Yb^{3+}-doped double-clad fiber laser with all fiber cavity

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Received April 19, 2004

A novel all fiber cavity Yb^{3+}-doped double-clad fiber laser (DCFL) based on two double-clad fiber (DCF) Bragg grating is presented. The fiber Bragg gratings (FBGs) as the input and output mirrors have been formed in Yb^{3+}-doped DCF with the phase-mask method, and their reflectivities are 99% and 22%, respectively. When the input pump power is 417 mW, the maximum output power is 144 mW with linewidth <0.1 nm at the wavelength of 1.057 μm, over 40-dB signal-to-noise ratio (SNR), and 50.8% slope efficiency.

OCIS codes: 060.2320, 140.3510, 140.3480.

Yb^{3+}-doped double-clad fiber lasers (DCFLs) are of great interest for many practical applications. Because of their geometry, pump light can be launched into the first cladding. For the energy levels of Yb^{3+} in silica are simple, there are no excited state absorption and low concentration quenching by interionic energy transfer. The Yb^{3+}-doped DCFL with high power can be used for many applications such as printers and free-space communication. So it is required for high output power and high beam quality[1-7].

However, to most of these high power lasers, diachronic mirrors are often used as inner and (or) outer cavity reflectors. This massive cavity does harm laser performances because the high pump power make many modes be excitated simultaneously in broad gain band rare-earth-doped fiber. Furthermore, because dichroic mirrors have wide reflective-band, these lasers cannot generate narrow linewidth and desired wavelength. Because dichroic mirrors are not fiber components, the compatibility and compactness of laser are limited[1-4]. The Bragg gratings that compose a laser cavity are fabricated in a high germanosilicate host fiber and then spliced with an Yb^{3+}-doped active fiber. The difference of parameters between two kinds of fibers leads to additional losses for both pump and signal lights[5,6]. Therefore it is evident that laser efficiency can be improved if Bragg gratings are written directly in an Yb^{3+}-doped fiber as a laser medium[7]. In this letter we report the fabrication of Yb^{3+}-doped double-clad fiber (DCF) gratings and the properties of lasers based on these gratings. This laser is a kind of all fiber cavity DCFL. The cavity is made of two gratings. One is formed in the hydrogen loaded DCF with the method of phase mask. The other is formed directly in the DCF with the same method. The reflectivities of fiber Bragg gratings (FBGs) are nearly 99% and 22%, respectively. When input pump power is 417 mW, the laser output power is 144 mW, linewidth $\Delta\lambda$ <0.1 nm at the wavelength of 1.057 μm, incident pump laser threshold is 139.8 mW, signal-to-noise ratio (SNR) is over 40 dB, and slope efficiency is 50.8%.

Taking account of the rate equations under steady state conditions for linear cavity Yb^{3+}-doped DCFL, the output power of laser is written as[1]

$$\begin{aligned} P_{\mathrm{out}} &= (1-R_2)\,P_s^+(L) \\ &= \frac{(1-R_2)\sqrt{R_1}\cdot P_{\mathrm{sat}}^{\mathrm{s}}}{(1-R_1)\sqrt{R_2}+(1-R_2)\sqrt{R_1}} \\ &\quad \times\left\{[1-\exp(\zeta)]\,\frac{\nu_{\mathrm{s}}}{\nu_{\mathrm{p}}}\cdot\frac{P_{\mathrm{p}}(0)}{P_{\mathrm{sat}}^{\mathrm{s}}} \right. \\ &\quad \left. -\left(N\Gamma_{\mathrm{s}}\sigma_{\mathrm{as}}+\alpha_{\mathrm{s}}\right)L-\ln\left(\frac{1}{\sqrt{R_1R_2}}\right)\right\}, \end{aligned} \tag{1}$$

$$\begin{aligned} \eta &= \frac{\mathrm{d}P_{\mathrm{out}}}{\mathrm{d}P_{\mathrm{p}}(0)} \\ &= \frac{(1-R_2)\sqrt{R_1}}{(1-R_1)\sqrt{R_2}+(1-R_2)\sqrt{R_1}}\,[1-\exp(\zeta)]\,\frac{\nu_{\mathrm{s}}}{\nu_{\mathrm{p}}}, \end{aligned} \tag{2}$$

where R_1 and R_2 are the power reflectivities of Bragg reflectors at $z=0$ and $z=L$, respectively. P_{out} is output power, $P_{\mathrm{s}}^{+}(L)$ is the positive direction signal power at $z=L$, $P_{\mathrm{sat}}^{\mathrm{s}}$ is saturation output power, $\zeta=\ln\frac{P_{\mathrm{p}}(L)}{P_{\mathrm{p}}(0)}$, $P_{\mathrm{p}}(L)$ and $P_{\mathrm{p}}(0)$ are the incident pump powers of positive at direction $z=L$ and $z=0$, respectively, z is a longitudinal position along the fiber, Γ_{s} is the signal mode field distribute parameter in fiber core, N is total density of Yb^{3+} ions, α_{s} is loss factor of laser in the cavity, and σ_{as} is signal absorption cross-section, ν_{s} and ν_{p} are signal and pump frequencies, respectively.

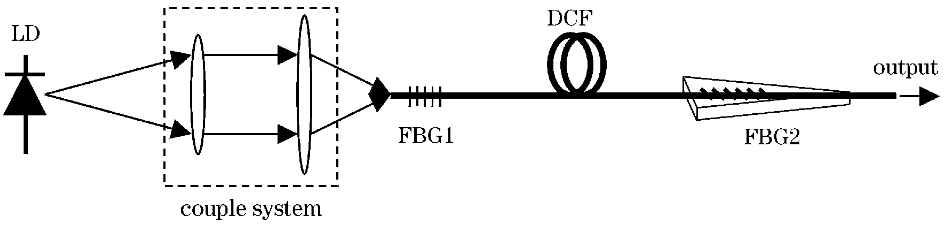

Fig. 1. Experimental setup of Yb^{3+}-doped DCFL with all fiber cavity.

From Eqs. (1) and (2), the output power and the slope efficiency depend on three sections: the quantum transition efficiency ν_s/ν_p, the loss of laser cavity, and the characteristics of Yb^{3+}-doped DCF. As a result, to optimize the cavity of high power Yb^{3+}-doped DCFL, we need to take into account the influences of all above factors.

Figure 1 is the experimental setup of all fiber cavity Yb^{3+}-doped DCFL. The pump source is a laser diode (LD), whose maximum output power at 976 nm from the pigtail is about 1 W. The diameter of the Yb^{3+}-doped DCF (the 46th Institute of China Electronics Technology Group Corporation and NanKai University) core is 5 μm, and the diameter of inner cladding is 125 μm. The all fiber cavity is made of 24-m Yb^{3+}-doped DCF, the reflectivities of gratings equal to 99% for the high reflector (FBG1) and 22% for the output coupler (FBG2). Because of the low germanium concentration in the Yb^{3+}-doped DCF core, we enhance its photosensitivity after out-diffusion of hydrogen about 10 days. We write the high reflectivity DCF grating and write another low reflectivity grating directly in one end of the Yb^{3+}-doped DCF core with the phase-mask method. The ultraviolet light source is a narrow-band KrF excimer laser operated at 248 nm. The phase mask period is 724.86 nm. Grating transmission spectra are measured with an Yb^{3+}-luminescence source pumped at 980 nm and Q8383 optical spectrum analyzer (OSA) with spectral resolution of 0.1 nm. Figures 2 and 3 show the transmission spectra of the two FBGs. Transmission dips appear at 1.057 and 1.055 μm, respectively. We splice the high reflectivity grating to the active fiber. To profit from the same fiber, we can use standard splicing technology with very minute splice loss. The active fiber and gratings are mode-matched to the core and inner cladding. It is most desirable to have low propagation losses at both pump and signal wavelengths, which ensure a low laser threshold. Because the reflecting centers of the two gratings are different, we use an equivalent-strength beam to chirp-free tune the center wavelength of the low reflectivity DCF grating matching to the wavelength of the high reflectivity DCF grating. A couple system is used between the pigtail of LD and the input end of fiber laser.

Figure 4 shows the output power of the fiber laser as a function of the input pump power. Laser emerges when the incident pump power increases to 139.8 mW. Laser output centered at 1.057 μm is observed. The maximum output power of 144 mW is measured at the absorbed pump power of 417 mW. The power is measured with laser power meter after residual pump laser is filtered. The slope efficiency of the laser with respect to launched pump power is about 50.8%. There is difference between this value and the limiting value of the ratio of laser to pump power in our work. This difference can be decreased by two main methods: 1) optimize the reflectivities of the FBG1 and FBG2 to approach to the optimally theoretical value; 2) optimize the parameters of the fiber such as Yb^{3+} concentration, inner cladding shape, and fiber length, etc..

The fiber laser emission spectrum is measured with OSA. During most the operating period, laser wavelength is stably clapped at 1.057 μm. No significant wavelength shift appears as the pump power increases. For the

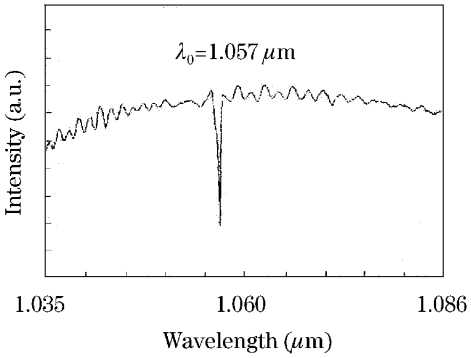

Fig. 2. Transmission spectrum of the FBG1.

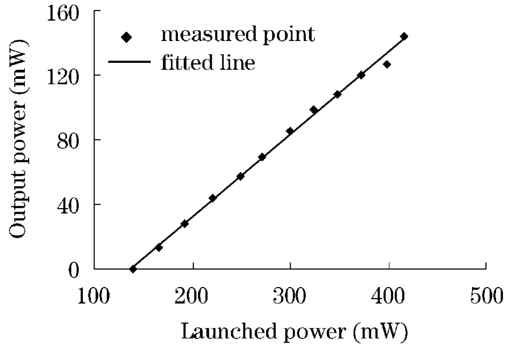

Fig. 4. Output power versus pump power.

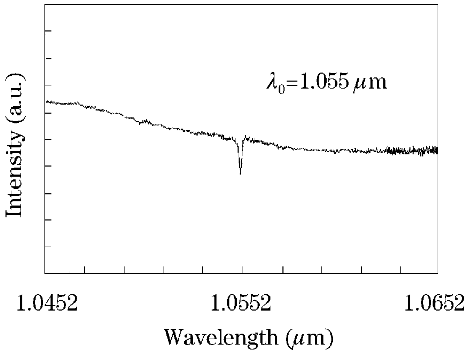

Fig. 3. Transmission spectrum of the FBG2.

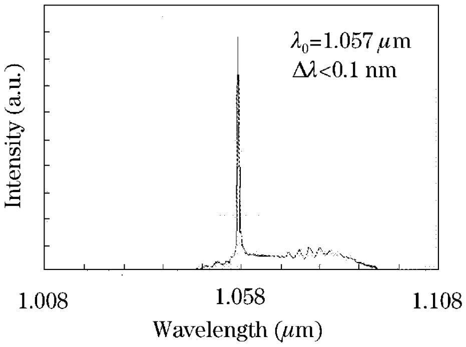

Fig. 5. Spectrum of the output laser.

reason that the laser cavity in our work uses double gratings selecting frequency, there is little mode in the laser emission spectrum. This is propitious to obtain narrower linewidth and more stable centeral wavelength of the output laser. Figure 5 shows the spectrum of the output of the fiber laser. The output linewidth (FWHM) of the fiber laser is less than 0.1 nm. Accurate measurement is limited by the resolution of OSA. SNR is over 40 dB.

In conclusion, we make an all fiber cavity DCFL with two FBGs. The high reflectivity grating is spliced to the active fiber as the input reflector of the cavity. The low reflectivity grating as output mirror of the cavity is directly written in one end of the active fiber. So the splice loss in the cavity of the DCFL is very little and the bulk of the DCFL is reduced. By virtue of the combination of cladding-pump scheme and distributed Bragg reflector (DBR) of FBG, wavelength-definite, narrow linewidth, high-efficiency, high-beam-quality laser performances are demonstrated, which are of great interest for many important applications[1-3].

This work was supported by the National Natural Science Foundation of China (No. 60137010) and the National "863" High Technology Project of China (No. 2003AA312100). L. Li's e-mail address is nankaillj@163.com.

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