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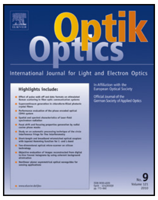

Numerical study on the continuous-wave Yb-doped fiber amplifiers operating near 980 nm

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ABSTRACT

In this paper, the properties of continuous-wave Yb-doped fiber amplifiers operating near 980 nm are investigated numerically. The effects of the seed light, active fiber configuration, pump power, pumping scheme and residual reflectivity of output port on performance of the 980-nm amplifier are revealed. It is found that besides the core-to-cladding ratio, both the seed power and pump power should large enough to realize the high output efficiency. It is also revealed that although the core-to-cladding ratio is important for the output power and efficiency, it only has a negligible effect on the optimum length of Yb-doped fiber. It is found that the optimum length is almost uniquely determined by the dopant concentration of Yb-doped fiber, and the plus of these two parameters are a constant almost unvaried with other parameters of Yb-doped fiber. With this result, a simple but effective method for estimating the optimum length of Yb-doped fiber is presented. Besides, it is also found that the residual reflectivity of output port should be no larger than 10^{-5} to optimize the output property of the 980-nm fiber amplifier. We believe that the pertinent results can provide significant guidance for deeply understanding and designing the 980-nm Yb-doped fiber amplifier.

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1. Introduction

Nowadays, the high-power Yb-doped fiber laser with the diffraction-limitation beam quality has been attracted much attention, because its output power has been increasing rapidly in the last decade from several watts in 2003 to 10 kW in 2009 [1,2]. One key driving the power of fiber lasers to 10 kW is the tandem-pumping scheme, which greatly promotes the pump power brightness by using the moderate-power fiber laser around 1010–1020 nm as the pump source [1]. Actually, the brightness of the tandem pump source can be two-order larger than the laser diode (LD) pump source. However, there is still an issue induced by the tandem pump source, i.e., the lower absorption cross section of Yb-ion at the wavelength around 1010–1020 nm. In order to realize the high enough pump absorption at the tandem pumping wavelength, the high doping concentration and large core-to-cladding ratio of Yb-doped fiber are required in the fiber laser system, which does not only increase the fabrication difficulty of Yb-doped fiber but also increase the difficulty of beam quality controlling (because of the unavoidable large core of Yb-doped fiber).

One promising way to solve the problem induced by the tandem pumping source around 1010–1020 nm is using the fiber laser operating near 976 nm as the tandem pumping source which can not only provide high brightness but also beneficial

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to the pump absorption of the Yb-doped fiber whose absorption cross section is maximized within the wavelength around 976 nm. Therefore, the high-power fiber laser operating near 976 nm (the wavelength ranging from 975 nm to 980 nm, also called as the 980-nm fiber laser) is considered as a better alternative of the tandem pumping source. Besides, the 980-nm fiber laser can also be used as the pump source of Er-doped fiber laser system and some other novel sources such as the blue source [3–6]. The 980-nm fiber laser becomes more and more attractive.

Currently, there were a number of experimental studies on the 980-nm fiber lasers. In 2003 and 2004, 977-nm fiber lasers of multi-watt level radiation were achieved by the use of a ring-doped and jacketed-air-clad (JAC) Yb-doped fiber [7,8]. In 2008, a maximum of 94W output power at 977 nm close to diffraction-limited beam quality has been demonstrated by using a rod-type photonic crystal fiber (PCF) which provides a large core-to-cladding area ratio while maintaining the high beam quality [9,10]. However, these studies mainly utilized the spatial-light coupling configuration. The all-fiber configuration owning the advantage of compactness and robustness is more attractive. Then, Bartolacci et al. used the standard single-mode Yb-doped fiber for the amplification of 980-nm radiation in an all-fiber master-oscillator power amplification (MOPA) scheme in 2011 [11]. Later, the all-fiber 980-nm double-cladding fiber laser was also experimentally studied and multi-Watt output power around 976-nm was obtained [12–14].

Although some outstanding improvement has been made in these experiments, the output powers of these fiber lasers were all limited to 100 W, and the optical-to-optical efficiencies were lower than 50% as well. Such a current state is mainly induced by the difficulty of lasing 980-nm radiation of Yb-doped fiber lasers. In the Yb-doped fiber laser, the 980-nm radiation is produced by the three-level transition of Yb-ion, and thus suffering not only a large pump threshold but also the gain competition with the emission of the quasi-four-level transition of Yb-ion around 1030 nm (i.e., the parasitic 1030-nm ASE). Some studies have revealed that increasing the core-to-cladding ratio of Yb-doped fiber is an effective way for suppressing the parasitic 1030-nm ASE [9,10,15,16]. Ref. [16] also made a systematic study on the 980-nm Yb-doped fiber oscillator. In spite of that, the detailed study on the 980-nm Yb-doped fiber amplifier which plays an important role on the power-scaling of 980-nm fiber laser, is also very limited, and there are still some questions needed to be further investigated. For example, how to design the seed light and Yb-doped fiber length for a 980-nm fiber amplifier, and how will the pumping scheme and residual optical reflectivity of output port affect the 980-nm fiber amplifier? These questions are important for design the 980-nm fiber amplifier but still not so clear at present.

Therefore, the properties of continuous-wave (CW) 980-nm Yb-doped fiber amplifiers are systemically studied in this paper. This paper is arranged as follows: In Section 2, the rate-equation model of 980-nm Yb-doped fiber amplifier will be introduced. Then, in Section 3, the effects of various configuration parameters on the output performance of amplifier will be studied by analyzing the numerical results. The conclusions will be summarized in Section 4.

2. Rate-equation model of 980-nm fiber amplifier

Considering the unavoidable parasitic 1030-nm ASE in the 980-nm Yb-doped fiber amplifier, the rate-equation model should take the ASE into account. Because we focus our discussion on the CW 980-nm fiber amplifier, the steady-state rate-equation model is utilized in this paper, which can be given as follows [17].

$$\frac{N_2(z)}{N} = \frac{\frac{[P_p^+(z)+P_p^-(z)]\Gamma_p\sigma_{ap}}{h\nu_p A} + \frac{\Gamma_s}{hcA}\int \sigma_a(\lambda)\cdot[P^+(z,\lambda)+P^-(z,\lambda)]\lambda d\lambda}{\frac{[P_p^+(z)+P_p^-(z)](\sigma_{ap}+\sigma_{ep})\Gamma_p}{h\nu_p A} + \frac{1}{\tau} + \frac{\Gamma_s}{hcA}\int(\sigma_a(\lambda)+\sigma_e(\lambda))\cdot[P^+(z,\lambda)+P^-(z,\lambda)]\lambda d\lambda} \tag{1}$$

$$\pm\frac{dP^{\pm}(z,\lambda)}{dz} = \Gamma_s\{[\sigma_e(\lambda)+\sigma_a(\lambda)]N_2(z)-\sigma_a(\lambda)N\}\cdot P^{\pm}(z,\lambda)$$
$$+\Gamma_s\sigma_e(\lambda)N_2(z)P_o(\lambda)-\alpha(z,\lambda)P^{\pm}(z,\lambda) \tag{2}$$

$$\pm\frac{dP_p^{\pm}(z)}{dz} = -\Gamma_p\{\sigma_{ap}(N-N_2(z))-\sigma_{ep}N_2(z)\}\cdot P_p^{\pm}(z)-\alpha(z,\lambda_p)P_p^{\pm}(z) \tag{3}$$

In these equations, N is the dopant concentration (averaged per unit volume) and N_2 (z) is the population density of the excited state. The powers of the signal and ASE are all included in $P^{\pm}(z,\lambda)$. $Pp^{\pm}(z)$ is the pump power at the wavelength of λ_p. The plus sign and the minus sign indicate the positive and negative propagation along the z-direction, respectively. The pump power filling factor Γ_p approximately equals the core-to-cladding area ratio. The signal power filling factor is Γ_s. $\sigma_e(\lambda)$ and $\sigma_a(\lambda)$ are the wavelength dependent emission and absorption cross section. σ_{ep} and σ_{ap} are abbreviation of $\sigma_e(\lambda_p)$ and $\sigma_a(\lambda_p)$ at the pump wavelength. $\alpha(z,\lambda)$ is the scattering loss with wavelength dependent. τ is the spontaneous emission lifetime, A is the efficient dopant cross section area, c is the speed of light in vacuum and h is Planck's constant. The spontaneous emission $P_0(\lambda)$ which results in the initial ASE is given by [18]

$$P_0(\lambda) = 2hc^2/\lambda^3 \tag{4}$$

Then, together with the following boundary conditions, the rate-equation model can be numerically solved and the power evolutions of optical fields in the fiber amplifier can be revealed.

$$P^+(0,\lambda_s) = P_{s0} \tag{5}$$

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