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Tunable second harmonic generation from a Kerr-lens mode-locked $Yb:YCa_4O(BO_3)_3$ femtosecond laser*

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We experimentally demonstrated a diode-pumped Kerr-lens mode-locked femtosecond (fs) laser with a self-frequency doubling $Yb:YCa_4O(BO_3)_3$ crystal. Sub-40 fs laser pulses were directly generated from the oscillator without extracavity compression. The central wavelength was tunable from 1039 nm to 1049 nm with a typical bandwidth of 35 nm and an average output power of 53 mW. For the first time, a self-frequency doubled second harmonic green laser with tunable range from 519 nm to 525 nm was observed.

Keywords: Kerr-lens mode-locking, lasers, ytterbium, laser, solid-state, harmonic generation

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1. Introduction

In the past decade, a great deal of effort towards solid-state lasers with broad spectral bandwidth, ultrashort pulse duration, and high output power has been attempted.[1–3] As we know, the most important techniques including passive mode-locking by semiconductor saturable absorber mirrors (SESAMs)[4–6] and Kerr-lens mode locking (KLM),[7–9] improved the performance of all solid-state lasers with regards to pulse duration, pulse spectral bandwidth, and pulse energy. In the 1-μm region, Yb^{3+}-doped materials are widely used in diode pumped solid-state lasers for generating sub-100-fs pulses. In 2006, pulse duration for the first time reached sub-50 fs by Zaouter *et al.*[10] By using SESAM, laser pulses as short as 47 fs with an average output power of 38 mW were generated from a $Yb:CaGdAlO_4$ (Yb:CALGO) oscillator. In 2011, by means of KLM, 35-fs laser pulses with an average output power of 107 mW were obtained from a Yb:YAG laser pumped by a laser diode.[11] In 2012, the tunable laser pulses of 40-fs with 31-nm bandwidth and 15-mW output power were obtained from a passively mode locked Yb:CALGO laser pumped by a 350-mW single-mode laser diode.[12] Recently, pumped by a polarized single-mode fiber laser, a KLM Yb:CALGO oscillator was realized delivering 32-fs pulse duration and 51-nm full width at half-maximum (FWHM) bandwidth.[13] This is the shortest pulse and the broadest spectrum from Yb-doped bulk materials. Pirzio *et al.* studied a mode-locking $Yb:CaYAlO_4$ (Yb:CALYO) laser by employing a 400-mW single-mode fiber-coupled laser diode as pump and a SESAM to start the mode-locking, 43-fs pulses with an optical spectra of 29 nm and an output power of 20 mW was delivered.[14] Most recently, based on a Yb:CALYO crystal, laser pulses as short as 33-fs with a spectral bandwidth of 49 nm were generated from a diode-pumped Yb:CALYO oscillator.[15]

Among the Yb^{3+}-doped materials, $Yb:YCa_4YO(BO_3)_3$ (Yb:YCOB) is widely recognized as excellent laser material in diode pumped solid state lasers for generating ultrashort pulses. Compared to Yb:CALGO and Yb:CALYO, Yb:YCOB exhibits the largest ground state splitting of $> 1000\ cm^{-1}$ and a longer fluorescence lifetime of 2.2 ms than other Yb^{3+}-doped oxide crystals.[16,17] Since Yb:YCOB has a monoclinic structure, its anisotropic spectral and laser characteristics were exhibited. All polarization configurations of Yb:YCOB have been studied in the CW laser regime, achieving a slope efficiency of 73%[18] and 83%.[19] In the CW operation, the widely tunable wavelength range from 997 nm to 1092 nm[17] and 1007 nm to 1100 nm[20] was obtained for $E \parallel X$ and $E \parallel Y$ polarizations, respectively, providing a potential to generate ultrashort femtosecond pulses. In 2000, the first passive mode-locking operation based on a Yb:YCOB crystal was demon-

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strated, delivering 210-fs laser pulses.[21] Benefiting from the broad and flat emission bandwidth, Yoshida *et al.* realized a 42-fs passively mode-locked Yb:YCOB laser by assistance of a SESAM.[22] In 2011, 35-fs pulses with the average output power of 36 mW were generated from a SESAM mode-locked Yb:YCOB oscillator.[23] Recently, we demonstrated a Kerr-lens mode-locked Yb:YCOB laser, generating 73-fs pulses at the central wavelength of 1042 nm.[24]

In this paper, we report the new results on the diode-pumped Kerr-lens mode-locked femtosecond laser operation based on the Yb:YCOB crystal. Employing a tight focusing cavity and precisely controlling the intracavity dispersion, sub-40-fs pulses were directly produced with an FWHM bandwidth of 35 nm at the central wavelength of 1049 nm. The average output power was 53 mW under the pump power of 4.4 W and the repetition rate was 140 MHz. To the best of our knowledge, these are the shortest pulses directly generated from a diode-pumped Kerr-lens mode-locked Yb:YCOB laser without extracavity compression. Due to the birefringence nature of Yb:YCOB, green laser by second harmonic generation (SHG) was observed with a tunable wavelength from 519 nm to 525 nm when the fundamental laser was tuned from 1039 nm to 1050 nm.

2. Experimental setup and results

In the experiment, a high quality Yb:YCOB crystal with Yb^{3+} concentration of 30 at.% was grown by the Czochralski technique. The sample was cut along the *X* principal axis. The uncoated Yb:YCOB crystal was 2-mm thick with an aperture of 3 mm×3 mm. Figure 1 shows the unpolarized absorption and fluorescence spectra of the sample at room temperature. The absorption spectrum of the sample was measured by using a Fourier-transform infrared spectrometer, and the fluorescence spectrum was measured by a monochrometer with an excitation laser diode at 940 nm. One can see from Fig. 1 that the absorption spectrum is mainly composed of two strong absorption peaks at 940 nm and 976 nm. Apparently, the absorption peak around 976 nm belongs to the zero-line transition between the lowest levels of $^2F_{7/2}$ and $^2F_{5/2}$ manifolds, which is highly suitable for a diode pump at room temperature. The coverage of the corresponding fluorescence spectral bandwidth is from 940 nm to 1130 nm, with three strong peaks: 976 nm, 1032 nm, and 1085 nm. The peak of 976 nm is the strongest of three fluorescence peaks, but the wavelength is the same as that of the strongest absorption peak, so this wavelength cannot be used in practice for laser output. The peaks of 1032 nm and 1085 nm can be useful wavelengths for laser output. With less reabsorption, the high power would operate at 1085 nm rather than 1032 nm. The very broad and smooth fluorescence spectrum is feasible to generate ultrashort pulses by means of mode-locking.

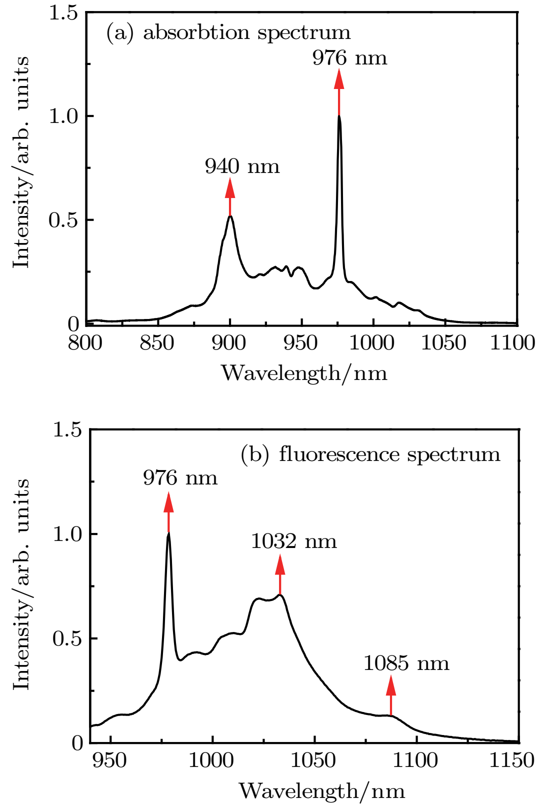

Fig. 1. (color online) The absorption spectrum (a) and fluorescence spectrum (b) of the *x*-cut 30 at.%-doped Yb:YCOB crystal at room temperature.

The experimental setup of the diode-pumped Kerr-lens mode-locked femtosecond Yb:YCOB laser is shown in Fig. 2. It is well known that high laser intensity in the crystal plays an important role for KLM. As a result, three measures were taken in our study. Firstly, we used a 7-W fiber coupled diode laser (Jenoptik, JOLD-7.5-BAFC-105) with a fiber core diameter of 50 μm as the pump source. The numerical aperture (NA) of the fiber was 0.22. A coupling system with a magnification of 0.8 was used to couple the pump laser into the crystal. Secondly, a tight-focus x-cavity was employed. Both M1 and M2 were plane-concave dichroic mirrors with the radii of curvature (ROC) of 50 mm, coated with high transmission at 976 nm and high reflection at a wide spectral range from 1020 nm to 1100 nm. The tight-focus cavity was helpful for reducing the laser beam waist and increasing the laser intensity in the crystal. Thirdly, we chose an output coupler (OC) with a small transmission of 0.4% for enhancing the intracavity laser intensity. In addition, a pair of SF6 prisms with the Brewster angle at a wavelength of about 1040 nm was used to compensate for the normal dispersion resulting from the crystal and the air inside the cavity, which limited the operation wavelength range of the diode-pumped Kerr-lens mode-locked femtosecond Yb:YCOB laser to a certain extent. By adjusting the distance between the prisms and the insertion of P2, the normal intracavity dispersion could be fully compensated and the short pulses could be obtained. What is more, an additional hard aperture H in the form of a pinhole was inserted in the cavity to assist for state mode locking. For an efficient heat removal, the Yb:YCOB crystal was wrapped with an indium film and placed in contact with a water-cooled copper mount at the set temperature of 12 °C. The Yb:YCOB crystal was placed in the middle of the two curved mirrors at a Brewster angle and oriented for $E \parallel Y$ polarization. The whole cavity length was about 1.07 m, corresponding to a repetition rate of 140 MHz. In this cavity design, the laser beam in the crystal was 12.3 μm×14.1 μm ($1/e^2$ level) based on the ABCD matrix calculation.

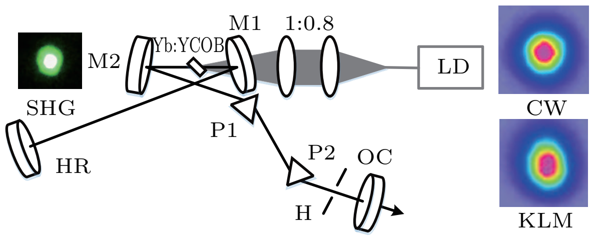

Fig. 2. (color online) The experimental setup of the diode-pumped Kerr-lens mode-locked Yb:YCOB femtosecond laser. LD: fiber-coupled diode laser; M1 and M2: plane-concave dichroic mirrors with ROC of 50 mm; HR: high reflection mirror; P1 and P2: SF6 prisms; OC: output coupler; H: pinhole. Right pictures are the beam profiles of the laser at CW and KLM operations and the green beam after M2.

At first, we finely adjusted the laser cavity to operate at the stable region and generate the maximum output power under the CW operation. The pumping threshold power was 1.0 W. Under the pump power of 4.4 W, the maximum average output power of 101 mW was obtained at the central wavelength of 1041 nm. In order to obtain KLM operation, we carefully adjusted the position of the curved mirror M2 to the stability edge of the cavity. In this situation, the CW output power decreased to 41 mW and the spectrum became disordered in the rage of 1030 nm to 1050 nm. Then, the KLM operation was obtained by a fast translation of the end mirror HR. Once mode-locked, the average output power increased to 53 mW and a green beam behind the M2 mirror was observed. The tip-to-tip distance of 230 mm between the SF6 prisms was set to precisely control the dispersion of the cavity. We measured the pulse duration by a commercial intensity autocorrelator (APE, pulseCheck USB). Figure 3(a) shows the intensity autocorrelation trace (the black dots) and the sech^2 fitting curve (red solid curve) of the KLM pulses. The FWHM bandwidth of the autocorrelation trace and the sech^2 fitting curve was about 60 fs and 39 fs, respectively. The corresponding spectrum measured by an optical spectrum analyzer (Ocean Optics, HR2000+) was shown as Fig. 3(b). The FWHM bandwidth of the spectrum was about 35 nm at the central wavelength of 1049 nm. The time-bandwidth product of 0.372 was close to the Fourier transform limitation of a sech^2 pulse (0.315). By using a commercial beam profiler (Beam Analyzer USB, Duma Optics), the beam profiles of the laser in the CW and KLM mode were measured as shown in Fig. 2.

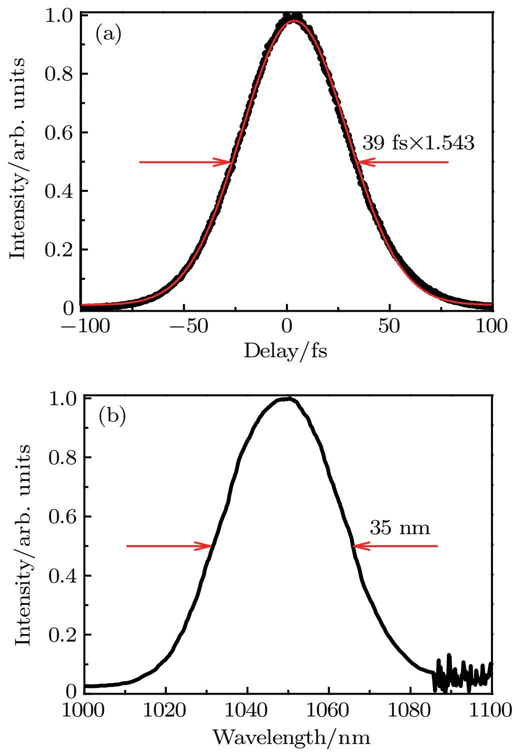

Fig. 3. (color online) (a) Autocorrelation trace of the KLM pulses (black dotted curve) with a sech^2 fitting (red solid curve). (b) The corresponding spectrum.

In our experiment, the near infrared laser wavelength could be tuned from 1039 nm to 1049 nm by adjusting the horizontal position of H, as shown in Fig. 4(a). The pulse duration varies from 39 fs to 55 fs and the average power ranges from 53 mW to 66 mW at different central wavelengths. During the mode-locking operation, green laser was simultaneously observed behind M2 by second harmonic generation in the Yb:YCOB crystal. The central wavelength of the green laser varies from 519 nm to 525 nm as the fundamental wavelength was tuned. The FWHM bandwidth was 9.6, 12.6, and 14.4 nm, centered at 519, 521, and 525 nm, supporting 30-, 23-, and 21-fs Fourier transform-limited pulse durations, respectively. The typical spectra of the green laser were shown in Fig. 4(b). The green laser shown in Fig. 2 was captured by a visible camera, which indicates the good beam quality of the second harmonic beam. The green laser power in this setup is only a few mW, which is difficult to measure the pulse duration of by the autocorrelation technique. We hope to further increase the SHG efficiency by special design of the phase matching angle of the Yb:YCOB crystal for simultaneous lasing and nonlinear frequency conversion. As a result, tunable femtosecond green pulses will be useful for application such as bio-photonics and florescent spectroscopy.

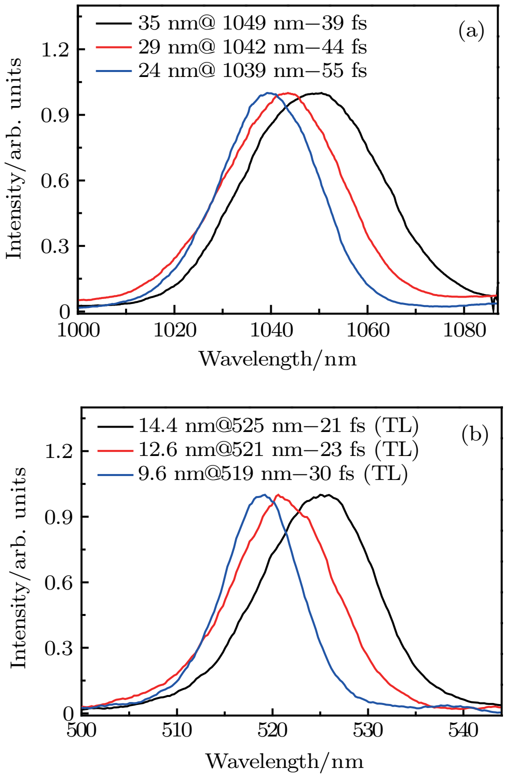

Fig. 4. (color online) The wavelength tuning curves of both the near infrared laser (a) and the green laser (b) by means of SHG of the KLM Yb:YCOB laser.

By the way, it should be pointed out that the Q-switched mode locking usually exists in the process of passive mode-locking by SESAMs. However, the Q-switched mode locking was not observed in our Kerr-lens mode-locked experiment, due to the high power intensity in the cavity.

3. Conclusion

In conclusion, we have demonstrated a diode pumped Kerr-lens mode-locked Yb:YCOB laser. Pulses as short as 39 fs with the average output power of 53 mW were generated at a repetition of 140 MHz. This is, to the best of our knowledge, the shortest pulses from a Yb:YCOB laser. In addition, we also observed self-frequency doubling green laser generation from the birefringent Yb:YCOB crystal. It is proved that Yb:YCOB is a promising laser material for generating sub-50-fs pulses in the near infrared range and simultaneously generating ultrashort green pulses from the single crystal.

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