Modelling and Design of MIR Chalcogenide Glass Fibre Lasers (invited)

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***Abstract*—We discuss the modelling and design of mid-infrared fibre lasers for realisation in a chalcogenide glass host doped with lanthanide ions. Three lanthanide dopant ions are considered: terbium, dysprosium and praseodymium. The laser configuration exploits the advantages of a cascade lasing scheme, which allows for a reduction in both the side effects of the long lifetime of the lower lying state and heat generation within the laser structure.**

I. INTRODUCTION

Mid-infrared (MIR: 3 µm to 25 µm) coherent light sources find application in medicine, environment monitoring, pharmaceutical industry, etc. Currently available MIR lasers include quantum cascade lasers (QCLs), optical parametric oscillators (OPOs), difference frequency generation (DFG) sources, solid state, fibre and gas lasers. In this contribution we focus on MIR fibre laser modelling and design. The MIR fibre lasers potentially offer: good quality of the output beam, large wavelength tuning ability, pulsed operation, relatively large pumping efficiency and contained beam delivery.

Fibre lasers are well established in the visible and near-infrared (NIR) part of the optical spectrum. These sources rely on the classical three and four level pumping scheme and wavelength up-conversion for reaching the shorter wavelengths. As far as the host glass is concerned, silica fibres have dominated this application area due to their robustness. However, for reaching wavelengths significantly longer than 2 µm other host glass materials need to be applied. This is necessary due to the large phonon energy of silica glass. Wavelengths nearly up to 4 micrometres can be reached using a fluoride glass host. A holmium-doped fluoride glass fibre laser currently holds the record longest lasing wavelength of 3.9 µm [1] obtained with liquid nitrogen cooling. In order to reach wavelengths beyond 4 micrometres other glass hosts need to be considered. So far the most promising glass host for the realisation of longer wavelength MIR fibre lasers seems to be a chalcogenide glass. The low phonon energy of these glasses (can be down to 250 cm^{-1}) potentially allows the realisation of lasers that operate well beyond the 4 micrometre barrier of the fluoride glasses. Chalcogenide glass has been demonstrated independently by many research laboratories to effectively dissolve lanthanide ions [2, 3, 4]. Further, core-clad and micro-structured chalcogenide fibres with low losses at MIR wavelengths have been realised [5,6]. Finally, we have recently demonstrated core-clad lanthanide doped chalcogenide glass fibres [7].

Various lanthanide ions have been considered for the realisation of MIR fibre lasers [6,7]. The most promising candidates for realising a MIR fibre laser include: dysprosium, terbium and praseodymium. In this contribution we therefore concentrate on studying the properties of chalcogenide glass fibre lasers doped with these three lanthanide ions.

II. MIR FIBRE LASER MODELLING

Fig.1 shows a simplified energy diagram of: (a) dysprosium; (b) praseodymium and (c) terbium trivalent ions. The long lifetimes of the relevant levels, and the low rate of the non-radiative transitions, make it extremely difficult to realise an efficient fibre laser that would operate within the classical 3 or 4 level system [8,9]. Therefore, a cascade lasing system was proposed for the MIR fibre lasers [10].

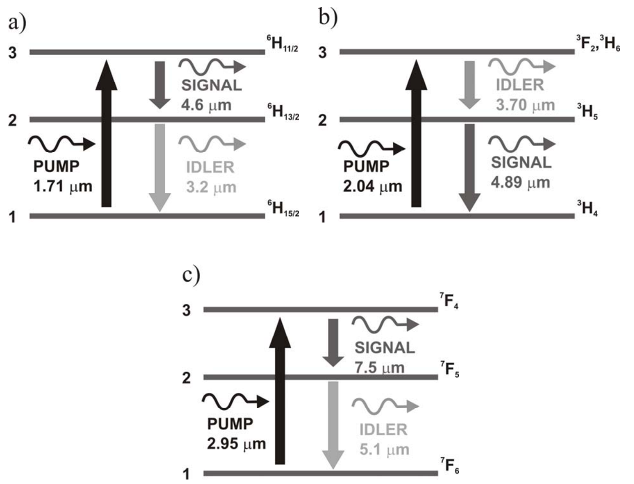

Fig. 1. Simplified energy level diagram for Dy^{3+} a), Pr^{3+} b) and Tb^{3+} c).

The cascade lasing system relies on trapping an idler wave within the laser cavity. The role of the idler is to provide an

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efficient depopulation mechanism. Additionally, relying on the idler, rather than on phonon-assisted transition, for the depopulation of the levels reduces the rate of heat generation within the device, which is a very important for low phonon energy (non-silica) glasses. The idler can be trapped using inscribed fibre gratings. However, it was also demonstrated that a sufficient depopulation rate can be readily achieved with simple Fresnel reflection from the fibre ends [11].

Apart from the difficulties in achieving the population inversion, there are several other challenges that need to be met before a long wavelength fibre laser can be realised. One of them is the purification of the precursors, including the lanthanide source, to eliminate contamination which increases the fibre attenuation. It is also important to consider that non-silica glasses tend to be mechanically less robust and more prone to optical damage (the current estimates of the optical damage threshold limit of the optical intensity is up to about 10 MW/m^2 for selenide chalcogenide glasses) than silica glass itself. Further, the availability of optical components for the relevant wavelengths is limited when compared with the visible and NIR wavelengths.

In order to study the potential of chalcogenide glass fibres for the realization of efficient MIR lasers we fabricated a series of GaAsGeSe chalcogenide glass fibreoptic preforms doped with dysprosium, praseodymium and terbium trivalent ions and from these drew fibre. We measured the absorption and photoluminescence both from bulk and fibre samples. From the experimental results we extracted the relevant radiative photoluminescence lifetimes using Judd-Ofelt theory and we used McCumber theory to extract consistently the emission and absoroption cross section spectra [4, 7, 8, 9, 11, 12]. Using the experimentally determined parameters we performed simulations of the fibre laser operation.

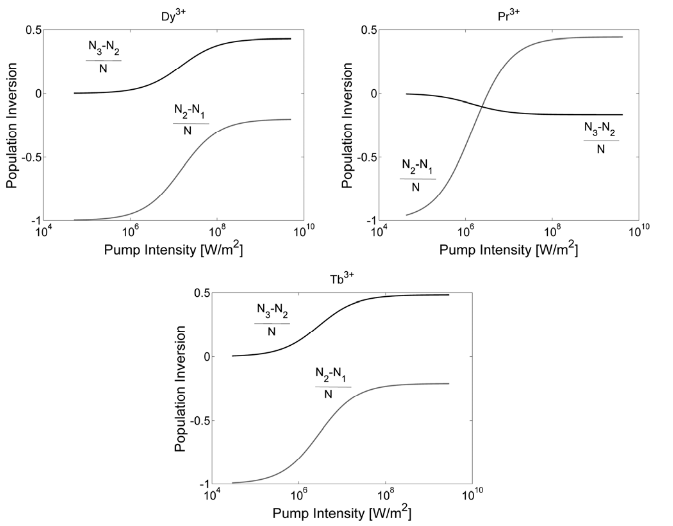

Fig. 2. Dependence of population inversion on the pump intensity for chalcogenide glass doped with trivalent dysprosium, praseodymium and terbium ions

Figure 2 shows the dependence of the population inversion for a chalcogenide glass doped with three trivalent ions: Dy^{3+}, Pr^{3+} and Tb^{3+}. A significant inversion of population for the signal wave is achieved with pump intensities lying between 1 and 10 MW/m^2. Praseodymium (III), due to its large pump absorption cross-section, is the dopant for which the population inversion can be achieved with the lowest incident pump intensity. Further simulations that were carried out using a full steady state lanthanide doped fibre laser model [8] show also that the praseodymium trivalent ion doped chalcogenide glass fibre lasers are also most tolerant to the intrinsic chalcogenide glass optical loss and light leakage through the mirrors.

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