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Generation of 85 fs laser pulses from a diode-pumped Kerr-lens mode-locking $Yb{:}(Y_{0.9}La_{0.1})_2O_3$ ceramic laser

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Abstract

We experimentally demonstrated a stable diode-pumped Kerr-lens mode-locking femtosecond laser with a Yb^{3+}-doped yttrium lanthanum oxide ceramic. Pulses as short as 85 fs at a central wavelength of 1074.5 nm were obtained at a repetition rate of 118 MHz. The average output power was 80 mW under a 4 W diode pump power. To the best of our knowledge, this is the first demonstration of a Kerr-lens mode-locked operation in a Yb^{3+}-doped yttrium lanthanum oxide ceramic laser with a sub-100 fs pulse width.

Keywords: $Yb{:}(Y_{0.9}La_{0.1})_2O_3$ ceramic, Kerr-lens mode-locking, laser diode

(Some figures may appear in colour only in the online journal)

1. Introduction

In recent years, the interest in compact, efficient and robust femtosecond lasers has been motivated by the fact that they have increasing scientific and industrial applications, such as in optical frequency combs, femtosecond optical coherent tomography, cutting thin silicon substrates, and processing for fine structures. Until now, the Ti:sapphire laser is the most developed laser system in the ultrafast laser regime. However, the Ti:sapphire laser system requires a complicated and expensive green laser as a pump, which limits its wide application either in scientific research or in industry. On the other hand, with the rapid development of semiconductor InGaAs laser diodes, they have been widely used as direct pump sources in various all-solid-state lasers benefitting from their high power, high brightness, compact size, long life and much lower cost. In the ultrafast laser regime, the Yb^{3+}-based laser has attracted much attention. First of all, the absorption bands of the Yb^{3+}-doped laser materials match well with the emission bands of the high power laser diode in a near infrared wavelength. Secondly, Yb^{3+}-doped laser materials also possess numerous excellent characteristics, such as no excited state absorption, no cross relaxation, a broad absorption and emission bandwidth, a small quantum defect and low thermal loading. In recent years, various kinds of Yb^{3+}-doped lasers realized mode-locking operations either with the help of saturable absorbers such as semiconductor saturable absorber mirrors (SESAM) [1–4], single wall carbon nanotubes (SWCNT) [5–8], grapheme [9, 10], graphene oxide [11], or by means of Kerr-lens mode-locking (KLM) [12]. KLM is a promising technique in diode-pumped solid state Yb^{3+} lasers for generating sub-100 fs pulses. Up to now, there have been several reported experiments on KLM operation of diode-pumped Yb^{3+} lasers at the sub-100 fs level, such as $Yb{:}YVO_4$ [13], Yb:YAG [14], Yb:YGG [15], $Yb{:}CaF_2$ [16], and Yb:KGW [17], $Yb{:}Sc_2O_3$ [18], $Yb{:}Lu_2O_3$ combined with nondoped Y_2O_3 [19], $Yb{:}Lu_2O_3$ [20] and so on.

Yb^{3+}-doped sesquioxide Re_2O_3 (Re=Y, Sc, and Lu) crystalline materials are very attractive materials for high power laser

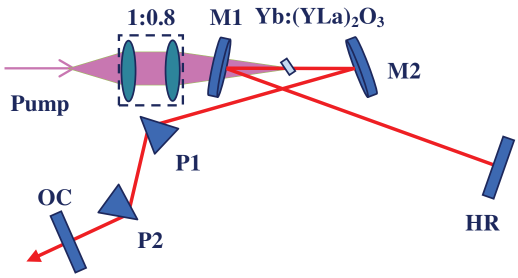

Figure 1. Schematic of the experimental setup. M1 and M2: curved high reflection mirrors with ROC=75 mm; HR: high reflection plane mirror; P1 and P2: SF6 prisms; OC: output coupler.

and ultrashort laser operation due to their excellent thermal conductivities and broad fluorescence spectra. Among them, Y_2O_3 has outstanding optical and thermal properties with a low phonon energy and high thermal conductivity compared to YAG [21]. However, a high-quality large-size Y_2O_3 single crystal is difficult to obtain using common growth methods because the melting temperature for a Y_2O_3 single crystal is as high as 2430 °C, and the structural phase transition temperature is at about 2280 °C. The transparent Y_2O_3 ceramic could be fabricated at a relatively low sintering temperature of 1700 °C [22], which is about 700 °C lower than the melting point of the Y_2O_3 single crystal. When La_2O_3 was added as a sintering aid in Y_2O_3 to form a Yb:$(Y_{1-x}La_x)_2O_3$ ceramic, the sintering temperature of the Yb:$(Y_{1-x}La_x)_2O_3$ ceramic was decreased to 1450–1650 °C [23], thereby shortening the fabrication time and reducing the cost of the production. The first mode-locking experiment with a Yb:$(Y_{0.9}La_{0.1})_2O_3$ ceramic was demonstrated by W. Li *et al* resulting in 174 ps pulses at a central wavelength of 1032.5 nm with an average output power of 162 mW [24]. Femtosecond passive mode-locking was first demonstrated by Z. L. Wang *et al* 730 fs pulses at a central wavelength 1033 nm were generated, and the average output power of the femtosecond laser was 92 mW [25]. Recently, 357 fs pulses with an average power of 670 mW were obtained with a Yb:$(Y_{0.9}La_{0.1})_2O_3$ ceramic by using a SESAM [26]. All the experiments reported above rely on SESAMs for initiating mode-locking and the pulse duration is far beyond 100 fs. Sub-100 fs pulses from a Yb:$(Y_{0.9}La_{0.1})_2O_3$ ceramic laser have not been reported so far.

In this letter, we report on a diode-pumped KLM femtosecond Yb:$(Y_{0.9}La_{0.1})_2O_3$ ceramic laser. Pulses as short as 85 fs at a repetition rate of 118 MHz were obtained. The full width at half maximum (FWHM) bandwidth of the laser spectrum was 17 nm at a central wavelength of 1074.5 nm. The maximum average output power was 80 mW under 4 W of pumping power. To the best of our knowledge, this is the first demonstration of a KLM Yb:$(Y_{0.9}La_{0.1})_2O_3$ ceramic laser with a sub-100 fs pulse duration.

2. Experimental setup

In our experiment, the high quality Yb:$(Y_{0.9}La_{0.1})_2O_3$ ceramic is the same as described in [26]. The overall experimental setup is described in figure 1. The Yb:$(Y_{0.9}La_{0.1})_2O_3$ ceramic was wrapped with an indium film and placed on a water-cooled copper mount at 14 °C. A 7 W high-brightness fibre-coupled diode laser emitting at 976 nm (Jenoptik, JOLD-7.5-BAFC-105) was used to end pump the laser ceramic. The diverging pump laser from the fibre (NA = 0.22, 50 μm core diameter) was focused into the ceramic by a coupling system with a magnification of 0.8, thereby resulting in a diameter in the ceramic of about 40 μm. The laser cavity was designed as an astigmatically compensated X-type cavity. The Yb:$(Y_{0.9}La_{0.1})_2O_3$ ceramic was positioned at Brewster's angle between two curved folding mirrors (M1 and M2) with a radius of curvature (ROC) of 75 mm. The output coupler had a transmission rate of 0.8% (1020 nm–1100 nm). Two SF6 prisms with a tip-to-tip distance of 261 mm were used to introduce a negative group delay dispersion of about −1500 fs^2 for the chirp compensation of the Yb:$(Y_{0.9}La_{0.1})_2O_3$ ceramic. The total cavity length was 1.27 m, corresponding to a repetition frequency of 118 MHz. Based on the above design and the ABCD matrix calculation, the laser beam waist diameters in the laser ceramic were 40 μm × 39 μm.

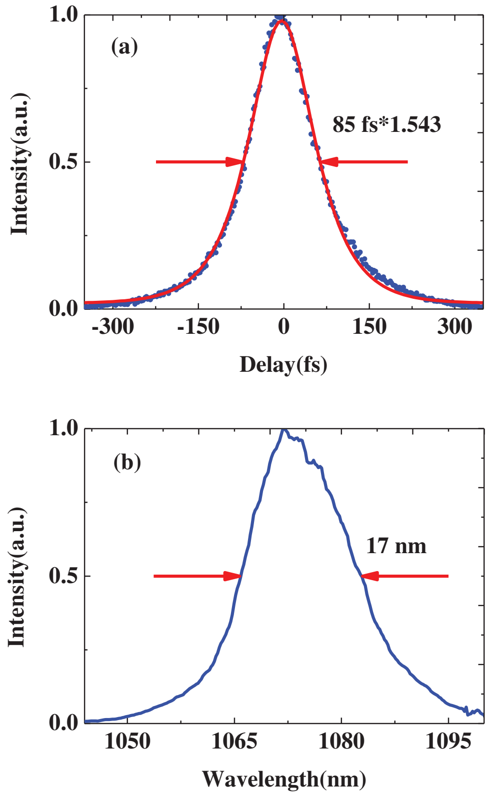

Figure 2. (*a*) Autocorrelation trace of the femtosecond pulses (blue dotted curve) with a sech^2 fitting (red solid curve). (*b*) The corresponding spectrum of the mode-locked pulses.

3. Experimental results and discussion

At first, we optimized the CW performance of the laser cavity. The maximum average output power was 250 mW under a pump power of 4 W. In order to realize KLM operation in the diode pumped Yb ceramic laser, two measures were taken. Firstly, we carefully designed the mode match between the

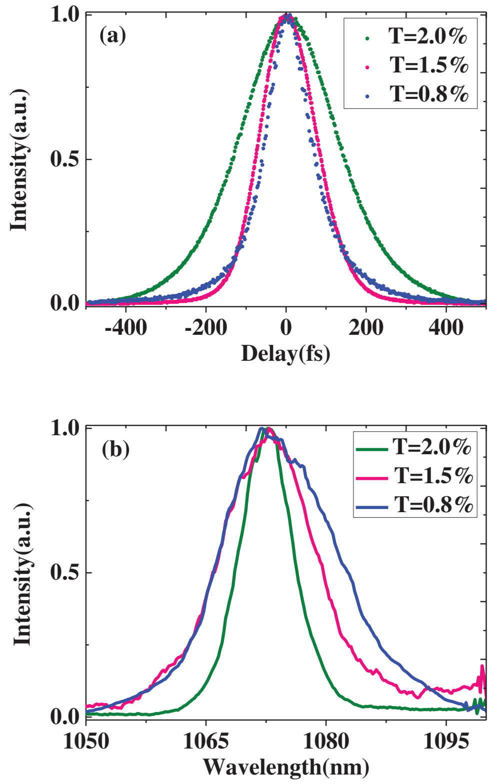

Figure 3. (*a*) Autocorrelation traces of the Kerr-lens mode-locked pulses under three different transmissions ($T = 0.8\%$, 1.5% and 2.0%, respectively). (*b*) The corresponding spectra of the Kerr-lens mode-locked pulses under three different transmissions ($T = 0.8\%$, 1.5% and 2.0%, respectively).

pump and the resonator in the crystal through the use of tight focusing with two curved mirrors with ROC of 75 mm. Next, as we know, the KLM operation was very sensitive to the cavity alignment, so we patiently adjusted the position of the curved mirror M2 to the edge of the stable region of the cavity. At this point the CW average output power dropped to about 70 mW. The resonator was in an almost unstable state and not fully astigmatically compensated in the CW operation at this position. Then the KLM operation was obtained by a fast translation of the HR mirror. Once mode-locked, the average output power increased to 80 mW. In order to get a shorter pulse duration, we precisely adjusted the insertion of the prism P2. Figure 2(*a*) shows the autocorrelation trace of the KLM pulses. The autocorrelation trace has a FWHM of 131 fs, corresponding to a 85 fs pulse duration if a $sech^2$-pulse shape was assumed. The corresponding spectrum is shown in figure 2(*b*). The FWHM bandwidth of the spectrum was about 17 nm at a central wavelength of 1074.5 nm. The corresponding time-bandwidth product of 0.375 was close to the Fourier transform limit of the $sech^2$-pulse.

In addition, we investigated the influence of the output couplers of different transmission on the performance of the KLM regime. We recorded the pulse duration, the corresponding spectrum, and the average output power at different output couplers with transmissions of 0.8%, 1.5% and 2.0%, respectively. Figure 3 shows the autocorrelation traces and the corresponding spectra of the KLM pulses under three different transmissions. The bandwidth (FWHM) of the autocorrelation traces were 131 fs, 164 fs, and 289 fs, repectively, for output couplers with transmissions of 0.8%, 1.5% and 2.0%, respectively, corresponding to the pulse durations of 85 fs, 106 fs, and 187 fs, respectively, by $sech^2$-fitting. The corresponding maximum output powers were 80 mW, 120 mW, and 260 mW, respectively, under pump powers of 4 W, 4.9 W, and 6 W, respectively. The bandwidths (FWHM) of corresponding spectra were about 17 nm, 13.4 nm and 8 nm, respectively, at central wavelengths of 1074.5 nm, 1072.8 nm and 1072.5 nm, respectively. The above experimental results indicate that the mode-locked pulse duration reduces with a smaller transmission of the OC at the expense of a smaller output power. The time-bandwidth products were 0.375, 0.363, and 0.367, respectively, closing to the Fourier transform limit of the $sech^2$-pulse.

4. Conclusion

In conclusion, we have presented the first experimental demonstration of a diode-laser pumped KLM Yb:$(Y_{0.9}La_{0.1})_2O_3$ ceramic laser. Pulses as short as 85 fs at a central wavelength of 1074.5 nm and an average output power of 80 mW were obtained at a repetition rate of 115 MHz. These are also the shortest pulses generated from the Yb:$(Y_{0.9}La_{0.1})_2O_3$ ceramic laser up to now. In addition, we compared the performance of the KLM operation under three different transmissions at different pump powers. With a 2% OC, 189 fs pulses with an average power of 260 mW were obtained. The experiment shows that the Yb:$(Y_{0.9}La_{0.1})_2O_3$ ceramic is an excellent laser material for the generation of sub-100 fs pulses. We believe that sub-50 fs pulses should be possible by using a smaller transmission output coupler as well as careful chirp compensation with chirped mirrors.

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