PHOTONICS Research

Direct generation of watt-level yellow Dy^{3+}-doped fiber laser

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Yellow lasers (~565–590 nm) are of tremendous interest in biomedicine, astronomy, spectroscopy, and display technology. So far, yellow lasers still have relied heavily on nonlinear frequency conversion of near-infrared lasers, precluding compact and low-cost yellow laser systems. Here, we address the challenge through demonstrating, for the first time, to the best of our knowledge, watt-level high-power yellow laser generation directly from a compact fiber laser. The yellow fiber laser simply consists of a Dy^{3+}-doped ZBLAN fiber as gain medium, a fiber end-facet mirror with high reflectivity at yellow and a 450-nm diode laser as the pump source. We comprehensively investigated the dependence of the yellow laser performance on the output coupler reflectivity and the gain fiber length and demonstrated that the yellow fiber laser with an output coupler reflectivity of 4% and a gain fiber length of ~1.8 m yields a maximum efficiency of 33.6%. A maximum output power of 1.12 W at 575 nm was achieved at a pump power of 4.20 W. This work demonstrated the power scaling of yellow Dy^{3+}-doped ZBLAN fiber lasers, showing their promise for applications in ophthalmology, astronomical exploration, and high-resolution spectroscopy.

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1. INTRODUCTION

Yellow lasers emitted at 565–590 nm have a wide range of research prospects for their existing and potential applications in ophthalmology, astronomy (e.g., laser guide star), medical treatment for acne melasma, Bose–Einstein condensation, and scientific research [1–5]. At present, visible light lasers operating in the red, green, and blue spectral regions have been well developed [6–16], but yellow lasers are relatively difficult and still rely heavily on dye lasers [17] or nonlinear frequency conversion (e.g., frequency doubling [18–20], sum frequency [21], and four-wave mixing [22]) of near-infrared lasers, and suffer from high maintenance cost, a complex system, and degenerated performance. Therefore, researchers always desire an alternative solution for a yellow laser source, which has the advantages of high performance, compactness, low cost, and being maintenance free. The yellow fiber lasers can meet these demands, so there is a strong motivation to develop compact fiber lasers in the yellow spectral region.

In recent years, the frequency downconversion using trivalent rare-earth ion-doped crystals or fibers (e.g., fluoride fiber) is a fascinating way to directly obtain visible emission [8]. Unfortunately, emission spectra of most crystals or fibers doped with rare-earth ions (e.g., Pr^{3+}, Er^{3+}, Ho^{3+}, Tm^{3+}, or Nd^{3+}) cannot cover the yellow range, which results in no significant progress in the high-power yellow fiber lasers. Recently, dysprosium (Dy^{3+})-doped fluoride fibers have been developed and exhibit the strong fluorescence emission in yellow spectral band (from $^4F_{9/2}$ to $^6H_{13/2}$ transition) [23–25], providing the potential of highly efficient yellow laser direct generation. However, up to now, little research progress in Dy^{3+}-doped fiber yellow lasers (usually <10 mW yellow power [26,27]) has been made. The main challenges for a long time have been: (1) the manufacture of Dy^{3+} fluoride fibers with low loss and high gain is relatively immature; (2) the commercially available high-power GaN blue laser sources with high beam quality are scarce; (3) the construction of yellow fiber laser cavity with high efficiency and simple structure is relatively difficult. Recently, thanks to the continuous breakthrough of both rare-earth-doped fluoride fiber manufacturing technology and high-power blue GaN laser diode (LD), high-power yellow-light generation in Dy^{3+}-doped fiber laser can be expected. Most recently, our research group reported a yellow wavelength-tunable (568–582 nm) Dy^{3+}:ZBLAN fiber laser [28], but the output power was still limited to only 142 mW due to the unoptimized cavity designs. Therefore, it is necessary to carry out in-depth research to obtain high-power yellow-light fiber laser for practical applications.

In this paper, we proposed and demonstrated a watt-level high-power yellow fiber laser for the first time. First, in order to obtain high-efficiency emission and high-power output, we experimentally optimized the output coupling and gain-fiber length of the yellow laser. Subsequently, we further demonstrated a yellow fiber laser with an output coupler reflectivity of 4% and a gain fiber length of ~1.8 m according to the optimized results. The laser directly generated 1.12 W yellow laser output with a central wavelength of ~575 nm and a slope efficiency of 33.6%, which has the advantages of simple structure, high performance, and low cost.

2. EXPERIMENTAL PRINCIPLE AND SETUP

A. Energy Level and Spectral Properties of Dy:ZBLAN Fiber

Figure 1(a) shows the energy level schematic of Dy^{3+} for visible fluorescence emission. As we know, all the frequency downconversion fluorescence in the visible spectral band by Dy^{3+}-doped ZBLAN fiber all originates from the $^4F_{9/2}$ level [26,29]. The excitation pathway is as follows: (1) the $^4I_{15/2}$ level is excited by ground-state absorption of the $^6H_{15/2}$ level with ~450 nm pumping; (2) nonradiative relaxation from $^4I_{15/2}$ to $^4F_{9/2}$; and (3) radiative transition from $^4F_{9/2}$ to $^6H_{15/2}$, $^6H_{13/2}$, $^6H_{11/2}$, and $^6H_{9/2}+{}^6F_{11/2}$, which can generate fluorescence emission in the visible spectral region [28]. In our experiment, the Dy^{3+}-doped ZBLAN fiber we used was fabricated by Le Verre Fluoré Inc. and has the following parameters: a dopant concentration of 2000 ppm (parts per million) by weight, a 0.16 numerical aperture, and 12.5/125 μm core/cladding diameters. We measured the ground-state absorption of Dy^{3+}-doped ZBLAN fiber from 400 to 1000 nm with a tungsten halogen lamp, as plotted in Fig. 1(b). The absorption spectrum shows several absorption lines in the blue and near-infrared region. As seen in the inset of Fig. 1(b), the blue absorption line has a peak absorption coefficient of 13.9 dB/m at 452 nm and is suitable for direct excitation. Moreover, it is worth noting that the absorption coefficient of the Dy^{3+}-doped ZBLAN fiber is 11.1 dB/m at our pump wavelength (i.e., 450 nm). As shown in Fig. 1(c), we also measured the fluorescence emission spectrum of the Dy^{3+}-doped ZBLAN fiber under a 450-nm laser excitation. The emission spectrum shows one strong emission line in the yellow (~573 nm) spectral region and other lines in the blue (~485 nm), red (~660 nm), and deep red (~749 nm) wave bands, implying the potential of these different visible-wavelength lasers. We pay special attention to the strongest emission line at ~573 nm from $^4F_{9/2}$ to $^6H_{13/2}$ transition. The branching ratio is 0.755 [30], and thus the transition happens more easily than any other process, implying that it is feasible to directly obtain a high-power yellow-laser emission from the Dy^{3+}-doped ZBLAN fiber pumped by a 450-nm diode laser. Furthermore, the lifetime of levels $^4F_{9/2}$ and $^6H_{13/2}$ is 1.21 ms and 0.65 ms respectively, which may cause laser signal reabsorption [31].

B. Experimental Setup

Figure 2(a) shows the experimental setup of our yellow Dy^{3+}-doped ZBLAN fiber laser, and Fig. 2(b) depicts the corresponding photograph of the yellow fiber laser. The yellow

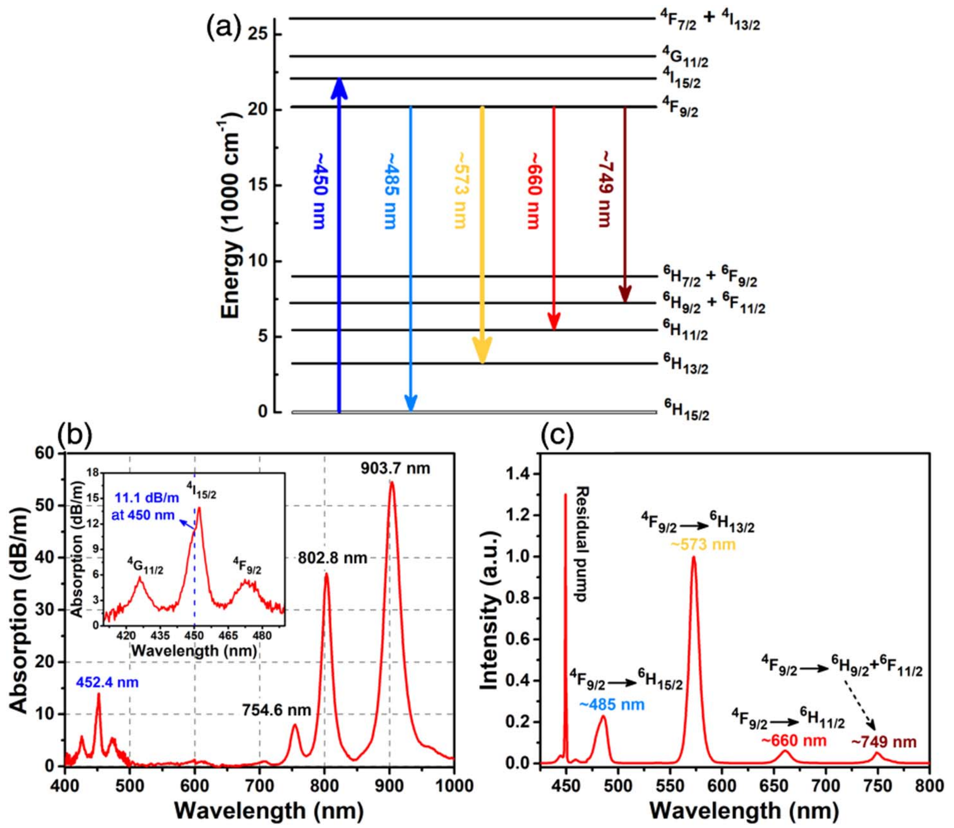

Fig. 1. (a) Energy-level schematic of Dy^{3+}; (b) absorption spectrum of 2000 ppm Dy^{3+}-doped ZBLAN fiber (inset, zoom-in absorption spectrum in a range of 410–490 nm); and (c) fluorescence emission spectrum of 3.9-m Dy^{3+}-doped ZBLAN fiber pumped at 450 nm.

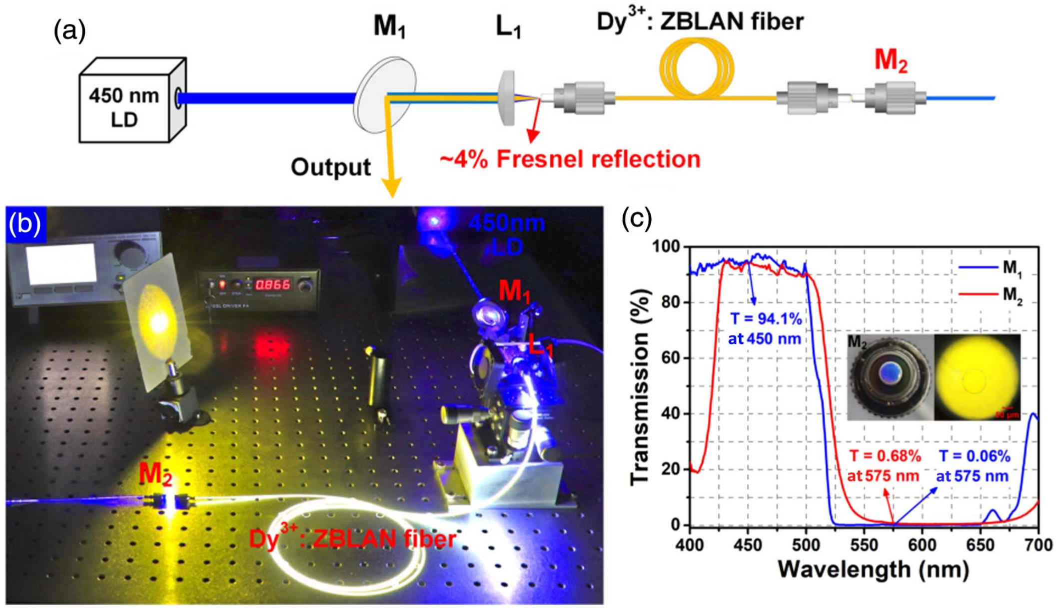

Fig. 2. (a) Schematic and (b) photograph of the proposed yellow Dy^{3+}-doped fiber laser; (c) optical transmission spectra of the yellow-reflection mirror (M_1) and the fiber end-facet mirror (M_2), respectively [insets, photo (left) and microscopic image (right) of the M_2].

laser consists of a 450-nm diode laser, a Dy^{3+}-doped ZBLAN fiber, a 45° yellow highly reflective dichroic mirror (M_1), and a fiber end-facet mirror (M_2). The commercial 12-W 450-nm diode laser as pump source was coupled into the Dy^{3+}-doped fiber by an aspheric lens with an 11-mm focal length. Due to the poor beam quality (beam waist size and divergence angle are 2.24×4.32 mm and 3.67×3.80 mrad, respectively), the maximum coupling efficiency of pump laser is only ~36%. It is worth mentioning that the power launched into the fiber was measured by recording the output power coupled into a 15-cm Dy^{3+}-doped ZBLAN fiber plus the absorbed power of the fiber. The compact all-fiber linear cavity for yellow-light oscillation is constructed by the homemade fiber end-facet mirror (M_2), together with a ~4% Fresnel reflection from the end facet of the Dy^{3+}-doped fiber. The M_2 was directly connected on the end facet of a matching silica fiber and has a ~99.3% reflectivity around 575 nm. A ceramic sleeve with a 2.5-mm inner diameter was used to realize the efficient coupling between the gain fiber and the M_2. The output laser was extracted with the 45° highly reflective yellow mirror (M_1). We measured the 45° transmission spectrum of the M_1, as shown in Fig. 2(c). The reflectivity of M_1 is as high as 99.9% in the whole yellow spectral region, and it has a high transmittance of 94.1% at 450-nm pump wavelength. Furthermore, in our experiment, the optical spectrum of the yellow laser was measured by a 350–1750 nm optical spectrum analyzer (AQ-6315E, Ando), and the output power was recorded by a 350–1100 nm integrating sphere optical power meter (S142C and PM320E, Thorlabs).

3. EXPERIMENTAL RESULTS AND DISCUSSIONS

A. High-Power Yellow-Laser Output

In our experiment, a 1.8-m Dy^{3+}-doped ZBLAN fiber was used as the gain medium according to our experimental optimization below. The continuous-wave yellow-laser threshold is about 831 mW. The output characteristics of the yellow-fiber laser are illustrated in Fig. 3. Figure 3(a) shows the laser output power as a function of the pump power. The output power linearly increases without any saturation, and the slope efficiency is as high as 33.6%. A maximum output power of 1123 mW was obtained, which is greatly scaled up to 10–100 times higher than those of the previously reported yellow Dy^{3+}-doped fiber lasers [26–28]. The evolution of output optical spectrum with the pump power is given in Fig. 3(b). With the increase of pump power, the lasing wavelength has slightly shifted towards the longer wavelength (i.e., wavelength redshift), and the red shift extends from 574.3 to 574.9 nm in the available pump power range [see Fig. 3(d)], possibly due to the laser signal reabsorption from the lower laser level (i.e., $^6H_{13/2}$) [32,33]. We measured the beam quality parameter and near-field intensity distribution of the yellow laser beam with a beam quality analyzer (WinCamD-UCD12, DataRay), as shown in Fig. 3(c). According to the measurement results, the measured M^2 value of the major and minor axes is 6.08 and 6.02, respectively. Therefore, the output laser beam has a multimode output, although the near-field intensity distribution from both the 2D and 3D photographs shows a Gaussian-like shape profile. As depicted in Fig. 3(d), to evaluate the operation stability of the yellow fiber laser, we monitored the output laser power every 5 min over 1 h at the pump power of 2.25 W. Based on the measured data, the root mean square error of the output power can be evaluated to be ~2.3 mW (corresponding to only a ~0.5% relative power fluctuation), showing the excellent stability of our yellow fiber laser. In addition, we measured the transmission loss of Dy^{3+}-doped fiber before and after high-power yellow laser operation, but no obvious photodarkening effect was observed, indicating the high-quality fabrication of the fluoride fibers by Le Verre Fluoré Inc.

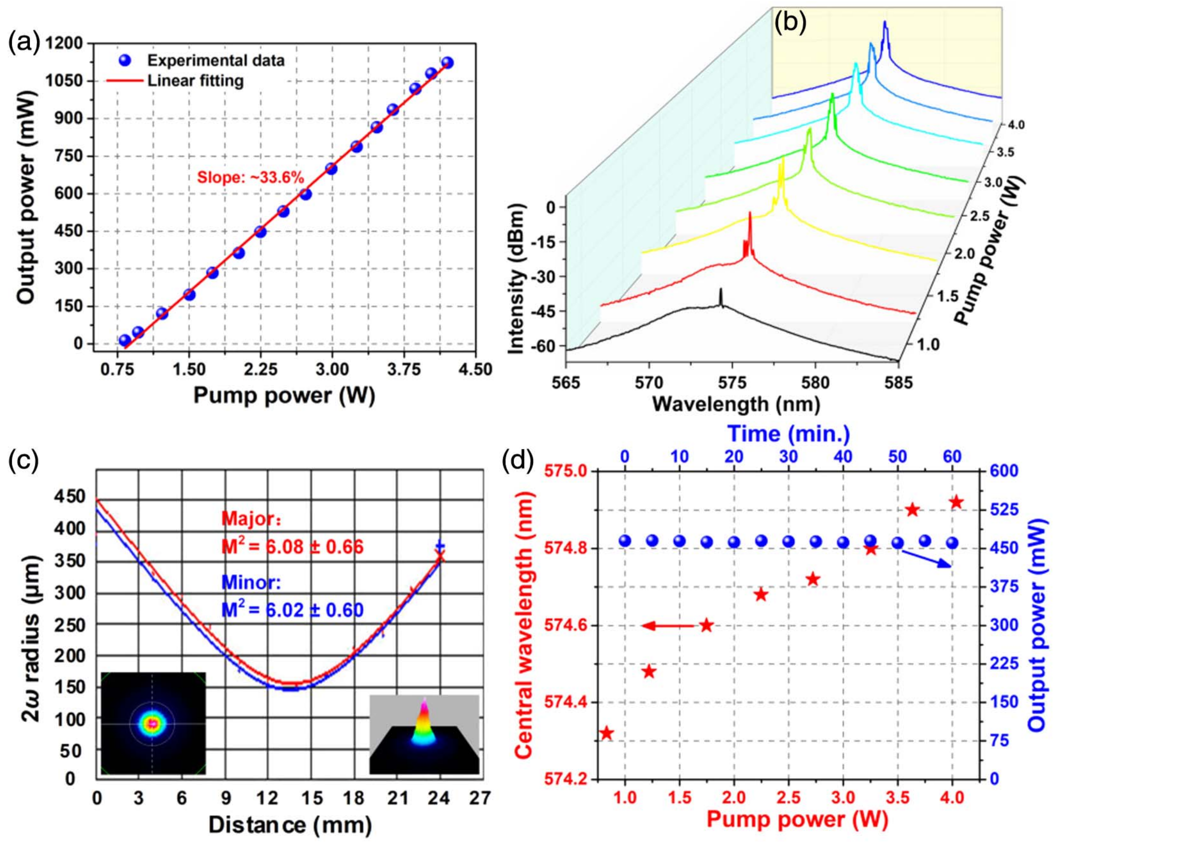

Fig. 3. Characteristics of yellow fiber laser with a 1.8-m Dy^{3+}-doped ZBLAN fiber. (a) The output power as a function of the pump power; and (b) the optical spectra under different pump powers; (c) the beam quality parameter and near-field intensity distribution of the output laser beam; (d) the central wavelength versus the pump power, and laser power stability measurement.

B. Experimental Optimization of High-Power Yellow Fiber Laser

In order to realize the highly efficient emission and high-power output from our yellow fiber laser, we performed the optimization of laser experiments using different output coupling and different lengths of Dy^{3+}-doped ZBLAN fiber. In the optimization experiment of output coupling, we used a 1.8-m Dy^{3+}-doped ZBLAN fiber as the gain medium. To find the optimal output coupling, we inserted five different coating flat mirrors at the laser output end of M_2. The transmittance of these mirrors is 13.4%, 27.0%, 39.8%, 81.8%, and 96% (i.e., Fresnel reflection of gain fiber end facet) at 575 nm, respectively. Figure 4 shows the output characteristics of the yellow Dy^{3+}-doped ZBLAN fiber laser with different output couplings. As shown in Fig. 4(a), when the output coupling varied from 13.4% to 96.0%, both the yellow output power and the laser slope efficiency sharply increased from 170 to 790 mW at the pump power of 3.25 W and from 6.0% to 33.6%, respectively, although the laser threshold correspondingly increased from 540 to 795 mW. Figure 4(b) gives the corresponding output spectra of the yellow fiber laser under a pump power of 1.51 W. It can be seen that the laser spectrum becomes narrow and highly pure as the output coupling increases, whereas the central wavelength remains unchanged. This can be interpreted as follows: as increasing the output coupling (equivalent to increasing the cavity loss), the edge-wavelength gain in the yellow fluorescence range is less than the cavity loss, and laser emission cannot be generated. Therefore, to achieve the highly efficient output and high-performance spectrum, the output coupling should be selected as ~96% (i.e., the Fresnel reflection of the fiber end facet).

Subsequently, the effect of the Dy^{3+}-doped ZBLAN fiber length on laser performance was investigated experimentally. In the experiment, we used the same experimental setup of the yellow fiber laser as shown in Fig. 2, and three different lengths of Dy^{3+}-doped ZBLAN fiber (i.e., 0.9, 1.8, and 3.9 m) were employed. The output characteristics of the yellow fiber laser with different-length Dy^{3+}-doped ZBLAN fibers are given in Fig. 5. Figure 5(a) shows the output power as a function of the pump power. One can see that the laser output power and slope efficiency using 1.8-m Dy^{3+}-doped ZBLAN fiber are the highest. The obtained maximum output power is 1123 mW, and the laser slope efficiency is as high as 33.6%. In addition, the laser output performance using 3.9-m Dy^{3+}-doped ZBLAN fiber has only a slight decline, with a 31.7% slope efficiency and a 1060 mW output power, but the performance using 0.9-m Dy^{3+}-doped ZBLAN fiber shows severe degeneration. The output optical spectra of the yellow fiber laser with different gain-fiber lengths are plotted in Fig. 5(b). As the gain-fiber length increases from 0.9 to 3.9 m, the central wavelength of

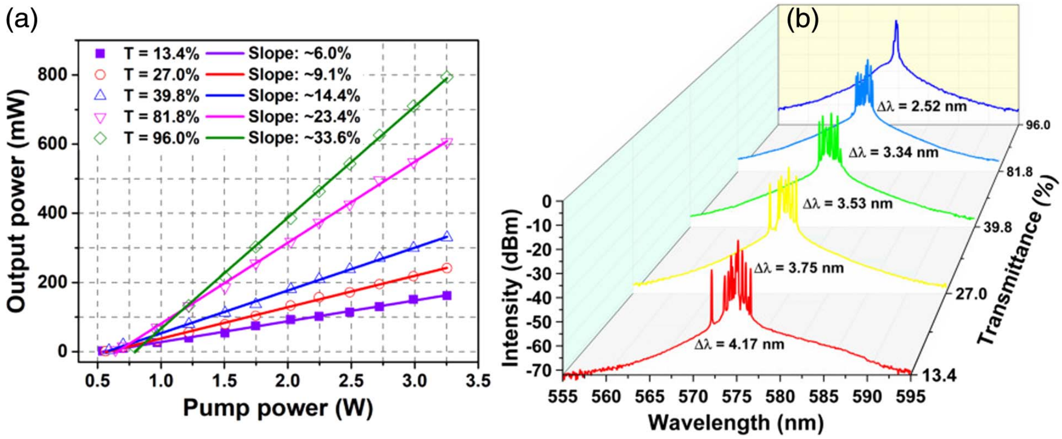

Fig. 4. Characteristics of yellow Dy^{3+}-doped ZBLAN fiber laser with different output couplings. (a) The output power versus the pump power; and (b) the optical spectra of the yellow fiber laser with different output couplings pumped at 1.50 W.

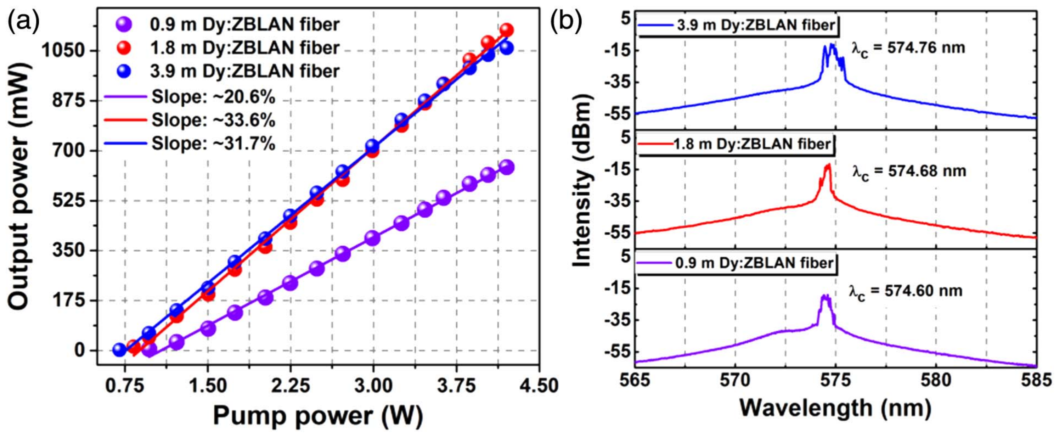

Fig. 5. Characteristics of yellow fiber laser with different lengths of Dy^{3+}-doped ZBLAN fiber. (a) The output power as a function of the pump power; and (b) the optical spectra of the 0.9, 1.8, and 3.9-m fiber laser pumped at 2.25 W.

the laser is slightly redshifted, which was caused by the laser signal reabsorption. Considering the purpose of a compact, low-cost, and high-power yellow fiber laser, the output coupling and the Dy^{3+}-doped ZBLAN fiber length should be designed to be 96% and ~1.8 m, respectively, according to the optimization results in Figs. 4 and 5.

4. CONCLUSION

In conclusion, we demonstrated a high-efficiency, watt-level yellow fiber laser with a central wavelength of ~575 nm by directly pumping Dy^{3+}-doped ZBLAN fiber with a 450-nm LD. We carried out experimental optimization of the effects of the output coupling and gain-fiber length on the yellow laser performance, revealing that ~96% output coupling and ~1.8 m gain fiber are optimal for high-power output and high-quality spectrum of the yellow fiber laser. According to the optimization results, the watt-level yellow-laser emission has been directly generated without additional frequency conversion elements (e.g., nonlinear crystal). The maximum output power is up to 1.12 W (1–2 orders higher than those reported previously), and the slope efficiency is as high as 33.6%. To the best of our knowledge, this is the largest output power from yellow fiber lasers so far. This work provides a new paradigm for compact high-power fiber lasers in the yellow spectral region.

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