Multiplying the repetition rate of passive mode-locked femtosecond lasers by an intracavity flat surface with low reflectivity

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Received September 2, 2004

By inserting a low-reflectivity flat surface inside the oscillator cavity, we demonstrate a flexible and phase-insensitive method for multiplying the repetition rate of a femtosecond passive mode-locked solid-state laser. Without mode matching and feedback control, we successfully multiplied the repetition rate of a passively mode-locked Cr:forsterite laser from 124 MHz to 1.24 GHz. High-repetition-rate femtosecond optical pulses with average power of >100 mW can be obtained with the demonstrated method.

OCIS codes: 140.3070, 140.7090, 320.7160.

High-repetition-rate femtosecond lasers facilitate a wide range of new applications in optical communication,[1] frequency metrology,[2] and biomedicine.[3] In general, for passive optical cavities the repetition rate of the output optical pulses is determined by the longitudinal mode spacing of the laser resonator. The simplest way to increase the repetition rate is to shorten the cavity length. A short-cavity mode-locked semiconductor laser can provide an extremely high repetition rate at the expense of a reduction in output power.[4] For high power and short pulse width, a passive mode-locked all-solid-state laser with a compact cavity is a popular choice.[5,6] But, once a high-repetition rate mode-locked laser is built, one cannot easily multiply the repetition rate without changing the cavity design. For passive mode-locked lasers, repetition-rate multiplication with a coupled external cavity is a more convenient and cost effective solution.[7] However, previously demonstrated methods require phase-sensitive mode matching to an external coupled cavity, and all previous studies operated only in the nanosecond or picosecond regime.[7–10] In this Letter we demonstrate repetition-rate multiplication by using an intracavity flat surface with low reflectivity in a passively mode-locked Cr:forsterite laser. In contrast to those in previous studies,[7–10] our intracavity low-reflectivity flat surface acts as a pulse seeder rather than as a coupler to a matched external resonant cavity. Controlling the ratio of the subcavity length can thus successfully multiply the repetition rate in the femtosecond regime in a flexible and phase-insensitive way.

Consider a linear cavity with optical path length l. Pulse repetition rate R_0 is equal to $c/2l$, where c is the speed of light. By inserting a flat surface with low reflectivity, one can partition the optical cavity into two subcavities with lengths l_1 and l_2 ($l_1 < l_2$). When $l_1/l_2 = N/M$ is a rational number (N and M are positive integers with no common denominators), for each split of a pulse the reflected pulse lags either $N/[(M+N)R_0]$ or $M/[(M+N)R_0]$ in time behind the transmitted pulse. With this property, the time interval between any split intracavity pulse and the initial single pulse can be expressed as $K/[(M+N)R_0]$, where K is an integer from 0 to $M+N-1$. The final number of intracavity pulses is $M+N$, and repetition rate R can be multiplied to $(M+N)R_0$. This means that, for a given main laser cavity, we can multiply the repetition rate by setting an appropriate ratio of the subcavity lengths.

The laser that we employed to demonstrate this approach is a femtosecond Cr:forsterite laser (Fig. 1). Its cavity is composed of one dichroic curved mirror (DC; $R = 10$ cm), two curved double-chirped mirrors (DCM2, DCM4; $R = 10$ cm), two plane double-chirped mirrors (DCM1 and DCM3), a semiconductor saturable-absorber mirror (SESAM), a 2% output coupler, and a Cr:forsterite crystal. Except for the SESAM and the output coupler, all mirrors had high transmission at the pump wavelength (1064 nm) with a broadband high-reflection coating around the lasing wavelength. We used a standard Z-fold cavity design for astigmatism compensation. The radii of curvature of the focusing mirrors were all 10 cm. The Cr:forsterite crystal was a 5 mm × 5 mm × 11.4 mm Brewster-cut crystal with an absorption coefficient of 1.5 cm^{-1}. The crystal was cooled by liquid and a TE cooler. To prevent condensation of water on the surface of the crystal, we purged the crystal with dry nitrogen. The SESAM, with a picosecond transient response, was used for self-starting and enhancement of the mode-locking force.[11] The double-pass

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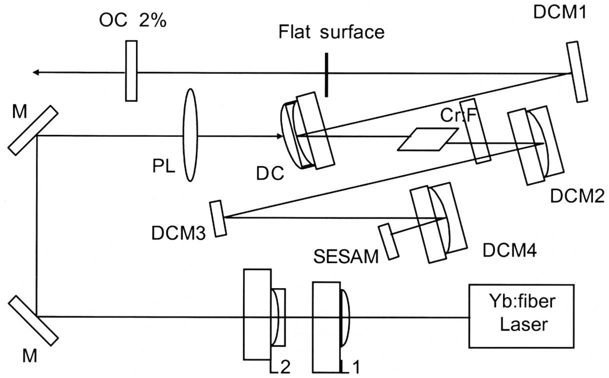

Fig. 1. Schematic diagram of the high repetition-rate femtosecond Cr:forsterite laser. M's, folding mirrors; L1, L2, mode-matching lenses; PL, pump lens; OC, output coupler; Cr:F, Cr:forsterite crystal; other abbreviations defined in text.

group-delay-dispersion (GDD) that arose from the laser crystal was 568 fs^2 near 1230 nm.[12] We employed double-chirped mirrors (DCMs) instead of prism pairs to compensate for the crystal's GDD.[13] Each DCM provides -150-fs^2 GDD near 1230 nm. To make solitonlike pulses operate in the stable regime, the net cavity dispersion should be slightly negative.[14] However, for a mode-locked cavity with a SESAM, too much intracavity energy will result in double- or multiple-pulse operation, which sets an upper limit for the output power.[15] To increase the upper limit, the net GDD should be more negative. Therefore we employed four DCMs (DCM1–DCM4) for higher available power, which resulted in -632-fs^2 net GDD within one round trip. The pump source was an Yb:fiber laser operating at 1064 nm. A self-consistent q-parameter analysis yielded a radius of the beam waist inside the crystal of approximately 28 μm, close to that of the pump beam at the same position. With 1 °C crystal temperature and 7-W pump power, we obtained 40-mW average output power at a 124-MHz repetition rate without multiple pulsing.[15] Without insertion of the flat surface, the output spectrum showed an 11-nm bandwidth at 1225 nm [Fig. 2(a)]. The background-free second-harmonic-generation autocorrelation trace measured 253 fs FWHM [Fig. 2(b)], indicating an ~164-fs pulse width when a sech^2 pulse shape was assumed.

We first placed a flat surface into the point where $l_1 = l/5$, trying to multiply the repetition rate as much as fivefold. The intracavity flat surface that we employed is BK7 glass of 150-μm thickness. To reduce bandwidth limitation from etalon effects, one side of the glass is antireflection coated for high transmission (transmission $T > 99.8\%$). The other, uncoated, surface provides ~4% reflection, serving as the intracavity flat surface. The glass was fixed onto a mirror mount and a translation stage with 1-μm resolution. After inserting the glass, we detected and monitored the output pulse train with a 2-GHz bandwidth photodetector and a 1.5-GHz bandwidth oscilloscope, respectively. Simultaneously we also measured the rf spectrum of the detected electrical signal with a rf spectral analyzer. Without careful alignment, the repetition rate did not multiply. In addition, with 8.4-W pump power the output spectrum showed a narrowed bandwidth (~0.3 nm), and the output power was 80 mW. After making the glass normal to the intracavity laser beam, we increased the average power to 180 mW. The detected pulse train showed a 620-MHz repetition rate in the oscilloscope. The rf spectrum, measured with a rf spectral analyzer, still showed the residual 124-MHz peak and some of its higher harmonics. With further fine tuning of the position of the translation stage and the tilt of the flat surface, we achieved a clean 620-MHz peak with its electrical power >60 dB higher than the noise level. Except for the fifth harmonics at 620 MHz, all harmonics of 124 MHz were attenuated below the noise level. At the same time, we can observe that the output spectrum broadened to ~9 nm FWHM [see Fig. 3(a)] with an ~3.3-nm period of slight modulation on the spectrum. This period corresponds to the free spectral range of the ~150-μm-thick BK7 glass ($n = 1.5$). Therefore this weak modulation was caused by the residual etalon effect caused by reflections from the antireflection-coated surface. It could be further reduced with improved antireflection coating or better dust and humidity control. The measured autocorrelation trace showed a 260-fs FWHM, indicating a 168-fs pulse width, assuming a sech^2 pulse shape [Fig. 3(b)]. For the 620-MHz cavity (with 180-mW output power) the pulse energy is similar to that of the 124-MHz cavity (with 40-mW output power), so a similar pulse-shaping mechanism

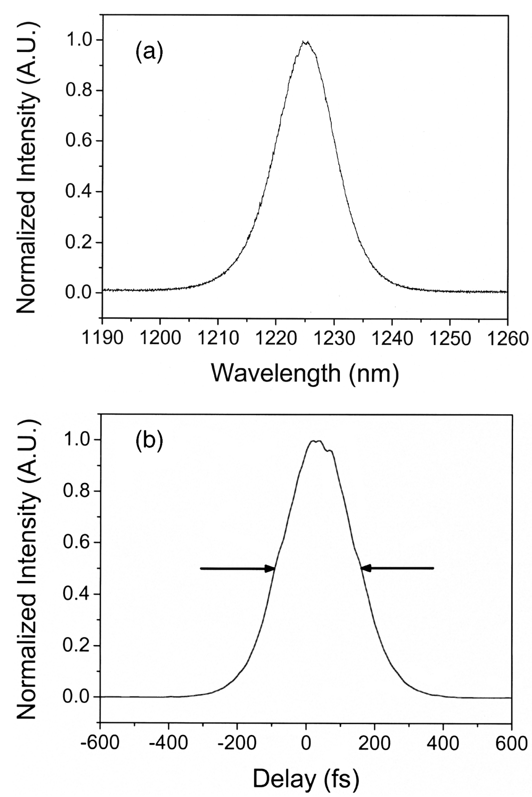

Fig. 2. (a) The spectrum and (b) the autocorrelation trace of the 124-MHz Cr:forsterite laser without a low-reflectivity flat surface inside the cavity. The arrows indicate 253-fs FWHM of the autocorrelation trace.

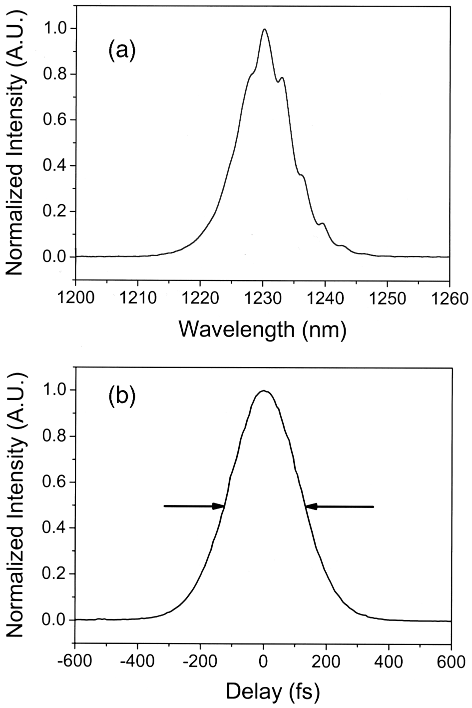

Fig. 3. (a) The spectrum and (b) the autocorrelation trace of the 620-MHz Cr:forsterite laser with a low-reflectivity flat surface inside the cavity. The arrows indicate 260-fs FWHM of the autocorrelation trace.

can be expected. We also investigated the case of $l_1 = l/10$ to reach a 1.24-GHz repetition rate, and 170-mW output power was obtained. This is to our knowledge the highest repetition rate reported for a mode-locked Cr:forsterite laser. From the rf spectrum measurement, a clean 1.24-GHz peak can be obtained with its electrical power >30-dB higher than the noise level. Except for the tenth harmonics at 1.24 GHz, all harmonics of 124 MHz were attenuated below the noise level. However, at such a high repetition rate, relatively low pulse energy cannot generate enough self-phase modulation. Therefore the pulse-shaping mechanism was dominated by the saturable absorption provided by the SESAM, and the measured pulse width thus deteriorated to 2 ps.

For the 620 MHz cavity, the detuning range for stable femtosecond-pulse generation is $\sim 5\ \mu$m. The pulse width was drastically broadened to several picoseconds if we moved the flat surface outside this range. For the 1.24 GHz cavity, the detuning range is as high as $\sim 100\ \mu$m with linear translation of the flat surface. This behavior is quite different from that observed in the coupled cavity methods,[7–10] which are phase sensitive and are easily affected by changes in their environmental conditions. Moreover, the self-consistent transverse modes of the subcavities cannot match at the flat surface. Therefore the low-reflectivity flat surface should act as a pulse seeder rather than as a coupler of the two subcavities. Pulse seeds grew to become stable femtosecond pulses, just as for the 124-MHz cavity. The output power is stable (fluctuation, <2%) when the variation in seeding position is much smaller than the length of the pulses, which was 50 μm for 168-fs pulses and ~0.6 mm for 2-ps pulses. The detailed mechanism of stable mode locking is not fully understood and requires further study.

In conclusion, we have demonstrated a flexible and phase-insensitive method with which to multiply the repetition rate of passively mode-locked femtosecond solid-state lasers. A glass with a high-transmission coating on one side can serve as a pulse seeder inside the cavity. With proper arrangement of the ratio of subcavity lengths, the repetition rate of the passively mode-locked Cr:forsterite laser can be multiplied to 620 MHz in the femtosecond regime and, for the first time to our knowledge, to 1.24 GHz.

This research is sponsored by National Science Council of Taiwan grant NSC 93-2120-M-002-004, by National Health Research Institute of Taiwan grant NHRI-EX93-9201EI, by National Science Foundation grant ECS-01-19452, and by U.S. Air Force Office of Scientific Research contract FA9550-04-1-0011. C.-K. Sun's e-mail address is sun@cc.ee.ntu.edu.tw.

References

1. T.-M. Liu, S.-P. Tai, H.-H. Chang, and C.-K. Sun, Opt. Lett. **26,** 834 (2001).
2. R. Holzwarth, T. Udem, T. W. Hänsch, J. C. Knight, W. J. Wadsworth, and P. St. J. Russell, Phys. Rev. Lett. **85,** 2264 (2000).
3. S.-W. Chu, S.-Y. Chen, T.-H. Tsai, T.-M. Liu, C.-Y. Lin, H.-J. Tsai, and C.-K. Sun, Opt. Express **11,** 3093 (2003), http://www.opticsexpress.org.
4. Y. K. Chen, M. C. Wu, T. Tanbun-Ek, R. A. Logan, and M. A. Chin, Appl. Phys. Lett. **58,** 1253 (1991).
5. A. Bartels, T. Dekorsy, and H. Kurz, Opt. Lett. **24,** 996 (1999).
6. T. R. Schibli, T. Kremp, U. Morgner, F. X. Kärtner, R. Butendeich, J. Schwarz, H. Schweizer, F. Scholz, J. Hetzler, and M. Wegener, Opt. Lett. **26,** 941 (2001).
7. J. Hirano and T. Kimura, Appl. Phys. Lett. **12,** 196 (1968).
8. M. N. Kong, J. K. Chee, and J. M. Liu, Opt. Lett. **16,** 73 (1991).
9. G. S. He, Y. Cui, G. C. Xu, and P. N. Prasad, Opt. Commun. **96,** 321 (1993).
10. P. Glas, M. Naumann, I. Reng, A. Schirrmacher, L. Dong, and J. Caplen, Fiber Integr. Opt. **17,** 207 (1998).
11. T.-M. Liu, H.-H. Chang, S.-W. Chu, and C.-K. Sun, IEEE J. Quantum Electron. **38,** 458 (2002).
12. I. Thomann, L. Hollberg, S. A. Diddams, and R. Equall, Appl. Opt. **42,** 1661 (2003).
13. N. Matuschek, F. X. Kärtner, and U. Keller, IEEE J. Sel. Top. Quantum Electron. **4,** 197 (1998).
14. I. Thomann, A. Bartels, K. L. Corwin, N. R. Newbury, L. Hollberg, S. A. Diddams, J. W. Nicholson, and M. F. Yan, Opt. Lett. **28,** 1368 (2003).
15. J. Aus der Au, D. Kopf, F. Morier-Genoud, M. Moser, and U. Keller, Opt. Lett. **22,** 307 (1997).