High-peak-power, single-mode, nanosecond pulsed, all-fiber laser for high resolution 3D imaging LIDAR system

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This study presents an eye-safe, single-mode, nanosecond-pulsed, and all-fiber laser source with master-oscillator-power-amplifier configuration at 1 550 nm that is suitable for high-resolution three-dimensional (3D) imaging light detection and ranging (LIDAR) system. The output peak power of 7.6 kW is obtained at the 1.2-ns pulse width and 50-kHz repetition rate. The single-mode pulse laser output ensures the range precision and imaging results of the LIDAR system. The laser is used as a transmitter for the 3D imaging LIDAR system. The detailed characteristics of the LIDAR system and the results of the 3D imaging are presented.

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The light detection and ranging (LIDAR) system has been proven to be a powerful tool for range finding, three-dimensional (3D) imaging, wind sensing, and differential absorption LIDAR systems[1]. A laser source with excellent quality is a key requirement in LIDAR systems. Three kinds of laser sources are used for 3D imaging LIDAR systems. For example, the commercial diode laser, which has limited pulse width and peak power, is used as a laser source for short distance range and low precision[2]. On the other hand, the solid-state laser can produce high-energy and narrow-pulse-width output[3−5] and has become an important laser source for LIDAR applications. Fiber laser sources have several appealing properties for use in LIDAR systems, including good beam quality, narrow linewidth, and versatility that allow the independent optimization of pulse duration, repetition rate, and shape. The single-mode all-fiber pulsed lasers pumped by laser diodes have obtained much attention because of the various advantages, including good beam quality, high efficiency, lightweight, low power consumption, and reduced heat generation[6,7]. In high-resolution 3D imaging LIDAR systems, the repetition rate of the laser sources decides the imaging speed, and the detectable distance precision depends on the peak power and the pulse width[2]. Therefore, this study develops a narrow-pulse, high-peak-power, single-mode, and all-fiber laser source to improve the performance of the LIDAR system.

Philippov *et al.* reported an erbium-ytterbium co-doped fiber (EYDF) master-oscillator-power-amplifier (MOPA) system for coherent LIDAR applications with a space-coupling power amplifier stage, and they obtained 0.29 mJ and 100 ns pulses with a repetition rate of 4 kHz[8]. Feng *et al.* introduced an all-fiber pulsed laser transmitter for space-based 3D imaging LIDAR system with a pulse repetition rate of 100 kHz and an amplified laser with output power of 2.3 W, in which a pulse width of 10 ns was generated[7]. Liu *et al.* developed an eye-safe, single-frequency pulsed all-fiber MOPA laser for a Doppler wind LIDAR system with repetition rate of 10 kHz and pulse duration of 500 ns[9]. They also presented another all-fiber laser with MOPA configuration[10−14]. The results show that both the pulse width and repetition rate are not optimized for high-resolution 3D imaging LIDAR systems.

In this letter, we present a single-mode, all-fiber laser source based on MOPA for the generation of eye-safe short optical pulses with high pulse peak power. 1.2-ns pulses and a maximum achievable peak power of 7.6 kW at a repetition rate of 50 kHz can be obtained. This laser was used as a transmitter in a high-resolution 3D imaging LIDAR system to achieve the function of 3D imaging and yield the laboratory scanning imaging results of spatial objects. The laser provides a distance precision of approximately ±7.5 cm. Long-distance experiments are currently being conducted.

Figure 1 shows the experimental setup of the all-fiber MOPA system. The seeder laser, which is a distributed feedback semiconductor laser, is directly modulated to generate optical pulses with 1.2-ns duration. The seed pulses pass through a three-stage fiber amplifier formed by two preamplifiers and a power amplifier. The preamplifiers are based on a single-mode erbium-doped fiber. A 10-m-long single-mode 5.8/125-μm erbium-doped fiber with a numerical aperture of 0.23 and peak absorption of 980 nm more than 3.0 dB/m is used for each stage. The preamplifiers are pumped by a continuous-wave (CW) laser diode that delivers a 255-mW optical power at 976-nm wavelength. A 40:60 fiber coupler splits the single-mode pump diode beam into two beams. A 1.6-nm linewidth pass-band filter is used to eliminate the out-of-band amplified spontaneous emission (ASE) generated by the erbium-doped fiber amplifiers (EDFAs). An isolator was inserted between the two amplifiers to enhance the noise figure. The single-mode Er:Yb co-doped double-clad fiber with a core diameter of 6 μm

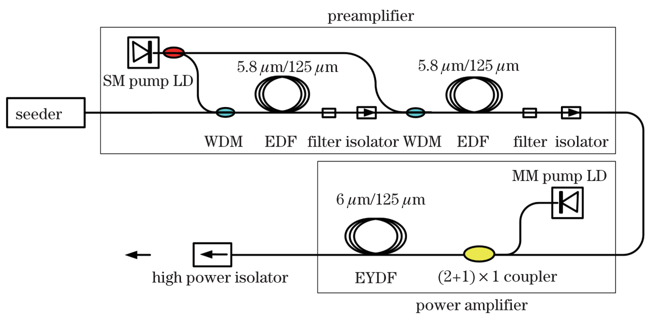

Fig. 1. Experimental setup of the all-fiber MOPA laser system.

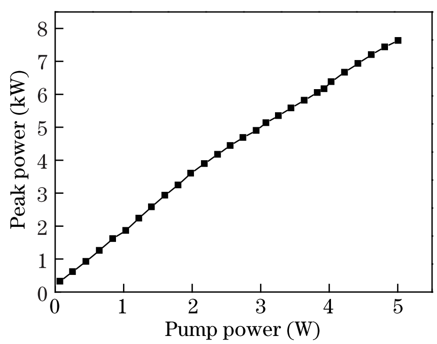

Fig. 2. Output peak power versus pump power with 50-kHz repetition rate and 1.2-ns pulse width.

and a 125-μm-wide-first cladding diameter is utilized in the third-stage power amplifier. Peak cladding absorption is 0.83 dB/m at 915 nm. The power amplifier has optimal length of 2.5 m. The multimode pump diode laser operates at a wavelength of 976 nm, and the double-clad fiber is pumped by a diode laser through a fiber combiner. The high power isolator is spliced on the output side of the fiber amplifier to decrease the reflection at the fiber end.

The pulsed seeder has an output average power of approximately 4.2 μW at a repetition rate of 50 kHz and pulse width of 1.2 ns, with corresponding peak power of 70 mW and pulse energy of 84 pJ. The preamplifiers can reach an average output power of 46 mW, with corresponding peak power of 0.76 kW, which leads to a calculated amplified pulse gain higher than 40 dB. Figure 2 shows the dependence of the output peak powers of the main amplifier on the pump powers. The output average power was measured using a power meter. The repetition rate and pulse width were recorded using a 10-GHz photo detector and a 6-GHz oscilloscope, respectively. The peak power and pulse energy were calculated from the output average power, repetition rate, and pulse width. The peak power of 7.6 kW was obtained under an output average power of 458 mW at pump power of 5 W with a 1.2-ns pulse width and a 50-kHz repetition rate, corresponding to the pulse energy of 9.16 μJ. The output pulse of the laser is single mode (TEM_{00}), which is an important factor for the distance precision of high-resolution 3D imaging LIDAR systems.

Figure 3 shows the temporal trace of the pulse output from the seeder and power amplifier at a 50-kHz repetition rate.

Nonlinear effects limit the increase in the pulse peak power of fiber amplifier systems. Thus, increasing the mode area and decreasing the length of the doped fiber are effective methods for reducing nonlinear effects. However, increasing the mode area of the fiber would increase the mode number of the output laser as well. Thus, in this letter, a 6-μm mode area of the fiber was used to maintain the single-mode output and design the length of the doped fiber to avoid pulse deformation. Moreover, higher doping concentrations in the fiber were used to counteract the decrease in pulse peak power associated with a lower gain saturation power value in a shorter amplifier. A 2.5-m-long Er:Yb co-doped double-clad fiber with 0.83-dB/m peak cladding absorption at 915 nm was used in the power amplifier to achieve clean, high-peak-power output pulses. Figure 4 shows the wavelength spectra of the seeder laser, preamplifier, and power amplifier output at 50-kHz repetition rate and 1.2-ns-long seed pulse. The signal-to-noise ratio (SNR) of the output optical spectrum was greater than 20 dB at the repetition rate of 50 kHz. Moreover, the amplified pulses spectra did not display any pulse deformation, and the output pulse remained clean.

The high-peak-power, single-mode, nanosecond, all-fiber laser was used as a transmitter for the 3D imaging LIDAR system and it plays a vital role in improving the performance of the LIDAR system. The LIDAR system with pulsed laser range in non-coherent detect mode uses an all-fiber pulsed laser as the laser source, detects objects by using avalanche photodiode (APD), and adopts an optics-mechanics rotating mirror scanner in object space to obtain the 3D image results. Figure 5 shows the experimental setup of the 3D imaging LIDAR system.

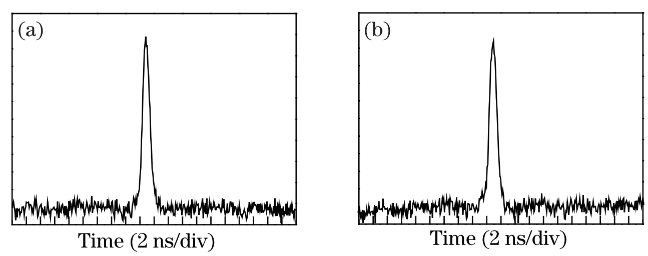

Fig. 3. Output temporal trace of the pulse at 50-kHz repetition rate (a) seeder laser and (b) power amplifier.

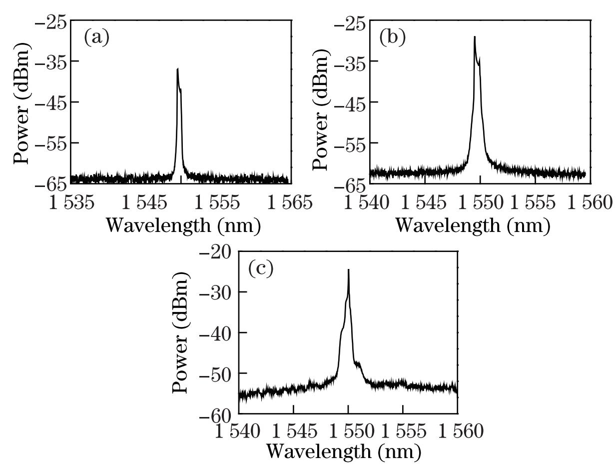

Fig. 4. Output wavelength spectra of (a) seeder laser, (b) preamplifier, and (c) power amplifier.

The resolution of high-resolution 3D imaging LIDAR systems depends on the peak power of the laser source. Increasing the peak power of the laser can enhance the echo peak power of the APD detector when the resolution is increased, while the decrease in the pulse width can enhance the peak power of the laser. However, the pulse width is limited by the corresponding bandwidth of the APD. A pulse width of less than 1 ns decreases the efficiency of APD and affects the detectable range precision of the LIDAR system. The repetition rate of the laser source is related to the imaging speed. The imaging speed and resolution of each frame image decide the minimum repetition rate. A pixel was obtained by averaging a set of ten output laser pulses to improve the distance precision and achieve low-power weak-signal detection. The resolution of each frame image reached 512×512 pixels. The minimum repetition rate of transmitter of 43.6 kHz (10×512×512/60) was achieved by controlling the imaging time to less than a minute. Thus, a repetition rate of 50 kHz was chosen.

Based on the all-fiber laser source, the high resolution 3D imaging LIDAR system achieved its 3D imaging function and yielded scanning imaging results of spatial objects at the 5-m detectable distance range. The range accuracy experiment was implemented in the laboratory, and the results showed the attainable distance precision of ±7.5 cm. Figure 6 shows the 2D chromatic images that were plotted using scanning data, in which the different colors correspond to the different distances. Figure 7 shows the 3D imaging results, distance information, and high-quality intensity information, which were obtained synchronously.

The imaging results of static objects, such as humans, computers, plants, and wall corners, show that the 3D images were similar to the actual shape of these objects. The slick objects produced a strong mirror reflection that can be difficult to detect. The laser achieved a ten-hour laser output in the experiments. The single-mode pulse laser output effectively reduced the output laser radiation angle of the transmitter. The results show that the pulse laser source with 1.2-ns pulse width and 7.6-kW peak power at 50-kHz repetition rate can meet the

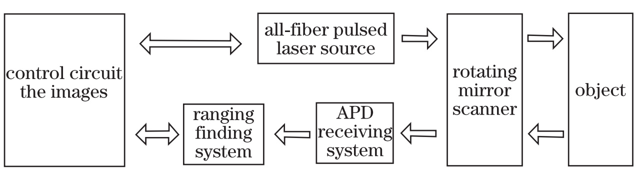

Fig. 5. Experimental setup of the 3D imaging LIDAR system.

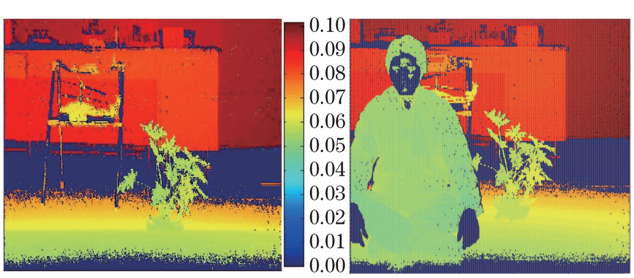

Fig. 6. Laboratory scanning 2D chromatic imaging results of the 5-m spatial object.

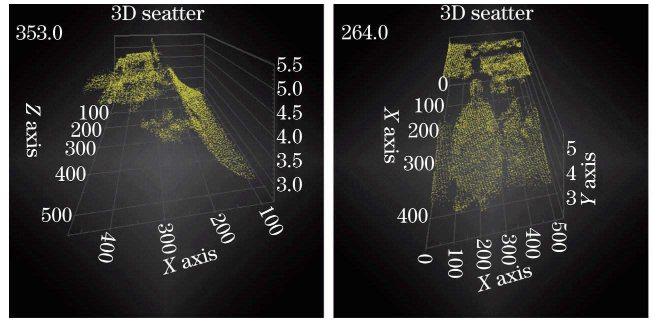

Fig. 7. Laboratory scanning 3D imaging results of the 5-m spatial object.

requirements of high-resolution 3D imaging LIDAR systems.

In conclusion, we demonstrate the use of an EYDF to establish a compact all-fiber MOPA laser source. A pulse peak power of 7.6 kW is obtained at the 1.2-ns pulse width and repetition rate of 50 kHz. In the experiment, the disturbance of nonlinear effects is effectively reduced, and the laser achieved steady, single-mode laser output. In addition, the 3D imaging LIDAR system yields scanning imaging results, with distance precision of approximately ±7.5 cm. The performance of the single-mode all-fiber laser source shows that the system is suitable for high-resolution 3D imaging LIDAR applications.

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