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Near infrared pumped full gain bandwidth tunable 3 micron dysprosium fiber laser

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ABSTRACT

Previously reported progress in 3 micron dysprosium doped ZBLAN fiber lasers achieved record conversion efficiency but was limited in tuneability due to the inband nature of the pumping scheme. Near infrared pumping has also been demonstrated but was limited in conversion efficiency due both to pump excited state absorption and large quantum defect. We address these limitations by employing a Raman fiber laser operating at 1700 nm as a pump source. Reduced quantum defect shows promise for efficiency gains while maintaining near infrared pumping and the increased gain bandwidth shows promise for pulsed operation.

Keywords: Fiber lasers, mid-infrared, dysprosium, tunable lasers

1. INTRODUCTION

Sources of tunable coherent mid-infrared (mid-IR) light find increasing application in spectroscopy and sensing due to the strong characteristic absorption features of many key functional groups in this spectral region. While mid-IR supercontinuum sources and frequency combs have recently made substantial progress[1–3] they currently remain quite limited in spectral brightness. For applications requiring higher power, directly tunable fluoride fiber mid-IR lasers offer a potential solution. Systems based on both holmium, and two different transitions of erbium, have demonstrated continuously tunable mid-IR laser emission.[4–6] However, as we see from the relevant transition emission cross sections in Fig. 1, there is a large portion of this spectral region which can only be accessed directly by dysprosium-based laser sources.

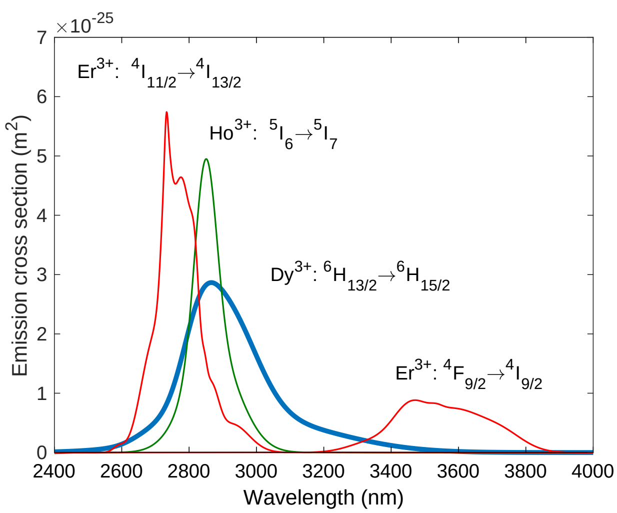

Figure 1. Emission cross sections in ZBLAN of the various mid-IR emitting rare-earth ions

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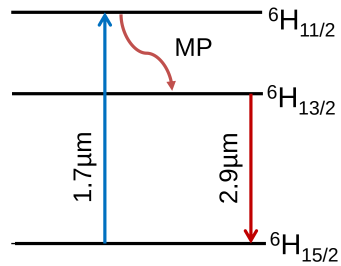

Figure 2. Simplified energy level diagram of Dy^{3+}:ZBLAN indicating pump transition, multiphonon (MP) relaxation, and 3 micron lasing transition

Previous demonstration of a tunable mid-IR dysprosium ZBLAN fiber laser successfully covered a portion of this spectral region with 400 nm of tunability, but was limited in total tuning range due to the inband pumping scheme used.[7] We demonstrate here a novel near-IR pumping scheme utlizing a 1.7 µm Raman fiber laser which allows for access to the full gain bandwidth of the dysprosium 3 micron transition.

2. EXPERIMENT

The experimental setup used for the dysprosium-doped tunable ZBLAN fiber laser is shown in Fig. 3. Due to the relative lack of commerically available high-brightness sources at 1.7 µm, we rely on a in-house constructed Raman fiber laser (RFL) to generate the required pump radiation. Though not shown explicitly in Fig. 3, the RFL consisted simply of a diode pumped Er/Yb co-doped fiber (Nufern) with emission centered around 1570 nm, coupled into 6 km of standard single-mode telecommunications fiber (SMF28). The Raman laser cavity was closed by fiber Bragg grating (FBG) mirrors of 100% and 10% reflectivity spliced to the input and output ends respectively. This arrangement produced narrow linewidth output with power up to 1.6 W.

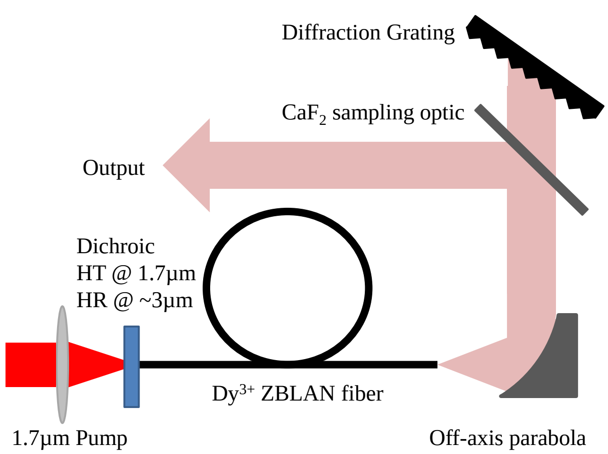

Figure 3. Laboratory schematic diagram of the tunable dysprosium fiber laser

The particular doped ZBLAN fiber used for this work (Le Verre Fluoré) had a Dy^{3+} concentration of 2000 ppm (3.63×10^{25} m^{-3}), a core diameter of 12 µm, a numerical aperture of 0.16, and a single mode cutoff wavelength of 2.6 µm. Pump light is coupled into the fiber with a matched pair of f = 25 mm aspheric lenses, with nominally 85% of incident power coupled into the fundamental mode. A dichroic mirror transmissive at the pump wavelength and broadband reflective around 3 µm is butt-coupled to the fiber input end and serves as the primary cavity mirror. Light at the output end of the fiber is collimated with a gold coated off-axis parabolic reflector (OAP), and cavity retro-reflection is provided by a ruled diffraction grating in the Littrow configuration, the angle of which defines the lasing wavelength. The OAP was chosen over a refractive element to maintain focal position over the broad tuning range. To sample laser output, a CaF_2 uncoated window is placed between the OAP and the diffraction grating at 45 degrees.

3. RESULTS

We first investigate the tuning limits of the dysprosium fiber laser using the maximum available pump power of 1.6 W. To minimize the potential impact of weakly pumped sections of fiber, we choose an active fiber length of 60 cm, which results in 95% absorption of injected pump power. As the angle of diffraction grating is adjusted, the optical spectrum of the sampled output is recorded. The accumulated optical spectra over the achievable tuning range are presented in Fig. 4. Narrow linewidth laser emission is observed over a continuous range from 2.807 to 3.380 µm; a range of nearly 600 nm. The spectral range of emission from this system is currently the

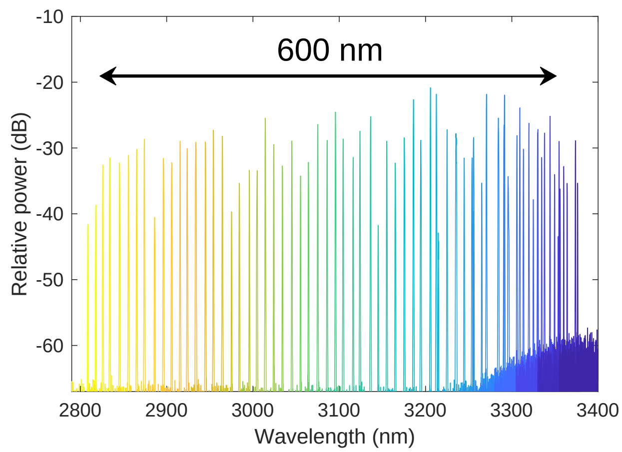

Figure 4. Measured optical spectra of laser emission over the achievable tuning range

widest of any rare-earth doped laser yet demonstrated, and also represent a substantial 150 nm increase over the previous record.[6] It is also of note that laser emission is achieved well beyond 3.2 µm, in a region where we see from Fig. 1 that the magnitude of emission cross sections are quite small. This would suggest that further infrared tuning may be possible with increased length of active fiber. However, it is found that any substantial increase in fiber length results in oscillation threshold beyond our available pump power.

Previous demonstration of a tunable dysprosium fiber laser[7] did not achieve emission below 2.95 µm due to the limitation imposed by the inband pumping scheme used. Utilizing a near infrared pump wavelength of 1.7 µm here allows for complete access to the gain bandwidth and directly results in a 150 nm increase in tuning range to the short wavelength side. The short wavelength tuning limit is predominantly determined by signal re-absorption. Though dysprosium exhibits appreciable emission cross sections well below the tuning limit here of 2.8 µm, Fig. 5 shows that only for high levels of population inversion is net gain ($g_{\text{net}} = \sigma_e N_2 - \sigma_a N_1$, where $\sigma_{e,a}$ are emission and absorption cross sections and $N_{1,2}$ are the level populations) positive below 2.8 µm.

In addition to continuous tunability, we are also interested to characterize this novel 1.7 µm pumping scheme for overall efficiency and output power. For this purpose we replace the parabolic reflector and diffraction grating section of the cavity simply with a butt-coupled dichroic mirror which is highly reflective at the pump wavelength of nominally 50% reflective across the 3 µm gain bandwidth. Lacking a frequency-selective element, this cavity exhibits free-running emission around the gain peak of 2.95 µm. The output power as a function of injected 1.7 µm pump power is seen in Fig. 6. A 42 cm length of fiber yields a slope efficiency with respect to injected power of 12% and an oscillation threshold of 1.05 W. As previously noted, signal re-absorption can have a detrimental impact on laser performance, and excess fiber length can result in comparatively large values of

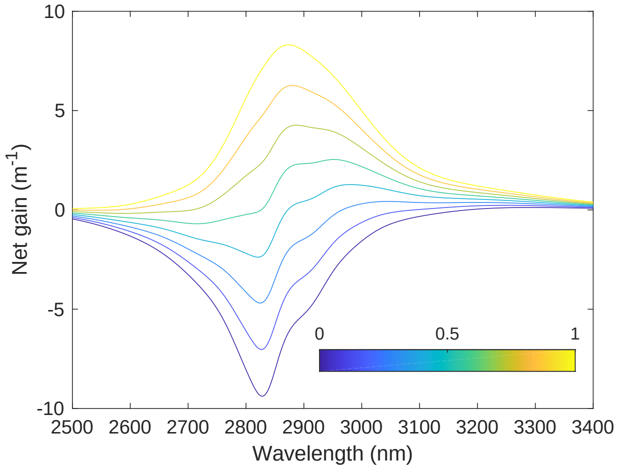

Figure 5. Net gain spectrum ($g_{\text{net}} = \sigma_e N_2 - \sigma_a N_1$) as calculated from measured cross section values of Dy^{3+} in ZBLAN for increasing fractional population inversion

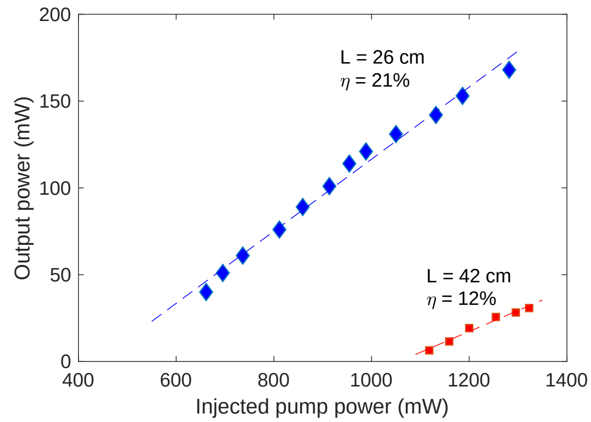

Figure 6. Laser output power as a function of injected pump power for two lengths of active fiber. A 26 cm length of fiber produces a slope efficiency (η) of 21% and a maximum output power of 170 mW

pump power required to reach oscillation. In an effort to address both of these concerns, we note that this length of fiber results in 90% pump absorption, thus it is likely that a substantially shorter active length combined with pump retroreflection may be preferable. This configuration more closely resembles a bi-directional pumping scheme where high levels of inversion can be achieved in short length of fiber. For a 26 cm length of fiber we measured a substantial increase of efficiency to a value of 21%, coupled with a maximum output power of 170 mW while further output power scaling is limited only by pump power availability.

4. DISCUSSION

We note that while the maximum slope efficiency achieved here of 21% exceeds that of previous near-infrared pumped dysprosium mid-IR fiber lasers (pumped both at 1.1 µm and 1.3 µm),[8,9] it is below the theoretical efficiency as defined by the Stokes limit of 55%. In previous demonstrations, excited state absorption (ESA) of pump light from the $^6H_{13/2}$ upper laser level was identified as a strong possible explanation for the reductions in realized efficiency. ESA is a likely possibility in this pumping scheme as well as shown in Fig. 7; absorption of a 1.7 µm pump photon from the $^6H_{13/2}$ level is equivalent to a total energy of 9373 cm^{-1} which is nominally resonant with the 9116 cm^{-1} energy of the $^6F_{9/2}$ and $^6H_{7/2}$ thermally coupled levels. Recent direct observation of 1.7 µm pump ESA from the upper 3 µm laser level in Dy^{3+}:PGS crystals[11] supports this hypothesis. Further empirical evidence of pump ESA is observed here when considering single pass pump absorption. Despite the low

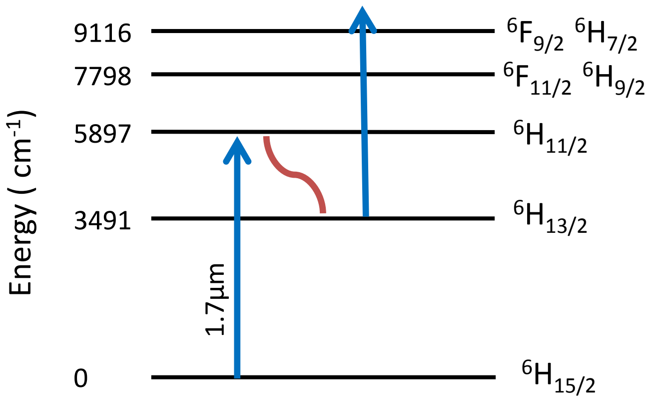

Figure 7. Energy level diagram of Dy^{3+}:ZBLAN depicting possible excited state absoprtion (ESA) of 1.7 µm pump photons from the upper 3 µm laser level (level positions from Ref. 10)

calculated pump saturation value calculated here as 100 mW, the measured pump absorption is well approximated by the small signal pump absorption coefficient even at elevated injected pump powers. This observation strongly suggests the presence of an additional pump absorption mechanism. A preliminary modeling effort focused on saturation of pump absorption including a free-parameter ESA term yields an estimate for the ESA cross section for the $^6H_{13/2} \rightarrow^6 F_{9/2},^6 H_{7/2}$ transition of 1×10^{-25} m^2. Further characterization of ESA around this pump band would be required for a more complete optimization of this laser system.

The wide gain bandwidth of the system demonstrated here has implications beyond a tunable continuous wave laser source. In particular, this system offers potential for mode-locked ultrafast operation; as the bandwidth of a transform-limited pulse is inversely proportional to the pulse duration. Recent demonstrations of ultrafast mid-IR ZBLAN fiber lasers based on erbium doping have achieved the femtosecond level[12] but the pulses did not achieve full spectral gain bandwidth largely due to atmospheric absorption water absorption between 2.7 µm and 2.8 µm in the free-space segments of the cavity. A reduction in pulse duration to below 200 fs was achieved in a holmium based system,[13] where the somewhat longer center emission wavelength of 2.85 µm is removed from atmospheric absorption. There the spectral width of the pulse closely approached the total available gain bandwidth of the system. While the achieved tuning range for laser emission provides an estimate of the total gain bandwidth of this system, for more direct comparison with the previous ultrafast systems we measure the amplified spontaneous emission (ASE) spectrum of our fiber (Fig. 8). It is clear that the ASE spectrum of

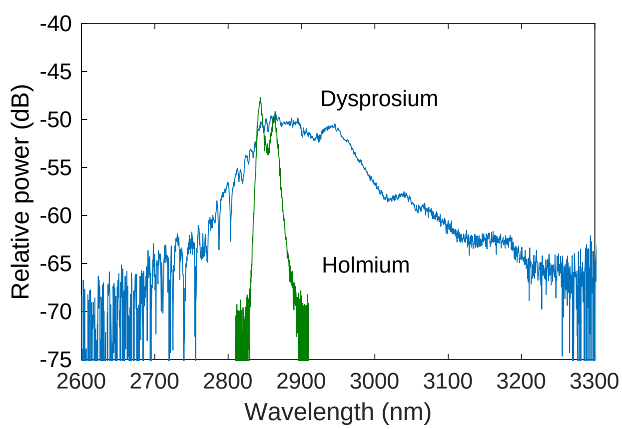

Figure 8. Measured amplified spontaneous emission (ASE) spectrum of the Dy^{3+}:ZBLAN fiber; with the measured ASE spectrum of holmium shown for comparision

dysprosium is not only substantially broader but the bulk of integrated emission is even further removed from detrimental atmospheric water absorption. The implication from this ASE spectrum is then that sub 100 fs pulses may be possible from a dysprosium mode-locked fiber laser.

5. CONCLUSION

We have demonstrated a novel near-IR pumping scheme for a mid-IR dysprosium doped ZBLAN fiber laser. With a simple diffraction grating-based cavity arrangement we achieve what is to date the broadest spectral tuning range of any rare earth doped laser; representing a substantial increase over the previous record. The emission range covers important functional group absorption features of OH/NH and CH based compounds. While we note that ESA is a likely detriment to this pumping scheme, the efficiency achieved an improvement over previous mid-IR pumping schemes, and further characterization of the influence of ESA may lead gains in system optimization. Continued scaling of the output power of this system should be readily achieved with both a bi-directional pumping scheme and a higher power pump source.

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REFERENCES

[1] Petersen, C. R., Møller, U., Kubat, I., Zhou, B., Dupont, S., Ramsay, J., Benson, T., Sujecki, S., Abdel-Moneim, N., Tang, Z., Furniss, D., Seddon, A., and Bang, O., "Mid-infrared supercontinuum covering the 1.4–13.3 μm molecular fingerprint region using ultra-high na chalcogenide step-index fibre," *Nature Photonics* **8**(11), 830–834 (2014).

[2] Hudson, D. D., Antipov, S., Li, L., Alamgir, I., Hu, T., El Amraoui, M., Messaddeq, Y., Rochette, M., Jackson, S. D., and Fuerbach, A., "Toward all-fiber supercontinuum spanning the mid-infrared," *Optica* **4**(10), 1163–1166 (2017).

[3] Schliesser, A., Picqué, N., and Hänsch, T. W., "Mid-infrared frequency combs," *Nature Photonics* **6**(7), 440–449 (2012).

[4] Libatique, N., Tafoya, J., Viswanathan, N., Jain, R., and Cable, A., "'field-usable' diode-pumped 120 nm wavelength-tunable cw mid-ir fibre laser," *Electronics Letters* **36**(9), 791–792 (2000).

[5] Crawford, S., Hudson, D. D., and Jackson, S. D., "High-power broadly tunable 3-μm fiber laser for the measurement of optical fiber loss," *IEEE Photonics Journal* **7**(3), 1–9 (2015).

[6] Henderson-Sapir, O., Jackson, S. D., and Ottaway, D. J., "Versatile and widely tunable mid-infrared erbium doped zblan fiber laser," *Optics letters* **41**(7), 1676–1679 (2016).

[7] Majewski, M. R. and Jackson, S. D., "Tunable dysprosium laser," *Optics letters* **41**(19), 4496–4498 (2016).

[8] Jackson, S. D., "Continuous wave 2.9 μm dysprosium-doped fluoride fiber laser," *Applied physics letters* **83**(7), 1316–1318 (2003).

[9] Tsang, Y. H., El-Taher, A. E., King, T. A., and Jackson, S. D., "Efficient 2.96 μm dysprosium-doped fluoride fibre laser pumped with a nd: Yag laser operating at 1.3 μm," *Optics express* **14**(2), 678–685 (2006).

[10] Adam, J., Docq, A., and Lucas, J., "Optical transitions of dy3+ ions in fluorozirconate glass," *Journal of Solid State Chemistry* **75**(2), 403–412 (1988).

[11] Jelínková, H., Doroshenko, M. E., Jelínek, M., Šulc, J., Osiko, V. V., Badikov, V. V., and Badikov, D. V., "Dysprosium-doped pbga$_2$s$_4$ laser generating at 4.3 μm directly pumped by 1.7 μm laser diode," *Optics letters* **38**(16), 3040–3043 (2013).

[12] Duval, S., Bernier, M., Fortin, V., Genest, J., Piché, M., and Vallée, R., "Femtosecond fiber lasers reach the mid-infrared," *Optica* **2**(7), 623–626 (2015).

[13] Antipov, S., Hudson, D. D., Fuerbach, A., and Jackson, S. D., "High-power mid-infrared femtosecond fiber laser in the water vapor transmission window," *Optica* **3**(12), 1373–1376 (2016).