Diode-pumped passively mode-locked Yb:Y$_3$Ga$_5$O$_{12}$ laser

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We experimentally demonstrated femtosecond operation in a diode-pumped Yb:Y$_3$Ga$_5$O$_{12}$ laser for the first time, to the best of our knowledge. By using Gires–Tournois interferometer mirrors for dispersion compensation and a semiconductor saturable absorber mirror for passive mode locking, pulses with a duration as short as 245 fs at the central wavelength of 1045 nm have been produced at a repetition rate of 64.3 MHz. Under the full pump power of 7 W, the maximum output power was 570 mW, with an average slope efficiency of 14.1%. © 2009 Optical Society of America

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With the remarkable progress of high power and high brightness diode lasers, trivalent ytterbium ion ($\text{Yb}^{3+}$) has been recognized as an interesting doping for solid-state laser materials, mainly because $\text{Yb}^{3+}$-doped materials have many excellent advantages, such as broad emission bands, small quantum defect, and desirable properties for diode pumping. Among these materials, Yb:YAG crystal shows remarkable characteristics and has received the most attention [1–3]. Employing a thin-disk design, a high average power of 80 W has been obtained in a mode-locked oscillator [2]. However, a narrow transition linewidth of only 6 nm at the main emission peak of 1031 nm confines the pulse duration to only 700–800 fs in the thin-disk laser and 340 fs in the bulk laser [4,5]. Although shorter laser pulses have been generated by tuning the central wavelength to around 1050 nm, the output power is much lower than that at 1031 nm [6,7]. To obtain shorter pulse duration, a number of crystals—such as Yb-doped KY(WO$_4$)$_2$, Sr$_5$Y(BO$_3$)$_3$, YVO$_4$, LuVO$_4$, CaGdAlO$_4$, CaF$_2$ [8–15]—have been studied and durations with sub-100 fs level have been reported. To date, searching particularly promising materials for high-power ultrashort pulse generation remains a fertile subject of laser field.

Similar to YAG, Y$_3$Ga$_5$O$_{12}$ (YGG) has many desirable advantages for laser materials—stable, hard, optically isotropic, having a good thermal conductivity (9 W/mK), and accepting substitutionally trivalent ions of both rare-earth metal and iron groups [16,17]. As a scintillator material, the Yb:YGG crystal has been well studied [18,19]. The laser transition linewidth at the main emission peak of 1.025 μm is approximately four times broader than that of the Yb:YAG [18], and the lifetime of the excited $^2P_{3/2}$ is about 1.1 ms [19]. Although the above results suggest that the Yb:YGG is a promising laser material for ultrashort pulse generation, no laser performance is reported so far. In this Letter, we demonstrate a directly diode-pumped passively mode-locked femtosecond Yb:YGG laser for the first time.

The Yb:YGG single crystal was grown by optical floating zone method. Figure 1 presents room-temperature absorption and fluorescence spectra (filtered out the exciting light of 970 nm) of the Yb:YGG crystal. The maximum absorption locates at 970 nm, giving an absorption cross section of $2.71 \times 10^{-20}$ cm$^2$ and a bandwidth (FWHM) of 2 nm. Besides this maximum absorption peak, there is a relatively strong and rather broad absorption band composed of two main peaks around 930 and 944 nm with cross sections of $1.33 \times 10^{-20}$ and $1.10 \times 10^{-20}$ cm$^2$, respectively. The bandwidth of this absorption band is 26 nm, which may provide great flexibility for diode laser pumping without an accurate temperature control. The emission spectrum is similar to that of the Yb:YAG, but with two main differences. First, the emission peak exhibits a blueshift from 1031 nm of the Yb:YAG with an emission cross section of $2.1 \times 10^{-20}$ cm$^2$ to 1025 nm of the Yb:YGG with an emission cross section of $2.6 \times 10^{-20}$ cm$^2$ esti-

Fig. 1. (Color online) Room-temperature absorption and fluorescence spectra of Yb:YGG crystal.
mated by using the reciprocity method [4]. Pumped by 970 nm diode laser, the quantum defect is only 0.05. Second, the Yb:YGG has a broad emission bandwidth of about 22 nm (FWHM) at the main emission peak, which is nearly four times wider than that of Yb:YAG. A clear comparison of luminescence spectra among Yb:YGG, Yb:YAG, and Yb:YAlO₃ (YAP) at similar conditions was presented by Kamenskikh et al. [18]. Using Yb:YAP as the gain medium, Kisel et al. [20] realized the mode-locking operation with a pulse duration of 225 fs. By comparing with Yb:YAG and Yb:YAP, Yb:YGG with a broader emission bandwidth should support shorter pulse generation, even less than 100 fs.

Laser action was performed with a 3-mm-long, antireflection-coated, and 10 at. %-doped Yb:YGG crystal. A high-brightness fiber-coupled diode laser emitting at 970 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 laser crystal where the laser spot radius was about 30 μm. About 90% of the pumping power was absorbed by the active material. Figure 2 is the schematic of the pumping geometry and laser cavity. A Z-fold cavity was employed for the mode-locking experiment. M1 was a plane dichroic mirror with high transmission at 970 nm and high reflection at 1020–1100 nm; M2, M3, and M4 were concave mirrors, with radii of curvatures of 300, 200, and 200 mm, respectively. A pair of Gires–Tournois interferometer (GTI) mirrors, with a group-velocity dispersion of −1400 fs² per bounce within the wavelength range from 1025 to 1045 nm, was used for dispersion compensation. Passive mode locking was realized by using a semiconductor saturable absorber mirror (SESAM) (BATOP), which has a saturable absorption of 0.4% at 1040 nm, a saturation fluence of 120 μJ/cm², a relaxation time of less than 500 fs, and a nonsaturable loss of less than 0.3%. A plane-wedged mirror with a transmission rate of 2.5% was used as the output coupler (OC). The total cavity length was approximately 2.3 m corresponding to a repetition rate of 64.3 MHz. With this cavity, the laser waist radii on the SESAM were calculated to be 46 μm x 56 μm (sagittal direction x tangential direction).

Stable mode-locking operation with single-mode output was self-starting when the incident pump power exceeded 3.4 W. The relationship between the output and the incident pump powers is shown in Fig. 3. Limited by the available pump power, the maximum output power was 570 mW under 6.9 W of the incident pump power. The average slope efficiency was 14.1%. We measured the intensity autocorrelation trace by using a commercial noncollinear autocorrelator (Femtochrome, FR-103MN). As shown in Fig. 4(a), the FWHM width of the autocorrelation trace was about 360 fs. If a sech²-pulse shape was assumed, the mode-locked pulse duration was 245 fs. Figure 4(b) depicts the corresponding spectrum of the stable mode locking, which had a FWHM bandwidth of 5.8 nm at the central wavelength of 1045 nm. The time–bandwidth product was calculated to be 0.39. As a test of the mode-locking Yb:YGG laser, the experimental results on the slope efficiency, optical conversion efficiency, and pulse width showed that the laser did not perform well. Many factors will influence the laser action. The main reason could be attributed to the high Yb³⁺ ion concentration for the YGG host. For a quasi-three-level system, the terminal laser level has thermal population at room temperature, which induces the reabsorption loss. When the laser medium with a high concentration is longitudinally pumped, the majority of the pump power is absorbed within a short distance, and the other portions of the laser medium that are not pumped strongly enough to reach population inversion can cause some reabsorption loss for the oscillating mode [6], which confines the slope and the optical conversion efficiencies. In addition, emissions around 1025 nm suffer from strong reabsorption losses, and then the oscillation at longer wavelengths is favorable. Pumped by relatively low power, the longitudinal modes at the short wavelength of the broad main emission band cannot reach the threshold, which consequently did not contribute to the mode-locking process and limited the pulse width in our experiment. Besides the reason of a high concentration, the oscillating modes may partly be influenced by the SESAM.
and GTI mirrors used for the mode-locking experiment. As a result, the laser occurred at the central wavelength of 1045 nm, at which the emission cross section was much smaller than that at 1025 nm and then did not show the perfect results.

In conclusion, we have reported the femtosecond operation of the Yb:YGG laser for the first time (to our knowledge). A pulse duration of 245 fs with an output power of 570 mW has been obtained at a repetition rate of 64.3 MHz. The Yb:YGG has shown to be a promising active material for ultrashort pulse generation not only because of its broad emission bandwidth of 22 nm at the main emission peak of nearly four times that of the Yb:YAG but also because it has excellent physical properties for high-power operation. By further optimizing the Yb$^{3+}$ ion concentration and the laser performance conditions, we believe that even higher power and shorter pulse will be possible and the Yb:YGG may be a good alternative to the widely used Yb:YAG at the high power and ultrafast laser operation.

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