Diode-pumped passively mode-locked Yb:GYSO laser generating 324 fs pulses at 1091 nm

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Received November 2, 2012; revised November 22, 2012; accepted November 23, 2012; posted November 27, 2012 (Doc. ID 179104); published December 12, 2012

We report the first demonstration of femtosecond operation in a diode-pumped Yb-doped $GdYSiO_5$ (Yb:GYSO) laser. With a semiconductor saturable absorber mirror for passive mode locking and a pair of SF6 prisms for intracavity dispersion compensation, we realized stable passive mode locking with the new Yb-doped laser material. Femtosecond pulses as short as 324 fs were obtained at the central wavelength of 1091 nm. The maximum average power is 450 mW for an absorbed pump power of 2.8 W, with a slope efficiency of 18.5% and a pulse repetition frequency of 80.1 MHz.

OCIS codes: 140.3480, 140.3615, 140.4050, 140.7090.

With the remarkable progress of high-power and high-brightness InGaAs laser diodes emitting in the 900–980 nm range, Yb^{3+}-doped materials have received great interest in recent years. This is because Yb^{3+} compared to Nd^{3+} has a very simple electronic level structure composed of only two manifolds $^2F_{5/2}$ and $^2F_{7/2}$, so that most of undesired effects, such as upconversion, excited-state absorption, cross relaxation, and concentration quenching can be well eliminated, resulting in low quantum defect as well as low thermal load. Moreover, its relatively large emission bandwidth makes it possible to generate ultrashort pulses down to several tens of femtosecond duration. Hence, Yb^{3+}-doped laser materials are greatly expected to be candidates of high-power and ultrafast laser mediums. Until now, various Yb-doped crystals have been successfully used to generate femtosecond laser operation [1–13]. Among them, Yb-doped oxyorthosilicate $Yb:Gd_2SiO_5$ (Yb:GSO) has been demonstrated with outstanding laser performance on both continuous-wave (CW) and CW mode-locking operations, which is because of the large ground-state splitting of the Yb^{3+} ion up to 1067 cm^{-1} and a large emission cross section. Li *et al.* have reported a CW Yb:GSO laser with low threshold of 127 mW and high slope efficiency of 86% [14], and 343 fs mode-locked operation has also been reported in Yb:GSO [3]. However, a strong tendency to cleave along (100) plane caused by the $P2_1/c$ monoclinic structure of GSO makes it difficult for industrial applications [15].

Recently, a new crystal material, Yb-doped $GdYSiO_5$ (Yb:GYSO), has been reported for the purpose of eliminating cleavage of Yb:GSO. The Yb:GYSO crystal not only combines the excellent laser performance of Yb:GSO with good mechanical properties of $Yb:Y_2SiO_5$ (Yb:YSO), but also possesses numerous optical advantages. First, there is a large ground-state splitting of the Yb^{3+} ion in Yb:GYSO up to 995 cm^{-1}, leading to a quasi-four-level operation and then a low pump threshold. Second, the Yb:GYSO crystal exhibits a comparatively large fluorescence lifetime, which is as high as 1.92 ms, and excellent thermo-optical properties. Both of these two factors make Yb:GYSO a promising candidate for generation of efficient high-power femtosecond laser pulses. Du *et al.* reported the first demonstration on the efficient tunable CW operation of a Yb:GYSO laser in 2006 [16]. In 2008, Li *et al.* reported a 2.5 ps pulse obtained from a diode-pumped Yb:GYSO laser [17]. And more recently, a 210 fs laser operation at 1093 nm pumped by a CW Ti:sapphire laser at 970 nm was demonstrated [18]. However, using a Ti:sapphire laser as the pump has clear disadvantages, especially at the emission edge of 970 nm, such as, lower output power, higher cost, and more complexity. As a result, it is favorable to realize robust and compact femtosecond operation with the diode-pumping concept, which will certainly benefit many applications.

In this Letter, we experimentally demonstrate femtosecond operation in a diode-pumped Yb:GYSO laser and obtain laser pulses with a duration of 324 fs at the central wavelength of 1091 nm. To the best of our knowledge, this is the first demonstration of femtosecond operation with diode-pumped Yb:GYSO laser. Laser action was performed by using a 3 mm long, 5 at. %-doped Yb:GYSO crystal with end faces of 6 mm × 5 mm finely polished and antireflection coated at a broad spectrum range around 1 μm as the laser gain medium. For efficient heat dissipation, the crystal was mounted tightly on a water-cooled copper heat sink, and the water temperature was maintained at 15°C, during the experiment. 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 laser medium. The pump-laser output from the fiber (with 50 μm core diameter and 0.22 NA) was coupled into the crystal by a coupling system with a magnification of 1. We first characterized the laser medium in CW operation. A schematic of the pump geometry and laser cavity is shown in Fig. 1(a). M1 was a plane dichroic mirror with high transmission at 976 nm and high reflection at 1020–1200 nm; M2 and M3 were concave mirrors with radii of curvature (ROC) of 200 and 300 mm, respectively; M4 was an end mirror with high reflection at 1000–1100 nm. A plane mirror with a transmission of 0.8% in the range of 1020–1200 nm was used as the output coupler (OC). We obtained a threshold pump power as

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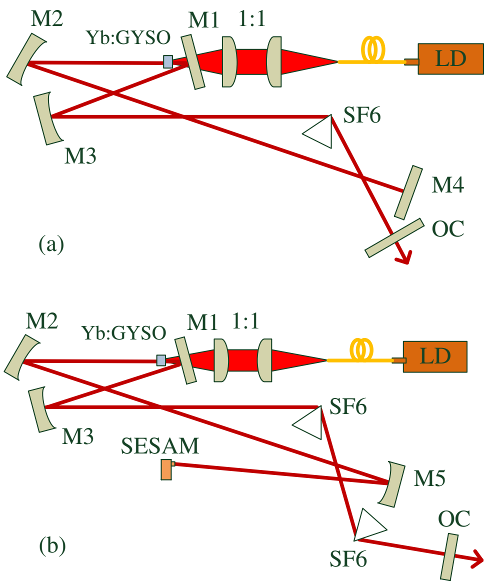

Fig. 1. (Color online) Experimental setups used to study the (a) CW and (b) femtosecond laser performance of the Yb:GYSO laser. LD, 976 nm laser diode; M1, dichroic mirror; M2, M3, and M5, concave mirrors with ROC of 200, 300, and 300 mm, respectively; M4, high reflection mirror; OC, 0.8% output coupler.

low as 120 mW. The highest CW output power of 1.3 W was obtained at 1091 nm under the absorbed pump power of 3.3 W, corresponding to a slope efficiency of 42.8%. With a SF6 prism inserted into the cavity, we implemented a tunable laser wavelength from 1005 to 1100 nm, corresponding to a tunable range of about 95 nm. The tuning curve is shown in Fig. 2. The tunable wavelength in our experiment is much broader than reported before [16,18]. The tuning wavelength beyond 1100 nm is restricted by the spectrometer used in our experiment (600–1100 nm, AvaSpec-3648). It is believed that the tuning wavelength can extend toward the longer wavelength for some extent.

The broad tunability of this Yb:GYSO laser makes it possible to generate ultrashort femtosecond laser pulses. The mode-locking experiment was carried out with a modified confocal cavity shown in Fig. 1(b). To start the mode locking, we used a curved folding mirror M5 with

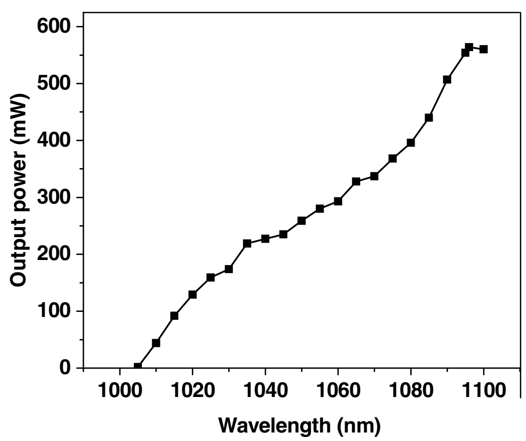

Fig. 2. Wavelength tuning curve of the Yb:GYSO laser with a 0.8% output coupler under the pump power of 2.5 W.

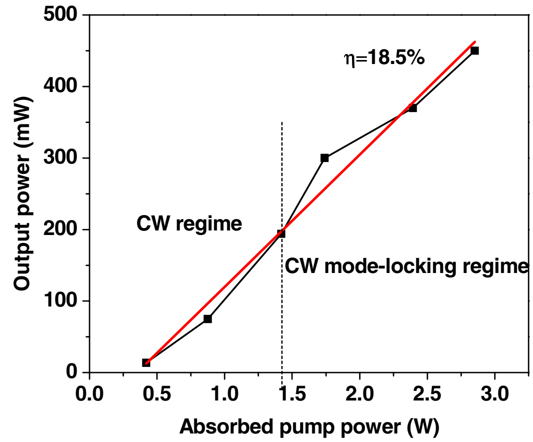

Fig. 3. (Color online) Output power versus absorbed pump power for the mode-locking operation.

ROC of 300 mm to focus the laser beam on a semiconductor saturable absorber mirror (BATOP GmbH), which was designed for a modulation depth of 0.4% at 1064 nm, a saturation fluence of 90 μJ/cm^2, and a relaxation time of less than 500 fs. In another arm of the cavity, a pair of SF6 prisms with a tip-to-tip distance of ~28 cm was used to introduce a negative group-delay dispersion of about −250 fs^2 for intracavity chirp compensation. The total cavity length corresponded to a repetition rate of about 80.1 MHz.

With optimization of the cavity alignment and chirp compensation, stable mode-locking operation with single-mode output was self-starting when the pump power exceeded 1.4 W. The maximum output power was 450 mW under the absorbed pump power of 2.8 W, corresponding to a slope efficiency of 18.5%. Figure 3 depicts the dependence of the output power on the absorbed pump power. Using a commercial intensity autocorrelator (FR-103MN, Femtochrome Research, Inc.), we measured the intensity autocorrelation trace shown in Fig. 4. If a sech^2 pulse shape was assumed, the mode-locked pulse duration was 324 fs. The corresponding spectrum of the mode-locked pulse exhibited a full width at half maximum bandwidth of 4 nm at the center wavelength of 1091 nm,

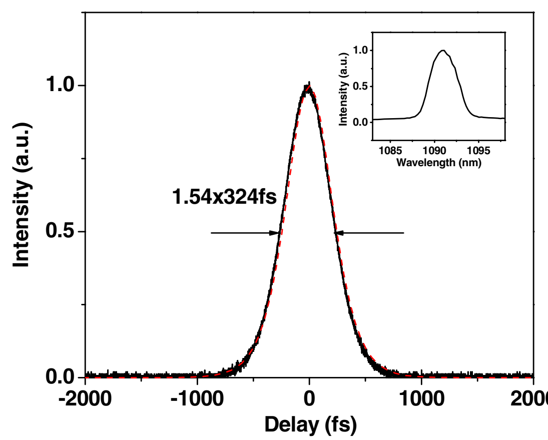

Fig. 4. (Color online) Intensity autocorrelation trace of the pulses. The experimental data are described by the solid curve and the sech^2 fitting by the dashed curve. Inset shows the pulse spectrum.

which yielded a time-bandwidth product of 0.327 that is close to the value of 0.315 for the transform-limited $sech^2$ pulse. Though we obtained almost transform-limited pulses from the cavity, the gain bandwidth was not fully covered by the observed spectrum. Considering the as large as 95 nm tunability achieved in the CW regime, we believe that shorter femtosecond pulses will be obtained by using broadband chirped mirrors or Gires–Tournois interferometer mirrors for dispersion compensation.

In conclusion, we have reported the femtosecond operation of the diode-pumped Yb:GYSO laser for the first time. Pulse duration of 324 fs at the central wavelength of 1091 nm was obtained. Under the absorbed pump power of 2.8 W, the maximum mode-locked output power was 450 mW, with a slope efficiency of 18.5%. Considering the broad wavelength tunability of the Yb:GYSO laser, shorter pulse duration less than 100 fs may be achieved by further optimizing the mode-locking bandwidth and chirp compensation. We believe Yb:GYSO to be an excellent laser crystal for a high-power and highly efficient diode-pumped ultrafast laser for many applications.

We acknowledge the helpful discussion with Qing Wang and Yuwan Zou. This work is partially supported by the National Natural Science Foundation of China (No. 61205130) and the Fundamental Research Funds for the Central Universities (No. K50511050001).

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