1. INTRODUCTION

With the remarkable development of the high brightness and high power InGaAs laser diodes, trivalent ytterbium ion (Yb\(^{3+}\)) has been recognized as a very attractive dopant for solid-state laser materials [1–12], this is mainly for the reason that Yb\(^{3+}\)-doped materials have many outstanding properties, such as small quantum defect, long energy storage lifetime, simple energy-level scheme, very high doping level, desirable properties for diode pumping, as well as broad absorption and emission bandwidths, which are fundamental conditions to support femtosecond laser generation, and so on. So far, many ytterbium-doped materials have been demonstrated to be used for laser operations. Among these materials, Yb-doped crystals show very excellent characteristics and many studies have been reported, such as garnet Yb:YAG [13–16], and Yb:YGG [17, 18], tungstates Yb:KGW [19], oxyorthosilicates Yb:LYSO, and Yb:GSO [20–22], etc. Recently, transparent polycrystalline ceramic laser materials have attracted much more attention, because they have many favorable characteristics compared with single crystals, such as high doping concentration, low cost, easy fabrication, mass producible and multilayer or multifunctional structures [23, 24]. Crystals with cubic symmetry such as YAG and Y\(_2\)O\(_3\), are suitable for ceramics fabrication. Cubic Y\(_2\)O\(_3\) crystal is a promising solid state laser medium because of its excellent optical, thermal, chemical and mechanical properties. Especially, its thermal conductivity is twice as large as that of YAG.

However, it is extremely difficult to grow high-quality large-size Y\(_2\)O\(_3\) single crystal due to its high melting point, which is 2430°C while the temperature of structural phase transition is 2280°C. Fortunately, transparent Y\(_2\)O\(_3\) ceramics could be fabricated at a relatively low sintering temperature of 1700°C, which is about 700°C lower than its melting point [25]. The Yb:Y\(_2\)O\(_3\) ceramics have shown remarkable laser properties in both CW and mode-locking operation. By adding La\(_2\)O\(_3\) as a sintering aid in Y\(_2\)O\(_3\) to form yttrium lanthanum oxide transparent ceramics Yb:(Y\(_{1-x}\)La\(_x\))\(_2\)O\(_3\), the sintering temperature could be further decreased to 1450–1650°C [26]. Similar to Y\(_2\)O\(_3\), (Y\(_{1-x}\)La\(_x\))\(_2\)O\(_3\) has many remarkable advantages for laser materials—stable, hard, having a good thermal conductivity and so on. In particular, the lifetime of Yb\(^{3+}\) in (Y\(_{1-x}\)La\(_x\))\(_2\)O\(_3\) host is longer than that in Y\(_2\)O\(_3\), which facilitates an enhanced energy storage for a high-power laser [27]. In continue-wave (CW) operation, Yb:(Y\(_{1-x}\)La\(_x\))\(_2\)O\(_3\) (x = 0.1) laser with 52% slope efficiency has been reported by Zhang et al. [18]. Mode-locking regime are also demonstrated by Li et al. [28] at 1032.5 nm with average power of 162 mW, but with relative long pulse width of 174 ps. In this letter, we report a diode-pumped passively mode-locked Yb:(Y\(_{0.9}\)La\(_{0.1}\))\(_2\)O\(_3\) ceramic sub-picosecond laser, laser pulse as short as 730 fs was obtained at the central wavelength of 1033 nm. Under the 6 W pump power, the output power is 92 mW.
2. EXPERIMENTAL SETUP AND RESULTS

Figure 1 shows the absorption and fluorescence spectra of the Yb:(Y\textsubscript{0.9}La\textsubscript{0.1})\textsubscript{2}O\textsubscript{3} ceramic at the room temperature (the exciting light of 940 nm was filtered out).

It can be seen from the figure, there are three main absorption peaks overlapping with each other to some extent in 850–1050 nm broad absorption band, with the center wavelengths at 909, 951, and 977 nm, respectively. The bandwidth (FWHM) of each absorption peak is larger than 10 nm. The absorption cross section at the wavelength of 977 nm is $0.61 \times 10^{-20}$ cm\textsuperscript{2}, the other two are about $0.49 \times 10^{-20}$ cm\textsuperscript{2} and $0.62 \times 10^{-20}$ cm\textsuperscript{2} for 909 and 951 nm, respectively. As a result, it is suitable for diode laser pumping. While there are two main emission peaks in the broad emission spectrum, with the center wavelengths at 1032 and 1075 nm, and the bandwidths (FWHM) of each emission peak are 20 and 24 nm, respectively, both support to generate sub-100 fs laser pulse in theory. Although the emission spectrum is similar to that of the Yb:Y\textsubscript{2}O\textsubscript{3} ceramics, both the emission cross sections of $1.0 \times 10^{-20}$ cm\textsuperscript{2} at 1032 nm and $0.7 \times 10^{-20}$ cm\textsuperscript{2} at 1078 nm are larger than that of the Yb:Y\textsubscript{2}O\textsubscript{3} ceramics [29].

The experimental schematic of the laser cavity and pumping geometry is shown in Fig. 2. We used a 5 at\%-doped Yb:(Y\textsubscript{0.9}La\textsubscript{0.1})\textsubscript{2}O\textsubscript{3} ceramic sample as the gain medium at Brewster-angle configuration (with no antireflection-coatings on both surfaces), which is 2 mm in long and $4 \times 3$ mm\textsuperscript{2} in aperture. To remove the heat load efficiently, the gain medium was placed in contact with a water-cooled copper mount at the set temperature of 9°C. A 7 W high brightness fiber-coupled diode laser emitting at 976 nm (Jenoptik, JOLD-7.5-BAFC-105) was used to end-pump the laser medium. The pump laser output from the fiber (with 50 µm core diameter and 0.22 numerical aperture) was coupled into the laser medium by a coupling system. The operating temperature of the pump laser was set to be 22°C in order to obtain stable laser output at the wavelength of 977 nm. The mode-locking experiment was carried out with a standard Z-fold cavity. M1 is a plane dichroic mirror with high transmission at 976 nm and high reflection at 1020–1200 nm; M2, M3, and M4 are concave mirrors with radii of curvature of 200 mm.

Passive mode-locking was started with a commercially available semiconductor saturable absorber mirror (SESAM) (BATOP GmbH), which has a modulation depth of 0.4% near 1040 nm, a saturation inten-

![Fig. 1. Room-temperature absorption and fluorescence spectra of Yb:(Y\textsubscript{0.9}La\textsubscript{0.1})\textsubscript{2}O\textsubscript{3} ceramic.](image1)

![Fig. 2. (Color online) Schematic diagram of the mode-locked Yb:(Y\textsubscript{0.9}La\textsubscript{0.1})\textsubscript{2}O\textsubscript{3} ceramic laser: LD, high brightness fiber coupled laser diode; M1, a plane dichroic mirror; M2, M3, and M4, concave mirrors with ROC of 200 mm; OC, output coupler.](image2)
sity of 120 µJ/cm², a nonsaturable loss of less than 0.3% and a relaxation time of less than 500 fs. The output coupler (OC) was selected to be a plane-wedged mirror with a transmission rate of 0.8%. To obtain the femtosecond laser operation, two Gires–Tournois interferometer (GTI) mirrors and a chirped mirror (Layertec GmbH) were used to introduce negative dispersion in order to compensate the positive dispersion inside the cavity. One of the GTI mirrors provides a second-order dispersion compensation of about $-1000 \pm 100$ fs² per bounce in the spectral range of 1030 to 1050 nm; the other one provides $-1300 \pm 200$ fs² per bounce, and the chirped mirror provides $-120 \pm 20$ fs² from 1000 to 1100 nm. The total cavity length was about 2.29 m, corresponding to a repetition rate of 65.5 MHz.

Figure 3 shows the dependence of the output on the incident pump power. The threshold of the laser action is about 2 W. When the pump power was exceeding 2.5 W, the laser changed from the Q-switched mode-locked regime (QML) to the CW mode-locked regime. A stable CW mode-locked operation was obtained by increasing the incident pump power. The maximum output power was 92 mW under the 6 W pumping. The calculated average slope efficiency is 2.2%. Because the efficiency of the couple system is only 90% and Brewster-angle configuration introduces large loss to the pumping laser, thus only 75% of the pump power is absorbed by the gain medium and leads to relatively low efficiency.

The pulse trains recorded with an oscilloscope are shown in Fig. 4. The intensity autocorrelation trace of the mode-locked pulses was measured by using a commercial noncollinear autocorrelator (FR-103MN, Femtochrome Research, Inc.). As presented in Fig. 5a, the FWHM width of the autocorrelation trace

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**Fig. 3.** Relationship between output and incident pump powers (the average slope efficiency is 2.2%, shown as the straight line).

**Fig. 4.** (Color online) Pulse trains observed with two different time scales: (a) 20 ns/div; (b) 20 µs/div.

**Fig. 5.** (Color online) (a) Intensity autocorrelation traces of the mode-locked laser pulses. The experimental data is shown by the black solid curve, while the sech²-fitting curve is shown by the red dash curve. (b) The spectrum of mode-locked operation.
was about 1125 fs. If a sech2-pulse shape was assumed, the mode-locked pulse duration was 730 fs. The corresponding spectrum of the pulse is described in Fig. 5b, which has a FWHM bandwidth of 1.9 nm at the central wavelength of 1033 nm. The time-bandwidth product is calculated to be 0.389, which is slightly larger than the Fourier transform limit for a sech2 pulse. To our knowledge, this is the first time to achieve the mode-locked sub-picosecond laser operation at 1033 nm by using the Yb:(Y0.9La0.1)2O3 ceramics.

3. CONCLUSIONS

In conclusion, we have demonstrated a diode-pumped passively mode-locked Yb:(Y0.9La0.1)2O3 ceramic sub-picosecond laser. The Yb:(Y0.9La0.1)2O3 ceramic is 2 mm in thickness and 5 at % Yb3+ doping. A maximum output power of 92 mW was obtained at central wavelength of 1033 nm with a repetition rate of 65.5 MHz. The pulse duration is as short as 730 fs. Our experiment demonstrate that the Yb:(Y0.9La0.1)2O3 ceramic is a promising laser medium for diode-pumped ultrafast lasers. We believe that, if we could choose a proper length of the ceramic and doping concentration, further optimize the laser performance conditions, and appropriately compensate the dispersion by other kinds of solution, the even higher power and shorter pulse may be possible, and it will be our future works.

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REFERENCES