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High-performance and narrow line-width nanosecond pulse laser amplifier for weak signal

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Abstract: A single mode, linearly polarized, narrow line-width, nanosecond pulsed fiber laser in master oscillator power amplifier (MOPA) configuration was demonstrated and the experimental results agreed with the theory. A single-frequency continuous wave laser operating at 1 064 nm was modulated by an acousto-optic modulator(AOM) to obtain pulses as the seed of the master amplifier. The repetition rate of the pulsed seed was 50 kHz and the average power was 25 μW. In the pre-amplification stage, the effect of nonlinear effect, amplified spontaneous emission (ASE), parasitic lasing and pump saturation were analyzed by simulation. By optimizing the parameters of the MOPA system, the parasitic lasing was suppressed and the enlargement factor was increased effectively. In the experiment, the laser with pulse width of 64 ns and average power of 75 mW was achieved. Finally, the key factors that affect the performance of the sub-milli-watt weak signal amplifier were discussed.

Key words: fiber laser;　master oscillator power amplifier;　amplified spontaneous emission

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用于微弱信号放大的高性能窄线宽纳秒脉冲光纤放大器

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摘　要： 搭建了一台主振荡功率放大(MOPA)结构的单模线偏振窄线宽纳秒脉冲全光纤放大器，理论仿真和实验结果较为吻合。通过声光调制器(AOM)对连续单频 1 064 nm 激光进行调制，获得了重复频率 50 kHz、平均功率 25 μW 的脉冲激光，作为放大器的种子源。对预放大过程中非线性效应、放大自发辐射、自激振荡及泵浦饱和问题进行了仿真分析。随后对种子光进行功率放大，通过光纤内参数的有效优化，进一步抑制了自激振荡，提升了弱信号的放大倍率。实验实现了脉冲宽度 64 ns、平均功率 75 mW 的脉冲激光输出。最后，对亚毫瓦弱信号放大器中决定系统性能的关键因素进行了总结。

关键词： 光纤激光器；　主振荡功率放大；　放大自发辐射

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0 Introduction

Fiber lasers have become an important development direction because of their essential characteristics of high conversion efficiency, excellent beam quality, steady operation, robust performance and so on. In recent years, narrow line-width nanosecond fiber lasers have attracted much attention for a range of applications such as remote sensing nonlinear frequency conversion, and LIDAR [1-5]. Most of the gain optical fiber is rare-earth doped, and the ytterbium-doped fiber amplifier offers a number of attractive features including broad-gain bandwidth and high efficiency, due to large part to its freedom from various competing processes seen in other rare-earth dopants[6].

The MOPA structure consists of a low-power single-frequency pulsed seed followed by high-power fiber amplifiers, as it is hard to obtain stable pulses with narrow line-width in a high-power oscillator. Fiber amplifiers can provide the high power, high gain and high efficiency [7]. However, For the MOPA structure, amplified spontaneous emission occurs in the whole amplification process especially when the repetition is lower than MHz, which does bad effect on the spectrum line-width and conversion efficiency. In the article, the numerical simulation and experimental validation of amplified spontaneous emission was completed and the suppression method was also discussed.

1 Theoretical model

According to the two energy-level structure of Yb^{3+} and the characteristics of laser transmission in the fiber, the rate equation of Yb^{3+} doped fiber can be described as[8]:

$$\pm\frac{\partial P_p^{\pm}(z,t)}{\partial z}+\frac{1}{\upsilon_p}\frac{\partial P_p^{\pm}(z,t)}{\partial t}=-\Gamma_p[\sigma_a(\lambda_p)N_1(z,t)-\sigma_e(\lambda_p)N_2(z,t)]\cdot P_p^{\pm}(z,t)-\alpha(\lambda_p)P_p^{\pm}(z,t) \tag{1}$$

$$\pm\frac{\partial P_k^{\pm}(z,t,\lambda_k)}{\partial z}+\frac{1}{\upsilon}\frac{\partial P_k^{\pm}(z,t,\lambda_k)}{\partial t}=-\Gamma_k[\sigma_e(\lambda_k)N_2(z,t)-\sigma_a(\lambda_k)N_1(z,t)]\cdot P_k^{\pm}(z,t,\lambda_k)-\alpha(\lambda_k)P^{\pm}{}_k(z,t,\lambda_k)+2\sigma_e(\lambda_k)N_2(z,t)\frac{hc^2}{\lambda_k^3}\Delta\lambda+S_{aRs}(\lambda_k)\cdot P_k^{m}(z,t,\lambda_k)\quad(k=1,2,3,\cdots,S,\cdots,K) \tag{2}$$

$$\frac{dN_2(z,t)}{dt}=\frac{\Gamma_p\lambda_p}{hcA}[\sigma_a(\lambda_p)N_1(z,t)-\sigma_e(\lambda_p)N_2(z,t)]\cdot[P_p^{+}(z,t)+P_p^{-}(z,t)]+\frac{\Gamma_k}{hcA}\sum_{k=1}^{K}\lambda_k[\sigma_a(\lambda)N_1(z,t)-\sigma_e(\lambda)N_2(z,t)]\cdot[P_k^{+}(z,t)+P_k^{-}(z,t)]-\frac{N_2(z,t)}{\tau} \tag{3}$$

$$N_t=N_1(z,t)+N_2(z,t) \tag{4}$$

All the other parameters and their physical meaning in the theoretical model can be checked in Tab.1.

Tab.1 Parameters in the theoretical model

$P_p^{\pm}(z,t)$	Forward and back propagating pump power at the moment t and the location z
$P_k^{\pm}(z,t,\lambda_k)$	Laser power transmitting in the core fiber at the wavelength λ_k
$\sigma_a(\lambda)$	Absorption cross section
$\sigma_e(\lambda)$	Emission cross section
N_t	The total population
N_1	Low-level population
N_2	Upper-level population
υ	Group velocity
Γ	Filling factor
A	Doped area
τ	Upper-level particle lifetime
α	Fiber attenuation coefficient
S_{aRs}	Rayleigh scattering coefficient

2 Numerical simulation and experimental validation

For the MOPA structure, the pulsed signal light from the AOM was weak that the pre-amplifier must consider the effect of ASE. According the absorption and emission cross section for Ytterbium iron described in Fig.1 and the parameter of the fiber structure, the power and spectrum of output signal light could be calculated with the rate equation described in the second section[9].

In our numerical simulation, we assumed the gain length was 1.5 m, the average power of The input light signal was 25 μW while the pump power was 0.1 W, 0.2 W, 0.3 W, 0.4 W.

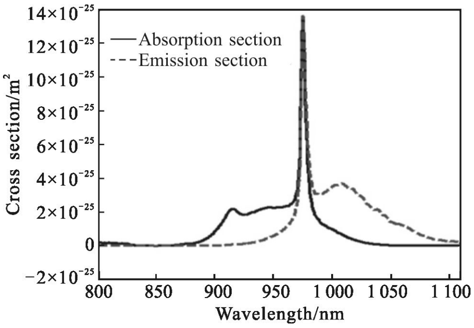

Fig.1 Absorption and emission cross section for Ytterbium iron

The output light of numerical simulation was shown in Fig.2 while the output light of experiment was shown in Fig.3. It is obvious that ASE of output spectrum soar with the pump power increasing. Considering the spectrum of output lasers was measured by scatting light, the absolute value of power was not so significant while the related value between ASE and the signal laser output matched well between the simulation and the experimental results. We also focused that in Fig.3 (c) and (d), the ASE and the signal power level stably which outlined that the pump power was over absorbed and the extra energy was transverse into self-oscillation which may cause the laser diode being damaged. Throughout the comparison between the simulation and experimental results, a fitful structure with optimized parameters was shown in the fourth section.

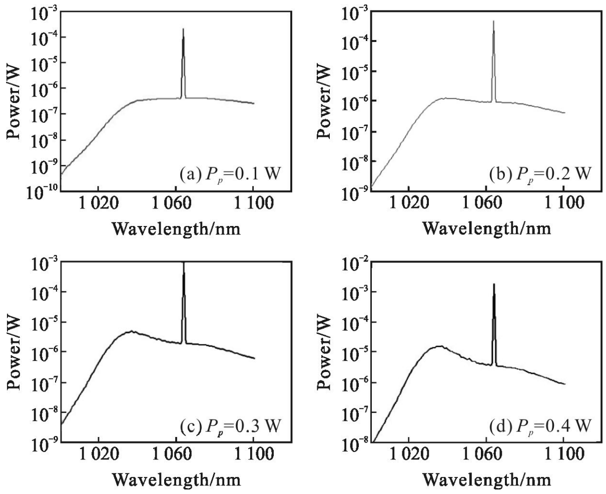

Fig.2 Output light of numerical simulation

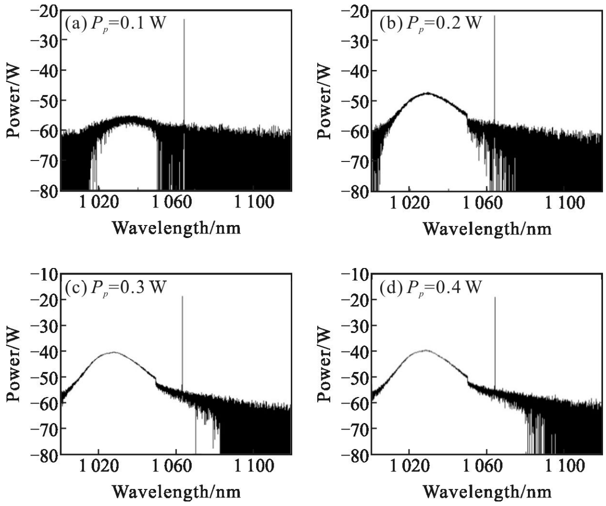

Fig.3 Output light of experiment

3 Experimental structure and result

Fig.4 shows a schematic of the narrow line-width

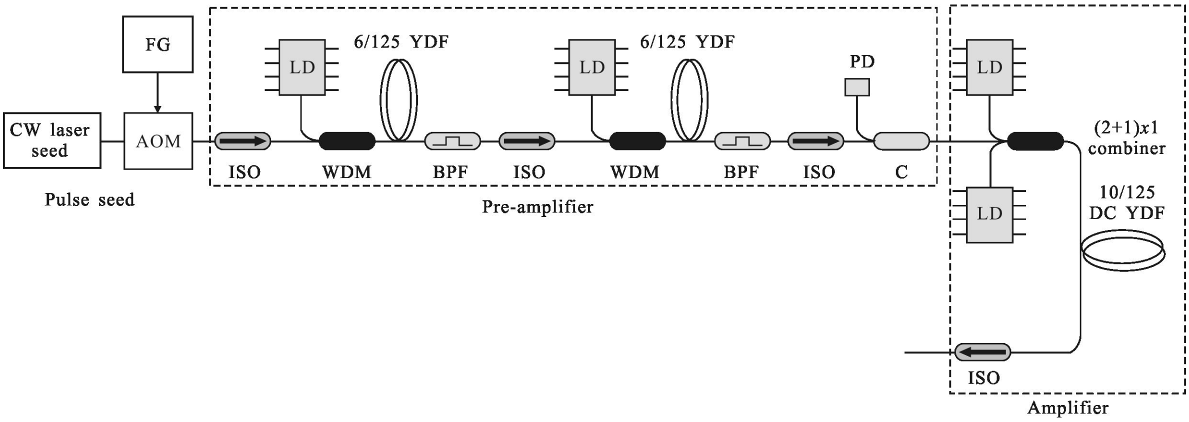

Fig.4 Schematic of pulsed fiber laser: CW laser, continuous wave laser; AOM, acousto-optic modulator; FG, function generator; ISO, isolator; LD, laser diode; WDM, wavelength division multiplexing; BPF, band pass filters; PD, photo-detector.

pulsed fiber laser at 1 064 nm in the MOPA configuration. The MOPA structure consisted of a dual-single-frequency CW laser, an acousto-optic modulator (AOM) and two amplifier stages. The AOM, which has a bandwidth of 150 MHz, was used to directly modulate the CW fiber laser. Driven by a Function generator (FG), the AOM offers the repeat frequency of the pulsed signal light to 50 kHz and the output average power was 25 μW. As shown in Fig.5, its pulse duration is about 27 ns.

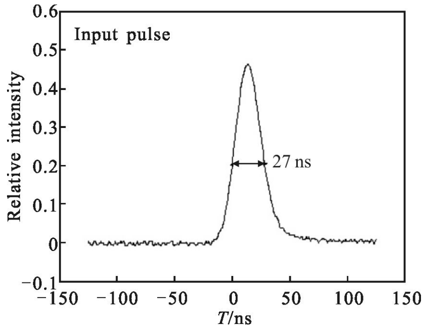

Fig.5 Pulse shape of the seed

The length of the first and second gain fiber in the Pre-amplifier was 1.2 m and 1.3 m, and a 4 m YDF with core diameter 10 μm and inner-cladding diameter 125 μm was used in the amplifier. The amplifier was clad pumped by single-mode fiber pigtailed 976 nm laser diodes(LD) via(2+1)*1 signal/pump combiners. Fiber isolators (ISO) were used between stages mainly to protect the components by preventing backward power such as ASE in the system. Finally, the pulse shape of the fiber amplifier is shown in Fig.6. The duration time is about 64 ns, and the average power is 75 mW.

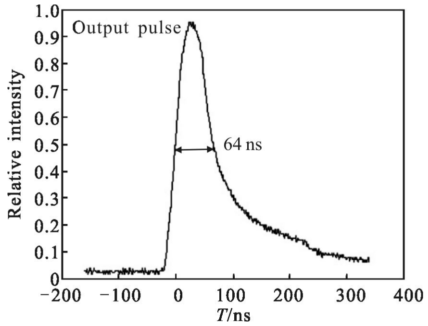

Fig.6 Pulse shape of the output laser

4 Conclusion

In conclusion, we have demonstrated an narrow line-width linearly polarized 1 064 nm all fiber pulse laser with the 50 kHz repeat frequency, 64 ns pulse duration, and 75 mW average power. Considering the optimization need, the dependencies of the gain in pulsed fiber amplifiers on fiber length and ASE were measured and discussed. The optimal fiber length was obtained and the self-oscillation of the ASE was eliminated.

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