Narrow Linewidth 49 W All Fiber Linearly Polarized Picosecond Laser Operating at 1016 nm

Chao Zhang, Sheng-Ping Chen, Bo Li, and Xiang-Ai Cheng

Abstract—**An all fiber linearly polarized narrow linewidth pulsed fiber laser operating at 1016 nm is demonstrated in a master oscillator power amplification (MOPA) configuration. Core-pumped double cladding ytterbium-doped large mode area fiber amplifiers are proposed as the pre-amplifiers to reduce the nonlinearity and the ASE. The laser exhibits 48.6 W average output power, ∼18 kW peak power, and 0.28 nm linewidth.**

Index Terms—**Fiber laser, 1016 nm, pulse, linear polarization.**

I. Introduction

The ytterbium-doped fiber (YDF) lasers at short wavelength below 1020 nm (also called as S band) have many potential applications, such as a pump source for lasers and amplifiers [1], [2], producing visible light by frequency doubling [3], producing deep-ultraviolet light for laser cooling of mercury atoms by frequency quadrupling [4], [5], and nonlinear imaging of biological samples [6]. However, the absorption and emission characteristics of ytterbium ions make it difficult for YDF lasers to operate below 1020 nm, because the emission cross section at 1000-1020 nm is much smaller than 1030 nm and the absorption cross-section increases as wavelength decreases at this wavelength band. In order to amplify the short wavelength laser effectively, amplified spontaneous emission (ASE) near 1030 nm must be suppressed.

With great effort to suppress the ASE and parasitic lasing light around 1030 nm, over 1 kW continuous wave output power has been achieved both at 1018 nm [7] and 980 nm [8]. However, the output power of pulsed YDF lasers below 1020 nm is almost an order of magnitude lower [9]–[11], because it is much more difficult to suppress the ASE and parasitic lasing light around 1030 nm in pulsed lasers than in continuous wave lasers. The ASE and parasitic lasing light might arise at the intervals between the signal pulses, especially at high power levels where the YDF exhibits a high-level ions inversion under high pump power. So, although the ASE suppression is well done in continuous wave S band YDF lasers, the ASE suppression is barely satisfactory in high power pulsed S band YDF lasers [10], [11].

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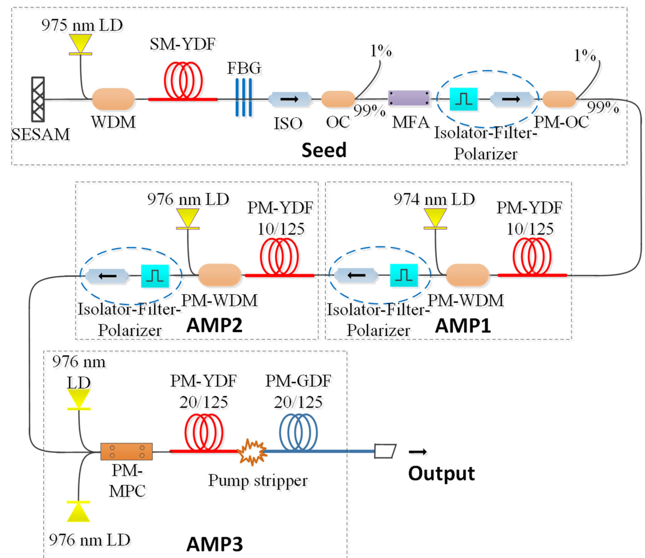

Fig. 1. Schematic diagram of the 1016 nm linearly polarized pulsed fiber laser in four-stage MOPA configuration. LD, laser diode; WDM, wavelength division multiplexer; YDF, ytterbium-doped fiber; GDF, passive fiber; ISO, optical isolator. FBG, fiber Bragg grating; OC, optical coupler; MFA, mode field adapter; PC, polarization controller; SM-, single mode; PM-, polarization maintaining.

In this paper, we demonstrate good ASE suppression of a high-power pulsed S band YDF laser. We proposed a novel scheme of core pumping the large mode area double cladding YDF, to simultaneously alleviate the ASE and excessive accumulation of nonlinear phase in S band fiber amplifier. A linearly polarized picosecond pulse laser at 1016 nm with 48.6 W output power, ∼18 kW peak power, 0.28 nm linewidth at −3 dB and 0.42 nm linewidth at −20 dB is obtained. This is also the first demonstration of a linearly polarized high-power pulsed S band YDF laser.

II. Experimental Setup

The 1016 nm linearly polarized fiber laser consists of a seed, two stage backward core-pumped pre-amplifiers and a main amplifier, as shown in Fig. 1. The seed consists of a narrow linewidth fiber Bragg grating (FBG), a semiconductor saturable absorber mirror (SESAM), an isolator, a 0.23 m long single mode YDF (the fiber core/inner cladding 4/125 μm, nominal absorption coefficient 250 dB/m at 975 nm), two 99:1 optical couplers, a mode field adapter, a polarization controller and an isolator-filter-polarizer. The main part of the seed is a SESAM mode locked fiber laser before the isolator, which is in a simple linear cavity with all single mode fibers. The SESAM has a modulation depth of 13%, a saturation fluence of 55 μJ/cm^2 and a relaxation time of 9 ps. The reflectivity, spectral bandwidth and center wavelength of the FBG is 10%, 0.048 nm and 1016 nm respectively. The isolator-filter-polarizer is a single optical component that possesses the combined functions of filter, isolator and polarizer, which reduces the pigtail fiber length as compared with three individual optical components, hence reduces the nonlinearity. The in-line filter exhibits 2.9 nm and 3.9 nm spectral bandwidth at -3 dB and -20 dB, respectively. Fibers before the isolator-filter-polarizer are non-polarization maintaining fibers. Fibers with and after the isolator-filter-polarizer are polarization maintaining large mode area fibers.

The first stage pre-amplifier AMP1 is a core-pumped double cladding YDF amplifier, with a piece of 0.24 m long YDF (the fiber core/inner cladding 10/125 μm, inner cladding peak absorption 4.95 dB/m at 975 nm, NA 0.075/0.46) as the gain fiber. A 974 nm single-mode laser diode with 630 mW maximum power is utilized to backward core pump the YDF through a wavelength division multiplexer (WDM). The fiber type of the WDM is Corning HI1060 and Nufern PM1060L, respectively for the pump port and other ports. The second stage pre-amplifier AMP2 has the same structure as AMP1 with a slightly shorter gain fiber length of 0.21 m, and a higher pump power of 1.67 W at 976 nm. The two isolator-filter-polarizers in the amplifiers are almost the same as the one in the seed, except that both the input and output fibers are polarization maintaining 10/125 fibers. It should be noted that the different pump wavelengths of the three pumping diodes at 974 nm, 975 nm and 976 nm are not intentionally arranged. We purchased them from three different manufactures at different times. According to our previous experimental experience, we anticipate similar pumping efficiencies of using these three kinds of pumping wavelengths.

The main amplifier AMP3 is a polarization maintaining large mode area double cladding fiber amplifier. The signal light from AMP2 and pumping light from two 60 W 976 nm laser diodes are coupled into 0.60 m YDF (core/inner cladding 20/125 μm, peak cladding absorption 5.7 dB/m at 920 nm, NA 0.08/0.46) through a $(2+1)\times 1$ fiber combiner. 0.60 m long GDF (polarization maintaining passive double cladding fiber with core/inner cladding of 20/125 μm and NA 0.08/0.46) is fusion spliced to the YDF. The AMP3 is placed on an aluminum water-cooling plate with temperature set to 24 °C to avoid thermal damage. The YDF is wound into circles with a diameter of 8 cm to suppress high-order modes. The coating layer of the GDF is removed near the splicing point with 8 cm long high refractive index gel covered to strip the residual pump light and signal light off the inner cladding.

III. Results and Discussion

A. Verification of the Core Pumping Scheme With 10/125 Fiber

As compared with the previously published high power 1016 nm pulsed lasers [10], [11], an important change in this study is that we use the core-pumped large mode area double cladding YDF amplifiers as the pre-amplifiers. The core diameter is increased from around 5 μm to about 10 μm as compared with the single mode fiber preamplifiers, to reduce the power density in the pre-amplifiers therefore suppress the spectrum broadening caused by nonlinearity. It should be noted that a core pumped double cladding YDF amplifier is also used in [12]. However, they used a small core gain fiber with core diameter of 4 μm in the amplifier, which is similar to that of conventional single-mode gain fiber. We use a large mode area double cladding fiber with 10 μm core diameter in the core pumping scheme in this paper. The large mode area fiber can greatly reduce nonlinear effect. As compared with clad pumping scheme, the core pumping scheme in the pre-amplifier here can greatly reduce the YDF length, hence to alleviate excessive accumulation of nonlinear phase and the ASE.

Because the double cladding 10/125 YDF is not designed for core pumping, we need to verify the feasibility of this scheme first and determine how long YDF should be used in the preamplifiers. A simple amplifier configuration, with a section of double cladding YDF pumped by a 974 nm laser diode through a WDM and an isolator to prevent backward reflection, is established to test the core pumping scheme. The test results performed by non-polarization-maintaining fibers are nonetheless convincing enough due to the similar fiber parameter with that of polarization-maintaining fibers.

Fig. 2(a) shows the output signal power at different input signal powers (10 mW and 100 mW), pump powers (300 mW and 600 mW), YDF lengths (0.15 m, 0.20 m, 0.25 m and 0.30 m), and pumping directions. The circles indicate small signal power of 10 mW. Stars indicate large signal power of 100 mW. Black means forward pumping. Red means backward pumping. Dash line corresponds to 300 mW pump power. Solid line corresponds to 600 mW pump power. By comparing the red lines with the corresponding black lines, we can see that the output power of the backward pumped amplifier is always higher than the forward pumped ones, except for the condition that the YDF is particularly short (15 cm) and the signal light is particularly weak (10 mW). So, backward pumping configuration is preferred in the core pumping scheme.

From the circles in Fig. 2(a), we can see that the output power increases first and decreases then with an increasing YDF length under the condition of a small signal power of 10 mW. The maximum power appears around 25 cm and 20 cm, respectively for 600 mW backward and forward pumping. In the case of 300 mW pumping, the maximum power appears around 20 cm for both backward and forward pumping. From the trends of lines with circles, it can be seen that the optimal YDF length increases with pump power for both backward and forward pump scheme. The signal and pump power for AMP1 is near 10 mW and 600 mW, so we intend to use 25 cm YDF in this stage. The actual YDF length in AMP1 is 24 cm in the experiment after cutting and fusion splicing.

In the case of large signal power of 100 mW, we can see from the stars in Fig. 2(a) that the output power decreases monotonically with an increasing YDF length in the range of 15 to 30 cm, indicating that the optimal YDF length for highest efficiency is shorter than 15 cm. Theoretically, the output power

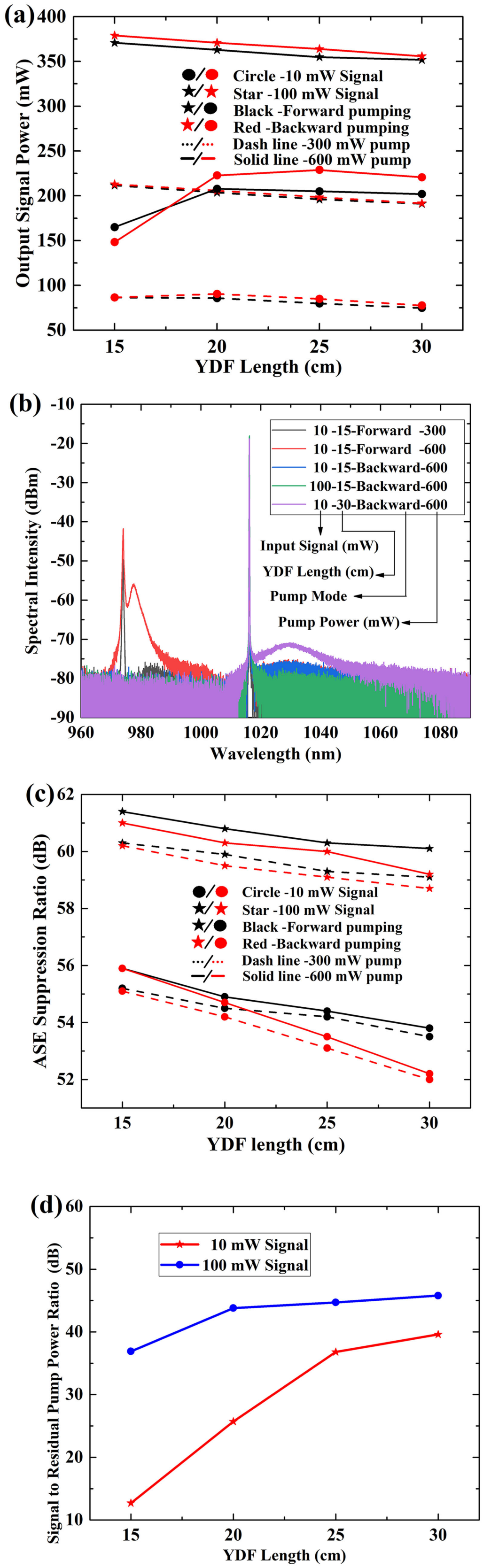

Fig. 2. Characteristics of core pumped 10/125 fiber amplifier. (a) Output power variation with YDF lengths; (b) Some typical output spectrums; (c) ASE suppression ratio under different parameters; (d) Signal to residual pump power ratio.

is expected to decrease when the YDF length is too short. For the backward pumping scheme, when input signal power is 100 mW, output power of the amplifier with 15 cm YDF length is 3.5% and 2.2% higher than that of 20 cm YDF length, respectively for 300 mW and 600 mW pump power. The difference is not so large, so we did not continue to shorten the YDF length. The difference tends to decrease when the pump power increases. So, we can anticipate that the optimal YDF length will also increase as pump power increases, just like the case of 10 mW small signal power. The pump power used in AMP2 is as high as 1.67 W. In this case, although not directly proved by experiments, we think that the amplified power with 15 cm YDF length might be only a little larger or very close to that with 20 cm YDF length. Furthermore, considering that longer YDF length is needed to absorb the higher pump light, we intend to use 20 cm YDF length in AMP2 without precise optimization. The actual YDF length in AMP2 is 21 cm in the experiment after cutting and fusion splicing.

Fig. 2(b) shows some typical laser spectra at different laser parameters. Residual pump light and ASE peak can be observed in the figure. Compare the black with the red line, we can see that residual pump light is higher when pump power is larger. The residual pump light of the backward pumped amplifier is not observed from the laser spectrum, because it propagates to the seed direction. We can see from the blue and green line that higher signal power results in a better ASE suppression. We can also see from the blue and purple line that shorter YDF length results in better ASE suppression.

Detail data analysis concerning the ASE suppression is illustrated in Fig. 2(c). Generally speaking, the ASE suppression ratio increases with a decreasing YDF length for both backward and forward pumping schemes. However, even in the worst condition of 10 mW signal in backward pumping scheme, the ASE suppression ratio is larger than 52 dB. So, we do not consider much about the ASE suppression ratio when choosing the YDF length in AMP1 and AMP2. Compare the stars and the circles, we can conclude that larger signal power results in higher ASE suppression. Compare the black line with the red line, we can conclude that the forward pumping scheme exhibits larger ASE suppression than the backward pumping scheme. However, the difference is less than 2 dB in most cases, which is quite small as compared with the total value of larger than 50 dB ASE suppression. Compare the dash line with the solid line, we can conclude that higher pump power is desired for better ASE suppression. This is attributed to the 1016 nm short wavelength signal. High-level ions inversion is desired for short wavelength amplification.

Fig. 2(d) illustrates the signal to residual pump power ratio variation with YDF length of the forward pumped amplifier. The ratio is calculated from the laser spectrum. The power of signal light is calculated from 1015.7 nm to 1016.7 nm, and that of the residual pump is calculated from 970 nm to 990 nm. Red stars correspond to 10 mW small signal power. Blue dots correspond to 100 mW large signal power. For both cases, the signal to residual pump power ratio increases with an increasing YDF length. In case of 100 mW input signal, the signal to residual pump power ratio is larger than 40 dB with YDF length larger

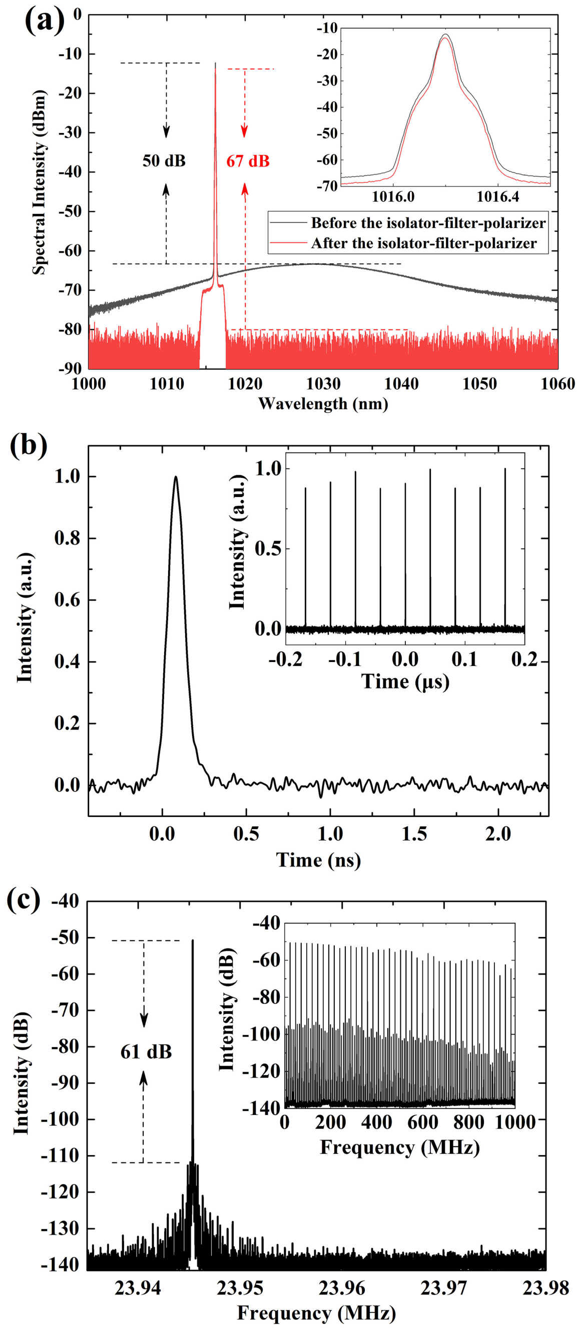

Fig. 3. Characteristics of the seed (a) The spectrum before (black) and after (red) the isolator-filter-polarizer; (b) The single pulse shape and pulse trains; (c) The RF spectrum of the seed pulse.

than 20 cm, indicating that the pump power is fully absorbed. In case of 10 mW input signal, the YDF length needs to be larger than 25 cm to get 35 dB signal to residual pump power ratio.

B. *Performance of the Linearly Polarized Seed*

Fig. 3(a) shows the seed laser spectrum before (black) and after (red) the isolator-filter-polarizer. From the black line, we can see that the ASE suppression ratio against 1030 nm is about 50 dB before the isolator-filter-polarizer, which means a very small amount of ASE components in the laser. However, this small amount of ASE near 1030 nm will cause serious upper energy level ions consumption in the followed amplifiers due to its strong amplification compared to the laser signal at 1016 nm, which will result in a very low ASE suppression ratio after amplification. The isolator-filter-polarizer improves the ASE suppression ratio against 1030 nm to be larger than 67 dB (limited by the sensitivity of the optical spectrum analyzer, should be larger than 90 dB theoretically). This clean seed is beneficial for the followed amplification of the 1016 nm signal. The -3 dB linewidth of the seed laser is measured to be 0.04 nm.

Fig. 3(b) shows the single pulse shape and the pulse train of the seed after the isolator-filter-polarizer. The pulse is measured by a 45 GHz bandwidth photodetector and a 36 GHz real-time oscilloscope. Fig. 3(c) shows the radio frequency (RF) spectrum. The repetition rate of the seed pulse is 23.95 MHz with a pulse width of about 0.1 ns. Because the SESAM mode locked fiber laser is randomly polarized and all fibers before the isolator-filter-polarizer are non-polarization maintaining fibers, the polarization state in the seed is random before the isolator-filter-polarizer, and linearly polarized after the isolator-filter-polarizer. In another word, the linearly polarized seed is generated by directly select one direction of polarization light from the randomly polarized laser through the isolator-filter-polarizer, resulting in an unstable pulse train. The pulse amplitude fluctuates about $\pm 6.6\%$ as shown in the inset of Fig. 3(b), which causes noise in the RF spectrum as shown in the inset of Fig. 3(c). The instability of the pulse train also affects the precise measurement of the pulse width, which changes in the range of 100 to 120 ps in the observe period of about ten minutes. The polarization extinction ratio changes from 25 to 32 dB when measured with an extinction ratio tester. The signal laser power of the seed is 20 mW before the isolator-filter-polarizer, and 7 mW after the isolator-filter-polarizer.

C. *Performance of AMP1*

According to the experimental results in Fig. 2, we choose the backward pumping configuration with about 24 cm YDF length in the first stage preamplifier (AMP1). Short YDF and 10 μm large core can effectively suppress the ASE and spectral nonlinear broadening in the process of amplification. Fig. 4(a) shows the output power variation with pump power. With the increase of pump power, the slope efficiency begins to increase and stabilized at 56%, which means that the output power will continue to increase with the increase of pump power. A 275 mW signal light is obtained at 622 mW pump power, with a -3 dB linewidth of 0.05 nm, and 1030 nm ASE suppression ratio of larger than 67 dB, as shown in Fig. 4(b).

D. *Performance of AMP2*

AMP2 also uses the backward core pumping scheme. Fig. 5(a) shows the linear increase of output power with the increase of pump power. Fig. 5(b) shows the evolution of output spectrum at different output powers. With the increase of output power, the spectrum gradually widens. When the output power exceeds 822 mW, a dip is formed at the central wavelength of 1016.2 nm,

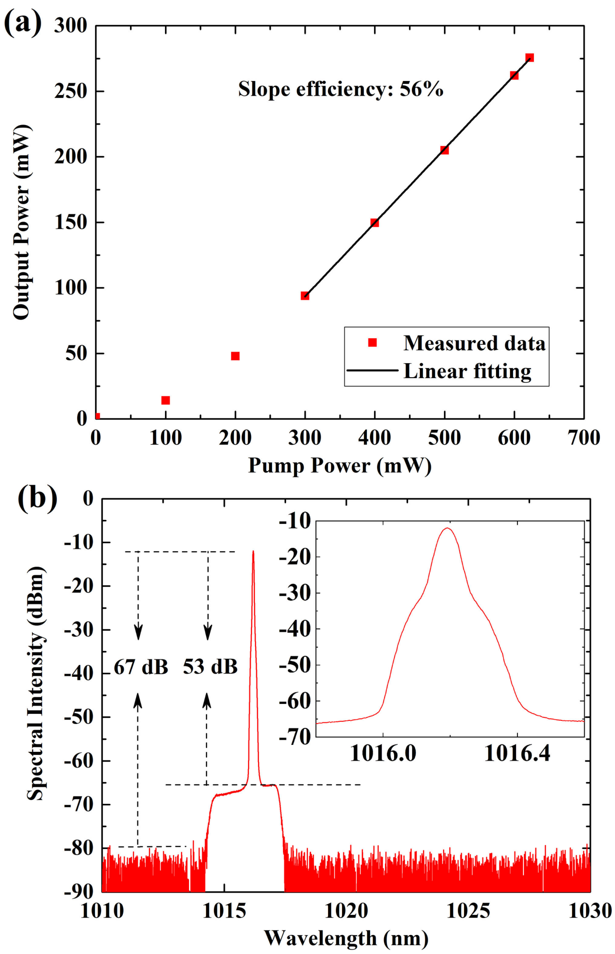

Fig. 4. Characteristics of AMP1 (a) The output power varies with the pump power; (b) The spectrum at the maximum output power, the inset shows the laser spectrum details.

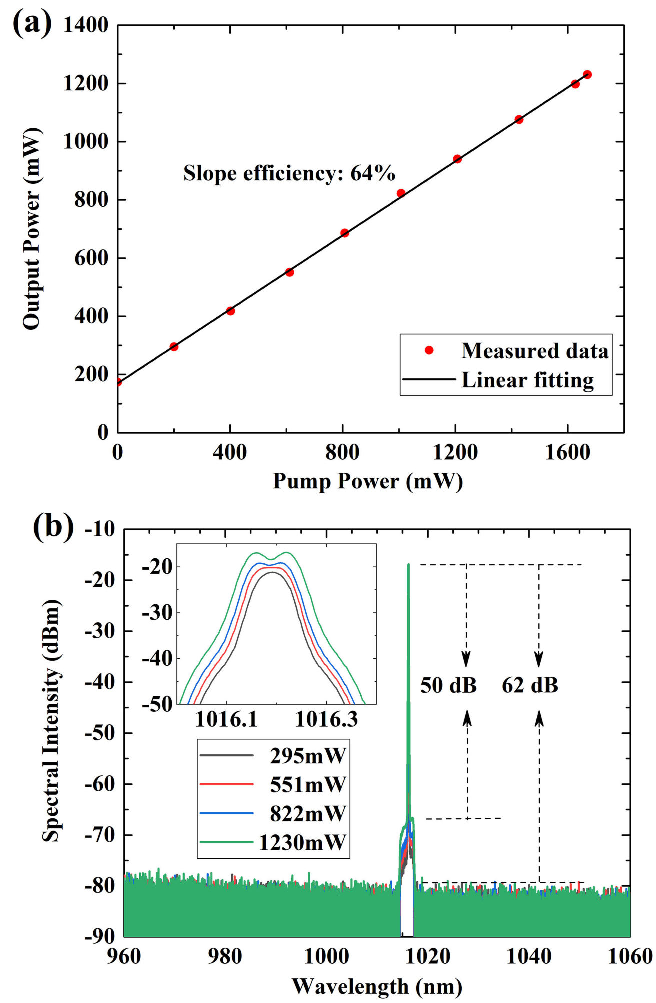

Fig. 5. Characteristics of AMP2 (a) The output power varies with the pump power; (b) The spectrum at different output powers, the inset shows the laser spectrum details.

and two symmetrical peaks are formed on both sides, which is due to the self-phase modulation in the fiber amplifier caused by the increase of pulse peak power. Finally, pumped by a 1.67 W single-mode laser diode, a pulsed laser with power of 1.23 W, −3 dB linewidth of 0.11 nm, and 1030 nm ASE suppression ratio of larger than 62 dB is achieved.

E. Performance of AMP3

In order to obtain higher output power, AMP3 uses the clad pumping scheme. Different from AMP1 and AMP2, forward pumping is utilized in AMP3, because we are lacking of backward fiber combiner with 20/125 μm input and output fibers at present. Furthermore, the excessive pigtail fiber of the fiber combiner in backward pumping scheme may cause serious nonlinear spectral broadening in this stage. 60 cm 20/125 highly doped double cladding YDF with a nominal cladding absorption of 5.7 dB/m at 920 nm is used in AMP3 as the gain fiber. Large mode area and short fiber length can effectively suppress the ASE and spectral broadening.

Fig. 6(a) shows the variation of output power with pump power in AMP3. The overall slope efficiency is only 41%, much lower than that of conventional band YDF amplifiers. There are three possible reasons. Firstly, the emission cross section of ytterbium ion in silica fiber at 1016 nm is smaller than that at 1064 nm and 1030 nm. Secondly, the input signal light may be weak, and AMP3 has amplified the power to about 40 times. Lastly, the YDF may be a little short that causes the absorption saturation of pump light, which can be verified by the slight decrease of slope efficiency with the increase of pump power in Fig. 6(a). However, it is difficult to simultaneously optimize the optical-to-optical conversion efficiency and the nonlinear effect suppression. Too short fiber will lead to low optical-to-optical conversion efficiency, and too long fiber will lead to ASE and spectral broadening. 48.6 W output power is obtained under 114 W pump power. The output power is too high to measure the polarization extinction ratio through the polarization extinction ratio tester. After collimating it with a lens and passing through a rotating polarizing beam splitter (PBS), the polarization extinction ratio is roughly measured by a power meter to be about 18 dB. Fig. 6(b) shows the output average power fluctuates about ±0.5% during 2000 seconds monitoring.

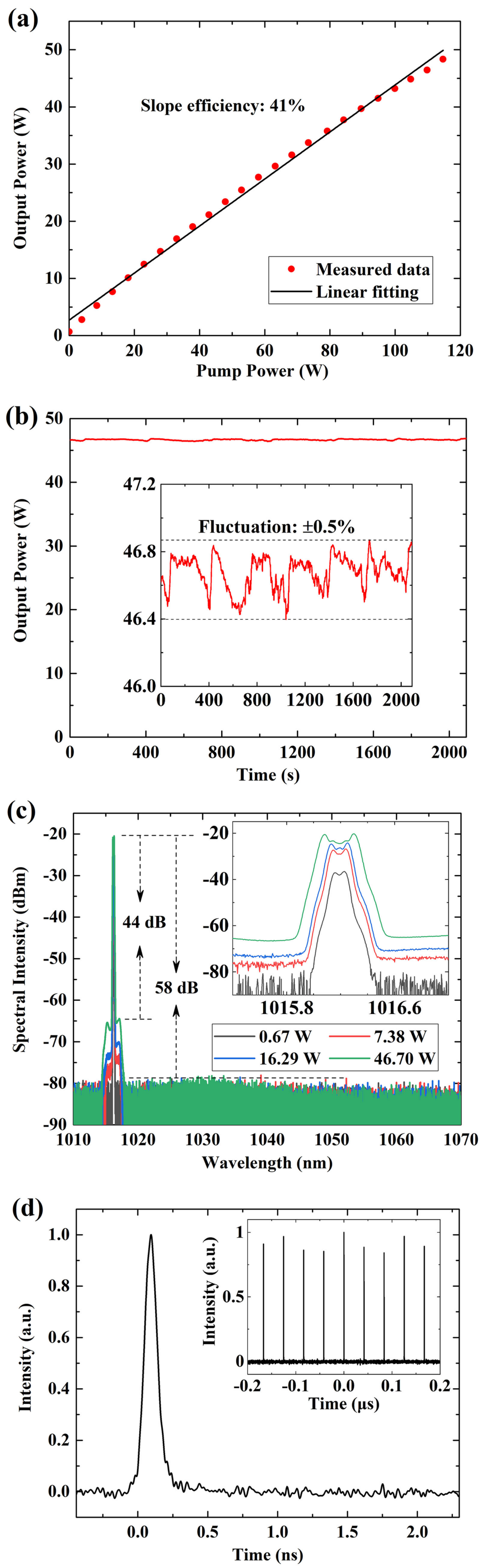

Fig. 6. Characteristics of AMP3 (a) The output power variation with pump power; (b) Stability of the laser average power; (c) The spectrum under different output powers; (d) The single pulse shape and pulse train.

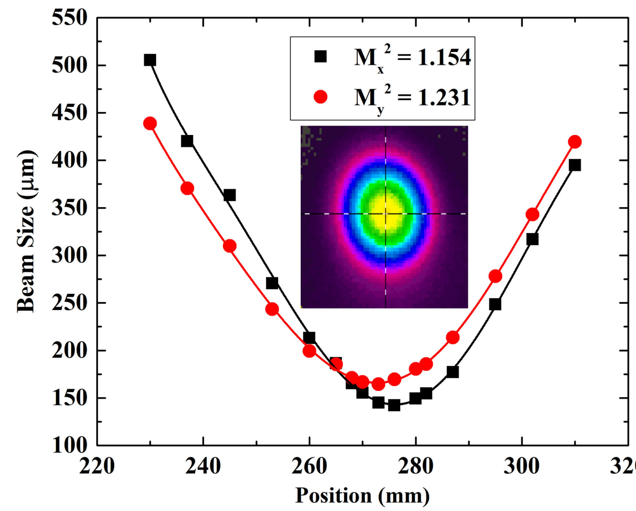

Fig. 7. The beam quality measurement results.

Fig. 6(c) shows the spectra at different output powers. The increase of pulse peak power makes the self-phase modulation stronger. The spectrum widens to both sides at the same time, the multiple peak structure appears in the spectral center, and the outermost peak intensity is the highest, which are the most significant features of self-phase modulation. Except for this, the spectrum is relatively pure that no ASE above 1020 nm and Raman peaks appear. The ASE suppression ratio above 1020 nm is higher than 58 dB. As for the overall ASE suppression ratio, we can see from Figs. 4(b), 5(b) and 6(c), it decreases from 53 dB to 50 dB, and then to 44 dB after amplification. The −3 dB linewidth is 0.28 nm and the 1016.2 nm power within the 0.42 nm (−20 dB) bandwidth accounts for 99.84% of the total power.

Fig. 6(d) shows the single pulse shape and pulse train. The pulse width changes in the range of 100 to 120 ps in the observe period of about ten minutes. The peak power is roughly calculated to be about 18 kW. The inset in Fig. 6(d) shows that the pulse amplitude fluctuates about ±8.6%.

Although the fiber in the main amplifier is a few-mode fiber, good beam quality is obtained. The YDF in the main amplifier is wound into circles with a diameter of about 8 cm to suppress high-order modes. The measured beam quality at the final output terminal is shown in Fig. 7. The M^2 value at both directions is near 1.2, indicating a good beam quality.

IV. Conclusion

A four-stage MOPA structure all-fiber linearly polarized narrow linewidth picosecond pulse laser at 1016 nm is demonstrated. The linearly polarized seed is generated by directly select one direction of polarization light from the randomly polarized laser through a polarizer. Two stages core-pumped pre-amplifiers and one stage main amplifier enhance the average power to 48.6 W. The peak power is ∼18 kW with a −3 dB laser linewidth of 0.28 nm. The core pumping scheme of large mode area double cladding fiber in the preamplifiers effectively enhances the suppression of the ASE and excessive accumulation of nonlinear phase. This is also the first demonstration of a linearly polarized high-power pulsed S band YDF laser, which can be frequency doubled to 508 nm and frequency quadrupled to 254 nm.

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