Pulsed pumped Yb-doped fiber amplifier at low repetition rate

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A pulsed pumped Yb-doped double-clad fiber (DCF) master-oscillator power amplifier (MOPA) at low repetition rate is reported. Seeded by a passive Q-switched Nd:YAG microchip laser, the fiber amplifier can generate 167-kW peak-power and 0.83-ns duration pulses at 200-Hz repetition rate. Because of the pulsed pump approach, the amplified spontaneous emission (ASE) and the spurious lasing between pulses are well avoided, and the repetition rate can be set freely from single-shot to 1 kHz. Peak power scaling limitations that arise from the fiber facet damage are discussed.

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Ytterbium-doped double-clad fiber (DCF) lasers and amplifiers attract more and more attentions due to their advantages, such as excellent spatial beam quality, high conversion efficiency, robustness and no need for water cooling. For many applications such as laser range finding, lidar, remote sensing, and nonlinear frequency conversion, the pulsed laser output with high peak-power and short duration is required. Such laser pulses can be generated from Yb-doped DCFs using master-oscillator power amplifier (MOPA). In 2002, a 100-W average power, high energy nanosecond fiber amplifier was demonstrated by Limpert *et al.*[1], which operates at repetition rates between 3 and 50 kHz, with pulse durations of 50—300 ns. An Yb-doped fiber amplifier generating diffraction-limited, 300-kW peak-power pulses with 0.8-ns durations at 8.5-kHz repetition rate was also reported[2]. In China, a 6-W average power DCF power amplifier was reported by Kong *et al.* in 2004[3].

All these previous researches used continuous-wave (CW) pump regime, and operated at high repetition rates, from several kHz to hundreds kHz. However, for some applications such as range finding, high repetition rates are not necessary. High repetition rate means high energy usage, which is not expected especially in military and portable applications. CW pump regime is not fit for low repetition rate operation, because duration between pulses at low repetition rate is too long, pump power will cause strong amplified spontaneous emission (ASE) or even spurious lasing[4], which will consume a great deal of upper-level population, and decrease the stored energy. This problem is hardly solved in CW pump regime.

In this paper, we present an Yb-doped DCF MOPA system for low repetition rate operation, which uses pulsed pump regime. Strong ASE or spurious lasing between pulses is avoided.

The experimental setup is shown in Fig. 1. A passive Q-switched Nd:YAG microchip laser is used as the seed source, which is pumped by a fiber-coupled 808-nm laser diode (LD), delivering seed pulse at 1064 nm with 1.5-μJ pulse energy, and 1.2-ns pulse duration. The seed light is coupled into the active core of Yb-doped DCF through a lens. The fiber is 5.2 m with a 30.5-μm diameter core (numerical aperture (NA) is 0.17) and 400/340-μm D-shaped inner cladding (NA = 0.37). The doping concentration is 6500 ppm(mol) Yb_2O_3. More than 95% of the injected pump light can be absorbed by the fiber. Both ends are polished at an angle of 12° to suppress the reflection of fiber facet. The pump source is a collimated LD with central wavelength of 976 nm, which is water-cooled to 20 °C. The pump light is coupled into the inner cladding of DCF through coupling optics. A piece of dichroic mirror is placed by an angle of 45° to separate the pump light and the amplified output light.

The seed LD and pump LD are driven by driver 1 and driver 2, respectively, which are externally triggered through a time delayer to generate the required timing for the pulsed pump method.

When pump LD launches, Yb ions in DCF absorb the pump power, so upper-level population and gain in active medium increase gradually. As gain reaches high levels, spontaneous emission propagating in the fiber will be greatly amplified, forming strong ASE. In addition, feedback from fiber facet and Rayleigh scattering may originate the spurious lasing. In CW pump regime, these effects may occur at low repetition rate, because the pulse duration may be longer than ASE built-up time. Here, ASE built-up time is defined as the duration from the pump LD launching to obvious ASE can be observed.

To avoid ASE and spurious lasing, pulsed pump regime should be used. The pump LD operates in pulsed mode, and the pulse duration should be shorter than ASE built-up time, which is on the order of hundreds of microsecond, and can be easily obtained by experimental measurements. The rising edge of driver 2 triggers the time delayer, then triggers driver 1 to make sure that the seed pulse is injected at the end of the pump pulse. At this time, the upper-level population is on a very high level, so the seed pulse will be amplified to become

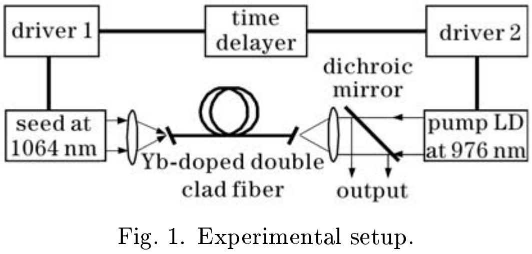

Fig. 1. Experimental setup.

a giant pulse with high peak-power and energy.

Because of this pulsed pump regime, generation of each giant pulse is an individual process. Consequently, the amplification characteristics are nearly independent of the repetition rate from single-shot to 1 kHz. This method provides many advantages at low repetition rate. The repetition rate can be set freely, and single pulse generation can be easily achieved, which is very useful. The pump LD does not work between pulses, so strong ASE and spurious lasing are avoided.

In our experiment, pulsed pumped operation is achieved at 200 Hz. The ASE built-up time of the DCF amplifier is measured to be about 500 μs at 13.2-W pump power. Tuning the pump pulse duration, we find the optimum value is 475 μs. When the peak pump power reaches 13.2 W, corresponding to average pump power of 1.25 W, giant pulses with 138.2-μJ output energy are obtained. The pulse energies at different pump powers are shown in Fig. 2.

Because of lack of high energy seed source, the seed pulse energy used in this experiment is only 1.5 μJ. Such low pulse energy is insufficient to extract the energy stored in the fiber amplifier, which will cause low conversion efficiency. Predicted by our model, if the seed energy increases to 50 μJ, the conversion efficiency will exceed 50%.

A 1.5-GHz Agilent oscilloscope (8-GHz Sa/S) and a 12-GHz photodetector are used to observe the temporal pulse shapes of the seed and the amplified pulses, which are shown in the inset of Fig. 2. The pulse duration is apparently reduced after amplification. The duration of the seed pulse is 1.2 ns. When amplified to 138.2-μJ pulse energy, the duration is reduced to 0.83 ns, corresponding to a peak power of 167 kW.

The output spectrum is measured by an Agilent 86142B optical spectrum analyzer. Figure 3 shows the comparison of output spectra between pulsed and CW pump regime at 200 Hz. We can find that for CW pump regime, spurious lasing occurs at wavelengths between 1069 and 1077 nm, while pulsed pump regime shows a very pure spectrum centered at 1064.64 nm, which indicates that ASE and spurious lasing are avoided.

Higher peak power pulse generation is limited by fiber facet damage. In experiments, we have observed fiber facet damage at higher peak power. The surface damage threshold of fused silica at 1064 nm is given in Ref. [5], which can be used to estimate the DCF facet damage threshold,

$$P_{\mathrm{th}} = 22(\Delta\tau_{\mathrm{p}})^{0.4}\pi\left(d_{\mathrm{core}}\times 10^{-4}/2\right)^2 \times 10^6/\Delta\tau_{\mathrm{p}}. \qquad (1)$$

In our experiment, the pulse duration $\Delta\tau_{\mathrm{p}} = 0.83$ ns, the diameter of DCF core $d_{\mathrm{core}} = 30.5$ μm, so the surface damage threshold of the pure fused silica fiber can be calculated $P_{\mathrm{th}} = 180$ kW. For Yb-doped fiber we used, the damage threshold should be slightly lower, which coincides with experimental result very well. Fiber facet damage limitations can be overcome by using a coreless end cap[1], therefore, higher peak power pulses could be generated, which will be researched in the near future.

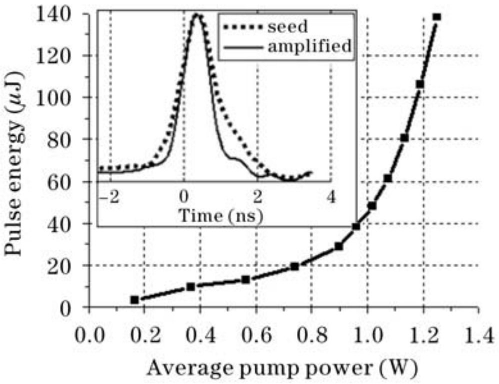

Fig. 2. Pulse energy at different pump powers. The inset shows the temporal pulse shapes before and after amplification.

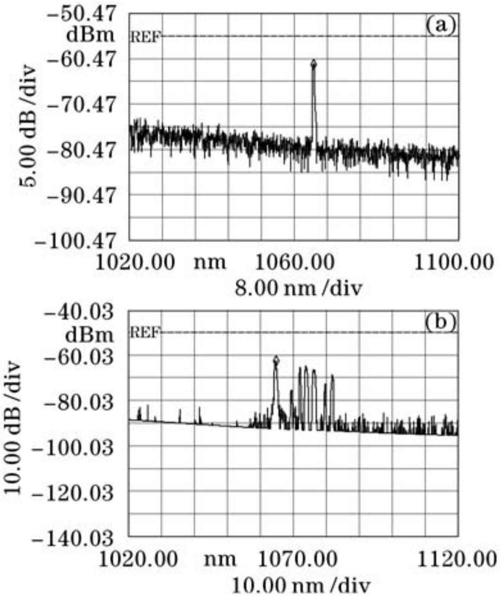

Fig. 3. Output spectra of pulsed pump (a) and CW pump (b).

In conclusion, we have demonstrated a pulsed pumped Yb-doped DCF MOPA system for low repetition rate operation. ASE and spurious lasing between pulses are avoided by controlling the pump duration and seed injecting delay time. Seeded with a passive Q-switched Nd:YAG microchip laser, amplified laser pulses with 167-kW peak power, 138.2-μJ pulse energy, and 0.83-ns duration are generated. Because of the pulsed pump regime, the repetition rate can be set freely from single-shot to 1 kHz. Fiber facet damage limitations are discussed.

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