High-efficiency watt-level mid-infrared fiber lasers beyond 3 μm using Dy:ZBLAN

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Abstract: We demonstrate an optimized in-band-pumped dysprosium fiber laser with 73% slope efficiency and 1.1 W output at 3.15 μm: the first watt-level fiber source in the 3.0–3.4 μm region and highest ever efficiency mid-IR fiber laser.

OCIS codes: (140.3510) Lasers, fiber; (140.3070) Infrared and far-infrared lasers; (140.5680) Rare earth and transition metal solid-state lasers.

1. Introduction

The mid-infrared spectral region offers many opportunities for new photonic technologies and applications, arising from strong fundamental absorption features in this region of many molecules important to healthcare, national security, and the environment. To exploit such opportunities, there is an urgent need for new compact, high-brightness mid-IR laser sources. Rare-earth-doped fluoride fibers have emerged as a particularly promising route to illuminating the mid-IR, bringing the well-established benefits of fiber laser technology to these challenging longer wavelengths.

To date, mid-IR fiber laser development has principally focused on erbium (Er) and holmium (Ho) ions (Fig. 1a), lasing in the ranges 2.6–3.0 μm and 3.3–3.8 μm (Fig. 1b summarizes high-power mid-IR fiber lasers to date, showing the maximum achieved efficiencies). While impressive high-average-power performance has been achieved, including up to 30 W output power at 2.94 μm [1], 5.6 W at 3.55 μm [2] (with dual-wavelength pumping [3]) and 50% slope efficiency [4], the intermediate wavelength region, spanning 3.0–3.3 μm, remains vastly under equipped by current mid-IR sources, despite prospects for important defense and manufacturing applications (e.g. polymer processing). This problem can be solved, however, by exploring alternative laser gain media, such as the relatively understudied lanthanide, dysprosium (Dy), which offers a broad emission cross section from 2.6 to 3.4 μm (for which we have recently demonstrated continuous tunability over 600 nm [5]) from the transition between the first excited manifold and the ground-state (Fig. 1e) [6]. Importantly, this transition can also be in-band pumped to minimize the quantum defect and enable higher slope efficiencies [7]. Despite the promising spectroscopic properties, reported Dy:fiber lasers to date have achieved a maximum output power of only 0.28 W (4.1% slope efficiency) [8] and the best slope efficiency is 51% (0.08 W maximum output) [7]; both demonstrations were also free-running around the Dy gain peak below 3 μm. Here, we report an optimized laser design using Dy:ZBLAN fiber to highlight the ion's excellent potential for high-power high-efficiency mid-IR sources beyond 3 μm.

2. Experimental Setup

A simple linear cavity (designed and optimized using rate equation modeling) is developed (Fig. 1d) using 1.2 m Dy:ZBLAN fiber (2000 ppm concentration) with 12.5 μm core diameter and 0.16 NA, pumped by an Er:ZBLAN fiber laser at the 2.83 μm peak of the dysprosium absorption cross section (Fig. 1c) [9]. Feedback is provided by a butt-coupled dichroic mirror at the input facet (highly transmissive for the pump, >99% reflective beyond 3 μm) and a bespoke FBG output coupler directly inscribed into the far end of the fiber using the core-scanned ultrafast laser direct write technique [10], centered at ∼3.15 μm with ∼60% reflectivity.

3. Results and Discussion

Lasing is observed at a pump threshold of 0.18 W, resulting in stable narrow-linewidth emission at 3.147 μm (Fig. 1f). The spectral bandwidth is measured to be <39 pm (1.2 GHz), limited by the resolution of our Fourier transform interferometer. With increasing pump power, the output power increases linearly (Fig. 1g), yielding a slope efficiency of 73% relative to launched power (77% relative to absorbed power), which is notably the highest efficiency from a

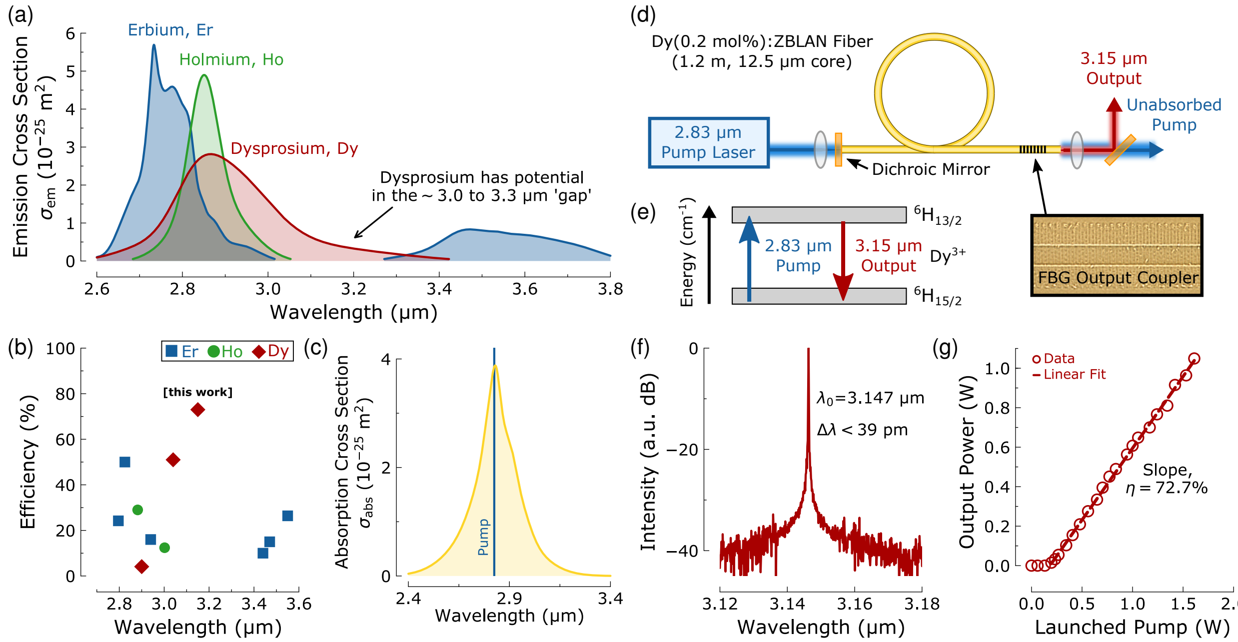

Fig. 1. (a) Emission cross sections for Er-, Ho- and Dy-doped ZBLAN; (b) maximum slope efficiencies for mid-IR fiber lasers to date (adapted from Ref. [9]); (c) Dy:ZBLAN absorption cross section; (d) cavity schematic; (e) Dy energy level diagram; (f) laser spectrum; (g) laser power characteristic.

mid-IR fiber laser to date. This value is still reduced compared to the theoretical Stokes-limited efficiency of 90%, which we attribute to fiber background loss (measured to be ∼0.3 dB/m at 3.39 μm). The strong linearity of the power curve also highlights an additional benefit of this in-band pumping scheme, which is the absence of excited-state absorption or deleterious energy transfer mechanisms which have limited the performance of dysprosium lasers pumped at shorter wavelengths [5, 8]. The maximum power of 1.1 W represents the first watt-level fiber source in the 3.0–3.3 μm region, and is limited only by the onset of thermomechanical instabilities in our setup; replacing the input butt-coupled mirror with an additional FBG to fully fiber integrate the design is expected to improve stability and lead to multi-watt output powers. This is a topic of ongoing work.

4. Conclusion

By taking advantage of the unique spectroscopic features of dysprosium-doped fluoride glass, watt-level coherent light has been generated from a fiber laser in the 3.0–3.3 μm region for the first time with record efficiency. This highlights the potential of dysprosium for high-power high-efficiency mid-IR lasers and further power-scaling work is ongoing.

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