

Independently tunable 1.3 W femtosecond Ti:sapphire lasers passively synchronized with attosecond timing jitter and ultrahigh robustness

Jinrong Tian, Zhiyi Wei, Peng Wang, Hainian Han, Jun Zhang, Linghui Zhao, Zhaohua Wang, and Jie Zhang

Laboratory of Optical Physics, Institute of Physics, Chinese Academy of Sciences, Beijing 100080, China

Tao Yang and Jianwei Pan

Department of Modern Physics, University of Science and Technology of China, Hefei 230026, China

Received March 15, 2005

A stable passively synchronized femtosecond laser has been realized by coupling two 1.3 W mode-locked Ti:sapphire lasers with a Kerr medium. An ultralong tolerance of 10 μm for the cavity length mismatch and a timing jitter of less than 0.4 fs were obtained. The relative carrier-envelope phase slip was directly observed by measuring the heterodyne output between the two lasers. © 2005 Optical Society of America
OCIS codes: 320.7090, 140.4050, 320.7160.

Synchronized femtosecond lasers have wide applications in ultrafast pump-probe spectroscopy,¹ difference-frequency generation,² and optical frequency metrology.³ Since the 1990s, passively synchronized femtosecond Ti:sapphire lasers have been developed with different designs^{4–6}; however, because they share one gain crystal, the accompanying gain competition effect greatly limits the stability and mismatch-length tolerance of the two cavities. In addition, the output power from each branch is limited to ~ 200 mW because of the limited pump load in a single crystal. In 2001 a novel passively synchronized femtosecond laser based on a cross-phase modulation effect between a Ti:sapphire and a Cr:forsterite laser⁷ was proposed. Stable two-color femtosecond pulses at completely different wavelengths were produced with subfemtosecond timing jitter and 3 μm mismatch tolerance.⁸ In this Letter we further promote this technique by intracavity coupling of two similar femtosecond Ti:sapphire lasers into a Kerr medium, achieving an ultralong-mismatch tolerance of more than 10 μm . Pumped with two independent 532 nm pump lasers, the system can deliver 1.3 W average power from each branch, running continuously for many hours. To our knowledge this is the most stable synchronized femtosecond laser with the highest output power to date.

A schematic of the experimental setup is shown in Fig. 1. Laser cavity 1 consists of mirrors M1–M6 and output coupler OC1; laser 2 consists of mirrors M7–M12 and output coupler OC2. Both lasers adopt the standard prism-dispersion control configuration⁹ and are coupled inside Kerr medium K, where F1 and F2 are 10 cm focal-length lenses; X1, X2, and K are 4 mm thick Brewster-cut Ti:sapphire crystals, and PM1, PM3 and PM2, PM4 are pairs of fused-silica prisms with a tip-to-tip distance of 80 cm. The size of the whole system is approximately 800 mm \times 400 mm. According to Refs. 10–12, the relative de-

lay change between two laser pulses through the crystal is determined by

$$\delta t = \frac{8\pi n_2 L T_0}{S} \left(\frac{P_1 D_2}{\lambda_2 \tau_1} + \frac{P_2 D_1}{\lambda_1 \tau_2} \right), \quad (1)$$

where P_i , λ_i , D_i , and τ_i ($i=1, 2$) are the intracavity peak power, central wavelength, intracavity dispersion, and pulse duration, respectively, for lasers 1 and 2; S is the interaction area, L is the effective interaction length (shorter than the crystal length), n_2 is the nonlinear refractive index of Ti:sapphire with the value 2.5×10^{-16} cm²/W,¹³ and T_0 is the normalized initial delay between the two lasers at the entrance surface of the crystal. According to Eq. (1), we align the two pairs of concave mirrors M5, M6 and M11, M12 such that the two lasers overlap in the Kerr medium at the focal points of the concave mirrors. We let the two laser beams intersect at as small an angle as possible by using D-shaped concave mirrors with two nearby mirrors spaced 1 mm apart.

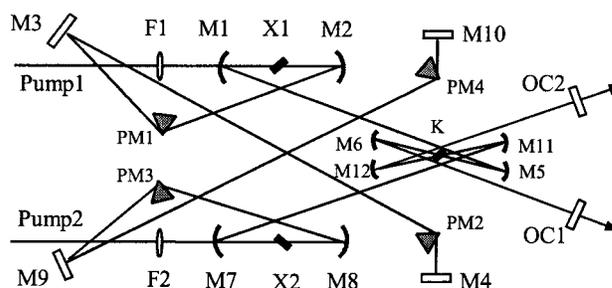


Fig. 1. Schematic of the cavity arrangement for the dual-wavelength passively synchronized Ti:sapphire laser: M1, M2, M5–M8, M11, and M12 are concave mirrors of 10 cm radius of curvature; M3, M4, M9, and M10 are flat reflectors; OC1 and OC2, are 20% output couplers; other abbreviations defined in text.

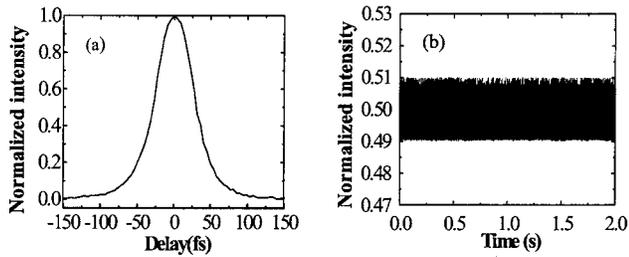


Fig. 2. (a) Normalized cross-correlation trace of the two Ti:sapphire lasers, corresponding to a FWHM of 59 fs, assuming a Gaussian profile. (b) Intensity fluctuations of the sum-frequency signal at half the peak height. The standard deviation of the fluctuations is 0.00653.

Output couplers OC1 and OC2 have a transmission of 20% to produce high output power, while all other mirrors are high reflectors of large bandwidth centered about 800 nm. Both pump lasers are frequency-doubled Nd:YVO₄ lasers (Coherent, Inc., Verdi V10) capable of delivering up to 10 W continuous wave output at 532 nm. To match the cavity length, end mirror M4 is mounted on a movable stage.

At 8 W pump power for each laser branch we obtained stable mode locking with output powers of 1.3 W from both oscillators. Further increase of the output power caused continuous components to appear in the spectrum, most probably owing to the thermal overload and strong Kerr effect in the crystal. Detecting the leakage from both lasers with two independent fast photodiodes connected to an oscilloscope (Tektronix, TDS520D), we were able to observe the synchronization between the two femtosecond lasers. Before synchronization, we measured both repetition rates with a frequency counter (Hewlett-Packard, HP 53131A) and tuned end mirror M4 manually to match the cavity length as well as possible. Through fine alignment of the overlap of the two beams in the third Ti:sapphire crystal, we obtained passively synchronized operation by observing the pulse trains on the oscilloscope. Compared with previous reports of starting and sustaining synchronization with a piezoelectric mount, we found that synchronized running in our experiment is not so critically dependent on fluctuations of cavity length. With optimized alignment, one can switch the system to synchronous from asynchronous mode merely by tuning end mirror M4 by hand. Even if the movable stage is touched within the calibration limit the synchronization remains stable, showing that the cavity-length mismatch tolerance is larger than 10 μm . We attribute this ultralong tolerance to the high peak power and large cross section inside the coupling Ti:sapphire crystal. From Eq. (1) we can see that the high peak powers allow a large delay change between the two pulse trains, which greatly extends the allowed locking range. Once in the synchronized mode, the laser could run stably synchronized for many hours. To our knowledge, this is the most stable passively synchronized femtosecond laser with an ultralong cavity-length mismatch tolerance to date, and the new piezoelectric-free configuration will enable us to carry out experiments on ultrafast pump probes, gen-

eration of nonlinear optical frequencies, etc. with unprecedented stability and feasibility.

Unlike for the asynchronous mode, we have not found observable changes in either the mode-locked power or pulse duration, and the wavelengths of both lasers could be tuned independently from 730 to 860 nm. To estimate the timing jitter we used a noncollinear cross correlator to measure the cross-correlation trace of the lasers with a 0.1 mm long β -barium borate crystal to generate a sum-frequency signal. A slit was used to block the residual fundamental and the second-harmonic waves, while a photomultiplier tube was used to detect the sum-frequency signal. Sweeping the relative time delay of the lasers, we obtained the typical cross-correlation trace shown in Fig. 2(a), which has a FWHM of 59 fs. We further determined the pulse durations of lasers 1 and 2 to be 45 and 39 fs, respectively, with Gaussian assumptions. Different materials inserted into the prisms lead to the difference in the pulse durations. From the relation between pulse duration and cross-correlation width¹¹ we can conclude that the timing jitter is less than 1 fs. Furthermore, fixing the time delay equal to the FWHM of the sum-frequency trace, we recorded the intensity fluctuation at 1 kHz bandwidth over a 2 s interval, as shown in Fig. 2(b). Numerical analysis showed that the normalized relative standard deviation was 0.00653, corresponding to a root-mean-square timing jitter of 0.4 fs.¹⁴ This result was reasonable because the high peak power leads to a much stronger cross-phase-modulation effect, which tightly locks the two lasers in the synchronous mode with an overwhelming superiority against environmental perturbations.

The ultralow timing jitter will enable us to further control the relative carrier-envelope phase slip between the two lasers with high accuracy. Such an experiment was reported by Shelton *et al.*¹⁵ based on actively synchronized Ti:sapphire lasers, which incorporated a revolutionary technique for the coherent synthesis of optical pulse trains from two independent femtosecond lasers. More recently, Betz *et al.* demonstrated the self-phase-locking phenomenon in a passively synchronized Ti:sapphire laser.¹⁶ To observe the relative carrier-envelope phase dynamics, we first tuned the central wavelengths of both lasers near 790 nm to ensure efficient spectral overlap and then superimposed on them the same layout as for the cross-correlation measurement. By removing the

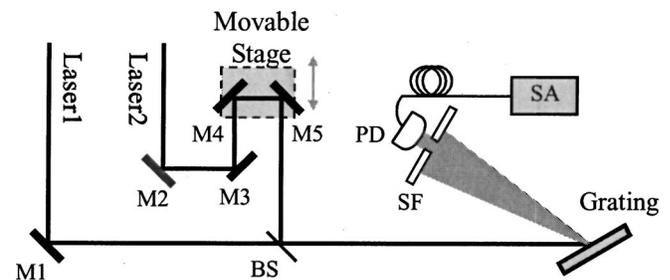


Fig. 3. Schematic of the beat frequency signal measurement: M1–M5, gold mirrors; PD, photodiode; BS, thin broadband beam splitter; SA, spectrum analyzer; SF, slit and filter; G, grating.

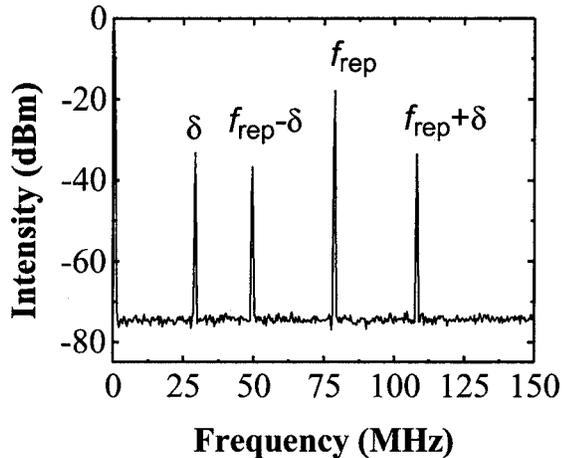


Fig. 4. rf power spectrum of both Ti:sapphire lasers over a span of 150 MHz. The resolution bandwidth and sweep time were set at 100 kHz and 50 ms, respectively. δ , beat signal; f_{rep} , repetition rate.

focusing lens and detecting the heterodyning signal with a p-i-n diode, we were able to observe the beat signal on a spectrum analyzer (Hewlett-Packard, HP E4402B).

The measurement setup is shown in Fig. 3, in which all the mirrors are gold coated to support a large bandwidth. A beam splitter (BS) was used to spatially superimpose the beams from the two lasers. Similarly to a typical f - $2f$ experiment,¹⁷ a holographic grating was used to disperse the heterodyning wavelengths for improving the signal-to-noise (S/N) ratio. After the laser overlap was optimized in both temporal and spatial domains, a heterodyne beat frequency with a S/N ratio of 41 dB was obtained at the resolution bandwidth of 100 kHz and a sweep time of 50 ms. Figure 4 depicts a typical rf power spectrum; the peak signal near 78.5 MHz represents the repetition rate f_{rep} of the laser, while the other peaks signify beat frequency δ and $f_{\text{rep}} \pm \delta$. It was observed that the beat frequency near 28.25 MHz randomly fluctuated with the environmental perturbations and that as the cavity length was tuned there was a periodic shift of the beat frequency from 0 to f_{rep} ; the corresponding cavity-length change was ~ 400 nm, in good agreement with other experimental results.¹⁶

We also attempted to observe the phase-locking regime by tuning the beat signal close to repetition rate f_{rep} . Unfortunately, we have not realized such operation under the present conditions in our laboratory, which is on the fourth level, where air flow and table vibrations are serious limitations. However, the high S/N ratio of the observed beat signal will enable us to realize very robust phase-locking operation with a stabilized phase-locked loop circuit.

In summary, we have developed a stable passively synchronized Ti:sapphire laser with two indepen-

dent gain media, with an average output power as high as 1.3 W from each branch for a pump power of 8 W. Because of the strong cross-phase-modulation effect induced by the two independent lasers in the third Kerr medium, the system can be easily switched into stable synchronous mode by tuning the cavity length by hand, which indicates that the tolerable cavity displacement is larger than 10 μm . The long sustaining time for many hours also verified the ultralong tolerance length. Measuring the fluctuations of the cross-correlation signal between the two lasers revealed a timing jitter of 400 attoseconds. Finally, we obtained a beat frequency with a S/N ratio as high as 41 dB by detecting the heterodyne output in the overlapping spectrum region.

The authors are grateful to Lingang Wu for reading the manuscript. This study was partly supported by the National Natural Science Foundation of China under grants 60225005 and 60490280. Z. Wei's e-mail address is wzhy@aphy.iph.ac.cn.

References

1. T. S. Rose, M. J. Rosker, and A. H. Zewail, *J. Chem. Phys.* **91**, 7415 (1989).
2. K. Kawase, M. Mizuno, S. Sohma, H. Takahashi, T. Taniuchi, Y. Urata, S. Wada, H. Tashiro, and H. Ito, *Opt. Lett.* **24**, 1065 (1999).
3. Th. Udem, R. Holzwarth, and T. W. Hänsch, *Nature* **416**, 233 (2002).
4. M. R. X. de Barros and P. C. Becker, *Opt. Lett.* **18**, 631 (1993).
5. Z. Zhang and T. Yagi, *Opt. Lett.* **18**, 2126 (1993).
6. A. Leitenstorfer, C. Fürst, and A. Laubereau, *Opt. Lett.* **20**, 916 (1995).
7. Z. Wei, Y. Kobayashi, Z. Zhang, and K. Torizuka, *Opt. Lett.* **26**, 1806 (2001).
8. Z. Wei, Y. Kobayashi, and K. Torizuka, in *Conference on Lasers and Electro-Optics*, Vol. 73 of OSA Trends in Optics and Photonics Series (Optical Society of America, 2002), paper CThz2.
9. M. T. Asaki, C. P. Huang, D. Garvey, J. P. Zhou, H. C. Kapteyn, and M. M. Murnane, *Opt. Lett.* **18**, 977 (1993).
10. C. Fürst, A. Leitenstorfer, and A. Laubereau, *IEEE J. Sel. Top. Quantum Electron.* **2**, 473 (1996).
11. Z. Wei, Y. Kobayashi, and K. Torizuka, *Appl. Phys. B Suppl.* **74**, S171 (2002).
12. R. R. Alfano, P. L. Baldeck, and P. P. Ho, *J. Opt. Soc. Am. B* **6**, 824 (1989).
13. S. Backus, C. G. Durfee III, M. M. Murnane, and H. C. Kapteyn, *Rev. Sci. Instrum.* **69**, 1207 (1998).
14. L.-S. Ma, R. K. Shelton, H. C. Kapteyn, M. M. Murnane, and J. Ye, *Phys. Rev. A* **64**, 021802 (2001).
15. R. K. Shelton, L.-S. Ma, H. C. Kapteyn, M. M. Murnane, J. L. Hall, and J. Ye, *Science* **293**, 1286 (2001).
16. M. Betz, F. Sotier, F. Tausser, S. Trumm, A. Laubereau, and A. Leitenstorfer, *Opt. Lett.* **29**, 629 (2004).
17. D. J. Jones, S. A. Diddams, J. K. Ranka, A. Stentz, R. S. Windeler, J. L. Hall, and S. T. Cundiff, *Science* **288**, 635 (2000).