Theoretical and experimental investigation on backward-pumped Yb^{3+}-doped double-clad fiber lasers

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Abstract **Based on the rate equations under the steady-state condition, strongly backward-pumped Yb^{3+}-doped double-clad fiber (YDCF) lasers are analyzed numerically. The effects of laser cavity feedbacks and length of YDCF on the laser performance and the dependency of the output laser power on the pump power are investigated. Using a 975 nm laser diode (LD) as the pump source, a backward-pumped YDCF laser with a slope efficiency of 82% is demonstrated experimentally. The output laser power at the wavelength of 1088 nm is up to 85 W. The experimental results are in good agreement with those by numerical simulations.**

I. INTRODUCTION

Rare-earth-doped double-clad fiber lasers (DCFLs) have attracted more and more attention in recent years because of their advantages over conventional solid-state lasers, such as high conversion efficiency, low cost, excellent beam quality and their potential applications in industry, military, medicine and modern telecommunication.

According to pumping configurations, DCFLs are generally classified into the forward-, backward- and bidirectional-pumping configurations. At present, forward- or bidirectional-pumped DCFLs have been intensively investigated [1-3]. In 2004, Jeong et al. [1] successfully achieved a continuous wave (CW) output power of 1.36 kW at the wavelength 1.1 μm from a large-core Yb^{3+}-doped DCFL. IPG Inc. also developed a DCFL with the output of up to 2 kW by combining output beams of several fiber lasers [2], and in 2006 they further scaled up the single-fiber output power to 3 kW [3]. Theoretically studies have shown that the backward-pumped DCFLs may offer a higher conversion coefficient [4-6], however, they have not been comprehensively investigated. In this paper, we numerically optimize the backward-pumped DCFL systems, and the experimental demonstration is then performed according to the optimization results.

II. THEORETICAL INVESTIGATION

A schematic of a DCFL with backward-pumping configuration is shown in Fig.1. The laser cavity consists of mirrors M_1 and M_2. The reflectivity of M_1 (R_1) is low and that of M_2 (R_2) is close to 1. The pump power is coupled into the fiber through M_1 and the output laser is also from M_1.

Under the strongly pumped condition, the effect of ASE is weak [7] and thus can be neglected. Then, the steady-state rate equations of DCFLs can be described as [6]:

$$\frac{dP^{+}(z)}{dz}=P^{+}(z)g(z)-\alpha_s P^{+}(z) \tag{1}$$

$$\frac{dP^{-}(z)}{dz}=-P^{-}(z)g(z)+\alpha_s P^{-}(z) \tag{2}$$

$$g(z)=\frac{\sigma_s\tau_f}{h\nu_p}\alpha_a P_p\exp[-(\alpha_a\Gamma_p+\alpha_p)z]\frac{\Gamma_p}{A_f}\frac{1}{1+[P^{+}(z)+P^{-}(z)]/P_s} \tag{3}$$

Where $g(z)$ is the gain coefficient along the fiber, P_p is the input pump power. α_a represents the absorption coefficient of the fiber core at the pump wavelength, α_p and α_s are the scattering loss coefficients at the pump wavelength and signal wavelength respectively. τ_f is the spontaneous lifetime, σ_s is the stimulated emission cross-section at λ_s. A_f is the cross-section area of the fiber core. Γ_p is the overlap factor of pump mode

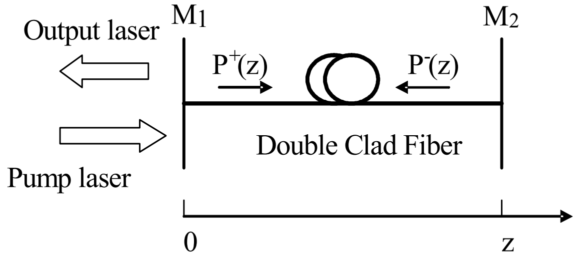


Fig.1 Schematic of backward-pumped YDCF laser

signal output power.

The boundary conditions are

$$P^{+}(0)=R_1P^{-}(0) \tag{4}$$

$$P^{-}(L)=R_2P^{+}(L) \tag{5}$$

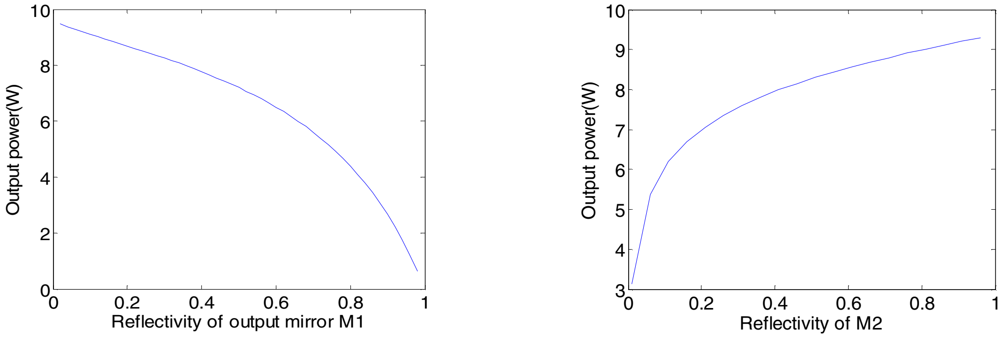
The output laser power is

$$P_{out}=(1-R_1)P^{-}(0) \tag{6}$$

To numerically solve the two-point boundary value problem formed by Eqs. (1)~(2) with the boundary conditions (4)~(5), Newton-Raphson method is used in this section, due to its fast convergency and good stability compared with the conventional Runge-Kutta method. The parameters used in the simulation are: $\sigma_s=2\times10^{-25}$ m²，$\tau_f=0.95$ ms，$\alpha_a=2.0$ dB/m，$A_f=4\times10^{-10}$ m²，$\alpha_p=13$ dB/km，$\alpha_s=20$ dB/km.

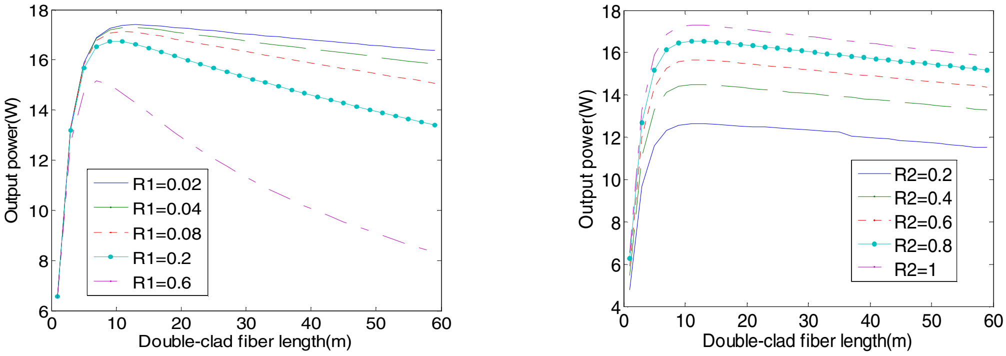
Fig.2 shows the effects of the fiber length and the reflectivities of M_1 and M_2 on the backward-pumping Yb-doped DCFL. From Fig.2 (a) and (c), one can find that the output laser power decreases with the increase of R_1 when the fiber length and R_2 are fixed, that is, in order to obtain higher output power, the reflectivity of M_1 should be small. In practice, one can take the Fresnel reflection of the fiber end into account, and use it as the cavity feedback ($R_1\approx0.04$). Fig.2 (b) and (d) show that when R_1 is a fixed value, the closer to 1 R_2 is, the higher power will be obtained in theory. Moreover, the optimal fiber length of about 12 m can be obtained from Fig.2 (c) and (d).

According to the results above, to obtain high conversion efficiency, the reflectivities of mirrors should be selected as R_1



(a) Output power vs. reflectivity of M_1 with R_2=1

(b) Output power vs. reflectivity of M_1 with R_1=0.04



(c)Output power vs. fiber length for different values of R_1 with R_2=1

(d)Output power vs. fiber length for different values of R_2 with R_1=0.04

Fig.2 Effects of the fiber length and the reflectivities of M_1 and M_2 on the backward-pumped YDCF laser (P_p=20 W).

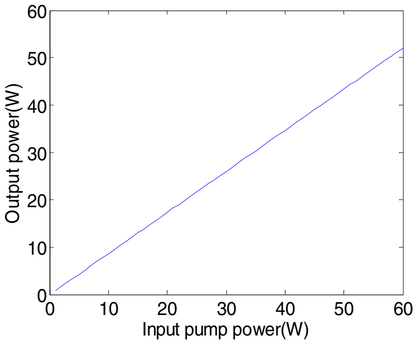


Fig. 3 Output power vs. pump power with L=12 m, R_1=0.04 and R_2=1

=0.04, and R_2=1, respectively, in addition to the optimal fiber length. With these optimal parameters, the relationship between the output power and pump power was simulated, and the results are given in Fig.3. From Fig.3, the optimal slope efficiency of a backward-pumped Yb-doped DCFL can be as high as more than 86%

III. EXPERIMENTAL INVESTIGATION

The pump source used in this work is a high power LD (LIMO200-F400－LD975), whose maximum output power at 975 nm is 200 W and typical linewidth is ~5 nm. A section of 14m-long Yb-doped double-clad fiber provided by Nufern Inc. is employed as the gain medium, whose absorption coefficient is 2.0 dB/m at 975 nm. The diameters of the fiber core and inner-cladding are 20 μm and 400 μm, and their numerical apertures are 0.06 and 0.46, respectively.

The experimental set-up of a backward-pumped Yb-doped DCFL is shown in Fig.4. The pump laser is collimated and focalized by two lenses L_1 and L_2 with their focus lengths of 25mm, and then coupled into the Yb-doped double-clad fiber. To provide 4% Fresnel reflection, the left facet of the fiber is polished perpendicularly. In contrast, the right facet of the fiber is angled polished to decrease the laser parasitical oscillations.

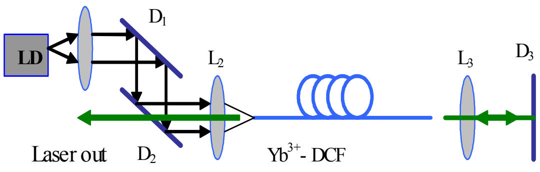


Fig. 4 Schematic of YDCF laser

The beam from the right facet of fiber is collimated by a lens L_3,and then reflected by a dichroic mirror D_3 (HT@975nm T>97% & HR@1090nm R>99%) and coupled back into the fiber. D_3 has a high reflectivity (up to 99.3%) over a wide wavelength range, as shown in Fig.5. The laser cavity is composed of the left facet of the fiber and dichroic mirror D_3. Dichroic mirror D_1 and D_2 (HR@975nm R>97% & HT@1090 nm T>85%) are placed parallelly with 45-degree angle, which separates the pump beam and output laser thus avoids damaging the pump source.

By measuring the laser cavity loss and the residual pump power and considering the fiber parameters, it is estimated that coupling efficiency of pump power from the LD into the Yb-doped double-clad fiber is ~72%. When the pump power in fiber is 1.1 W, the laser reaches its threshold and the lasing oscillation can be observed. The output power of the backward-pumped Yb-doped DCFL was measured for different pump powers, and the results are shown in Fig.6. With the

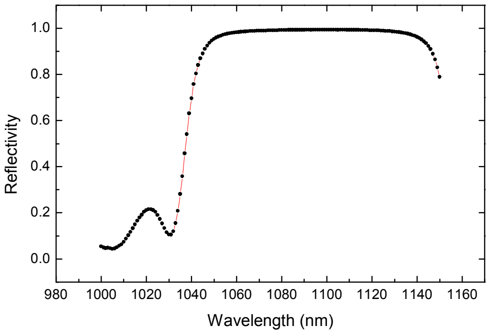


Fig.5 The reflective curve of D_3

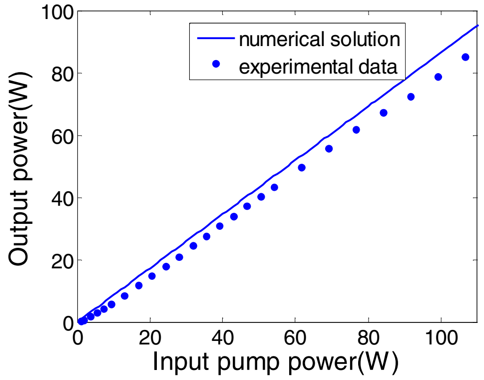


Fig. 6 Output power vs. pump power for L=14 m. Dots: measured data. Line: results of simulation

injected pump power of 107 W, the output laser power at 1088 nm is 85 W. Simultaneously, the corresponding numerical simulation is also performed to compare with the experimental results. The full-line in Fig.6 represents the numerical results. The experimental results are in an excellent agreement with the numerical results. Especially, the measured slope efficiency is approximately 82%, which is close to the numerical result of 86%.

Fig.7 is the laser output spectrum with the input pump power P_p=17 W. It is clearly observed the multiple longitudinal-mode oscillations in the spectrum. It is mainly attributed to the broadband reflection of the dichroic mirror D_3 and the emission spectrum of Yb ions.

IV. CONCLUSION

The characteristics of backward-pumped Yb-doped double-clad fiber laser are investigated both theoretically and experimentally. Based on steady-state rate equations, effects of the reflectivities of laser cavity and fiber length on output laser power as well as the relationship between the pump power and output power have been analyzed numerically. According to the numerical results, the laser has been designed with a 975 nm LD as the pump source, 14m-long Yb-doped double-clad fiber as the gain medium and one of the fibre end-faces with 4% Fresnel reflection as output coupler of the cavity. A CW laser output of 85 W at 1088 nm with the slope efficiency of 82% has been demonstrated. The experimental results are in good agreement with numerical ones.

ACKNOWLEDGMENT

This work was supported by the key scientific project of Fujian, China under Grant No. 2005H089 and the research funding of Xiamen University under Grant No. 0630-X01125.

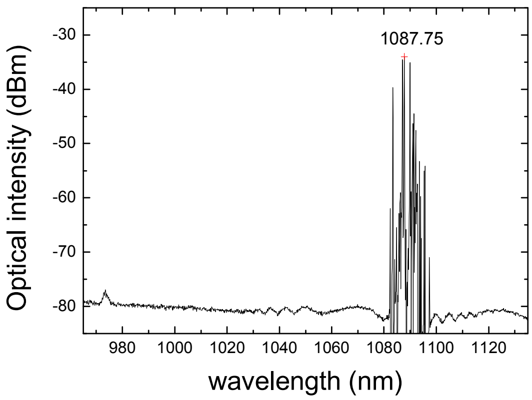


Fig. 7 Spectrum of output laser

REFERENCES

[1] Y. Jeong, J. K. Sahu, D. N. Payne, J. Nilsson. Ytterbium-doped large-core fiber laser with 1.36kW continuous-wave output power. [J] Opt. Express, 2004, 12(25): 6088-6092.

[2] D. Gaponstev. Fiber lasers grow in power. [J] Lasers Focus World, 2005, 41(1): 9.

[3] www.ipgphotonics.com (2007)

[4] I. Kelson, A.A. Hardy. Strongly pumped fiber lasers.[J] IEEE J. Quantum Electron. 1998, 34(9): 1570-1577.

[5] I. Kelson, A.A. Hardy. Optimization of strongly pumped fiber lasers.[J] J. Lightwave Technol. 1999, 17(5): 891-898.

[6] Z.Q. Luo, C. C. Ye, G.Y. Sun, Z. P. Cai, M.L. Si, Q.B. Li. .Simplified analytic solutions and a novel fast algorithm for Yb^{3+}-doped double-clad fiber lasers. [J] Opt. Commun. 2007, 277(1): 188-124.

[7] A.A. Hardy, R. Oron. Amplified spontaneous emission and rayleigh backscattering in strongly pumped fiber amplifiers.[J] J. Lightwave Technol. 1998, 16 (10): 1865-1873.