Generation of 210 fs laser pulses at 1093 nm by a self-starting mode-locked Yb:GYSO laser

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We report the first demonstration, to our knowledge, of the femtosecond laser operation by using a new alloyed Yb:GYSO crystal as the gain medium. With a 5 at. % Yb^{3+}-doped sample and chirped mirrors for dispersion compensation, we obtained pulses as short as 210 fs at the center wavelength of 1093 nm. The average mode-locking power is 300 mW, and the pulse repetition frequency is 80 MHz. © 2008 Optical Society of America

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With the remarkable progress and widespread applications of ultrafast laser science and technology, ultrafast sources with directly diode-pumped schemes have attracted more and more interest because of the compactness and low cost compared to the well-developed femtosecond Ti:sapphire laser. Among the available laser hosts that can be used for diode laser pump at present, the Yb^{3+}-doped materials have excellent advantages because of its larger emission bandwidth than the Nd-doped crystals, thus permitting even shorter pulse generation. Furthermore, the Yb^{3+} ion has a very simple electronic level structure, composed of only two manifolds ($\Delta E \approx 10{,}000\ \mathrm{cm}^{-1}$). Therefore most of the parasitic effects, such as upconversion, excited-state absorption, or concentration quenching, can be well avoided, resulting in low quantum defect and consequently low thermal load. Owing to these characteristics, the Yb^{3+}-doped materials offer high potential as a laser gain medium for generating high-average-power ultrashort laser pulses with high efficiency. Until now, extensive mode-locking research has been reported with various Yb-doped crystals, such as garnet Yb:YAG [1], vanadate $Yb:YVO_4$ [2], oxyorthosilicates Yb:LSO and Yb:GSO [3,4], tungstates Yb:KGW and Yb:KYW [5,6], borates Yb:BOYS and Yb:GdCOB [7,8], fluorite Yb:YLF [9], sesquioxide $Yb:Sc_2O_3$ [10], and silicate Yb:SYS [11].

Recently, a promising crystal, Yb-doped $GdYSiO_5$ (Yb:GYSO), has shown several attractive advantages compared to many new Yb-doped crystals. First, it exhibits large splitting of the $^2F_{7/2}$ ground state. The splitting is as high as $995\ \mathrm{cm}^{-1}$. This makes the population of the transition lower level much less sensitive to the temperature. Second, this Yb:GYSO crystal has a comparatively high fluorescence lifetime of 1.92 ms and good thermo-optical properties, showing superiority in the development of high-energy high-peak-power laser sources. Third, Yb-:GYSO crystal has both high laser performance and good mechanical properties. All of these factors are indicative of the very high potential for the development of efficient high-power femtosecond laser sources based on this novel crystal. Since the first demonstration on the efficient tunable CW operation of a Yb:GYSO laser by Du *et al.* [12], superior performance for ultrashort laser running is expected. More recently, a 74 mW picosecond Yb:GYSO laser operating at 1045 nm was demonstrated [13].

In this Letter, we present experimental research on the self-starting femtosecond Yb:GYSO laser. Stable laser pulses with a duration of 210 fs at the center wavelength of 1093 nm were obtained. To our best knowledge, this is the first demonstration for femtosecond operation with this new crystal. The experiment was performed by using a 3-mm-long, 5%-doped Yb:GYSO crystal with end faces ($6\ \mathrm{mm} \times 5\ \mathrm{mm}$) polished for laser grade quality. The crystal was cut along the optical Y axis, which was also chosen as the propagation direction of the laser beam. To choose an efficient pump wavelength, we used a tunable CW Ti:sapphire laser as the pump, which is capable of an output power of 2 W around 970 nm. Our experiment showed that the active material can absorb 95% pump laser at the wavelength of 976 nm. We first characterized the laser crystal in CW operation. Figure 1(a) is the schematic layout. It consisted of a pair of curved folding mirrors, M1 and M2, with a radius of curvature (ROC) of 100 mm, a flat end mirror M3, and a 1% output coupler. With the optimized alignment, we realized a threshold pump power as low as 180 mW. The highest CW output power of 920 mW with a diffraction-limited beam pattern was obtained at the wavelength of 1091 nm under the full pump power of 2 W, corresponding to a slope efficiency of 54% with regard to the absorbed pump power. A 2% output coupler was also used. However, the maximum output power was only 760 mW, and the threshold pump power was 350 mW. The slope efficiency also reduced to 51%. The reduced performance can be due to the low optimum output transmissivity for the oscillator. With a different cavity configuration, higher pump power, and shorter crystal length, slope efficiency as high as 79% from a diode-pumped

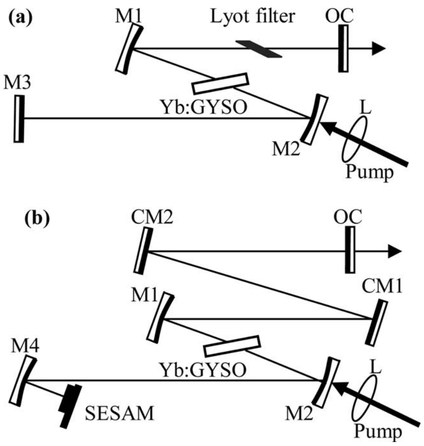

Fig. 1. Cavities used to study the (a) CW and (b) femtosecond laser performance of Yb:GYSO. M1, M2, M4, concave mirrors with ROC of 10 cm; M3, flat reflector; CM1, CM2, flat chirped mirrors; L, lens with 10 cm focal length; OC, 1% output coupler.

CW Yb:GYSO laser has been demonstrated [13]. According to [14] the theoretical maximum slope efficiency of the Yb:GYSO laser can be near 89% at optimum cavity parameters (for a laser wavelength of 1091 nm). To test the tunability of this laser, we inserted a Lyot filter (bandwidth $\approx$ 0.1 nm) in the CW cavity and realized a tunable laser wavelength from 1033 to 1110 nm, corresponding to a tunable range of about 77 nm. Figure 2 shows the tuning curves. Compared with the similar experimental result reported in [12], the tunable wavelength in our experiment extended more than 20 nm towards the longer wavelength. This is believed to be the widest tuning range in Yb:GYSO oscillators so far.

The broad tunability of the Yb:GYSO laser is promising for mode-locking operation to generate femtosecond laser pulses. To start the mode-locking running, we replaced the flat end mirror M3 by the combination of a curved folding mirror M4 and a semiconductor saturable absorber mirror (SESAM). The mirror M4 had a ROC of 100 mm and focused the laser beam on the SESAM. This SESAM was designed for 0.4% modulation depth and saturation fluence of 120 $\mu J/cm^2$. Its nonsaturable loss was specified to be 0.3%, and the relaxation time less than 500 fs. In another arm of the cavity, we used a pair of chirped mirrors (CM1, CM2) for group-velocity-dispersion (GDD) compensation. Figure 1(b) is the

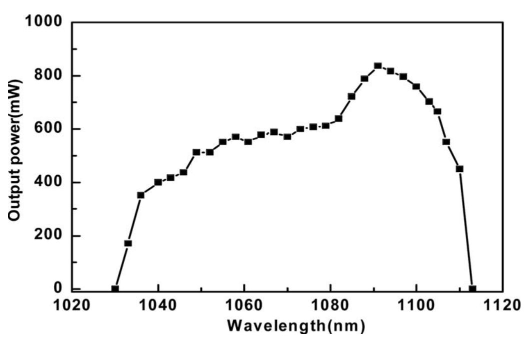

Fig. 2. Tuning range of the Yb:GYSO with a 1% output coupler and using a Lyot filter for wavelength selection.

schematic layout of the cavity for mode-locking work. The total cavity length corresponds to a repetition rate of about 80 MHz.

The dispersion is an important issue to obtain very short pulses. In our experiment, the 3-mm-long 5%-doped Yb:GYSO crystal introduced about 210 fs^2 GDD at the wavelength of 1090 nm in a single pass [15]. The chirped mirrors were designed with GDD of -120 fs^2 per bounce within the wavelength range from 1000 to 1200 nm. Therefore, the net intracavity GDD remained at a minus value by introducing two bounces onto the chirped mirrors. After optimization of the cavity alignment, stable and self-starting femtosecond pulses were obtained. The observed transversal mode of the femtosecond laser remained TEM_{00} in the experiment. Using a commercial noncollinear autocorrelator (FR-103MN, Femtochrome Research, Inc.), we measured the autocorrelation trace of the mode-locked pulses. As shown in Fig. 3(a), the FWHM width of the autocorrelation trace is about 324 fs. If a $sech^2$-pulse shape is assumed, the mode-locked pulse duration is 210 fs. The spectral width (FWHM) of the pulses was measured as 6.4 nm at the central wavelength of 1093 nm. Figure 3(b) shows the typical spectrum, compared with the one in the CW mode, the central wavelength redshifted slightly from the peak wavelength. Based on the measured data, we calculated the time-bandwidth product to be 0.34, which is close to the value of 0.315 for the transform-limited $sech^2$ pulse. This indicates that almost transform-limited pulses were directly obtained from the cavity. However, we observed that the gain bandwidth was not fully covered by the obtained spectrum, especially in the shorter wavelength. That means the gain of Yb:GYSO crystal is not fully exploited. Considering the 77 nm tunability achieved in the CW mode, we believe that even shorter femtosecond pulses are possible. Under the full pump power of 2 W from the CW Ti:sapphire laser, the average mode-locking power output from the Yb:GYSO laser was 300 mW at a repetition rate of 80 MHz, corresponding to an energy per pulse of 3.75 nJ and a peak power of 17.9 KW. The corresponding slope pump power efficiency is 16.7%. The lower slope efficiency compared with the one at CW operation is due to the intracavity losses caused by the added mirrors for mode locking. Further, by replacing the pump laser by a diode laser at the same wavelength of 976 nm, we believe that an even higher mode-locking laser power can be obtained. In view of the excellent mechanical properties of the Yb:GYSO crystal, this work will lead to a new kind of femtosecond laser with high output power and compactness.

In conclusion, we have generated 210 fs laser pulses at the central wavelength of 1093 nm with the Yb:GYSO laser. To our best knowledge, this is the first demonstration of a mode-locked Yb:GYSO laser operating at femtosecond pulses. Under the 2 W pump power from the 976 nm CW Ti:sapphire laser, stable mode-locking laser pulses with the average power of 300 mW were obtained, leading to 16.7%

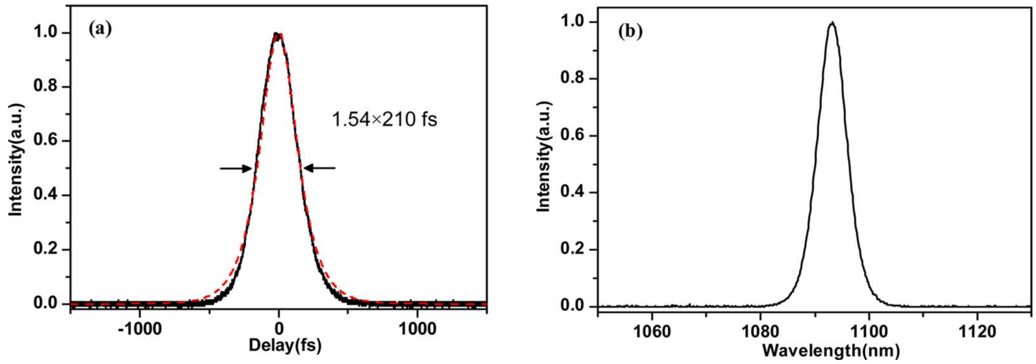

Fig. 3. (Color online) (a) Typical intensity autocorrelation trace of the pulses. The experimental data are shown by the solid curve and the $sech^2$-fitting curve by the dashed curve. (b) The laser spectrum of mode-locking operation.

slope pump efficiency. This work not only paves a possible way for using a diode laser at 976 nm wavelength as the pump but also provides us with a new kind of femtosecond laser at a low cost. Because of the advantages it has over the femtosecond Ti:sapphire laser, in compactness and its potential in output power, we expect that this laser can be well used in many fields.

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