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Letter

Highly efficient and high-power diode-pumped femtosecond Yb:LYSO laser

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Abstract

A diode-pumped high-power femtosecond Yb:LYSO laser with high efficiency is demonstrated. With a semiconductor saturable absorber mirror for passive mode-locking and a Gires–Tournois interferometer mirror for intracavity dispersion compensation, stable mode-locking pulses of 297 fs duration at 1042 nm were obtained. The maximum average power of 3.07 W was realized under 5.17 W absorbed pump power, corresponding to as high as 59.4% opt–opt efficiency. The single pulse energy and peak power are about 35.5 nJ and 119.5 kW, respectively.

Keywords: Yb:LYSO, femtosecond laser, diode-pumped, high efficiency

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

1. Introduction

Power femtosecond lasers have versatile applications in industrial, medical and scientific researches, attracting a wide range of studies for a long time. In the 1 μm wavelength band, Yb-doped active media are well known as an optimal alternative in this aspect and a variety of Yb-doped materials have been reported such as Yb:YAG [1], Yb:KYW [2], Yb:YCOB [3], Yb:Lu_2O_3 [4], Yb:$LuScO_3$ [5], and Yb:SSO [6], which generated high power femtosecond pulses by means of thin-disk technology as well as Yb-doped fiber lasers [7]. In addition, high power femtosecond pulses generated from bulk solid-state lasers were also reported with Yb:CaF_2 [8], Yb:CALGO [9, 10], Yb:KGW [11, 12] crystals. The key factors for high-power femtosecond-pulse generation are good thermal conductivity of the gain medium and thermal management of the laser.

Due to its outstanding laser performance and good mechanical properties, Yb:$LuYSiO_5$ (Yb:LYSO) is another excellent candidate to generate high-power femtosecond pulses. At first, the ground state splitting of Yb^{3+} ion in Yb:LYSO is as large as 993 cm^{-1} [13], leading to a quasi-four level operation and a low pump threshold. Secondly, the Yb:LYSO crystal also has a broad emission spectrum with as large as full width at half maximum (FWHM) bandwidth of 70 nm, which indicates a potential to generate sub-50 fs pulses. The room-temperature absorption and emission spectra of Yb:LYSO crystal are reported in [13]. The absorption cross section at the main absorption peak of 977 nm is 1.13×10^{-20} cm^2 and the corresponding emission cross section at 1033 nm is 0.22×10^{-20} cm^2. In addition, due to the relatively broad absorption bandwidth at 977 nm of Yb:LYSO, it is not necessary to use volume Bragg grating (VBG) to stabilize the pump wavelength at 976 nm when pumping this crystal to realize high efficiency. Above all, Yb:LYSO has a rather high thermal conductivity of about 5 W m^{-1} K^{-1} for 5 at.% Yb doping, which is close to the value of Yb:YAG and larger than that of Yb:KGW. All these properties indicate that Yb:LYSO crystal has the potential to directly support high-power ultrashort pulse generation. So far, some studies on the continuous wave (CW) or mode locking operation of a Yb:LYSO laser have been reported. The first efficient tunable CW operation of a Yb:LYSO laser was demonstrated in 2006 [13], where a maximal slope efficiency of 96% was achieved. In 2011, the first femtosecond Yb:LYSO laser was mode-locked by a semiconductor saturable absorber mirror (SESAM) and produced 780 fs pulses at a central wavelength around 1042 nm [14]. With a double-wall carbon nanotube saturable absorber (DWCNT-SA), Yang *et al* implemented dual-wavelength mode-locking with 8.0 ps pulses simultaneously running at 1045.5 and 1059.0 nm in 2012 [15]. Most recently, the authors achieved the Kerr-lens mode-locking femtosecond operation in a diode-pumped Yb:LYSO laser with pulse durations as short as 61 fs at the central wavelength of 1055.4 nm [16]. However, the maximum peak power delivered from previous Yb:LYSO lasers is only 13.1 kW, which left huge room for improvement.

In this letter, we experimentally demonstrated an efficient femtosecond mode-locking operation in a diode-pumped Yb:LYSO laser with up to 3 W average power. Stable mode-locking operation with 297 fs pulse duration at 1042 nm was obtained. The maximum average power of 3.07 W was realized under 5.17 W absorbed pump power, corresponding to 59.4% opt–opt efficiency. The single pulse energy and peak power are 35.5 nJ and as high as 119.5 kW, respectively. This work demonstrates that the Yb:LYSO crystal is an excellent candidate for high-power femtosecond pulse generation.

2. Experiment setup

To take advantage of the high thermal conductivity and the broad emission spectrum of Yb:LYSO crystal, we optimized the cavity parameters in [16], aimed to obtain high power pulses with ultrashort pulse duration. The laser gain medium is the same as the one used in [16], which was water-cooled at 10 °C during the experiment. The laser crystal was end-pumped by a fiber-coupled diode laser at 976 nm. The core diameter of the fiber is 105 μm and the numerical aperture (NA) is 0.22. An imaging system with a magnification of 1 was used to couple the pump laser from the fiber into the crystal.

Figure 1 shows the schematic of the experimental setup. A modified Z-folded cavity was employed. M1 was a dichroic flat mirror coated for high reflection in the range of 1020–1200 nm and high transmission at 800–1000 nm. C1, C2 and C3 were concave mirrors with radii of curvature (ROC) of 200, 200 and 300 mm, respectively. A Gires–Tournois interferometer mirror (GTI) with group velocity dispersion

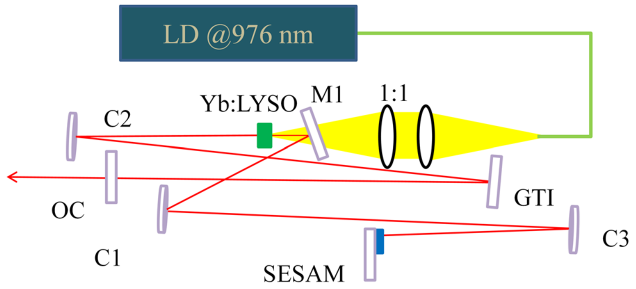

Figure 1. Experimental setup of the mode-locked Yb:LYSO laser.

of -1200 fs^2 per bounce in the 1035–1055 nm range was used for dispersion compensation. Output couplers (OC) with 4.5% and 10% transmission at 1020–1200 nm were used in this experiment. A SESAM (BATOP GmbH) was used to start the mode-locking. The total cavity length was about 1.74 m corresponding to a repetition rate of 86.4 MHz. The beam waist diameters at the crystal and the SESAM were calculated based on the ABCD matrix to be 114×110 μm and 157×152 μm ($1/e^2$), respectively. Such a design was for a stable cavity with good mode matching between the pump and the lasing beam in the center of the crystal. In our experiment, 52% pump power was absorbed by the Yb:LYSO crystal without lasing.

3. Experimental results and discussions

At first, we used a flat mirror with high reflection around 1020–1200 nm to replace the SESAM and aligned the laser cavity to optimize the output power under CW operation. Figure 2(a) depicted the CW output performances with 4.5% and 10% OC, respectively. The corresponding laser thresholds in terms of absorbed pump power for 4.5% OC and 10% OC were 1 and 1.4 W, respectively. With 5.6 W absorbed pump power, the maximum output powers were 3.77 and 3.89 W, corresponding to 85.6% and 92.1% slope efficiencies for 4.5% and 10% OCs, respectively. It is obvious that both the slope efficiency and average power of the 10% OC were higher than that of the 4.5% OC. Different from [13], the output CW laser with 10% OC in our experiment was centered at 1058 nm, due to the higher intracavity loss. Thus, the corresponding slope efficiency is a bit smaller than that of 96% in [13]. Figure 2(b) gives the corresponding opt–opt efficiencies with 4.5% and 10% OCs, the maximum values were 67.4% and 69.6%, respectively.

When characterizing the mode-locked operation, we chose a proper SESAM which was designed for 1.2% modulation depth at 1040 nm, 60 μJ cm^{-2} saturation fluence, and a relaxation time of less than 1 ps. Stable mode-locked pulses were easily obtained when the absorbed pump power of Yb:LYSO crystal increased to 2.5 W. As shown in figure 2(c), the maximum average output power of the mode-locking operation with 4.5% and 10% OCs were 1.75 and 3.07 W under 5.17 W absorbed pump power, corresponding to the slope efficiencies of 53.4% and 89.7%, respectively. Figure 2(d) depicts the corresponding opt–opt efficiencies with 4.5% and 10% OCs, with the maximum values of 33.8% and 59.4%, respectively.

With the 3.07 W output power, we measured the mode-locked optical spectrum using a commercial optical spectrum analyzer

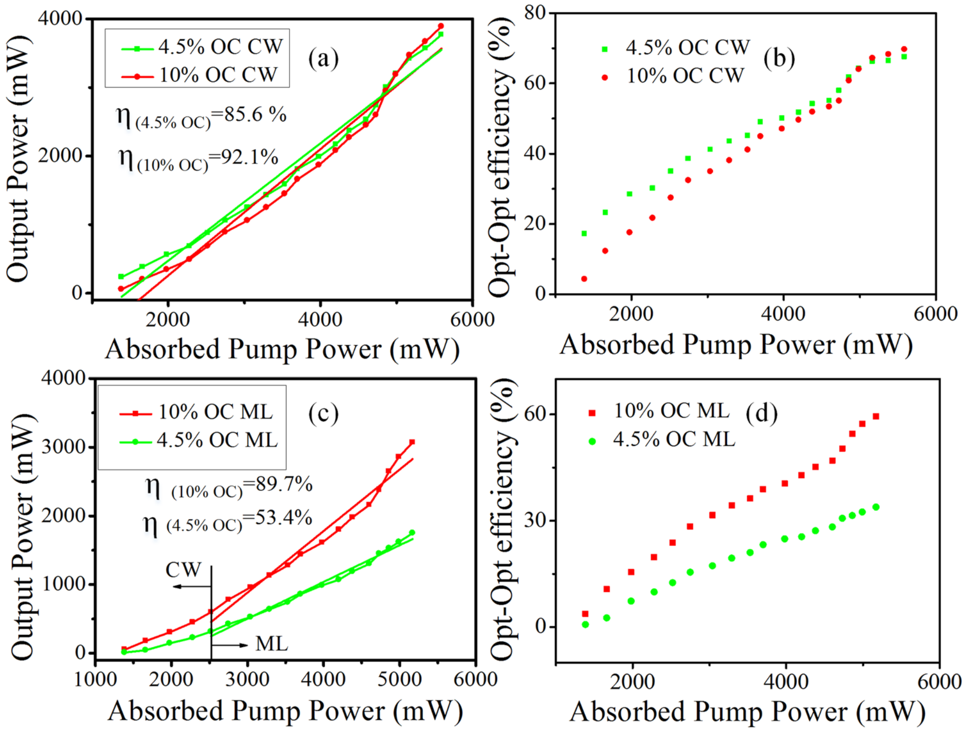

Figure 2. Output powers of the CW (a) and mode-locked (c) Yb: LYSO laser with 4.5% (green) and 10% OCs (red), respectively. The corresponding opt–opt efficiencies for CW operations (b) and mode-locking operations (c) with 4.5% OC (green) and 10% OC (red), respectively.

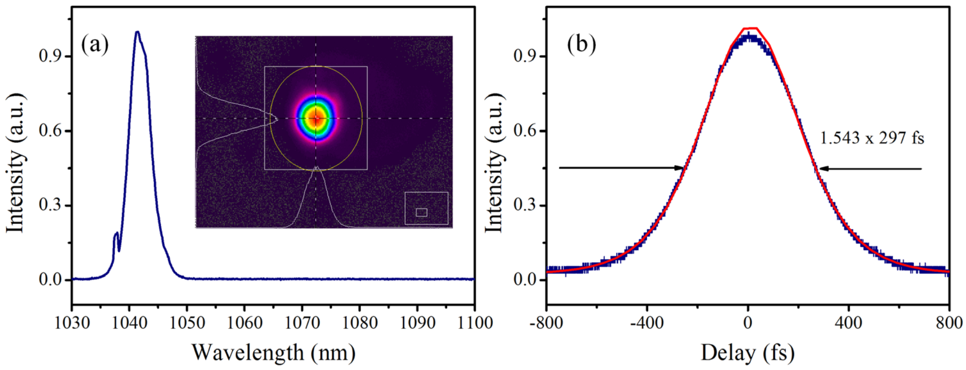

Figure 3. Spectrum (a) along with the output beam profile (inset) and corresponding intensity auto-correlation trace (b) of the mode-locked laser. The red and blue curves in (b) stand for the $sech^2$-fitting curve and the experimental data, respectively.

(YOKOGAWA, AQ6370C), as shown in figure 3(a). The FWHM of the spectrum was 4.3 nm with a central wavelength at 1041.8 nm, which supported a transform-limited pulse of 211.4 fs. The corresponding intensity autocorrelation trace was measured by a commercial intensity autocorrelator (FR-103MN, Femtochrome Research, Inc.), as shown in figure 3(b). The FWHM bandwidth of the autocorrelation trace was about 457 fs, corresponding to 297 fs pulse duration if a $sech^2$ pulse shape was assumed, resulting in a time bandwidth produce (TBP) of 0.353, which is close to the transform-limited value of 0.315. At the maximum output power, the beam quality of the mode-locked laser was measured using a commercial M^2 factor meter (Spiricon M2-200s), the M^2 factors were measured to be $M_x^2 = 1.3$, $M_y^2 = 1.4$ in the horizontal and vertical directions, respectively. The beam profile in near field which has a typical Gaussian profile was also shown as the inset in figure 3(a).

To characterize the stability of the mode-locking operation, we firstly measured the power stability at the maximum output power in 3 h as shown in figure 4. The root-mean-square (RMS) of long term power fluctuation is only about 1.1%.

Then the radio frequency spectrum was also recorded using an RF spectrum analyzer (Agilent E4407B) and a high-speed detector, as shown in figure 5. Figure 5(a) reveals a fundamental beat note at 86.4 MHz with a contrast ratio up to 64.8 dBc in a frequency span of 800 kHz with a resolution bandwidth (RBW) of 1 kHz. The wide-span measurement (1 GHz) which exhibits the high harmonics of the fundamental beat note was shown in figure 5(b) with RBW of 100 kHz. Stable mode-locking operation is confirmed by the clean radio frequency spectra in figure 5, where no side peaks of the harmonics of the fundamental frequency were observed.

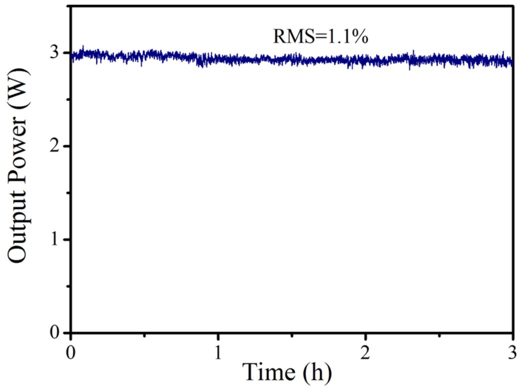

Figure 4. The power stability of the mode-locked laser at the maximum output power in 3 h.

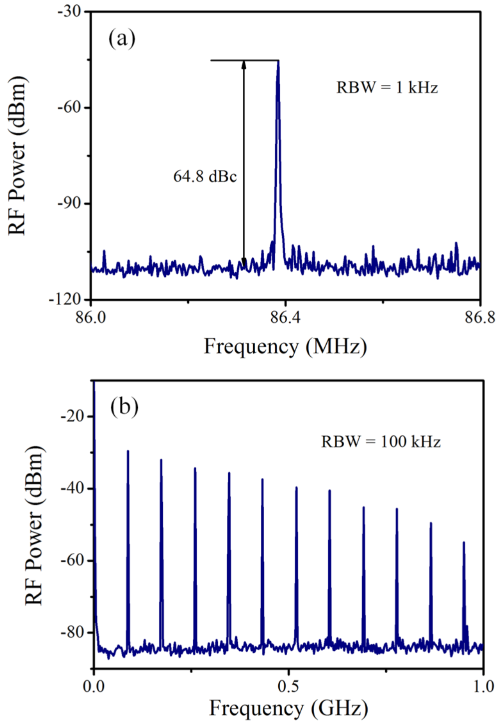

Figure 5. Radio frequency spectra of the mode-locked Yb:LYSO laser. (a) RF spectrum of fundamental beat note with the RBW of 1 kHz. (b) RF spectrum of 1 GHz wide-span range with the RBW of 100 kHz.

The limitation in the current experiment is that when the pump power is rising, mode-locking operation comes to be unstable and multi-pulse operation, which is mainly due to the thermal effect. Moreover, the multi-peak structure of the emission spectrum makes it difficult to generate shorter pulses. Even using better dispersion, it is difficult to obtain pulses shorter than 100 fs. One way to get such short pulses with high power is believed to combine with the KLM technology. With better thermal management, the thin disk geometry is also a good choice. Because the Yb:LYSO crystal has excellent mechanical properties without hydrolysis and cleavage, as thin as 150 μm with a diameter of 25 mm Yb:LYSO disk can be obtained. We believe Yb:LYSO crystal will be an excellent candidate for high power (hundreds Watts level) femtosecond pulse generation with such a thin-disk geometry.

4. Conclusion

In conclusion, a high-efficiency diode pumped femtosecond Yb:LYSO laser was demonstrated. Stable femtosecond pulses with 297-fs pulse duration at 1042 nm were obtained. With 10% OC, the maximum average power was 3.07 W under 5.4 W absorbed pump power, corresponding to as high as 59.4% opt–opt efficiency. The single pulse energy and peak power are about 35.5 nJ and 119.5 kW, respectively. Compared with the previous result of passively mode-locked Yb:LYSO laser with a SESAM [13], here we not only obtained higher power with high efficiency, but also pushed the pulse duration from 780 fs down to 300 fs, which corresponds to 2.5 times shorter. Whilst contrasted with the preceding Kerr-lens mode-locked Yb:LYSO laser with 61 fs and 40 mW [16], two orders of magnitude enhancement in output power was realized with the tradeoff of no more than five times pulse broadening. This result also shows that Yb:LYSO crystal is an excellent laser material for high-power ultrafast pulse generation.

Acknowledgments

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References

[1] Brons J, Pervak V, Fedulova E, Bauer D, Sutter D, Kalashnikov V, Apolonskiy A, Pronin O and Krausz F 2014 *Opt. Lett.* **39** 6442–5
[2] Brunner F *et al* 2002 *Opt. Lett.* **27** 1162–4
[3] Heckl O H, Kränkel C, Baer C R E, Saraceno C J, Südmeyer T, Petermann K, Huber G and Keller U 2010 *Opt. Express* **18** 19201–8
[4] Baer C R E, Kränkel C, Saraceno C J, Heckl O H, Golling M, Peters R, Petermann K, Südmeyer T, Huber G and Keller U 2010 *Opt. Lett.* **35** 2302–4
[5] Saraceno C J, Heckl O H, Baer C R E, Schriber C, Golling M, Beil K, Kränkel C, Südmeyer T, Huber G and Keller U 2012 *Appl. Phys.* B **106** 559–62
[6] Wentsch K S, Zheng L H, Xu J, Ahmed M A and Graf T 2012 *Opt. Lett.* **37** 4750–2
[7] Baumgart M, Jansen F, Stutzki F, Jauregui C, Ortaç B, Limpert J and Tünnermann A 2011 *Opt. Lett.* **36** 244–6
[8] Machinet G *et al* 2013 *Opt. Lett.* **38** 4008–10
[9] Sévillano P, Georges P, Druon F, Descamps D and Cormier E 2014 *Opt. Lett.* **39** 6001–4

[10] Greborio A, Guandalini A and der Au J A 2012 *Proc. SPIE* **8235** 823511
[11] Li J F, Lin H, Zhang H Y and Liang X Y 2012 *Laser Phys. Lett.* **9** 415–20
[12] Zhao H T and Major A 2013 *Opt. Express* **21** 31846–51
[13] Li W X *et al* 2006 *Opt. Express* **14** 6681–6
[14] Liu J, Yang J M, Wang W W, Zheng L H, Su L B and Xu J 2011 *Laser Phys.* **21** 659–62
[15] Yang Q, Wang Y G, Liu D H, Liu J, Zheng L H, Su L B and Xu J 2012 *Laser Phys. Lett.* **9** 135–40
[16] Tian W L *et al* 2014 *Opt. Express* **22** 19040–6