Modelling of multimode selenide-chalcogenide glass fibre based MIR spontaneous emission sources

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ABSTRACT
Chalcogenide glass fibres have been demonstrated as a suitable medium for the realisation of spontaneous emission sources for mid-infrared photonics applications with a particular emphasis on sensor technology. Such sources give a viable alternative to other solutions due to their potentially low cost, high reliability and robustness when pumped using commercially available semiconductor lasers. We present a comprehensive analysis of the properties of selenide-chalcogenide glass fibres applied as spontaneous emission sources. We extract the modelling parameters from measurements using in house fabricated bulk glass and fibre samples. We apply the well-established rate equations approach to determine the level populations, the distribution of the photon intensity within the fibre and the output power levels. We compare the modelling results with experiment.

Keywords: Mid-infrared photonics, chalcogenide glass fibres, numerical modelling.

1. INTRODUCTION

Mid-infrared (MIR) light has many applications in medicine, pharmacy, security and environment monitoring. Many kinds of sources of MIR light have been developed. These include include quantum cascade lasers (QCLs), optical parametric oscillators (OPOs), difference frequency generation (DFG) sources, solid state, fibre lasers, gas lasers, solid state lasers, Globar© blackbody type and spontaneous emission fibre sources. Chalcogenide fibre based spontaneous emission fibre sources find gradually more and more applications in the sensor technology. So far dysprosium (III) and praseodymium (III) doped sulfide chalcogenide glass based sources have been used for gas and water pollutant sensing [1-3]. The chalcogenide glass based spontaneous emission sources are relatively easy to fabricate, have fairly robust structure and are potentially very reliable when pumped with laser diodes. In this contribution we explore the luminescence properties of selenide-chalcogenide glass fibres doped with praseodymium, dysprosium and terbium ions for potential application as MIR spontaneous emission sources for MIR light based sensors.

2. MODEL DESCRIPTION

For the level configurations presented in Fig.1-3 (assuming that $^3F_2$ and $^3H_6$ for Pr^{3+} shown in Fig.2 are thermally coupled) one obtains the following set of 3 algebraic equations:

$$\begin{bmatrix} 1 & 1 & 1 \\ 0 & a_{22} & a_{23} \\ a_{31} & 0 & a_{33} \end{bmatrix} * \begin{bmatrix} N_1 \\ N_2 \\ N_3 \end{bmatrix} = \begin{bmatrix} N \\ 0 \\ 0 \end{bmatrix} \tag{1}$$

where the coefficients a_{nn} are given by the following formulae:

$$a_{22} = -\left(\frac{1}{\tau_2} + \frac{1}{\tau_{21}^{mp}}\right); \quad a_{23} = \frac{\beta_{32}}{\tau_3} + \frac{1}{\tau_{32}^{mp}} \tag{2a}$$

$$a_{31} = \sigma_{13}^{a}\phi_p; \quad a_{33} = -\left(\sigma_{31}^{e}\phi_p + \frac{1}{\tau_3} + \frac{1}{\tau_{32}^{mp}}\right) \tag{2b}$$

and the values of the parameters, i.e. the branching ratio for the 3-2 level transition: β_{32}, level 3 and 2 life radiative times: τ_3, τ_2, and multiphonon transition lifetimes: τ_{21}^{mp} and τ_{32}^{mp} are given in Tables 1-3. The values of modelling parameters have been extracted from measurements carried out on in-house prepared chalcogenide glass samples. The assumed dopant concentration N is assumed to be equal to $0.93x10^{25}/m^3$. A series of experimental studies has demonstrated that such an ion concentration can be achieved in selenide chalcogenide glass without triggering any deleterious effects [4-11]. N_1, N_2 and N_3 stand for the populations of levels 1, 2 and 3, respectively (Fig.1, Fig.2 and Fig.3) while ϕ_p is the pump photon flux. The equations (1) can be solved analytically.

3. RESULTS

Figure 4 shows the dependence of level populations on the pump intensity for Tb^{3+} doped glass. The pump wavelength is selected near the maximum of the absorption cross section, which is attained approximately at 2.95 μm. This figure shows that in the case of Tb^{3+} a complete inversion of population is possible with sufficiently large pump intensity. When wavelength is detuned from the absorption cross section maximum the curves shift to the right (Fig.5), i.e. larger pump power is required to achieve a given level of the population inversion. Nonetheless, the complete inversion of population is still possible with sufficiently high pump power. In the case of Pr^{3+} and Dy^{3+} doped glass both level 3 and level 2 participate in MIR emission (Fig.6-Fig.9). Fig.6-Fig.9 show that the selection of the pump wavelength has much more significant impact on the level of the achievable population inversion than in the case of Tb^{3+} doped samples. Especially, in the case of Dy^{3+} sample pumped at 1.8 μm (Fig.9) only 0.2 N of all ions can be brought to level 3. In Fig. 10 we compare experimental and numerical results for the output power from a 5 cm long Pr^{3+} doped fibre with 200 μm diameter, which is pumped at 1.46 μm. In the experiment the fibre was pumped by a fibre coupled laser diode module whilst the MIR light was collected through a monochromator, set at the centre wavelength emission of 4.7 μm, using a calcium fluoride lens and a germanium filter, which is used to suppress the residual pump power. When calculating the power distribution along the fibre the equations 1 have to be complemented by the ordinary differential equation describing the pump power evolution within the fibre [12]. Numerical solution was obtained using a coupled solution method [13,14,15]. The rate equations for the relevant energy levels are given in [14]. A fairly good qualitative agreement between experimental and numerical results is observed.

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Table 1. Modelling parameters for Tb^{3+}.

Parameter	Unit	Value
β_{32}		0.088
τ_2	ms	13.1
τ_3	ms	5.9
τ_{32}^{mp}	μs	12
τ_{21}^{mp}	ms	42

Table 2. Modelling parameters for Pr^{3+}.

Parameter	Unit	Value
β_{32}		0.39
τ_2	ms	12
τ_3	ms	4
τ_{32}^{mp}	s	1.6
τ_{21}^{mp}	ms	70

Table 3. Modelling parameters for Dy^{3+}.

Parameter	Unit	Value
β_{32}		0.08
τ_2	ms	6.1
τ_3	ms	2.2
τ_{32}^{mp}	s	0.17
τ_{21}^{mp}	s	160.0

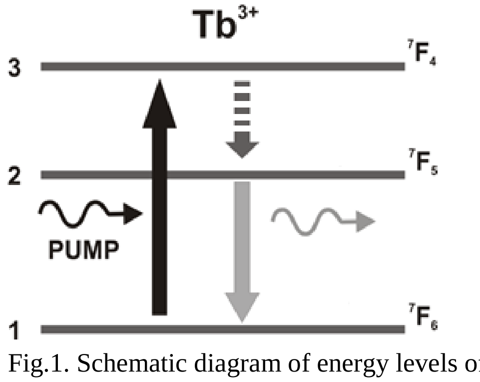

Fig.1. Schematic diagram of energy levels of Tb^{3+} pumped at approximately 3 μm.

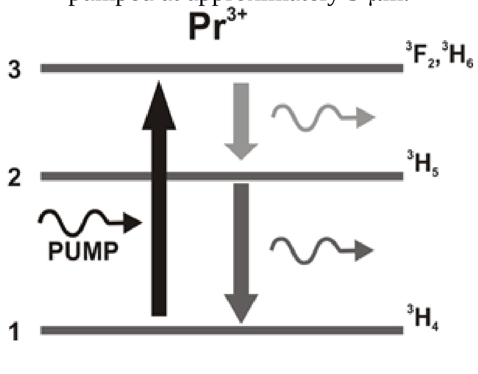

Fig.2. Schematic diagram of energy levels of Pr^{3+} pumped at approximately 2 μm.

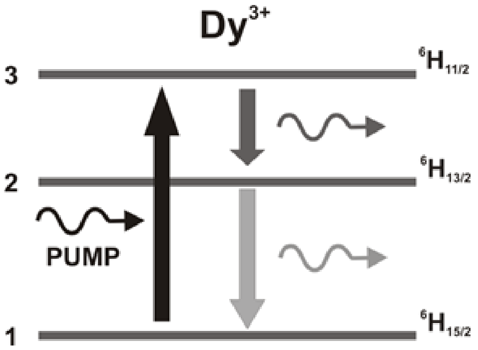

Fig.3. Schematic diagram of energy levels of Dy^{3+} pumped at approximately 1.7 μm.

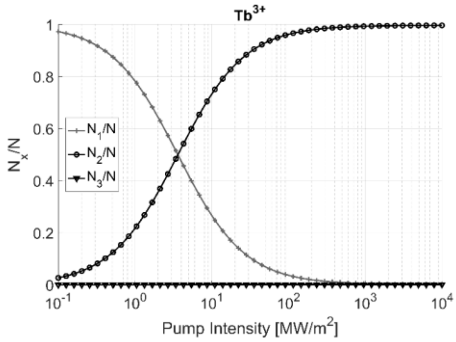

Fig.4. Dependence of level populations on the pump intensity for Tb^{3+} doped chalcogenide glass pumped at 3 μm.

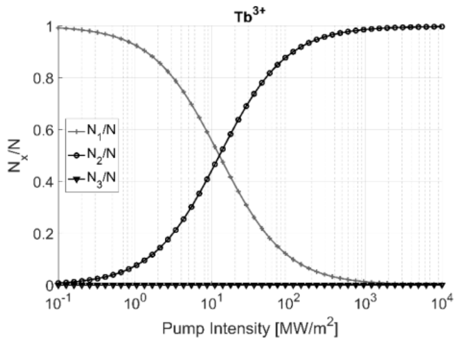

Fig.5. Dependence of level populations on the pump intensity for Tb^{3+} doped chalcogenide glass pumped at 2.8 μm.

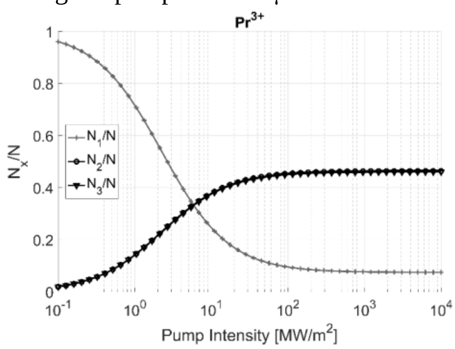

Fig.6. Dependence of level populations on the pump intensity for Pr^{3+} doped chalcogenide glass pumped at 2 μm.

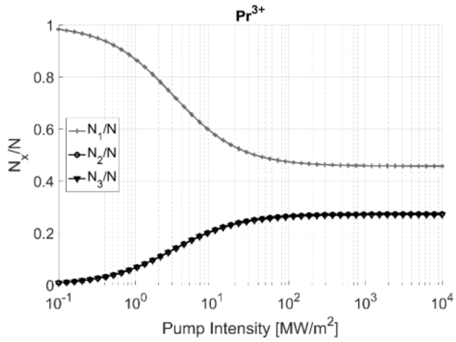

Fig.7. Dependence of level populations on the pump intensity for Pr^{3+} doped chalcogenide glass pumped at 2.2 μm.

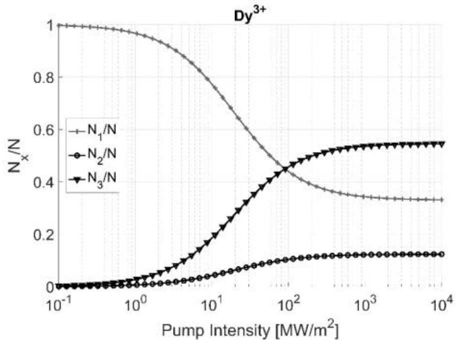

Fig.8. Dependence of level populations on the pump intensity for Dy^{3+} doped chalcogenide glass pumped at 1.7 μm.

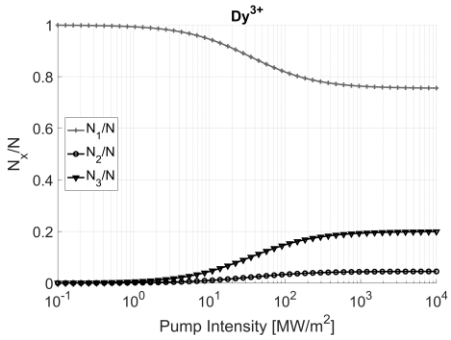

Fig.9. Dependence of level populations on the pump intensity for Dy^{3+} doped chalcogenide glass pumped at 1.8 μm.

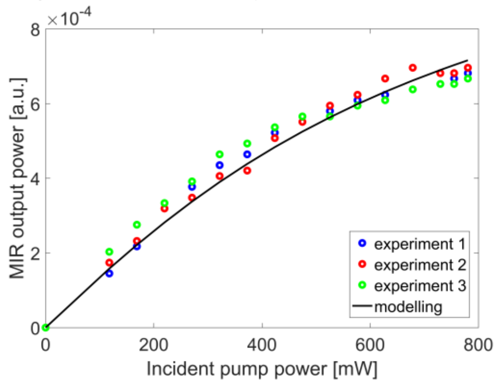

Fig.10. Dependence of MIR spontaneous emission output power on pump power for Pr^{3+} doped chalcogenide glass fibre pumped at 1.46 μm.

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