High-power "Watt-level" CW operation of diode-pumped 2.7 μm fiber lasers using efficient cross-relaxation and energy transfer mechanisms

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Abstract: We report the demonstration of high power (660 mW) CW operation of a diode-pumped mid-IR Er fiber laser. This was achieved by using efficient depopulation of the lower laser level via enhanced cross-relaxation between Er ions and energy transfer to Pr ions (at doping densities much higher than those used previously in Er:ZBLAN), along with optimal pumping of such lasers via custom-designed double-clad fluoride fibers.

OCIS codes: (140.3510) Fiber Lasers; (140.3480) Diode-Pumped Lasers; (060.2390) Infrared Fiber Optics; (140.3500) Erbium Lasers

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20. These results were submitted for presentation at the Conference for Lasers and Electro-Optics (CLEO) '99 as a postdeadline paper on 4/26/99 (paper #CPD23, CLEO '99, Baltimore, May 23-28, 1999).
21. This fiber was obtained from Thorlabs, Inc., NJ, USA.
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Because of the strong water absorption near 3 μm in tissue and the consequent ultrashort penetration depths (of a few microns), compact high power (100 mW to 1 W) 2.7 μm laser sources with TEM_{00} beam quality have several important applications in ultrafine intra-ocular and endoscopic laser surgery including transmyocardial revascularization and other intra-arterial procedures [1-7]. Compact and efficient sources of mid-IR radiation are also needed for infrared countermeasures applications, and for ppb (parts per billion) level spectroscopic monitoring [8] of several important species such as carbon monoxide (CO), formaldehyde (H_2CO), nitric oxide (NO), nitrogen dioxide (NO_2), hydrogen sulphide (H_2S), arsine (AsH_3), and phosphine (PH_3).

The 2.7 μm transition in Er:ZBLAN is well-suited for several of the above applications. For instance, the broad tunability [9] of this transition (2.65-2.83 μm) should enable ppb spectral monitoring of H_2S (2.65 μm) and NO (2.7 μm). However, as has been frequently stated, the longer natural lifetime of the lower laser level ($^4I_{13/2}$, 9.4 ms) relative to that of the upper laser level ($^4I_{11/2}$, 7.5 ms) of the 2.7 μm transition often results in a population bottleneck that inhibits efficient steady-state (CW) lasing in Er:ZBLAN fiber lasers [6,7,10-12]; as such this transition has been frequently called "self-terminating" [10,13]. We have previously demonstrated alleviation of this bottleneck and strongly enhanced efficiencies and output powers [7,14] by a simple technique, namely the use of fibers with high concentrations (>10,000 ppm) of Er. It was hypothesized that such high concentrations not only reduce the problem of ground state bleaching, but also cause significantly enhanced cross-relaxation via the formation of Er ion clusters [15], whose net effect is to relax the excitation from the lower laser level ($^4I_{13/2}$) to the ground state ($^4I_{15/2}$), while upconverting an adjacent ion to the $^4I_{9/2}$ state. A fringe benefit of the use of high Er doping densities is the natural amenability of the consequent high core absorption to optimized designs of double-clad fibers [16,17] capable of being pumped by relatively inexpensive high power diode arrays.

In this Letter, we demonstrate further improvements in the power and efficiency of CW lasing at the 2.7 μm transition in Er^{3+}:ZBLAN fiber lasers by utilizing a complementary technique [6,10,18,19] for enhancing the rate of depletion of the $^4I_{13/2}$ level of Er by energy transfer to the $^3F_3$ and the $^3F_4$ levels of Pr (see Fig. 1). In particular, we demonstrate 660 mW of CW output from a 791 nm diode array-pumped Er/Pr:ZBLAN rectangular-clad fiber laser with a slope efficiency of 13% with respect to the absorbed pump power [20]. The output power demonstrated here is nearly an order of magnitude higher than the highest powers previously reported [14] for a diode-pumped mid-IR fiber laser, and shows evidence of easy scalability to Watt power levels (by very simple improvements such as optimization of the Er-Pr concentrations, increase of the pump power and coupling efficiencies, and the use of optimized output coupling).

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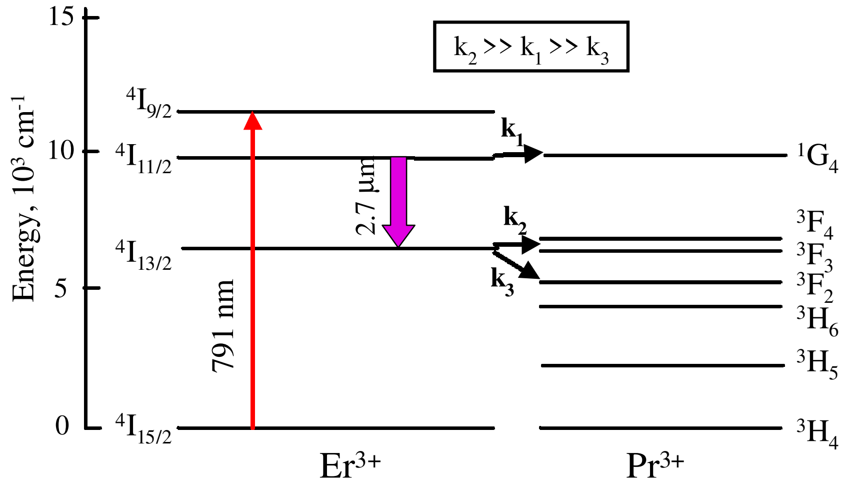

Figure 1. Dominant energy transfer pathways between laser levels in Er and resonantly-matched energy levels in Pr ($k_1 = 0.15\text{x}10^3\ s^{-1}$ and $k_2 = 0.93\text{x}10^3\ s^{-1}$ for our 20,000/5,000 ppm Er/Pr:ZBLAN fiber)

The fiber used in this work was a custom-designed rectangular-clad Er/Pr:ZBLAN fiber [21]. The rare-earth concentrations in the core (dia.=13 µm, NA=0.16) were chosen to be 20,000 ppm of Er and 5,000 ppm of Pr, based on the requirements of efficient absorption in Er and rapid depopulation of the lower laser level (via enhanced cross-relaxation in Er and efficient energy transfer to Pr). The lifetimes for the $^4I_{11/2}$ and the $^4I_{13/2}$ upper and lower laser levels were measured to be 2.5 ms and 0.7 ms respectively (corresponding to a lifetime ratio κ of 3.57) for this specific co-doped system versus lifetimes of 4 ms and 2 ms respectively ($\kappa = 2.0$) for a singly-doped 20,000 ppm Er:ZBLAN fiber, and 7.5 ms and 9.4 ms respectively ($\kappa = 0.8$) [22,23] for the traditional ≤1,000 ppm low concentration self-terminating 2.7 µm Er:ZBLAN laser. Further details on the criteria used for choosing such dopant concentrations are given below.

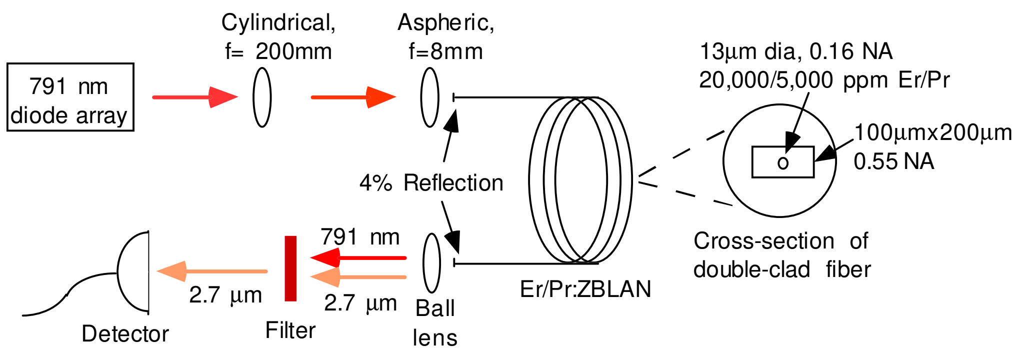

Figure 2. Schematic diagram of diode-pumped double-clad fiber laser

A schematic diagram of the diode-pumped fiber laser setup is illustrated in Fig. 2. In our work, we used an OptoPower 791 nm diode array capable of delivering 10 Watts as the pump source. The inner cladding dimensions and NA of the undoped cladding of the double-clad fiber were chosen to be (100µmx200µm) and 0.55 respectively to facilitate high coupling efficiencies for the diode beam (whose characteristics are 8 mm square size, 6.5 mrad divergence in the vertical plane and –13 mrad divergence in the horizontal plane) to be used, as well as to obtain significantly high effective absorption coefficients [16,17]. In order to match the diode array beam shape to the rectangular-clad fiber, we used a cylindrical lens of 20 cm focal length and rotated its axis with respect to the plane of the diode array, to compensate simultaneously for beam-shaping and astigmatism effects and thereby optimize the coupling. The net coupling efficiency and the effective pump (791 nm) absorption coefficient were measured to be 65% and 0.6 dB/m respectively. Given the measured value of the effective pump absorption coefficient and the estimated value of the background losses (0.1 dB/m) at the lasing transition, we chose a fiber length of 14 m for the present experiments; the value of the measured pump absorption for the fiber was ~85%.

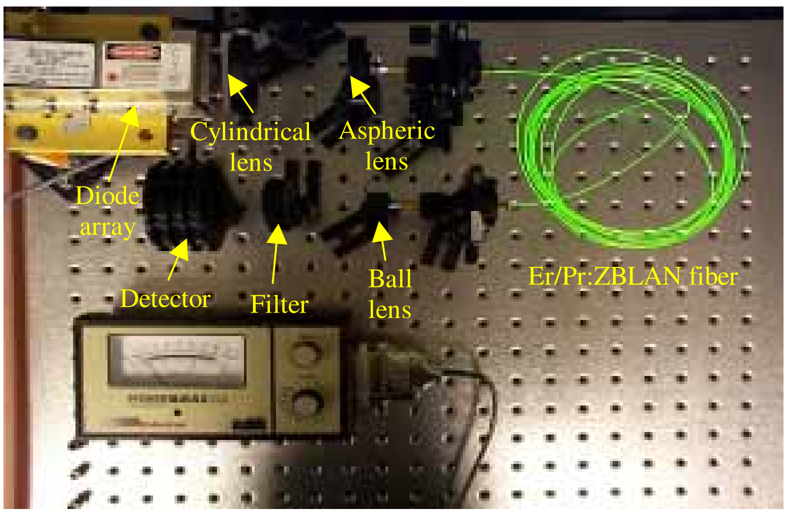

Figure 3. Photograph of the experimental setup shown schematically in Fig. 2

Fig. 3 shows a photograph of the experimental setup. Strong green (544 nm) fluorescence is observed when the diode radiation is coupled optimally to the fiber (and was used as a visual indicator to optimize coupling). As illustrated in Fig. 4, this fluorescence is caused by excited state absorption (ESA) [24] from the $^4I_{11/2}$ level to the $^4F_{5/2}$ level, followed by rapid non-radiative decay to the $^4S_{3/2}$ level and subsequent fluorescence from the $^4S_{3/2}$ level to the $^4I_{15/2}$ level. Despite its visual advantages (including facilitation of the optimization of coupling), this upconversion mechanism represents a detrimental pathway for depopulation of the upper laser level. As such, the choice of the 791 nm pump wavelength was made in part to reduce the detrimental effects of this ESA (the ESA cross-section at 791 nm is approximately 100 times weaker than that at the peak value at 808 nm). Even lower values of ESA from the $^4I_{11/2}$ level can be obtained by detuning the pump laser to shorter wavelengths, but at the expense of reduced ground state absorption and a reduction in the "beneficial" lower laser level ($^4I_{13/2}$) depleting ESA. Wavelength detuning of the order of 2-3 nm may be optimum for this case, and is well within the tuning range of the pump diode array. For a given power level, precise optimization is best done by detuning the pump wavelength for highest output powers.

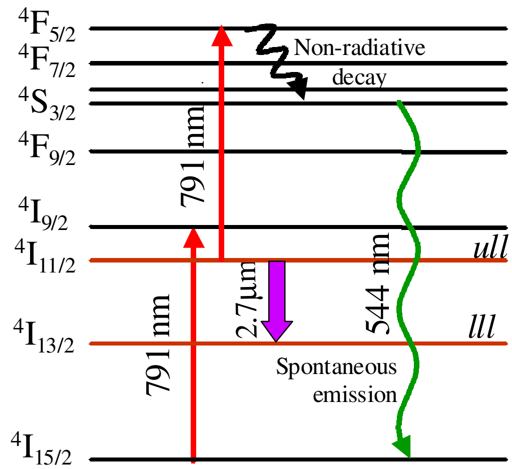

Figure 4. Role of the excited state absorption (of 791 nm) from the upper laser level ($^4I_{11/2}$) in generation of green (544 nm) upconversion fluorescence in the Er-doped fiber

Because of the availability of sufficiently high pump powers and gains, we were able to achieve lasing off the 4% Fresnel reflections from the two ends of the fiber. All the data reported here corresponds to this condition. Fig. 5 shows the 2.7 μm output power as a function of the absorbed 791 nm diode power. As seen from the above plot, the laser threshold is 330 mW and the slope efficiency is 13% with respect to the absorbed power. The linearity of the plot and the lack of any evidence of saturation at the high pump powers clearly indicates scalability to over 1 Watt power levels simply by using higher pump powers or more efficient pump coupling and pump absorption techniques.

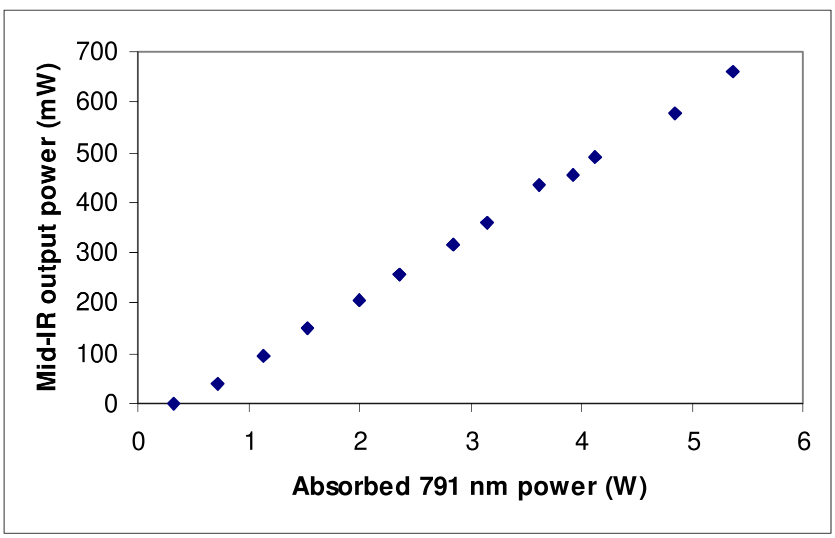

Figure 5. CW 2.7 μm output power vs. absorbed 791 nm pump power for our Er/Pr:ZBLAN fiber

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Given the round-trip losses in the cavity, the round-trip gain is estimated to be as high as 29.4 dB at the threshold pump power density of 1.65 kW/cm^2. The significantly lower threshold pump densities used, compared to the ≥100 kW/cm^2 reported by earlier workers [10-12], are attributed to the choice of a double-clad fiber. The relatively high slope efficiency achieved in our work compared to other non-cascade lasing schemes [10,12] is attributed to relatively efficient depopulation of the lower laser level. Further improvements in the threshold pump densities and slope efficiencies can be made by further optimization of the dopant concentrations, optimization of the output coupling efficiency, and reduction of intra-cavity losses (background absorption in the fiber at the lasing wavelength and scattering losses at the fiber ends).

In order to further optimize the Er and Pr concentration, we are currently developing a detailed model for calculating the gain in such co-doped glasses, based in part on our own spectroscopic and lifetime measurements for the $^4I_{11/2}$ and the $^4I_{13/2}$ levels as a function of dopant concentrations, particularly for ZBLAN fibers (since these values tend to be different from those reported in bulk glasses [23]). Critical issues related to development of such a model are the rates of diffusion-assisted energy transfer and cross-relaxation in the presence of high fractions of Er ions in clusters [15] and the rates of depletion (k_2, k_1) of the $^4I_{13/2}$ and $^4I_{11/2}$ levels as a function of Pr concentration [18,19]; as such, we will measure these quantities empirically for a parametric set of Er: and Er/Pr:ZBLAN fibers for the development of a reliable model.

In future work, we will also investigate power scaling of such sources by coherent array and beam-combining techniques. Additional work is also in progress on the demonstration of wavelength-tunable and pulsed (Q-switched, mode-locked and master-oscillator-pulsed power amplifier) high peak power sources based on such 2.7 μm fiber lasers; the latter should also enable the generation of longer mid-IR wavelengths relatively easily via efficient nonlinear optical (Raman/Difference Frequency Generation) techniques.

In summary, we report the first demonstration of high power (660 mW) CW operation of a diode-pumped mid-IR Er fiber laser. This was achieved by using efficient depopulation of the lower laser level via enhanced cross-relaxation between Er ions and energy transfer to Pr ions (at doping densities much higher than those used previously in Er:ZBLAN), along with optimal pumping of such lasers via custom-designed double-clad fluoride fibers. With optimized coupling optics, higher pump powers, and improved fiber design, >1 Watt power levels at 2.7 μm are anticipated in the near future.

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