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# Efficient ultrashort-pulse generation of Yb:YAG laser overcoming the fluorescence spectrum limit by using nonlinear medium

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**Abstract:** One-hundred-ten-fs and 72-fs pulse-widths were obtained directly from a mode-locked Yb:YAG laser with SESAM and without SESAM, respectively. The laser-spectrum-center and the fluorescence-center were almost same. The oscillation-spectra were much broader than the fluorescence.

In recent years, there has been great interest in mode-locked lasers with high average output powers, high efficiency, high reliability, and compactness. They have several applications in scientific and industrial fields such as wavelength conversion, nonlinear spectroscopy, and superfine material processing. To achieve high power short pulse laser, a broad emission spectrum and favorable thermal properties are important. $Yb^{3+}$-ion doped materials are believed to be the most promising materials to satisfy those needs. $Yb^{3+}$-ion has only two Stark manifolds, which reduces undesirable effects such as excited state absorption, cross-relaxation and quantum defect so that the thermal loads are reduced. Their broad spectra allow for directly diode-pumped high power short pulse lasers. Several kinds of diode-pumped $Yb^{3+}$-ion doped laser generating sub-100 fs pulses as well as high power femtosecond lasers have been reported.

The $Yb^{3+}$-ion doped crystals used to generate sub-100 fs pulses so far, however, have favorable thermal properties. In addition their extremely broad fluorescence spectrum tends to have a large overlap with the corresponding absorption spectrum, which leads to reabsorption loss. For example, monoclinic double tungstates and orthovanadates are good alternatives, and 100-fs and 120-fs pulses were produced with a SESAM for the laser materials of $Yb:KY(WO_4)_2$ (abbreviated as Yb:KYW) and $Yb:YVO_4$, respectively. Sub-100-fs pulses were also obtained with a SESAM from an $Yb:LuVO_4$ laser as well as from an Yb:glass laser. Pulses as short as 47 fs were recently generated from a passively mode-locked $Yb:CaGdAlO_4$ laser with a SESAM. Passively mode-locked Yb:YAG lasers with a SESAM in low-output-power regions generated pulses as short as 340 fs at 1030 nm and 136 fs at 1050 nm , and in high-output-power regions a pulse energy as high as 5.1 μJ in 800-fs pulses was achieved.

The pulse width of the all lasers was restricted to the limit of the fluorescence spectrum. In the case of Yb:YAG, at the gain center wavelength of 1030 nm, the fluorescence spectral width is 9.5 nm in FWHM and the Fourier transform limited pulse width is 120 fs. Spectral broadening by filtering of the gain center was achieved previously. The pulse width of 100 fs was observed and the laser center wavelength was shifted to be a low gain center of around 1050 nm; however, for efficient laser oscillation, it is suitable that the center of the gain and the lasing is almost same. The shortest pulse width at the gain center was achieved previously to be around 300 fs for hundreds mW output power regions and around 1 ps for over tens W output power regions.

In this paper, efficient spectral broadening by nonlinear medium and the ultrashort-pulse generation overcoming the limit of the fluorescence spectrum are achieved. Around and below 100 fs pulse width at the gain center wavelength of 1030 nm were obtained directly from mode-locked Yb:YAG lasers pumped by a low-brightness, broad-area laser-diode with SESAM and without SESAM. A Yb:YAG microchip gain module was used for the short pulse mode-locked laser. Highly efficient CW laser operation was demonstrated by using the microchip gain module [1]. The Yb:YAG crystal (Scientific Material Corp.) was used with the ion density of 20 at.% and 3 mm x 3mm size surface perpendicular to the <100> axis with 1 mm thickness. The pump surface is used as the end mirror of the laser resonator and high-reflection coated between 1030 nm to 1080 nm laser wavelength and anti-reflection coated at 940 nm pump wavelength. Another surface of the crystal is antireflection coated for the pump and the laser wavelength. The Yb:YAG crystal is adhered to a 1 mm thickness Sapphire plate with antireflection coated on both surfaces and mounted to a copper heat-sink for cooling. The pump beam from a single emitter, low brightness wide area laser diode was focused 25 μm x 75 μm spot diameter in the laser crystal. The LD wavelength was 942 nm and the absorption efficiency of the gain module was 80%.

A nonlinear medium was used in the mode-locked laser oscillator to generate a broad emission spectrum caused by SPM. The laser beam in the cavity was strongly focused into the nonlinear medium. The pulse duration of 72 fs was obtained from Kerr-lens mode-locked laser without SESAM and the autocorrelation trace is shown Fig.1(a).

The center wavelength was 1030 nm and the spectral bandwidth was 17 nm [Fig.1(b)]. This broadening was considered to be caused in the strong self-phase modulation effect in the nonlinear material. The pulse repetition rate was 62 MHz. The average output power was 78 mW for the pump power of 2.5 W. In our knowledge, the pulse duration is shortest for mode-locked Yb:YAG laser at center wavelength of 1030 nm. Kerr-lens mode-locked Yb:YAG laser was realized by using a nonlinear medium in the laser cavity.

A pulse duration of 110 fs was achieved from the mode-locked Yb:YAG laser with SESAM and the autocorrelation trace is shown in Fig. 1 (a). The laser center wavelength and the spectral width were 1030 nm and 12 nm, respectively [Fig. 2(b)]. The average output power was 220 mW at a pump power of 1.6 W. The optical-to-optical conversion efficiency is 14% for the incident pump power. In spite of a large insertion loss of SESAM and a low mode-matching efficiency between laser beam and an elliptical multimode pump-beam from the low-brightness-laser-diode, is estimated to be around only 30%, the value of the optical-to-optical conversion efficiency is high.

In conclusion, we have demonstrated femtosecond pulse generations from a directly diode pumped Yb:YAG laser overcoming the gain spectral limit by using a nonlinear medium in the laser cavity with and without SESAM. The shortest pulse duration of 72 fs was obtained from a Kerr-lens mode-locked Yb:YAG laser with an average power of 78 mW at 1030 nm center wavelength. The shortest pulse duration of 110 fs was also generated from mode-locked Yb:YAG lasers with SESAM with a optical-to-optical conversation efficiency of 14%. We believe that short pulse nearly 50 fs and high average power over 1 W will be obtained in mode-locked Yb:YAG laser by the nonlinear medium and high power pumping.

References

[1] Matsubara, S., Ueda, T., Kawato, S., and Kobayashi, T., “Highly efficient laser oscillation of Yb:YAG at room temperature”, 2007, Jpn. J. App. Phys., **46**, L132-L134.

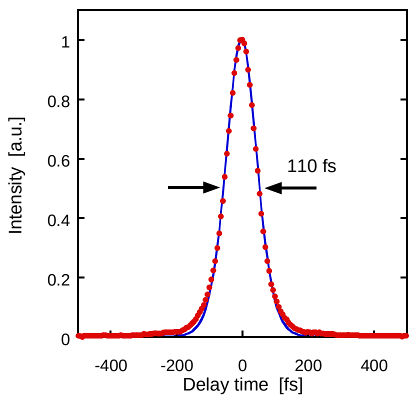


Fig.1(a). Autocorrelation trace of 72 fs pulse for the Kerr-lens mode-locked Yb:YAG laser. The experimental data (circles) and $sech^2$-fitting curve (solid curve) are shown.

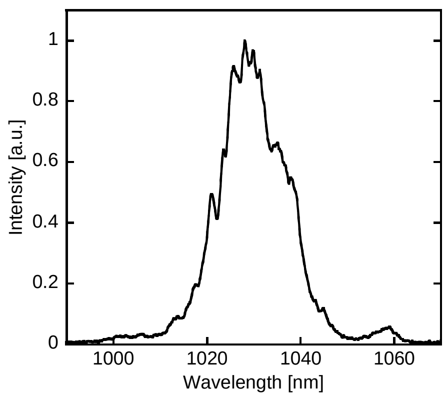


Fig.1(b). Spectrum of 72 fs pulse from the Kerr-lens mode-locked Yb:YAG laser.

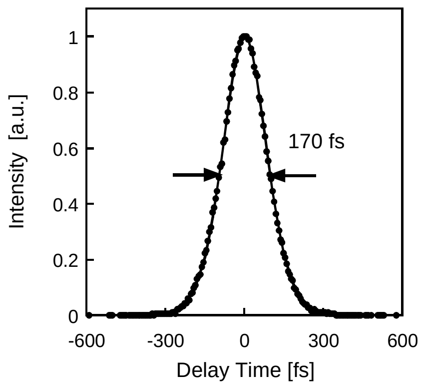


Fig. 2(a) Autocorrelation trace of the mode-locked Yb:YAG laser with SESAM. The experimental data (circles) and $sech^2$-fitting curve (solid curve) are shown. The pulse width was estimated to be 110 fs.

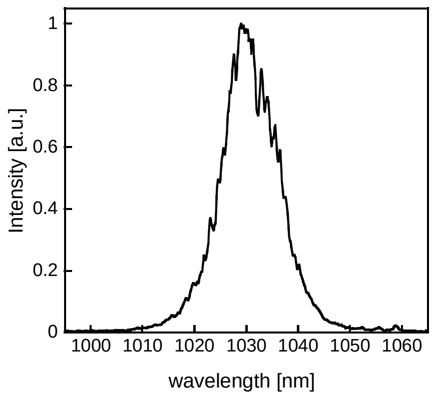


Fig. 2(b) Spectrum of the mode-locked Yb:YAG laser with SESAM. The spectral width was 12 nm in FWHM.