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ULTRASHORT-PULSE GENERATION CLOSE TO THE FLUORESCENCE SPECTRUM LIMIT OF THE GAIN MATERIAL IN MODE-LOCKED YB:YAG LASER WITH SEMICONDUCTOR SATURABLE ABSORBER MIRROR

[1]Y. Sasatani, [1]H. Hitotsuya, [1]S. Matsubara, [1]M. Inoue, [3]Y. Ishida, [1]N. Shimojo, [1,2,4]S. Kawato
[1]Graduate School of Engineering, University of Fukui, 3-9-1 Bunkyo, Fukui, Fukui 910-8507, Japan,
sasatani.yoshinobu@gmail.com
[2]Japan Synchrotron Radiation Research Institute, 1-1-1 Kouto, Sayo, Hyogo 679-5148, Japan, kawato@u-fukui.ac.jp
[3]The Institute of Physical and Chemical Research, Riken Wako Insutitute, 2-1 Hirosawa, Wako, Saitama 351-0198, Japan
[4]Research and Education Program for Life Science, University of Fukui, 3-9-1 Bunkyo, Fukui, Fukui 910-8507, Japan

Abstract : **We report on a diode-pumped ytterbium-doped yttrium aluminum garnet (Yb:YAG) laser with an intracavity nonlinear medium and semiconductor saturable absorber mirror (SESAM). The center of the laser spectrum was 1030 nm and the laser spectrum width was 12 nm, which is broader than the fluorescence of the Yb:YAG crystal. The output pulse width was 131 fs which is close to the Fourier transform limit of the fluorescence.**

Keywords *– SESAM, Mode-locking, Femtosecond pulsed laser, Yb:YAG, Diode-pumped*

I. INTRODUCTION

To date, no mode-locked laser has directly generated short pulses that approach the Fourier transform limit (FTL) of the fluorescence spectrum of the gain materials such as dyes [1], Ti:sapphire [2]–[8], [11], [13], and Yb-ion-doped materials [9], [11], [12]. For these lasers, spectrum filters are used to obtain ultrashort pulses or broad lasing spectra that approach the FTL of the fluorescence. The filter technique is theoretically an effective method for limiting the gain-narrowing effect. However, the lasing spectra are still limited by the gain spectrum. In the general method involving the filter, the broadening of the lasing spectrum has not exceeded the gain spectrum wings.

It is important to have a technique that generates ultrashort pulses and a broad lasing spectrum to exceed the gain limit for the mode-locked lasers. The technique implies the generation of ultrashort pulses beyond the FTL of the fluorescence of the gain material. Intracavity spectral broadening is advantageous to obtain ultrashort pulses directly from the mode-locked laser in that large high-order dispersion is removed from the spectral phase, and regular short-duration pulses can be maintained during each round trip using soliton-like mode-locking. Moreover, intracavity spectral broadening is effective for increasing the nonlinear effects because its pulse peak power is higher than that output by several orders of magnitude. The lasing spectrum and pulse width can approach the monocycle region only when the lasing spectrum is not influenced by the gain-narrowing effect. To date, intracavity spectral broadening has not yet reached the fluorescence limit of the gain material, even when using nonlinear materials in the laser cavity [10].

For the first demonstration of the generation of ultrashort pulses beyond the fluorescence limit directly from the mode-locked laser with an intracavity highly nonlinear material [13]–[16], we selected a ytterbium-doped yttrium aluminum garnet (Yb:YAG) crystal for the gain material. Yb-doped materials have high quantum efficiency and high capability of laser diode pumping. The fluorescence bandwidth of Yb:YAG is approximately 9 nm and the FTL pulse width is almost 120 fs. In this paper, we report on a semiconductor saturable absorber mirror (SESAM) mode-locked Yb:YAG laser with an intracavity nonlinear medium. The maximum spectrum width of 12 nm has exceeded the fluorescence of the gain material, and a pulse width of 131 fs is close to the FTL of the fluorescence.

II. EXPERIMENTAL SETUP

Figure 1 shows a schematic set-up of diode-pumped mode-locked Yb:YAG laser with SESAM. The pump source is a single emitter laser diode with low brightness, a wide emitter width of 100 μm and the maximum output power of 2.5 W. Two cylindrical lenses shown in Fig. 1 compensate astigmatism of the pump beam. The tangential plane of the beam is collimated by an aspherical lens in Fig. 1 with a focal length f = 2.5 mm (L1). The sagittal plane of the beam is expanded by a cylindrical plano-concave lens with f = –7.7 mm (L2) and collimated by a cylindrical plano-convex lens with f = 80 mm (L3). The collimated beam is focused by an achromatic lens with f = 80 mm (L4). The pumping beam is focused to a spot in the laser crystal with a diameter of 24 μm for the vertical axis and 74 μm for the horizontal axis. The maximum pump intensity is 180 kW/cm^2. The pump wavelength is 941 nm and the absorption efficiency is 80%.

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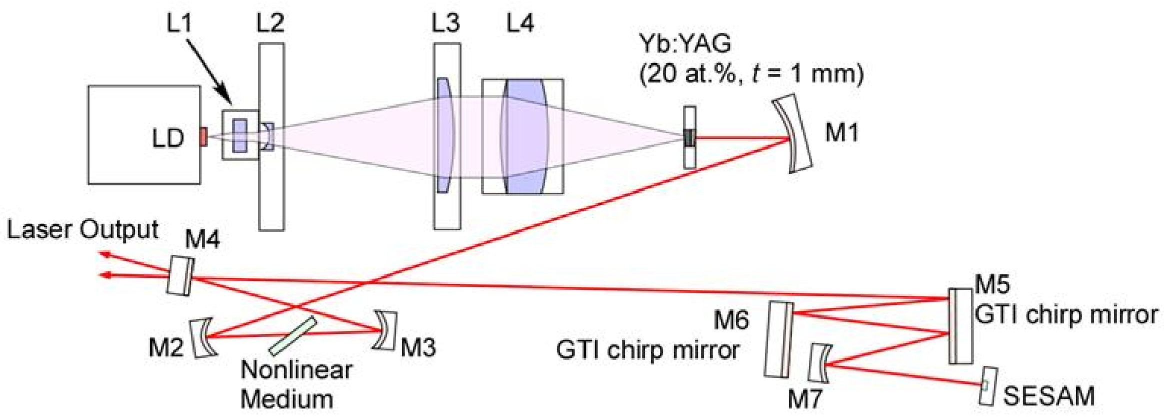

Fig. 1 Schematic of diode-pumped mode-locked Yb:YAG laser with SESAM.

A Yb:YAG crystal (Scientific Material Corp.) is used as a gain medium with an ion density of 20 at.%. The crystal has a 3 mm × 3 mm size surface that is perpendicular to the <100> axis and a 1 mm thickness. The pumping surface is the anti-reflection coated at 940 nm pump wavelength, and is used as the end mirror of laser resonator which is high-reflection coated between 1030 nm and 1080 nm laser wavelength. Another surface of the crystal is anti-reflection coated for the pump and the laser wavelengths. The crystal is adhered to a 1-mm-thick sapphire plate that is anti-reflection coated on both surfaces of the pumping surface, and it is mounted to a copper heat sink for cooling to around a room temperature of 20 °C.

The laser cavity extends from high-reflection coating in the Yb:YAG to SESAM. The concave mirrors, M2 and M3, with radius of curvature (ROC) of 100 mm provide a focus in the highly nonlinear medium. M7 with ROC of 250 mm is used to compensate for astigmatism from the other mirrors in the laser cavity. Three concave mirrors, M1, M2 and M3, have negative second-order dispersion with –100 fs^2. The Gires-Tournois interferometer mirror, M5 and M6, provide negative second-order dispersion of –3000 fs^2. The total negative second-order dispersion is –3300 fs^2 in the cavity. M4 is used as an output coupler with a transmittance of 5%, resulting in two output beams.

III. RESULTS

Figure 2 shows the autocorrelation trace of the laser pulses form the mode-locked Yb:YAG laser. A pulse width of 131 fs is estimated by assuming a $sech^2$ pulse shape. The pulse width is close to the FTL pulse width of 120 fs on Yb:YAG fluorescence which width is around 9 nm. Figure 3

shows the output spectrum of the mode-locked laser and the fluorescence spectrum of the Yb:YAG crystal. The peak wavelength of the fluorescence spectrum is 1030 nm, which is same as that of the lasing spectrum. The lasing spectrum width of 12 nm is broader than the fluorescence spectrum width of 9 nm. The spectrum broadening is caused by highly nonlinear effects in the cavity, such as self-phase modulation. The average output power is 220 mW at a incident pump power of 1.63 W.The optical-to-optical conversion efficiency is 13.5% for the incident pump power.

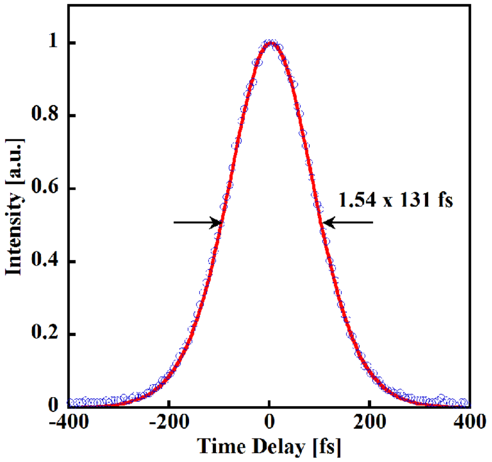

Fig. 2 Autocorrelation trace of the mode-locked Yb:YAG laser. The experimental data (circles) and a $sech^2$-fitting curve (solid curve) are shown. The pulse width is estimated to be 131 fs.

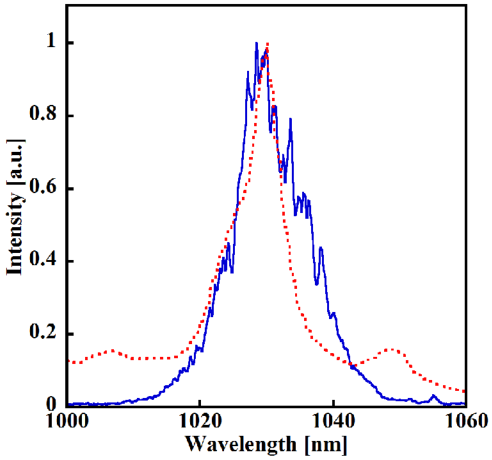

Fig. 3 Output spectrum of the mode-locked Yb:YAG laser (solid curve) and the fluorescence spectrum of Yb:YAG (dotted curve).

IV. CONCLUSION

In this paper, we have demonstrated ultrashort pulse generation from the SESAM mode-locked Yb:YAG laser with highly nonlinear medium. The pulse width is estimated to be 131 fs, which is close to the FTL pulse width of Yb:YAG fluorescence. The lasing spectrum width of 12 nm is broader than the fluorescence spectrum width of a Yb:YAG. The spectrum broadening is caused by highly nonlinear effects in the laser cavity. Shorter pulse width below the FTL pulse width of the fluorescence and higher average output power over 1 W with high efficiency will be obtained directly from the SESAM mode-locked Yb:YAG laser with highly nonlinear medium. Much shorter pulses will be obtained from the other Yb-ion doped materials by using the mode-locked laser scheme.

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