High-efficiency diode-pumped femtosecond Yb:YAG ceramic laser

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A highly efficient diode-end-pumped femtosecond Yb:yttrium aluminum garnet (YAG) ceramic laser was demonstrated. Pumped by a 968 nm fiber-coupled diode laser, 1.9 W mode-locked output power at a repetition rate of 64.27 MHz was obtained with 3.5 W absorbed pump power, corresponding to a slope efficiency of 76%. Our measurement showed that the pulse duration was 418 fs with the central wavelength of 1048 nm.

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The ytterbium (Yb^{3+}) doped yttrium aluminum garnet (YAG) material is very attractive for the application of diode-pumped solid-state lasers. It has several important advantages, such as high quantum efficiency, long fluorescence lifetime, absence of excited-state absorption, as well as large emission bandwidth, which can support femtosecond pulse generations, and so on. Therefore, intensive studies have been carried on lasers based on Yb:YAG crystals in recent years [1–4]. A high-power cw Yb:YAG laser with an output power of 0.95 kW [2] and a mode-locked thin-disk Yb:YAG laser with pulse energy up to 25.9 μJ were reported [4]. Recently, by the vacuum sintering technique and nanocrystalline technology, highly transparent Yb:YAG ceramics for solid-state laser gain medium have been successfully developed [5]. Compared with Yb:YAG crystals, highly transparent Yb:YAG ceramics have such advantages as favorable mechanical properties [6], high doping concentration, low cost, and easy fabrication of large-size samples. These advantages promise the Yb:YAG ceramic even extensive potential for the development of a high-efficiency and high-power ultrafast laser.

Up to now, cw laser performances of the Yb:YAG ceramic have been extensively studied by several groups [5,7–10]. In the first Yb:YAG ceramic laser experiment, the cw output power was 345 mW with a slope efficiency of 26% [5]. With the improvement on the Yb^{3+} doping concentration, excellent cw laser performances by Yb:YAG ceramics have been demonstrated. Employing a 1-mm-thick 9.8 at. % doped Yb:YAG ceramic sample fabricated by Konoshima Chemical, Dong *et al.* realized a 1.73 W cw output power with the absorbed pump power of 2.87 W, corresponding to a slope efficiency as high as 79% [7]. A cw output power as high as 6.8 W with the slope efficiency of 72% was further demonstrated by Nakamura *et al.* [9]. In the pulsed operation, Dong *et al.* achieved a passively Q-switched Yb:YAG ceramic laser with 172 μJ pulse energy and 237 ps pulse width at 3.5 kHz repetition rate [11]. More recently, Yoshioka *et al.* successfully demonstrated the first mode-locked operation of a Yb:YAG ceramic laser [12]. However, the achieved efficiency for the femtosecond operation was relatively low; the output power was 250 mW at the pump power of 26.6 W.

In this Letter, we report the high-power and high-efficiency operation of a diode-end-pumped femtosecond Yb:YAG ceramic laser. With 968 nm laser diode pumping, stable femtosecond laser pulses were obtained with 1.9 W output power, and the corresponding slope efficiency was as high as 76%. To our best knowledge, this is the highest efficiency achieved from both diode-pumped mode-locked ceramic and crystal based Yb:YAG lasers. This work also demonstrates that the ceramic Yb:YAG can promise even higher-power ultrafast laser than the crystal.

For self-starting femtosecond laser operation, a more complicated cavity configuration is needed than for the cw laser operation. Lots of additional cavity losses are thereby introduced, such as the insertion losses by the prisms, the nonsaturable loss by the semiconductor saturable absorber mirror (SESAM), and the broadband reflection losses by intra-cavity reflectors, among others. To obtain an efficient mode-locking operation, we made several major improvements compared with [12]. First, other than prisms, we adopted highly reflective negative-dispersion mirrors for dispersion compensation. This avoided the insertion losses by the prisms, which usually caused low efficiency in mode-locked Yb-doped solid-state lasers. Experimental results on this kind of lasers have shown the significant efficiency increase by negative-dispersion mirrors replacing prisms [13,14]. Second, a piece of SESAM with the nonsaturable loss parameter as low as 0.3% was used to further minimize the intracavity losses. Third, we optimized the transmission of the output coupler mirror for the femtosecond operation. Finally, high pumping intensity is much helpful to obtain an efficient laser operation. Since we did not have a high brightness diode laser at the wavelength of 940 nm, we used a 7 W high brightness

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fiber coupled diode laser (Jenoptik laserdiode GmbH) at 968 nm as the pump. The fiber core diameter is 50 μm, with an NA of 0.22.

A schematic of the laser cavity and pump geometry is shown in Fig. 1. The pump laser was reimaged into the laser medium through a coupling system. The cavity was a standard Z-shape structure, with a piece of high reflective plane mirror (M4) folding one arm of the cavity to fit the short focusing length of the pump light. M1 and M2 were curved folding mirrors with radii of curvature (ROCs) of 200 and 300 mm, respectively. As the absorption peak at 968 nm is lower and narrower than the main absorption peak at 940 nm [7], we chose a 2-mm-thick 10 at. % doped Yb:YAG ceramic for the gain medium (from Konoshima Chemical). For an efficient heat removal, the gain medium was placed in contact with a water-cooled copper mount at the set temperature of 12°C. The end faces of the ceramic (4 mm × 4 mm) were antireflection coated in a wide spectral range from 1000–1100 nm. The cavity was designed to sustain a fundamental mode with a beam waist of 65 μm × 67 μm in the gain medium. The absorption of the ceramic to the pump laser was around 50% in the experiment.

To start passive mode locking, we used a commercially available SESAM (Batop GmbH). The SESAM was designed to operate near 1040 nm with a modulation depth of 0.4% and a nonsaturable loss parameter as low as 0.3%. The saturation fluence of the SESAM is 120 $\mu J/cm^2$. We selected a folded mirror with an ROC of 200 mm (M3) to focus the cavity mode to a waist of 58 μm × 65 μm on the SESAM. For the femtosecond laser operation, we introduced negative dispersion by a Gires–Tournois interferometer (G–TI) mirror and a chirped mirror (Layertec GmbH) to compensate the positive dispersion inside the cavity. The G–TI mirror provides a second-order dispersion compensation of about -1000 ± 300 fs^2 per rebound in the spectral range from 1030 to 1050 nm, and the chirped mirror provides -120 ± 20 fs^2 from 1000 to 1100 nm. This solution was proven experimentally to be the most fitting. The total cavity length corresponds to a repetition rate of 64.27 MHz.

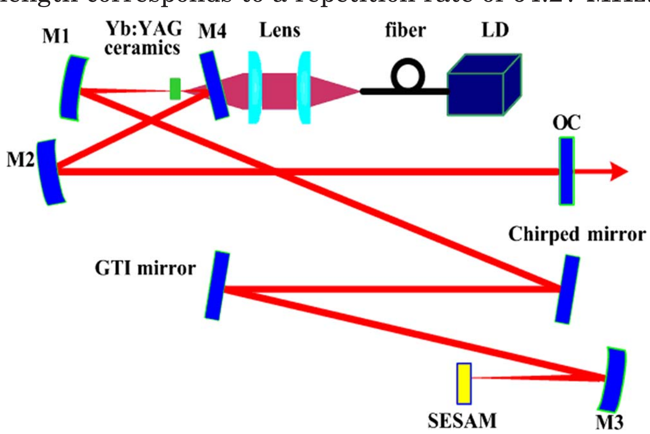

Fig. 1. (Color online) Schematic of the mode-locked Yb:YAG ceramic laser: LD, high brightness fiber coupled laser diode; M1 and M3, concave mirrors with ROC of 200 mm; M2, concave mirror with ROC of 300 mm; M4, plane high reflection mirror; OC, output coupler.

Three different mirrors were used as output couplers with different transmissions of 1%, 2.5%, and 4% from 1020 to 1080 nm. A stable soliton mode-locking regime was observed with 1% and 2.5% output couplings. Figure 2 shows the output power as a function of the absorbed pump power for these two output couplers. With the decreasing of mirror reflectivity from 99% to 97.5%, the threshold incident pump power for the cw mode-locking operation increased from 1.9 to 2.5 W. The maximum cw mode-locked output power was achieved with the 97.5% reflectivity output coupler. Under the incident pump power of 7 W (the measured absorbed pump power was 3.5 W), a stable mode-locked output power of 1.9 W was obtained, corresponding to a slope efficiency of 76% with respect to the absorbed pump power. With the 1% output coupler, the maximum mode-locked power was 1.2 W with the slope efficiency of 44.7%. With 4% output coupler and under the maximum pump power, the output power was slightly higher than the output power by the 2.5% coupler; however, stable cw mode locking could not be realized at this coupling. By a commercial noncollinear autocorrelator (FR-103MN, Femtochrome Research, Inc.), we measured the autocorrelation trace of the mode-locked pulses at the highest output power. As shown in Fig. 3, the FWHM width of the autocorrelation trace is about 645 fs. If a $sech^2$-pulse shape is assumed, the mode-locked pulse duration is 418 fs. The spectral width (FWHM) of the pulses was measured as 3.4 nm at the central wavelength of 1048 nm (inset in Fig. 3). The time-bandwidth product is calculated to be 0.388, which is slightly above the Fourier limit for a $sech^2$ pulse.

To characterize the performance of the femtosecond pulse train at the high-power operation, we measured the rf spectrum of the pulses by a high speed photodiode and an electrical spectrum analyzer. The spectrum shows a clean peak at a repetition rate of 64.27 MHz without side peaks, implying that the Q-switching instabilities have been fully depressed (Fig. 4). A wider acquisition frequency span (from 0 to 300 MHz with 100 kHz resolution bandwidth) was

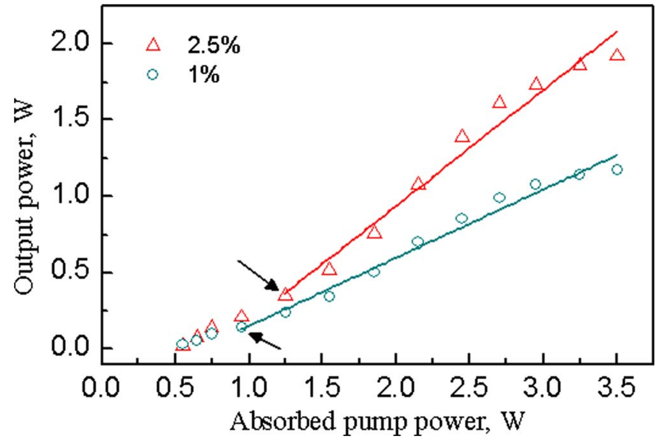

Fig. 2. (Color online) Average output power versus absorbed pump power of the mode-locked Yb:YAG ceramic laser with output couplings of 2.5% (triangles) and 1% (circles). The cw mode-locking thresholds are indicated by arrows.

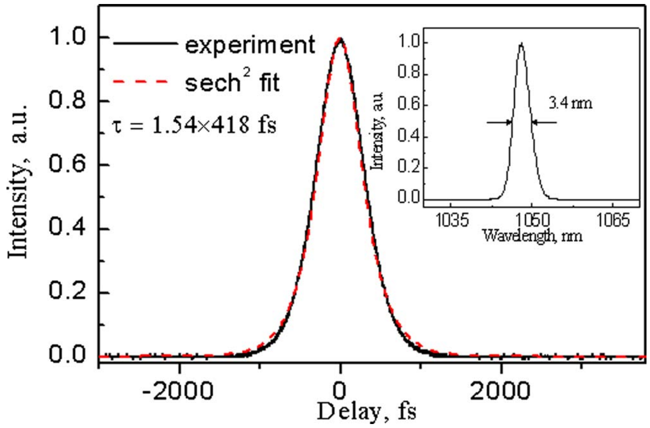

Fig. 3. (Color online) Intensity autocorrelation traces of the mode-locking laser pulses with 1.9 W average power. The experimental data are shown by the solid curve, and the $sech^2$-fitting curve is shown by the dashed curve. Inset, the corresponding laser spectrum.

also performed (inset in Fig. 4), which was a clear indication for the single-pulse operation in a high output power level.

In conclusion, we have demonstrated what is to our best knowledge the most efficient and powerful diode-end-pumped femtosecond Yb:YAG ceramic laser. With a gain medium of 2 mm thickness and a 10 at. % Yb^{3+} doping concentration, the mode-locked output power as high as 1.9 W was obtained at the absorbed pump power of 3.5 W. The corresponding slope efficiency was as high as 76%. The measured pulse width is 418 fs, and the spectrum is centered at 1048 nm with a bandwidth of 3.4 nm. Our experiment definitely affirmed that the Yb:YAG ceramic is an excellent laser medium for high-power and high-efficient diode-pumped ultrafast lasers and amplifiers.

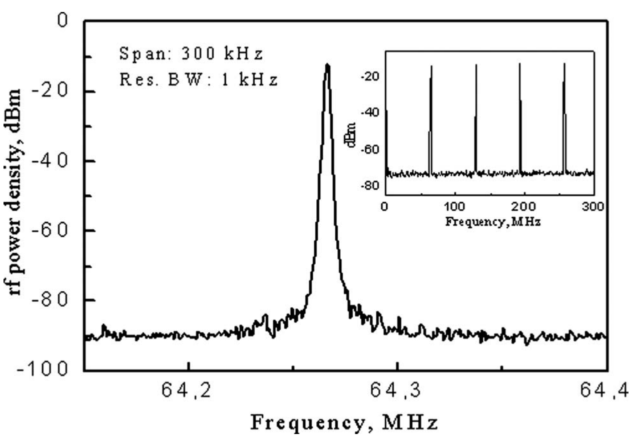

Fig. 4. The rf spectrum at fundamental repetition frequency of the 418 fs pulse train from the mode-locked Yb:YAG ceramic laser. Inset, resolution bandwidth (Res. BW) of 100 kHz and span of 300 MHz.

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