Output characteristics of LMA Yb^{3+}-doped photonic crystal fiber lasers

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ABSTRACT

The output characteristics of fiber lasers built with large-mode-area(LMA) Yb^{3+}-doped double-clad PCF are experimentally investigated. The gain fiber used in the experimental setup is a LMA Yb^{3+}-doped double-clad PCF, which contains an Yb^{3+}-doped core of 23μm in diameter and a holy inner clad of 420μm in diameter. In the forward-output configuration the maximum output is 3.43W and the slope efficiency is 34.6%. At the same pump power, the maximum output in the backward-output configuration is 3.63W and the slope efficiency is 38%. The spectra show that the fiber lasers in both forward-output and backward-output configurations produce multi-wavelength output in a range from 1067nm to 1076nm and unstable. Single wavelength output at 1067.5 nm with a FWHM of about 0.2nm is demonstrated by using a dual-end-output configuration, and a maximum output of 4.25W with a slope efficiency of 44.1% is obtained.

Keywords: fiber laser, Yb^{3+}-doped, photonic crystal fiber, large-mode-area

1. INTRODUCTION

In recent years, fiber lasers have been rapidly developed and applied in many fields such as sensing, optical communication, industrial manufacture, defense and nonlinear optics. To overcome the mismatch between the high power multimode diode pumps and the rare earth-doped gain media in the small size fiber core region, double-clad fibers (DCFs) have been widely used in high power fiber lasers, and makes it possible to carry out continuous wave emission above 1 kW in multimode and hundreds of watts in single mode from one active fiber. However, for the sake of single mode operating, the mode diameter of most conventional DCFs are only of several microns, which not only limits the absorption of pump light but also results in obvious nonlinearities and significant fiber damage under high power condition. In order to improve the output power while keeping the high beam quality, rare earth-doped large-mode-area (LMA) DCFs designed with the concept of photonic crystal fiber (PCF) [1] are used as the active fiber in fiber lasers, recently. Taking advantage of its novel structure and optical properties, the core diameter of PCF can be scaled to infinity while staying single-mode by proper design of the holey cladding. Fiber lasers built with LMA Yb^{3+}-doped double-clad PCF have been demonstrated, and continuous wave emission in single mode of hundreds of watts has been achieved[2-3]. In this paper, the experimental study on the output characteristics of fiber lasers built with LMA Yb^{3+}-doped double-clad PCF in different configurations is reported. Specially, the spectral stability of LMA Yb^{3+}-doped double-clad PCF lasers is investigated for the first time to our knowledge, which is of great importance to practical applications.

2. DESIGN OF THE EXPERIMENT SETUP

The gain fiber used in our experiment is a LMA Yb^{3+}-doped double-clad PCF provided by crystal fiber A/S Co., which contains an Yb^{3+}-doped core of 23μm in diameter and a holy inner cladding of 420μm in diameter, as shown in Fig.1. To efficiently collect and guide pump light in the pure silica multimode inner cladding, there is a micro-structured region (a ring of air holes) around the inner cladding of the double-clad PCF. Due to the very low effective index of the air hole ring, the inner cladding has an extremely high numerical aperture (NA) of about 0.55, which ensures an efficient coupling for the pump light. Within the inner cladding is the Yb^{3+}-doped core, and the numerical aperture of which is about 0.05. Theoretically, this fiber is single-transverse mode for the signal light about 1060nm. The absorption coefficient of the Yb^{3+}-doped fiber core for the 976nm pump light is about 0.9dB/m. The fiber length used in our experiment is 6.5m, which is an available maximum fiber length for us by now but not an optimized fiber length.

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International Symposium on Photoelectronic Detection and Imaging 2009: Laser Sensing and Imaging,
edited by Farzin Amzajerdian, Chun-qing Gao, Tian-yu Xie, Proc. of SPIE Vol. 7382, 738250
 · doi: 10.1117/12.835661

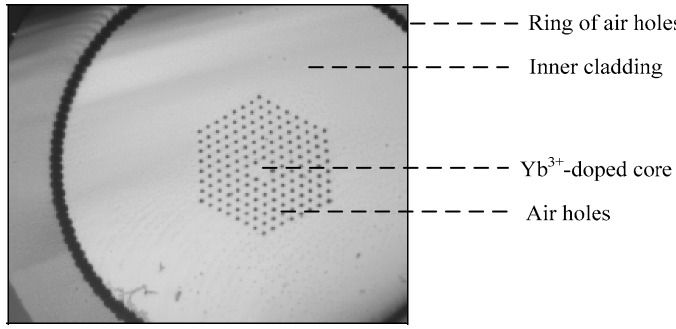


Fig.1. the SEM image of the LMA Yb^{3+}-doped double-clad PCF used in our experiment.

The experimental setup of the fiber laser is composed of a gain fiber (LMA Yb^{3+}-doped double-clad PCF), a pump laser diode, two dichroic mirrors (DM1, DM2), a total reflective mirror (TRM), and three lenses (L1, L2, and L3). The pump used in our experiment is a laser diode system (LD) provided by Coherent Co., USA, which operates with a center wavelength of 976nm. Generally, there are three basic configurations as shown in Fig.2 (a) to Fig.2(c).

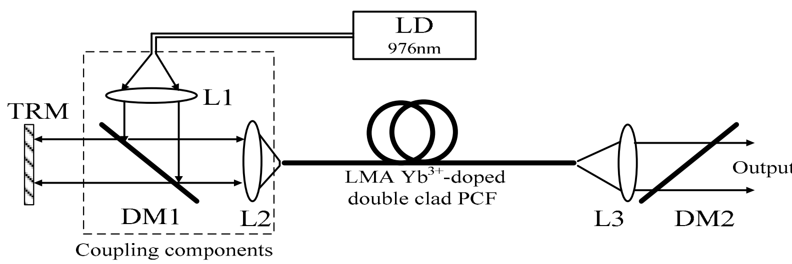


Fig.2(a). Yb^{3+}-doped double-clad PCF laser in forward-output configuration.

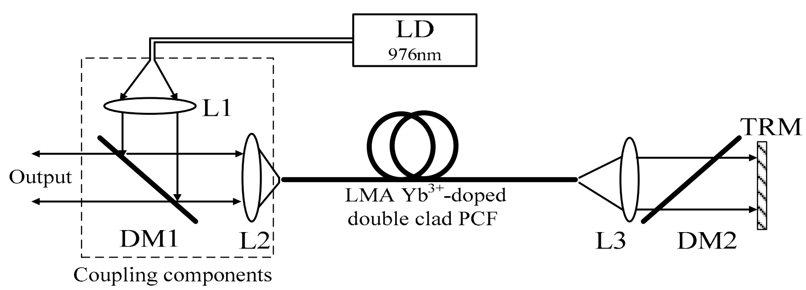


Fig.2(b). Yb^{3+}-doped double-clad PCF laser in backward-output configuration.

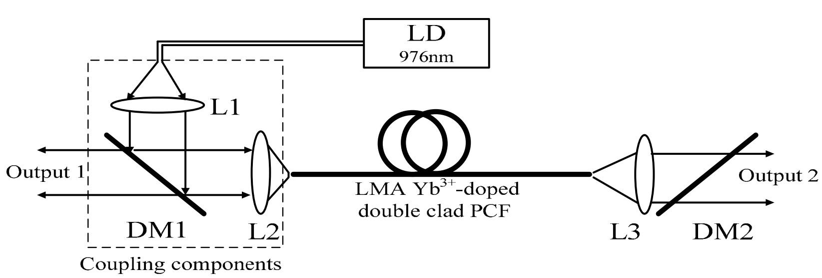


Fig.2(c). Yb^{3+}-doped double-clad PCF laser in dual-end-output configuration.

In the forward-output configuration as shown in Fig.2 (a), the resonator is made up of a total reflective mirror (TRM) and a polished end of the Yb^{3+}-doped PCF for laser output. DM1 and DM2 both have high reflection of more than 99% for the 976nm pump light and high transmission for the signal light about 1060nm, and are placed in an angle of 45 degree to the fiber axis. Lens L1, L2 and DM1 constitute a coupling system for pump light. DM2 is used to remove the residual pump light from output. Lens L3 is set between the PCF and DM2 to collimate the output beam. In this configuration, the input pump light and the laser output propagate in the same direction.

In the backward-output configuration as shown in Fig. 2(b), the TRM is placed after DM2, that is the resonator is made up of the TRM and the fiber end for pump input, and the input pump light and the laser output propagate in the contrary direction. The other components are just as same as in Fig.2 (a).

Fig.2(c) shows a dual-end-out configuration used in our experiment. In this configuration, the TRM is removed. The resonator is formed by the polished two fiber ends of the Yb^{3+}-doped double-clad PCF laser, and the output light emit from both end of the PCF.

3. EXPRIMENTAL RESULTS AND DISCUSSIONS

The output laser power and spectra are measured with a laser power meter (LP-3C, Physcience Opto-electronics Co., Ltd., China) and an optical spectrum analyzer（AQ6317C, Yokogawa Electrics Co., Japan）, respectively.

3.1 Output characteristics of fiber laser in forward-output configuration

Firstly , the output power at different pump levels of the fiber laser in Fig.2(a) is measured using laser power meter. Fig.3 shows the measured output power (the black squares) as a function of the pump power. The linear fit data (the real line) in Fig.3 shows that the threshold of the fiber laser is about 2.2W, and the slope efficiency is about 34.6%. A maximum output power of 3.43W is obtained as the pump power is increased to the maximum value of 12.11W, and the corresponding optical-to-optical efficiency is 28.3%.

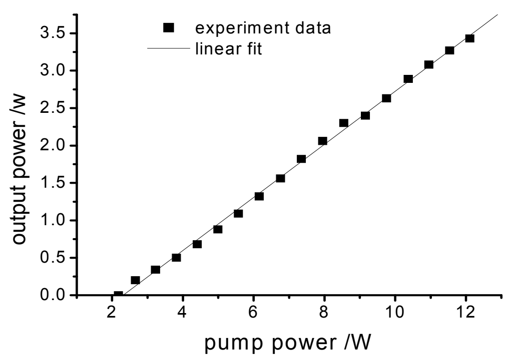
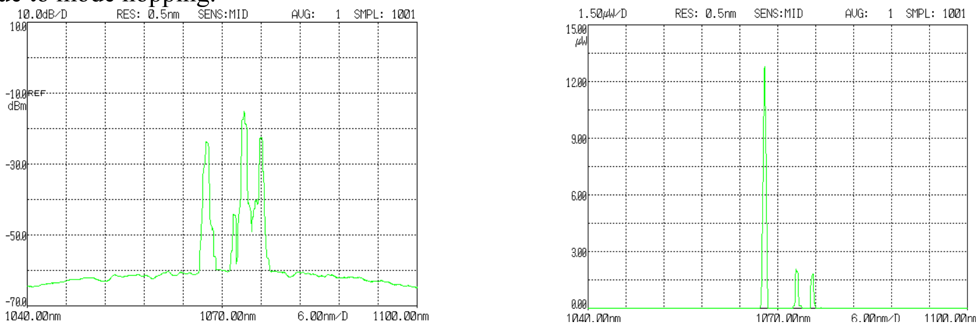


Fig.3. Output power of the Yb^{3+}-doped double-clad PCF laser as a function of the pump power.

When the input pump power is below the threshold, we observe a smooth fluorescence spectrum in the region from 1000nm to 1180nm, which is produced by the amplification of spontaneous emission (ASE) in the Yb^{3+}-doped double-clad PCF. As the pump power is increased above the threshold of the laser, there are several little peaks arising from the fluorescence spectrum. Fig.4 (a) shows the spectrum at a pump power of 3.8 W, from which we can see the center wavelength of these spectral peaks are from 1067nm to 1076nm and the intensity of them vary randomly.

As the pump power is increased to a value far above the threshold, the number of the spectral peaks is reduced. Fig.4 (b) shows the measured spectrum at a pump power of 5W. We can see there are only three peaks at 1067.5nm, 1073nm, and 1076nm, and the intensity of the peak at 1067.5nm is obviously greater than that of the other two peaks. But when observe for some time, we find the wavelength of the peak with the maximum intensity shifts among above mentioned three wavelength, irregularly. This phenomenon is well known as "mode hopping"[4], which is induced by competition between the longitudinal modes. As the pump power is increased to the maximum value of 12.11, the output spectrum is still unstable due to mode hopping.



(a) pump power is 3.8W (b) pump power is 5.0W

Fig.4. Spectra of the Yb^{3+}-doped double-clad PCF laser at different pump power

3.2 Output characteristics of fiber laser in backward-output configuration

The output power of the fiber laser in backward-output configuration is shown in Fig.5. We can see that the threshold of this fiber laser is about 2.6W. The maximum output power of 3.63W is obtained at a pump power of 12.11 W, and the optical to optical conversion efficiency is about 30%. A slope efficiency of 38% is obtained by linear fitting calculation. As compared with the forward-output fiber laser, the backward-output fiber laser seems to have a higher efficiency, which is in accord with the theoretical calculation results presented by us[5].

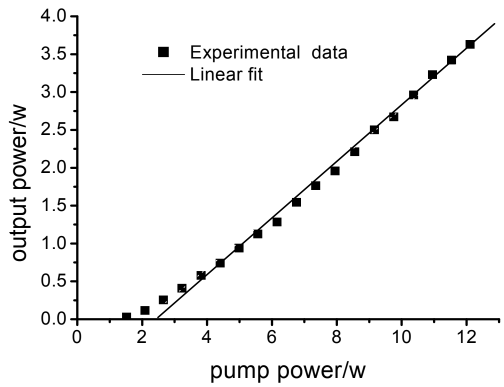
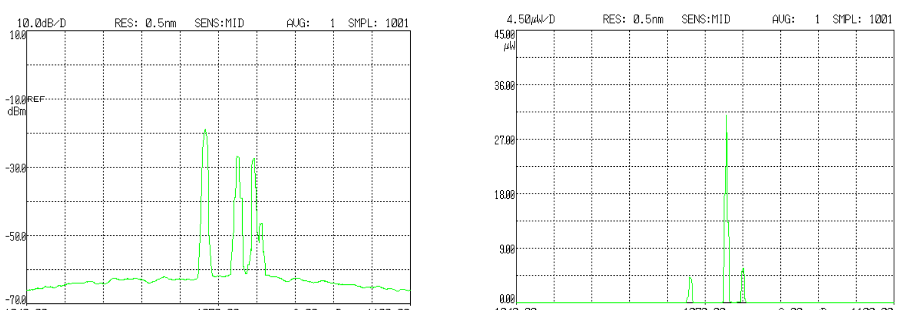


Fig.5. Output power of the Yb^{3+}-doped double-clad PCF laser as a function of the pump power.

Fig.6(a) and (b) show the spectra of the Yb^{3+}-doped double-clad PCF laser at a pump power of 3.8W and 7.35W, respectively. There is obvious mode hopping as similar to the spectra of the forward-output fiber laser.



(a) pump power is 3.8W (b) pump power is 7.35W

Fig.6. Spectra of the Yb^{3+}-doped double-clad PCF laser at different pump power

3.3 Output characteristics of fiber laser in Dual-end -output configuration

Because many applications which require stable single wavelength are not met by the lasers shown in Fig.2 (a) and Fig.2 (b), we present a dual-end-output configuration as shown in Fig.2(c) to get a better spectral stability. In this configuration, the TRM is removed, and laser emits from each end of the Yb^{3+}-doped double-clad PCF.

The output power of the dual-end-output fiber laser is measured and shown in Fig.7, where the output1, output2, and output1 and 2 denote the backward output, the forward output and the total output, respectively. At the maximum pump power of 12.11W, output1 and output2 are 2.48W and 1.77W, respectively. The total output of output1 and output2 is 4.25W with a slope efficiency of 44.1%, and the optical to optical conversion efficiency is about 35.1%.

Comparing the output power of the fiber lasers in different configurations, we can see that both the total output and the efficiency of dual-end-output fiber laser are greater than that of one-end-output (the forward-output fiber laser and the backward-output) fiber laser. The main reason, in our opinion, is that the resonator of the one-end-output fiber laser is formed with a TRM and a fiber end, and there is unavoidable coupling loss when signal light propagates into or out of the fiber, while, in the dual-end-output fiber laser the resonator is formed by two fiber ends and there is no such coupling loss for signal light, so that a higher efficiency is obtained.

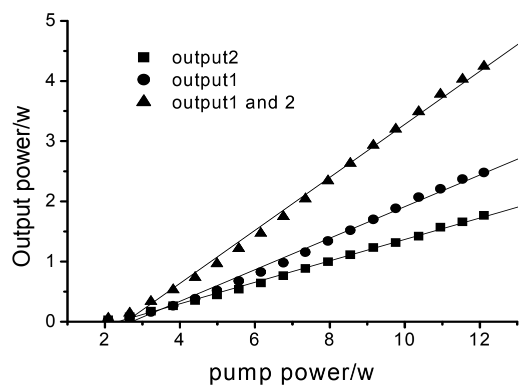
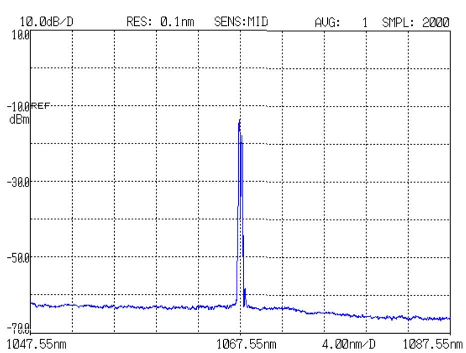
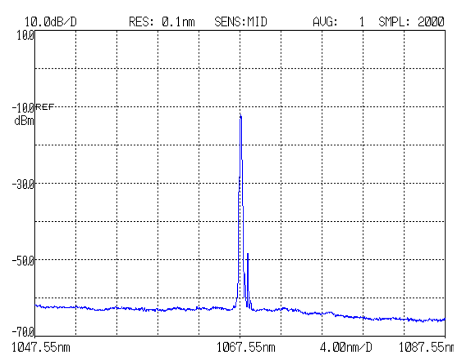


Fig.7. Output power of the Yb^{3+}-doped double-clad PCF laser as a function of the pump power.

The spectra of output1 and output2 at a maximum pump power of 12.11W are shown in Fig.8, and they both show a single wavelength at 1067.5nm, with a FWHM of about 0.2nm. The spectral stability of the fiber laser is significantly improved. By our primary analysis, because the resonator of the dual-end-output fiber laser is composed of two fiber ends which provide only about 4% Fresnel reflection, the output loss in this configuration is much higher than that in the one-end-output configurations, which results in a higher threshold for all the longitudinal modes and thus the number of the operating modes is reduced. The reason of the improvement on spectral stability requires further study.



(a) output1



(b) output2

Fig.8. Spectra of the Yb^{3+}-doped double-clad PCF laser at a pump power of 12.11W

4. CONCLUSION

In conclusion, we have reported on the output characteristics of fiber lasers built with LMA Yb^{3+}-doped double-clad PCF in different configurations. At the same pump power, the maximum output of the forward-output fiber laser is 3.43W with a slope efficiency of 34.6%, while the maximum output of the backward-output fiber laser is 3.63W with a slope efficiency of 38%. The spectra of the forward-output fiber laser and backward-output fiber laser both show multi-wavelengths with mode hopping. Single wavelength output at 1067 nm with a FWHM of about 0.2nm is demonstrated by using a novel dual-end-output configuration, and a maximum output of 4.25W with a slope efficiency of 44.1% is obtained. Because there is no saturation in the output, higher output power will be achieved by optimizing the optical coupling system and increasing the pump power.

5. ACKNOWLEDGMENTS

This work is supported by the Doctorial Research Fund of Education Department of Hebei Provice, China (grant. B2004502), the Doctorial Research Fund of Hebei University (grant. 2004028), and the Pre-research fund of Hebei University (grant. 2005Y12).

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