2240 W high-brightness 1018 nm fiber laser for tandem pump application

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Abstract
In this letter, we present a 2240 W high-brightness 1018 nm fiber laser by power combination. The system consists of seven 1018 nm ytterbium-doped fiber lasers and a homemade 7 × 1 all-fiber power combiner. The output core diameter of the power combiner is 50 µm and the numerical aperture is 0.2. The overall transmission efficiency is about 99%. This high-power, high-brightness fiber laser can be used as a pump source in tandem pumping configurations for several kilowatts of power scaling.

Keywords: 1018 nm fiber laser, tandem pump, power combination, high power

1. Introduction
High power Yb-doped fiber lasers (YDFLs) have been a research interest for many years for their wide application in scientific research, industrial manufacturing and defense technology [1–3]. In the past decade, most high-power fiber lasers were pumped by laser diode (LD) sources. Up to now, the output power of YDFLs directly pumped by LDs has reached 4–5 kW [4–6]. However, there are still several factors limiting further power scaling in diode pumping schemes, which include low pump brightness, thermal issues, nonlinear effects and mode instability [7–9]. For achieving higher power fiber lasers whilst maintaining excellent beam quality, the tandem pumping technique has been proposed and demonstrated to be a feasible approach [10]. It is reported that the 10 kW single-mode fiber lasers developed by IPG photonics were pumped by 1018 nm fiber lasers based on tandem pumping [10]. From then on, the important role of YDFLs operating around 1018 nm attracted much attention for the use of tandem pumping [11–13]. After intensive theoretical and experimental investigations, the important rules to build high power 1018 nm YDFLs are well known, which include employing YDF with a high core/inner cladding area ratio, shortening the YDF length, suppressing Fresnel reflection and so on. To date, the output power of 1018 nm YDFLs has reached over 200 W in a single-mode operation [14, 15] and over 800 W in a multimode output beam [16]. Further power scaling is very probable if more powerful pump sources are provided. In contrast, reports on high power tandem pumped YDFLs are still rare.

In 2015, a 2.14 kW YDFL tandem pumped by 1018 nm fiber lasers was achieved. Six high-power 1018 nm fiber lasers were employed as a pump source [11]. Each 1018 nm fiber laser provided about 400 W from the 30/250 µm delivery fiber and was directly spliced to the pump fiber of the combiner, which was the 105/125 µm multimode (MM) fiber. The output power was limited by the available pump power only. With the power combining with 1018 nm YDFL arrays, the pump power was increased [17]. In this scheme, the laser power...
from four 1018 nm YDFLs with 15/130 µm output fibers was coupled into a 105/125 MM fiber via a 4 × 1 power combiner and obtained 650 W of laser power from the combiner. The output fiber of the power combiner was identical to the pump input fiber of the (6 + 1) × 1 combiner. In this configuration, 24 YDFLs operating at 1018 nm were employed to provide over 4 kW of pump power and the seed laser was boosted to 3.5 kW. However, the pump power was still the limiting factor for higher power scaling.

In this letter, we focus on further increasing the power of the 1018 nm laser source to meet the need of the pump source of >5 kW tandem pumped YDFLs. By enhancing the output power of each single 1018 nm laser and input ports of the power combiner simultaneously, the 2240 W laser was emitted from a 50 µm MM fiber with good beam quality, which indicates its excellent brightness compared with the MM fiber-coupled diode lasers. This high power laser source can be applied as a pump source directly into several kW level fiber laser systems.

2. Experimental setup

The schematic diagram of the 1018 nm YDFL is depicted in figure 1. The fiber laser is pumped by seven laser diodes emitting at 975 nm. The laser oscillation cavity consists of a pair of fiber Bragg gratings (HR & OC) and a length of ytterbium-doped double-cladding fiber. The core and inner cladding diameter of this YDF are 15 µm (NA = 0.07) and 130 µm (NA = 0.46) respectively. The cladding absorption coefficient of this YDF is 5.5 dB m⁻¹ at 976 nm. In consideration of the ASE suppression and an adequate pump absorption, the length of the YDF is chosen to be 4 m. The reflectivity of the high reflection (HR) fiber Bragg grating is more than 99% at a center wavelength of 1017.9 nm (FWHM 1 nm). The OC FBG centered at 1017.9 nm has a reflectivity of 20% with a bandwidth of 0.7 nm. A pump stripper is utilized before the OC FBG to remove unabsorbed pump lasers. The output end of the OC FBG is an angle cleaved to suppress backward reflection.

The schematic diagram of our homemade 7 × 1 power combiner is plotted in figure 2. Seven 15/130 µm input fibers (NAcore = 0.08, NACLadding = 0.46) are bundled by a fluorine-doped glass tube (NA = 0.2). The inner and outer diameters of this glass tube are 600 µm and 1500 µm respectively. The input fibers and the glass tube are fused and tapered until the entire fiber cores match well with the chosen output fiber. Then, the input fiber bundle is cleaved at the taper waist, where diameters are measured to be 125 µm for the glass tube and 45 µm for the fiber cladding area. Finally, the input fiber bundle is spliced with the output fiber (d = 50/100/360 µm, NA = 0.2). It should be noted that the splicing process should be in perfect alignment because of the mismatch between outer diameters of the input fiber bundle and the output fiber.

The experimental configuration of the high-power 1018 nm source is shown in figure 3. The source consists of seven 1018 nm YDFLs and a homemade all-fiber power combiner. The 1018 nm YDFL arrays with 15/130 µm output fibers are spliced to the input fibers of the combiner. A homemade endcap is spliced at the end of output fiber to avoid facet reflection and ensure the long-term stability of the system. The output beam from the endcap is collimated and propagates onto a wedge mirror. The reflectivity of the wedge mirror is 4%. The reflected laser is coupled into the beam quality analyzer (PRIMES LQM system) while the transmitted light is collected by the power meter.

3. Results and discussion

3.1. Output properties of the 1018 nm YDFL

Figure 4 plots the output properties of the 1018 nm laser. The maximum laser power is 330 W when the 460 W pump power is launched into the cavity. As shown in figure 4(a), the output power increases gradually with the injected pump power. Due to the wavelength shift of the LDs, the efficiency is improved as the input pump power rises and the overall conversion efficiency is 71.7%. Figure 4(b) shows the output spectrum of the 1018 nm fiber laser, which is measured by an optical spectrum analyzer (Yokogawa AQ6370C) with a resolution of 0.02 nm. The spectrum is centered at 1018.08 nm and the 3 dB bandwidth is 0.46 nm at 330 W. Amplified spontaneous emission is well suppressed and no roll-over power is observed. Therefore, it can be deduced that further power scaling is only limited by the available pump power.
Seven fiber lasers emitting at 1018 nm are built in the same way. The specific maximum output powers of these YDFLs are measured to be 294 W, 317 W, 319 W, 323 W, 329 W, 330 W and 344 W respectively. Owing to the different performances of the LDs employed, the output powers of seven YDFLs are not exactly the same. The total output power of seven fiber lasers is 2256 W.

3.2. Output characteristics of the combined 1018 nm laser source

The power emitted from the combiner is measured and plotted in figure 5(a). The insertion loss of the combiner is trivial and the transmission efficiency is higher than 99%. The output power after the combiner increases linearly with the input power and the maximum output power is 2240 W. Figure 5(b) shows the output spectrum at full power. The central wavelength is 1017.98 nm and the 3 dB bandwidth is measured to be 0.63 nm. The center wavelength shift and spectral width broadening after the power combination is owing to the slightly different spectrums of seven input lasers. The temperature rise in the tapered region of the power combiner is below 25 °C during the test. The low insertion loss and the temperature rise indicates that this combiner can handle a much higher power.

Figure 4. Output properties of the 1018 nm fiber laser. (a) Output versus pump power and (b) output spectrum at 330 W. Inset: spectrum in large scale.

Figure 5. Output properties of the combined 1018 nm laser source. (a) Output power in dependence of input power and (b) laser output spectrum at 2240 W. Inset: spectrum in large scale.

Figure 6. Beam quality for single input port versus output power.

Besides the insertion loss and power, the beam quality of the combined laser is another key feature that should be considered. Figure 6 plots the measured beam quality $M^2$ factor of each single 1018 nm laser after the combiner. The best beam quality is $M^2 \sim 3.5$, which corresponds to the central input port of the $7 \times 1$ power combiner. The values of the $M^2$ factor for the other six input ports range from 4 to 7 for different input ports. The difference is a result of the imperfections in the
manufacturing of the power combiner. From figure 6 it can be found that the beam quality changes little versus the input power, implying the good stability of the combiner.

Figure 7 shows the measured beam quality of the combined laser when all the seven 1018 nm YDFLs are turned on. The beam quality factor $M^2$ is measured to be 5.47 at 2240 W. The evolution of the beam quality and the beam profile with an increasing output is shown in figure 8. The beam profile is not strictly symmetrical due to the imperfect fabrication process of the combiner. But the $M^2$ factor changes little for different output powers.

Although the beam quality deteriorates after the beam combining because of the relatively large output core, the laser brightness obtained in this paper ($M^2 = 5.47$) is one order of magnitude higher than that of the common semiconductor laser. Due to its high brightness character, this 1018 nm laser source was successfully injected into a $(6 + 1) \times 1$ combiner with little loss, although there was a mismatch between the core diameters (50/360 $\mu$m and 105/125 $\mu$m respectively). Moreover, attributed to its high beam quality, the laser source is able to be guided into a small inner cladding to improve the pump overlap with the core, indicating a better pump absorption.

According to [18], the laser source produced in this paper has a great potential for further power scaling owing to its relatively small output diameter and numerical aperture. The total power will exceed 12000 W if six such laser sources are injected into the $(6 + 1) \times 1$ signal/pump combiner, which can meet the demand of a pump power for a 10 kW fiber laser.

4. Conclusion

In summary, we have produced a high-power, high-brightness fiber laser source operating at 1018 nm based on a power combination. Up to 2240 W of output is achieved with the input power of 2256 W. The $M^2$ factor is 5.47 at the maximum output power and the beam quality is independent of power. To the best of our knowledge, this is the highest output for a short wavelength laser at 1018 nm, with the help of a power combining method. The high-power, high-brightness 1018 nm fiber laser we presented is suitable for applications in high-power tandem-pumping systems.
References

[1] Limpert J, Roser F, Klingebiel S and Schreiber T 2007 The rising power of fiber lasers and amplifiers IEEE J. Sel. Top. Quantum Electron. 13 537–45
[2] Nilsson J, Ramachandran S, Shay T M and Shirakawa A 2009 Introduction to the issue on high-power fiber lasers IEEE J. Sel. Top. Quantum Electron. 15 1–2
[3] Richardson D J, Nilsson J and Clarkson W A 2010 High power fiber lasers: current status and future perspectives (Invited) J. Opt. Soc. Am. B 27 B63–92
[4] Farrow R, Liao K H, Zhang C, Morehead J J, Segall J, Tai K, Kharlamov B, Yu H and Myers L 2011 Fused fiber pump and signal combiners for a 4 kW ytterbium fiber laser Proc. SPIE 7914 395–410
[5] Zhan H, Liu Q, Wang Y, Ke W, Ni L, Wang X, Peng K, Gao C, Li Y and Lin H 2016 5 kW GTWave fiber amplifier directly pumped by commercial 976 nm laser diodes Opt. Express 24 27087–95
[6] Wang X, Zhang H, Tao R, Su R, Zhou P and Xu X 2016 Laser diode pumped 4.1 kW all-fiber laser with master oscillator power amplification configuration Chin. J. Lasers 43 502002
[7] Otto H, Jauregui C, Limpert J and Tünnemann A 2016 Average power limit of fiber-laser systems with nearly diffraction-limited beam quality SPIE Laser 97280E
[8] Zhu J, Zhou P, Ma Y, Xu X and Liu Z 2011 Power scaling analysis of tandem-pumped Yb-doped fiber lasers and amplifiers Opt. Express 19 18645–54
[9] Dawson J W, Messerly M J, Beach R J, Shverdin M Y, Stappaerts E A, Sridharan A K, Pax P H, Heebner J E, Siders C W and Barty C P 2008 Analysis of the scalability of diffraction-limited fiber lasers and amplifiers to high average power Opt. Express 16 13240
[10] Stiles E 2009 New developments in IPG fiber laser technology 5th Int. Workshop on Fiber Lasers pp 4–9
[11] Xiao H, Leng J, Zhang H, Huang L, Xu J and Zhou P 2015 High-power 1018 nm ytterbium-doped fiber laser and its application in tandem pump Appl. Opt. 54 8166
[12] Malinowski A, Price J H V and Zervas M N 2015 Sub-microsecond pulsed pumping as a means of suppressing amplified spontaneous emission in tandem pumped fiber amplifiers IEEE J. Quantum Electron. 51 1–7
[13] Theeg T, Ottenhues C, Sayinc H, Neumann J and Kracht D 2016 Core-pumped single-frequency fiber amplifier with an output power of 158 W Opt. Lett. 41 9
[14] Ottenhues C, Theeg T, Hausmann K, Wysmolek M, Sayinc H, Neumann J and Kracht D 2015 Single-mode monolithic fiber laser with 200 W output power at a wavelength of 1018 nm Opt. Lett. 40 4851–4
[15] Glick Y, Sintov Y, Zuitlin R, Pearl S, Feldman R, Horvitz Z and Shafrir N 2016 Single mode 1018 nm fiber laser with power of 230 W SPIE Laser p 97282T
[16] Yan P, Wang X, Li D, Huang Y, Sun J, Xiao Q and Gong M 2017 High power 1018 nm ytterbium-doped fiber laser with output of 805 W Opt. Lett. 42 7
[17] Zhou P, Xiao H, Leng J, Xu J, Chwa Z, Zhang H and Liu Z 2017 High-power fiber lasers based on tandem pumping J. Opt. Soc. Am. B 34 3
[18] Sévigny B and Faucher M 2009 Pump combiner loss as a function of input numerical aperture power distribution Proc. SPIE 7195 719523