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1 September 2000

OPTICS
COMMUNICATIONS

Optics Communications 183 (2000) 159–163

www.elsevier.com/locate/optcom

1.25-MW peak-power Kerr-lens mode-locked Ti:sapphire laser with a broadband semiconductor saturable-absorber mirror

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Received 21 March 2000; received in revised form 30 May 2000; accepted 21 June 2000

Abstract

We report a 1.25-MW high peak-power self-starting Kerr-lens mode-locked Ti:sapphire laser pumped by a frequency-doubled diode-pumped Nd:YVO₄ laser. The mode-locking was initiated by a low-loss and broad reflection band semiconductor saturable-absorber mirror (SESAM). Pulses as short as 16 fs at a repetition rate of 75 MHz was obtained with an average output power of 1.5 W. The laser was operated at a center wavelength of 780 nm with a spectral bandwidth of 63 nm in a TEM₀₀ mode. © 2000 Elsevier Science B.V. All rights reserved.

PACS: 42.60.F; 42.65; 42.80

Keywords: Mode-locking; Ti:sapphire laser; Femtosecond pulse; Saturable absorber

Since the discovery of the Kerr-lens mode-locked (KLM) Ti:sapphire laser in 1991 [1], remarkable progress has been made in ultrashort-pulse generation. In the course of such progress, pulses as short as sub-two-cycles have been demonstrated with a combination of chirped mirrors and a pair of prisms as dispersion-controlling elements [2,3]. Few emphases, however, have been placed on the generation of sub-20-fs pulses with peak powers exceeding 1 MW. So far, three methods have been reported to increase the peak power of output pulses: cavity

dumping, high power pumping and extended-cavity. The cavity dumping has been employed to produce pulses with 5-MW peak power at a low repetition rate of 200 kHz [4]. This is relatively complex and expensive because it requires a high-quality Bragg diffraction cell in a laser cavity. On the other hand, peak powers more than 1 MW were extracted from standard KLM lasers by increasing pump power and reducing pulse duration. Xu et al. [5] produced sub-10-fs pulses with a peak power of 1.5 MW using a mirror-dispersion-controlled KLM Ti:sapphire laser operated at a repetition rate of 75 MHz, while Beddard et al. [6] obtained a peak power of 1 MW at a repetition rate of 110 MHz with a ring-cavity KLM laser. Recently, the extended-cavity has been employed to produce a peak power of more than 1 MW

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by reducing the repetition rate [7]. Although a saturable Bragg reflector (SBR) was used in the extended-cavity laser, the function of the SBR was not to make the mode-locking self-start but to stabilize the mode-locking. In addition, the average output power was very low, and the spectral bandwidth was narrow owing to the narrow reflection bandwidth of the SBR. To our knowledge, no self-starting KLM Ti:sapphire lasers capable of generating a peak power of more than 1 MW at a repetition rate near 100 MHz have been demonstrated. In the paper we describe the design and the operation of a 1.25-MW peak-power self-starting KLM Ti:sapphire laser initiated with a low-loss, broadband SESAM.

The schematic of the system is shown in Fig. 1. We first set up a standard 4-mirror Z-fold resonator without a SESAM. The 4-mm long Ti:sapphire crystal was highly doped at 0.25% to have a large absorption rate of 4.1 cm^{-1} , and yet the figure of merit was greater than 150 (Union Carbide). The concave mirrors (CVI Laser) have a radius-of-curvature of 10-cm and a pair of fused-silica prisms separated by 45 cm are accommodated in the long arm of the cavity for dispersion compensation. The prisms and the output coupler were mounted on two separate rails so as to permit varying the prism separation easily. The coolant temperature was kept at -10°C in order to remove heat from the crystal

efficiently. The surface of the crystal was purged with dry air. Excessive heat in the pumped volume results in a reduction of the upper-state lifetime. This causes an enhanced oscillation threshold and a reduction of output power [8]. At this temperature, we obtained the highest CW output power. The 3.5-mm-thick BK7 output coupler has a transmittance of 20% at a central wavelength of 800 nm. The total cavity length is 181.5 cm, with 65.5 cm in one arm of the laser and 106 cm in the side of the dispersion-compensating prisms. A pair of extra-cavity fused-silica prisms separated at an interval of 50 cm was used to compensate for chirp and spatial (transverse) dispersion.

The laser was pumped by a 10-W frequency-doubled diode-pumped Nd:YVO₄ laser (Spectra-Physics Millennium X) through a 88-mm focal-length lens. An output power of 1.9 W with a repetition rate of 82 MHz was obtained using a pump power of 8 W. Fig. 2 shows a typical interferometric autocorrelation trace and the corresponding spectrum. The pulse duration estimated from this measurement was 22 fs, assuming a $\text{sech}^2(t)$ intensity profile, corresponding to a peak power of 1.1 MW. The FWHM bandwidth of the spectrum is 40 nm and the central wavelength is 780 nm. Critical alignment of the cavity was necessary to achieve such high output power in a TEM₀₀ mode.

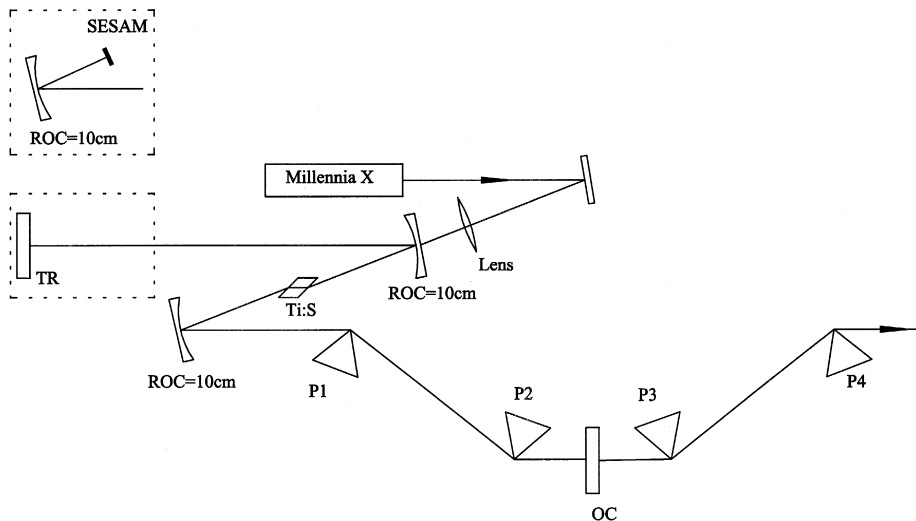


Fig. 1. Schematic of the high peak-power self-starting Kerr-lens mode-locked Ti:sapphire laser. Ti:S, Ti:sapphire crystal; ROC, radius of curvature; P1, P2, fused-silica prisms; OC, output coupler; TR, total reflector.

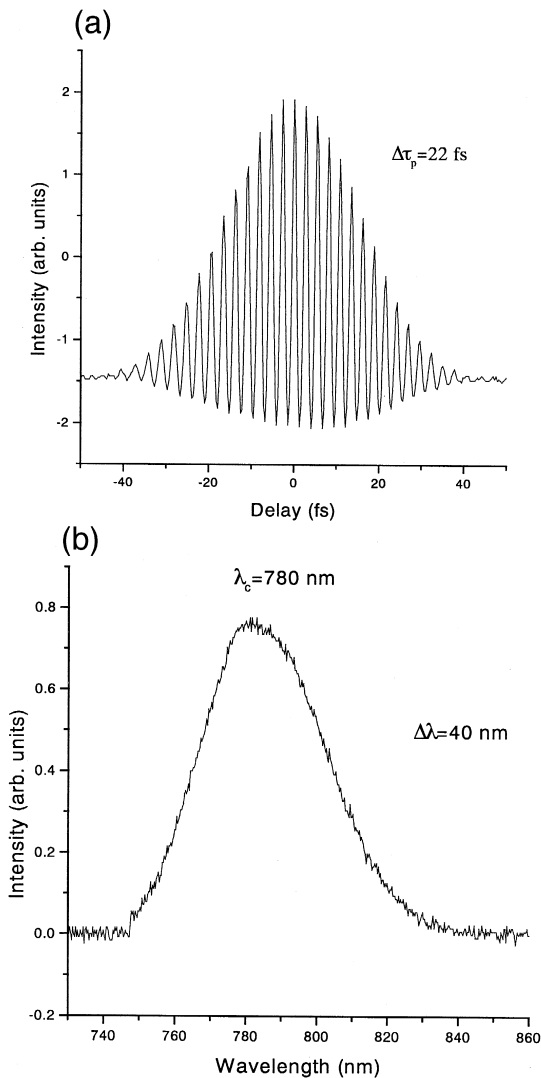


Fig. 2. Measured autocorrelation trace (a) and spectrum (b) of the KLM Ti:sapphire laser without a SESAM. The pulse duration $\Delta\tau_p$ is estimated to be 22 fs, assuming a $\text{sech}^2(t)$ intensity profile. The central wavelength λ_c is 780 nm, and the corresponding band-width $\Delta\lambda$ is 40 nm.

In order to achieve self-starting operation and relieve the critical alignment of the cavity, we used a low-loss, broadband SESAM and a concave mirror with a radius-of-curvature of 10 cm instead of the total reflector shown in Fig. 1. The optimum separation between the mirror and the SESAM was 46 mm. The SESAM was glued onto a copper heat sink by a

kind of two-component thermoconductive epoxy. No special cooling system was used to cool the SESAM. We also replaced the 20% output coupler by a 30% one to avoid the damage to the SESAM. One of the current techniques for making a broadband SESAM is to stack a metal layer (silver or gold) onto a grown semiconductor saturable absorber, and then etch off the semiconductor substrate [9,10]. The major problem of such a metal-based SASAM is its high non-saturable loss. Although the reflectivity of bare silver or gold is greater than 98% in the range of visible and near-infrared wavelength, such a reflectivity is difficult for a semiconductor-film mirror coated by gold or silver to maintain. The non-saturable loss of silver mirror SESAMs has been reported to be 3–5% [9,10]. Reducing the loss of the SESAM is essential for high peak-power operation of more than 1 MW. The SESAM employed in the present experiment was featured by its low-loss and broad reflection band. The detailed structure and manufacturing process of the SESAM have been described elsewhere [11]. To meet the requirements for low-loss over wide spectral range, low refractive-index dielectric, Al_2O_3 and high refractive-index semiconductor, AlGaAs, were selected as stacking materials. The index of the AlGaAs is about twice as large as that of the Al_2O_3 . Stacking these materials on a metal mirror brought about a reflectance of 99% at a wavelength of 785 nm, which was much higher than that of a SESAM without dielectric layers. The measured reflectance was larger than 98% in a wide spectral range of 715 to 915 nm. The non-saturable loss was therefore estimated to be less than 2%. The saturable-absorber was a 5-nm thick single $\text{In}_{0.08}\text{Ga}_{0.92}\text{As}$ quantum well sandwiched by two layers of $\text{Al}_{0.65}\text{Ga}_{0.35}\text{As}$ (the total thickness was 160 nm), which were grown by MBE on a GaAs substrate at a temperature of 500°C. The saturation measurement of the SESAM with 22 fs pulses at the center wavelength of 780 nm resulted in a saturation fluence of 220 $\mu\text{J}/\text{cm}^2$ and a maximum modulation depth of 0.82%.

When the SESAM-starting KLM Ti:sapphire laser was pumped at a power of 10 W, an output power of 1.5 W was obtained with a repetition rate of 75 MHz. Fig. 3 shows a typical interferometric autocorrelation trace and the corresponding spectrum of the output pulses. Assuming a $\text{sech}^2(t)$ intensity profile,

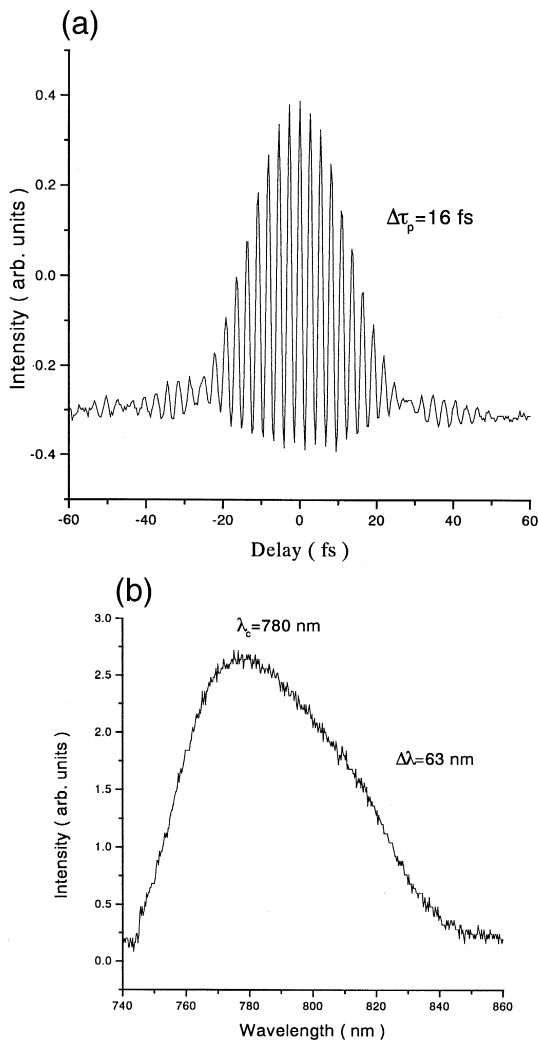


Fig. 3. Measured autocorrelation trace (a) and spectrum (b) of the self-starting KLM Ti:sapphire laser initiated by the SESAM. The pulse duration $\Delta\tau_p$ is estimated to be 16 fs, assuming a $\text{sech}^2(t)$ intensity profile. The central wavelength λ_c is 780 nm, and the corresponding bandwidth $\Delta\lambda$ is 63 nm.

the pulse duration was estimated to be 16 fs, associated with the spectrum centered at 780 nm with a spectral width of 63 nm. The corresponding peak power is 1.25 MW. Compared with the pure KLM Ti:sapphire laser described above, the spectral bandwidth increased by 23 nm though no prism insertion and separation were changed. It seems that the newly developed SESAM provides a reliable mode-locking

mechanism even at a high peak power of more than 1 MW in a TEM_{00} mode. The decreased output power is probably ascribed to the 30% output coupler, considering that a 20% output coupler produced the highest output power of 12%, 20% and 30% ones at the operation of the KLM laser without the SESAM. The beam radius on the SESAM was calculated to be 35 μm , resulting in a fluence of 1.7 mJ/cm^2 incident on the SESAM. This incident pulse energy was almost 8 times above the saturation fluence, but no multiple pulsing was observed. When the 20% output coupler was used in the place of the 30% one at a pump power of 8 W, the maximum average output power was 1.7 W. Though almost the same spectrum width was maintained, the spectrum profile became unstable. We therefore had to change the incident spot on the SESAM frequently in order to maintain a stable bandwidth of 63 nm. The pulse fluence incident on the SESAM was estimated to be 2.9 mJ/cm^2 . We deduced from the above phenomenon that the SESAM was damaged by this level of incident fluence.

In conclusion, we have demonstrated a 1.25-MW self-starting KLM Ti:sapphire laser. The mode-locking was initiated with a newly developed broadband SESAM. It seems reasonable to say that the SESAM has paved the way for a reliable high peak-power operation of Ti:sapphire laser in the femtosecond regime. We will use the laser system described here as a high-intensity pump source for an optical parametric oscillator.

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