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Mid-infrared technologies and opportunities using dysprosium-doped fluoride fiber

(Invited Paper)

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***Abstract*—The mid-infrared (mid-IR) spectral region holds many opportunities for new optical technologies and potentially transformative applications in medicine, manufacturing and defence. To date, however, such applications have been held back by a lack of high-brightness coherent light sources at mid-IR wavelengths with sufficient flexibility and robustness for practical deployment. Rare-earth-doped fluoride fibers are currently emerging as a promising and highly versatile platform for mid-IR laser technology and in the past few years, there has been particularly strong progress using the dysprosium ion, which offers broadband emission from ∼2.7–3.5 µm and even has potential to enable a new class of 4-µm fiber lasers. In this presentation, we review the spectroscopy of dysprosium-doped fluoride fibers and present recent developments of compact, high-power, broadly tunable mid-IR sources, in addition to offering an outlook towards further developments and practical applications.**

***Index Terms*—mid-infrared, fiber, laser, dysprosium**

I. Introduction

The mid-infrared (mid-IR) region of the electromagnetic spectrum (∼2.5–30 µm) contains a number of important features which offer new opportunities for optical applications, including: absorption signatures of many molecules that can be used for sensing in defence, research and healthcare environments; atmospheric transmission windows at ∼3–5 and 7–14 µm for low-loss free-space communication; and absorption resonances of important technical materials (e.g. polymers) that can be targeted for improved micro-machining processes [1]. To practically enable these applications, an urgent need exists for new compact, high-brightness mid-IR laser sources. Rare-earth-doped fluoride fibers are currently showing promise as an approach to illuminate the mid-IR, bringing the benefits of fiber laser technology to these longer wavelengths. Mid-IR fiber laser research to date has focused principally 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 powers and efficiencies). Impressive performance has been achieved, including up to 30 W output power at 2.94 µm [2], 5.6 W at 3.55 µm [3] (with dual-wavelength pumping [4]) and the generation of mode-locked pulses around 2.8 µm [5], [6], with durations as short as 70 fs (7 optical cycles) [7]. However, it remains an open question how to generate light at important wavelengths in

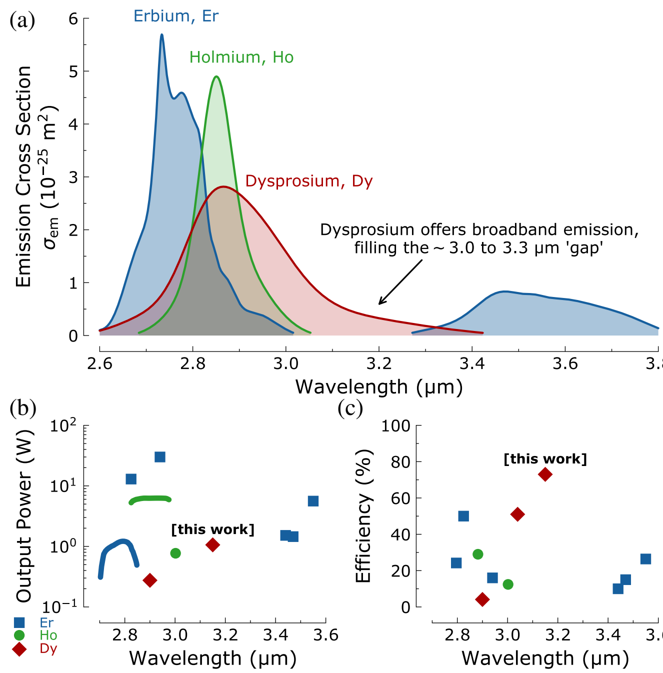

Fig. 1. State-of-the-art mid-IR fiber lasers: (a) emission cross-sections for Er-, Ho- and Dy-doped ZBLAN; (b) maximum reported output powers and slope efficiencies.

the intermediate wavelength region, spanning 3.0–3.3 µm, and beyond ∼3.8 µm, where Er and Ho are spectroscopically limited. This problem can be solved, however, by exploring alternative laser gain media.

Dysprosium (Dy) is a relatively understudied rare-earth ion offering a broad emission cross section for the transition from the first excited state to the ground state, extending from less than 2.6 µm to beyond 3.4 µm [8]. Early work used sources at 1.1 µm [9] and 1.3 µm [10] to pump Dy:ZBLAN fiber, although the maximum reported output power was 0.28 W (4% slope efficiency) [9], partly limited by strong pump excited state absorption (ESA) (Fig. 2). The lasers also operated free-running around the Dy gain peak below 3 µm. In recent years, however, we have re-investigated dysprosium fiber using new pump schemes and laser designs, as discussed in this presentation, yielding record performance and showcasing the potential of dysprosium for mid-IR laser technology.

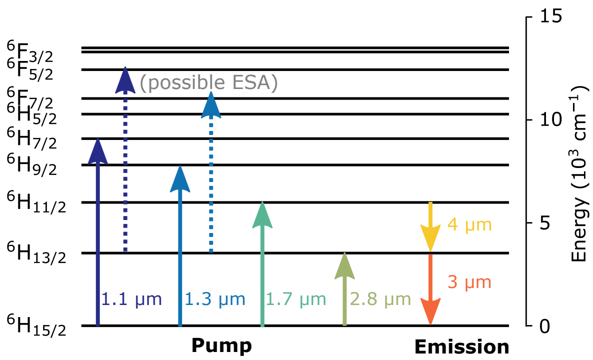

Fig. 2. Energy level diagram for dysprosium, showing possible pump and emission transitions with their corresponding approximate wavelengths (dotted lines indicate possible excited state absorption (ESA) transitions).

II. High-Efficiency Watt-Level Sources Beyond 3 µm Using Dy:ZBLAN Fiber

To achieve high output power and efficiency, we note that the 3 µm Dy transition can be in-band pumped (i.e. to minimize the quantum defect) at 2.8 µm (e.g. using an Er:ZBLAN laser), which also avoids deleterious ESA transitions [11]. Additionally, for emission at a particular wavelength in the broad Dy emission bandwidth, narrowband feedback is required: for example, using a fiber Bragg grating (FBG). While FBGs are ideal for this purpose, they are not yet commercially available in fluoride fiber and would typically require fabrication using a costly phase mask technique [12]. To overcome this limitation, we employed femtosecond laser inscription to directly write a refractive index modification pattern into the Dy:fiber core (method described in [13]), forming an output coupler with ∼60% reflectivity. The other end of the fiber was butt-coupled to a dichroic mirror that transmitted the pump, but exhibited broadband reflectivity beyond 2.9 µm.

This simple linear laser cavity delivered excellent performance (Fig. 3): above the 0.18 W threshold, stable narrow-linewidth emission at 3.15 µm was achieved. The slope efficiency was recorded as 73% relative to launched power (77% relative to absorbed power), which is notably the highest efficiency from any mid-IR fiber laser. This value is below the maximum possible Stokes-limited efficiency of 90%, however, which is believed to relate to the fiber background loss (measured as ∼0.4 dB/m), thus ongoing improvements to ZBLAN fiber fabrication are expected to lead to even higher slope efficiencies by reducing background attenuation. A maximum output power of 1.1 W was achieved (limited by thermal damage to the fiber tip), representing the first watt-level fiber source in the 3.0–3.3 µm region [14].

III. Broadly Tunable Dy:ZBLAN Sources for Mid-IR Spectroscopy

While pumping at 2.8 µm can enable optimal efficiencies, in-band pumping intrinsically limits the output tuning range. Therefore, to assess the potential of Dy:ZBLAN for developing widely tunable sources for spectroscopy, we employed a

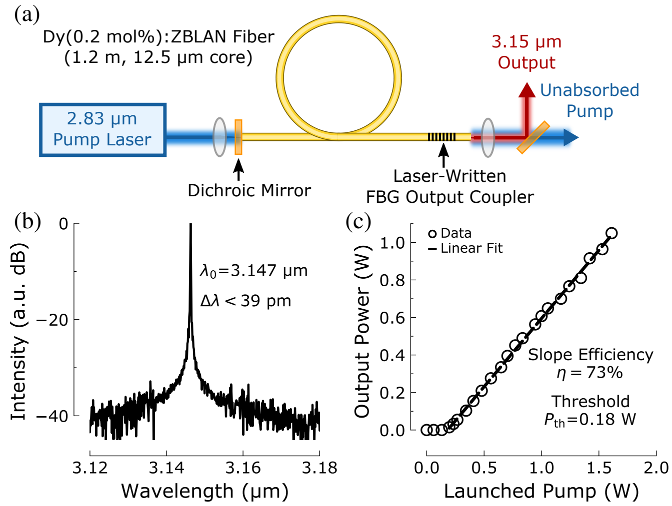

Fig. 3. Watt-level Dy:ZBLAN fiber laser: (a) setup; (b) optical spectrum; (c) power characteristic. Adapted from [14].

1.7 µm Raman fiber laser as the pump source and replaced the fixed FBG component with an external cavity including a diffraction grating in Littrow configuration (thus enabling wavelength tuning by grating rotation) (Fig. 4a).

With a maximum pump power of 1.6 W (limited by our pump laser), extremely broadband tuning was achieved from ∼2.8 to 3.4 µm, spanning a range of nearly 600 nm [15]. This represents the widest tuning range achieved to date from any rare-earth doped fiber laser. Importantly, this range covers absorption features of OH, NH and CH functional groups, thus future work will apply this source for spectroscopic and sensing applications. Using the 1.7 µm pump arrangement, up to 0.17 W output power was produced with 21% slope efficiency.

We note, however, that the measured slope efficiency is lower than expected (even when accounting for background loss), compared to numerical modeling using rate equations. This suggests there may be pump ESA from the $^6H_{13/2}$ level to the nearly resonant $^6H_{7/2}$ level, which is also supported by a recent observation of 1.7 µm ESA in a study of Dy-doped PGS crystals [16]. Preliminary modeling including this effect suggests the ESA cross section to be on the order of 1×10^{-25} m^2, although further work is required to verify this and to measure the exact shape of the ESA profile, leading to an improved understanding of the relative merits of 1.7 µm as a Dy pump wavelength.

IV. Opportunities Beyond 4 µm Using Dy:InF_3 Fiber

Mid-IR fiber laser technology to date has employed ZBLAN fibers (with ZrF_4 as the principal glass former), which offer a transparency window up to ∼4 µm and a phonon energy of ∼600 cm^{-1} (significantly improving upon silica fiber with transparency only up to ∼2.4 µm and a large 1100 cm^{-1} phonon energy) [17]. ZBLAN glass therefore represents a distinct limitation to further wavelength scaling. While promising spectroscopic results have been published

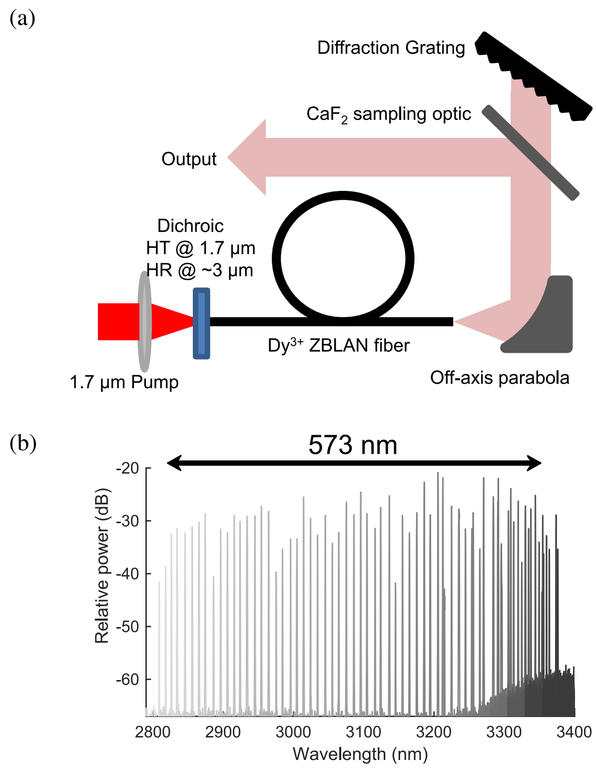

Fig. 4. Widely tunable Dy:fiber laser pumped at 1.7 µm: (a) setup; (b) output spectra (tuned by rotating diffraction gratings). Adapted from [15].

using doped chalcogenide glasses (transparent to >8 µm), mid-IR chalcogenide fiber action has yet to be demonstrated due to the high loss of the fibers and impurity multiphonon relaxation [18]. Therefore, it is preferable to explore other fluoride-based glasses.

By replacing ZrF_4 with InF_3 as the principal glass former, indium fluoride (InF_3) glass is produced, which increases the transparency window to ∼5 µm and lowers the phonon energy to ∼509 µm [19]. Fig. 5a shows the measured attenuation of step-index ZBLAN and InF_3 fibers (fabricated by Le Verre Fluoré [20], [21]), demonstrating the InF_3 advantage.

Using ZBLAN fiber, the longest wavelength room-temperature fiber laser to date is ∼3.8 µm [22]. To achieve longer wavelength emission (e.g. at ∼3.9 µm [23]), it was found that cryogenic cooling was required, to reduce the impact of multiphonon relaxation. However, by using an InF_3 fiber, the lower phonon energy and lower loss offer the exciting opportunity of breaking the 4 µm barrier for CW room-temperature laser action.

Dysprosium is an ideal rare-earth dopant for achieving this goal using the ${}^6H_{11/2} \rightarrow {}^6H_{13/2}$ transition, pumped at 1.7 µm [24]. We measured the emission cross-section of this transition by pumping a short length of 2000 ppm Dy:InF_3 fiber and processing the measured fluorescence (detected using a PbSe photoconductive detector connected to a lock-in amplifier) using the Füchtbauer-Ladenburg equation [25]. Broad emission from ∼4.1–4.5 µm was observed, shown in Fig. 5b (the dip at 4.3 µm can be attributed to atmospheric CO_2). Further evidence of the advantage of using InF_3 fiber over ZBLAN fiber was demonstrated by measuring the upper state lifetime for the 3 µm transition in both fibers (since the 4 µm transition could not be observed in ZBLAN): the lifetime in InF_3 was found to be ∼30% longer [25], which is explained by the reduced phonon energy of InF_3. These results demonstrate the promise of doped InF_3 fibers for pushing mid-IR fiber laser technology beyond the historic 4 µm wavelength barrier.

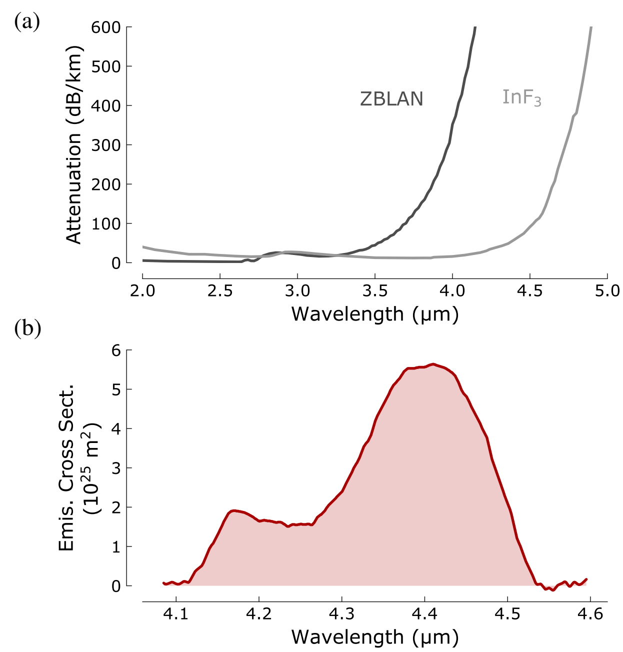

Fig. 5. (a) Comparison of attenuation in passive ZBLAN and InF_3 fluoride fibers. (b) Measured emission cross section (${}^6H_{11/2} \rightarrow {}^6H_{13/2}$) beyond 4 µm in Dy:$InF_3$ with 1.7 µm pumping. Adapted from [25].

V. Outlook

We have shown that dysprosium-doped fluoride fiber technology holds great potential for the development of future mid-IR sources. The 3 µm transition lies between the first excited state and ground state, permitting simple in-band pumping for high-efficiency, in addition to broadband tuning over the absorption features of numerous important functional groups. Our maximum power of 1.1 W was limited by damage to the input fiber facet, which was butt-coupled to a dichroic mirror and hence formed a critical interface in the system. It has recently been shown that moving the mirrors inside the fiber (i.e. replacing the dichroic mirror with a second FBG) can alleviate this problem [3], thus we believe there are excellent opportunities for further power scaling Dy:fiber lasers to the multi-watt level. Additionally, with ongoing improvements to the fluoride fiber fabrication process, the background loss is expected to reduce, leading to even higher efficiencies than the 73% value achieved here.

Dysprosium also offers the exciting opportunity to create a new class of 4 µm fiber laser technology, using lower-phonon-energy indium fluoride glass in place of conventional ZBLAN glass. Our measurements here represent the first observation of fluorescence beyond 4 μm in any fluoride glass, permitting new modeling work to design appropriate cavities for high-power 4 μm lasing and ultimately, experimental demonstrations.

Finally, dysprosium also offers many opportunities for mid-IR pulse generation through mode-locking. The gain bandwidth significantly exceeds that of Er- and Ho-doped fibers, offering reduced transform-limited pulse durations and opportunities for novel dispersion engineered mode-locked operating regimes that can exploit the large bandwidth for high-energy ultrashort pulse generation (e.g. similaritons) [26]. Such long-wavelength pulse sources would be ideal for pumping octave-spanning mid-IR supercontinua [27], [28], enabling new applications such as molecular fingerprinting and optical biopsy [29] and suitable for practical deployment in resource-limited environments due to the compact, robust nature of fiber-based systems.

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