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A 54-fs diode-pumped Kerr-lens mode-locked Yb:LuYSiO$_5$ laser

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We demonstrate a Kerr-lens mode-locked Yb:LuYSiO$_5$ (Yb:LYSO) laser with the pulse duration of 54 fs, corresponding to a spectral bandwidth of 25 nm centered at 1062 nm. To the best of our knowledge, this is the shortest pulse duration obtained from Yb:LYSO laser. At the repetition rate of 378.3 MHz, an output power of 111.6 mW is obtained using an output coupler with 0.6% transmittance, which can maintain long-time stable mode-locking more than 13 h.

Keywords: diode-pumped, mode-locking, femtosecond, all-solid-state laser

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1. Introduction

The ytterbium (Yb) ion is one of the most popular dopants in solid-state laser during the past two decades, which profits from its simple electronic level structure so that it can be free from the adverse effects such as concentration quenching, upconversion, excited-state absorption, and cross relaxation. Benefiting from the wide fluorescence spectrum, Yb^{3+} laser can support the generation of sub-100 fs pulse and be greatly applied in material processing, medical treatment, microscopic imaging, scientific research, and so on. In the pursuit of ultra-short pulse, excellent results have been reported for a variety of Yb-doped crystals such as Yb:CaYAlO$_4$ (Yb:CYA),[1–3] Yb:CaGdAlO$_4$ (Yb:CALGO),[4–6] Yb:Y$_3$Al$_5$O$_{12}$ (Yb:YAG),[7–9] Yb:LuYSiO$_5$ (Yb:LYSO),[10] and Yb:Ca$_4$(Gd,Y)O(BO$_3$)$_3$ (Yb:GdYCOB).[11,12] Among them, Yb:LYSO is an excellent candidate crystal to generate ultrashort pulses, an alloyed oxyorthosilicate crystal integrating the advantages of broad emission spectra and excellent mechanical properties.[13] The absorption spectrum includes one strong absorption band around 977 nm and two weak absorption bands around 899 nm and 923 nm.[14] The absorption peak at 977 nm well matches with the emission wavelength of the commercial InGaAs laser diodes. The multi-type substitutional sites in Yb:LYSO provide an inhomogeneous strong crystal field for ytterbium ions, which causes inhomogeneous splitting of $^2F_{7/2}$ manifold, and the ground state splitting of Yb^{3+} ion is as large as 993 cm^{-1}, which can promise low pump threshold laser operation.[15] Since both Yb:YSO and the Yb:LSO possess large full widths at half maximum (FWHMs), the alloyed crystal Yb:LYSO has also a very large FWHM bandwidth of 70 nm[16] which supports generation of sub-50 fs pulses. At the outset, the first mode-locked Yb:LYSO laser was demonstrated by Liu *et al.* with 7.8 ps pulse duration.[17] In 2011, Liu *et al.* acquired the first mode-locked femtosecond pulse based on Yb:LYSO using a semiconductor saturable absorber mirror (SESAM) with 780 fs pulse duration.[18] In 2014, the first Kerr-lens mode-locked (KLM) Yb:LYSO laser was demonstrated by Tian *et al.* with 61 fs pulse duration,[10] which has the average power of 40 mW.

In this work, we experimentally generate 54-fs pulses at the central wavelength of 1062 nm from a diode-pumped KLM Yb:LYSO laser, which is the shortest pulse duration ever produced from an Yb:LYSO laser, to our knowledge. Using a single mode fiber-coupled laser-diode as the pump source with the maximum output power of 1.8 W, the average output power of 111.6 mW was obtained by using a 0.6% output coupler, and the laser can maintain long-time stable mode-locking operation more than 13 h. The spectral bandwidth is about 25 nm, making the laser an excellent seed for femtosecond amplifiers.

2. Experimental setup

A schematic diagram of the experimental setup is shown in Fig. 1. A 3-mm-long Yb:LYSO crystal with 5 at.% doping level was used as the laser gain medium. The crystal had a dimension of 3 mm × 3 mm in the cross section. In addition, it was antireflection coated around 940 nm–980 nm and

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1000 nm–1100 nm on both surfaces. The oscillator was free from the circulating cooling water in view of the small amount of excessive heat under low pump power. The crystal was wrapped with indium foil and imprisoned in a copper heat sink to promote heat dissipation. A single mode fiber-coupled laser diode at 976 nm with a maximum output power of 1.8 W was used as pump source. A collimator and a plano-convex lens with focal length of 100 mm was used to couple the pump laser from the fiber into the Yb:LYSO crystal. By our experimental measurements, the focused pump spot diameter was about 38 μm ($1/e^2$ level). We employed a Z-folded four-mirror cavity with the total cavity length of 396.5 mm in this experiment. The concave mirrors M1 and M2 were dichroic mirrors with high-reflection coatings for the laser wavelength (1020 nm–1200 nm) and anti-reflection coatings for the pump wavelength (808 nm–980 nm). Both of them had a small radius of curvature (ROC) of just 50 mm, which focused a very narrow beam waist into the crystal to enhance the Kerr–lens effect. In addition, mode matching is essential for Kerr-lens mode locking. To create a soft-aperture diaphragm, the laser mode was slightly larger than the focused pump spot size at the waist position.[19,20] Based on the ABCD matrix approach, the laser beam waist diameters on the crystal was calculated to be ~ 41 μm ($1/e^2$ level), which was suitable for soft-aperture KLM. To compensate for dispersion and to obtain a broad mode-locking spectrum, we adopted a Gires–Tournois interferometer mirror (GTI) providing a group delay dispersion (GDD) of -1000 fs^2 around 1055–1075 nm. A plane mirror with 0.6% transmission at 1000–1100 nm was chosen as the output coupler (OC) in order to provide appropriate Kerr-lens effect while generating high power output.

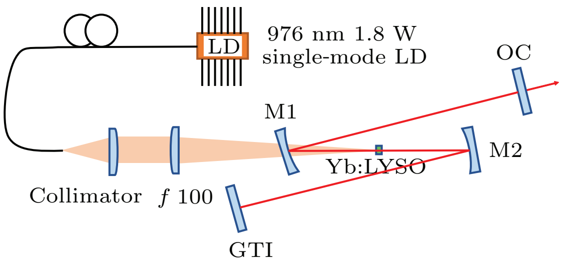

Fig. 1. Schematic diagram of the LD pumped KLM Yb:LYSO laser.

3. Results and discussion

The Yb:LYSO oscillator was initially optimized in the continuous-wave (CW) regime. With careful cavity alignment, the maximum CW output power of 340 mW was obtained at the maximum pump power of 1.8 W, corresponding to an optical-to-optical efficiency of 18.9%. When the position of M2 was slowly tuned, the wavelength of CW laser was changed from 1084 nm to 1060 nm and then to 1010 nm as the output power decreased. We constantly pushed the translation stage under the GTI while turning the position of M2 to seek for obvious spectrum broadening. Once the spectrum-broadening observed, which means that the oscillator had been adjusted to the edge of the stability regime, we finely turned the pitch angle of the end mirror GTI and stable Kerr-lens mode locking could be initiated if a weak perturbation happened. The optical spectrum of the mode-locked pulses was measured by a commercial optical spectrum analyzer (AvaSpec-ULS4096CL-EVO) as shown in Fig. 2(a). It was centered at 1062 nm with an FWHM bandwidth of 25 nm, which could support a 40 fs Fourier-transform-limited sech^2-shaped pulse. Because the GDD of the dichroic mirrors and GTI mirror changed sharply at the short wavelength, there was a strong spectral spike around 1012 nm, and the similar phenomenon was observed in both Yb:CYA[3] and Yb:CGA[21,22] mode-locked lasers, which has a certain contribution to the pulse width.[23,24] If a wide-band GTI mirror is used to compensate for the dispersion of 1010-1050 nm band, it is expected to obtain a wider mode-locked spectrum and achieve sub-50 fs laser output. The autocorrelation trace was measured using a commercial intensity autocorrelator (A.P.E. Pulse Check) as shown in Fig. 2(b). The FWHM bandwidth of the autocorrelation trace was about 83 fs, corresponding to a pulse duration of 54 fs if a sech^2-pulse shape was assumed. The time-bandwidth product (TBP) of the mode-locked pulses was calculated to be about 1.14×0.315 (TBP for Fourier-transform-limited sech^2 pulse).

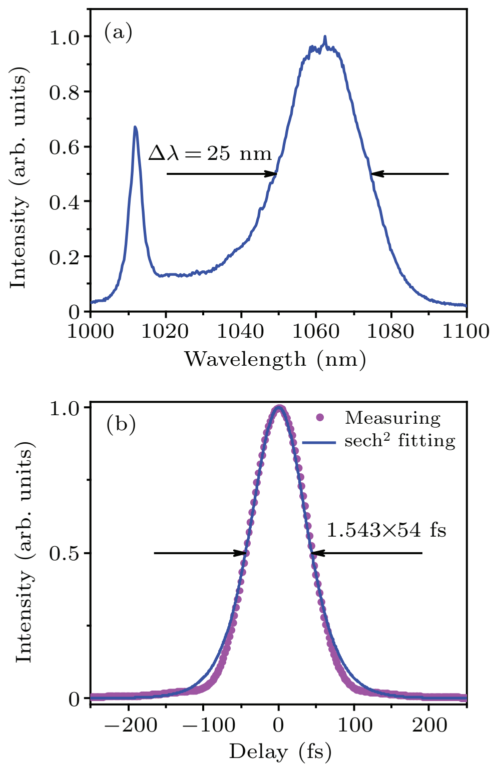

Fig. 2. (a) Measured optical spectrum of the mode-locked pulses. (b) Corresponding auto-correlation trace of the experimental data (dots) and the sech^2-fitting curve (solid).

We measured the RF spectrum of the mode-locked pulses using a commercial radio frequency (RF) spectrum analyzer (Agilent E4407B), and the results are depicted in Fig. 3 to illustrate the states of the mode-locking operation visually. It is revealed that the repetition rate of the mode-locked pulses is about 378.3 MHz and the signal-to-noise ratio is about 58 dB when recorded with a 1 kHz resolution bandwidth (RBW), as shown in Fig. 3(a). Furthermore, as shown in Fig. 3(b), there is no significant spectral modulation in the 1 GHz RF spectrum with 10 kHz RBW, implying that the oscillator was in a stable mode-locking state.

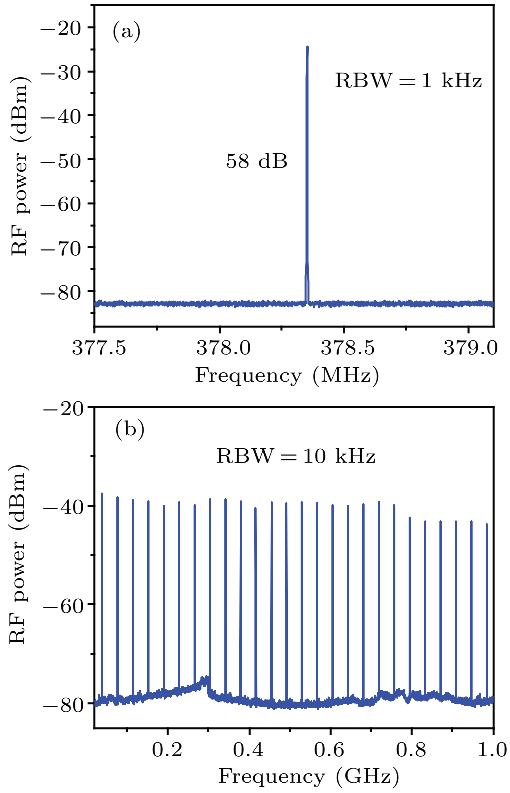

Fig. 3. (a) RF spectrum at the fundament beat note with the resolution bandwidth of 1 kHz. (b) RF spectrum at 1 GHz wide-span range with the resolution bandwidth of 100 kHz.

The oscillator can maintain a long-time stable mode-locking operation. As shown in Fig. 4(a), the power stability of the mode-locked laser was measured by a power meter (OPHIR Nova-Ⅱ). The average mode-locking output power was 111.6 mW and the root-mean-square (RMS) value of the power fluctuations is only 0.8% over 13 h. In addition, the M^2 parameter measurement was performed by a commercial M^2 factor meter (BSQ-SP920), the results are plotted in Fig. 4(b) together with the beam profile at the output (inset). The beam quality factors (M^2) in the horizontal and vertical directions were measured to be 1.199 and 1.441, respectively. The difference between the beam quality in the horizontal and vertical directions is due to the astigmatism caused by the two folded concave mirrors, for which we could use a Brewster angle-cut crystal to compensate in the future.

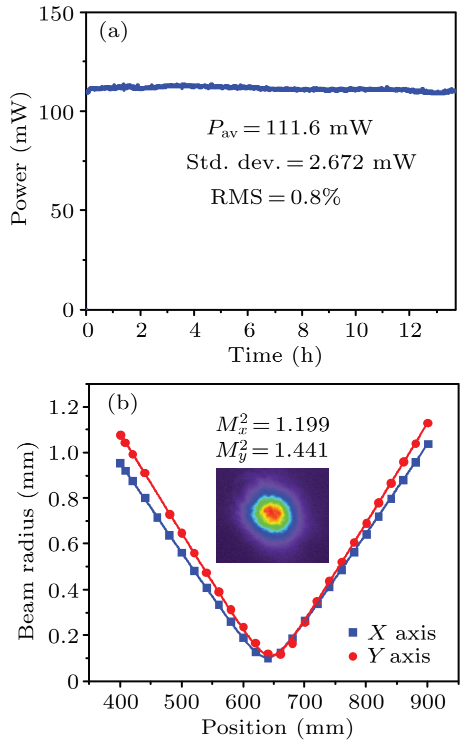

Fig. 4. (a) The power stability of the mode-locked Yb:LYSO laser. (b) The M^2 factor measurement result and the profile of the laser output beam (inset).

4. Conclusion and perspectives

In conclusion, we have demonstrated an LD-pumped femtosecond Kerr-lens mode-locking of Yb:LYSO laser with pulse duration as short as 54 fs at the repetition rate of 378.3 MHz. To the best of our knowledge, this is the shortest pulse duration ever generated from Yb:LYSO crystals. The average output power is 111.6 mW and the central wavelength is at 1062 nm with 25 nm bandwidth. Compared to the mode-locking average power of 40 mW in our previous work[10] with 61 fs pulse duration, the average power reported here is increased by two times. It is believed that the pulse duration could be shortened by using a shorter crystal and more suitable GTI mirrors to optimize the intracavity dispersion. Additionally, we anticipate that by replacing the single pump source with a high power fiber laser, the average output power could be significantly boosted.

Acknowledgements

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