Single-frequency Dy:ZBLAN fiber laser tunable in the wavelength range from 2.925 to 3.250 μm

Pinghua Tang, Yuchen Wang, Edoardo Vicentini, Francesco Canella, Lisa M. Molteni, Nicola Coluccelli, Paolo Laporta, and Gianluca Galzerano

***Abstract*—We report on an in-band-pumped Dy-doped ZBLAN fiber laser with tunable emission wavelength in the mid-IR range from 2.925 to 3.250 μm and single-frequency operation. Using the combination of an intracavity germanium etalon and a reflective diffraction grating, we demonstrate the selection of single-frequency operation with emission linewidth narrower than 110 kHz, maximum output power of ~ 40 mW, and relative intensity fluctuations at a level of 0.9% over an integration bandwidth from 1 Hz to 10 MHz.**

***Index Terms*—Dy-doped fiber lasers, Mid-infrared lasers, Tunable lasers, Single-frequency lasers.**

I. INTRODUCTION

SINGLE-FREQUENCY tunable lasers in the molecular mid-infrared (mid-IR) finger-print region (from 2 to 20 μm) are enabling a large variety of spectroscopic and sensing technologies based on probing the strong, distinctive mid-IR absorption features of important functional groups, such as proteins, lipids, amides, and inorganic materials. In particular, the spectral region around 3 μm (corresponding to 3300 cm^{-1}) assumes a strategic role thanks to the spectral coincidence with the C-H vibration bonding and liquid water absorption spectra, which enables a large variety of applications in the fields of bio-medicine, chemistry, and surgery [1]. In addition, the coincidence with one of the atmospheric spectral transmission window from 3 to 4 μm, allows also interesting applications in remote sensing and free-space optical communications [2], [3]. Conventional single-frequency sources directly emitting in this spectral region are based on semiconductor lasers, such as intercascade quantum laser [4]–[6] and lead-salt lasers [7], [8], solid-state Cr-doped chalcogenide lasers [9], and non-linear parametric sources such as optical parametric oscillators (OPOs) [10], [11] and difference frequency generation (DFG) schemes between near-infrared laser sources [12], [13]. Each of these technologies has advantages and disadvantages: the compact and robust semiconductor lasers have reduced tunability ranges and poor beam spatial qualities, the broadly tunable and narrow emission linewidth OPOs require rather complex architectures, while the simplest DFG sources have low output powers requiring high-power single-frequency pump lasers.

In the last ten years, soft-glass optical fibers doped with ions of the rare-earth elements, such as Er, Ho, Tm, are demonstrating excellent mid-IR emission properties [14]. Mid-IR fiber laser technology provides indeed simplicity, flexibility, adequate heat management, and excellent output beam quality. Single-frequency mid-infrared fiber emission has been first obtained using fiber Bragg grating inscribed directly into a Ho/Pr co-doped ZBLAN (Zirconium Barium Lanthanum Aluminum Sodium Fluoride) fiber, demonstrating 0.4-nm linewidth at 2.914 μm [15]. Much narrower emission linewidth down to 20 kHz has been demonstrated in π-phase-shifted Bragg grating Er-doped fluoride fiber at 2794.4 nm [16]. In both these single-frequency fiber laser demonstrations, the output power is limited to $\sim$10 mW and the wavelength tunability is extremely reduced by the narrow spectral bandwidth of the Bragg gratings. Among the several rare-earth-doped fibers, the Dy-doped fluoride fiber [17] shows great potentials for high-efficiency and broad laser emission both in continuous-wave (CW) [18]–[21] and pulsed regimes [22]–[24]. Characterized by a broader emission cross-section with respect to Er- and Ho-doped fluoride fibers, Dy-based fiber lasers promise wider wavelength tuning range combined to high efficiency, thanks to the extremely low quantum defect adopting the in-band pumping configuration. In recent years, CW Dy-doped fluoride fiber lasers demonstrated interesting performance in terms of efficiency and output power levels, as high as 73% and 10 W, respectively [18], [19], and a broad wavelength tuning range larger than 400 nm [20], [21]. Currently, to the authors' knowledge, single-frequency emission in Dy-doped fiber laser has not been demonstrated yet.

In this letter, we present an in-band pumped Dy:ZBLAN laser emitting a single-longitudinal mode in the broad wavelength range from 2.925 to 3.250 μm with maximum output power of $\sim$ 40 mW and instrumental limited linewidth of 110 kHz. A complete characterization of the laser performance is presented with specific attention to the laser emission linewidth and relative intensity noise, showing the potential for applications of this broadly-tunable laser source in high-resolution molecular spectroscopy and mid-infrared laser-based metrology.

II. EXPERIMENTAL SETUP

Figure 1 shows the Dy:ZBLAN single-frequency laser layout. The adopted active Dy:ZBLAN fiber (Le Verre Fluore,

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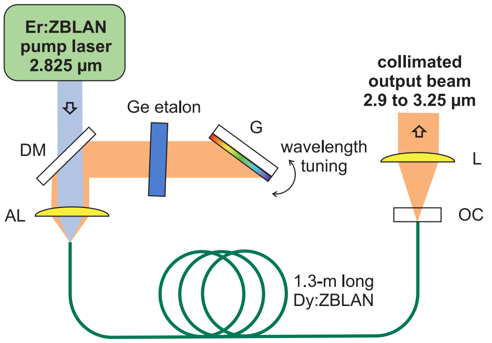

Fig. 1. Experimental layout of the tunable single-frequency Dy:ZBLAN laser. AL: aspheric lens; DM: dichroic mirror; G: reflection gold grating; L: plano-convex lens; OC: output coupler.

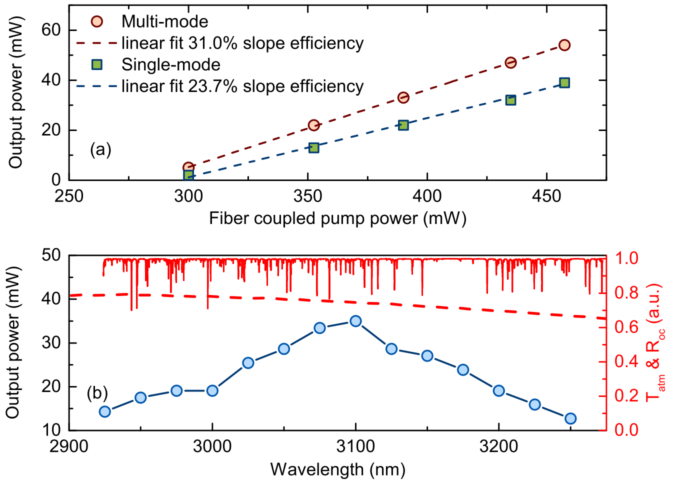

Fig. 2. (a) Output power versus fiber-coupled pump power for multi-(circle) and single-longitudinal mode (squares) regimes. (b) Wavelength tunability in single-frequency regime together with a simulation of atmospheric transmission over 1 m path using HITRAN database [25] (red curve) and with the measured reflectivity of the used output coupler (dashed red curve).

France) has a doping level of 2000 ppm (corresponding to a Dy ions density of 3.63×10^{25} m^{-3}), a core diameter of 12.5 μm, and a numerical aperture of 0.16, allowing for single-transverse mode operation down to 2.55 μm. The Dy:fiber laser is in-band pumped by a single-transverse-mode Er:ZBLAN fiber laser at 2.825 μm with a maximum output power of 10 W and multi-longitudinal mode linewidth $<$ 1 nm (LumIR laser, model 2800). The collimated pump beam at the Er:ZBLAN output is coupled to the Dy:ZBLAN fiber through a 45-degree dichroic mirror (T=55% at 2.825 μm and $R >$ 95% for wavelengths longer than 3 μm) and an antireflection (AR) coated aspheric ZnSe plano-convex lens with a focal lengths of 12.7 mm. The measured coupling efficiency, using Dy:ZBLAN fiber samples of different lengths, is 75±5% of the incident pump light. The linear laser resonator is constituted by a 1.3-m long Dy:ZBLAN fiber, a 20% output coupler, butt coupled to the end fiber tip, and a reflective diffraction grating in a Littrow configuration. The aluminium coated diffraction grating has 450 groves/mm with a designed blaze angle of 32° at 3.1 μm, allowing for a reflection efficiency into the first diffraction order higher than 85% (Thorlab, mod. GR1325-45031). The wavelength resolution of the Littrow configuration is ∼0.88 nm, corresponding to a frequency resolution of 27 GHz, so that many longitudinal modes of the Dy:ZBLAN laser, spaced in frequency by ∼72 MHz, can be reflected from the illuminated grating and coupled back into the cavity. A 5-mm thick uncoated Ge etalon (Thorlab, model WG91050) is interted into the cavity between the dichroic mirror and the diffraction grating to further increase wavelength selectivity and to force single-longitudinal-mode operation. The combination of the filtering effects of the grating and the uncoated Ge-etalon, characterized by a free-spectral-range of 7.5 GHz and a frequency resolution narrower than 2.5 GHz, introduces a spectral attenuation between adjacent longitudinal modes of the order of 0.6%, which is sufficient to select single-mode operation.

Figure 2(a) shows the output power characteristics of the Dy:ZBLAN laser in multi- and single-longitudinal mode regimes as a function of the fiber-coupled pump power. In multi-mode regime, without the intracavity Ge-etalon, the slope efficiency is 31% and the maximum output power is 54 mW for a coupled pump power of 460 mW (corresponding to an optical-to-optical efficiency of 12%). Compared to the results reported in literature [18], these slightly lower values are ascribed to additional round-trip internal losses (15% as measured using a modified Findlay-Clay analysis [26]) and to a non-optimal fiber length. In particular, with a shorter fiber length of 0.7 m, we obtained higher efficiency and output power; however, due to the remarkable mid-IR absorption of the fiber polymeric coating, the butt-coupled tip frequently burnt due to the polymeric absorption of the retro-reflected unabsorbed pump power. For this reason, we adopted a longer Dy:ZBLAN fiber at the price of a lower efficiency to increase the stability of the laser.

In single-frequency regime, due to the additional losses of the uncoated Ge-etalon, the laser performance is slightly reduced. In particular, the maximum output power is 39 mW at the same pump power level of 460 mW with a laser slope efficiency of ∼23%. For pump power levels larger than 460 mW, the laser emission turns into a multi- (two/three) longitudinal mode regime. By fine rotation of the diffraction grating, the emission wavelength of the Dy:ZBLAN laser can be tuned over a ∼300-nm wide spectral range. Figure 2(b) shows the measured tuning range in single-longitudinal mode for the maximum pump power of 460 mW. In single-longitudinal-mode regime, the laser wavelength can be continuously tuned, by the combination of grating angle tuning and Ge-etalon tilting, from 2.925 up to 3.25 μm. Mode-hop-free tuning up to 500 MHz (corresponding to 6-7 times the Dy:ZBLAN free-spectral range) is obtained by a fine tilting of the Ge-etalon. Emission wavelengths shorter than 2.925 μm can not be generated due to the spectral gain reduction of the in-band pumped configuration, whereas emission wavelengths longer than 3.25 μm cannot be achieved due to the limited spectral bandwidth of the output coupler combined to the gain reduction for the given length of Dy:ZBLAN fiber. To further broaden the gain bandwidth and therefore our wavelength tuning range, as reported in Ref. [21] a pumping

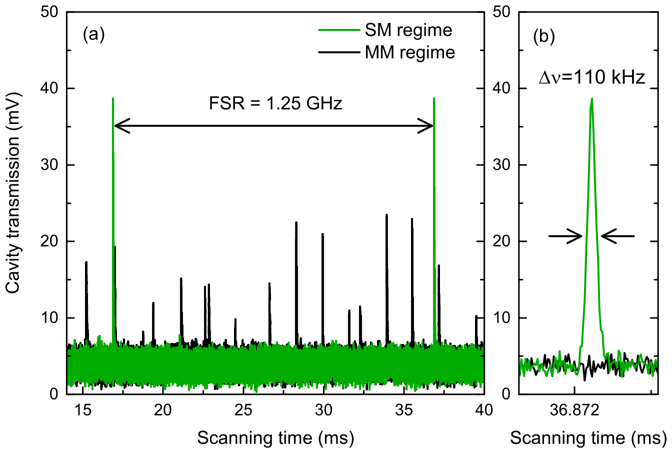

Fig. 3. (a) Dy:ZBLAN optical spectrum measured by a scanning cavity with 1.25 GHz free-spectral-range and ∼11700 finesse. Black and green curves represent, respectively, multi-longitudinal and single-longitudinal mode operations. (b) Enlarged view at around the single mode peak showing the cavity resolution of 110 kHz.

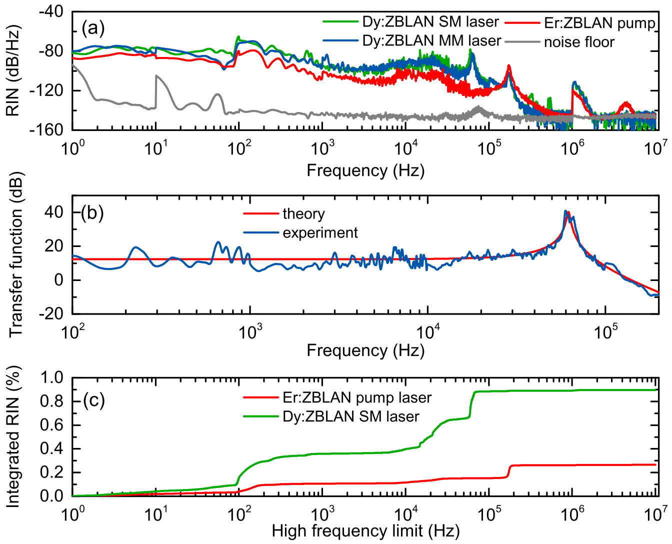

Fig. 4. (a) Relative intensity noise (RIN) spectra. (b) Dy:ZBLAN transfer function to pump intensity noise. (c) Cumulative standard deviation of the laser intensity noise.

configuration at 1.7 μm and shorter fiber lengths have to be adopted together with the use of broadband intracavity components. Figure 2(b) also reports the measured reflectivity of the used output coupler (dashed red line) and the calculated transmission over a propagation length of 1 m through the atmosphere using HITRAN database [25] (red curve). It is worth noting that the laser emission range well fits the fundamental vibrational bands of many interesting atmospheric and greenhouse molecules such as, CH_4, C_2H_2, C_2H_4, NH_3, N_2O, H_2O, HCN, which present intense absorption lines with line-strength intensity as large as 10^{-19} cm/mol [25]). This spectral coincidence enables the direct use of the single-frequency Dy:ZBLAN laser in high-resolution spectroscopy methods for trace-gas sensing, atmospheric remote sensing, fundamental physics, and frequency metrology.

Single-frequency operation was monitored using a scanning linear optical resonator constituted by a plane high-reflectivity (HR) ($R > 99.9\%$) input mirror and a spherical, 1-m radius of curvature, HR ($R > 99.9\%$) output mirror mounted on a piezoelectric actuator. The optical cavity is set with a free-spectral-range of 1.25 GHz. Efficient coupling of the Dy:ZBLAN laser to the fundamental TEM_{00} mode of the scanning resonator is obtained focusing the laser beam to the input plane mirror of cavity with a beam waist of 0.55 mm by using a two plano covex lenses of 20 and 500 mm focal lengths, respectively. Figure 3(a) shows the laser spectra in multi- (black curve) and single-longitudinal (green curve) operation for an output power level of 39 mW. In multimode-operation up to 12-13 modes can be observed within the free spectral range of the scanning resonator. When the Ge-etalon is inserted into the Dy:ZBLAN laser resonator, only one longitudinal mode is selected. The single mode is characterized by a linewidth of 110 kHz, as it is shown in the detailed view of Fig. 3(b), which is limited by the finesse of the scanning resonator at level of ∼11,700. The limited signal-to-noise ratio sets a side longitudinal mode suppression ratio of approximately 20 dB. A larger longitudinal suppression ratio up to 55 dB has been measured comparing the RF power of the beatnote signal between longitudinal modes measured by a fast liquid-nitrogen cooled MCT photodetector with 200 MHz bandwidth with respect to the average DC power.

Finally, we measured the relative intensity noise (RIN) of the Dy:ZBLAN laser by analyzing the power spectral density of the photocurrent detected by a 10-MHz bandwidth InAsSb photodetector. Figure 4(a) shows the RIN power spectral density of the Dy:ZBLAN laser, both in multi- and single-longitudinal mode regimes, in comparison with the RIN spectrum of the Er:ZBLAN pump laser. No substantial difference is observed between the Dy:ZBLAN RIN in multi- and single-longitudinal mode operation. The RIN of the single-frequency Dy:ZBLAN laser in general retraces that of the pump Er:ZBLAN source with a degradation of approximately 10 dB in the Fourier frequency range from 1 to 10 kHz. A further RIN degradation is observed at around the relaxation oscillation resonance, centered at 61 kHz, reaching a RIN value of -78 dB/Hz. For frequencies larger than 100 kHz the RIN decreases reaching the detector noise floor level at -146 dB/Hz at Fourier frequencies larger than 2 MHz (the peak located at around 2 MHz is ascribed to longitudinal mode beating in the Er:ZBLAN pump laser). Figure 4(b) reports the transfer function between the measured Dy:ZBLAN and pump Er:ZBLAN intensity noises, as computed by the ratio between the RIN spectra reported Fig. 4(a), together with a simple model constituted by a pair of complex conjugate poles representing the relaxation oscillations of the Dy:ZBLAN laser system. Figure 4 (c) depicts the cumulative standard deviations (CSD) of both Er:ZBLAN and Dy:ZBLAN lasers, as calculated by the formula $CSD = \sqrt{\int_{1Hz}^{f_H} RIN(f)df}$, as a function of the high cutoff frequency, f_H. The cumulative standard deviation of the Dy:ZBLAN laser intensity amounts to 0.89% over the integration frequency range from 1 Hz to 10 MHz, a factor of 3.5 times larger than the pump laser cumulative standard deviation of 0.26%. The higher intensity noise is due to the observed 10-dB RIN degradation in the frequency range from 100 Hz to 10 kHz and to the Dy:ZBLAN relaxation oscillations contribution.

III. CONCLUSION

Single-frequency operation of a Dy:ZBLAN fiber laser broadly tunable at around 3 μm is demonstrated. The in-band pumped Dy:ZBLAN laser is characterized by a maximum output power of 39 mW, an emission linewidth of 110 kHz, and a continuous wavelength tunability from 2.925 to 3.250 μm with an integrated relative intensity noise of 0.9% in a bandwidth from 1 Hz to 10 MHz. Our results highlight the potential of Dy:ZBLAN single-frequency fiber laser for high-resolution sensing applications and spectroscopy in the molecular fingerprint mid-infrared spectral region.

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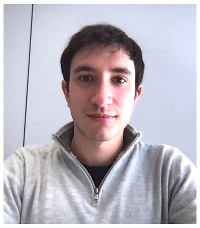

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