Fibre Lasers Beyond 3 μm using PrYb:ZBLAN

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Abstract: We propose a new mid-infrared laser transition in praseodymium-doped ZBLAN fibre, diode pumped at 0.975 μm via ytterbium sensitiser, and identify optimal cavity designs through detailed spectroscopic measurements and numerical modelling.

OCIS codes: 060.3510 Lasers, fiber

1. Introduction

The past decade has seen significant progress in the development of mid-infrared (mid-IR) fibre laser technology, primarily based on holmium- and erbium-doped ZBLAN, resulting in up to 30 W all-fibre sources [1] and femtosecond mode-locked systems at ∼2.8 μm [2]. Demand exists, however, to push the laser wavelengths further into the mid-IR to open up new applications in medicine, sensing and manufacturing. Recent work has demonstrated lasing up to 3.3 μm in Dy:ZBLAN [3] and watt-level power from a 3.4 μm transition in Er:ZBLAN, although this requires complicated dual-wavelength pumping [4]. Here, we propose a new route to longer wavelengths using a previously unexplored transition in praseodymium (Pr), conveniently diode-pumped via co-doping with ytterbium (Yb) sensitizer. Building upon spectroscopic measurements, we develop a thorough numerical model demonstrating new opportunities for high-power lasing beyond 3 μm, which is guiding ongoing experimental work.

2. Spectroscopy and Numerical Methods

Our proposed $^1G_4 \rightarrow {}^3F_4$ transition in Pr (Fig. 1a) exhibits a broad emission cross section from ∼3.1 to 3.9 μm (Fig. 1b) and ∼70 μs upper state lifetime [5]. Close spacing of subsequent lower levels ensures fast de-excitation to the ground state by multiphonon relaxation (MPR). The absorption cross section to excite upper level $^1G_4$ is unfortunately weak (peak cross section at 1.01 μm $\sim 0.4\times10^{-25}$ m^2). By co-doping with Yb sensitizer, however, strong Yb excitation can be achieved based on high absorption at 0.975μm (cross section $\sim 10\times10^{-25}$ m^2) followed by an efficient energy transfer (ET) process Yb:$^2F_{5/2} \rightarrow$Pr:$^1G_4$, with only weak backwards ET—as previously demonstrated for 1.3 μm Pr fibre amplifiers which operate on $^1G_4 \rightarrow {}^3H_5$. We also measure the broad ground state absorption ($^3H_4 \rightarrow {}^3H_5$), noting undesirable overlap with the mid-IR laser transition of interest at longer wavelengths (Fig. 1b). To evaluate mid-IR PrYb laser designs, we develop a comprehensive numerical model including atomic population and optical power dynamics for all relevant transitions (including ASE and competing emission at 1 & 1.3 μm). Briefly, the power evolution $P(z)$ within each spectral channel λ is governed by:

$$\frac{\mathrm{d}P(\lambda,z)}{\mathrm{d}z} = \pm\left(P(\lambda,z)\left(\Gamma(\lambda)\left[\sum_{j,k}\sigma_{kj}(\lambda)N_k(z)-\sigma_{jk}(\lambda)N_j(z)\right]-l\right)+P_{\mathrm{spon}}\right) \tag{1}$$

where Γ is the core overlap factor, σ_{ij} is the $i \rightarrow j$ cross section, l is the background loss and spontaneous emission P_{spon} is included using the standard approach [6]. The level populations for all m levels $\mathbf{N} = [N_0, N_1 \dots N_m]$ are governed by rate equations, expressed in matrix notation:

$$\frac{\mathrm{d}\mathbf{N}}{\mathrm{d}t} = \begin{bmatrix} -\sum_{i=0}^{m} R_{0i} & \cdots & R_{m0} \\ \vdots & \ddots & \vdots \\ R_{0m} & \cdots & -\sum_{i=0}^{m} R_{mi} \end{bmatrix}\mathbf{N} + \begin{bmatrix} \sum_{\substack{i,j,k,l \\ k=0 \text{ or } l=0}} k_{ijkl}N_iN_j - \sum_{\substack{i,j,k,l \\ i=0 \text{ or } j=0}} k_{ijkl}N_iN_j \\ \vdots \\ \sum_{\substack{i,j,k,l \\ k=m \text{ or } l=m}} k_{ijkl}N_iN_j - \sum_{\substack{i,j,k,l \\ i=m \text{ or } j=m}} k_{ijkl}N_iN_j \end{bmatrix} \tag{2}$$

where the linear population change rate terms are:

$$R_{ij} = \underbrace{\beta_{ij}/\tau_i}_{\text{radiative relaxation}} + \underbrace{C(T)\exp(-\alpha\Delta E_{ij})}_{\text{nonradiative relaxation}} + \underbrace{\sum_{\lambda}\sigma_{ij}(\lambda)\frac{P(\lambda)\Gamma A_{\mathrm{eff}}}{hc/\lambda}}_{\text{stimulated abs. / emis.}} \tag{3}$$

and k_{ijkl} is the energy transfer coefficient for the interionic process: $i \rightarrow k$ & $j \rightarrow l$. Spectroscopic parameters (at room temperature) including branching ratios β, radiative lifetimes τ and multiphonon decay constants (C & α)

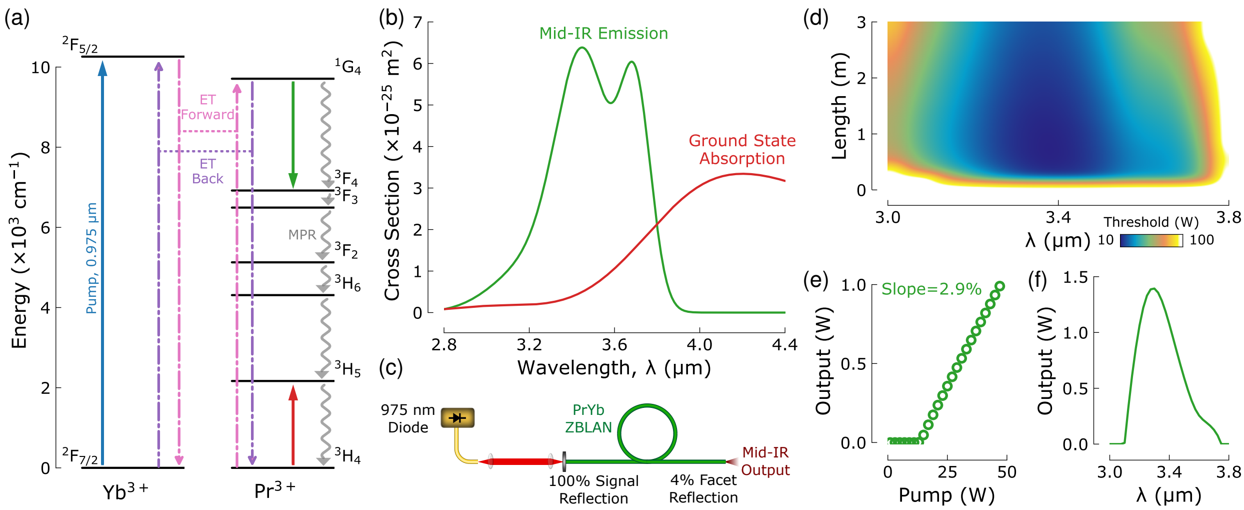

Fig. 1. (a) PrYb energy levels; (b) mid-IR cross sections; (c) cavity design; modelling results: (d) pump threshold variation with signal wavelength and fibre length; (e) 3.4 µm output power against pump for 0.5 m length; (f) variation of output power with wavelength for 50 W incident pump.

are obtained from direct measurement, Judd-Ofelt analysis or literature [5]. The system of equations is solved for the steady state $dn/dt = 0$ using a fourth-order collocation algorithm to identify a self-consistent evolution of power values along the fibre, subject to our chosen boundary conditions (i.e. cavity mirror reflectivity values).

3. Results and Discussion

A simple linear cavity is modelled (Fig. 1c) with Yb(1 mol%)Pr(1 mol%)-doped double-clad ZBLAN fiber (15 µm core diameter and 0.16 NA; single-mode cut-off ∼3.1 µm; 240 µm cladding diameter), which has recently been fabricated based on our spectroscopic measurements. An ensemble of simulations are run with varying lengths and signal wavelengths (as set by a narrowband 100% reflective cavity mirror (e.g. dichroic mirror or FBG) and 4% reflective planar cleaved fibre facet), revealing the lowest lasing thresholds are achieved around 3.4 µm, near the first peak in the emission cross section, with 0.5–1.0 m fibre length (Fig. 1d). A sharp increase in thresholds at longer wavelengths—despite the high emission cross section—highlights the deleterious effect of strong ground state absorption, which is unavoidable.

Even with this limitation, the pump thresholds we calculate are readily achievable from highly efficient commercially available diode lasers. Therefore, PrYb:ZBLAN fibres do offer a promising route to compact mid-IR sources beyond 3 µm with a single convenient pump wavelength. To demonstrate this, we consider a 0.5 m PrYb fibre laser operating at 3.4 µm: lasing is observed numerically at an incident pump threshold of 13 W with 2.9% slope efficiency (5 W threshold, 9.3% slope efficiency in terms of absorbed pump power) (Fig. 1e). For 50 W launched pump power, with varying mirror wavelength, the model suggests over 1 W CW output power could be generated over the range ∼3.2 to 3.45 µm (Fig. 1f), which importantly lies in the 3-5 µm atmospheric window and corresponds to high absorption in many plastics for advanced manufacturing applications.

4. Conclusion and Outlook

We proposed and numerically verified a route towards longer wavelength mid-IR fibre lasers using a previously unexplored Pr transition, conveniently pumped using a diode laser via Yb sensitizer co-doping. Detailed spectroscopic measurements and simulations have identified optimal cavity designs for watt-level emission over 3.2–3.45 µm. Our proposed fibre has been fabricated and experimental work is ongoing.

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