

Eye-safe, high-energy, single-mode all-fiber laser with widely tunable repetition rate

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We present a novel high-energy, single-mode, all-fiber-based master-oscillator-power-amplifier (MOPA) laser system operating in the C-band with 3.3-ns pulses and a very widely tunable repetition rate, ranging from 30 kHz to 50 MHz. The laser with a maximum pulse energy of 25 μ J and a repetition rate of 30 kHz is obtained at a wavelength of 1548 nm by using a double-clad, single-mode, Er:Yb co-doped fiber power amplifier.

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Recently, light detection and ranging (LIDAR) technique is basically applied in range finding, three-dimensional (3D) imaging, wind sensing, and differential absorption lidar (DIAL)^[1]. A key requirement in LIDAR systems is the excellent quality of the laser source. And high-energy all-fiber laser systems pumped by laser diodes have acquired much attention due to their various advantages, such as high beam quality, stability, and efficiency, low weight, compactness, low power consumption, and reduced heat generation compared with other traditional laser systems. Furthermore, it is possible to take advantage of Er³⁺-doped fibers to build lasers or amplifiers operating at wavelengths close to 1.5 μ m. This spectral region is eye-safe and exhibits strong penetrability in foggy weather, so it is attractive to be adopted as the optimal wavelength for lighting at seaside.

Up to now, a 1.15-mJ pulsed all-fiber optical source has been demonstrated by using master-oscillator-power-amplifier (MOPA) systems^[2]. However, in that work the pulse width was extended from 70 to 575 ns by nonlinear effects, making the maximum pulse peak power less than 2 kW. Other approaches, based on large core area fiber amplifiers, allow to produce high output pulses energy and peak power^[3–9]. However, these kinds of sources require the use of free-space optical components, preventing the implementation of all-fiber configurations. In this letter, we present a fully fiber-based, single-mode, MOPA laser source for generating eye-safe short optical pulses with widely tunable repetition rate for future LIDAR systems. The proposed architecture can overcome some disadvantages of conventional lasers, such as low efficiency, poor flexibility, difficulty to be packaged, and strong sensitivity to the system's operating conditions. With our scheme, 3.3-ns pulses with a repetition rate of as high as 50 MHz can be obtained, and the maximum achievable peak power is 7.5 kW at a repetition rate of 30 kHz.

The setup of the all-fiber MOPA system is shown in Fig. 1. The seed laser, a distributed feedback semicon-

ductor laser (DFBL), is directly modulated to generate square-shaped optical pulses whose time durations can be varied in the range between 3.3 and 200 ns, with corresponding single pulse energy ranging from 60 pJ to 3.6 nJ. The seed pulses pass through a three-stage fiber amplifier, formed by a preamplifier, a booster amplifier, and a power amplifier. The preamplifier and booster amplifier are based on single-mode Er³⁺-doped fiber pumped by a continuous-wave laser diode delivering 300-mW optical power at 976-nm wavelength. A pass-band filter is used to eliminate the out-of-band amplified spontaneous emission (ASE) generated by the Er³⁺-doped fiber amplifiers (EDFAs). A pulse energy of 2 μ J is obtained after the two amplifiers at a repetition rate of 30 kHz with a pulsewidth of 3.3 ns, leading to a calculated gain of the amplified pulse higher than 45 dB. The gain medium of the third-stage power amplifier is a 4-m-long Er:Yb co-doped double-clad fiber with a core diameter of 7.5 μ m and a 125- μ m-wide first cladding diameter, pumped at 4 W by a multimode 976-nm optical source. In order to decrease the reflection at the fiber end, an end cap with 8° angle is spliced on the output side of the fiber amplifier.

Dependence of the pulse energy and peak power on the repetition rate with a launched pump power in the power amplifier of 3.5 W is shown in Fig. 2. The tunable repetition rate varies from 30 kHz to 50 MHz, and the input seed pulse width is fixed at 3.3 ns. From the figure it can

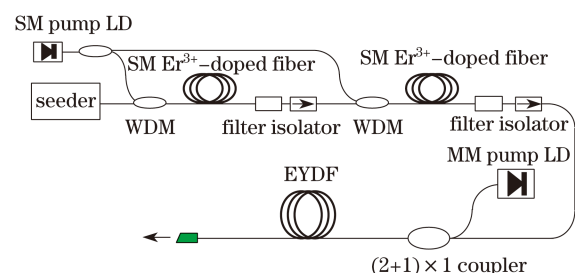


Fig. 1. Experimental setup of the all-fiber MOPA system.

be seen that the average output power increases with the repetition rate, and gradually saturates. On the other hand, the pulse energy decreases quickly when the repetition rate increases up to 200 kHz, and then the energy decreases slowly. The maximum output average power of 0.9 W can be achieved at repetition rates of higher than about 200 kHz, though, as expected, at these values the pulse energy is reduced to less than $4.5 \mu\text{J}$. Whereas the maximum pulse energy of $25 \mu\text{J}$ can be achieved at the minimum repetition rate of 30 kHz in the system. Figure 3 shows the temporal trace of the pulse output from the power amplifier at 30-kHz repetition rate, which is recorded by a 45-GHz photodetector and a 6-GHz oscilloscope.

When the input pulsewidth of the seeder increases to 110 ns, a pulse energy of $30 \mu\text{J}$ can be obtained with repetition rate of 30 kHz. With such a broad seed pulse being injected, the effect of the amplifier is to re-shape the pulse by steepening its leading edge, whereas the trailing edge is smoothed as shown in Fig. 4. The seed square pulse (trace a) evolves gradually to a sharp pulse as it travels through the various stages of the amplifier. At the output of the preamplifier, a trapezoidal-shaped, 65-ns-long pulse (trace b) is achieved, which is found to be narrowed down to 4.9 ns (trace c) at the final-stage output. Compared with the seed pulse of 3.3 ns, the peak power of the output pulse is reduced because some part of the pump energy is used to increase the energy in the trailing edge of the pulse, although the total pulse energy increases.

As we know, the magnitude of the nonlinear effects depends on the effective mode area and the interaction length of the guided waves in the fiber^[10]. Thus,

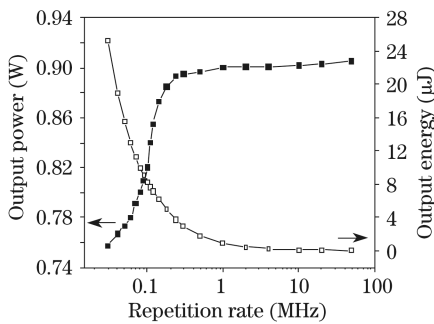


Fig. 2. Output power and pulse energy versus input repetition rate with 3.3-ns pulsewidth.

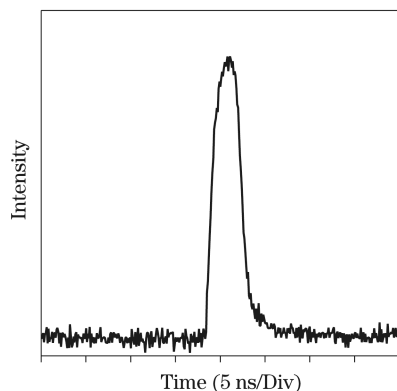


Fig. 3. Output temporal trace of pulse at 30-kHz repetition rate.

increasing the diameter of the core and/or decreasing the length of the doped fiber are effective methods to increase the threshold of Stimulated Raman Scattering (SRS) and Stimulated Brillouin Scattering (SBS), and reduce the nonlinear effects that limit the increase of pulse energy in the fiber amplifier system. However, increasing the mode area of the fiber leads to an increase of the mode number of output laser as well. In our experiments, different spans of various lengths of doped fiber are used in the power amplifier. At the repetition rate of 30 kHz and for an input seed pulse width of 3.3 ns, the maximum output energy of $12 \mu\text{J}$ and $20 \mu\text{J}$ are achieved with 1-m- and 2-m-long spans of doped fiber, respectively. Of course, using the shorter fiber can advantageously suppress the nonlinear effects for the same value of output peak power. Figure 5 shows the spectrum traces of the output laser pulse for 1-m-, 2-m-, and 4-m-long doped fiber, respectively, with the same value of output energy of $12 \mu\text{J}$ and an input seed pulse at a repetition rate of 30 kHz and a width of 3.3 ns. It can be seen that, in the case of the 4-m-long doped fiber (Fig. 5(c)), the output pulse spectrum is deformed by the nonlinear effects during its propagation along the amplifier, whereas it remains clean in the case of the 1-m-long fiber amplifier (Fig. 5(a)). As expected, the nonlinear effects in the case of 2-m-long fiber are weaker than the 4-m-long case, as shown in Fig. 5(b). So, we can purposely design the length of the doped fiber to avoid the pulse deformation due to the nonlinear effects in the amplifier, and higher doping

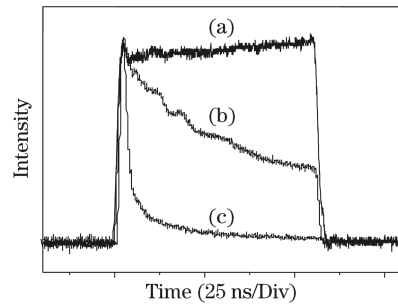


Fig. 4. Temporal trace of output pulse of (a) seeder, (b) preamplifier, and (c) power amplifier.

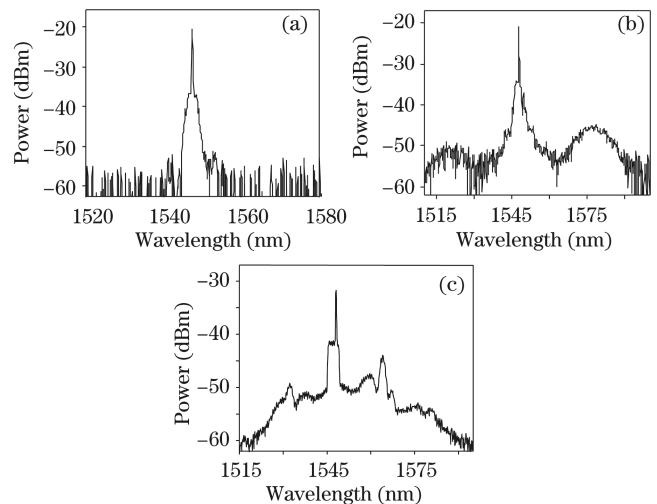


Fig. 5. Wavelength spectrum of power amplifier output at 30-kHz repetition rate with 3.3-ns-long seed pulse for (a) 1-m-long, (b) 2-m-long, and (c) 4-m-long doped fiber, respectively.

concentrations in the fiber can be used to counteract the pulse energy decrease associated with a lower gain saturation power value in a shorter amplifier. In this way, clean, high-energy output pulse can be achieved. However, some undesirable effects may appear in highly doped fiber, such as ion quenching, photodarkening, index increase, and thermal effect^[11]. These disadvantages should be comprehensively considered in the design of the high energy fiber amplifier.

In conclusion, we experimentally demonstrate a diode-pumped Er:Yb co-doped single mode fiber master-oscillator power amplifier. A pulse energy of 25 μ J corresponding to a pulse peak power of 7.5 kW is obtained at repetition rate of 30 kHz. In experiment, we effectively reduce the disturbance of nonlinear effects by using a shorter span of doped fiber, and present its effect on the output signal spectrum. Additionally, by using a long seed pulse, the pulse shaping effect is generated in the amplifier. The performance of the single mode all-fiber laser show that the system can be very suitable for LIDAR applications.

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