Optimization of linear cavity design of Yb-doped double-clad fiber laser

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The output characteristics of a linear cavity Yb-doped double-clad fiber (DCF) laser, including the effects of fiber length, fiber loss, and output mirror reflectivity on laser output power and threshold pump power have been studied theoretically and experimentally. In this paper, the linear cavity of double-clad fiber laser (DCFL) was composed of a pair of fiber Bragg gratings, while the facet of fiber was anti-reflection (AR) coated at 1070nm to erase the Fresnel reflection. Analysis showed that the laser output increases as the reflectivity of the fiber Bragg grating used as the output mirror decreases. At last, under the pump power of 14.4 W, single-mode laser output at 1070 nm was up to 10.8 W, with slope efficiency of 75 %.

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Yb-doped fiber is a very good candidate in the spectral range of 1 − 1.1 μm for several reasons: Yb ions present a large absorption cross-section around 980 nm, allowing for a pumping with low cost commercially available laser diodes[1]; the large fluorescence spectral range is well adapted for tunable laser applications[2]; moreover, an Yb ion has a simple two-level energy system that can avoid any pump or signal excited-state absorption (ESA)[3]. The double-clad fiber lasers (DCFLs) have very high conversion efficiency, which can improve heat dissipation and lead to less critical thermal management as compared to bulk lasers[4]. Yb-doped DCFLs are largely used as the pump source for Raman fiber lasers, which are used for pumping erbium-doped fiber amplifier (EDFA) and Raman amplifiers. What's more, Yb-doped DCFLs also can be widely used in the fields of medical, military, and industrial processing.

The keys to improve the performance of DCFL include the coupling of laser diode and double-clad fiber (DCF), and the design of resonant cavity. Recently, Yb-doped DCF with directly written Bragg grating was reported to compose a laser cavity without additional loss by the difference of beam parameters between DCF and Bragg grating directly imprinted on a standard fiber[5]. In this paper, the effects of fiber length, fiber loss, and reflectivity of fiber Bragg grating (FBG) used as output mirror on laser output power and threshold pump power were analyzed. A taper fiber was used to reduce connection loss between DCF and laser diode. The linear cavity was composed of a pair of FBGs. Under the pump power of 14.4 W, single-mode laser output at 1070 nm was up to 10.8 W, with slope efficiency of 75 %.

A linear cavity can be modeled as Fig. 1. The rate equations under steady state conditions for linear cavity Yb-doped DCFL can be written as[6]

$$\frac{\mathrm{d}p^{\pm}(z)}{\mathrm{d}z} = \pm\left[\frac{\sigma_{\mathrm{s}}\tau_{\mathrm{f}}}{h\nu_{\mathrm{p}}}\alpha_{\mathrm{a}}p_{\mathrm{p}}(0)\mathrm{e}^{-(\alpha_{\mathrm{a}}+\alpha_{\mathrm{p}})z}\frac{F_{\mathrm{p}}}{A_{\mathrm{f}}}\frac{p_0+p^{\pm}(z)}{1+\frac{p^{+}(z)+p^{-}(z)}{p_{\mathrm{s}}}} - \alpha_{\mathrm{s}}p^{\pm}(z)\right], \quad (1)$$

$$g(z) = \frac{\sigma_{\mathrm{s}}\tau_{\mathrm{f}}}{h\nu_{\mathrm{p}}}\alpha_{\mathrm{a}}p_{\mathrm{p}}(0)\mathrm{e}^{-(\alpha_{\mathrm{a}}+\alpha_{\mathrm{p}})z}\frac{F_{\mathrm{p}}}{A_{\mathrm{f}}}\frac{1}{1+\frac{p^{+}(z)+p^{-}(z)}{p_{\mathrm{s}}}}. \quad (2)$$

The related variables and constants used in Eqs. (1) and (2) are defined as follows: $P_{\mathrm{p}}(0)$ is the input pump power, $P^{+}(z)$ and $P^{-}(z)$ are the forward and backward powers, respectively, $\alpha_{\mathrm{a}}P_{\mathrm{p}}(0)\mathrm{e}^{-(\alpha_{\mathrm{a}}+\alpha_{\mathrm{p}})z}$ is the fractional amount of $P_{\mathrm{p}}(0)$ absorbed between z and $z+\mathrm{d}z$, σ_{s} is the stimulated emission cross section, α_{s} is the loss factor of laser propagation in the core, α_{a} is the absorption coefficient of the core at the pump wavelength of λ_{p}, α_{p} is the loss coefficient of the fiber at λ_{p}, τ_{f} is the fluorescence lifetime, $h\nu_{\mathrm{p}}$ is the pump photon energy, A_{f} is the cross-sectional area of the fiber core, F_{p} is the dimensionless coefficient related to the spatial overlap integral between the pump and signal modes, P_{s} is the saturation output power, and P_0 is a constant accounting for spontaneous emissions which is the power associated with N photons in the gain bandwidth $\Delta\nu_{\mathrm{s}}$

$$P_{\mathrm{s}} = (h\nu_{\mathrm{s}}/\sigma_{\mathrm{s}}\tau_{\mathrm{f}})\cdot A_{\mathrm{f}}, \quad (3)$$

$$P_0 = Nh\nu_{\mathrm{s}}\cdot(\pi\Delta\nu_{\mathrm{s}}/2). \quad (4)$$

The boundary condition of Eqs. (1) and (2) is $P^{+}(0) = R_1P^{-}(0)$ and $P^{-}(1) = R_2P^{+}(1)$.

$P^{+}(1)$ can be obtained by solving Eq. (1) using Rounge-Kutta method. The laser output power P_{las} equals to the product of $(1-R_2)$ and $P^{+}(1)$. The threshold pump power was $P_{\mathrm{p}}(0)$ when the output power was zero. Values of the parameters used in the simulations were: $P_{\mathrm{p}}(0) = 20$ W, $\lambda_{\mathrm{p}} = 975$ nm, $\lambda_{\mathrm{s}} = 1070$ nm, $\sigma_{\mathrm{s}} = 2.6\times10^{-24}\ \mathrm{m}^2$, $\alpha_{\mathrm{a}} = 0.157\ \mathrm{m}^{-1}$, $\alpha_{\mathrm{p}} = 0.01\ \mathrm{m}^{-1}$,

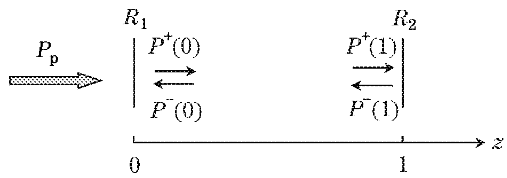

Fig. 1. Analysis model of linear cavity of DCFL.

$\tau_f = 0.76\times10^{-3}$ s, $h = 6.626\times10^{-34}$ J·s, $D_{\rm core} = 10$ μm, $R_1 = 1$, $R_2 = 0.03$. Figure 2(a) shows the effects of fiber length on laser output power and threshold pump power under different α_s. It is clear that there exists an optimized fiber length to make the highest laser output power and the lowest threshold pump power. The optimized fiber length was in inverse proportion to the loss factor of signal light propagation in the core α_s. Under the same pump power, the laser output power of the fiber with low α_s was higher than that with high α_s. However, the threshold pump power of the fiber with low α_s was lower than that with high α_s.

The FBG used as output mirror was defined as FBG2. Figure 2(b) shows the effect of reflectivity of FBG2 on laser output power. Here, the fiber length was 20 m. In Fig. 2(b), the laser output power decreases with the increase of reflectivity of FBG2 and it was concluded that the optimum FBG2 for high power DCFL should has a very low reflectivity (about 2% – 5%). The higher the pump power was, the higher the laser output power was.

The structure diagram of the DCFL was shown as Fig. 3(a). The diameter of the pigtailed fiber core from 975-nm laser diode array and the inner clad of DCF were 400 and 200 μm, respectively. The DCF core was 3000 ppm Yb-doped and had a diameter of 4 μm and a numerical aperture (NA) of 0.175. The loss factor α_s of signal light propagation in the core of DCF was 0.003 m^{-1}. The DCF with flower shape cross-section with a NA of 0.45 was chosen to decrease helical waves coming from pigtailed fiber from 975-nm laser diode, which resulted in a mode scrambling effect to enhance the pump absorption into the Yb-doped core. A taper fiber was used to reduce connection loss between DCF and laser diode. The linear cavity of DCFL was composed of a pair of FBGs. The tapered end was spliced into the FBG used as high reflection mirror, which had a reflectivity of 99.9% at 1070 nm. According to the simulation above, the optimum length of DCF was 20 m when the pump power was 15 W. The output mirror of the linear cavity was a FBG whose reflectivity was 3% at 1070 nm, while the fiber facet was AR coated at 1070 nm to erase the Fresnel reflection.

Figure 3(b) shows the laser spectrum of DCFL obtained from optical spectrum analyzer with the resolution of 0.02 nm. The FWHM of spectrum was 0.125 nm. The 4-μm core diameter of DCF ensured the single mode laser signal emission and the M^2 factor of laser beam was measured to be 1.05, as shown in the inset of Fig. 3(b). The threshold power was 150 mW. The maximum laser output power at 1070 nm was up to 10.8 W under the pump power of 14.4 W, with slope efficiency of about

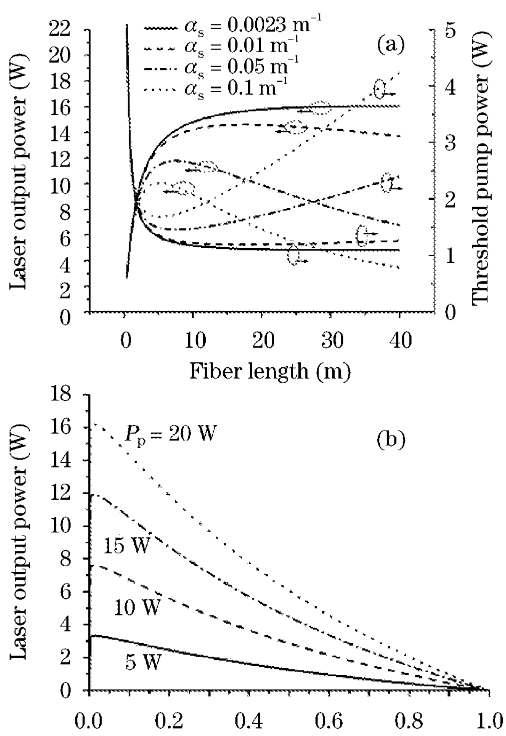

Fig. 2. (a) The effect of fiber length on laser output power and threshold pump power; (b) the effect of reflectivity of FBG2 on laser output power.

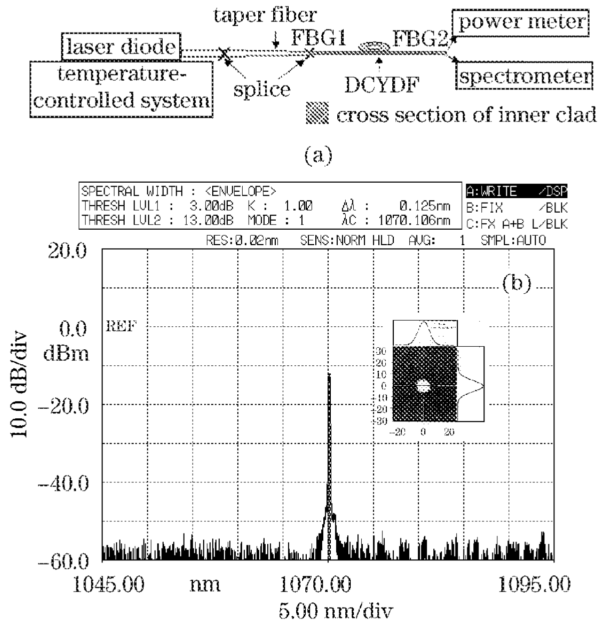

Fig. 3. Experimental setup (a) and laser spectrum (b). DCYDF: double-clad Yb-doped fiber.

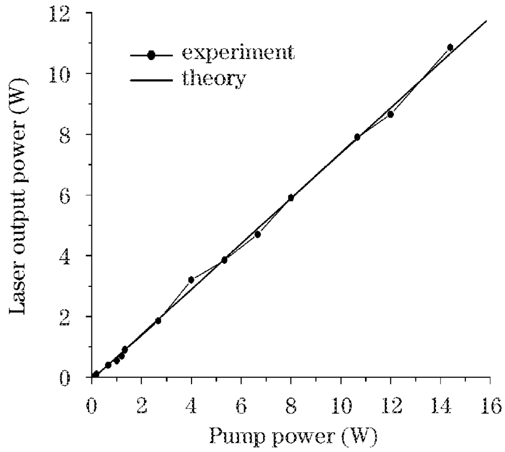

Fig. 4. Laser output power under different pump power.

75%, as shown in Fig. 4. The experimental result was in good agreement with the simulation.

In conclusion, the output characteristics of a linear cavity Yb-doped DCFL have been studied theoretically and experimentally in this paper. There exists an optimized fiber length to achieve maximum laser output, which is in inverse proportion to the loss factor of signal light propagation in the core α_s. And the laser output increases as the reflectivity of the output mirror decreases. At last, a linear cavity composed of a pair of FBGs was used in the DCFL, while one facet of fiber was AR coated at 1070 nm to erase the Fresnel reflection. Under the pump power of 14.4 W, single-mode laser output at 1070 nm was up to 10.8 W, with slope efficiency of 75%.

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