CHINESE OPTICS LETTERS

Vol. 21, No. 4 | April 2023

Q-switched Er^{3+}/Dy^{3+} codoped ZrF_4 fiber laser: continuously tunable pulse generation from 3.06 to 3.62 μm

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Received October 9, 2022 | Accepted November 25, 2022 | Posted Online April 6, 2023

In this Letter, we report on widely tunable pulse generation from a red-diode-clad-pumped mid-infrared (mid-IR) Er^{3+}/Dy^{3+} codoped ZrF_4 fiber laser, for the first time, to the best of our knowledge. Using a Fe^{2+}:ZnSe crystal, continuously tunable *Q*-switched pulses across the range of 3.06–3.62 μm have been attained, which not only represents the widest range (in wavelength domain) from a pulsed rare-earth-doped fiber laser at any wavelength, but also almost entirely covers the strong absorption band of C-H bonds in the mid-IR, providing a potential way for gas detection and polymer processing. In addition, the commercial InAs quantum-well-based saturable absorbers (SAs) have been employed instead, and the obtained longest *Q*-switching wavelength of 3.39 μm is slightly shorter than 3.444 μm determined by its nominal direct bandgap of 0.36 eV.

Keywords: *Q* switching; continuous tunability; Fe^{2+}:ZnSe; InAs; ZrF_4 fiber.

DOI: 10.3788/COL202321.041402

1. Introduction

There is an increased interest in developing mid-infrared (mid-IR) laser sources in the region of 3–4 μm because of their huge potential in spectroscopy[1–3]. Since overlapping with the stretching frequency of C-H bonds with different forms (i.e., alkane, alkene, and alkyne) in the range of 2800–3300 cm^{-1} (i.e., 3.03–3.57 μm)[4], the laser sources in this region can find direct applications in lidar for gas detection and processing polymer, where C-H bonds are rich [including methane, ethane, propane, polypropylene, poly(methyl methacrylate), polyethylene, etc.][5–8]. Among them, short pulsed rare-earth-doped fiber laser with tunable wavelengths is a competitive option, owing to its potential compactness and robustness (compared to external nonlinear wavelength conversion[9]), higher peak power than continuous wave (CW), and flexible wavelength. To cover this band, Dy^{3+}- and Er^{3+}-doped ZrF_4 fiber lasers operating on the transitions of $^6H_{13/2} \rightarrow {}^6H_{15/2}$ and $^4F_{9/2} \rightarrow {}^4I_{9/2}$, respectively, have been developed to be the two most common platforms for realizing short pulses based on *Q* switching[10–13] or gain switching[14–16]. Despite 10 W CW output from a 2.83 μm pumped all-fiber Dy^{3+}-doped laser[17], near-infrared pumping at 1.69 μm has enabled continuous wavelength tuning from 2.71 to 3.42 μm[18]. By employing an InAs saturable absorber (SA), *Q*-switched pulses tunable across the range of 2.76–3.34 μm have been achieved[11]. Based on the dual-wavelength pumping scheme at 980 and 1.976 μm, the maximum CW power of 14.9 W[19] and tunable wavelength from 3.33 to 3.78 μm[20] have been obtained from an Er^{3+}-doped ZrF_4 fiber laser (not simultaneously). By *Q* switching with a Fe^{2+}:ZnSe crystal SA[13], continuously tunable short pulses in the range of 3.4–3.7 μm have been generated. All these results are the current records of the two systems in this band. However, it is quite challenging for a Dy^{3+}- or Er^{3+}-doped system alone to entirely cover the absorption band of C-H bonds mentioned above. Recently, we proposed a new laser scheme (i.e., red-diode-clad-pumped Er^{3+}/Dy^{3+} codoped ZrF_4 fiber laser), which can excite the emissions of the $^4F_{9/2} \rightarrow {}^4F_{9/2}$ transition of Er^{3+} and the $^6H_{13/2} \rightarrow {}^6H_{15/2}$ transition of Dy^{3+} simultaneously, via the energy transfer between them and in-band absorption of Dy^{3+} around 2.8 μm, thus extending the emission band in this spectral region[21]. Continuous tuning in the range of 3.05–3.7 μm has been enabled, almost entirely covering the strong mid-IR absorption band of C-H bonds. This provides not only a promising platform for widely tunable pulse generation, but also an opportunity to accurately assess the long wavelength edges (in terms of pulse generation) of widely used commercial InAs quantum-well-based SA, which has a nominal direct bandgap of 0.36 eV (i.e., 3.444 μm) and has been frequently employed in *Q*-switched and mode-locked ZrF_4 fiber lasers around 3 μm[22].

In this work, we adopted a Fe^{2+}:ZnSe crystal as the SA to demonstrate continuously tunable Q switching from a red-diode-clad-pumped Er^{3+}/Dy^{3+} codoped ZrF_4 fiber laser. The continuous range of 3.06–3.62 μm (~560 nm) not only represents the current widest level (in wavelength domain) from a pulsed rare-earth-doped fiber laser at any wavelength, but also almost entirely covers the strong absorption band of C-H bonds in the mid-IR. Replacing the Fe^{2+}:ZnSe crystal with the commercial transmitting- and reflecting-type InAs quantum-well-based SAs (BATOP, Germany), respectively, their long wavelength operation edges have been also experimentally assessed.

2. Experiments

2.1. Setup

Figure 1 displays the experimental setup of the tunable Q-switched Er^{3+}/Dy^{3+} codoped ZrF_4 fiber laser, of which the main body is similar to our previously reported tunable CW version[21]. The gain is a segment of 4.3 m double-clad Er^{3+}/Dy^{3+} codoped ZrF_4 fiber (Fiberlabs, Japan) with the doping concentrations of 4% and 0.25% (molar fractions), and core/clad (circular) diameter and NA of 17.3/249 μm and 0.13/0.5, respectively. The fiber end close to the pump was perpendicularly cleaved and then butted against the front mirror (FM) (98% transmission at 659 nm and >95% reflection at 2.7–3.7 μm). The other end was cleaved at an angle of 4° to avoid the parasitic lasing caused by its Fresnel reflection. After that, L3 was adopted to collimate the output laser (including the signal and residual pump). To ensure that the SA was free from damage due to the large residual pump, the dichroic mirror (DM) (97% transmission at 659 nm and >96% reflection at 2.7–3.7 μm at 45° angle) was used to remove the pump and then project the signal onto a grating (Thorlabs, GR2550-30035) in a Littrow configuration, of which the first-order diffraction was resonated and the zeroth-order one acted as the output coupler. A confocal scheme consisting of two same lenses (i.e., L4 and L5) was placed between the DM and grating. Subsequently, a Fe^{2+}:ZnSe crystal with the size of 6.7 mm × 6.7 mm × 1.7 mm and a measured initial transmission of ~80% around 3.5 μm, and a transmitting-type InAs quantum-well-based SA (BATOP, SA-2800-10-10ps-x) with a modulation depth of 6%, a nonsaturable loss of 4%, and a saturation fluence of 300 μJ/cm^2 at 2.8 μm (provided by the manufacturer), mounted by a three-dimensional adjuster, were inserted into the confocal scheme in turn. In addition, a reflecting-type InAs quantum-well-based SA (BATOP, SAM-3000-33-10ps-x) with a modulation depth of 18%, a nonsaturable loss of 15%, and a saturation fluence of 70 μJ/cm^2 at 3 μm (provided by the manufacturer) was also tested using a Littman configuration grating-based cavity. The relative arrangement is not plotted in Fig. 1, and the details are available in our previous report[10]. Note that the two InAs devices are the current most widely used commercial long wavelength semiconductor SAs. Due to lack of a proper pulsed laser source, it failed to characterize their saturable absorption at the laser wavelengths. The output power of the laser was recorded using a high-resolution thermal sensor (Laserpoint, A-02-D12-BBF). The temporal pulses and radio-frequency (RF) spectrum were captured using an InAs detector (Judson J12D) with a response time of 2 ns connected with a 500 MHz bandwidth digital oscilloscope and an 18 GHz electrical spectrum analyzer, respectively. The optical spectra were measured using a spectrometer (APE, waveScan MIR) with a nominal resolution of 3 nm.

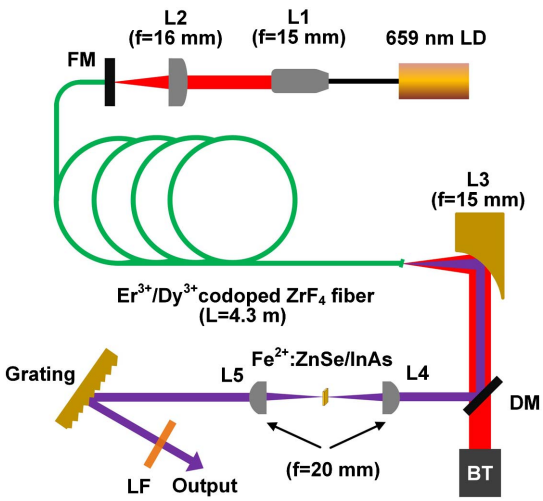

Fig. 1. Experimental setup of the tunable Q-switched Er^{3+}/Dy^{3+} codoped ZrF_4 fiber laser using the Fe^{2+}:ZnSe crystal or InAs SA. LD, laser diode; L1 and L2, aspheric lenses; L3, off-axis parabolic reflector; FM, front mirror; DM, dichroic mirror; L4 and L5, CaF_2 plano-convex lenses; LF, longpass filter; BT, beam trap.

2.2. Results

First, the Fe^{2+}:ZnSe crystal was employed and relative laser performances have been characterized. At the locked wavelength, targeting the largest gain, the laser exhibited stable passive Q switching, as displayed in Fig. 2. In the time domain, the pulses with tens of kilohertz of repetition rates and several microseconds' widths show low peak-to-peak amplitudes fluctuation of ±0.6% [Fig. 2(a)]. In the frequency domain, the first beat note of the RF spectrum gives a signal-to-noise ratio (SNR) of 50 dB [inset of Fig. 2(b)]. Both highlight stable Q switching. With the function of the used grating, the laser wavelength was always locked at 3414.9 nm [see Fig. 2(b)], without multi-spectral lines, as observed in the free-running state[21]. Due to the relatively low resolution of the spectrometer, it failed to accurately measure the spectral width. Moreover, the evolutions of the pulse parameters with the varied launched pump power have been also recorded as plotted in Figs. 2(c) and 2(d). Typical passive Q-switching behavior, i.e., linearly increased repetition rate and monotonously reduced pulse width with the increased pump, has been observed. At 11.7 W maximum launched pump power, 24 mW average power with 3.6% slope efficiency and 0.67 μJ pulse energy have been achieved. Such low output levels mainly result from the low output coupling ratio.

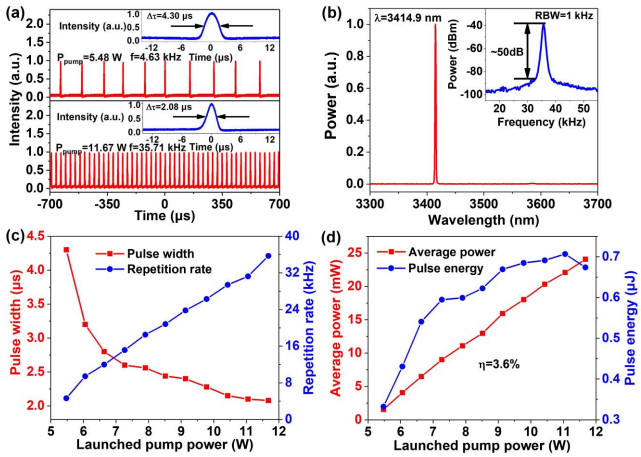

Fig. 2. Fe^{2+}:ZnSe crystal based laser output characteristics at a fixed wavelength. (a) Temporal behaviors; (b) optical and RF (inset) spectra; (c) pulse width and repetition rate versus pump power; (d) average power and pulse energy versus pump power.

Then the grating was rotated to tune the wavelength, with the relative output evolutions shown in Fig. 3. The wavelength in the Q-switching region could be continuously tuned in the range of 3.06–3.62 μm [see Fig. 3(a)] at the available maximum launched pump power of 11.7 W, slightly narrower than its CW version[21] due to the additional losses introduced by the lenses, DM, and SA. Of particular note is that no ~2.8 μm laser was generated in the process due to the strong absorption of Dy^{3+}. Further extending the range is expected by appropriately shortening the fiber length while boosting the pump power, considering the wide absorption band of the Fe^{2+}:ZnSe crystal. Even so, this continuously tunable range still represents the current widest level (in wavelength domain), to the best of our knowledge, from a pulsed rare-earth-doped fiber laser at any wavelength. More importantly, it almost entirely covers the strong absorption band of C-H bonds in the mid-IR. With the tuned wavelength, the profile of the pulse width evolution looks like two mountains, as shown in Fig. 3(b), where there are two peaks at 3.3 and 3.5 μm. This trend is different from our previously reported 2.9–3 μm Ho^{3+}- and 3.4–3.7 μm Er^{3+}-doped ZrF_4 fiber lasers Q-switched by the Fe^{2+}:ZnSe crystal SA[13,23] and should be related to the varied modulation depth in this region. This issue can be identified by characterizing its nonlinear transmission using a tunable pulsed source with high peak powers in the future. The repetition rate exhibits a similar evolution trend to our previous reports[11,13], with the maximum value of 35.7 kHz at 3.414 μm, corresponding to the local minimum pulse width. Figure 3(c) shows the situations of the average power and pulse energy, where the power evolution is almost the same as its CW version[21], with the maximum value obtained at 3.414 μm. This implies great accordance with the fiber gain profile despite the decreased absorption of the SA in this range. The similar evolution of the pulse energy is also observed but with a blueshifted peak at 3.24 μm.

After that, the Fe^{2+}:ZnSe crystal was replaced by the transmitting-type InAs SA. By rotating the grating, the laser wavelength could be still continuously tuned in the range of 3.06–3.61 μm [see Fig. 4(a)]; however, stable Q switching was only achievable in the left subrange of 3.06–3.34 μm. In this range, the pulse-width evolution exhibits a similar trend to our previously reported tunable Dy^{3+}-doped ZrF_4 fiber laser based on the same InAs[11]; however, the repetition rate evolution is contrary to the pulse width, which should be related to the different gain profiles, indicated by their tunable CW versions[18,21]. As tuning beyond 3.34 μm, Q switching became unstable with strong timing jitter, and then degenerated into CW with further tuning beyond 3.36 μm. At longer wavelengths, we can find the power variation is flat, as shown in Fig. 4(c), suggesting that the disappeared Q switching was caused by the invalidity of the SA at long wavelengths. In addition, the reflecting-type InAs SA has been also tested in a Littman configuration, where the longest

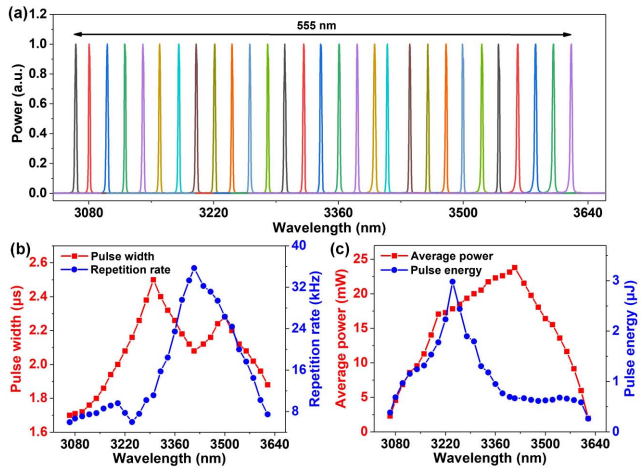

Fig. 3. Fe^{2+}:ZnSe crystal-based laser output characteristics with the tuned wavelength. (a) Optical spectra; (b) pulse width and repetition rate versus wavelength; (c) average power and pulse energy versus wavelength.

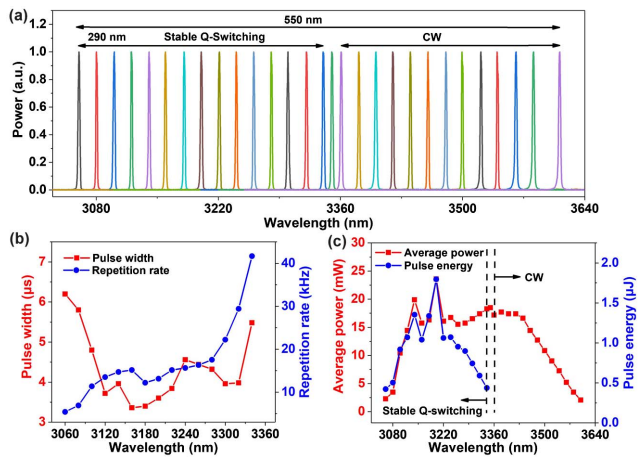

Fig. 4. InAs SA-based laser output characteristics with the tuned wavelength. (a) Optical spectra; (b) pulse width and repetition rate versus wavelength; (c) average power and pulse energy versus wavelength.

Q-switching wavelength was slightly pushed to 3.39 μm. Anyway, both are shorter than that determined by InAs's nominal direct bandgap of 0.36 eV (i.e., 3.444 μm). Of particular note is that in our experiment, Q switching would disappear immediately once the SA was removed out of the cavity, excluding the possibility of self-pulsing[24,25].

3. Conclusion

In summary, we demonstrate widely tunable short-pulse generation, for the first time to our knowledge, from a red-diode-clad-pumped Er^{3+}/Dy^{3+} codoped ZrF_4 fiber laser with a Fe^{2+}:ZnSe crystal SA as the Q switch. The achieved Q-switched pulses with several microseconds of pulse widths and tens of kilohertz of repetition rates can be continuously tuned across the range of 3.06–3.62 μm (~560 nm), representing the widest level (in wavelength domain) until now from a pulsed rare-earth-doped fiber laser at any wavelength. More importantly, the laser almost entirely covers the mid-IR strong absorption region of C-H bonds, thus providing a versatile tool (with further narrowed width by shortening fiber length and increasing SA modulation depth, and scaled power/energy based on an Er^{3+}/Dy^{3+} codoped ZrF_4 fiber amplifier) for real-world applications of gas lidar and polymer processing. In addition, this laser platform has been used to assess the long wavelength edges (in terms of pulse generation) of commercial InAs quantum-well-based SAs, showing the 3.39 μm longest Q-switching wavelength, despite the fact that the absorption edge of a recent home-made InAs superlattice-based SA has been extended to 5.4 μm[26].

Acknowledgement

This work was supported by the National Natural Science Foundation of China (NSFC) (No. 62005040), the Fundamental Research Funds for the Central Universities (No. ZYGX2020KYQD003), and the Science and Technology Project of Sichuan Province (No. 2021YJ0368).

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