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Widely wavelength tunable Dy^{3+}/Er^{3+} co-doped ZBLAN fiber lasers

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Abstract: Wavelength tunable dysprosium-erbium (Dy^{3+}/Er^{3+}) co-doped ZBLAN (ZrF_4-BaF_2-LaF_3-AlF_3-NaF) fiber lasers pumped at 980 nm were developed with a bulk grating blazed at 3.1 µm in the Littrow configuration and their performances were investigated. A wavelength tunable range of 674.4 nm (2709.2 nm −3373.6 nm) was achieved with a 4.5-m 0.25 mol.% Dy^{3+}/ 4 mol.% Er^{3+} co-doped ZBLAN fiber. Our experiments demonstrated that either Er^{3+} or Dy^{3+} can be lasing individually in a Dy^{3+}/Er^{3+} co-doped ZBLAN fiber and a fiber laser with wavelength tunable range from 2.7 µm to 3.4 µm or longer wavelengths can be achieved with proper fiber and cavity design.

1. Introduction

Wavelength tunable lasers have been developed with almost all types of current laser technologies because of their extensive practical applications in spectroscopy, optical communications, frequency metrology, hyperspectral imaging, device characterization, and remote sensing, among other areas. Wavelength tunable lasers in the mid-infrared (MIR) have attracted significant interest because most molecules have intense fundamental vibrational absorptions in this region, which are more than 3-orders of magnitude stronger than that in the near-infrared, offering tremendously improved molecule detection sensitivity and accuracy. Nonlinear wavelength convertors such as optical parametric oscillators (OPOs) and difference-frequency generators (DFGs) have been widely used to achieve wavelength tunable mid-IR lasers [1–4]. However, OPOs and DFGs always have low efficiency and require complex manufacturing and frequent maintenance. Direct mid-IR laser generation based on rare-earth or transition-metal doped materials and semiconductor materials provides a simple and high-efficiency approach to achieve wavelength tunable mid-IR lasers. For example, Cr^{2+}:ZnSe and Fe^{2+}:ZnSe crystals have been used to develop wavelength tunable lasers with tuning ranges of 2.1-2.8 µm and 3.7-5 µm, respectively [5–6]. Recently, advances in quantum cascade lasers (QCLs) and interband cascade lasers (ICLs) have enabled very compact and high-efficiency wavelength tunable laser sources covering 3-12 µm or even longer wavelengths [7–8]. However, the output power levels of crystal and semiconductor lasers are generally limited by thermal management issues. Due to outstanding heat dissipation capability and excellent output beam quality, rare-earth doped fluoride fiber lasers are promising platforms for wavelength tunable lasers at 3 µm, where erbium (Er^{3+}), holmium (Ho^{3+}), and dysprosium (Dy^{3+}) have efficient emissions while ICLs still have low efficiency and low output power [9].

The first wavelength tunable fiber laser at 3 µm was demonstrated with a 2 mol. % Er^{3+}-doped ZBLAN (ZrF_4-BaF_2-LaF_3-AlF_3-NaF) fiber in 2000 [10]. A wavelength tunable range of 2.71-2.83 µm with output power < 5 mW was achieved. In 2007, a watt-level wavelength tunable fiber laser was demonstrated with highly Er^{3+}-doped and Er^{3+}/Pr^{3+} codoped ZBLAN fibers [11]. Due to the improved laser efficiency of highly Er^{3+}-doped ZBLAN, a 10-watt-level wavelength tunable

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fiber laser with tuning range of 170 nm (2.71-2.82 μm) was demonstrated [12]. Since Ho^{3+} has a transition with an emission wavelength greater than Er^{3+} in the 3 μm wavelength region, a Ho^{3+}/Pr^{3+} co-doped ZBLAN fiber laser with wavelength tuning range from 2.83 μm to 2.9 μm was demonstrated in 2011 [13]. A 42 nm wavelength tuning (2923 ~ 2965 nm) from the Ho^{3+} doped self-Q-switched all-fiber laser is achieved by applying the novel loss-adjusting technique [14] Compared to Er^{3+}- and Ho^{3+}-doped ZBLAN fiber lasers, Dy^{3+}-doped ZBLAN fiber lasers have recently attracted more attention as a wavelength tunable laser source because the $^6H_{13/2} \rightarrow {}^6H_{15/2}$ transition in Dy^{3+} has very broad emission band (2.6-3.4 μm). In 2016, a Dy^{3+}-doped ZBLAN fiber laser with wavelength tunable range of 2.95 - 3.35 μm was demonstrated by in-band pumping at 2.8 μm [15]. By changing the pump source to a 1.7 μm Raman fiber laser, the wavelength tunable range of the Dy^{3+}-doped ZBLAN fiber laser was increased to nearly 600 nm (2.8-3.38 μm) [16]. In this paper, we report the study of wavelength tunable Dy^{3+}/Er^{3+} co-doped ZBLAN fiber lasers using a grating blazed at 3.1 μm in the Littrow configuration. A wide wavelength tunable range of 674.4 nm (2709.2 nm −3373.6 nm) was achieved with a 4.5-m 0.25 mol.% Dy^{3+}/4 mol.% Er^{3+} co-doped ZBLAN fiber exhibiting laser operation of both Dy^{3+} and Er^{3+} ions in the co-doped system.

Dy^{3+}/Er^{3+} co-doped ZBLAN was originally proposed for lasers at 3 μm that could be pumped at Er^{3+} absorption bands, where commercial high-power high-efficiency diodes are readily available [17]. The partial energy-level diagrams of Dy^{3+} and Er^{3+} are shown in Fig. 1. When Dy^{3+}/Er^{3+} co-doped ZBLAN is pumped at 980 nm, Er^{3+} ions are excited from the ground state ($^4I_{15/2}$) to the excited state ($^4I_{11/2}$). Because the energy of the $^6F_{9/2}$ state of Dy^{3+} is close to that of the $^4I_{11/2}$ state of Er^{3+}, which has a long lifetime (6.9 ms) in ZBLAN, efficient energy transfer from Er^{3+} to Dy^{3+} can occur. This has been verified by both spectroscopic study and fiber laser demonstration [17,18]. A Dy^{3+}/Er^{3+} co-doped ZBLAN fiber laser at 3.27 μm pumped by a 980 nm diode has recently been successfully demonstrated [18]. In addition to the energy transfer, the electrons in the $^4I_{11/2}$ state of Er^{3+} are also depleted via light emission at 2.7 μm through transitions from $^4I_{11/2}$ to $^4I_{13/2}$, resulting in very broad emission due to the contributions of both Er^{3+} and Dy^{3+} emissions. Figure 2(a) shows the 3 μm fluorescence spectra of a 1 mol.% Er^{3+}-doped ZBLAN glass pumped at 980 nm, a 1 mol.% Dy^{3+}-doped pumped at 1090 nm, and a 0.25 mol.% Dy^{3+}/4 mol.% Er^{3+} co-doped ZBLAN glass pumped at 980 nm. It is clear that the emission bandwidth of the Dy^{3+}/Er^{3+} co-doped ZBLAN is enhanced compared to that of singly Dy^{3+}-doped or Er^{3+}-doped ZBLAN. Although Dy^{3+}-doped ZBLAN has broad fluorescence spanning from 2.6 μm to 3.4 μm, it is difficult to obtain laser operation below 2.8 μm because the emission cross-section of Dy^{3+} is smaller than the absorption cross-section in this band. Because emission from the $^4I_{11/2}$ - $^4I_{13/2}$ transition is still very strong in 0.25 mol.% Dy^{3+}/ 4 mol.% Er^{3+} co-doped ZBLAN, laser operation below 2.8 μm can still be achieved by forcing Er^{3+} ions to lase. The amplified spontaneous emission (ASE) spectrum of a 4.5-m 0.25 mol.% Dy^{3+}/4 mol.% Er^{3+} co-doped ZBLAN fiber pumped at 980 nm was measured and is shown in Fig. 2(b). As a comparison, the ASE spectrum of singly Dy^{3+}-doped ZBLAN fiber pumped at 1090 nm and singly Er^{3+}-doped ZBLAN fiber pumped at 980 nm were also measured and are shown in Fig. 2(b). Much broader ASE covering 2.5-3.6 μm was measured with the Dy^{3+}/ Er^{3+} co-doped fiber. The ASE from Er^{3+} in Dy^{3+}/ Er^{3+} co-doped fiber at 2.7-2.8 μm is 5 dB higher than that of Dy^{3+} at 3 μm, showing the potential for laser operation based on Er^{3+} transitions at 2.7-2.8 μm in the co-doped system and allowing us to achieve a wide wavelength tunable fiber laser with a tuning range of 2.7-3.4 μm.

In this research, we used the 0.25 mol.% Dy^{3+}/ 4 mol.% Er^{3+} co-doped ZBLAN fiber to demonstrate widely wavelength tunable Dy^{3+}/Er^{3+} ZBLAN fiber lasers and investigate their performance. Continuously wavelength tunable emission from 2.71 μm to 3.38 μm was obtained due to the laser operation of both Er^{3+} and Dy^{3+} ions in the co-doped system.

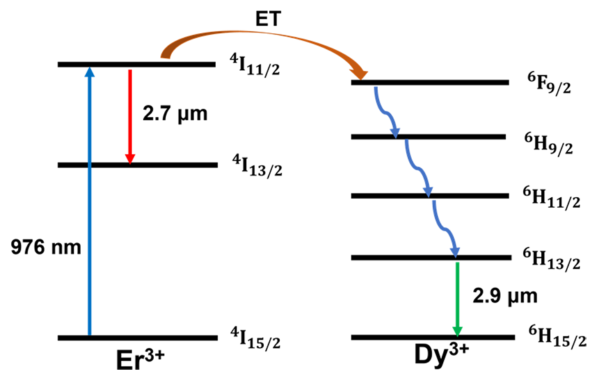

Fig. 1. Partial energy-level diagrams of Er^{3+} and Dy^{3+} and transitions/energy transfer processes related to the laser emission at 3 µm.

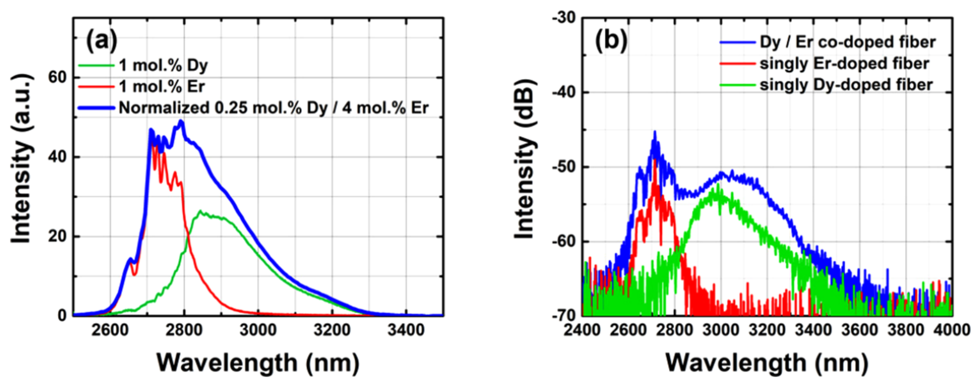

Fig. 2. (a) Measured fluorescence spectra of 1 mol.% Dy^{3+}-doped, 1 mol.% Er^{3+}-doped, 0.25 mol.% Dy^{3+}/ 4 mol.% Er^{3+} co-doped ZBLAN samples in the 3 µm wavelength region. (b) Measured ASE spectra of Dy^{3+}/ Er^{3+} co-doped, singly Er^{3+}-doped, and singly Dy^{3+}-doped ZBLAN fibers.

2. Experimental setup

The schematic of the wavelength tunable Dy^{3+}/ Er^{3+} co-doped ZBLAN fiber laser is shown in Fig. 3. The core of the Dy^{3+}/Er^{3+} co-doped fiber has a diameter of 18 µm and numerical aperture (NA) of 0.14. Its inner cladding has a D-shaped cross section of 250 µm × 200 µm and an NA of 0.5, which enhances the pump absorption by deflecting the skew rays through the fiber core. A commercial 980 nm laser diode was used as the pump source, and a pair of CaF_2 lens with a focal length of 2.54 cm were used to collimate the pump light and couple the pump into the D-shape inner cladding of Dy^{3+}/Er^{3+} co-doped ZBLAN fiber. A dichroic mirror (Dichroic Mirror 2) with reflectivity of 70% at 3 µm and high transmission at 980 nm was butt-coupled to the flat cleaved front end of the gain fiber and used as an output coupler. Another CaF_2 lens was placed after the angle cleaved rear end of the gain fiber to collimate the 3 µm emission light. A blazed grating (Thorlab GR1325-45031) was placed at 3 cm after the collimating CaF_2 lens to reflect the diffracted beam at a specific wavelength back into the core of the gain fiber, working as the wavelength selective cavity mirror. Another dichroic mirror (Dichroic Mirror 1) with high reflection around 3 µm and high transmission at 980 nm was placed between the collimating lens and focusing lens at 45° to the laser beam to deliver the 3 µm laser beam to the detector. An 1850 nm long pass filter was placed before the detector to make sure that only the 3 µm laser was

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detected. A thermal detector (Thorlabs S415C) and an optical spectrum analyzer (Yokogawa, AQ6376) were used to measure the output power and optical spectrum, respectively.

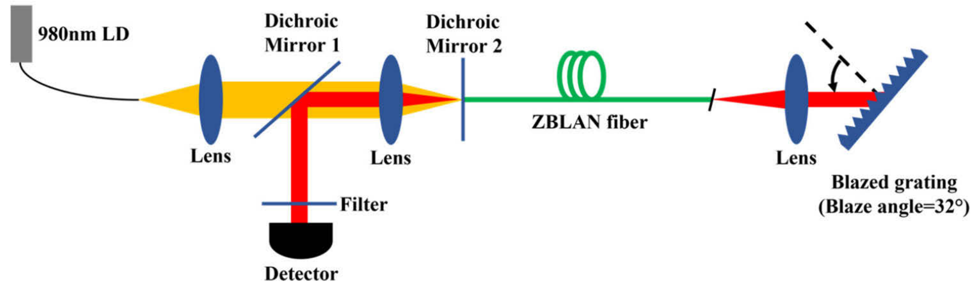

Fig. 3. Schematic of tunable 3-μm Dy^{3+}/ Er^{3+} co-doped ZBLAN fiber laser pumped by a 980 nm laser diode.

3. Experimental results and discussion

In our experiment, the performance of wavelength tunable Dy^{3+}/Er^{3+} co-doped ZBLAN fiber lasers with different gain fibers was investigated. Figure 4(a) shows the optical spectra of the wavelength tunable fiber laser with 3.5-m gain fiber operating at different wavelengths. Wavelength tunable laser operation from 2708 nm to 3296.8 nm was achieved. It should be noted that the wavelength tunable range of the 3.5-m fiber laser was limited by the onset of parasitic lasing at 2930 nm, which can be suppressed by using optical components with highly anti-reflective coatings to reduce the reflections inside the cavity. Using long gain fiber is an alternative approach to conquer the parasitic lasing at 2930 nm and extend the laser operating wavelength because a longer gain fiber can usually produce higher gain at long wavelength, where the emission cross-section of the gain medium is small. To extend the tunable wavelength range of a Dy^{3+}/Er^{3+} co-doped ZBLAN fiber laser beyond 3.3 μm, 4.5 m and 6 m gain fibers were then used in our experiment. The optical spectra of the 4.5-m Dy^{3+}/Er^{3+} co-doped ZBLAN fiber laser operating at different wavelengths are shown in Fig. 4(b). A wavelength tuning range of 2709.2-3373.6 nm was achieved. Figure 4(c) shows the optical spectra of the 6-m Dy^{3+}/Er^{3+} co-doped ZBLAN fiber laser operating at different wavelengths beyond 3.2 μm. The longest operation wavelength achieved with the 6-m gain fiber was 3.38 μm. Further tuning the blazed grating didn't result in laser operation at a longer wavelength but rather onset of parasitic lasing at 3240 μm. Because the ASE of a Dy^{3+}/Er^{3+} co-doped ZBLAN fiber can extend to 3.6 μm as shown in Fig. 2(b), it is very possible to achieve laser operation beyond 3.4 μm if the parasitic lasing is suppressed and a longer gain fiber is used.

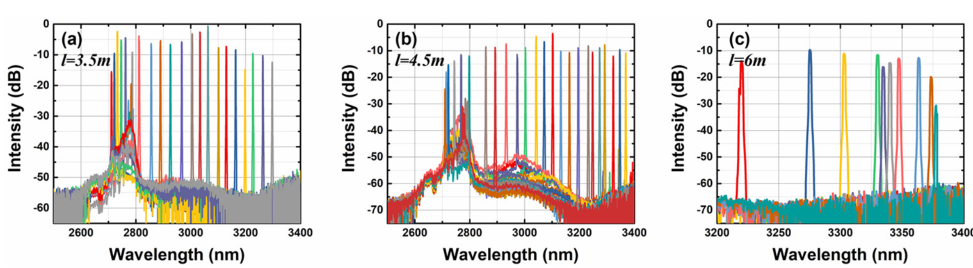

Fig. 4. Measured optical spectra of wavelength tunable Dy^{3+}/Er^{3+} co-doped ZBLAN fiber laser with gain fiber length of (a) 3.5 m and (b) 4.5 m operating at different wavelengths.

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The spectral bandwidth of the wavelength tunable fiber laser was measured by an optical spectrum analyzer with a resolution of 0.1 nm. Figures 5(a) and 5(b) show the typical optical spectrum of the wavelength tunable fiber laser operating at 2.89 μm in logarithmic and linear scales, respectively. The spectral bandwidth was about 0.32 nm, which is determined by the distance between the collimating lens and the blazed grating, the groove density of the blaze grating, and the fiber core diameter of the gain fiber. The spectral linewidth of the wavelength tunable laser can be reduced by increasing the distance between the collimating lens and the blazed grating and using a grating with larger groove number.

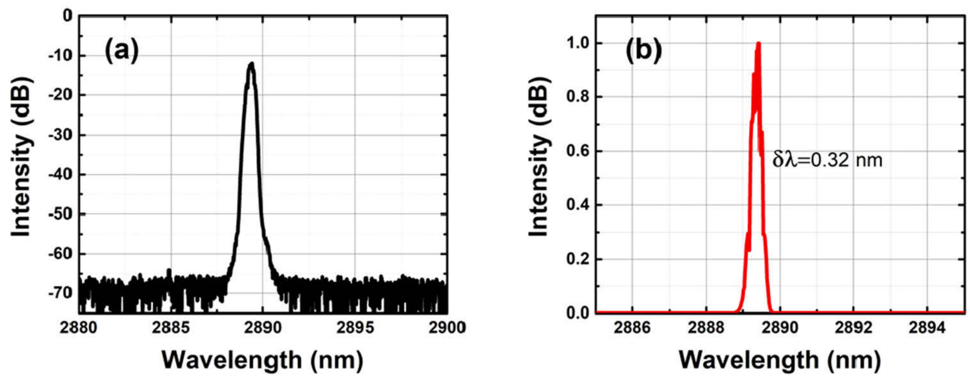

Fig. 5. Measured optical spectrum of the wavelength tunable Dy^{3+}/Er^{3+} co-doped ZBLAN fiber laser operating at 2889 nm with intensity plotted in (a) logarithmic scale, and (b) linear scale.

The output power as a function of the launched pump power for the wavelength tunable 4.5-m Dy^{3+}/Er^{3+} co-doped ZBLAN fiber laser operating at different wavelengths was measured and is shown in Fig. 6. It is clear that the wavelength tunable laser has different pump thresholds and slope efficiencies as it operates at different wavelengths. The slope efficiencies and pump thresholds are summarized in Table 1. The 3 μm laser has the highest efficiency because the 4.5-m Dy^{3+}/Er^{3+} co-doped ZBLAN fiber has the largest gain around 3 μm as shown by the ASE spectrum. The 2.785 μm laser produced by Er^{3+} has the lowest efficiency of 0.56%, which is even much less than that of a single Er^{3+}-doped ZBLAN fiber laser, because it suffers from high loss caused by the energy transfer from Er^{3+} to Dy^{3+} and the strong absorption of Dy^{3+} at this wavelength. When the laser wavelength was tuned to 2.85 μm, the laser efficiency increased to 1.52% because the laser emission was produced by Dy^{3+}. The laser efficiency increased with increasing operating wavelength until reaching a maximum of 3.28% at 3 μm and then decreased with increasing operating wavelength due to the reduced gain at long wavelengths. A slope efficiency of 1.23% was measured for the wavelength tunable fiber laser operating at 3.2 μm. The pump threshold of the 4.5-m Dy^{3+}/Er^{3+} co-doped ZBLAN fiber laser, however, decreased as the operating wavelength increased from 2.85 μm to 3.1 μm. The pump threshold of the wavelength tunable laser operating at 2.85 μm was 12 W and decreased to a minimum value of 5.77 W at 3.1 μm, where the blazed grating has the maximum reflection. Further increasing the laser wavelength led to an increase of the pump threshold due to the decreasing emission cross-section. Because the laser emission below 2.8 μm result only from the $^4I_{11/2}$ -$^4I_{13/2}$ transition of Er^{3+}, the pump threshold of the 2.785 μm laser was 8.2 W, which is smaller than that of the 2.85 μm laser that is produced by the $^6H_{13/2}$ - $^6H_{15/2}$ transition of Dy^{3+}.

The output power at different wavelengths of the 4.5-m wavelength tunable Dy^{3+}/Er^{3+} co-doped ZBLAN fiber laser was measured at pump powers of 15.4 W and 18.5 W, respectively, and is shown in Fig. 7(a). The output power increases with increasing operating wavelength until it

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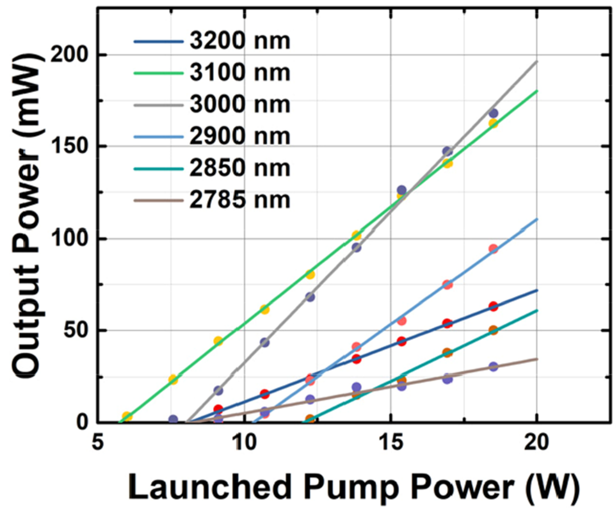

Fig. 6. The output power as a function of launched pump power for the 4.5-m wavelength tunable Er^{3+}/Dy^{3+} co-doped fiber laser operating at different wavelengths.

Table 1. Slope efficiencies and thresholds of the 4.5-m wavelength tunable Er^{3+}/Dy^{3+} co-doped ZBLAN fiber laser operating at different wavelengths.

Wavelength (nm)	Slope Efficiency (%)	Threshold (W)
2785	0.56	8.20
2850	1.52	12.03
2900	2.26	10.28
3000	3.28	8.02
3100	2.53	5.77
3200	1.23	8.28

reaches a maximum at 3 µm and then decreases with increasing operating wavelength above that. A maximum output power of 168 mW at 3 µm was obtained at a pump power of 18.5 W. Higher output power can be obtained with higher pump power, but increases the likelihood of fiber damage due to the thermal management issues at the pumping end. It is also worth noting that the wavelength tunable 4.5-m Dy^{3+}/Er^{3+} co-doped ZBLAN fiber laser cannot operate at 2740 nm or a shorter wavelength at the two pump power levels due to the gain shrinkage of singly Er^{3+}-doped ZBLAN fiber laser, which was also observed in [11]. The output power of the laser at 2740 nm at different pump power levels was measured and is shown in Fig. 7(b). It is clear that the output increased with the increasing pump power until reaching a maximum value of 10 mW at a pump power of 11.32 W. Further increase of the pump power led to quick decrease of the output power and the 2740 nm lasing vanished as the pump power exceeded 13 W. Nevertheless, the operating wavelength of the 4.5-m Dy^{3+}/Er^{3+} co-doped ZBLAN fiber laser can be tuned to 2709 nm at low pump power. The Dy^{3+}/Er^{3+} co-doped ZBLAN fiber laser has the wavelength tuning property similar to that of a single Er^{3+}-doped ZBLAN fiber laser, confirming that Er^{3+} in the codoped system can be forced to lase individually. However, the efficiency of the Dy^{3+}/Er^{3+} co-doped ZBLAN fiber laser is much smaller than that of that of singly Er^{3+}-doped fiber lasers because Dy^{3+} has large absorption in the 2700nm region. The efficiency of a wavelength tunable Dy^{3+}/Er^{3+} co-doped ZBLAN fiber laser can be further improved by optimizing the doping levels of Dy^{3+} and Er^{3+}.

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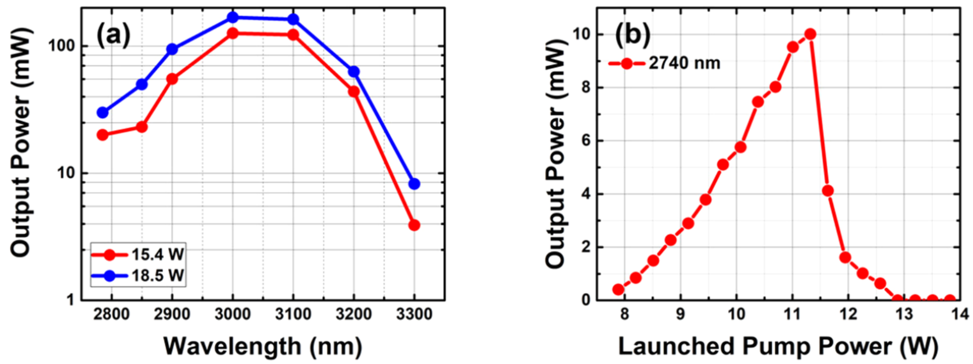

Fig. 7. (a). Output power of the 4.5-m wavelength tunable Dy^{3+}/Er^{3+} co-doped fiber laser operating at different wavelengths pumped at 15.4 W and 18.5 W. (b). Output power as a function of launched pump power for the 4.5-m wavelength tunable Dy^{3+}/Er^{3+} co-doped fiber lasers operating at 2740 nm.

4. Conclusion

In conclusion, we have demonstrated widely wavelength tunable Dy^{3+}/Er^{3+} co-doped fiber lasers using 0.25 mol.% Dy^{3+}/ 4 mol.% Er^{3+} co-doped ZBLAN fiber. A continuous wavelength tunable range of nearly 700 nm was achieved. The efficiency and wavelength tunable range of Dy^{3+}/Er^{3+} co-doped fiber lasers can be further improved by optimizing the doping levels of Dy^{3+} and Er^{3+}. More powerful wavelength-tunable laser in the 2.7-3.4 µm can be obtained by using higher pump power with improved thermal management or using fiber amplifiers.

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Disclosures. The authors declare no conflicts of interest.

Data availability. Data underlying the results presented in this paper are not publicly available at this time but may be obtained from the authors upon reasonable request.

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