Impacts of seed power on amplification performance in pulsed double-clad fiber amplifier

Fangpei Zhang (张芳沛)[1], Qihong Lou (楼祺洪)[1], Jun Zhou (周 军)[1], Hongming Zhao (赵宏明)[1], Songtao Du (杜松涛)[1], Jingxing Dong (董景星)[1], Yunrong Wei (魏运荣)[1], Bing He (何 兵)[1], Jinyan Li (李进延)[2], Jianqiang Zhu (朱健强)[1], and Zhijiang Wang (王之江)[1]

[1]*Shanghai Institute of Optics and Fine Mechanics, Chinese Academy of Sciences, Shanghai 201800*
[2]*Fiberhome Telecommunication Tech Co. Ltd., Wuhan 430073*

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A pulsed master-oscillator fiber power amplifier system with near diffraction-limited output by use of China-made large-mode-area fiber and a $(2+1)\times 1$ multimode combiner is reported. The effect of the seed power on the amplification performance is found. For the seed power, there exists a range within which the pulsed fiber amplifier can operate safely and reliably at a certain pump power. With the seed average power of 70 mW, the amplification performances of the fiber amplifier are investigated.

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Pulsed fiber lasers and amplifiers attract a growing interest as compact, robust, and efficient sources due to their advantages of several kilohertz pulse repetition rates, high peak power, high pulse energy, narrow spectral linewidth, high signal-to-noise ratio, and diffraction-limited beam quality. Their applications include scientific and military airborne lidar and imaging, harmonic generation and material processing, and remote sensing. For these applications demanding on higher pulse energy and peak power, the so-called master-oscillator power amplifier (MOPA) architecture which uses a low-power pulsed seed source followed by high-power amplification seems to be an attractive solution.

In the past several years, nanosecond master-oscillator fiber power amplifier (MOFPA) have been studied experimentally and theoretically[1−4]. For instance, using a 25-m-long low numerical aperture (NA = 0.06) large-mode-area (LMA) fiber with a core diameter of 30 μm, Limpert *et al.* described a typical MOFPA that was capable of generating an average output power up to 100 W at a repetition rate of 50 kHz (2-mJ pulse energy) at 1064 nm with the overall optical-optical conversion efficiency of 71%[1]. In 2005, Cheng *et al.* presented a high-energy and high-peak-power nanosecond fiber amplifier system achieving 82 mJ with 500-ns pulse duration, 27 mJ for 50-ns pulse duration, and 2.4-MW peak power for 4-ns pulse duration at 1064 nm by use of 3.5-m-long Yb-doped double-clad fiber with a 200-μm-diameter core (NA = 0.062) and a 600-μm-diameter octagon-shaped inner cladding[2]. In 2006, we reported a MOFPA system with a 4-m-long Yb-doped China-made LMA double-clad fiber[3].

It is well known that the gain can not increase infinitely with the increase of pump power in the MOFPA system. In fact, the amplification of pulses in fiber would be limited by the saturation energy E_{sat} which is a key parameter for the amount of energy stored in the amplifier. It is given by[5]

$$E_{\text{sat}} = \frac{h\nu_{\text{s}} A}{(\sigma_{\text{es}} + \sigma_{\text{as}})\Gamma_{\text{s}}}, \quad (1)$$

where $h\nu_{\text{s}}$ is the signal photon energy, σ_{es} and σ_{as} are the emission and absorption cross sections respectively at the signal wavelength, A is the doping area, and Γ_{s} is the signal overlap with an active dopant. However, the impact of seed power on the pulsed fiber amplifier has not been reported up to now in our knowledge. In addition, the pumping configuration adopted by the above-mentioned pulsed fiber amplifiers is the traditional end-pumping, which is bulky and unreliable. Compact all-fiber lasers and amplifiers can be realized by the commercial $(N+1)\times 1$ multimode combiner. In this paper, based on China-made LMA Yb-doped double-clad fiber and a $(2+1)\times 1$ multimode combiner, we constructs a MOFPA system with a near diffraction-limited beam quality ($M^2 = 1.2$). The impacts of seed power on amplification performance are mainly discussed, and an important conclusion is drawn and verified.

The experimental setup consists of a pulse fiber laser (IPG YLP-0.5/40/10) as the master-oscillator and a China-made double-clad Yb-doped LMA fiber (Fiberhome Telecommunication Tech Co. Ltd., China) as the power amplifier, which is shown in Fig. 1. The seed source delivers average power up to 1 W through several coupling lenses at repetition rates between 20 and 100 kHz and pulse durations in the range of 40 − 400 ns centered at a wavelength of 1064 nm. A Faraday isolator is employed to protect the seed source against back-reflections or counter directionally running beams

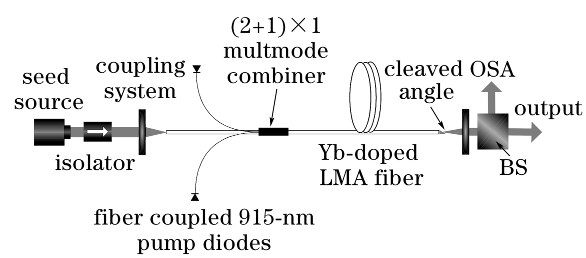

Fig. 1. Schematic setup of MOFPA. OSA: optical spectrum analyzer; BS: beam splitter.

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from the amplifier. The fiber core is 18 μm (NA = 0.07), inner cladding is 400/450 μm (NA = 0.48), and the fiber length is about 5 m.

In the experiment, two 7-W fiber-coupled pump diodes (supplied by Alfalight, Inc., USA) are employed to provide approximately 14-W pump power at the wavelength of 915 nm through a $(2+1)\times 1$ multimode combiner, which consists of LMA compatible 20/400 double-clad fiber on the output side and two 200/220 (NA = 0.22) pump delivery fibers on the input side. Adopting such a key component can make the seed light couple to the core and the pump light to the inner cladding of the LMA double-clad fiber efficiently. It is worth emphasizing that splicing technique is of the most critical during this course. Splicing must ensure that the core of the gain fiber is exactly connected with the core of the $(2+1)\times 1$ multimode combiner, or else the MOFPA system will fail to amplify the signal. Both the 1 signal-input end of the multimode combiner and the output end of the LMA fiber are polished at an angle of 8° to suppress amplification of spontaneous emission (ASE) or even spurious lasing in the fiber power amplifier. After being collimated, the amplified radiation is split into two beams by a beam splitter. One is sampled to monitor the spectrum evolutions using an optical spectrum analyzer (OSA Yokogawa AQ6370), and the other is measured by a power meter (Spectral-Physics 407A).

Figure 2 shows the amplification gain as a function of input seed power at the launched pump power of 5 W. To our surprise, the gain does not decrease monotonously with increasing the monotonous of the seed power, but there exists the largest gain of 20 dB corresponding to the seed power of 3.78 mW within the whole range of signal power. Once the seed power beyond 3.78 mW, the gain curve descends little by little, and finally has the trend to saturate while the gain drops to about 11 dB that is not difficult to understand. However, why the gain is relatively smaller while the input signal is very small (less than 3.78 mW)? Maybe the optical emission spectrum recorded by optical spectrum analyzer (OSA) can give the exact answer. For example, it is noted that there appears ASE along with the amplified radiation while the seed power is 2.36 mW, as shown in Fig. 3(a), and the ASE power is estimated to be 75% of the total output power. The reason why ASE appears can be explained from the Yb^{3+} energy level structure. While the input signal power is very small, the counter-propagating ASE at the signal-input end consumes a great deal of upper-

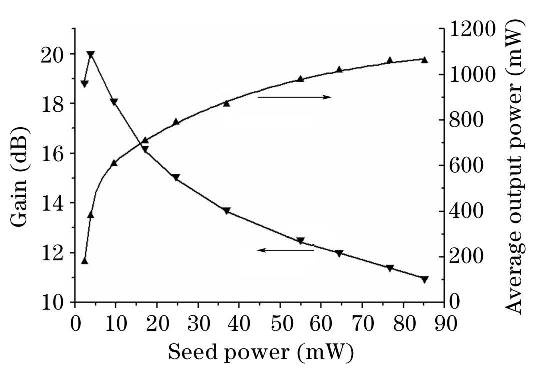

Fig. 2. Amplification gain and average output power as functions of seed power at the launched pump power of 5 W.

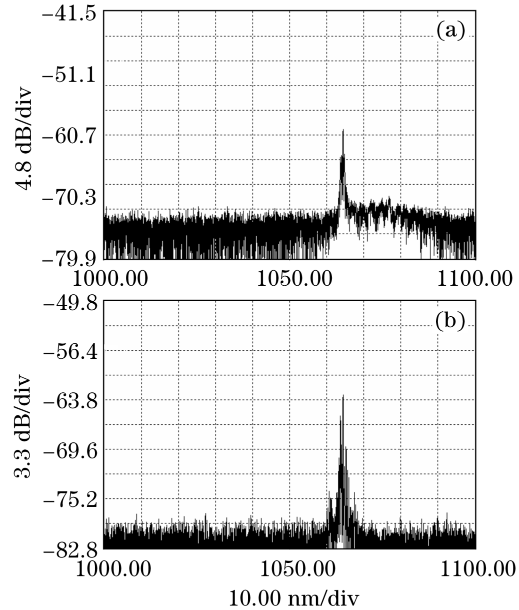

Fig. 3. Emission spectra corresponding to (a) smaller signal of 2.36 mW and (b) larger signal.

level inversion populations and the ASE power increases. Accordingly, the small-signal gain drops. Nevertheless, with the increase of the input signal power, most of the stored energy is extracted and the ASE is suppressed and disappears, as shown in Fig. 3(b). It is well known that the counter-propagating ASE would be detrimental to the seed source and the fiber coupled pump diodes. Therefore, in order to ensure sate and reliable performance of this MOFPA system, the input signal power must be larger than a certain value (3.78 mW).

However, the average output power can not increase infinitely with the increase of the seed power. In fact, for the input signal, there also exists a maximum. The average output power as a function of input seed power at the same pump power is also plotted in Fig. 2. The average power increases steeply while the seed power is relatively larger. However, the curve levels off gradually with the increase of the seed power, and until the input signal power increases to 76.62 mW the largest average output power of 1.06 W can be obtained. Subsequently, the average power almost does not change any more with the increase of signal power, which means that the seed power of about 77 mW is sufficient to saturate this LMA fiber amplifier.

From the above discussion, an important conclusion can be reached that for this MOFPA system only the seed powers between 3 and 77 mW can ensure safe and reliable operation. To further verify this conclusion, we choose the seed power of 70 mW and carry out amplifying. The output power characteristic at the maximum launched pump power is given in Fig. 4. The maximum average power of 4.8 W is achieved at 100-kHz repetition frequency with a launched pump power of ~ 13 W, and the overall slope efficiency with respect to the launched pump power is about 50%. Obviously, The output power increases almost linearly over the whole pump power range and no roll-off due to undesirable nonlinear scattering (such as stimulated Brillouin scattering) or indeed any other effect (such as ASE) is observed.

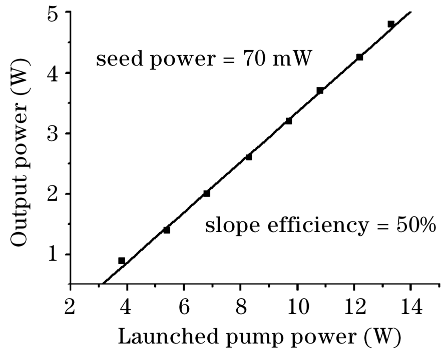

Fig. 4. Output power with respect to the launched pump power.

This suggests that it is possible to improve the amplified power level still further by increasing the pump power. The reason for this relatively low slope efficiency can be attributed to two factors. Firstly, the fiber length (5 m) is a bit shorter, and about 30% of the pump power is unabsorbed. Taking into account this factor, the slope efficiency with respect to the absorbed pump power is more than 63%. We believe that further optimization would improve the slope efficiency to some extent. Secondly, the mismatching between the core-diameter of multimode combiner (20 μm) and that of the LMA fiber (18 μm) would result in some loss, and further reduce the slope efficiency.

Figure 5 shows the gain as a function of launched pump power at the seed power of 70 mW. It is obvious that the gain increases gradually with the increase of the launched pump power, and we do not observe any saturation until the maximum pump power, which also confirms our conclusion from another point of view. Under this circumstance, we measure the beam quality using a knife-edge detection apparatus. The amplifier output beam is characterized in Fig. 6, which shows a near-field image taken through the output end by a charge coupled device (CCD) camera. The following equation is used to fit the measured beam radius and obtain M^2 factor[6]

$$\omega^2(z) = \omega_0^2 + M^4 \frac{\lambda^2}{\pi^2 \omega^2}(z - z_0)^2, \tag{2}$$

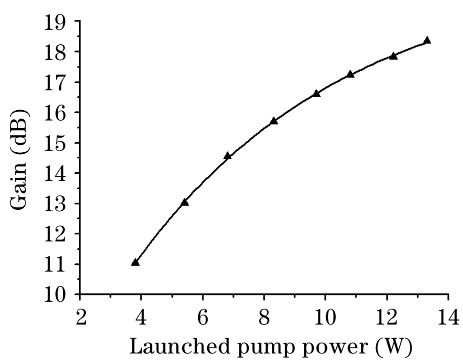

Fig. 5. Gain changes as a function of launched pump power at the seed power of 70 mW.

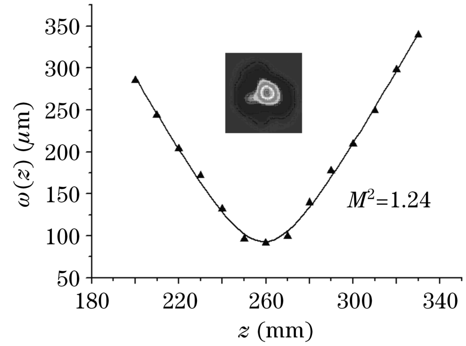

Fig. 6. $1/e^2$ radius of the amplified output beam versus location. Inset: near-field image of the amplifier output taken at the highest average power.

where λ and ω_0 are the wavelength and the radius at the waist position z_0 respectively. Evidently, the best-fit value of M^2 is 1.24 ± 0.03 (two standard deviations), which confirms that the beam is near diffraction-limited.

To sum up, adopting a China-made LMA fiber and a (2+1)$\times$1 multimode combiner, we creates a MOFPA system with a near diffraction-limited beam quality ($M^2 = 1.2$). Grounded on this system, the impacts of seed power on amplification capability are systematically investigated. By discussing the changes of gain and average output power along with the input seed power, we find that the signal cannot be amplified unlimitedly at a certain pump power, but there exists a maximum of seed power owing to the restriction of saturation energy E_{sat}. On the other hand, owing to the absorbing of core of LMA fiber towards the signal wavelength (1064 nm) to some extent, there also exists a minimum of seed power to keep the system reliable. In a word, for the seed average power, there exists a range in which the pulsed fiber amplifier can run safely and stably. We believe that this significant conclusion can be instructive to choose the appropriate seed source in the future work.

F. Zhang's e-mail address is zhangfangpei@sohu.com.

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