Generation of 73 fs pulses from a diode pumped Kerr-lens mode-locked Yb:YCa$_4$O(BO$_3$)$_3$ laser

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We realized a stable Kerr-lens mode-locked operation in a Yb:YCa$_4$O(BO$_3$)$_3$ laser. Pulses as short as 73 fs were generated at the central wavelength of 1043 nm, with a bandwidth of 19 nm. The femtosecond oscillator operating at a repetition rate of 110 MHz delivers an average output power of 70 mW under 3 W diode pump power. To the best of our knowledge, this is the first demonstration of a pure Kerr-lens mode-locked operation in a diode-pumped Yb:YCa$_4$O(BO$_3$)$_3$ laser. © 2014 Optical Society of America

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With the rapid development of diode-pumped ultrafast lasers in recent years, it has opened many new applications in scientific research and industry due to its high efficiency, compact size, and low cost. In particular, Yb^{3+}-doped materials have shown to be ideal candidates as gain media for many advantages, such as no excited state absorption, no cross-relaxation, long fluorescence, broad emission bands, and less quantum defect. By using a semiconductor saturable absorber mirror (SESAM) for passive mode-locking, stable laser pulses with sub-100-fs duration have been widely demonstrated with Yb^{3+}-doped materials, such as Yb:glass [1], Yb:Sr$_3$Y(BO$_3$)$_3$ [2], Yb:CaGdAlO$_4$ [3], Yb:LuVO$_4$ [4], Yb:NaY(WO$_4$)$_2$ [5], Yb:CaF$_2$ [6], and Yb:YCa$_4$O(BO$_3$)$_3$ [7,8]. Kerr-lens mode-locking (KLM) is another well-developed technique for generating ultrashort femtosecond pulses [9–11]. It does not impose any bandwidth limitation, and the obtainable pulse width is limited only by the gain bandwidth of the active mediums and dispersion bandwidth of the laser cavity. Hence, it has the advantage of producing shorter pulses than with a SESAM. Until now, sub-100 fs pulses have been generated in some Yb^{3+}-doped materials by KLM, such as Yb:KY(WO$_4$)$_2$ [12], Yb:YVO$_4$ [13], Yb:Lu$_2$O$_3$ [14], Yb:Sc$_2$O$_3$/Yb:Y$_2$O$_3$ [15], Yb:LuScO$_3$ [16], Yb:CaF$_2$ [17], and Yb:Y$_3$Ga$_5$O$_{12}$ [18].

Among all available Yb^{3+}-doped materials, Yb^{3+}-doped YCa$_4$O(BO$_3$)$_3$ (Yb:YCOB) has attracted the most attention until now, because it exhibits a large ground-state splitting of 1000 cm^{-1} of the ground-state manifold ($^2F_{7/2}$), which is greater than many other Yb^{3+}-doped materials, and its fluorescence lifetime is as long as 2.20 ms [19], which is one of the longest upper-state lifetimes observed for Yb^{3+}-doped oxide crystals [20]. The ~100 nm emission bandwidth indicates it has potential to generate ultrashort pulses with less than 50 fs duration [7,19,21]. The first mode-locked Yb:YCOB laser generated 210 fs pulses by using an ion-implanted saturable-absorber mirror for passive mode-locking [22]. Then 42 fs pulses were generated with a SESAM [7]. The pulse width was further shortened to 35 fs by external compression [8]. Although such short pulse is partially due to the Kerr lensing effect, it still relies on SESAM for initiating and stabilizing the mode-locked operation.

In this Letter, we demonstrate a pure KLM operation in a diode-pumped Yb:YCOB laser. By precisely adjusting the cavity alignment, pulses as short as 73 fs were produced with a bandwidth of 19 nm at the central wavelength of 1043 nm. The average output power was 70 mW under the pump power of 3 W at a repetition rate of 110 MHz. To the best of our knowledge, this is the first demonstration of a pure KLM Yb:YCOB laser.

In this experiment, the Yb:YCOB crystal was grown by the Czochralski method and cut along the x-axis with a Yb concentration of 20 at. %. The uncoated Yb:YCOB crystal was 2 mm thick, with an aperture of 3 mm× 3 mm. The polarized absorption spectrum (E//Y) and the unpolarized fluorescence spectrum of the Yb:YCOB crystal are shown in Figs. 1(a) and 1(b), respectively. The absorption spectrum is measured by a Fourier-transform infrared spectroscopy and the fluorescence spectrum by a monochromator with an excitation laser diode at 940 nm. The overall absorption bandwidth is from 850 to 1050 nm with peaks at 900 and 976 nm. The sharp 976 nm zero phonon line is highly suitable for diode pumping at room temperature. The coverage of the broad fluorescence spectral bandwidth is from 940 to 1110 nm, with very smooth spectral structure, which supports very short femtosecond pulses.

The overall experimental setup is described as shown in Fig. 2. 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 Yb:YCOB crystal. The pump beam from the fiber (with 50 μm core diameter and 0.22 NA) was focused into the Yb:YCOB crystal by a coupling system with a magnification of 0.8, resulting in a beam waist of about 20 μm measured by the knife-edge method. Based on the ABCD matrix calculation, the laser-beam waist in the crystal was 20 μm × 19 μm, well matching that of the pump beam. The 2-mm-thick Yb:YCOB crystal was wrapped with an indium foil and mounted tightly in a

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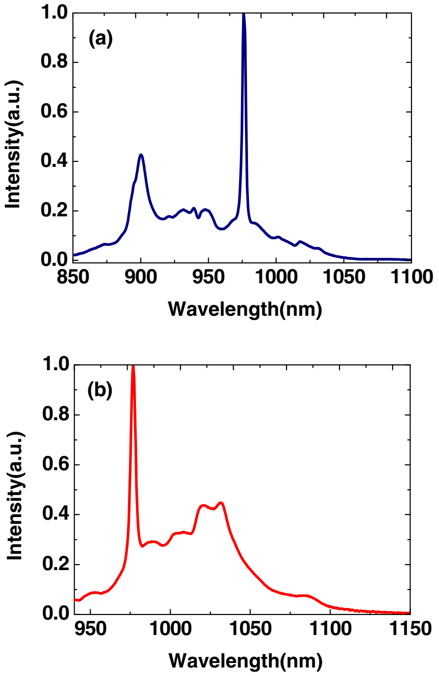

Fig. 1. (a) Absorption spectrum of the x-cut 20 at. % doped Yb:YCOB crystal at room temperature. (b) The corresponding fluorescence spectrum excited by a 940 nm diode.

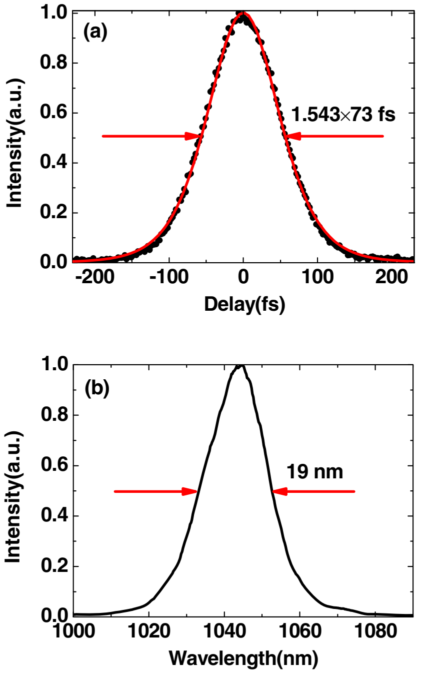

Fig. 3. (a) Autocorrelation trace of the KLM pulses (dotted curve) with a sech^2 fitting (red solid curve). (b) Spectrum of the KLM pulses.

water-cooled copper heat sink maintained at 12°C. The crystal was oriented for E//Y polarization and positioned at Brewster angle in the middle of the astigmatism compensated x-type cavity between two cured mirrors with 75 mm radius of curvature (ROC). For compensating the normal dispersion resulted from the crystal, a pair of SF6 prisms with a tip-to-tip distance of ~295 mm was inserted inside the cavity. The output coupler (OC) with transmission of 0.8% in the range of 1020–1200 nm was used for coupling out the laser. The total length of the cavity was about 1.36 m, corresponding to a repetition rate close to 110 MHz.

At first, we optimized the CW performance of the laser. Under the pump power of 3 W, a maximum output power of 120 mW was obtained at the central wavelength of 1040 nm. In order to get the KLM operation, we adjusted the position of the M2 mirror. The CW output power dropped down to 60 mW. At this position, the central wavelength of 1040 nm was split into three at 1030, 1040, and 1050 nm, respectively. Then a stable KLM was initiated by lightly shaking the HR mirror. The output power increased to 70 mW. Once mode-locked, a green beam behind the M2 mirror was clearly observed due to self-frequency-doubling in the Yb:YCOB crystal. The long time fluctuation of the output power was measured to be about 3% (RMS), which is mainly due to the air turbulence and lab vibration. Using a commercial intensity autocorrelator (APE: PulseCheck USB), we measured the intensity autocorrelation trace shown in Fig. 3(a). Assuming a sech^2-pulse shape, the pulse duration is 73 fs. The spectrum in Fig. 3(b) shows the pulses are centered at 1043 nm, with a full width at half-maximum (FWHM) bandwidth of 19 nm, corresponding to the time-bandwidth-product of 0.382.

It is well known that the Kerr-lens effect strongly depends on the laser intensity inside the crystal. Therefore, the pump power plays an important role for the stable KLM operation. In the experiment, we also investigated the pulse duration with respect to the average output power at the different pump powers. In the process of increasing the pump power, the oscillator was not adjusted. The results are displayed in Fig. 4. As the pump

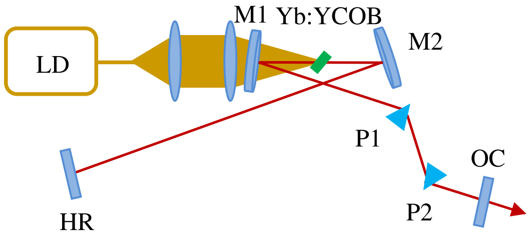

Fig. 2. Experimental setup of the KLM Yb:YCOB laser. LD, fiber-coupled laser diode; M1, M2, concave mirrors with ROC of 75 mm; HR, high reflection mirror; OC, plane output coupler with transmission $T = 0.8\%$; P1, P1, SF6 prisms.

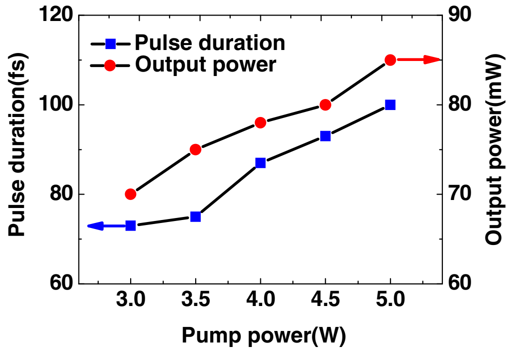

Fig. 4. Pulse duration and output power of the KLM Yb:YCOB laser as a function of the pump power.

power increased, the pulse duration became longer and the average output power became larger. When the pump power was 3 W, the shortest pulse duration of 73 fs was obtained with an output power of 70 mW. When the pump power increased to 5 W, the maximum output power slightly grew to 85 mW. The corresponding pulse duration was 100 fs. In fact, if we precisely adjust the oscillator in the process of increasing the pump power, the pulse duration could be shortened to 73 fs. However, in this case the output power reduced to 70 mW again. According to the result, we inferred that it's not easy to get short pulse duration and high output power simultaneously by simply increasing the pump power. We think that by using a thicker crystal (for example, 3 mm thickness) and higher transmission OC as well as fine dispersion compensation, short pulses with higher output power will be possible by the KLM scheme.

In conclusion, we have reported on a KLM operation of a diode-pumped Yb:YCOB laser. Laser pulses as short as 73 fs were obtained at the central wavelength of 1043 nm, with a spectral bandwidth of 19 nm. The average power is 70 mW under 3 W pump. Taking advantage of the broad bandwidth property of KLM, shorter pulses of sub-50-fs are expected to generate by carefully managing the cavity dispersion. Furthermore, due to the birefringent property of Yb:YCOB crystal, it should be possible to generate sub-100-fs pulses in the green by means of self-frequency doubling.

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