4-W single transverse mode Yb^{3+}-doped fiber laser pumped by 915-nm laser diode array

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A cladding-pumped ytterbium-doped fiber laser is described in this letter. Using unusual pumping source with 915-nm wavelength, slope efficiency up to 75% with respect to absorbed input power and output power is obtained, a maximum output power of 4.006 W with fundamental mode is measured.

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In the 1960's, the lanthanide-doped glass fiber laser was invented by Snitzer *et al.*[1], soon after the solid-state glass laser appeared. However the output power of these lasers was ultimately limited by the launching excitation energy directly into the core of the fiber. With the development of the cladding pump fiber and the semiconductor laser diode in 1988, this limitation was removed. Now high power double-clad fiber lasers (DCFLs) have become a reality.

In addition, DCFL has a number of intrinsic advantages over lamp and diode pumped YAG lasers including size, reliability, wavelength selectivity, heat dissipation, and operational cost. Especially high output power DCFL could maintain good beam equality. So DCFL has many potential applications in machining, telecommunication, medicine, sensors, and military weapons.

In China the high power fiber laser has been speedily developed. The continuous wave (CW) output power of 137 W from D-shaped DCFL was reported by Yan *et al.*[2]. Subsequently Lou *et al.* have also realized output power of DCFL of > 200 W[3]. In addition many researchers have all studied on fiber lasers and made great progresses in different aspects[4,5]. But they almost used 975—980 nm laser diode array (LDA) as a pumping source. The pumping source around 975 nm has many advantages, especially for the high absorption rate by the double-clad fiber (DCF), as shown in Fig. 1. However the pumping source around 915 nm has some unique benefits itself.

First the pumping source around 915 nm has a wider absorption bandwidth than that around 975 nm. From Fig. 1, we can see that the absorption curve around 915 nm is more smooth than that around 975 nm. Full-width at half-maximum (FWHM) at 915 nm peak is about 50 nm, while only about 8 nm at 975 nm peak. The realization of good performance of fiber lasers has high request for pump wavelength stability if the pumping source around 975 nm is chosen. However using the pumping source of 915 nm can decrease this request to a great extent. So the pumping sources of 915 nm, especially as a mixed pumping source[6], are widely used to realize high output power of fiber lasers.

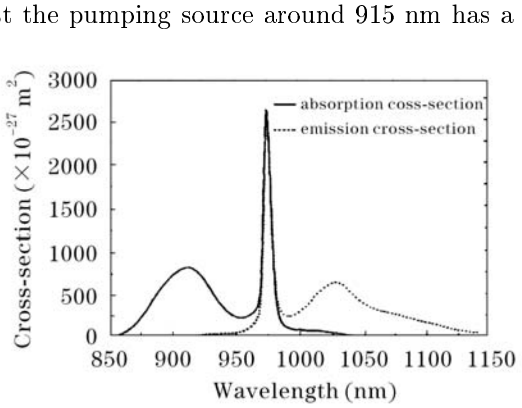

Fig. 1. Absorption and emission cross-sections versus wavelength in the DCF.

Secondly it offers convenience for the design and fabrication of dichroic mirror (or film). Because the pumping source around 975 nm is very near to the laser wavelength (around 1060 nm). For fabrication of dichroic mirror with high reflection (HR) at 1060 nm and high transmission (HT) at 975 nm, the wavelength difference is to small, so some exact control measures are required in the fabrication of the dichroic mirror (or film) and it brings difficulties in designing the dichroic mirror (or film). But using the pumping source around 915 nm can avoid these questions.

Thirdly the pumping source around 915 nm has lower request for the DCF quality. In ytterbium-doped silica fibers the excited state lifetime of the Yb ions is easy to be decreased to a very small value, leading to a strong unbleachable loss, especially if the pump or signal wavelength is around 975 nm[7]. It seems to be caused by certain impurity or structural defect of fibers as proposed in Ref. [7]. If using pumping source around 915 nm, situation will get better. Of course this also is valued for the same kind of DCF. Therefore there has a wider choice for DCF if the pump wavelength is around 915 nm, which can better facilitate the realization of products of DCFL in the future. In this paper, we realized 4.006-W output power with single transverse mode by using 915-nm pumping source.

The experimental setup is shown in Fig. 2. For this CW fiber laser implementation, we use 0.06 numerical aperture (NA) and 20-μm core Yb^{3+}-doped fiber (NUFERN Corp., USA). It has a 400-μm inner cladding with a NA of 0.46. The doped Yb^{3+} concentration is 0.44 wt.-%. Absorption peak at 915 nm is 0.6 dB/m. In the experiment we use this kind fiber of 20 m. 915-nm

LDA (Hi-Tech Optoelectronics Co., Ltd.), whose FWHM is 2.7 nm, coupled with fiber that has pumping source of 1.1 mm diameter and 0.11 NA. The pumping source offers 31-W output power. The LDA is water-cooled to match the absorption of Yb^{3+}-doped fiber.

The light from the pumping source passes through the elaborate coupling systems to focus on the aperture of 400 μm. A dichroic mirror (915 nm, $T > 97\%$; 1060—1100 nm, $R > 99\%$) is placed between the pump and the fiber, which tightly touches the front end of DCF. Resonance cavity is composed of the dichroic mirror, DCF, and the perpendicularly polished back end of DCF. The Yb^{3+}-doped fibers are coiled to a radius of 50 mm.

We adjusted the experimental setup for getting best result. Figure 3 shows the measured total output power versus absorbed input power. A maximum output power of 4.006 W is measured by P1000 power meter. The measured optical-to-optical conversion efficiency is 62%. The slope efficiency has not obvious decrease with increasing the pump power. The measurement result shows that the pump light is absorbed sufficiently and the unabsorbed pump power is below 150 mW. 75% slope efficiency of the fiber laser is obtained.

Figure 4 shows the output spectrum of the fiber laser measured by SBP 150 spectrograph. The output spectrum is centered at 1076.8 nm.

The output light is single transverse mode because the fiber coiling to 50-mm radius suppresses high-order modes such as LP_{11} although the diameter of the core is 20 μm. As is well known there is an upper limit to the core diameter beyond which single mode operation is not guaranteed. Specifically for a step-index fiber single mode operation, the unitary frequency $V = \pi d_{\text{core}} NA_{\text{core}}/\lambda$ remains below 2.405, where $d_{\text{core}} = 20$ μm is the core diameter, $NA_{\text{core}} = 0.06$ is core numerical aperture, and $\lambda = 1076.8$ nm is the wavelength of operation[8]. We can calculate $V = 3.501 > 2.405$. So there are many high-order modes in the fibers. At very low NA (below 0.06) fibers exhibit high bend sensitivity

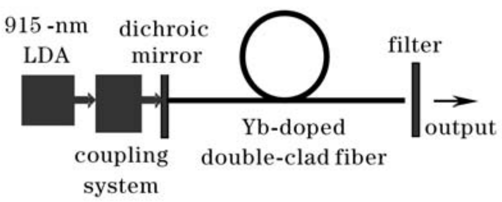

Fig. 2. Experimental setup of Yb-doped DCFL.

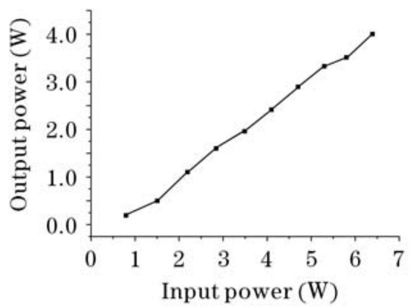

Fig. 3. Output power versus the input pump power of the Yb^{3+}-doped fiber laser.

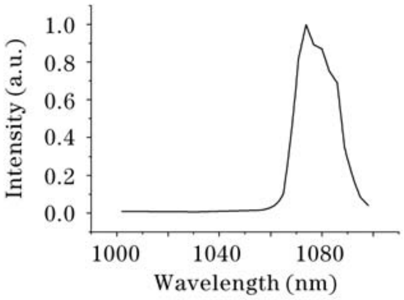

Fig. 4. Output spectrum of the Yb^{3+}-doped fiber laser.

and the fundamental mode is least sensitive to bend loss[9,10]. Bend loss can be used as a form of distributed spatial filtering. For all modes, the bend-loss attenuation coefficient (α, in decibels per meter) depends exponentially on the radius of curvature. By calculating the value of α we can get that the LP_{11} experiences around 50 dB/m of attenuation (and higher order modes are even more attenuated) while the LP_{01} mode experiences only around 0.01 dB/m. Therefore using bend loss to discriminate against high-order modes allows the core diameter to be increased significantly beyond the single mode (SM) limit, i.e., we coil the fibers to make the high-order modes attenuate mostly along the total length of fibers. At last there is only fundamental mode left.

In conclusion, we have described the cladding-pumped DCFL. We use an unusual pumping source with 915-nm wavelength and discuss its some advantages. The output power of 4.006 W with single transverse mode is obtained. The high slope efficiency (75%) in a DCFL operating at 1076.8 nm is demonstrated. The output power and the conversion efficiency can be further improved by increasing the pump power and the pump coupling efficiency, especially the latter.

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