Various pumping modes of high-power double clad fiber laser

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Abstract. As one of the first invented laser categories, fiber laser plays a crucial role in many specific fields, e.g., filed-optic communication, sensing, industrial processing, national defense, military. In order to effectively couple the pump light into the single-mode fiber, double-clad fiber laser was invented, i.e., the power and efficiency of fiber lasers have been significantly improved. There are two mainly categories of pumping mode for double clad fiber laser, named as end smoothing the gain curve pumping and side pumping. This paper will focus on the analysis and comparison of these two pumping modes in terms of the power, efficiency, relative population density, thermal load and feasibility. The experimental procedure will be achieved based on the MATLABR2021b and SFTool. The aim of the paper is to investigate the effects on the forward pumping and backward pumping in the process of side pumping and end pumping. According to the analysis, side pumping and bi-direction pumping smooth the gain curve effectively. Choosing appropriate pumping mode can reduce the loss and save the cost of optical transmission to a large extent. These results shed light on selection of pumping mode for high power fiber laser.

Keywords: High power double clad fiber laser, end pumping, side pumping, forward pumping, backward pumping, Yb doped Fiber Laser.

1. Introduction

Fiber laser was firstly invented by Snitzer from American Optical Company, Massachusetts [1, 2]. Since then, the efficiency and allowable power of fiber laser have been of developed and popularized radically. In 1993, Zenteno using 2.5W semiconductor laser as pumping source and rectangular inner cladding, which received the result of 750mW laser output [3]. Two years later, the output power of double clad Nd doped fiber laser is increased to 9.2W [4]. However, a major problem with this kind of application is the optical-to-optical conversion efficiency was severely reduced because of the large D-value between the pump wavelength and laser wavelength (over 200nm). Typically, the thermal load of the laser is enlarged accordingly at high power output circumstances. As a result, the output for Nd doped fiber laser cannot continue to increase significantly. In 1994, Pask and Hanna using Yb-Doped Silica Cladding-Pumped Fiber Laser Pumped at 974nm and the outcome was Yb^{3+} doped fiber laser at 1040nm wavelength [5]. Ytterbium particle has a wide absorption spectrum which exactly include the output peak spectrum of most semiconductor lasers. Subsequently, the optical-optical conversion efficiency and theoretical maximum output power for fiber laser has been totally ameliorate.

The recent research topic about double clad fiber laser mainly focuses on Eliminating the impact from the Stimulated Raman scattering effect and Stimulated Brillouin scattering effect or ensuring high power fiber laser beam quality. IPG Photonics is in the leading position in high power laser industry. They became the first company uses cascade pumping technology in ytterbium doped laser which leaped the output power from 3kW to 6kW [6]. Another advantage for cascade pumping is the laser beam wavelength is much closer to the output wavelength compared with semiconductor wavelength, which effectively reduces the thermal effect caused by quantum loss. After 2013, the IPG Photonics make this breakthrough one step further: the first 100 kW optical fiber laser system is announced in ASSL conference [7]. Spectrum synthesis and coherent synthesis gradually replaced the position of original power synthesis because of the ability to maintain beam quality.

In 2019, a high-brightness single-end pumping monolithic fiber laser with 10.6 kW output power was firstly demonstrated in University of Science and Technology of China, which prove the possibility of holding good thermal management ability, and is promising for higher power scaling in single-end pumping method [8]. The laser owns an optic-to-optic efficiency of 82.6% and the measured βFL factor of the laser at the maximum output power is about 2. It means that single end pumping ending pumping enable to create high brightness compact source. As for side pumping, the coupling efficiency also significantly changed by a novel structure for double clad fiber laser by Zhang and Wang, they design a setup of side-coupling into D-shaped DCF (Dispersion Compensating Fiber), a periodically modulated gold rectangular grooves corresponding to the one for side coupling is added into inner cladding [9,10].

However, there have been no controlled studies which compare signal differences in different pumping direction for both side pumping and end pumping. The research to date has tended to focus on intracavity gain rather than long distance attenuation. The aim of this study was to evaluate and validate the distribution for both pumping modes. The rest part of the paper is organized as follows. The Sec. 2 will introduce the fundamental formulas and theories. Subsequently, the simulations parameters setups will be presented in Sec. 3. Afterwards, the results and discussions will be demonstrated as well as the research limitations in Sec. 4. Eventually, a brief summary will be given in Sec. 5.

2. Analytical models

Rate equation of ytterbium particles belongs to the four energy level systems, after neglecting the particle relaxation events from E_3 to E_2 and considering the factors of spontaneous emission. The rate equation could describe as:

$$\frac{dN_3}{dt} = I_p\left(N_0\sigma_{ap} - N_3\sigma_{ep}\right) - \frac{N_3}{\tau_3} \tag{1}$$

$$\frac{dN_2}{dt} = I_s(N_0\sigma_{as} + N_1\sigma_{es}^* - N_2\sigma_{es}) - \frac{N_2}{\tau_2} + \frac{N_3}{\tau_3} \tag{2}$$

$$\frac{dN_1}{dt} = I_s(N_2\sigma_{es} - N_1\sigma_{es}^*) - \frac{N_2}{\tau_1} + \frac{N_2}{\tau_2} + \frac{N_3}{\tau_3} \tag{3}$$

$$N = N_0 + N_1 + N_2 + N_3 \tag{4}$$

where σ_{es}^* is absorption cross section of laser energy level to laser wavelength; net $\tau_2$and$\tau_3$are relaxation time of metastable and pumped levels, respectively; $\sigma_{as}(\sigma_{es})$and $\sigma_{ap}(\sigma_{ep})$ represent the emission cross section and absorption cross section for laser beam and pumping beam; I_s and I_p represent the intensity for both beams, respectively. When using LD as the fiber laser pumping source, the spectral linewidth of pump light and output light is rather narrow. As for Yb^{3+}doped double clad end pumping laser, the rate equation could be briefly described as:

$$\frac{dP_p^+(z)}{dz} = -\Gamma_p\left[\sigma_{ap}N - (\sigma_{ap} + \sigma_{ep})N_2(z)\right]P_p^+(z) - \alpha_p P_p^+ \tag{5}$$

$$\frac{dP_p^-(z)}{dz} = \Gamma_p\left[\sigma_{ap}N - (\sigma_{ap} + \sigma_{ep})N_2(z)\right]P_p^-(z) - \alpha_p P_p^-(z) \tag{6}$$

$$\frac{dP_s^+(z)}{dz} = \Gamma_s[-\sigma_{as}N + (\sigma_{as} + \sigma_{es})N_2(z)]P_s^+(z) - \alpha_s P_s^+(z) + \Gamma_s\sigma_{es}N_2(z)P_0 \tag{7}$$

$$\frac{dP_s^-(z)}{dz} = -\Gamma_s[-\sigma_{as}N + (\sigma_{as} + \sigma_{es})N_2(z)]P_s^-(z) + \alpha_s P_s^-(z) + \Gamma_s\sigma_{es}N_2(z)P_0 \tag{8}$$

$$\frac{N_2(z)}{N} = \frac{\frac{\left[P_p^+(z) + P_p^-(z)\right]\sigma_{ap}\Gamma_p}{h\nu_p A_c} + \frac{\left[P_s^+(z) + P_s^-(z)\right]\sigma_{as}\Gamma_s}{h\nu_s A_c}}{\frac{\left[P_p^+(z) + P_p^-(z)\right](\sigma_{ap} + \sigma_{ep})\Gamma_p}{h\nu_p A_c} + \frac{1}{\tau} + \frac{\left[P_s^+(z) + P_s^-(z)\right](\sigma_{as} + \sigma_{es})\Gamma_s}{h\nu_s A_c}} \tag{9}$$

For both pumping directions, $P_p^+(z)$ and $P_p^-(z)$represent the forward and backward power of pumping beam; $P_s^+(z)$ and $P_s^-(z)$ represent the forward and backward power of fiber laser.τrepresent the average lifetime of Yb^{3+}energy level; Γ_s and $\Gamma_p$represent the power fill factor of fiber laser and pumping beam; the doping concentration of gain medium is *N*; *A* is Cross section area of fiber core; *h* is Planck constant; $\sigma_{as}(\sigma_{es})$ and $\sigma_{ap}(\sigma_{ep})$ represent the emission cross section and absorption cross section for laser beam and pumping beam; frequency of pump light and laser are ν_p and ν_s. As for boundary conditions of linear resonators:

$$P_p^+(0) = P_p^l \tag{10}$$

$$P_p^-(L) = P_p^r \tag{11}$$

$$P_s^+(0) = R_1 P_s^-(0) \tag{12}$$

$$P_s^+(L) = R_2 P_s^+(L) \tag{13}$$

Here, P_p^l and P_p^rrepresent the pumping power injected from left end and right end. The sketch of the end pumped fiber laser is illustrated in Fig. 1.

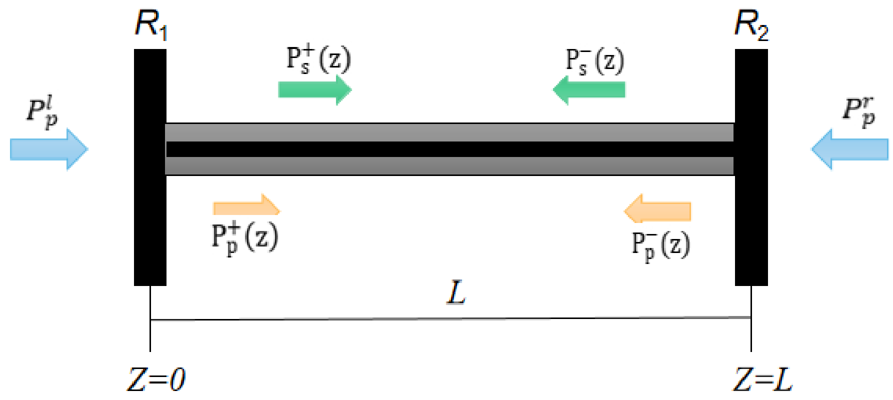

Figure 1. sketch of end pumped fiber laser.

3. Simulation setups

In the simulation part, this paper mainly uses the Matlab as the computing software and SFtool as the auxiliary simulation software during whole process. Since boundary problem in fiber basically consists of ordinary differential equations and two boundary conditions, the function bvp4c() is used which belongs to the build in software as the solving method perfectly simplifies the process.

The parameter settings are given as follows. Generally, the central wavelength for pumping light is 976nm, central wavelength of fiber laser is 1024nm, the close wavelength gap is conducive to optic-to-optic efficiency for fiber laser. Average energy level lifetime of ytterbium particles was set to 0.8 ms. Absorption cross section for pumping light and emission cross section for pumping light are $2.4\times10^{-20}cm^2$. Absorption cross section for fiber laser is 1×10^{-23} cm^2 and emission cross section for fiber laser is 1.8×10^{-21} cm^2. Doping concentration in inner cladding is $5.8\times10^{19}cm^{-3}$. in the distant fiber transmission system, the pumping transmission loss fiber laser transmission loss are set as $2\times10^{-5}cm^{-1}$ and 4×10^{-6} cm^{-1}.

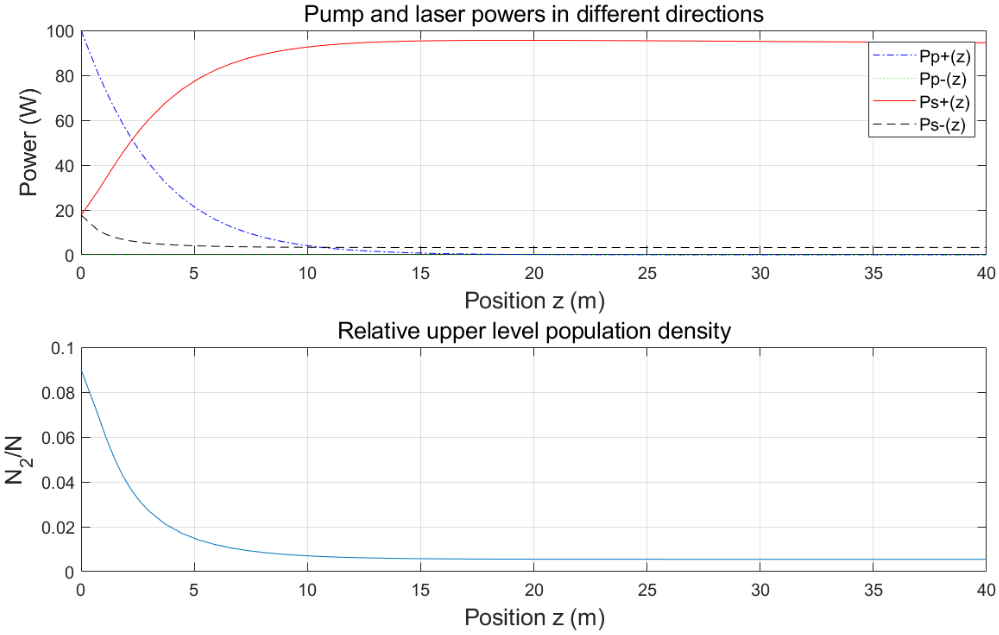

Figure 2. Pump and laser power in different directions and relative upper-level population density for forward pump.

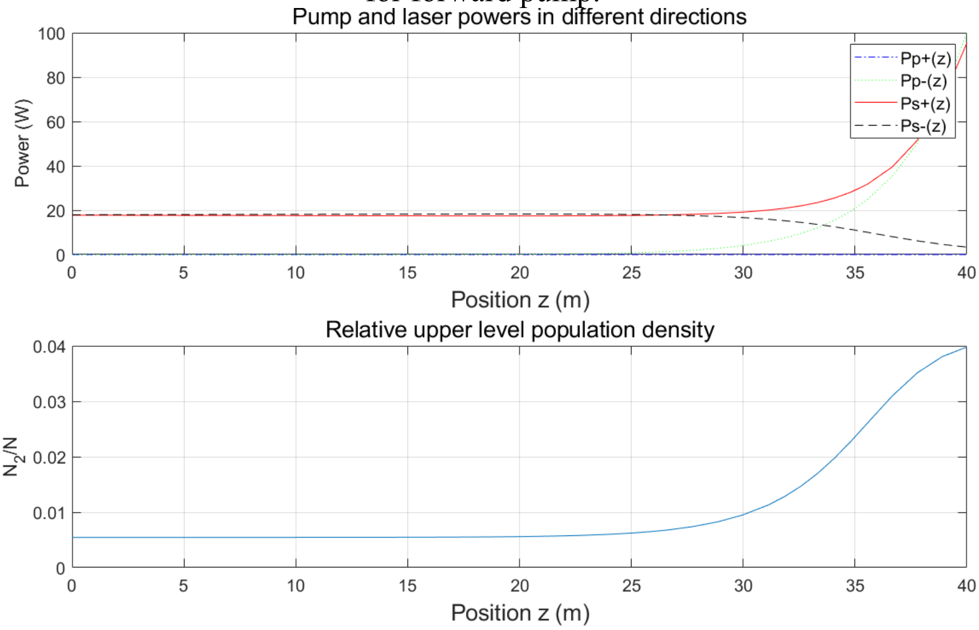

Figure 3. Pump and laser power in different directions and relative upper level population density for backward pump.

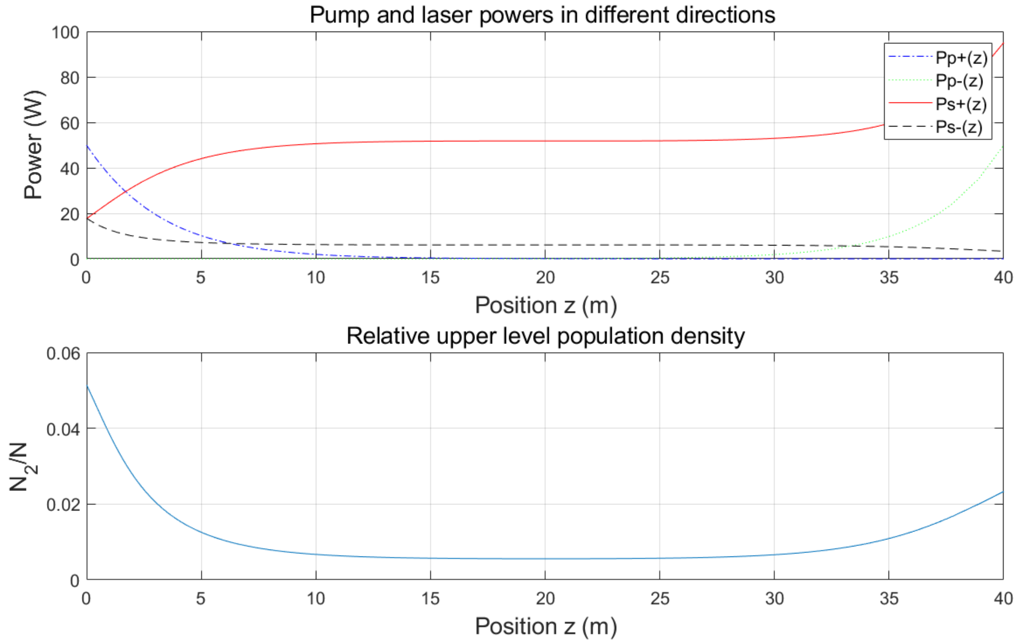

Figure 4. Pump and laser power in different directions and relative upper level population density for bi-direction pump

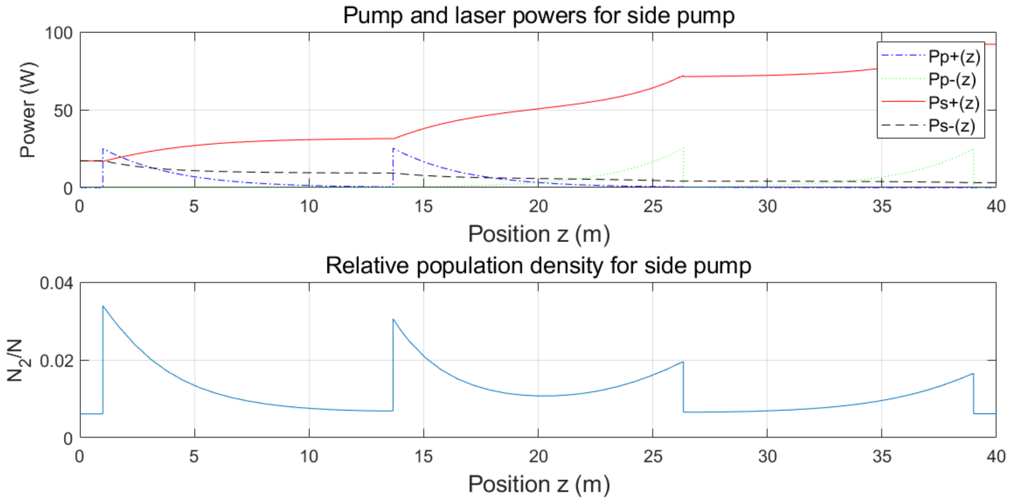

Figure 5. Pump and laser power in different directions and relative upper level population density for side pump.

4. Results & Discussion

The relative upper-level population density which is equivalent to gain distribution for backward pumping. As the Fig. 2 demonstrated, during the previous half, forward pumping has already concordant with the peak value while the backward pumping only increased by a large margin during latter procedure. From the perspective of reducing nonlinear effects, backward pumping owns superiority without doubt. However, the Fig. 3 also shows that the gain curve is rather steep if only adopt the backward pump. In contrast, bi-direction pump in Fig. 4 is more congruous with reducing thermal load, particularly in high power fiber laser transmission which generate maximal heat. The intensity of the output laser increases relatively uniformly and the laser gain increases obviously at the injection point.

In the Fig. 5, for side pumping power, the optical laser loss is comparatively small when passing through the pumping point. On the other hand, on account of the injection of pumping beam, the mutation of beam curve is generated which directly leads to the mutation of energy level particle number concentration. Thermal stress may occur in specific points. The two ends of the fiber have vacancy so that the Easier operation of optical fiber fusion process and signal measurement could become realization.

From some aspects, this simulation still has certain research limitations. In the study of laser performance under high energy conditions, there is no effective calculation of accurate nonlinear phase shift, which may result in the difficulty in improving the pulse energy. The nonlinear refractivity depending on the precision of optical fiber fabrication. Secondly, the effects estimate in the model are based on predictive observational study, which are therefore subject to biases and confounding that may have influenced model estimate. The scattering effect of the simulation results of this experiment under the condition of ultra-high strength may be more obvious. Considerably more work will need to be done to monitor and simulate Stimulated Raman scattering and Stimulated Brillouin scattering.

5. Conclusions

In summary, this paper mainly investigates output characteristic of different pumping mode for double clad fiber laser based on Matlab and SFtool. The basic principles are introduced and determinant differential equations are derived to calculate gain characteristics and output comparison under different pump conditions, which include beam output at different pump direction ratios. Although bidirectional pumping can effectively reduce the thermal effect, the gain curve is still not as flat as muti-point side pump. However, the beam leakage may induce the drop of pump efficiency. It should be noted that there will be new coupling techniques in the future to eliminate this shortcoming, and combine the advantages of both. Overall, this paper offers a guideline for selection of pumping technology under high power circumstance as well as clarify the issues and problems that remain to be ameliorated.

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