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Diode-pumped Kerr-lens mode-locked femtosecond Yb:YAG ceramic laser*

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We experimentally demonstrated a diode-pumped Kerr-lens mode-locked femtosecond laser based on an Yb:YAG ceramic. Stable laser pulses with 97-fs duration, 2.8-nJ pulse energy, and 320-mW average power were obtained. The femtosecond oscillator operated at a central wavelength of 1049 nm and a repetition rate of 115 MHz. To the best of our knowledge, this is the first demonstration of a Kerr-lens mode-locked operation in a diode-pumped Yb:YAG ceramic laser with sub-100 fs pulse duration.

Keywords: diode pump, Yb:YAG ceramic, Kerr-lens mode-locking

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1. Introduction

In recent years, there has been a growing interest in diode-pumped all-solid-state ultrafast laser with short pulse duration, high average output power, high efficiency and high reliability for many applications, including optical frequency comb, ultrafast nonlinear spectroscopy, femtosecond optical coherent tomography, and superfine material processing. Among the various Yb^{3+}-based lasers,[1–3] Yb:YAG laser plays an important role, owing to the excellent thermal and optical properties of Yb:YAG crystal. Since the first room-temperature diode-pumped Yb:YAG laser was reported,[4] intensive continuous wave (CW) and mode-locked Yb:YAG lasers have been studied.[5–9] With the help of semiconductor saturable absorber mirrors (SESAMs),[10] femtosecond pulses with durations of 540 fs[5] and 340 fs[7] were obtained from a diode-pumped Yb:YAG laser. However, Yb:YAG crystal has a sharp and narrow emission spectrum band at a central wavelength of 1030 nm, and as a result, the pulse duration was limited to several hundreds of femtoseconds. By transferring the central wavelength from 1030 nm to 1050 nm, a broader wavelength bandwidth was expected to be excited to support the shorter pulse duration. The 136 fs[8] and 170 fs[9] pulses were generated from a passively mode-locked Yb:YAG laser in this way. By using the Kerr-lens mode-locking (KLM),[11] sub-100 fs pulses from Yb:YAG laser have been demonstrated.[12,13] Pulses as short as 35 fs with an average power of 107 mW were obtained from a diode-pumped KLM Yb:YAG laser.[13]

On the other hand, by employing the vacuum sintering technique and nanocrystalline technology,[14,15] high-quality, transparent Yb:YAG ceramics have manifested their unique advantages, such as high-doping concentration, capability of large-size fabrication, low cost, mass production, and multilayer and multifunctional components compared with the Yb:YAG crystals. It is desirable to realize high-power, high-intensity lasers based on Yb:YAG ceramics. Up to now, many experimental studies of continuous wave (CW) and mode-locked laser performances have been conducted.[15–22] The first laser action was reported in 2003, delivering a CW average output power of 345 mW with a slope efficiency of 26%.[15] Later, Yoshioka *et al.* successfully demonstrated the first passive mode-locking operation with an Yb:YAG ceramic, generating 233 fs pulses with an average output power of 20 mW.[20] They also reported dual-wavelength mode locking simultaneously at 1033.6 nm and 1047.6 nm based on the Yb:YAG ceramic in 2010.[21] With 3.5-W absorbed pump power, Zhou *et al.* realized unprecedented high-efficiency femtosecond mode-locking with the Yb:YAG ceramic, generating 1.9-W average power with 76% slope efficiency.[22] To date there has been no report on sub-100-fs laser pulse generation from an Yb:YAG ceramic by either passive mode-locking or KLM technique.

In this paper, we report on a diode-pumped Kerr-lens mode-locked Yb:YAG ceramic oscillator. Laser pulses as short as 97 fs are generated from a KLM Yb:YAG ceramic laser. The femtosecond oscillator operating at a repetition rate of 115-MHz delivers an average output power of 320 mW. The spectral bandwidth of the KLM pulses reaches 13 nm at a central wavelength of 1049 nm. This is, to the best of our

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knowledge, the first demonstration of a Kerr-lens mode-locked Yb:YAG ceramic laser and the shortest pulses generated from the Yb:YAG ceramic laser so far.

2. Experimental setup and results

In a preliminary experiment, the laser performance of the Yb:YAG ceramic was investigated with a three-mirror folded cavity. Figure 1 shows the schematic setup of the CW laser and wavelength tuning experiment. The Yb:YAG ceramic with an Yb^{3+} concentration of 10 at.% had a thickness of 3 mm with an aperture of 4 mm×4 mm. Both faces were anti-reflection coated for both the pump and laser wavelengths. The Yb:YAG ceramic was wrapped with an indium film and placed on a water-cooled copper mount maintained at 10 °C. The pump source was a fiber-coupled laser diode (LD) with a fiber core diameter of 100 μm and a numerical aperture of 0.22. The LD emits at a central laser wavelength of 970 nm at room temperature. The diverging pump beam from the fiber output was focused into the laser ceramic by a coupling system with a magnification of 1:0.8, resulting in a focusing spot diameter of about 80 μm. The Yb:YAG ceramic was placed between a dichroic plane mirror and a curved folding mirror with a radius of curvature (ROC) of 200 mm. In the case of CW laser operation, an output coupler (OC) with a transmission of 2.5% at 1000 nm–1100 nm was used. The nonlasing pump power absorption rate was measured to be 43.1% for the 3-mm 10-at.% Yb^{3+}-doping ceramic. The dependence of the CW output power on the absorbed pump power is illustrated in Fig. 2(a). The maximum output power reached 2.62 W at a central wavelength of 1050 nm under an absorbed pump power of 6.03 W, corresponding to a slope efficiency of 50.5%. Using a single prism inserted in the cavity to tune the laser wavelength, we characterized the wavelength tuning property of the Yb:YAG ceramic. An SF6 prism with an apex angle of 58.8° was employed in the experiment. Under an absorbed pump power of 2.11 W, the laser wavelength could be tuned from 1030 nm to 1085 nm for an OC of 0.8% transmission at 1000 nm–1100 nm. The broad tuning range over 55 nm indicates the potential of the Yb:YAG ceramic to generate ultrashort mode-locked pulses. Moreover, laser action below 1030 nm was suppressed due to reabsorption of our 3-mm thick, 10-at.% doping Yb:YAG ceramic,[22] giving us a chance to achieve mode-locking at 1050 nm for shorter pulse generation.

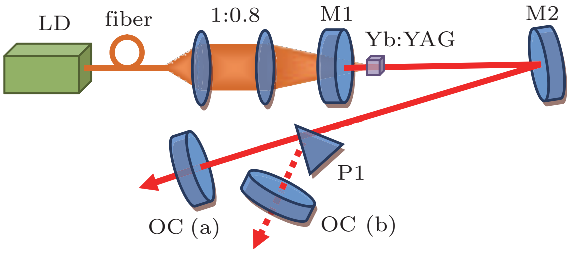

Fig. 1. (color online) Schematic diagram of the continuous wave (with OC (a)) and wavelength tuning (with OC (b)) experiments with the Yb:YAG ceramic. LD: fiber-coupled laser diode; M1: dichroic plane mirror; M2: concave mirror with ROC of 200 mm; P1: SF6 prism; OC: output coupler.

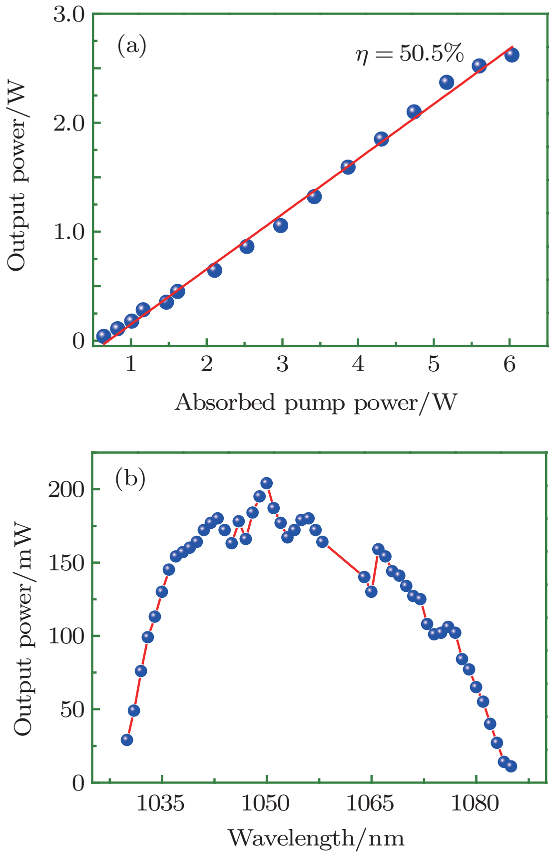

Fig. 2. (color online) (a) CW average output power as a function of the absorbed pump power, and (b) wavelength tuning curve of the Yb:YAG ceramic with a 0.8% transmittance OC under an absorbed pump power of 2.11 W.

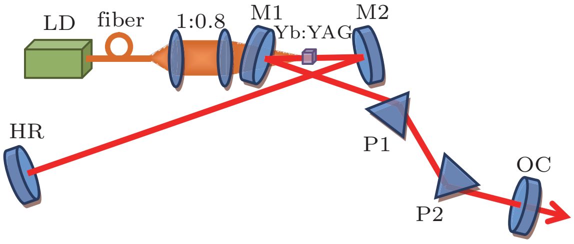

Fig. 3. (color online) Schematic diagram of the diode-pumped Kerr-lens mode-locked Yb:YAG ceramic laser. LD: fiber-coupled laser diode; M1 and M2: concave mirrors with ROC of 75 mm; HR: plane high reflection mirror; P1 and P2: a pair of SF6 prisms; OC: output coupler.

In the experiment of KLM operation, a standard X-folded linear cavity was employed. Figure 3 shows the schematic of the overall experimental setup. The Yb:YAG ceramic was positioned between two curved folding mirrors with an ROC of 75 mm. Both curved folding mirrors (M1 and M2) were plane-concave dichroic mirrors coated with a high transmission of more than 98% at 970 nm and a high reflection rate of more than 99.9% at 1020 nm–1200 nm. A high-reflective mirror (HR), coated with a high reflection rate of more than 99.9% in the 1020 nm–1200 nm range, was used as an end mirror of the cavity. A pair of SF6 prisms was used to compensate for the chirp of the Yb:YAG ceramic. To increase the intracavity laser power, an output coupler with 0.8% transmittance at 1020 nm–1200 nm was used to couple out the laser power.

At first, we adjusted the cavity in order to generate the highest CW output power. Under an absorbed pump power of 5.4 W, the maximum average output power was 370 mW. Subsequently, we finely adjusted the position of mirror M2 to the stability edge of the cavity. When the absorbed pump power exceeded 4.9 W, a stable Kerr-lens mode-locking operation was obtained by slightly translating the end mirror. Once mode-locked, the average output power increased from 283 mW to 303 mW. The Kerr-lens mode-locked pulse train was detected by a fast photodiode and recorded with a digital storage oscilloscope. Figure 4 shows the mode-locked pulse trains at 10 ns/div and 1 ms/div respectively; the stability is very good without any modulation. Figure 5 shows the dependences of the output power on the absorbed pump power under CW and KLM operations, respectively. Stable mode-locking could be sustained until the absorbed pump power reached 5.4 W. At this point, the maximum output power reached 320 mW. The KLM operation became unstable by increasing the absorbed pump power. In order to optimize the chirp compensation, we precisely adjusted the distance between the two prisms and the insertion. For the best performance, the tip-to-tip distance of the SF6 prism pair was set to be 237 mm, introducing group delay dispersion (GDD) of about -1620 fs^2 at 1049 nm. Considering the normal GDD of about 390 fs^2 introduced by the 3-mm insertion of the prisms and the material dispersion of about 190 fs^2 by the Yb:YAG ceramic, the net GDD in the cavity was about -2080 fs^2 per round trip. Using a commercial intensity autocorrelator (APE: PulseCheck USB), we measured the intensity autocorrelation traces of the KLM pulses as shown in Fig. 6(a). Assuming a sech^2-pulse shape, the duration of the KLM pulses was 97 fs. The corresponding spectrum is shown in Fig. 6(b). The full width at half maximum (FWHM) of the spectrum is about 13 nm at a central wavelength of 1049 nm. The corresponding time-bandwidth product is about 0.344, close to the Fourier transform limit of 0.315 for sech^2-shape pulses.

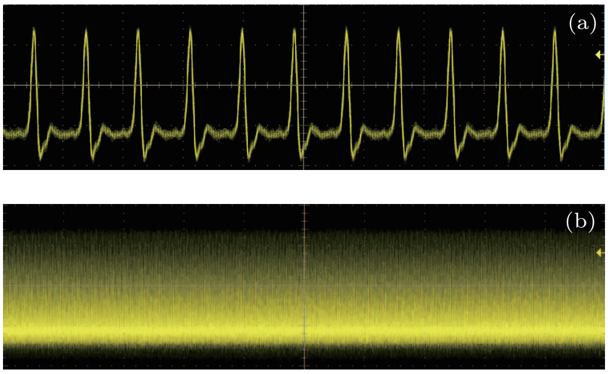

Fig. 4. (color online) Kerr-lens mode-locked pulse trains at (a) 10 ns/div and (b) 1 ms/div.

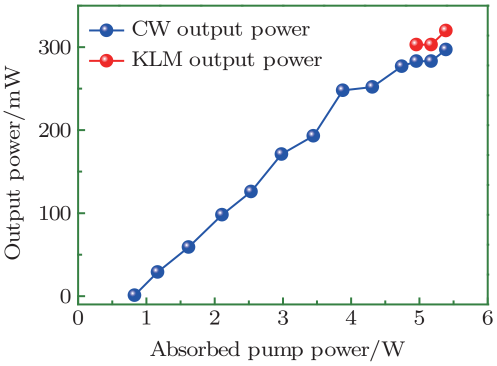

Fig. 5. (color online) Average output powers of the Yb:YAG ceramic laser each as a function of absorbed pump power for both CW operation and KLM operation, respectively.

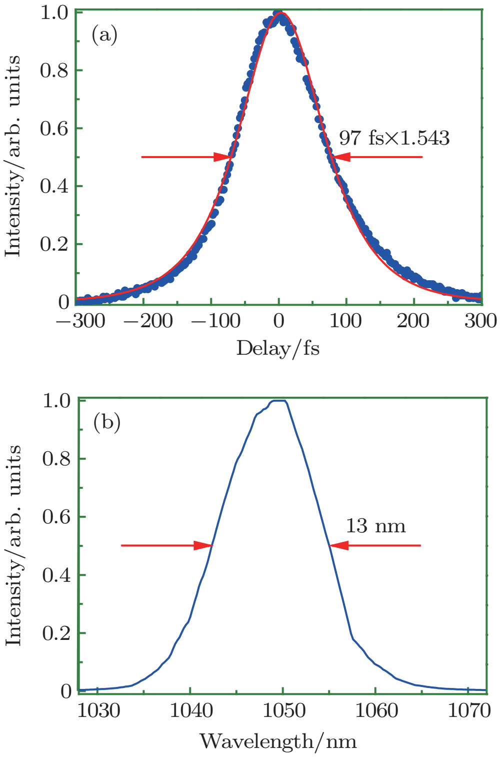

Fig. 6. (color online) (a) Autocorrelation traces of the Kerr-lens mode-locked pulses (blue dotted curve) with a sech^2 fitting (red solid curve), and (b) the corresponding mode-locking spectrum.

3. Conclusions

In this paper, we demonstrate the first sub-100-fs pulse generation from a diode-pumped Kerr-lens mode-locked Yb:YAG ceramic laser. The laser pulse duration is as short as 97 fs at a central wavelength of 1049 nm. The average output power is 320 mW under an absorbed pump power of 5.4 W. To the best of our knowledge, this is the first time Kerr-lens mode-locking operation has been realized in an Yb:YAG ceramic. In terms of their advantages, Yb:YAG ceramic is a promising candidate for constructing the high-power femtosecond laser amplifiers with sub-100 fs pulse duration.

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