Appl. Phys. B 58, 323–326 (1994)

Applied Physics B Lasers and Optics

Tunable Ti:Sapphire Regenerative Amplifier for Femtosecond Chirped-Pulse Amplification

K. Yamakawa*, **A. Magana, P.H. Chiu**

Continuum, 3150 Central Expressway, Santa Clara, CA 95051, USA (Fax: +1-408/727-3550)

Received 12 October 1993/Accepted 25 November 1993

Abstract. We describe a tunable Ti:Sapphire regenerative amplifier which is used to amplify 120 fs pulses from a self-mode-locked Ti:Sapphire laser to energies in the range of 7–12 mJ from 760 nm to 855 nm. We have used three sets of cavity mirrors in the regenerative amplifier to vary the output wavelength of the laser.

PACS: 42.55.Rz, 42.60.–v, 42.65.Re

The study of ultrafast processes in nonlinear optics, physics and chemistry relies on the use of laser systems that produce tunable ultrashort optical pulses. Traditionally, the passively mode-locked dye laser has been a widely used, reliable source of femtosecond pulses. The Colliding-Pulse Mode-locked (CPM) dye laser made possible generation of pulses with less than 100 fs and 1 kW peak power [1]. Applications of nonlinear spectroscopy require much higher peak-power pulses. The combination of CPM dye laser and dye amplifier can produce gigawatt peak powers [2]. However, the CPM dye laser and the amplifier have limited tunability and produce a large amount of Amplified Spontaneous Emission (ASE). Furthermore, these systems are not easily scaled in energy to the millijoule level due to the low saturation fluence (mJ/cm^2) of the dye amplifier.

The large gain bandwidth of Ti:Sapphire (Ti:Al_2O_3), which permits both an extensive tuning range and the capability of ultrashort pulse generation, has led to its becoming an attractive solid-state laser material. Spence et al. reported on a self-mode-locked Ti:Sapphire laser over the wavelength range of 750–950 nm by using two sets of optics [3]. Recently pulses with a duration less than 11 fs from a self-mode-locked Ti:Sapphire laser has been reported by Asaki et al. [4]. Ti:Sapphire has also been shown to be an effective amplifier for producing ultrahigh peak-power pulses [5–7]. A study of a tunable high-peak power, ultrashort pulse Ti:Sapphire laser is suitable for III–V semiconductor material systems. However, there has been no report of a tunable Ti:Sapphire amplifier used for femtosecond pulse amplification.

We report here a tunable Ti:Sapphire regenerative amplifier pumped by a frequency-doubled Q-switched Nd:YAG laser which is used to amplify 120 fs pulses at a 20 Hz repetition rate. The generation of 131–175 fs pulses of several milijoules of energy, tunable from 760 nm to 855 nm, is achieved by using three sets of cavity mirrors in the regenerative amplifier. Forty-eight gigawatt peak-power pulses of duration as short as 140 fs have been generated at 790 nm.

A schematic of the laser system is shown in Fig. 1. Our system uses the technique of Chirped-Pulse Amplification (CPA) [8] to amplify the output of a self-mode-locked Ti:Sapphire laser. This technique has been applied to a variety of solid-state materials, including Nd:Glass [9–11], alexandrite [12], Ti:Sapphire [5–7], and Cr:$LiSrAlF_6$ [13]. The low energy seed pulse is obtained from a self-mode-locked Ti:Sapphire laser (Coherent, Mira) which produces 10 nJ, 120 fs ($\Delta\nu\,\Delta\tau = 0.49$) pulses at a 76 MHz repetition rate. This laser can be tuned with an intracavity birefringent filter over the wavelength range of 770–900 nm. The seed pulses were stretched by a factor of approximately 1500 with a 4-pass grating stretcher. The stretcher consists of a single 1800 lines/mm holographic grating; a 600 mm focal-length achromatic lens, and two zero-degree mirrors. The incidence angle on the grating is 55°, at 790 nm. The lens is a cemented doublet and exhibits a $df/d\lambda = 0.58$ µm/nm at 800 nm. The effective length of the 4-pass grating stretcher is 60 cm and overall throughput efficiency of greater than 50% with pulses stretched to 180 ps at 790 nm.

After the stretcher and Faraday isolator, only 1 nJ remains to seed the regenerative amplifier. The regenerative amplifier is a TEM_{00} cavity with a beam radius w_0 of 2.0 mm [6]. The resonator is 1.65 m long and uses two cavity mirrors. The cavity consists of a 10 m radius of curvature concave dielectric mirror and a 20 m radius of curvature convex dielectric mirror. The Brewster-cut Ti:Sapphire crystal is 15 mm long with 0.15 wt.% doping. The frequency-doubled Q-switched, 20 Hz Nd:YAG laser (Continuum, NY-60) was used to pump the regenerative amplifier. This rod is end pumped with 60 mJ, 7 ns pulses of 532 nm radiation. A

* On leave from Institute of Laser Engineering, Osaka University, 2–6, Yamada-oka, Osaka 565, Japan (Fax: +81-6/877-4799)

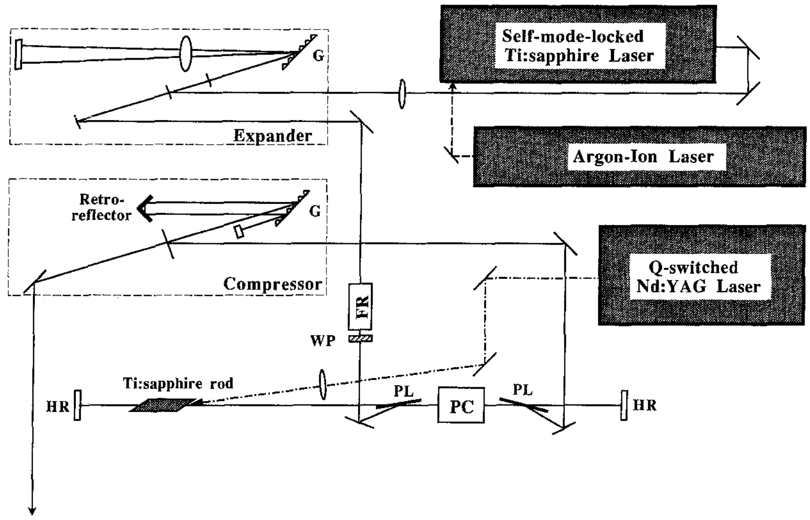

Fig. 1. Schematic of the tunable Ti:Sapphire-laser system. PC: Pockels cell; PL: thin-film polarizer; HR: high-reflection mirror; WP: 1/2 wave plate; FR: Faraday isolator; G: grating

50 cm focal-length lens images the pump beam onto the Ti:Sapphire crystal with the pump fluence on the first face of the crystal measured to be $\approx 1.2\ \mathrm{J/cm^2}$. Pulse injection in the regenerative amplifier is achieved by an intracavity Pockels cell placed between thin film dielectric polarizers. The Pockels cell was coated with a sol-gel material to avoid spectral modulation of the chirped pulse due to etalon effects. Thin film polarizers were coated 80% s-polarization reflectivity and >95% p-polarization transmission having a bandwidth of 130 nm centered at 800 nm. A high voltage thyratron pulser capable of producing 6 kV pulses with a FWHM of 5 ns was used to drive the Pockels cell. Pulsing the Pockels cell to its half-wave voltage traps a single pulse inside the cavity, where it remains until the pulse buildup reaches a threshold value. The same electrical pulse returns after passing through a delay line to the Pockels cell, cavity dumps the amplifier, and yields a single pulse with an energy as high as 12 mJ. The number of round trips in the regenerative amplifier is 12.

In general, to tune far from the gain center of Ti:Sapphire, an intracavity birefringent filter is necessary. We have tried to use the birefringent filter inside our regenerative amplifier to tune the laser wavelength. It was found that only a limited tuning range (785–820 nm) can be achieved when the cavity mirrors were coated at high reflectance between 760–840 nm (centered at 800 nm). A large amount of ASE was observed regardless of increasing the seeding pulse energy up to 2 nJ when the regenerative amplifier was operated outside the limited tuning range. The reason can probably be attributed to the fact that there were not enough round trips for the birefringent filter to actively suppress the gain at the peak of the Ti:Sapphire (790 nm). Also, the intracavity birefringent filter was found to produce an etalon effect. Therefore, we have used three sets of cavity mirrors to vary the output wavelength of the laser from 760 nm to 855 nm. Mirror-set 2 are high reflector centered at 800 nm, where mirror-sets 1 and 3 were centered at 730 nm and 860 nm, respectively, and both sets 1 and 3 had maximum transmission (>85%) between 780–800 nm to reduce the gain at the peak of Ti:Sapphire emission. Alignment procedures used in the tuning process could be performed within 20 min.

Figure 2 shows the output energy tuning curve generated from the regenerative amplifier [14]. The unseeded spectrum of the regenerative amplifier measures greater than 32 nm centered at 787 nm by using the mirror-set 2. The ASE spectrum of the regenerative amplifier by using the mirror-sets 1 and 3 were centered at 765 nm and 825 nm and had bandwidths of 15 nm and 14 nm, respectively. An output energy as high as 2.5 mJ has been obtained at 860 nm. The low output energy at 860 nm is due to a rapid decrease in the reflection of the thin film dielectric polarizers at wavelengths greater than 860 nm. The self-mode-locked Ti:Sapphire oscillator tunability limited the short wavelength tuning range, and the thin film dielectric polarizers limited the long wavelength tuning range. It should be mentioned that tuning from 700 nm to 900 nm can be easily achieved in principle by changing the thin film dielectric polarizers to ones centered at 750 nm and 850 nm, respectively.

The amplified pulse is double passed through a grating pulse compressor to remove the positive frequency chirp due to the stretcher. The compressor grating is identical to the stretcher grating. In principle, the compressor gratings

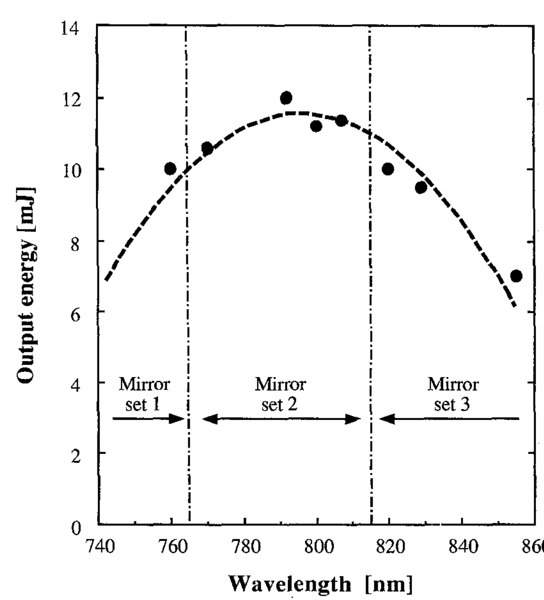

Fig. 2. Output energy tuning curve of the Ti:Sapphire regenerative amplifier in which three sets of cavity mirrors are used to vary the wavelength

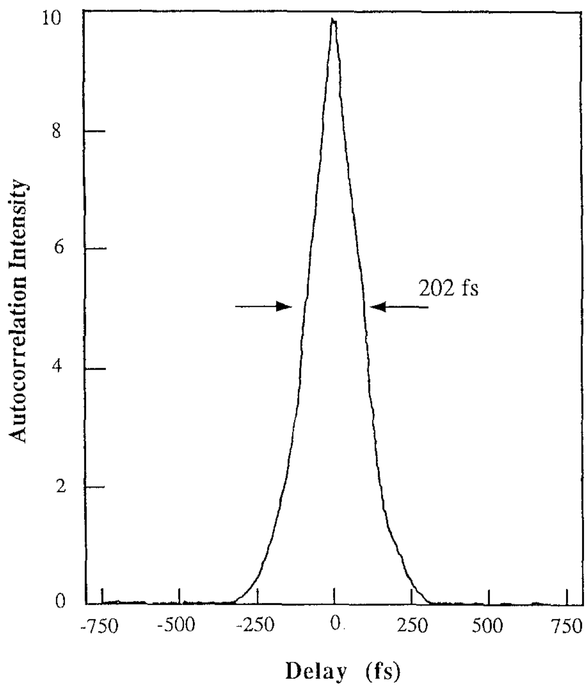

Fig. 3. Slow-scanning autocorrelation trace of the compressed pulses. The pulse duration is 131 fs, assuming a $sech^2$ shape

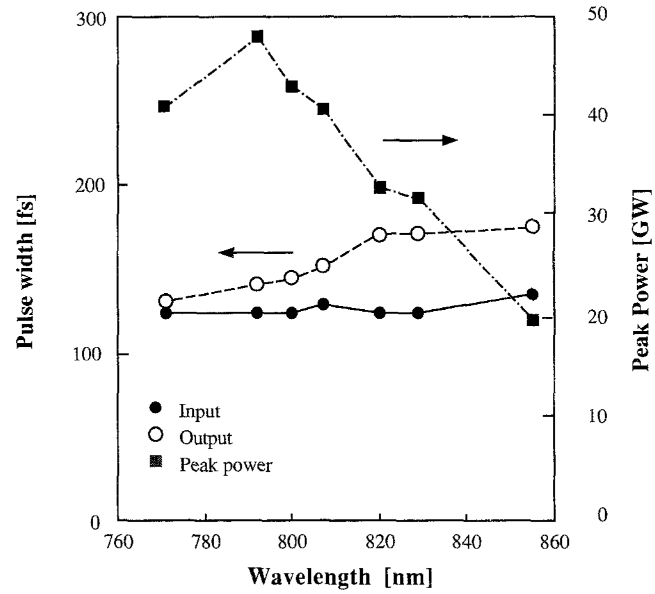

Fig. 5. The variation of the duration of the compressed pulses plotted as a function of the laser wavelength. The peak power of the compressed pulses are also shown

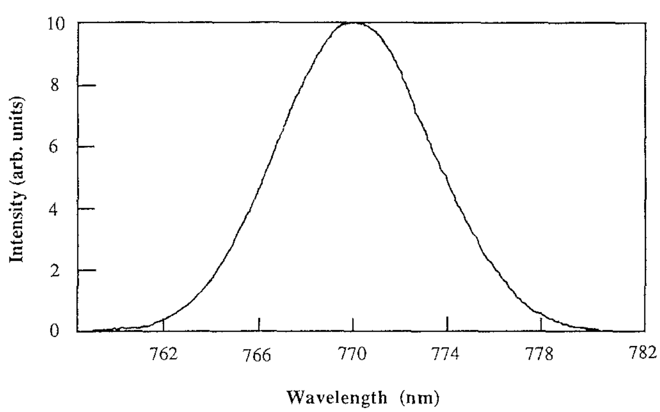

Fig. 4. Spectrum of the pulses after amplification and compression (FWHM is 7.6 nm)

should be set with the same incidence angle and as that in the stretcher. However, the spectrum of the amplified pulse was shifted 1–3 nm toward the red as compared with that of the seed pulse due to the slightly saturated amplification in the regenerative amplifier. Also to compensate for the linear dispersion inside the regenerative amplifier, the separation of the compressor gratings had to be increased as compared with effective length of the stretcher. Therefore, the incidence angle and separation of the compressor gratings were carefully adjusted for minimum pulse width.

A slow-scanning autocorrelator was used to measure the compressed pulses. A typical autocorrelation trace of the compressed pulses at 770 nm is shown in Fig. 3. The temporal FWHM is 131 fs, assuming a $sech^2$ shape. The bandwidth of the compressed pulse was 7.6 nm (Fig. 4), resulting in a time-bandwidth product of 0.50. Within the overall tuning range, the measured peak power and pulse width were 20–48 GW and 131–175 fs, respectively, as shown in Fig. 5. Pulse broadening of a factor of 1.06–1.38 was observable during the wide tuning range. We believe that the dominant broadening effect is caused by the mismatch of the higher-order dispersion introduced by the stretcher and compressor. Since the compressor must be adjusted to compensate both the spectral shift of the amplified pulse and the additional second-order dispersion in the materials, this leads to a serious mismatch of the effective dispersive lengths of the stretcher and compressor. This mismatch results most significantly in a large net third-order dispersion and resultant pulse distortions.

We have also tested a 4-pass grating pulse compressor. It consists of a single 1800 lines/mm holographic grating and a right-angle retro-reflection mirror instead of the second grating. The use of only one grating (stretcher and compressor) greatly simplifies the alignment of both the stretcher and compressor when the wavelength was tuned. The results indicated that the compressed pulses were approximately of the same duration as compared to that of the double-pass compressor.

The contrast (defined as the ratio of the peak to background intensity) of the compressed pulses at 790 nm have been determined by means of the same slow-scanning autocorrelator. The contrast ratio is measured to be 10^6 (which was limited by the dynamic range of the detection system) within 300 ps before and after the pulse peak. A peak to prepulse intensity ratio of $10^4:1$ was measured by using a fast photodiode. We detected this prepulse 12 ns before the main pulse. This corresponds to the cavity round-trip time of the regenerative amplifier. The current limit on the peak to prepulse intensity ratio is due to the extinction ratio of the polarizer placed at the output of the regenerative amplifier.

The peak to prepulse intensity ratio of better than 10^6 can be achieved by placing a pulse slicer at the output of the regenerative amplifier [15, 16].

We have determined the spatial beam quality by focusing the attenuated output and measuring the spot size at the focus with a CCD camera. The 2 mm diameter Gaussian beam at 790 nm is focused with a 1.5 m focal-length lens. The result indicates that the output beam is near diffraction limited in the s-plane and < 1.2 times diffraction limited in the p-plane. With short focal-length lens, this system can produce an intensity of $> 10^{17}$ W/cm^2. Such an intensity should be capable of generating white-light continuum in an ethylene glycol jet [2, 17, 18], ultrashort X-ray pulses from solid targets [19] or higher harmonics in atomic gases [20].

In conclusion, we have developed a tunable Ti:Sapphire-laser system capable of producing 20–48 GW pulses with 131–175 fs duration at a 20 Hz repetition rate over a spectral range from 760 nm to 855 nm. To our knowledge, this is the first demonstration of the amplified, wavelength tunable Ti:Sapphire laser based on chirped-pulse amplification. This laser system will be useful for both femtosecond spectroscopy and high-intensity physics.

Acknowledgements. We thank C. P. J. Barty for discussions and comments. K. Yamakawa acknowledges the support of a fellowship of the Japan Society for the Promotion of Science.

References

1. R.L. Fork, B.I. Greene, C.V. Shank: Appl. Phys. Lett. **38**, 671 (1981)
2. W.H. Knox: J. Opt. Soc. Am. B **4**, 1771 (1987)
3. D.E. Spence, P.N. Kean, W. Sibbett: Opt. Lett. **16**, 42 (1991)
4. M.T. Asaki, C.-P. Huang, D. Garvey, J. Zhou, H.C. Kapteyn, M.M. Murnane: Opt. Lett. **18**, 977 (1993)
5. J. Squier, F. Salin, G. Mourou, D. Harter: Opt. Lett. **16**, 324 (1991)
6. J.D. Kmetec, J.J. Macklin, J.F. Young: Opt. Lett. **16**, 1001 (1991)
7. A. Sullivan, H. Hamster, H.C. Kapteyn, S. Gordon, W. White, H. Nathel, R.J. Blair, R.W. Falcone: Opt. Lett. **16**, 1406 (1991)
8. D. Strickland, G. Mourou: Opt. Commun. **56**, 219 (1985)
9. P. Maine, D. Strickland, P. Bado, M. Pessot, G. Mourou: IEEE J. QE-**24**, 398 (1988)
10. F.G. Patterson, R. Gonzales, M.D. Perry: Opt. Lett. **16**, 1107 (1991)
11. K. Yamakawa, H. Shiraga, Y. Kato, C.P.J. Barty: Opt. Lett. **16**, 1593 (1991)
12. M. Pessot, J. Squier, G. Mourou, D. Harter: Opt. Lett. **14**, 797 (1989)
13. M.D. Perry, D. Strickland, T. Ditmire, F.G. Patterson: Opt. Lett. **17**, 604 (1992)
14. The data taken at 760 nm was obtained by using a different self-mode-locked Ti:Sapphire oscillator tuning range from 700 nm to 800 nm
15. W.E. White, J.R. Hunter, L. Van Woerkom, T. Ditmire, M.D. Perry: Opt. Lett. **17**, 1067 (1992)
16. P.H. Chiu, A. Magana, K. Yamakawa, J.D. Kmetec: In SPIE Proc. (SPIE, Los Angeles 1993) paper 1861-05 (to be published)
17. W.H. Knox, M.C. Downer, R.L. Fork, C.V. Shank: Opt. Lett. **9**, 552 (1984)
18. T.B. Norris: Opt. Lett. **17**, 1009 (1992)
19. M.M. Murnane, H.C. Kapteyn, R.W. Falcone: Phys. Rev. Lett. **62**, 155 (1989)
20. X.F. Li, A. L'Huillier, M. Ferray, L.A. Lompre, G. Mainfray: Phys. Rev. A **39**, 5751 (1989)