence emission and lifetimes, the radiative quantum efficiency at 1.3μm is determined and the potential for amplification at this important wavelength is assessed.

Radiative properties: In preparation for a spectroscopic analysis, a series of gallium-lanthanum sulphide (Ga:La:S) glasses in the molar ratio $70Ga_2S_3$:$30La_2S_3$ were prepared by melt quenching [5]. To determine the radiative properties of Dy^{3+}-doped Ga:La:S glass, a Judd-Ofelt (J-O) analysis was performed. A sample of thickness 1.2cm and doped with 5000*ppm* by weight of Dy_2S_3 was prepared and optically polished on both sides. Ground state absorption spectra were obtained over the wavelength range 190–3200nm on a two beam double-grating spectrometer with a white light source. Oscillator strengths and the centre position of each absorption band were obtained directly from the measured absorption, as given in Table 1. The refractive index was 2.38 at 1.3μm, with a wavelength dependence as given in [5].

Table 1: Absorption peak positions, measured and calculated oscillator strengths for Dy^{3+}-doped Ga:La:S glass

Transition	Wavelength	Oscillator strength × 10^{-8}		
		Measured	Calculated	Deviation
$^6F_{3/2}$	nm			1
$^6F_{5/2}$	742	1	0	−18
$^6F_{7/2}$ + $^6H_{5/2}$	759	110	128	20
$^6H_{7/2}$ + $^6F_{9/2}$	890	247	227	−6
$^6F_{11/2}$ + $^6H_{9/2}$	1074	266	272	−4
$^6H_{11/2}$	1245	1795	1799	−9
$^6H_{13/2}$	1600	203	212	−
	2757	−	−	
Total deviation				−16

All transitions are from the ground state to the level indicated

Considering only the electric dipole transitions and following the procedure of Hormadaly and Reisfeld [6], who studied Dy^{3+} in an oxide glass, the three J-O parameters were obtained: $\Omega_2 = 11.3 \times 10^{-20}cm^2$, $\Omega_4 = 1.0 \times 10^{-20}cm^2$, $\Omega_6 = 1.3 \times 10^{-20}cm^2$.

Unlike praseodymium, for which J-O analysis is difficult, the fit between measured and calculated oscillator strengths, shown in Table 1, was excellent, as indicated by the low RMS deviation.

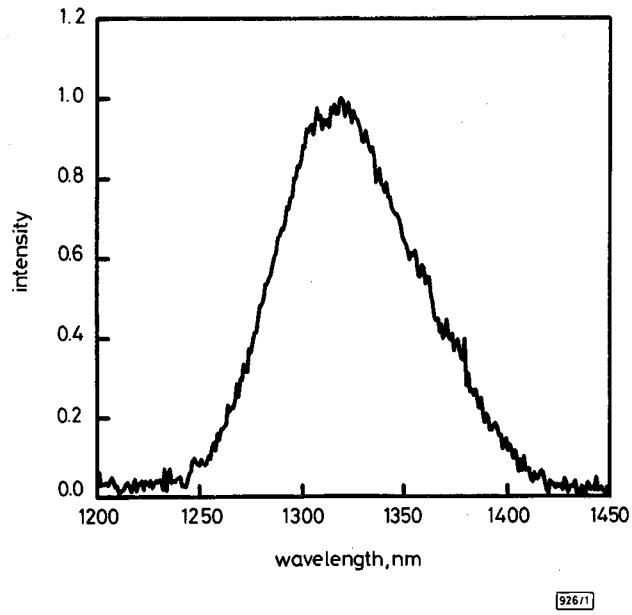

Fig. 1 *Absorption spectrum of Dy^{3+}-doped Ga:La:S glass*

Using the three J-O parameters, the radiative rates for all transitions were determined. Radiative lifetimes of each energy level follow directly from the sum of all radiative rates. Within the 20% accuracy of the J-O theory there was no difference in the calculated radiative rates when the hypersensitive $^6H_{9/2}$ and $^6F_{11/2}$ levels were omitted. We thus include these levels in the calculations presented here. For the $^6H_{9/2}$ and $^6F_{11/2}$ levels, radiative lifetimes of 176 and 4220μs respectively are calculated. As these manifolds are in thermal equilibrium, being separated by only 380cm^{-1}, their decay rates should be combined taking into account a Boltzmann population distribution, for a total radiative lifetime of 203μs.

Fluorescence could be observed by pumping at 814 and 914nm, which excites the $^6F_{7/2}$ energy level and $^6H_{5/2}$ and $^6F_{7/2}$ doublet, respectively. Through a multiphonon cascade via the closely spaced energy levels, all lower lying bands could be populated. Fluorescence spectra were measured on an optical spectrum analyser. By chopping the pump beam and analysing the decay of the fluorescence intensity, the total lifetimes could be measured. These lifetimes consist of decay through radiative, multiphonon and other nonradiative mechanisms. To minimise any possible concentration quenching, lifetime measurements were performed on samples doped with 500*ppm*/wt Dy^{3+}.

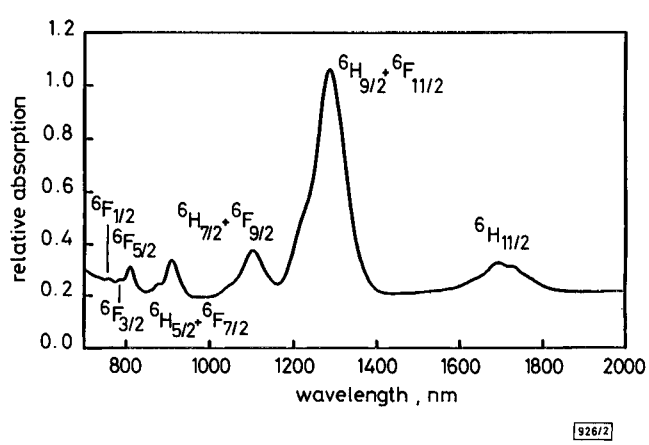

Fig. 2 *$^6H_{9/2}$ - $^6H_{15/2}$ fluorescence spectra obtained by pumping at 0.814μm*

1.3μm emission: The fluorescence spectrum in the region of 1.3μm is shown in Fig. 2. Emission which peaks at 1317nm with a half width of 83nm is observed, predominantly from the $^6H_{9/}$, energy level. The total lifetime of this level was measured to be 59μs, compared to a calculated radiative lifetime of 203μs. This yields a total radiative quantum efficiency of 29%. Nonradiative de-excitation contributes to the decay mechanism largely through multiphonon decay to the lower lying $^6H_{11/2}$ level. These levels are separated by an energy gap of ~1850cm^{-1}. Branching ratios for the $^6H_{9/2}$ and $^6F_{11/2}$ levels follow directly from the J-O analysis. These are combined taking into account their Boltzmann population distribution to obtain effective branching ratios which are given in Table 2. For 1.32μm emission, an effective branching ratio of 0.93 is predicted, compared to 0.60 for Pr^{3+}-doped Ga:La:S. The radiative quantum efficiencies for the 1.32 μm transition of Dy^{3+}-doped Ga:La:S glass is then 27% compared to 32% for Pr^{3+}[7]. This value compares well with the 17% efficiency estimated using a radiative rate calculated from measured absorption and emission spectra [8].

Table 2: Effective branching ratios for $^6H_{9/2}$ and $^6F_{11/2}$ energy levels

Transition	Radiative rate	Branching ratio
	s^{-1}	
$^6F_{11/2} + {}^6H_{9/2} - {}^6H_{11/2}$	13	0.002
$^6F_{11/2} + {}^6H_{9/2} - {}^6H_{13/2}$	318	0.06
$^6F_{11/2} + {}^6H_{9/2} - {}^6H_{15/2}$	4606	0.93

For a three-level system, the gain per unit absorbed pump power can be assessed from the product of the peak emission cross-section and the measured lifetime. From the calculated radiative rate and measured fluorescence spectrum, an emission cross-section of 3.8 × 10^{-20}cm^2 was calculated. With a lifetime of 59μs, this yields a στ product of ~220 (× 10^{-26}cm^{2}s), compared to 250 for Pr^{3+}-doped Ga:La:S, 45 for Pr^{3+}-doped ZBLAN and 160 for Nd^{3+}-doped ZBLAN.

In addition to pumping at 814 and 914nm, in-band pumping at 1.25μm, which directly excites the $^6F_{11/2}$ - $^6H_{9/2}$ manifold, may be feasible. Most significant here is that the absorption cross-section of Dy^{3+} when pumped at 1.25μm is ~20 times greater than Pr^{3+} pumped at 1.01μm. This suggests that radically shorter devices may be possible, relaxing the tolerances on fibre background loss.

Summary: Emission at 1.32μm is observed from Dy^{3+}-doped Ga:La:S glass. A total lifetime of 59μs is measured for a total radiative quantum efficiency of 29% with an effective branching ratio of 0.93. Gain per unit absorbed pump power four times higher than Pr^{3+}-doped ZBLAN is estimated. A significantly higher absorption cross-section suggests short devices may be possible, opening an alternate route to optical fibre amplification at this important telecommunications wavelength.

Acknowledgements: This work was supported by a DTI/SERC LINK project, GOAL. Chalcogenide materials were supplied by Merck, Ltd., Poole, Dorset, United Kingdom.

26 April 1994
Electronics Letters Online No: 19940645

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