1412

Properties of Dysprosium Doped GaLaS Fibre Amplifiers Operating at 1.3μm

B.N. Samson, T. Schweizer, D.W. Hewak and R.I. Laming

Optoelectronics Research Centre

University of Southampton

Southampton, U.K.

SO17 1BJ

Tel:+44 1703 594523

Fax:+44 1703 593142

Email: bns@orc.soton.ac.uk

Abstract

In light of the recent progress on the fabrication of GaLaS fibres we have modelled the performance of dysprosium doped GaLaS fibre amplifiers operating at 1.3μm. Based on experimental data, we find the incorporation of a co-dopant (terbium) in the fibre core significantly shortens the optimum amplifier length from >30m to ~3m. Such a device may be practical given the fibre losses currently achieved in GaLaS fibres.

Recently Dysprosium (Dy^{3+}) doped chalcogenide glass have been proposed as a possible efficient 1.3μm optical fibre amplifier[1,2]. One of the most suitable host glasses for such an application is Gallium Lanthanum Sulphide (GaLaS) which combines a high rare earth solubility with a low phonon energy. Core/clad structures of this glass have been drawn indicating the good fibre drawing characteristics for this family of glass and we have recently demonstrated a Nd^{3+}-doped GaLaS fibre laser[3]. In this paper we develop a model for a Dy^{3+}-doped fibre amplifier based on our measured bulk glass cross sections and lifetimes. Our results indicate that the optimum fibre length for a 500ppm Dy^{3+}-doped device is ~30m primarily due to the long lifetimes of the intermediate energy levels $^3H_{11/2}$ and $^3H_{13/2}$. This places a strict tolerance on the fibre background loss (<0.1dB/m). However, the incorporation of terbium ions (Tb^{3+}) in the glass significantly reduces the measured lifetimes of these two energy levels. In this case our model predicts optimum device lengths ~3m or less, hence significantly relaxing the tolerance on the fibre background loss.

The simplified energy level diagram used to model the Dy^{3+}-doped GaLaS fibre amplifier is shown in figure 1. Unlike the Pr^{3+}-doped amplifier which must be pumped around 1μm, there are a number of possible pump wavelengths for the Dy^{3+}-doped device. However, we choose to model the fibre amplifier as pumped 'in-band' at 1240nm since this wavelength is suitable for direct diode pumping. This is analogous to 1480nm pumping of the Er^{3+}-amplifier.

The rate equations used to describe the Dy^{3+}-system are;

$$\frac{dn_1}{dt} = -(R_{14}+W_{14})n_1 + (\frac{1}{\tau_2}+ET_2)n_2 + (A_{31}+ET_3)n_3 + (A_{41}+R_{41}+W_{41}+ET_4)n_4 \qquad 1$$

$$\frac{dn_2}{dt} = -(\frac{1}{\tau_2}+ET_2)n_2 + MP_{32}n_3+A_{42}n_4 \qquad 2$$

$$\frac{dn_3}{dt} = -(A_{31}+A_{32}+MP_{32}+ET_3)n_3 + MP_{43}n_4 \qquad 3$$

$$\frac{dn_4}{dt} = (R_{14}+W_{14})n_1 - (A_{41}+R_{41}+W_{41}+A_{42}+MP_{43}+ET_4)n_4 \qquad 4$$

where R_{ij} and W_{ij} are the pump and signal rates, A_{ij} is the spontaneous emission rates and MP_{ij} are the multiphonon decay rates. The pump and signal rates are defined;

$$R_{ij} = \frac{P_p(Z)\,\sigma_{ij}^{p}\psi_p(r)}{h\upsilon_p} \qquad 5$$

$$W_{ij} = \frac{P_s(z)\,\sigma_{ij}^{s}\psi_s(r)}{h\upsilon_s} \qquad 6$$

where $P_p(z)$ and $P_s(z)$ are the pump and signal powers respectively (assumed to be co-propagating), $\psi_p(r)$ and $\psi_s(r)$ refer to the intensity distribution functions for the pump and signal respectively. We are interested in step index fibres where only the core is doped with rare earth ions and the mode distributions are treated with the weakly guiding analysis. The parameters ET_n represent the energy transfer rates from the Dy^{3+}-ions to the neighbouring Tb^{3+}-ions in the co-doped sample. Their values are derived from the measured lifetimes of the various energy levels and are set to zero when the Tb^{3+}-concentration is zero.

These rate equations together with the propagation equations for the pump and signal waves are solved numerically using standard routines used to describe the Er^{3+}-doped amplifier. We neglect the effects of amplified spontaneous emission (ASE) in this work. The optimum pump wavelength is around 1240nm where there is a compromise between the pump absorption and any residual pump stimulated emission. We anticipate negligible excited state absorption (ESA) from the 1.3μm metastable energy level. This is easily justified by close inspection of the energy level diagram where no energy level exists between 750nm and 470nm. For signal ESA to occur, we would require an energy level around 660nm. However, from the energy level diagram we do expect some 1.3μm ESA from either (or both) of the intermediate energy levels 2 and 3 ($^6H_{13/2}$ and $^6H_{11/2}$) to occur. Since we have no accurate information on these cross sections we do not include the effects of ESA from these levels in the model.

The measured lifetimes for the 3 energy levels used in the model are detailed in table I for a 500ppm-Dy_2S_3 doped sample. These measurements were performed on bulk glass samples pumped at 800nm. The absorption cross sections in the region of the

$1.3\mu m$ transition are calculated from the bulk glass spectrum and the Dy^{3+} concentration. The emission cross section is then calculated from the absorption spectrum with the aid of the M^c^Cumber relation between the emission and absorption spectra[2,4]. The values for the radiative and multiphonon rates were obtained from either the Judd-Ofelt analysis[5], the McCumber analysis or our recent low temperature measurements on bulk glass samples[6]. We have used a Dy^{3+}-concentration of $6.4x10^{-24}m^{-3}$ (500ppm Dy_2S_3) in all the following calculations. The full list of parameters used our model are given in table II.

In the modelling results presented here the fibre is assumed to have an NA=0.4, comparable with the current Pr^{3+}-doped ZBLAN devices. The cutoff wavelength is 1200nm and the pump power is assumed to be 100mW. The optimum device length is strongly related to the lifetimes of the two intermediate energy levels 2 and 3 ($^6H_{13/2}$ and $^6H_{11/2}$). As an example of this we plot in figure 2 the optimum fibre length (ie maximum small signal gain) whilst varying the value of the intermediate energy levels. We assume no significant background loss is this calculation. For lifetimes of the order $2000\mu s$ the optimum fibre length is >30m; this is the case for a 500ppm Dy^{3+}-doped device where the lifetimes are $1300\mu s$ and $3600\mu s$ (see table I). Decreasing the intermediate level lifetime shortens the device length and we obtain optimum fibre lengths less than 2m for intermediate level lifetimes less than $100\mu s$. Such short device lengths are obviously attractive in terms of the permissible fibre background loss.

We have studied the affects of terbium (Tb^{3+}) co-doping on the various Dy^{3+} energy lifetimes. The Tb^{3+}-energy level diagram is also shown in figure 1. In samples with high Tb^{3+} concentrations we might expect significant energy transfer between Dy^{3+}-ions and neighbouring Tb^{3+}-ions due to the well matched energy levels of the two sets of ions. The measured lifetimes for a 500ppmDy^{3+}/4000ppm Tb^{3+} sample are included in table I. Note the much reduced lifetimes for the intermediate energy levels 2 and 3. We assume that the Dy^{3+} lifetimes are reduced through energy transfer from the excited Dy^{3+}-ions to the Tb^{3+}-ions which in turn undergo rapid non-radiative decay to the ground state. We have included the effects of the Tb^{3+}-co-doping in the amplifier model described above. The effect of the Tb^{3+} co-dopant contributes another term in each of the rate equations (1-4). These parameters (ET_n) describe the energy transfer between the Dy^{3+}-ions and the neighbouring Tb^{3+}-ions and are obviously different for each energy level. Values for these parameters may be calculated from the measured lifetimes in table I;

$$ET_n = \frac{1}{\tau_{dy/tb}} - \frac{1}{\tau_{dy}} \qquad 7$$

the calculated values for these energy transfer rates are; $ET_4 = 8845s^{-1}$, $ET_3 = 4230s^{-1}$ and $ET_2 = 1645s^{-1}$ for the samples listed in table I.

Clearly the presence of the Tb^{3+} co-dopant will shorten the amplifier length through the decrease in the level 2 and 3 lifetimes. However we would also expect a decrease in the device efficiency since the level 4 (1.3μm) lifetime has also been decreased. In order to quantify this effect we have plotted the optimised gain versus the fibre background loss in figure 3 for the fibres with and without Tb^{3+}- co-doping. At very low values of background loss (<0.1dB/m) we expect the Tb^{3+}- device to perform rather worse due to the decrease in the 1.3μm quantum efficiency. However as soon as the fibre loss increases above this level it is clear that the co-doped device has a superior performance due to the significantly shorter optimum length. For the 500ppm/4000ppm co-doped sample studied here we anticipate an optimum fibre length around 3m. Furthermore, this is considerably shorter than the 10-20m fibre length needed for a 500ppm Pr^{3+}-doped amplifier.

In conlusion, we have presented experimental results which suggest that a dysprosium/terbium co-doped GaLaS 1.3μm fibre amplifier will be significantly shorter in length than a similar dysprosium doped device. Consequently our modelling results indicate that such a device will outperform the dysprosium doped amplifier in cases where the fibre background loss is greater than 0.1dB/m. Indeed with further optimisation amplifier lengths considerably shorter than 1m may be possible using this co-doping scheme and a slightly higher Dy^{3+} concentration. These results indicate that the current level of background loss measured in GaLaS multimode fibres[3] need not adversely affect the amplifier performance.

Acknowledgements

Chalcogenide starting materials were provided by Merck Ltd.

References

[1] K. Wei, D.P. Machewirth, J. Wenzel, E, Snitzer and G.H. Sigel, Optics Lett., **19**, 904, (1994).

[2] B.N. Samson, J.A. Medeiros Neto, R.I. Laming, D.W. Hewak, Electron. Lett., **30**, 1617, (1994).

[3] T. Schweizer, B.N. Samson, R.C. Moore, D.W. Hewak and D.N. Payne, accepted for publication, Electron. Lett, (1997).

[4] W.J. Miniscalco and R.S. Quimby, Optics Lett., **15**, 258, (1991).

[5] D.W. Hewak, B.N. Samson, J.A. Medeiros neto, R.I. Laming, Electron. Lett., **30**, 968, (1994).

[6]B.N. Samson, T. Schweizer, D.W.Hewak and R.I.Laming, accepted for publication, J. Luminescence, (1997).

Table I Measured Lifetimes of Dy^{3+} and Dy^{3+}/Tb^{3+} co-doped samples.

Energy Level	wavelength (nm)	500ppm Dy^{3+} doped sample	500ppm Dy^{3+}/4000ppm Tb^{3+} co-doped sample
4	1320nm	55μs	37μs
3	1800nm	1300μs	200μs
2	2800nm	3600μs	520μs

Table II Parameters used in modelling Dy^{3+}-doped GaLaS fibre amplifier

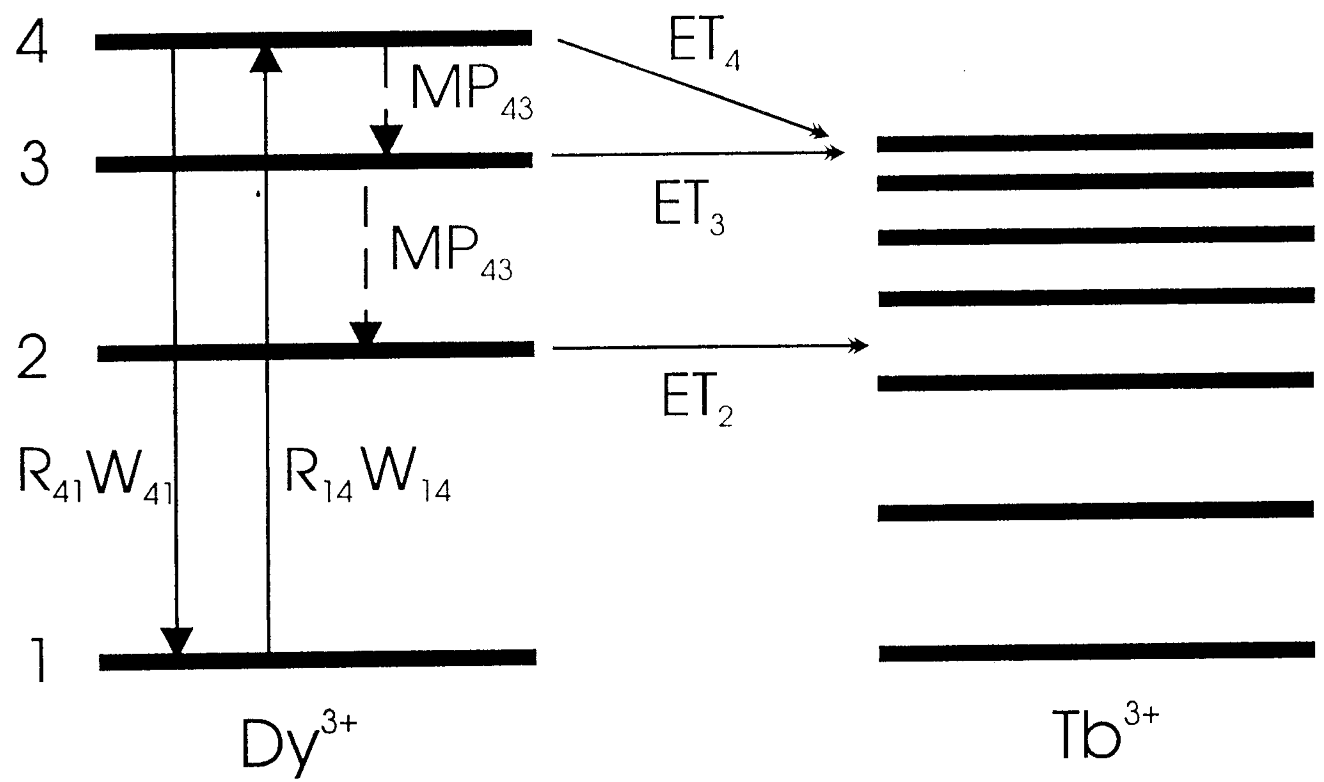
Parameter	Value	Comments
σ^{p}_{14}	$1.0 \times 10^{-24} m^2$	pump absorption cross section
σ^{p}_{41}	$0.1 \times 10^{-24} m^2$	pump emission cross section
σ^{s}_{14}	$1.7 \times 10^{-24} m^2$	signal absorption cross section
σ^{s}_{41}	$2.8 \times 10^{-24} m^2$	signal emission cross section
τ_4	$55 \mu s$	measured lifetime
A_{41}	$1800 s^{-1}$	radiative decay rate
A_{42}	$455 s^{-1}$	radiative decay rate
MP_{43}	$14930 s^{-1}$	multiphonon decay rate
τ_3	$1300 \mu s$	measured lifetime
A_{31}	$338 s^{-1}$	radiative decay rate
A_{32}	$55 s^{-1}$	radiative decay rate
MP_{32}	$380 s^{-1}$	multiphonon decay rate
τ_2	$3600 \mu s$	measured lifetime

Figure Captions

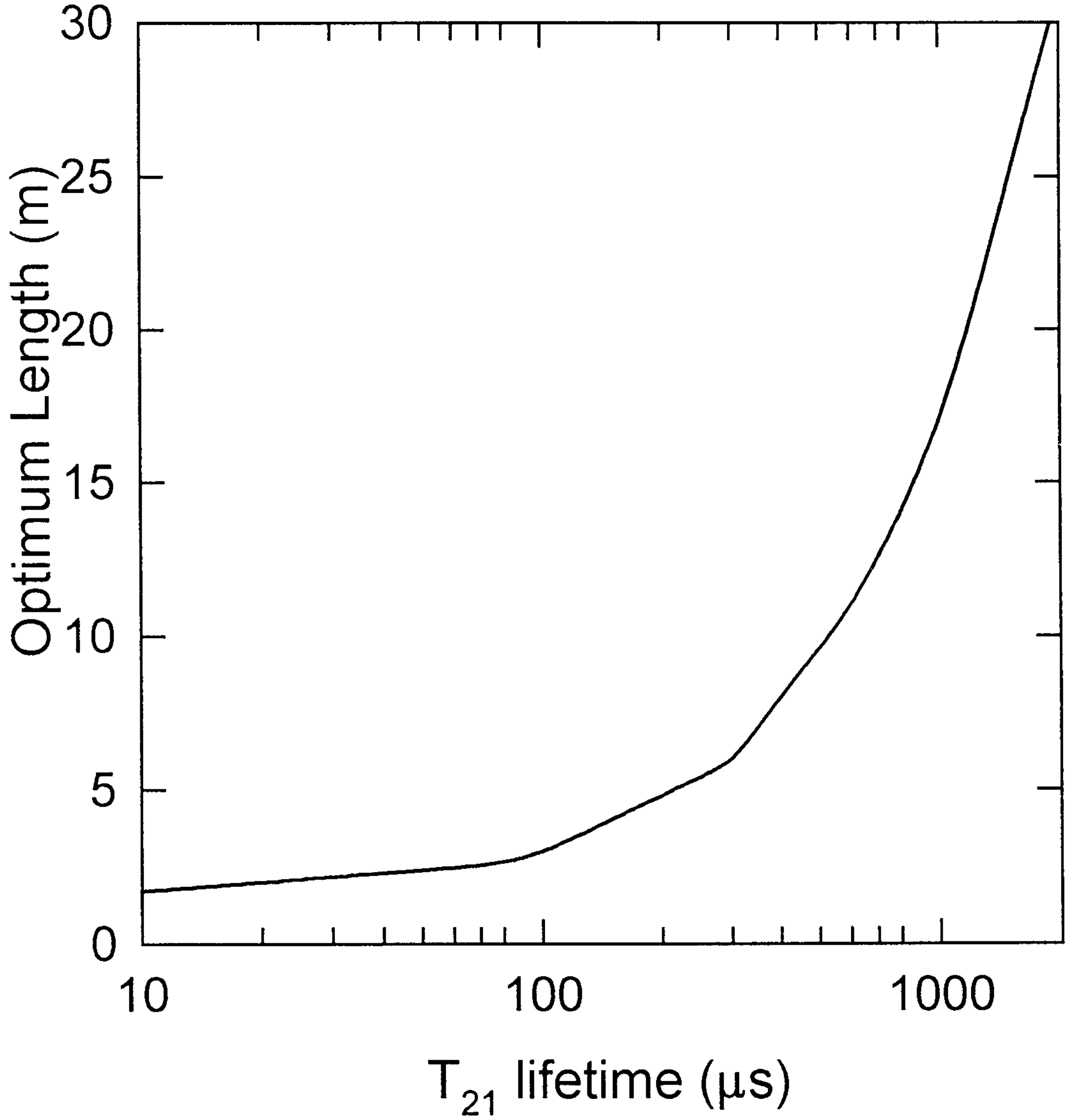
Figure 1. Simplified Energy level diagram used to model Dy^{3+}/Tb^{3+}-co-doped amplifier. The pump rates (R_{ij}), signal rates (W_{ij}) and multiphonon decay rates (MP_{ij}) are indicated along with the energy transfer rates (ET_n) between the Dy^{3+} and Tb^{3+} energy levels.

Figure 2. Effect of intermediate energy level lifetime (τ_{21}) on the optimum fibre length for Dy^{3+}-doped amplifier.

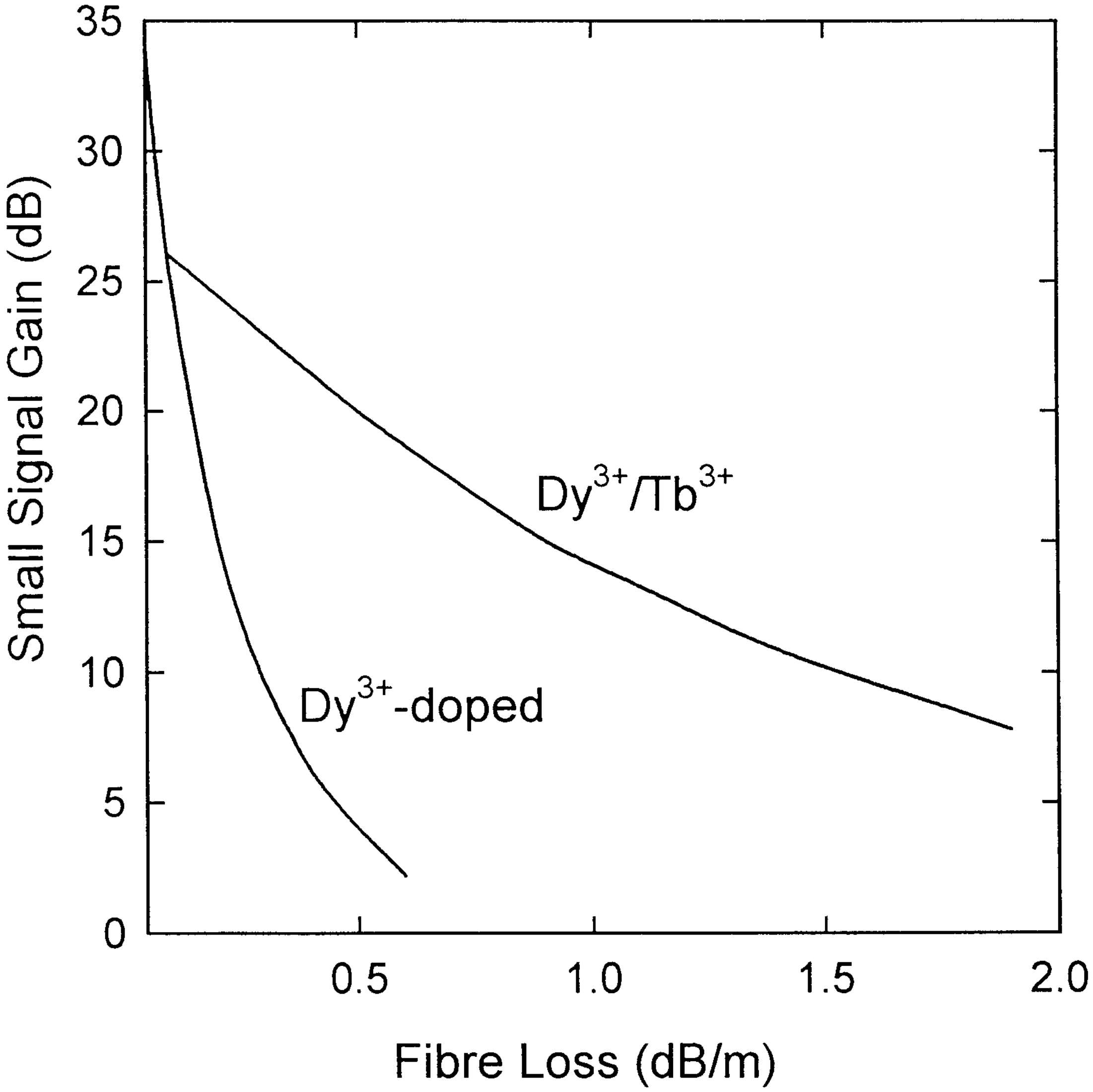
Figure 3. Comparison of the affect of fibre loss on Dy^{3+} and Dy^{3+}/Tb^{3+}-co-doped fibre amplifiers. The shorter intermediate level lifetimes in the co-doped case lead to a much shorter device length.



4
3
2
1
MP43
MP43
R41W41
R14W14
ET4
ET3
ET2
Dy3+
Tb3+



Optimum Length (m)
0
5
10
15
20
25
30
10
100
1000
T21 lifetime (μs)



35
30
25
20
15
10
5
0
Small Signal Gain (dB)
0.5
1.0
1.5
2.0
Fibre Loss (dB/m)
Dy3+/Tb3+
Dy3+-doped