Pulsed-pumped optical fiber amplifier

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With the use of pulsed pumping, an optical fiber amplifier with all-fiber structure is developed based on the fused tapered fiber combiner and Yb^{3+}-doped double cladding fiber (YDCF). From the experimental results, 47-dBm peak power and 100-ns pulse duration are obtained when the repetition rate of pumping pulses is 100 Hz. The gain of the amplifier is up to 30 dB. It is shown that due to the use of pulsed pumping, pump light emits only when the signal light reaches the amplifier and thus the amplified spontaneous emission (ASE) is significantly suppressed.

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High-peak-power lasers and amplifiers are increasely utilized in many fields such as laser telemeter, lidar, spatial optical communication, remote controlling, and remote sensing[1−4]. Recently, Yb-doped fiber lasers and amplifiers have attracted more attention because they have high conversion efficiency, good beam quality, and high reliability[5−7]. In 2002, Limpert *et al.* demonstrated a high energy nanosecond fiber amplifier with 100-W average power operating at the repetition rate between 3 kHz and 50 kHz with the pulse duration of 50 - 300 ns[8]. Meantime, an Yb^{3+}-doped fiber amplifier which outputs 300-kW peak-power pulses with 0.8-ns duration at 8.5-kHz repetition rate was also reported[9]. Thereafter, a pulsed pumped Yb^{3+}-doped double-cladding fiber (YDCF) amplifier was presented by Ye *et al.* in 2005[10], where the amplifier was seeded by a passive Q-switched Yb^{3+}-doped fiber laser. The fiber amplifier was likely to output 167-kW peak power and 0.83-ns duration pulses at 200-Hz repetition rate.

Except for the scheme in Ref. [10], the optical amplifiers in most other schemes use continuous-wave (CW) pumping and operate at high repetition rates from several to hundreds of Kilohertzs. However, high repetition rate means high energy usage and it is unnecessary for some applications such as laser ignition. When the amplifier operates at a low repetition rate, strong amplified spontaneous emission (ASE) and even spurious lasing is caused by CW pumping. As a consequence, a great deal of upper-level population is consumed and the stored energy decreases. This problem can hardly be solved for CW pumping. Instead, pulsed pumping was utilized in the scheme of Ref. [10], where discrete optical devices were used in experimental setup, so the structure of the system is incompact.

In this letter, we develop an optical fiber amplifier using pulsed pumping and all-fiber structure, instead of CW pumping and the bulky structure of discrete optical devices with water cooling. Due to the use of pulsed pumping, pump light emits only when the signal light arrives at the amplifier. Consequently, the ASE is remarkably suppressed and the pumping source does not need water cooling. The amplifier size is reduced due to the use of all-fiber structure.

The schematic diagram of the proposed pulsed-pumped Yb^{3+}-doped fiber amplifier is illustrated in Fig. 1, where optical circuits and electric modules are also depicted. In this scheme, the source pulsed light is split into two parts. The primary one acts as signal light, and the remaining one is converted by an optic-electric (O/E) detector to synchronous electric signal, which triggers the driver circuit. The timing relation between the pumping light and signal light is adjusted by the driver circuit. The rising edge, width, and amplitude of the pumping

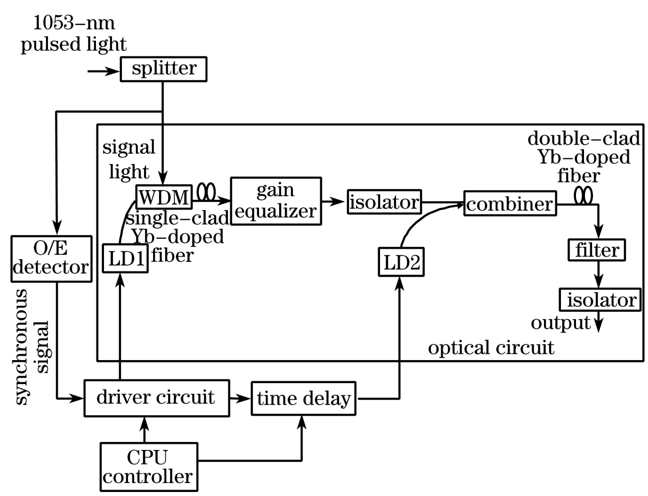

Fig. 1. Schematic diagram of pulsed-pumped Yb^{3+}-doped fiber amplifier. WDM: wavelength division multiplexer; LD: laser diode.

light can be controlled by the CPU controller. The signal light reaches the Yb-doped fiber at the rear end of the pumping light pulse by properly adjusting the pumping light delay relative to the signal light.

The principle of amplification of signal light is briefly explained in the following. The rising edge of the synchronous signal triggers the driver circuit and then the pumping light emits from the LDs. After the pumping light emits to the Yb-doped fiber and Yb ions absorb the pumping energy, the number of high-level ions increases. When the signal light reaches the Yb-doped fiber at the end of the pumping light pulse and a sufficient number of high-level ions are collected, the signal light is amplified. High peak power and high energy pulse can thus be obtained. In our scheme of pulsed pumping, the pumping source does not work continuously, so ASE can be suppressed and the pumping source does not need water cooling.

Two-stage amplification is adopted in the optical circuit. The first stage is pre-amplifier, composed of WDM, single-clad Yb-doped fiber, gain equalizer, and isolator. The gain equalizer can increase the gain flatness and also suppress the ASE since its bandwidth is only 20 nm. In the second stage, combiner, double-clad Yb-doped fiber, and optical filter of 20-nm bandwidth are used to improve the output power. The combiner is a specific component for high power pumping which makes the system compact and increases the coupling efficiency. The isolators in two stages can prevent the reflected laser from damaging optical components.

To demonstrate the performance of the proposed scheme of optical fiber amplifier, an experiment setup was established according to Fig. 1. In this scheme, 1053-nm pulsed light with the 3-dB spectral width of 1.2 nm is used as source light. Through the light splitter, pulsed light with 100-ns pulse duration and 17-dBm peak power becomes the signal light. Different fibers and LDs are used in two stages. The single-clad Yb-doped fiber is used in the pre-amplifier stage. Because the gain threshold power of single-clad Yb-doped fiber is low, the maximum output power of the first LD is only 150 mW and the power is coupled into the Yb-doped fiber through WDM. In the second stage, to improve the output power, the second LD delivers a power up to 1 W. Pigtail fiber of the LD is 100 μm in diameter with the numerical aperture (NA) of 0.22. Signal light and pumping light are coupled into the fiber through the high power combiner. The pump transmission efficiency of the combiner is more than 95% and the pump input fiber core is 100 μm in diameter with the NA of 0.22. The signal transmission efficiency of the combiner is more than 85% and the signal input fiber is Corning Hi 1060. The output fiber of the combiner is passive double-clad fiber which well matches the double-clad Yb-doped fiber (also called active fiber), so that the splice loss of the two types of fibers is very small. The core diameters of both passive and active double-clad fibers are 6 μm and the NAs are 0.15. The fiber core is located in the middle of a 125-μm octagonal-shaped inner cladding with the NA of 0.46. Due to the use of double-clad Yb-doped fiber, the pump light is reflected in the inner cladding of the fiber back and forth, so the coupling efficiency is higher than the traditional side-pumping scheme and thus high amplification gain is obtained. The cladding absorption of the double-clad Yb-doped fiber at 975 nm is 3 dB/m, and an 8-m-long fiber is used.

In our experiment, pulses with 47-dBm peak power and 100-ns duration can be obtained when the repetition rate of pumping pulses is 100 Hz. By tuning the width of pump pulse, we find the optimum value of 800 μs. When the pump pulse width is less than 800 μs, the gain of the amplifier is compromised. Meantime, the gain value does not increase any more if the pulse width is wider than 800 μs. This is due to the fact that the net relaxation of Yb ions at metastable energy level is about 800 μs, and the maximum gain cannot be reached at a pump pulse width less than 800 μs. The values of ASE under pulsed pumping and CW pumping were respectively measured with a power meter. The result shows that the ASE under the pulsed pumping is 10 dB less than that under

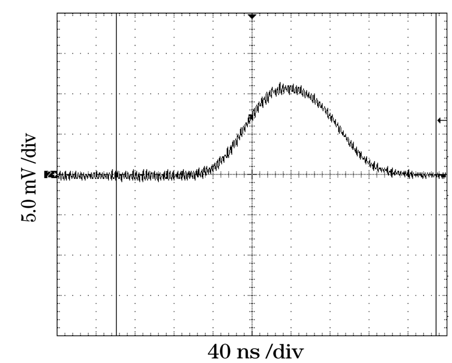

Fig. 2. Amplified signal pulse.

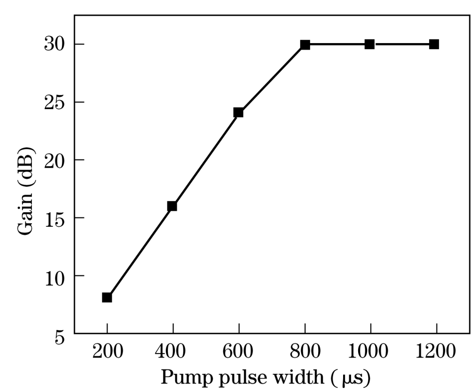

Fig. 3. Gain versus pump pulse width.

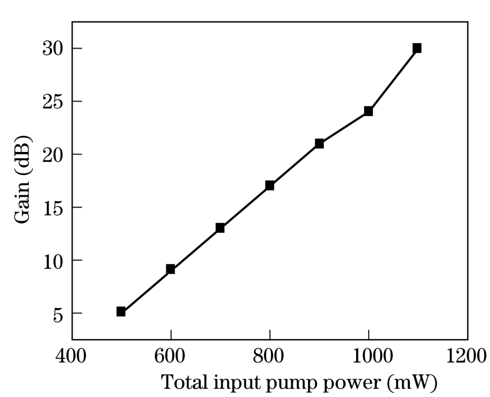

Fig. 4. Gain versus total pump power.

CW pumping. The amplified signal pulses are illustrated in Fig. 2 (attenuated 37 dB). Figure 3 shows the relation between the amplifier gain and the pump pulse width where the pump power values of the first and second amplification stages are respectively 100 and 1000 mW.

In addition, the curve of the amplifier gain varying with the total pump power is plotted in Fig. 4, where the pump power values in two stages are also 100 and 1000 mW, respectively. It is shown that the amplifier gain of 30 dB can be achieved when the pulses with the peak power of 47 dBm are obtained under the signal power of 17 dBm.

In conclusion, we have developed an optical amplifier using pulsed pumping and all-fiber structure. The amplifier can operate well at a low repetition rate. Amplified laser pulses with 47-dBm peak power and 100-ns duration are obtained. The ASE is suppressed by controlling the timing relation between pumping light and signal light. Moreover, the system is relatively compact due to the use of all-fiber structure.

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