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Dynamics of nanosecond pulsed pump ytterbium-doped double-clad fiber amplifier

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ABSTRACT

Pulsed pump is an effective method to suppress the amplified spontaneous emission (ASE) between pulses of high power pulsed fiber lasers. For the pulsed pump, the most important factors need to be determined during amplifier design are the pump power (P_P) and pump duration (t_p). In this paper, the high power ytterbium-doped double-clad fiber amplifier with pulsed pump is numerically studied. The relationship between pulse energy, efficiency and ASE with pump power and duration is investigated and experimental results are provided. The conclusions are valuable for the design of pulsed pump fiber amplifiers.

1. Introduction

High-power ytterbium-doped pulsed fiber lasers (YDPFLs) have been intensively studied by researchers [1–4], and are widely used in industry because of their many advantages [5,6]. However, the inter-pulses amplified spontaneous emission (ASE) is a concern for the lasers as it consumes the upper level populations leading to lower efficiency of the final output laser, heats the components in the laser cavity which in turn affects the robustness of the system, causes self-lasing which results in the instability of the laser operation and reduces the maximum achievable pulse energy extracted from the laser cavity, and so on. By adopting pulsed pump instead of continuous-wave (CW) pump to suppress the ASE is a widely-used method suggested by researchers. For example, in 2009, Huang et al, achieved 30 dB gains from an ytterbium-doped double-clad fiber amplifier (YDFA) through the pulsed pump to suppress the ASE for a 100 ns pulse at 100 Hz pulse repetition rate [7]. In 2014, a fiber laser with 55 mJ pulse energy and 10 ns pulse duration at 10 Hz pulse repetition rate was reported [8]. The laser was made up of seven cascaded amplifiers and pulsed pump with different pump power (P_P) and pump duration (t_p) was implemented.

Theoretical modeling and numerical analysis provide the necessary guidance for YDFA design. A number of papers have been reported on the dynamics of the laser pulses amplified by an YDFA with CW pump [9,10]. However, few are available for pulsed pump. In 2013, Wei T. et al,reported the study on the optimal duration of the pulsed pump, the study was focusing on one particular pump power level [11]. For pulsed pump, the most important factors to be identified for the amplifier design are the P_P and t_p. Driven by this, in this paper, the laser pulse evolution in a pulsed pumped YDFA is numerically studied by solving the time-dependent rate equations. The dynamics of the ASE, pulse energy and efficiency of the YDFA with pulsed pump at different P_P and t_p are investigated. Experimental results are provided.

2. Theoretical model

The configuration of the YDFA is demonstrated in Fig. 1. The 7 m-length gain fiber has a core/cladding diameter of 30/250 μm. The 200 ns trapezoidal shape laser pulses with rising and falling edges of 1 ns are used as the seed laser pulses. The optical spectrum bandwidth of the seed laser pulses is 2 nm (full width half modulation (FWHM)). Sixteen ASE channels with $\Delta\lambda_k$ of 5 nm are considered in the calculation. Two isolators are put at the ends of the amplifier to block the reflection light and pump power is coupled into the amplifier with the backward pump scheme. The other parameters are listed in Table 1 and the simplified rate equations for the YDFA are as follows [10,11], where z and t

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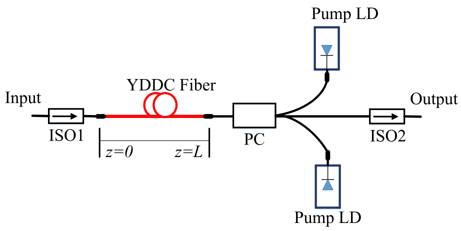

Fig. 1. The YDFA with backward pulsed pump scheme (ISO: isolator, PC: pump combiner, LD: laser diode).

Table 1
Part of the parameters used in the simulations.

λ_p 915 nm	λ_s 1064 nm	λ_1 1020 nm	λ_K 1100 nm
τ 880 μs	$S_{\alpha RS}$ 1.2×10^{-7} m^{-1}	N_0 7.7×10^{25} m^{-3}	A 7×10^{-10} m^2
Γ_p 0.01	Γ 0.83	$\Delta\lambda_s$ 2 nm	$\Delta\lambda_k$ 5 nm

represent the coordinate and time respectively. N_0 is the ytterbium dopant concentration. N_1 and N_2 are the ground and upper level population respectively. σ_a and σ_e are the absorption and emission cross-section of the ytterbium-doped double-clad (YDDC) fiber (the values are from Nufern Inc.). λ_p, λ_s and λ_k represent the central wavelengths of the pump, signal and ASE respectively. τ is the life time of the upper level ions. Γ_p and Γ are the filling factors of the pump and laser signal. $S_{\alpha RS}$ is the Rayleigh scattering factor. A is the fiber core size and α is the attenuation coefficient of the fiber. υ_p and υ are the group velocities of the pump and signal (ASE). $P_p^{\pm}$, $P^{\pm}(z,t,\lambda_k)$ and $P^{\pm}(z,t,\lambda_s)$ are the power of the forward and backward pump, ASE and signal. P_{pin} and $P_{\sin}$ are the power of the pump and signal injected into the amplifier.

$$\begin{aligned}\frac{dN_2(z,t)}{dt} &= \frac{\Gamma_p\lambda_p}{hcA}\left[\sigma_a(\lambda_p)N_1(z,t)-\sigma_e(\lambda_p)N_2(z,t)\right] \\ &\cdot\left[P_p^+(z,t)+P_P^-(z,t)\right]-\frac{N_2(z,t)}{\tau} \\ &+\frac{\Gamma}{hcA}\sum_{k=1}^{K}\lambda_k\left[N_1(z,t)\sigma_a(\lambda_k)-N_2(z,t)\sigma_e(\lambda_k)\right] \\ &\cdot\left[P^+(z,t,\lambda_k)+P^-(z,t,\lambda_k)\right]\end{aligned} \tag{1}$$

$$N_0 = N_1 + N_2 \tag{2}$$

$$\begin{aligned}\pm\frac{\partial P_p^{\pm}(z,t)}{\partial z}+\frac{1}{\upsilon_p}\frac{\partial P_p^{\pm}(z,t)}{\partial t} &= -\Gamma_p\left[\sigma_a(\lambda_p)N_1(z,t)-\sigma_e(\lambda_p)N_2(z,t)\right] \\ &\times P_p^{\pm}(z,t)-\alpha(\lambda_p)P_p^{\pm}(z,t)\end{aligned} \tag{3}$$

$$\begin{aligned}\pm\frac{\partial P_p^{\pm}(z,t,\lambda_k)}{\partial z}+\frac{1}{\upsilon}\frac{\partial P_p^{\pm}(z,t,\lambda_k)}{\partial t} &= -\Gamma\left[\sigma_e(\lambda_k)N_2(z,t)-\sigma_a(\lambda)N_1(z,t)\right] \\ &\times P^{\mp}(z,t,\lambda_k)-\alpha(\lambda_k)P^{\pm}(z,t,\lambda_k)+2\sigma_e(\lambda_k)N_2(z,t)\frac{hc^2}{\lambda_k^3}\Delta\lambda_k \\ &+S\alpha_{RS}(\lambda_k)\times P^{\mp}(z,t,\lambda_k)\; k=1,\ldots K, k\neq S\end{aligned} \tag{4}$$

$$\begin{aligned}\pm\frac{\partial P^{\pm}(z,t,\lambda_k)}{\partial z}+\frac{1}{\upsilon}\frac{\partial P^{\pm}(z,t,\lambda_k)}{\partial t} &= \Gamma\left[\sigma_e(\lambda_s)N_2(z,t)-\sigma_a(\lambda_s)N_1(z,t)\right] \\ &\times P^{\pm}(z,t,\lambda_s)-\alpha(\lambda_s)P^{\pm}(z,t,\lambda_s) \\ &+2\sigma_e(\lambda_s)N_2(z,t)\frac{hc^2}{\lambda_s^3}\Delta\lambda_s+S\alpha_{RS}(\lambda_s)\times P^{\mp}(z,t,\lambda_s).\end{aligned} \tag{5}$$

The initial boundary conditions are as follows:

$$\begin{aligned}&P_p^+(0)=0,\quad P^-(L,t,\lambda_s)=0, \\ &P_p^-(L,t)=P_{pin}(t),\quad P^+(0,t,\lambda_s)=P_{sin}(t), \\ &P^+(0,t,\lambda_k)=0,\quad P^-(L,t,\lambda_k)=0,\quad k=1,\ldots,K, k\neq s.\end{aligned} \tag{6}$$

For the simulation, the rate equations are numerically solved in the step of 250 ps. The calculation of the laser pulses is ceased only when the variation of the peak power is less than 0.3% for the successive pulses. The seed laser pulses are kept at 10 μJ pulse energy and 100 Hz pulse repetition rate. The YDFA absorbs more than 98% pump power and it has a reasonable signal gain of 10 ∼ 30 dB. In the following paragraph, the pump duration t_p corresponding to reaching at the maximum pulse energy and efficiency is referred as t_{maxPE} and t_{maxEff}, respectively.

3. Simulation and experimental results

3.1. Amplifier working with different P_P and t_p

From the simulation results, the output pulse energy increases as a function of t_p at different P_P levels (Fig. 2(a)). However, the maximum achievable pulse energy increased for higher P_P is insignificant because of the saturation of the stored energy in the YDFA as show in Fig. 2(c). As expected, the t_{maxPE} is quickly shortened with higher P_P, and it is 300 μs, 500 μs and 1500 μs for the 30 W, 20 W and 10 W P_P respectively.

Fig. 2(b) shows the maximum achievable efficiency grows with the increase of P_P. However, the improvement slows down as the P_P increases. The t_{maxEff} is shorter than t_{maxPE} as after that more pump energy contributes to the ASE.

The stored energy in the YDFA before seed laser injected is shown in Fig. 2(c). Obviously, it grows rapidly with longer t_p and then saturates. The t_p for reaching saturation is longer than t_{maxPE} and t_{maxEff}. The reason is that the increase in ASE power becomes significant when pump duration is longer than t_{maxPE}. It results in the change of the N_2 distribution along the gain fiber. This will be further discussed in the following paragraph.

The simulation results of the forward and backward ASE before the seed laser pulses injected into the YDFA are shown in Fig. 3. The ASE power is in a low level when the pump duration is less than the t_{maxEff}. It grows quickly after that, and eventually gets saturated and reaches a plateau, where the amplifier can be considered as working in CW mode. Obviously, the higher the P_P, the higher the ASE power. The forward ASE power is higher than the backward one as the backward pump scheme is used.

The N_2 distribution along the gain fiber before the seed laser injecting into the amplifier is shown in Fig. 4(a) with 20 W P_P and several t_p from 300 μs to 700 μs in the step of 100 μs. It increases along the fiber and reached its peak at the pump end of the fiber when the t_p is less than 400 μs. When t_p increases from 500 μs to 700 μs, the N_2 distribution peak moves toward the opposite end. The reason is that the stronger ASE generated consumes more upper level ions and leads to lower N_2 distribution at the pump end of the fiber.

Figs. 4(b) and (c) shows the pulse energy and efficiency of the simulation and experimental results. The trend of these curves is in consistence. The efficiency and pulse energy peak at 400 μs and 500 μs respectively. From the experimental results, it confirms the conclusion in the simulation that the t_{maxEff} is shorter than t_{maxEP}. The pulse energy and efficiency of the experimental results are much lower than that of the simulation results. This is mainly due to the stimulated Raman scattering (SRS) caused by the high peak power of the laser pulses, and the insert loss of the combiner and isolator in the experiments.

3.2. Amplifier working with same pump energy

From Fig. 2(a), the t_{maxEff} is shortened and the pulse energy increases with higher P_P. To further study this, the simulation and experiments with the YDFA working at fixed pump energy of 12 mJ are carried out. The sets of P_P and t_p are listed in Table 2.

From Fig. 5(a), although the pump energy is the same, the stored energy in the YDFA continues to increase with shorter t_p. From Fig. 5(b), it shows that the pulse energy keeps growing rapidly when t_p is shortened from 4000 μs to 1000 μs. When t_p is longer than 4000 μs,