High power wavelength-defined all-fiber Yb^{3+}-doped double clad fiber laser

**Hongxin Su (苏红新), Kecheng Lü (吕可诚), Peiguang Yan (闫培光),
Yigang Li (李乙钢), and Xiaoyi Dong (董孝义)**

College of Physics, Nankai University, Tianjin 300071

Received August 27, 2002

An all-fiber Yb^{3+}-doped double-clad fiber laser using FBGs as cavity mirrors is investigated in this paper. Continuous-wave (CW) output power of 1.18 W with defined wavelength at 1.06 μm and narrow line-width of less than 0.1 nm is obtained. The slope efficiency and the maximum optical-to-optical efficiency of laser output are 68% and 51%, respectively, with respect to absorbed pump power.

OCIS codes: 140.3510, 060.2320.

High power fiber lasers have been actively studied because of their excellent performance including very high conversion efficiency, immunity from thermal lensing effect, simplicity of optical cavity construction, excellent beam quality and small volume and weight. Nowadays, double-clad fiber lasers can provide output power up to hundreds of Watt and diffraction-limited beam quality[1−4], and have been regarded as substitute to the conventional solid-state lasers. For many practical applications it is of essential importance to be able to design the laser for a given oscillation wavelength. However, to our knowledge, the optical cavities of most of those more than 1-W high power fiber lasers are composed of broad-band dichroic mirrors (which have high transmission for pump and high reflectivity for laser) and cleaved fiber ends. Because there is no narrow-band wavelength selective element in the cavity, the output wavelength of the fiber lasers depends on the length of the active fiber. Because theoretically there is an optimum fiber length to get the maximum output efficiency, usually we cannot get the expected wavelength with the maximum efficiency. What is more, the compactness, reliability, and compatibility of the fiber lasers will be greatly reduced when bulk dichroic mirrors are used as cavity elements. As a resolution to these problems, we build an all-fiber Yb^{3+}-doped double clad fiber laser based on distributed Bragg reflection (DBR) with fiber Bragg gratings (FBGs). In this paper we present the principle of DBR and the experimental performance of our device. As all fundamental factors in rare-earth doped fiber lasers are taken account, the net gain at the signal wavelength λ_s through one-round-trip can be written as

$$G(\lambda_s) = \exp\{2\int_0^L [g(x,\lambda_s) - \delta(x,\lambda_s)]\mathrm{d}x\} \cdot R_1(\lambda_s)\cdot R_2(\lambda_s)\cdot K(\lambda_s), \qquad (1)$$

where $g(x,\lambda_s)$ and $\delta(x,\lambda_s)$ are the gain coefficient and the transmission loss coefficient of the signal wave propagating in the fiber, respectively. $R_1(\lambda_s)$ and $R_2(\lambda_s)$ are the reflective ratio of the two optical mirrors. $K(\lambda_s)$ denotes all of the splicing loss of the fiber resonator. Because most of the rare-earth doped fiber lasers have large fluorescence range and there is no significant difference between the transmission loss of adjacent longitudinal modes within the gain-band, $g(x,\lambda_s)$ and $\delta(x,\lambda_s)$ in Eq. (1) for adjacent modes are almost equal. If there were no narrow-band frequency-selective components in the fiber cavity, lots of adjacent longitudinal modes will generate and develop simultaneously, which will result in a very large line-width in the laser output.

Under the condition of weak-coupling approximation, the effective reflectivity of FBG can be written as[5]

$$R(\lambda) = \frac{\Omega^2\sinh^2(SL_g)}{\Delta\beta^2\sinh^2(SL_g) + S^2\cosh^2(SL_g)}, \quad (\Omega^2 > \Delta\beta^2), \qquad (2)$$

$$R(\lambda) = \frac{\Omega^2\sinh^2(QL_g)}{\Delta\beta^2 - \Omega^2\cos^2(QL_g)}, \quad (\Omega^2 < \Delta\beta^2), \qquad (3)$$

where λ is the wavelength of the reflected wave, L_g is the length of FBG, Ω is the coupling coefficient, which is a function of fiber composition and grating exposure. $\Delta\beta = \beta - \pi/p$, where β is the wave constant, and p is the period of FBG. $S = (\Omega^2 - \Delta\beta^2)^{1/2}$, and $Q = (\Delta\beta^2 - \Omega^2)^{1/2}$. From Eqs. (2) and (3) we can see that by selecting the above parameters carefully, we can obtain FBGs with desired reflective spectrum. From Eqs. (1), (2) and (3) we can see that the gain spectrum of the fiber laser will be controlled when narrow reflective-band FBGs are used as the reflective mirrors. As a result, the resonating modes and the output frequency as well as

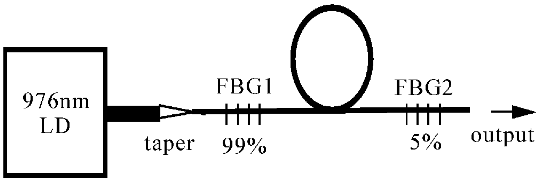

Fig. 1. Schematic diagram of DBR Yb^{3+}-doped double clad fiber laser.

the line-width of the fiber laser can be controlled.

The schematic experimental setup is shown in Fig. 1. The pump power source is a laser diode (LD) module provided by the Semiconductor Institute, Chinese Academy of Science. The maximum output power at 976 nm from the pigtail of the LD is about 5 W. The Yb-doped double-clad fiber used in our work is fabricated by modified chemical vapor deposition (MCVD) technique. The mode-field diameter of the Yb-doped fiber core is about 7 μm, and the dimension of the square inner cladding is 125 x 125 μm^2. The numerical apertures (NAs) of the inner cladding and the core are 0.38 and 0.11, respectively. The all-fiber cavity of our experimental setup is made of 10 m Yb-doped double-clad fiber, with gratings of reflectivities at 1.06 μm equal to 99% for the high reflector and 5% for the output coupler. The FBGs are spliced to each end of the double-clad fiber, the estimated splicing loss is less than 0.1 dB. To increase the incident efficiency of the pump power, a taper coupler is used between the pigtail of LD module and the input end of fiber laser.

Figure 2 shows the measured power from the output of the fiber laser as a function of the absorbed pump power. Laser output centered at 1.06 μm is observed when the incident pump power was increased to 0.3 W, only insignificant amounts of transmitted pump wave can be detected. The slope efficiency of the 1.06-μm emission with respect to the incident pump power is about 68%. A maximum output power of 1.18 W is measured at an absorbed pump power of 2.3 W, and the corresponding optical-to-optical conversion efficiency is more than 50%.

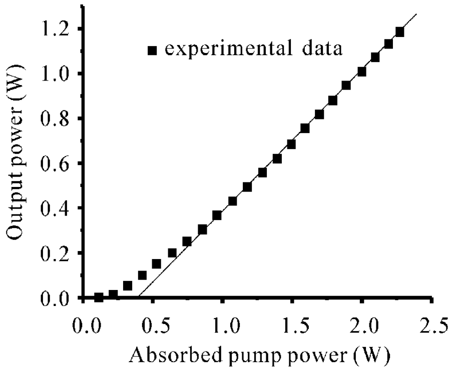

Fig. 2. Output power versus the absorbed pump power.

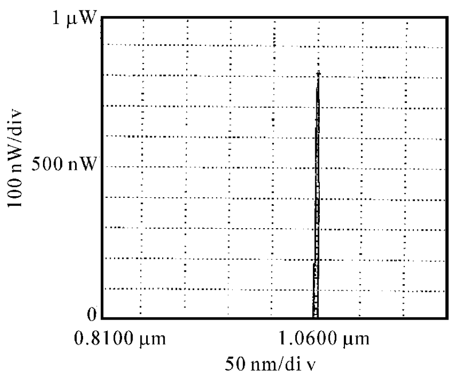

Fig. 3. Output spectrum of the fiber laser.

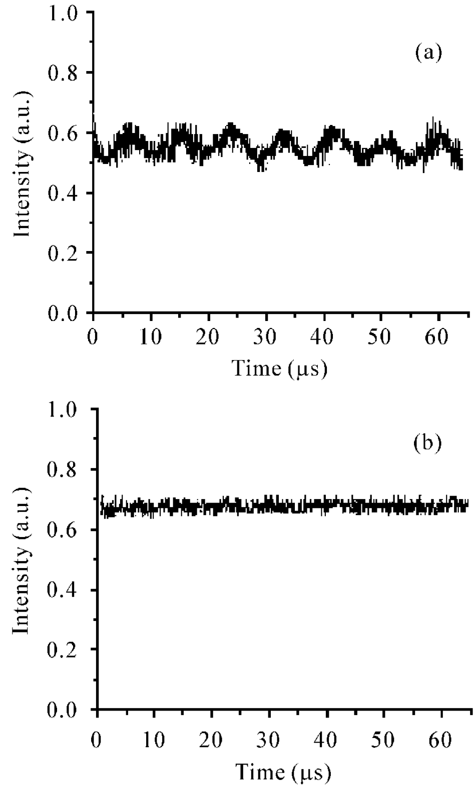

Fig. 4. Temporal behavior of the fiber laser. (a) Pulsation output, P_{ab} = 1.5 W. (b) Continuous-wave output, $P_{ab} = 2.3$ W.

The output beam, viewed with an infrared up-converter, seems to be confined to the lowest-order transverse mode.

The laser emission spectrum at the output of the fiber laser is measured with optical spectrum analyzer (OSA) MS9001B1. During most of the operating period laser wavelength is clapped stably at 1.06 μm, and there is no significant wavelength shift as the pump power is increased. Figure 3 shows the spectrum with the maximum output power of 1.18 W. By estimation, the output line-width (FWHM) of the fiber laser is less than 0.1 nm, accurate measurement is limited by the resolution of OSA.

The output temporal behavior of the fiber laser is detected by an electronic system composed of a fast PIN photodiode connected to a sampling oscilloscope. When the input pump power is near the threshold, sinusoidal curve shaped pulsation is observed. At the first period the oscillating amplitude of the pulsation grows up with the increased pump power, then decreases with the increased pump power gradually. Figure 4(a) shows the output pulsation with the maximum amplitude at an absorbed pump power of 1.5 W, the repetition rate is about 8 – 9 μs. When the absorbed pump power exceeds 1.85 W, pulsation disappears and continuous wave output is obtained. Figure 4(b) shows the temporal characteristics at the maximum output power of 1.18 W, which corresponds to an absorbed pump power of 2.3 W. The behavior of this laser is similar to that of a laser with a saturable absorber[7].

In conclusion, we have fabricated an all-fiber Yb-doped double-clad fiber laser with CW output of more than

1 W. By virtue of the combination of clad pumping and DBR, wavelength-definite, narrow line-width, high-efficiency, high beam quality laser performance is demonstrated. If even high pump power is available, output power of several watts can be obtained with this compact system, which will be interesting for lots of important applications.

This project was supported by the National Natural Science Foundation of China under grant No. 6103701. H. Su's e-mail address is suhx@eyou.com.

References

1. H. Po, J. D. Cao, and B. M. Laliberte, Electron. Lett. **29,** 1500 (1993).
2. G. Mitchaard and R. Waarts, Laser Focus World **35** (1), 113 (1999).
3. V. Dominic, S. MacCormaack, R. Waarts, and S. Sanders, Electron. Lett. **35,** 1158 (1999).
4. I. Bennion, J. A. R. Williams, L. Zhing, and K. Sugden, Opt. and Quantum Electron. **28,** 93 (1996).
5. D. Marcuse, IEEE J. Quantum Electron. **29,** 2390 (1993).