Development of High-Brightness Mid-IR Fiber Sources

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Abstract: We review the recent advances in fluoride fiber lasers operating around 2.8 µm and at longer wavelengths, in both CW and pulsed regimes.

1. Introduction

There is currently a strong incentive to develop high-power fiber lasers operating in the mid-infrared. Fiber lasers offer several advantages over other laser technologies resulting from their compactness, high efficiency and high brightness due to an unmatched beam quality. Several promising applications in the medical and material processing fields would benefit from bright mid-IR laser radiation. Most of them are based on the interaction with various molecular resonances, such as OH (at 2.8 µm) and CH (3.4 µm) symmetric stretches. At this time, however, additional research is needed to improve the long-term reliability of mid-IR fiber sources and to meet the applications requirements in terms of both average power and pulse energy.

Mid-infrared fiber sources are mostly based on rare-earth-doped fluoride fibers, such as zirconium fluoride glass, which presents a broad transmission window up from the UV to about 4.2 µm and has an excellent rare-earth solubility. Nowadays, fluoride fibers with background losses near the dB/km level are becoming commercially available and fluoride-based passive components, such as single-mode splices, protective endcaps, fiber Bragg gratings (FBGs), pump combiners, are also starting to emerge. This has led to a substantial improvement in the performances of mid-IR fiber sources, especially at wavelengths near 2.8 µm using erbium-doped fluoride fibers. Figure 1 shows the output average power and pulse energy achieved with different rare-earth ions (Er, Dy and Ho) in the 2.8 - 4 µm spectral range. The overall decreasing trend of the performances with respect to wavelength is a result of both the decreasing lifetimes (related to multi-phonon decay) and the growing quantum defect between the emission wavelength and the near-infrared pump sources, which significantly affect the conversion efficiency.

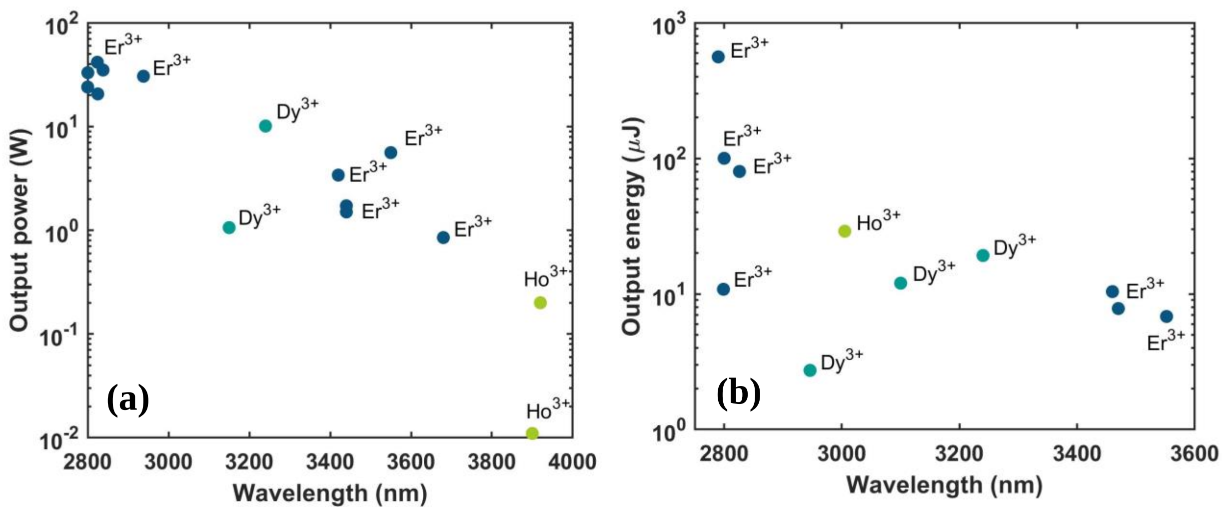

Fig. 1. Output (a) average power and (b) pulse energy as a function of wavelength for a selection of mid-IR fiber laser demonstrations.

2. Er-doped fiber lasers around 2.8 µm

Mid-IR fiber lasers based on the erbium transition $^4I_{11/2} \rightarrow {}^4I_{13/2}$ are clearly the most mature technology among the fluoride glass fiber sources. While erbium's laser emission is typically centered around 2.8 µm, it was reported to support laser operation on a 300 nm wavelength range, i.e. from 2.7 µm to 3.01 µm. Such sources are pumped around 980 nm, and therefore benefit from widely available high-power diodes at this wavelength.

In the CW regime, erbium-doped fluoride fiber lasers have recently broken the 40 W barrier [1]. In this demonstration, the FBG-based laser cavity was bidirectionally pumped at 980 nm to reduce the heat load on the doped fiber. The generation of such high power level also relied on the development of protective endcaps made of various optical materials [2]. In fact, fiber tip photodegradation caused by OH diffusion is one of the main hurdles that limits the long-term reliability of fluoride fiber lasers near 2.8 µm.

Several demonstrations of pulsed erbium-doped laser cavities at 2.8 µm were also reported recently. To date, more than 500 µJ have been achieved from Q-switched laser cavities [3] and about 100 µJ from gain-switching [4]. Gain-switched erbium-doped cavities, which use a modulated pump at 980 nm, benefit from an increased robustness since they can be packaged in an all-fiber configuration without any free-space optical component (e.g. acousto optic modulators, lenses, isolators, etc.). Ultrafast oscillators producing pulses of a few hundred fs with about 3.5 kW of peak power have also been reported [5].

3. Fiber lasers emitting beyond 3 µm

In the last few years, many other rare-earth dopants have been studied to produce a laser emission at longer wavelengths between 3 and 4 µm. Dy-doped fiber lasers, which can be efficiently pumped in-band at 2.8 um, can now deliver more than 10 W at 3.24 µm in the continuous wave regime [6]. Nanosecond pulses with energies exceeding 10 µJ were also demonstrated in the Q-switching [7] and gain-switching regimes [8].

Several laser systems were also developed based on the second mid-IR transition of the Er^{3+} ion ($^4F_{9/2} \rightarrow {}^4I_{9/2}$), which spans from about 3.4 to 3.7 µm. While the first lasing experiment was performed in the early 90's, there has been a renewed interest for this transition since an efficient dual wavelength pump scheme was introduced (i.e. by co-pumping at 980 nm and 2 µm) [9]. Based on this new approach, more than 5 W of average power [10] and pulses with ~10 µJ have been reported around 3.5 µm [11].

With the recent availability of low loss indium fluoride fibers providing an extended transmission up to 5 µm, even longer operating wavelength can be achieved. In a recent demonstration involving a heavily holmium-doped fluoroindate fiber, a record 200 mW output power was produced at 3.92 µm [12]. This is currently the longest wavelength ever generated by a fiber laser at room temperature.

4. Conclusion

Fiber lasers have recently made significant progress in the 2.8 - 4 µm spectral region, and are expected to address a wide range of mid-IR applications. Several studies are underway to further improve their average power, pulse energy as well as their overall features including compactness, ruggedness and long-term operation.

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