Theoretical and experimental study of transient response of the Yb-doped fiber amplifier

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Some analysis of the transient response of the Yb-doped fiber amplifier are performed by solving a set of time-dependent rate and power transfer equations based on finite-difference method. Meanwhile, the variation of time to reach the steady state for upper level population distribution, the forward and backward amplified spontaneous emissions (ASEs) and stored energy on the system parameters including pump power, fiber length, Yb-doped concentration, and core area are numerically simulated, respectively. The results show that, by optimizing pump pulse width, stored energy can reach or even exceed the steady state value of continuous wave (CW) pump. By increasing Yb-doped concentration and core area, stored energy is increased, the ASE is suppressed and the ASE built-up time is postponed. In addition, the experimental results show the validity of the theoretical ASE built-up time. The obtained results can provide important guiding for the optimization of pump pulse width and fiber parameters.

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The high energy pulses with millijoule (mJ) level and nanosecond order duration are required for many practical applications such as atmospheric optical communication, laser range finding, remote sensing, lidar, and nonlinear frequency conversion. Compared with Q switching and mode locking methods, a semiconductor seed source followed by a multi-stage fiber master oscillator power amplifier (MOPA) system would be an effective technology to obtain the high energy pulse[1−3]. In the low-repetition-rate high-energy MOPA system, it is very important to optimize the pump pulse width in order to achieve the best amplification results, meanwhile, suppress the amplified spontaneous emission (ASE) and reduce the heat generated in the amplification process[4,5]. So, it is necessary to analyse the time to reach the steady state for stored energy, and the built-up time of ASE. A few theoretical models for Yb-doped fiber amplifiers have been proposed. Hardy *et al.* deduced a set of approximate analytical expressions to describe the steady state signals, ASE, and Rayleigh scattering, for modeling of high power double-clad fiber amplifiers[6−8]. Wang *et al.* analysed the dynamic characteristics of high power pulse amplification and Raman effect in detail[9,10]. Chang *et al.* comparatively studied the small signal pulse and high power pulse amplification[11]. Xu *et al.* introduced the influence of the pump power, fiber length, and core diameter to the ASE power[12]. However, in the previous researches, before inputting the signal, amplifiers are assumed to have achieved the steady state under continuous wave (CW) pump. Furthermore, the theoretical and experimental study of time to reach the steady state for stored energy and the ASE built-up time of the Yb-doped fiber amplifier have not been reported in the literature.

The focus of this letter is the transient response of stored energy and ASE before injecting the seed light. By solving a set of time-dependent rate and power transfer equations based on finite-difference method, the variation of time to reach the steady state for stored energy and ASE under different pump power, fiber length, ytterbium doped concentration, and core area are numerically simulated, respectively. The experimental results match the simulation very well. The obtained results can provide important guiding for optimization of pump pulse width and fiber parameters.

The configuration of a typical Yb-doped double-clad (YDDC) fiber amplifier, which can be bidirectionally pumped through two dichroic mirrors, is schematically shown in Fig. 1. In order to suppress the facet reflection and avoid the self-oscillation, the fiber with a length of L is angle-cleaved at two ends. The ASE spectrum fluctuates greatly with the wavelength in a large regime, so it is divided into X channels with central wavelengths of λ_x, x=1, $\cdots$, X, and an even spacing $\Delta\lambda$. The input pulse is a narrow bandwidth signal with $\Delta\lambda_{\rm s}$=2 nm, and the spacing time $\Delta\lambda = \Delta\lambda_{\rm s}$ is reasonable, i.e., the rate equation expressions for the ASE and the signal have the same format. Then, the rate and power transfer equations for YDDC fiber amplifier can be expressed as[9]

$$\begin{aligned}\frac{\partial N_2(z,t)}{\partial t} = {} & \frac{\lambda_{\rm p}\Gamma_{\rm p}}{hcA}[\sigma_{\rm pa}N_1(z,t)-\sigma_{\rm pe}N_2(z,t)] \\ & \cdot[P_{\rm P}^{+}(z,t)+P_{\rm P}^{-}(z,t)] - \frac{N_2 z,t}{\tau} \\ & + \frac{\Gamma_{\rm s}}{hcA}\sum_{x=1}^{X}\lambda_x[\sigma_{\rm sa}(\lambda_x)N_1(z,t) \\ & - \sigma_{\rm se}(\lambda_x)N_2(z,t)][P^{+}(z,t,\lambda_x) \\ & + P^{-}(z,t,\lambda_x)], \end{aligned} \quad (1)$$

$$N = N_1(z,t) + N_2(z,t), \quad (2)$$

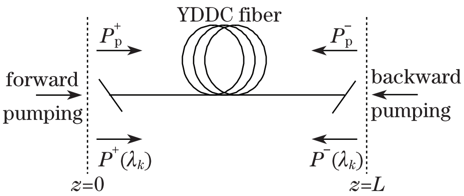

Fig. 1. Configuration of the YDDC fiber amplifier.

$$\pm\frac{\partial P^{\pm}(z,t,\lambda_x)}{\partial z}+\frac{1}{v}\frac{\partial P^{\pm}(z,t,\lambda_x)}{\partial t}$$
$$=\mathit{\Gamma}_{\rm s}[\sigma_{\rm se}(\lambda_x)N_2(z,t)-\sigma_{\rm sa}(\lambda_x)N_1(z,t)]$$
$$\times P^{\pm}(z,t,\lambda_x)-\alpha_{\rm s}P^{\pm}(z,t,\lambda_x)$$
$$+2\sigma_{\rm se}(\lambda_x)N_2(z,t)\frac{hc^2}{\lambda_x^3}\Delta\lambda, \quad (3)$$

$$\pm\frac{\partial P_{\rm p}^{\pm}(z,t)}{\partial z}+\frac{1}{v_{\rm p}}\frac{\partial P_{\rm p}^{\pm}(z,t)}{\partial t}=-\mathit{\Gamma}_{\rm p}[\sigma_{\rm pa}N_1(z,t)$$
$$-\sigma_{\rm pe}N_2(z,t)]\times P_{\rm p}^{\pm}(z,t)-\alpha_{\rm p}P_{\rm p}^{\pm}(z,t), \quad (4)$$

where N is the Yb-dopant concentration and assumed to be uniform along the fiber; $N_1(z, t)$ and $N_2(z, t)$ are the ground and upper level populations, respectively; $P_{\rm p}(z, t)$ is pump power; $P(z, t, \lambda_x)$ is the ASE power of each channel; $P(z, t, \lambda_{\rm s})$ is the signal power when x =s; positive and negative correspond to forward and backward propagations, respectively; A is the doped area of the YDDC fiber; $\lambda_{\rm p}$ and $\lambda_{\rm s}$ denote pump and signal wavelengths, respectively; h is Planck's constant; $\mathit{\Gamma}_{\rm p}$ and $\mathit{\Gamma}_{\rm s}$ are the overlapping factors for the pump and signal, respectively; $\sigma_{\rm a}$ and $\sigma_{\rm e}$ represent the absorption and emission cross sections of Yb ions, respectively; α is the scattering loss coefficient; τ is the lifetime of Yb^{3+} in upper level; $v_{\rm p}$ and v are the group velocities of the pump and ASE (signal) in the fiber, respectively.

The initial boundary conditions of Eqs. (1)−(4) are written as

$$P_{\rm p}^{+}(0)=P_1, P_{\rm p}^{-}(L)=P_2, \quad (5)$$

$$P^{+}(0,t,\lambda_x)=0, P^{-}(L,t,\lambda_x)=0, x=1,\cdots,X, x\neq {\rm s}, \quad (6)$$

where P_1 and P_2 are the input forward and backward pump powers, respectively. The system of Eqs. (1)−(4), as functions of coordinate z and t, can be solved numerically by using the finite-difference method where the space and time are decomposed into a grid of $M\times N$ discrete elements, respectively[13].

The transient response of the fiber amplifier is detailed studied in the following simulations, under a forward pump, by solving Eqs. (1)−(6). In order to compare with the experimental result, the parameters listed in the right column of Table 1 are from the experimental parameters of fiber amplifier.

Evolution of upper level population at each position of the fiber under pump power of 10 W and fiber length of 10 m is shown in Fig. 2. The rates of built-up of the population inversion are different at different positions. In order to indicate the average upper level population of the gain medium, the stored energy $E_{\rm s}$ is given as[15]

Table 1. Parameters of Amplifier

$\lambda_{\rm s}$(nm)	1 064	$\mathit{\Gamma}_{\rm p}$	0.0069
$\lambda_{\rm p}$(nm)	975	$\mathit{\Gamma}_{\rm s}$	0.85
λ_1(nm)	1 020	τ(ms)	0.84
λ_X(nm)	1 100	$\alpha_{\rm p}$(m^{-1})	3×10^{-3}
$\sigma_{\rm pa}$(m^2)	2.5×10^{-24}	$\alpha_{\rm s}$(m^{-1})	3×10^{-3}
$\sigma_{\rm pe}$(m^2)	2.5×10^{-24}	$\Delta\lambda$(nm)	2
$\sigma_{\rm sa}(\lambda_{\rm s})$(m^2)	5×10^{-27}	N	2×10^{26}
$\sigma_{\rm se}(\lambda_{\rm s})$(m^2)	3.4×10^{-25}	A(m^2)	9.67×10^{-11}
$\sigma_{\rm sa}(\lambda)$(m^2)	Ref. [14]	N(II)	3×10^{26}
$\sigma_{\rm se}(\lambda)$(m^2)	Ref. [14]	A(II)(m^2)	2.18×10^{-10}

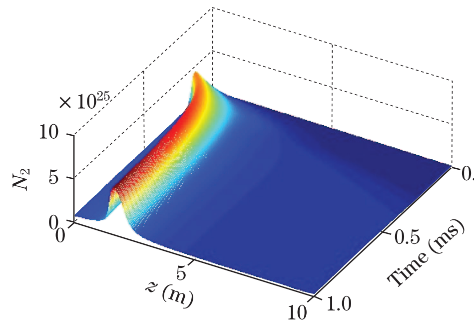

Fig. 2. Evolution of upper level population at each position of the fiber.

$$E_{\rm s}(t)=h\nu_{\rm s}A\int_0^{\rm L}N_2(z,t){\rm d}z, \quad (7)$$

where $h\nu_{\rm s}$ is the signal photon energy.

Influences of pump power, fiber length, Yb-doped concentration, and core area on the transient response of fiber amplifier are studied, respectively. With fiber length of 10 m, evolutions of the ASE and stored energy under pump power of 10 and 15 W are plotted in Fig. 3.

The built-up time of backward ASE is earlier than that of forward ASE and the backward ASE power is higher than the forward ASE power because of forward pumping configuration, depicted in Fig. 3(a). At the fiber input end, an upper level population peak occurs and then reaches the steady state that is due to the transient built-up of the backward ASE that depletes the population inversion, described in Fig. 2. And as the decrease of upper level population at the fiber input end, the backward ASE power also generates a peak and then gets to its steady state. But the forward ASE power monotonously increases and then reaches to the steady state, shown in Fig. 3(a). The descent of $E_{\rm s}$ after its maximum is due to the increase of the strong ASE, which consumes the upper level population, plotted in Fig. 3(b). This is very important for the pump pulse width optimization. The pump pulse width can set to be the time that stored energy reaches the same value with its steady state result under CW pump. Then the same amplification can be obtained, as well as the ASE is

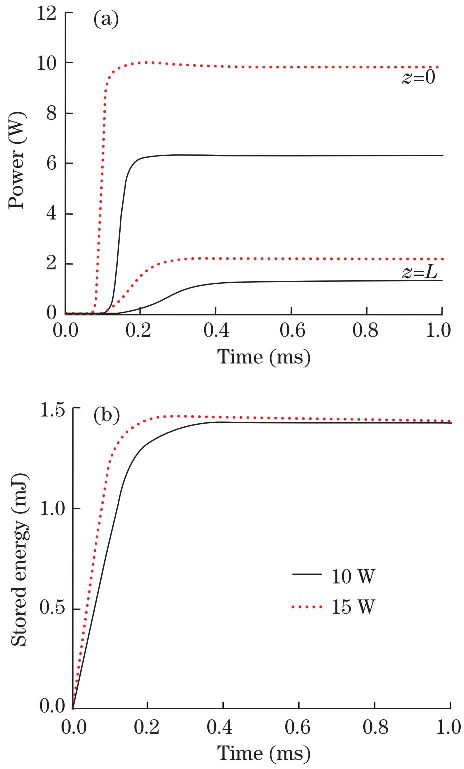

Fig. 3. Evolution of (a) ASE and (b) stored energy (L=10 m, P_p=10 and 15 W).

suppressed.

As depicted in Fig. 3(a), the higher the pump power, the sooner the ASE builds up, the peak occurs and the response reaches the steady state. So does the stored energy, described in Fig. 3(b). However, it is found that both the forward and backward ASE powers increase, the stored energy is approximately the same. That is, to the extent, the additional pump power is simply lost as ASE, instead of significantly increasing the stored energy.

With pump power of 10 W, evolutions of the ASE and stored energy under fiber length of 10 and 7.5 m are shown in Fig. 4.

Seen in Fig. 4(a), with the shorter fiber length, the backward ASE built-up time is almost the same, but power is lower; correspondingly the forward ASE built-up time is sooner, but power is higher. It means that fiber length increasing can restrain the forward ASE. With the same pump power, although the amplifier can be pumped more fully under the shorter fiber length, stored energy is lower and reaches its peak earlier, shown in Fig. 4(b).

Under pump power of 15 W and fiber length of 7.5 m, the Yb-doped concentration N is changed to be N(II) and the core area A is changed to be A(II), respectively. And the evolutions of the ASE and stored energy are plotted in Fig. 5.

Under the increasing of doped concentration, the backward ASE built-up time is almost the same, but power is a little higher; and the forward ASE built-up time is later and power is lower, depicted in Fig. 5(a). The stored energy has a slight increasing, described in Fig. 5(b). Thus, the forward ASE can be suppressed by increasing the doped concentration. When the core area A is increased to be 2.25 times, shown in Fig. 5, the forward and backward ASE built-up times are significant later, as well as power is marked lower. And the stored energy

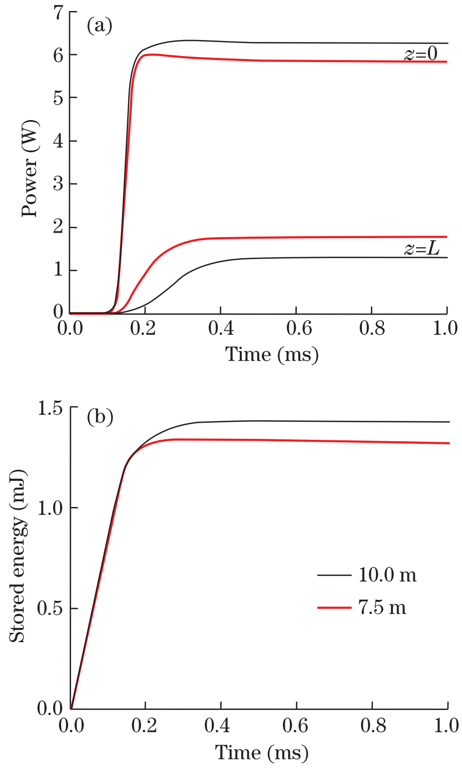

Fig. 4. Evolution of (a) ASE and (b) stored energy (P_p=10 W, L=10 and 7.5 m).

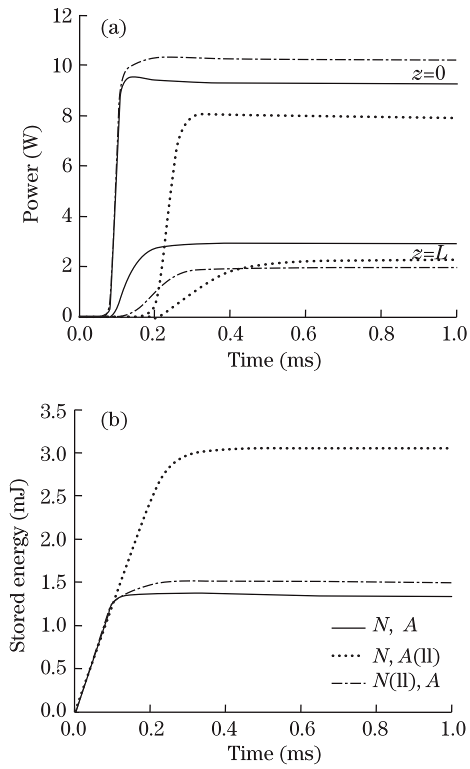

Fig. 5. Evolution of (a) ASE and (b) stored energy (P_p=15 W, L=7.5 m).

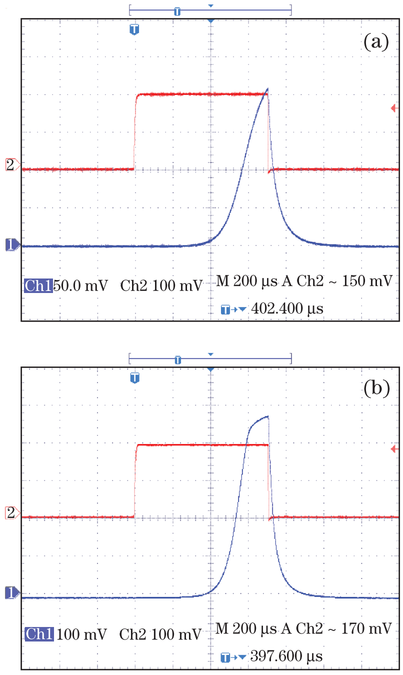

Fig. 6. Evolution of (a) forward and (b) backward ASEs.

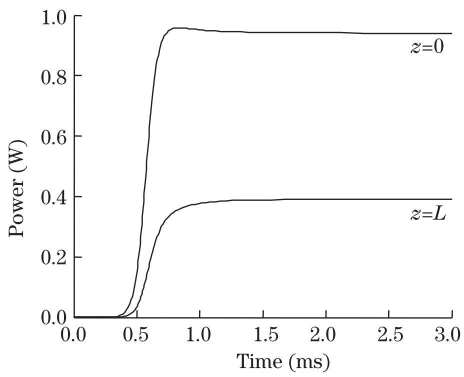

Fig. 7. Evolution of ASE.

is increased to be 3.028 from 1.328 mJ, 2.28 times the original. Obviously we can see that the stored energy can be increased, meanwhile both the forward and backward ASE can be suppressed by enlarging the core area.

The experimental study of ASE built-up time is also presented. The amplifier is forward pulsed pumped by 975-nm semiconductor laser. The fiber, named YDF-10/125 and produced by Nufern corporation, has a 10-μm-diameter, 0.08-NA step-index core, 125-μm-diameter fiber cladding, i.e., the parameters listed in the right column of Table 1. The forward and backward ASEs are received by photoelectric detector, and the pump pulse width and the ASE bullt-up time are measured through oscilloscope. The experimental results under pump power of 3 W and fiber length of 5 m are shown in Fig. 6. Mark 1 is ASE, and mark 2 is the pump pulse. The ASE built-up time is about 300 μs, but the backward ASE is a little earlier. And the backward ASE power is about 2.35 times the forward ASE power. Using the same parameters, the numerical simulation result is plotted in Fig. 7. As shown, the ASE built-up time is about 300 μs, and the backward ASE is a little sooner. The forward and backward ASE powers are 0.38 and 0.95 W, respectively. And the backward ASE power is 2.5 times the forward ASE power. This simulation matches the experimental result depicted in Fig. 6 very well, and shows its validity.

In conclusion, by solving a set of time-dependent rate and power transfer equations based on finite-difference method, transient response of the Yb-doped fiber amplifier under different pump power, fiber length, Yb-doped concentration, and core area are numerically simulated, respectively. The simulation shows that, by optimizing pump pulse width, stored energy can reach or even exceed the steady state value of CW pump. In addition, the stored energy is effectively increased, the ASE is suppressed and the ASE built-up time is obviously postponed through increasing Yb-doped concentration and core area. The experimental results show the validity of the simulation. The obtained results can provide important guiding for the optimization of pump pulse width and fiber parameters for the low-repetition-rate high-energy MOPA system.

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