Multiplying the Repetition Rate of Passive Mode-locked Femtosecond Lasers by an Intracavity Flat Surface with Low Reflectivity

Tzu-Ming Liu and Chi-Kuang Sun
Graduate Institute of Electro-Optical Engineering and Department of Electrical Engineering, National Taiwan University, Taipei 10617, TAIWAN
Phone□886-2-23659703, FAX□886-2-23677467, E-mail□f8941002@ee.ntu.edu.tw

Franz X. Kärtner and James G. Fujimoto
Department of Electrical Engineering and Computer Science and Research Laboratory of Electronics, Massachusetts Institute of Technology, Cambridge, Massachusetts 02139

Abstract: We demonstrate a flexible and phase insensitive method to multiply the repetition-rate of passive mode-locked solid-state lasers in femtosecond regime. It was achieved by inserting a low-reflectivity flat surface inside the oscillator cavity.

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High repetition-rate (HRR) femtosecond lasers enable a wide range of new applications in optical communication [1], and frequency metrology [2]. For spectroscopy and sensing applications, HRR lasers reduce the peak intensities while maintaining a high average power, which is important for achieving high signal-to-noise ratios. In order to increase the repetition rate, the simplest way is to shorten the cavity length. Considering high power and short pulse-width, passive mode-locked all solid-state lasers with a compact cavity is a popular choice [3,4]. But once a HRR mode-locked laser is built, the repetition rate cannot be easily multiplied 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 [5]. However, previously demonstrated methods require phase-sensitive mode matching to an external coupled cavity and all previous studies only operated in the nanosecond or picosecond regimes [5-8]. In this letter, we demonstrate repetition-rate multiplication by using an intracavity flat surface with low reflectivity in a passively modelocked Cr:forsterite laser. In contrast to all previous studies [5-8], our intracavity low-reflectivity flat surface acts as a pulse seeder rather than a coupler to a matched external resonant cavity. By controlling the ratio of the subcavity length, repetition-rate can thus be successfully multiplied in the femtosecond regime in a flexible and phase insensitive way.

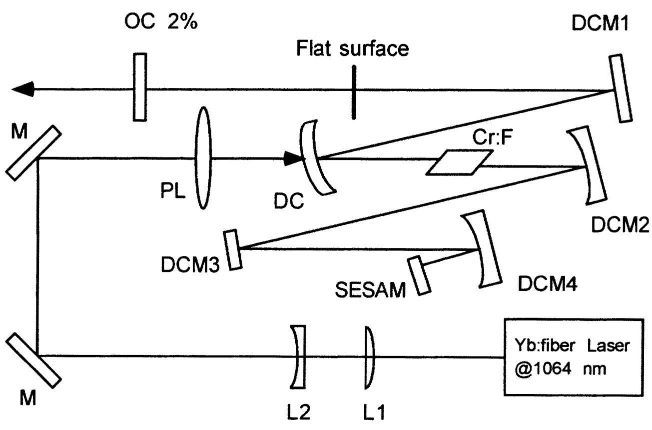


Fig. 1. Schematic diagram of the high repetition-rate femtosecond Cr:fosterite laser. M: folding mirror; L1, L2: mode-matching lenses; PL: pump lens; DC: dichroic curve mirror (R=10 cm); DCM1, DCM3: flat double chirped mirrors; DCM2, DCM4: curved double chirped mirrors (R=10 cm); SESAM: semiconductor saturable absorber mirror; OC: output coupler; Cr:F: Cr:forsterite crystal.

Consider a linear cavity with an optical-path length l, the 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, the optical cavity can be partitioned 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 one lags either N/[(M+N)R_0] or M/[(M+N)R_0] in time to the transmitted one. 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 the 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 we employed to demonstrate this approach is a femtosecond Cr:forsterite laser (Fig. 1). Its cavity is composed of one dichroic curved mirror (DC), two curved double-chirped mirrors (DCM2, DCM4), 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 have high transmission at the pump wavelength (1064 nm) with broadband high reflection coating around the lasing wavelength. We use a standard z-fold cavity design for astigmatism compensation. The radius-of-curvature of the focusing mirrors are all 10-cm. The Cr:forsterite crystal is a 5mm×5mm ×11.4mm Brewster-cut crystal with an absorption coefficient of 1.5 cm^{-1}. The crystal was cooled by liquid and a TE cooler. To prevent water condensation on the surface of the crystal, it was purged with dry nitrogen. The SESAM with a picosecond transient response is for self-starting and enhancement of the mode-locking force [9]. The double-pass group-delay-dispersion (GDD) arose from the laser crystal is 568 fs^2 around 1230 nm [10]. We employ double-chirped mirrors (DCMs) instead of prism pairs to compensate the crystal GDD [11]. Each DCM provides −150 fs^2 GDD around 1230 nm. To make soliton-like pulses operate in the stable regime, the net cavity dispersion should be slightly negative [12]. However for a mode-locked cavity with a SESAM, too much intracavity energy will result in double or multiple-pulse operation, which set an upper limit for the output power [13]. To increase the upper limit, the net GDD should be more negative. Therefore, we employ 4 DCMs (DCM1~4) for higher available power, which results in -632 fs^2 net GDD within one roundtrip. The pump source is an Yb:fiber laser operating at 1064 nm. After a lens pair (L_1 and L_2) and a pump lens with a 10-cm focal distance, pump beam was focused into the crystal with ~30 μm beam radius at the focus. Using a self-consistent q-parameter analysis, the radius of beam waist inside the crystal was 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 can obtain 40-mW average output power at a 124-MHz repetition-rate without multiple pulsing [13]. Without inserting the flat surface, the output spectrum showed 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 ~164-fs pulse width assuming a $sech^2$ pulse shape.

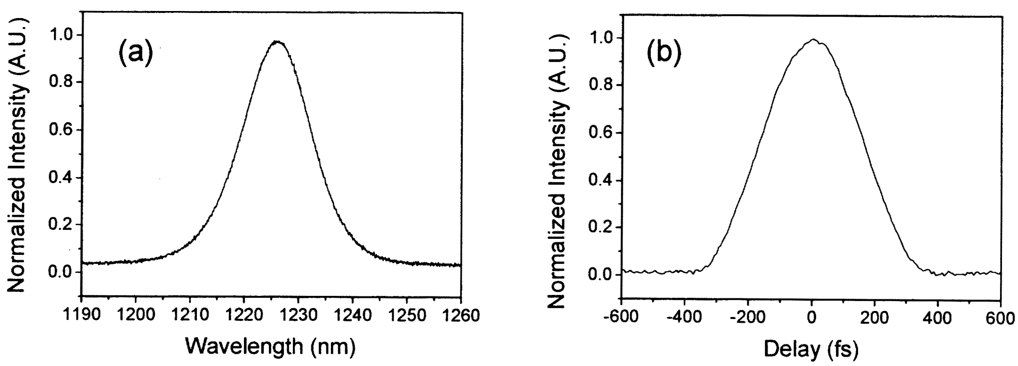
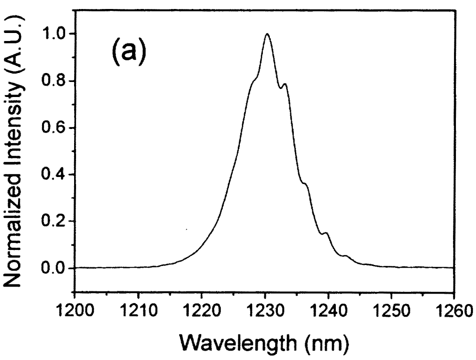


Fig. 2. The spectrum (a) and the autocorrelation trace (b) of the 124-MHz Cr:forsterite laser without inserting a low-reflectivity flat surface inside the cavity.

We first placed a flat surface into the point where $l_1=l/5$, trying to multiply the repetition rate up five-fold. The employed intracavity flat surface is a BK7 glass with 150-μm thickness. In order to reduce bandwidth limitation from etalon effects, one side of the glass is anti-reflection 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 on a mirror mount and a translation stage with a 1-μm resolution. After inserting the glass, without any careful alignment, the repetition rate did not multiply. In addition, under 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, the average power was increased to 180 mW. The detected pulse train showed a 620-MHz repetition rate in the oscilloscope. At the same time, we can observe the output spectrum broadened to ~9 nm FWHM (see Fig. 3(a)) and the measured autocorrelation trace showed 260-fs FWHM, indicating 168-fs pulse width by assuming $sech^2$ pulse shape (Fig. 3(b)). We also investigated the case of $l_l=l/10$ in order to reach a 1.24-GHz repetition-rate and 170-mW output power was obtained. The measured pulse width was around 2 ps. This is the highest repetition rate ever reported for a mode-locked Cr:forsterite laser. The detuning range and stability criterion of the repetition rate multiplication will be discussed in the conference.



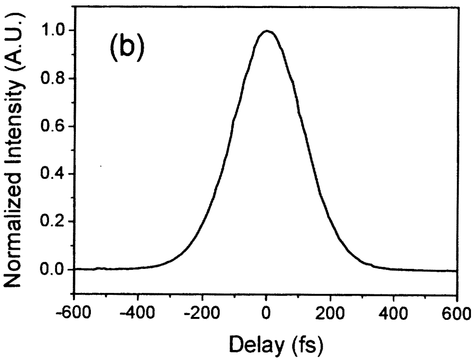


Fig. 3 The spectrum (a) and the autocorrelation trace (b) of the 620-MHz Cr:forsterite laser with a low-reflectivity flat surface inside the cavity.

4. References

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