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300-W-average-power monolithic actively Q-switched fiber laser at 1064 nm

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Abstract
We demonstrate a high power monolithic nanosecond pulsed fiber laser source at 1064 nm. This laser was configured as a master oscillator-power amplifier (MOPA) seeded by an acousto-optic Q-switched fiber laser with varied pulse duration and repetition rate. Over 300 W average power is achieved for ~ 475 ns pulses at 100 kHz repetition rate with an optical to optical efficiency of 75.4%. The M^2 at both directions is <1.6 measured at the highest average power.

Keywords: Q-switched laser, high power, fiber laser

(Some figures may appear in colour only in the online journal)

1. Introduction

Over the past decade, high power fiber lasers and amplifiers have seen progressive developments in laser performance and accordingly, their application ranges have been extended significantly. High power fiber lasers have been replacing the conventional bulky solid-state lasers to become an indispensable tool for industry manufacture due to their high power/pulse energy, excellent beam quality, compactness, robustness, higher efficiency, easy thermal management etc For continuous wave (CW) fiber lasers, both 10 kW diffraction-limited laser beams and 100 kW multi-mode laser beams were produced by fiber lasers [1, 2]. Kilowatts level CW fiber lasers have been widely utilized for cutting, welding, drilling, cladding or cleaning various industrial materials in a variety of industries. Pulsed fiber lasers, with tens of watts average power, hundreds of nanosecond pulse duration, and tens of kHz repetition rate, also find industrial applications in laser marking, engraving, etc Higher average power for these pulsed lasers is desired for some applications, such as deep engraving, deep marking or laser cutting.

A master oscillator-power amplifier (MOPA) seeded by a pulsed fiber laser oscillator is a typical design to achieve high energy, high power laser pulses. A lot of limit factors, including nonlinear effects induced by high peak power, the extractable energy, the fiber damage, etc, make the power scaling for pulsed fiber lasers very challenging [3, 4]. Thanks to the developments in large-core rare-earth-doped fibers, pulsed fiber lasers with hundreds of watts average power and tens of millijoule pulse energy were developed [4–6]. However, these lasers contain some bulk optical components, which, to some extent, sacrifice the benefits of the fiber laser system. All fiber format laser systems are always highly desired in industrial applications due to their robustness, compactness and easy maintenance [7–9]. Most recently, Malinowski *et al* reported a fully spliced fiber laser system, producing nanosecond laser pulses with up to 265 W average power by amplifying a gain-switched laser diode [10]. However, this laser has relatively poor beam quality due to the fact that a multimode active fiber with ~ 50 μm core was utilized in the final fiber amplifier. We reported a monolithic pulsed fiber laser system with 230 W average power [11]. The Raman scattering appeared due to the very long active fiber, utilized in the final amplifier.

Here, we report a 300 W average power all-fiber format pulsed laser source at ~1064 nm in MOPA configuration using an actively acousto-optical Q-switched fiber oscillator as the seed source. To the best of our knowledge, this is the highest power demonstration for an all fiber Q-switched laser system. This laser, benefiting from the output hundreds of watts average power, kilowatts peak power and the all-fiber construction, is well suited for a lot of industrial applications, including laser marking, laser cutting, laser deep engraving, laser micro-machining, etc [12].

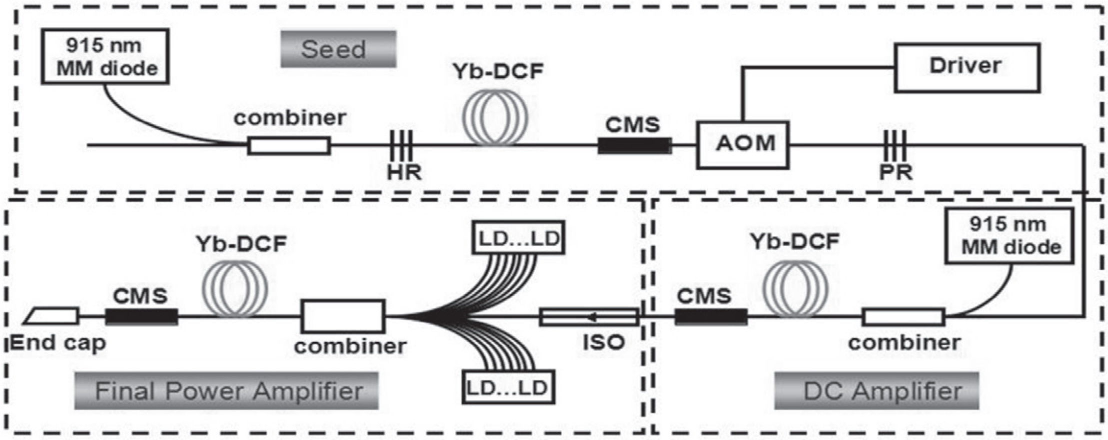

Figure 1. The schematic diagram of the 300 W average power monolithic actively Q-switched fiber laser. ISO: isolator; LD: laser diode; Yb-DCF: Yb^{3+}-doped DC fiber.

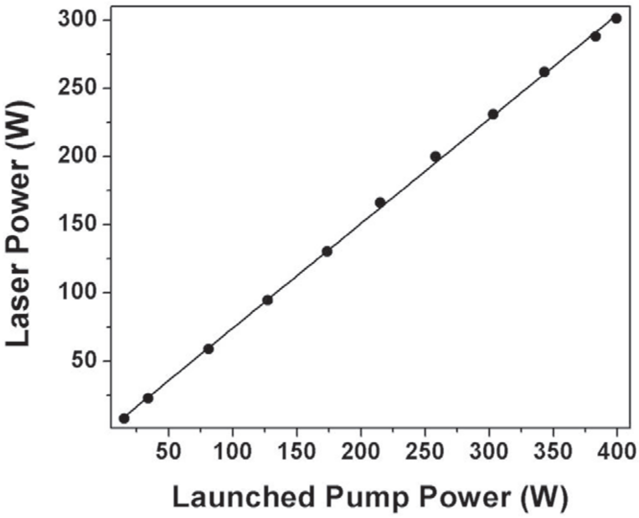

Figure 2. The average power versus the launched pump power at the repetition rate of 100 kHz.

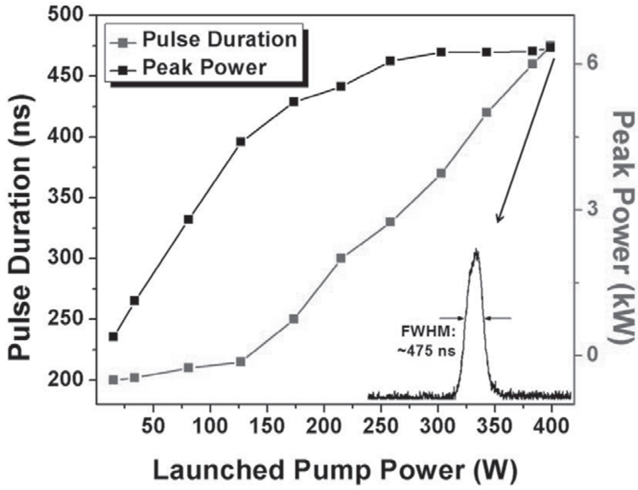

Figure 3. The pulse duration and the peak power at different pump power. Inset: the trace of the pulse at the highest output power.

2. Experimental setup

The schematic diagram of the 300 W average power monolithic actively Q-switched fiber laser is shown in figure 1. The master oscillator is an acousto-optic Q-switched fiber laser. This oscillator is a linear cavity laser, with a pair of fiber Bragg gratings (FBGs) centered at the wavelength of 1064 nm. The active fiber utilized in the oscillator is 4 m 10/125 μm double cladding (DC) Yb-doped fiber. The active Q-switching is established by a fiber coupled acousto-optic modulator (AOM) driven by an arbitrary waveform generator (AWG). The repetition rate of the oscillator can be easily tuned by adjusting the repetition rate of the electrical pulses output from the AWG. For this oscillator, the repetition rate can be tuned from 20 to 120 kHz, while the pulse duration can be varied from ~ 80 to ~ 220 ns. In order to boost the average power of the laser pulses as high as possible, ~ 200 ns pulses at 100 kHz repetition rate with ~ 2 W average power were chosen as the seed.

One DC pre-amplifier was built to boost the pulse power/energy of the seed pulses. The active fiber used in the pre-amplifier is 5 m 20/125 μm (diameter of the core/inner cladding) DC Yb-doped fiber. The active fiber was pumped by a 915 nm multimode diode connected by a (1+1)*1 combiner. A home-made cladding mode stripper (CPS) was utilized to remove the unabsorbed pump light. Around 200 ns laser pulses at 100 kHz repetition rate with ~ 10 W average power was achieved from this DC pre-amplifier.

One final power amplifier was developed using 10 m 30/250 μm DC Yb-doped fiber to further boost the average power/energy of the laser pulses. The numerical aperture (NA) is 0.06/0.46 (core/inner cladding). The active fiber was pumped by 915 nm multimode laser diodes connected by an (18+1)*1 combiner. The cladding absorption at 915 nm of this active fiber is ~ 2.2 dB m^{-1}. The residual pump was dumped out by a home-made CMS. A polished endcap with an angle of 8° is utilized as the output end to mitigate the facet reflection. One high-power isolator was inserted between the two DC amplifier stages to block the counter-propagating light.

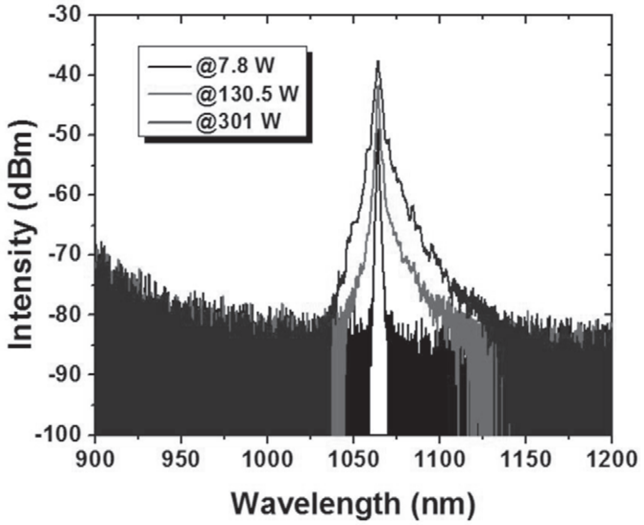

Figure 4. The emission spectra at different laser power; the repetition rate is fixed at 100 kHz.

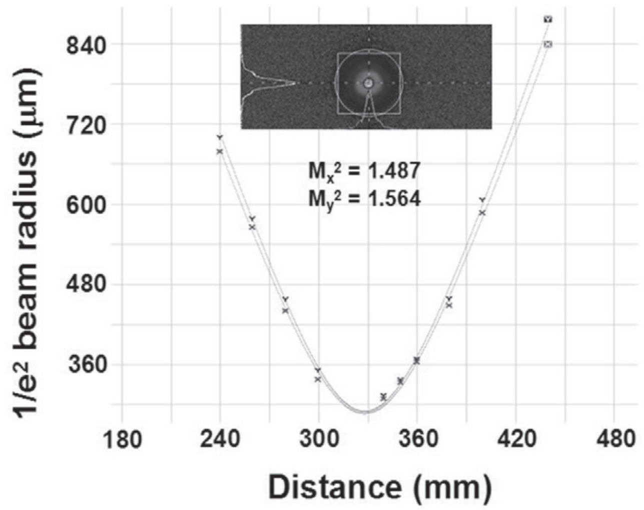

Figure 5. Measured beam-quality factor (M^2). Inset: beam profile of the laser pulses with ~301 W average power.

3. Results and discussion

Figure 2 shows the average power of the laser pulses as a function of the launched pump power when the repetition rate was fixed at 100 kHz. The maximum average power of 301 W was obtained when 399 W pump power was launched, leading to an optical-to-optical efficiency of ~75.4%, and the corresponding slope efficiency is 76.7%. As we can see from figure 2, the laser power is increasing linearly with the pump power, and has no sign of saturation. The achieved laser power in the current system was limited by the available pump power. Note that active wind cooling for the laser diodes and the active fiber was required.

The pulse width of the laser pulses at 100 kHz repetition rate under different pump power was measured using a fast optical detector. As figure 3 shows, the pulse width does not change much at low pump power, but starts to increase when the launched pump power is higher than ~125 W. The pulse width increases to ~475 ns when the laser power is ~301 W (~399 W launched pump power). The measured pulse shape is shown in the inset of figure 3. The pulse width increase for the amplified Q-switched laser pulses was also observed in previous reports [3, 8]. Figure 3 also demonstrates the peak power of the laser pulses at 100 kHz repetition rate under different pump powers, calculated from the measured average power and the measured pulse width. The maximum peak power of ~6.37 kW was achieved.

The spectra of the laser pulses with different average power are depicted in figure 4. The center wavelength is located at ~ 1064 nm. The spectra is very clean; no amplified spontaneous emission (ASE) and stimulated Raman scattering (SRS) appeared. The signal-to-noise ratio is > 40 dB. The 3 dB linewidth of the spectrum for the pulses at 301 W was measured to be ~ 2.4 nm.

The measured beam quality factor (M^2) at the maximum average power of 301 W is shown in figure 5 and the beam profile is inserted. An output beam quality of M^2 = 1.487, 1.564 in the x, y direction, respectively, was achieved.

4. Conclusion

In conclusion, a monolithic actively Q-switched nanosecond fiber laser source in MOPA configuration was developed, producing ~ 475 ns pulses at 100 kHz repetition rate with >300 W average power and with good beam quality (M^2 < 1.6 in both directions). To our best knowledge, this is the highest average power demonstration for an actively Q-switched fiber laser in all-fiber format. The optical to optical efficiency of the final power amplifier reaches ~ 75.4%. The output laser pulses have >40 dB signal-to-noise ratio from the spectrum (no Raman appeared). The all fiber construction of the whole laser system enables compact size, maintenance-free, robust operation and thus allows various practical applications in laser marking, laser cutting, deep engraving etc

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