Low-threshold self-starting femtosecond Ti:sapphire laser

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A low-threshold self-starting Kerr-lens mode-locked Ti:sapphire laser is demonstrated that uses a tight-focusing cavity design in conjunction with a semiconductor saturable-absorber mirror (SESAM). With 3% and 12% output couplers, we achieve mode-locking thresholds as low as 390 and 600 mW, respectively. Stable femtosecond laser pulses with average power of 114 mW are generated at a pump power of 1.2 W, which corresponds to a typical duration of 17 fs and bandwidth of 47 nm. Mode-locking operation is achieved in a pump power range of 600 mW to 4.8 W at an output coupling of 12%; the advantages of using a SESAM for low-power mode-locking operation are demonstrated. © 2006 Optical Society of America

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1. Introduction

With the rapid development of ultrafast laser techniques, the Kerr-lens mode-locked (KLM) Ti:sapphire laser has become a common tool in many fields such as frequency metrology, biomedical imaging, and high-speed optical communication.[1] Combined with chirped-pulse amplification, it is also capable of producing an extreme intensity greater than 10^{21} W/cm^2 at a tabletop size.[2] However, because of its high cost, a femtosecond Ti:sapphire laser still is an expensive high-technology device for many users, which greatly limits its widespread application. Normally a standard KLM Ti:sapphire laser can produce average powers of ~500 mW with a 5 W pump laser at the 532 nm wavelength at which the diode-pumped, all-solid-state pump laser is the most costly, whereas those pump lasers that generate several hundred milliwatts of power can be more than five times lower in cost. In fact, in many applications, for example, for the seed pulse of a chirped-pulse amplification system, the average output power of a femtosecond laser is not critical. Therefore there is widespread interest in developing a low-cost femtosecond laser. Although the use of a diode-pumped KLM Cr:LiSAF laser is a simple way to produce femtosecond laser pulses,[3] the unreliability of high-power red diode lasers and poor beam quality limit its use.

Femtosecond Ti:sapphire lasers with low-power pump sources can significantly reduce the cost of ultrafast laser technology, and a mode-locking threshold of less than 1 W has been demonstrated.[4–6] Recently Kowalevicz *et al.* demonstrated an ultralow-threshold KLM Ti:sapphire laser by extending the laser cavity and using a double-pass pump configuration. Stable mode locking was reported with an incident pump power of 156 mW and an output transmissivity of ~1%. In general, initiating and sustaining mode locking become more difficult at low pump power, which obviously can cause the long-term stability of a femtosecond Ti:sapphire laser to deteriorate. In this paper we present a low-threshold self-starting KLM Ti:sapphire laser with a semiconductor saturable absorber mirror (SESAM).[8] Using an output coupler with a transmissivity of 3%, we achieved reliable mode locking with a threshold power of 390 mW. Compared with pulse durations of 18 fs (Ref. 4) and 14 fs (Ref. 7) with Ti:sapphire crystal lengths of 4.75 and 2 mm, respectively, we found a pulse duration of 17 fs with a 4.5 mm Ti:sapphire crystal length. To the best of our knowledge, this is the lowest threshold in a self-starting femtosecond Ti:sapphire laser with a SESAM, which demonstrates an easy-operating, low-cost femtosecond laser for many applications, such as a seeding source for chirped-pulse amplification lasers.

2. Experimental Layout

The design of the laser cavity in this experiment is similar to the standard design in previous reports, and Fig. 1 is a schematic of the experimental setup. The

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pump source is a 532 nm frequency-doubled, diode-pumped Nd:YVO_4 laser (Verdi5; Coherent, Inc.), and the gain medium is a 4.5 mm long Brewster-cut Ti:sapphire crystal with an absorption coefficient of $\alpha = 4\ cm^{-1}$ (Shanghai Institute of Optics and Precision Mechanics, China). To increase the power density inside the crystal we used a pair of focusing mirrors, M1 and M2, each with a 50 mm radius of curvature (ROC). Both mirrors are coated with dichromatic dielectric films that have transmissivities greater than 95% at 532 nm and reflectivities greater than 99.8% at 750–900 nm. Use of focusing mirrors with shorter ROCs will considerably reduce the pump threshold power. Our simulation has shown that the mode size in the crystal, compared with a mode size of 26 μm in the standard cavity (M1 and M2 with 100 mm ROC), will be reduced to 12 μm for the shorter-ROC mirrors. With the decrease of the focal spot area $(26/12)^2$, or 4.7, the laser intensity might be increased ~4.7 times in the crystal. In fact, because the intensity-induced lens inside the Kerr medium is proportional to the square of the beam spot area,[9] i.e., 4.7^2, the likelihood of obtaining self-mode-locking will be enhanced greatly, which will enable us to considerably reduce the mode-locking threshold.[4,9] To pursue a good mode match we designed the focal length of pump lens F to be 50 mm, which corresponds to a focused spot of 8 μm, so the pump coefficient is 0.66, which approaches the optimum pump coefficient of 0.5 based on the stimulation.[10] To self-start the mode locking we used a SESAM as the end reflector at the shorter arm, and folding mirror M3 with 100 mm ROC was inserted into the arm to focus the laser beam on the SESAM. The SESAM used a 5 nm thick single InGaAs quantum well as the absorber, sandwiched by two AlGaAs layers with a total thickness of 160 nm, which were grown by molecular beam epitaxy onto a GaAs substrate at a temperature of 500 °C. To increase reflectivity and bandwidth, we inserted a low-index dielectric layer between the silver and the semiconductor films,[8] which resulted in a bandwidth wider than 200 nm and a reflectivity greater than 99%; such a SESAM has been successfully used in a high-average-power Ti:sapphire laser for self-starting of mode locking.[11] Obviously the SESAM will support a shorter pulse duration and a lower mode-locking threshold. In the longer arm, we set a pair of Brewster-cut fused-silica prisms to compensate for the positive dispersion of the Ti:sapphire medium, and the residual negative dispersion balanced the self-phase modulation (SPM) in a soliton. The output coupler was placed at the end in the longer arm. Following the output coupler, another pair of prisms was set symmetrically outside the cavity to compensate for the spatial chirp of the laser beam. The distance between the prisms was approximately 62 cm to ensure that the laser could operate near the zero-dispersion point. The lengths of the short and the long arms were 54 and 104 cm, respectively, corresponding to a repetition rate of ~92 MHz. As a first step, we aligned the laser running at maximum output power in cw mode by using 1.5 W of pump power and a 12% output coupler. The SESAM was placed near the inner side of the focused plane of curved mirror M3, which ensured self-starting of mode locking at low pump powers.

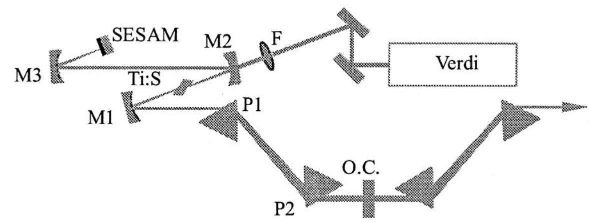

Fig. 1. Schematic diagram of the low-threshold self-starting femtosecond Ti:sapphire (Ti:S) laser: F, lens with 50 mm focal length; M1–M3, mirrors with 50 mm ROC; P1, P2, fused-silica prisms; O.C.; output coupler; Verdi; Nd:YVO_4 laser.

3. Results and Discussion

Based on the steps described above, we could observe mode locking by carefully adjusting the distance between two curved mirrors, M1 and M2, to match the inner boundary of the outer stability zone[12] and moving the prisms to a suitable insertion depth. During critical mode locking, the cw beam pattern for this type of cavity was spider shaped, a bit similar to Fig. 5(a) of Ref. 13, and not a vertical oval-shaped mode as in the standard design. In mode-locking operation, the beam spot had an approximately oval shape. When the pump power was decreased to 750 mW, we obtained stable mode-locking pulses with an average power of 48 mW by fine alignment of the cavity to compensate for the thermal lensing effect of the crystal. When the pump power decreased to 600 mW, the pulse train began self-Q-switched operation.[14] Further decreasing the pump power led to disappearance of the mode-locking pulse train. So the threshold power for mode locking was as low as 600 mW for a 12% output coupler; we measured an average output power of a stable femtosecond laser train of 24 mW for this pump power. When the pump power was larger than the threshold power, mode-locking could be self-started in the optimized cavity. The characteristics of output mode-locking power versus pump power are shown in Fig. 2. The data in the middle of the curve were neglected because we concentrated on the two ends of the pump power in the mode-locking range. When we increased the pump power to 4 W, the oscillator still ran well in the KLM mode. The mode locking became unstable when the pump power increased to more than 4.8 W, which required the cavity to be realigned because the cw and the mode-locking modes were blended. From Fig. 2 we can also find that the pump power range of stable mode locking is very wide, with a sloping efficiency of ~18%. Such a wide pumping range would satisfy various requirements for output power.

An output coupler with high transmissivity can significantly increase laser oscillation loss. To further reduce the threshold power of mode locking we re-

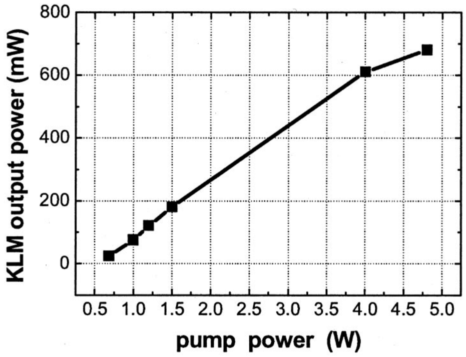

Fig. 2. Characteristics of mode-locking power versus pump power at a 12% output coupler.

Table 1. Pump Power and Output Power for Two Output Couplers

Output Coupler (%)	Threshold Pump and Output Power (mW)	Optimum Pump and Output Power (mW)	Maximum Pump and Output Power (mW)
3	Pump, 390; output, 18	Pump, 680; output, 53	Pump, 3000; output, 376
12	Pump 600; output, 24	Pump, 1200; output, 114	Pump, 4800; output, 680

placed the output coupler with a transmissivity of 3%. Threshold power as low as 390 mW was demonstrated after realignment of the laser configuration, which is as low as in previous reports. Under this condition, the pump range for stable mode-locking operation was maintained from 390 mW to 3 W, which showed obvious progress compared with previous results.[4]

Compared with standard KLM Ti:sapphire lasers, the low-threshold femtosecond oscillator has a smaller spot size and a shorter focal depth in the gain medium, which makes the mode-locking operation quite sensitive to intracavity power density and dispersion. In this experiment we first achieved self-starting Kerr-lens mode locking by decreasing the insertion depth of P2 to make the intracavity dispersion more negative than that for the optimum laser pulse duration. Especially when self-Q-switched operation occurs, the laser can convert the self-Q-switched mode into the mode-locking status only when the prism is set at an appropriate dispersion position. After mode locking is initiated, prism P2 can be inserted slowly into the path with more material to achieve optimum spectrum and pulse durations. For a 12% output coupler and a 1.2 W pump power, we measured a pulse duration of ~30 fs, with a corresponding bandwidth of ~35 nm. After optimizing the intracavity dispersion by varying the prism insertion, we obtained further pulse durations as short as 17 fs with an average power of 114 mW. In this case the time for stable mode-locking operation was longer than 20 h. With a spectrometer we observed a spectrum broadened to 47 nm, corresponding to a time–bandwidth product of 0.37, assuming a sech^2 pulse shape. Figure 3 shows a typical pulse duration and spectrum. For a 3% output coupler, a similar pulse duration and a similar spectrum were obtained at a pump power of 680 mW. Table 1 lists the pump power and the output power at each output coupler. In the experiment we used an interferometric autocorrelator to measure the pulse duration; the signal was generated and detected based on the two-photon effect of a GaAsP photodiode.[15]

The duration of the output pulse depends significantly on the pump power. To explore the characteristics of mode locking, we further measured the pulse duration versus the pump power for a 12% output coupler. Considering that the SPM varies with the laser intensity inside the Kerr medium, we optimized the cavity alignment and the prism insertion to ensure the shortest pulse duration at each measuring point. Figure 4 reveals the shortest pulse duration at the corresponding pump power. It is evident that the pulse duration changes smoothly in the range of 1.1–2.5 W. When the pump power exceeds this range, no matter how the dispersion compensation is optimized, the pulse duration will became greater, in agreement with the result of Wang *et al.*[5] We believe that this performance can be explained as follows: Femtosecond operation with a SESAM is sustained by both a soliton effect and a Kerr-lens effect, and there are critical operating points for Kerr-lens mode locking. The pulse width is determined by a nonlinear phase shift in the Kerr medium, group-delay dispersion and pulse energy in the cavity, and the ratio of pulse duration to pulse energy, which varies with parameter $r = L_r/L_s$ that defines the discrete soliton-like shaping and the deviation of a solitary pulse from

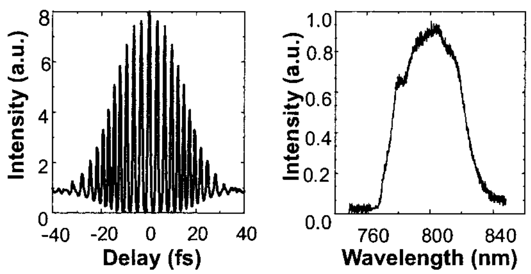

Fig. 3. Left, interferometric autocorrelation trace and (right) the corresponding spectrum for a pump power of 1.2 W. The pulse duration is 17 fs, assuming a sech^2 pulse shape, and the FWHM bandwidth is 47 nm.

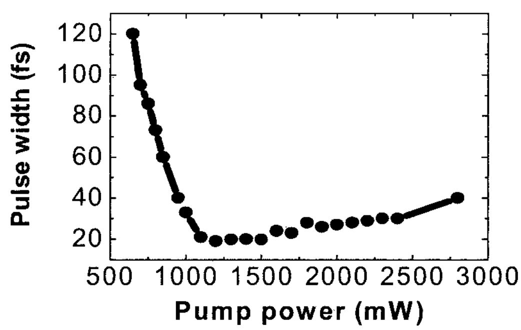

Fig. 4. Shortest pulse duration versus pump power at a 12% output coupler.

a soliton shape,[16] where L_r is the round-trip length of the resonator and L_s is the soliton period. When the pump power is lower than 1.1 W, passive amplitude modulation has a negligible influence on the pulse duration. In this case $r \to 0$ and the weak SPM easily keeps the pulse operating in the condition of an $N = 1$ soliton; in this case the pulse is inversely proportional to the pump power. In the range of 1.1–2.5 W, the mode-locking operation is determined mainly by Kerr-lens mode locking, and the varied dispersion from the prism could prevent the pulse from having linear increments. However, when pump power exceeds 2.5 W, high power density in the medium induces strong SPM and passive amplitude modulation, which leads to mode-locking operation in a solitary system ($r > 0$) in the range of 2.5–4.8 W. Unlike in a soliton-supporting system ($r = 0$), in which the increment of the pulse width is linearly proportional to the pulse energy or the pump power and is independent of the group-delay dispersion,[16] an optimum pump power exists for the minimum pulse duration. In this experiment the shortest pulse width was obtained at 1.2 W pump power.

4. Conclusions

In conclusion, we have successfully built a self-starting low-threshold femtosecond Ti:sapphire laser by using a tight-focus cavity design and a SESAM. The use of the SESAM improves stability at low pump operation and relaxes the requirement for cavity alignment. Compared with mode locking without a SESAM, the pump power range for mode locking was broadened from 0.61–1.7 to 0.6–4.8 W for an output coupler of 12%, in which the range of pump power for mode locking was widened by as much as a factor of 3. A similar case occurs for a 3% output coupler, too. Focusing mirrors of 50 mm ROC efficiently improve the power density inside the gain medium, which is thus capable of achieving even low pump thresholds. Using a 12% output coupler, we demonstrated a threshold power as low as 600 mW, and stable femtosecond laser pulses with an average power of 24 mW were generated. The mode-locking operation can be maintained until the pump power reaches 4.8 W. The shortest pulse, 17 fs, was found at a pump power of 1.2 W. By replacing the output coupler with 3% transmissivity, we further demonstrated a threshold power for Kerr-lens mode locking as low as 390 mW. To our best knowledge, this is the lowest threshold power for a self-starting femtosecond Ti:sapphire pump laser with a SESAM. We believe that we can further reduce the threshold as follows: First, use a lower output coupler of 1%, which will reduce the threshold; second, use a double-pass pump configuration combined with a retroreflector, which is helpful in utilizing residual pump light and reducing threshold[2]; and third, use a longer cavity length to improve the pulse energy in the cavity, which will strengthen the Kerr effect and reduce the threshold.[7] We have shown a high-performance, low-cost femtosecond laser that we hope will make femtosecond lasers more readily available and easier to handle.

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References

1. D. E. Spence, P. N. Kean, and W. Sibbett, "60-fsec pulse generation from a self-mode-locked Ti:sapphire laser," Opt. Lett. **16,** 42–44 (1991).
2. M. Aoyama, K. Yamakawa, Y. Akahane, J. Ma, N. Inoue, H. Ueda, and H. Kiriyama, "0.85-pW, 33-fs Ti:sapphire laser," Opt. Lett. **28,** 1594–1596 (2003).
3. J. R. Lincoln, M. J. P. Dymott, and A. I. Ferguson, "Femtosecond pulses from an all-solid-state Kerr-lens mode-locked Cr: LiSAF laser," Opt. Lett. **19,** 1210–1212 (1994).
4. K. Read, F. Blonigen, N. Riccelli, M. Murnane, and H. Kapteyn, "Low-threshold operation of an ultrashort-pulse mode-locked Ti:sapphire laser," Opt. Lett. **21,** 489–491 (1996).
5. Q. Y. Wang, J. M. Dai, W. L. Zhang, H. Y. Liang, R. B. Zhang, and Q. R. Xing, "15 fs-pulse generation from a self-mode-locked Ti:sapphire laser with low pump power," Chin. J. Lasers A **24,** 1057–1060 (1997).
6. K. Lamb, D. E. Spence, J. Hong, C. Yelland, and W. Sibbett, "All-solid-state self-mode-locked Ti:sapphire laser," Opt. Lett. **19,** 1864–1866 (1994).
7. A. M. Kowalevicz, Jr., T. R. Schibli, F. X. Kärtner, and J. G. Fujimoto, "Ultralow-threshold Kerr-lens mode-locked $TiAl_2O_3$ laser," Opt. Lett. **27,** 2037–2039 (2002).
8. Z. Zhang, T. Nakagawa, H. Takada, K. Torizuka, T. Sugaya, T. Miura, and K. Kobayashi, "Low-loss broadband semiconductor saturable absorber mirror for mode-locked Ti:sapphire laser," Opt. Commun. **176,** 171–175 (2000).
9. G. J. Valentine, D. Burns, and D. W. Sibbet, "Low-threshold all-solid-state femtosecond lasers," in *Femtosecond Technology: From Basic to Application Prospects,* T. Kamiya, F. Saito, O. Wada, and H. Yajima, eds. (Springer-Verlag, 1999), pp. 258–263.
10. W. J. Ling, J. A. Zheng, Y. L. Jia, and Z. Y. Wei, "Theoretical study on the Ti:sapphire laser with low pump threshold," Acta Phys. Sin. **54,** 1619–1622 (2005).
11. J. H. Sun, R. B. Zhang, Q. Y. Wang, L. Chai, D. Q. Pang, J. M. Dai, Z. G. Zhang, K. Torizuka, T. Nakagawa, and T. Sugaya, "High-average-power self-staring mode-locked Ti:sapphire laser with a broadband semiconductor saturable-absorber mirror," Appl. Opt. **40,** 3539–3541 (2001).
12. M. S. Pshenichnikov, W. P. de Boeij, and D. A. Wiersma, "Generation of 13-fs, 5-MW pulses from a cavity-dumped Ti: sapphire laser," Opt. Lett. **19,** 572–574 (1994).
13. J. H. Lin, M. D. Wei, W. F. Hsieh, and H. H. Wu, "Cavity configurations for soft-aperture Kerr-lens mode locking and multiple-period bifurcations in Ti:sapphire lasers," J. Opt. Soc. Am. B **18,** 1069–1075 (2001).
14. Q. R. Xing, W. L. Zhang, and K. M. Yoo, "Self-*Q*-switched self-mode-locked Ti:sapphire laser," Opt. Commun. **119,** 113–116 (1995).
15. J. K. Ranka, A. L. Gaeta, A. Baltuska, M. S. Pshenichnikov, and D. A. Wiersma, "Autocorrelation measurement of 6-fs pulses based on the two-photon-induced photocurrent in a GaAsP photodiode," Opt. Lett. **22,** 1344–1346 (1997).
16. T. Brabec, Ch. Spielmann, and E. Krausz, "Mode locking in solitary lasers," Opt. Lett. **16,** 1961–1963 (1991).