Pr^{3+}-Doped Mixed Halide Glasses for 1.3μm Fibre Amplifiers

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Abstract

Using experimental measurements of cross-sections and a $^1G_4$ lifetime of 315μs, we have characterised the expected performance of a Pr^{3+}-doped mixed halide fibre amplifier for operation at 1.3μm. Our model predicts a small-signal gain of 20dB for 75mW of pump.

Introduction

The search for a suitable Pr^{3+}-doped low phonon energy glass for operation as an efficient 1.3μm fibre amplifier has recently expanded to include mixed halide glasses[1,2,3]. The need for a low phonon energy glass stems from the fact that the lifetime of the $^1G_4$ metastable level in existing Pr^{3+}-doped ZBLAN glasses is dominated by multi-phonon decay to the lower lying $^3F_4$ energy level (an energy gap of 3000cm^{-1} typically) leading to low amplifier quantum efficiency. Lowering the phonon energy of the glass generally increases the non-radiative lifetime, making the transition predominantly radiative. Mixed halide glasses can have lower phonon energies (as measured by Raman scattering) than pure fluoride glasses, although their thermal characteristics are usually worse: Tg=132°C in our samples. They also tend to be more hygroscopic. However, the Hruby factor in our CdF_2-NaCl-$BaCl_2$ glass (H_r=1.3) indicates good fibre drawing possibilities.

To date the highest reported $^1G_4$ lifetime of 309μs in a mixed halide glass[1] indicates that quantum efficiencies greater than the 4% measured in Pr^{3+}-doped ZBLAN amplifiers are possible. In this paper we measure a $^1G_4$ lifetime of 315μs in a 610ppm Pr^{3+}-doped mixed halide sample, from which we calculate a possible amplifier quantum efficiency of 12%. This value is based upon a total $^1G_4$ radiative lifetime of 1.84ms, as calculated from Judd-Ofelt analysis. Comparison of the calculated $^3P_0$ and $^1D_2$ radiative lifetimes with our measured values highlights the accuracy of our Judd-Ofelt fitting. We have also carried out numerical modelling to compare the expected amplifier performance of a Pr^{3+}-doped mixed halide glass with that of standard ZBLAN. The model includes the effects of excited state absorption (ESA), ground state absorption (GSA) and amplified spontaneous emission (ASE), all at the signal wavelength. These results indicate a small-signal gain figure of 20dB at 75mW pump and 34dB at 200mW, which are significantly better than the value of 20dB at 140mW we calculate for a ZBLAN Praseodymium doped fibre amplifier (PDFA).

Experimental Results

The Pr^{3+} $^1G_4$ lifetime can be seriously reduced by the effects of concentration quenching, which in turn can seriously degrade the performance of Pr^{3+}-doped amplifiers[4]. Figure 1 shows experimental results on a series of mixed halide samples doped with various levels of Pr^{3+} in the range 200-3000ppm PrF_3. The scatter in the data is due to the presence of impurities. The longest measured lifetime (315μs) occurred in a 610ppm sample, which also corresponds to the sample with the lowest level of impurities.

Based on the measured ground-state absorption spectrum, we have carried out a Judd-Ofelt analysis of Pr^{3+}-doped mixed-halide glass. The measured and calculated oscillator strengths are summarised in Table 1, along with the Judd-Ofelt parameters derived from the fitting. As can be seen, the agreement is good. Further vindication of these parameters is achieved by comparing our measured $^3P_0$ and $^1D_2$ lifetimes (305μs and 35μs) with the calculated values (390μs and 41μs). These calculated radiative lifetimes are in excellent agreement with those previously published[3] based on a local field correction to the accepted ZBLAN values.

From the values in Table 1, we have calculated a radiative lifetime for the $^1G_4$ level of 1.84ms which, together with the measured lifetime (315μs), yields an amplifier quantum efficiency of 12%. This is a significant improvement over the 4% measured in ZBLAN PDFA's and is the direct consequence of the decreased multi-phonon decay rate.

It is well known that GSA and ESA at the signal wavelength can effect the performance of PDFA's[5]. An estimate of the 1.3μm GSA cross section (due to the short wavelength tail of the $^3F_4$ absorption peak) can be obtained from the measured infra-red absorption data (see Figure 2). As can be seen, the mixed-halide glass has a larger GSA in the wavelength region around 1.3μm, owing to the increased oscillator strength of the $^3F_4$ absorption peak.

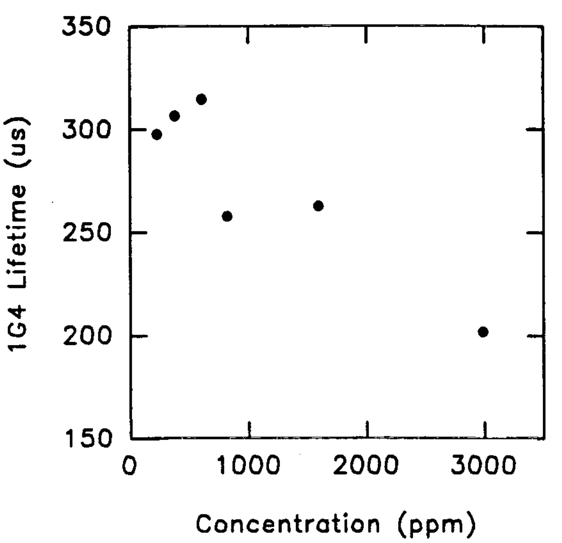

Figure 1. Measured effect of concentration quenching on 1G4 lifetime.

Table 1. Measured and calculated oscillator strengths. The sample was doped with 600ppm Pr^{3+}.

Transition	Measured Oscillator Strength (10^{-8})	Calculated Oscillator strength (10^{-8})
3P0+3P1	343	344
1D2	279	122
1G4	-	17
3F4+3F3	1141	1153
3F2+3H6	352	351

Judd-Ofelt parameters: Ω_2=1.88, Ω_4=7.27, Ω_6=7.27.

Recently the 1.3μm ESA cross-section for Pr^{3+}-doped ZBLAN has been measured using a M^{c}Cumber analysis on the $^1D_2$-$^1G_4$ emission spectrum[6]. We have carried out a similar analysis on a mixed halide sample, the results of which are shown in Figure 3 along with our own measurements on a ZBLAN sample. The difference between the ESA and $^1G_4$-$^3H_5$ emission cross-sections yields a net cross-section which dictates the shape of the gain curve for the host glass[6]. Comparing the values for ZBLAN and the mixed halide, we see that the peak of the gain is expected at 1307nm in the mixed halide, some 8nm shorter than our calculated value for ZBLAN. In the mixed-halide glass the peak cross-section is slightly smaller than the peak value in ZBLAN; due primarily to the increased linewidth in the mixed halide. The shorter operating wavelength is an advantage from the point of view of the GSA curve shown in Figure 2.

Amplifier Model

The numerical model uses our own measured and calculated lifetimes and cross-sections to simulate the small-signal performance of a mixed halide glass amplifier operating at 1.307μm. The model includes the effects of GSA, ASE due to the $^1G_4$-$^3H_5$ transition, and the effects of ESA by using the difference between the $^1G_4$-$^3H_5$ and $^1G_4$-$^1D_2$ cross-sections summarised in Figure 3. The effects of bottlenecking[7] at the $^3H_5$ energy level are neglected because of the uncertainty in the non-radiative rates.

The small-signal gain as a function of pump power, for both ZBLAN and the mixed halide glass, is shown in Figure 4. The calculations are based upon the fibre parameters relevant to the experimental results of Miyajima *et al*[8] (NA=0.42, λ_c=1260nm). We have compared our ZBLAN model results with the experimental data and found good agreement, taking into account the 4dB loss at low pump power due to GSA. In modelling the mixed halide we have used the values for the lifetimes, $^1G_4$-$^3H_5$ and GSA cross-sections discussed above. We have also included the effects of the increased $^1G_4$-$^3H_5$ linewidth on the ASE.

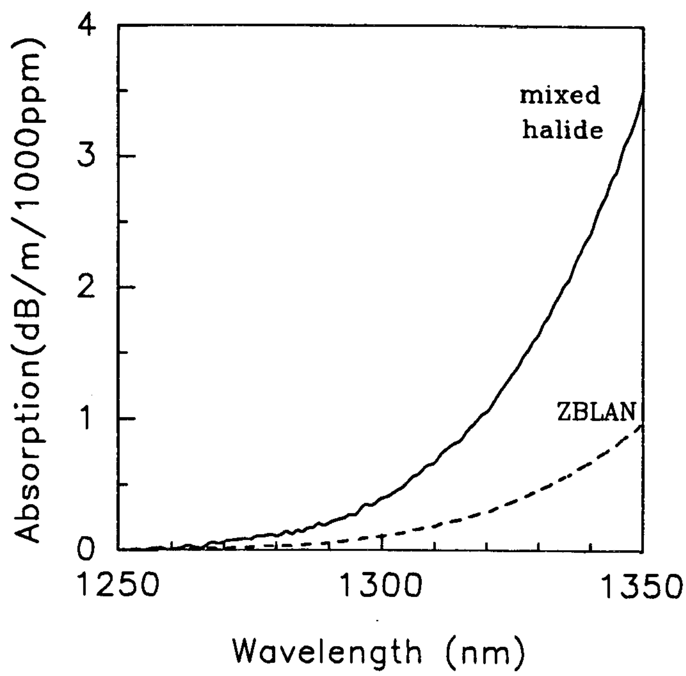

Figure 2. Measured 1.3μm GSA spectra.

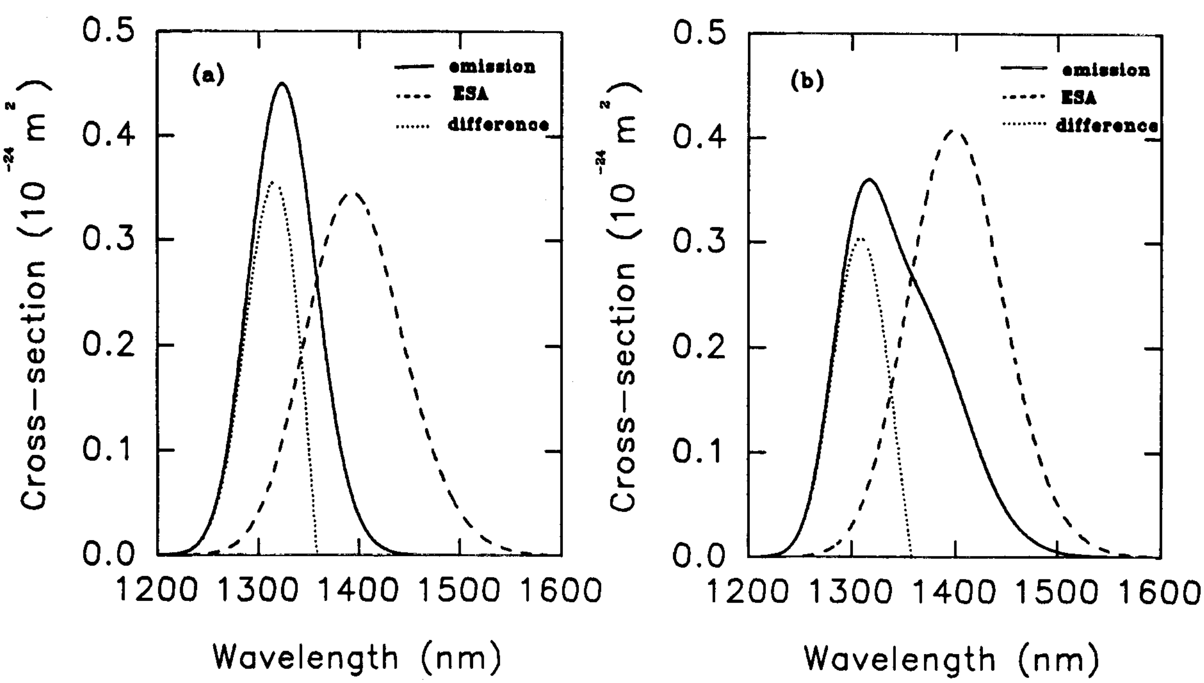

Figure 3. Measured 1G4 emission cross-section and ESA for (a)ZBLAN and (b)mixed-halide glass.

Comparing the two graphs in Figure 4, at low pump powers the gain in the mixed halide amplifier is strongly attenuated by the larger GSA. By contrast, the mixed halide amplifier shows a small-signal gain figure of 20dB at 75mW pump and 34dB at 200mW. This compares with 140mW pump required for 20dB of gain in ZBLAN glass.

Conclusion

Numerical modelling based on our measured and Judd-Ofelt derived cross-sections and lifetimes indicates that Pr^{3+}-doped mixed-halide glass amplifiers operating at 1.3μm have small-signal gain characteristics significantly superior to ZBLAN ones. Our model takes into account the differences in ESA and GSA in the mixed halide amplifier. Based on these calculations, we expect a small-signal gain of 20dB for 75mW pump in a mixed halide amplifier.

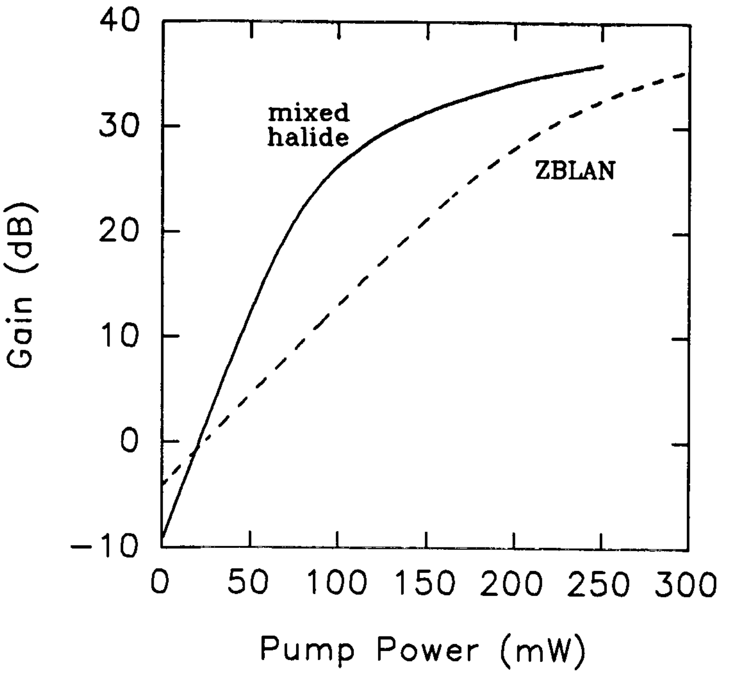

Figure 4. Calculated small-signal gain curves using fibre parameters of NA=0.42 and λ_c=1.26μm.

Acknowledgements

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