Highly Efficient Self-Starting Femtosecond Cr:Forsterite Laser *

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We report a highly efficient and high power self-starting femtosecond Cr:forsterite laser pumped by a 1064-nm Yb doped fibre laser. Five chirped mirrors are used to compensate for the intra-cavity group-delay dispersion, and the mode-locking is initiated by a semiconductor saturable absorber mirror (SESAM). Under pump power of 7.9 W, stable femtosecond laser pulses with average power of 760 mW are obtained, yielding a pump power slope efficiency of 12.3%. The measured pulse duration and spectral bandwidth (FWHM) are 46 fs and 45 nm; the repetition rate is 82 MHz.

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Chromium-doped forsterite (Cr^{4+}:Mg_2SiO_4) is an important solid-state laser which produces broadly tunable laser radiation in the near infrared around 1300 nm. This wavelength range is very attractive. For instance, it is the zero-dispersion wavelength of optical fibres, and light scattering in biological tissues is highly reduced at this wavelength than other wavelengths. Therefore, Cr:forsterite lasers have important applications in fibre communication,[1] ultrafast spectroscopic,[2] optical coherence tomography (OCT),[3] etc. Recently, femtosecond Cr:forsterite lasers have also shown their great potentials in domains of optical frequency measurement,[4] ultrashort pulse synthesis,[5] and high-peak-power laser system.[6] Since the first demonstration of cw pulsed Cr:forsterite laser in 1988[7] and 1991,[8] intense studies have been performed on this kind of lasers, and different techniques have been employed for femtosecond Cr:forsterite lasers, such as additive pulse mode locking,[9] Kerr-lens mode-locking,[10,11] and passively soliton mode-locking.[12] Pulses as short as 14 fs has been realized.[11]

Contrasted to the Ti:sapphire crystal, the Cr:forsterite crystal has much lower gain, whose figure of merit (FOM) is almost an order of magnitude lower than that of the former. In addition, its thermal conductivity coefficient is also significantly smaller. Due to the above-mentioned factors, it is usually difficult to obtain efficient mode-locking operation with this host medium.[8–12] Based on our previous work about the setup of a femtosecond Cr:forsterite laser, which was also with comparative low pump efficiency,[13] in this Letter we report a highly efficient stable femtosecond Cr:forsterite laser with a pump power slope efficiency of 12.3%, and the mode-locking of this laser is always self-starting. To our best knowledge, this is the highest slope efficiency for mode-locking Cr:forsterite lasers so far.

A schematic of the laser is shown in Fig. 1. The laser uses an astigmatically compensated Z-fold cavity design. The size of Cr:forsterite crystal is 4 mm×2 mm×9 mm, cut for propagation of light along the a axis and emitting beam polarization along the c axis (P_{mnb} notation). It has an absorption coefficient of $\alpha = 1.69\,\mathrm{cm}^{-1}$ at 1.064 μm. Each face was polished and cut at Brewster's angle. The temperature of the crystal was cooled to 5° by a thermoelectric cooler. An Yb doped fibre laser on the wavelength of 1064 nm was used as the pump (AYDLS-PM-10, Amonics). The maximum available pump power is 7.9 W. The output coupler has 3% transmission. All the mirrors in the cavity are chirped mirrors except for the output coupler. CM1, CM2, CM3 are concave mirrors with the radius of curvature (ROC) of 100 mm; M1 and M2 are plane mirrors. With this cavity design, the repetition rate is about 82 MHz.

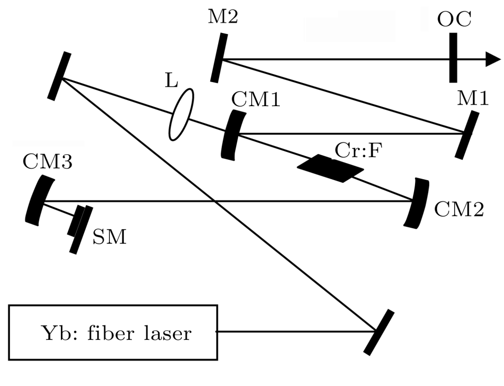

Fig. 1. Schematic of arrangement of the femtosecond Cr:forsterite laser. Cr:F: Cr:forsterite crystal; CM1–CM3: Chirped concave mirrors with ROC of 100 mm; M1 and M2: plane chirped mirrors; OC: output coupler; SM: SESAM.

Intra-cavity dispersion compensation is important

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for the formation of femtosecond pulses. In our experiment, the crystal of 9-mm-long Cr:forsterite introduced 162 fs^2 group-delay dispersion (GDD) at the central wavelength of 1277 nm.[14] The dispersion compensation was accomplished by the five pieces of chirped mirrors. Each bounce brought single pass GDD of $-60 \pm 20\,fs^2$ by the mirrors CM1, CM2, CM3 and $-70 \pm 20\,fs^2$ by mirrors M1 and M2 respectively. Considering the positive GDD that the 1.82-m-long gas will bring, one can obtain a net intra-cavity GDD at the level of $-130\,fs^2$. Because there are small oscillations in the GDD introduced by the chirped mirrors, the existent net negative GDD is necessary for the stability of mode-locking. Compared with conventional prism pairs for dispersion compensation, there are several advantages of using chirped mirrors. First, Cr:forsterite is a low-gain material, thus minimizing the cavity loss is critical for enabling an efficient mode-locking. Second, chirped mirrors have higher reflectivity than normal dielectric mirrors when a broad spectral range is covered, and the inserting loss caused by the prisms also is avoided. Hence it will lead to lower intra-cavity loss. Third, for the scheme by using prism pairs, the high order dispersion caused by the prism materials will exist, it will cause pulse broadening. In contrast, the high order dispersion can be well reduced by chirped mirrors.

For self-starting mode-locking, a concave mirror with a 10-cm ROC was used as a fold mirror to focus the laser beam on the SESAM. The SESAM is commercial available (BATOP GmbH) and has a small saturation fluence of $70\,\mu J/cm^2$. In order to reduce the inserting losses, we chose a nonsaturable loss of the SESAM less than 0.5%.

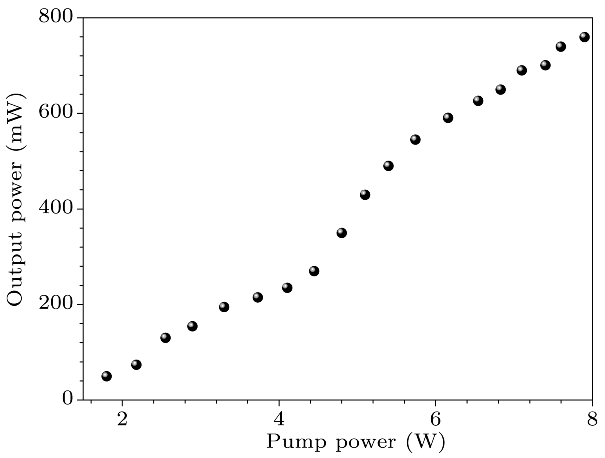

Fig. 2. Variation of the mode-locked output power as a function of the pump power.

Figure 2 shows the output power of the mode-locked pulses as a function of the pump power. When the pump power was added to 1.8 W, stable mode-locking operation could be initiated with output power of 49 mW. At the maximum pump power of 7.9 W, mode-locking pulses power as high as 760 mW was reached, which indicates a record slope efficiency as high as 12.3%. Similar high average power has only been reported by Petrov *et al.*,[15] whereas a pump power as high as 12 W was used, which was 1.5 times higher than the pump power in our experiment. To optimize the output power of mode-locking operation, we find that a slight adjustment of the concave mirror CM2 is necessary when the laser cavity is firstly optimized alignment at a pump power, We contribute this to the effect of thermal loading in the Cr:forsterite crystal. The mode-locking power of the Cr:forsterite laser is almost linear till the pump power up to 7.9 W. Hence we believe that even higher output power can be expected if we use a higher power pump laser.

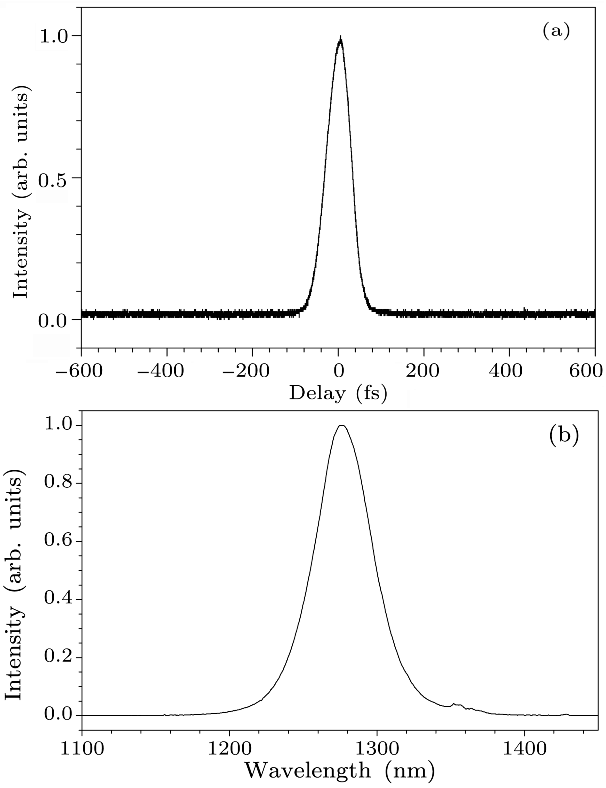

Fig. 3. Typical intensity autocorrelation trace of the pulses (a) and the laser spectrum of mode-locking operation (b).

A typical intensity autocorrelation trace (obtained by an FR-103MN autocorrelator, Femtochrome Research, Inc.) of the output pulse is shown in Fig. 3(a). The autocorrelation width is 71 fs. Assuming a $sech^2$ pulse shape, one can obtain the FWHM pulse duration of 46 fs. A simultaneous measurement of the pulse spectrum is illustrated in Fig. 3(b). It shows a width of 45 nm (FWHM) with the central wavelength of 1277 nm. The time-bandwidth product is calculated to be 0.38, indicating that the pulses are nearly transform limited. The mode locking is observed to be stable over periods of several hours.

In conclusion, we have demonstrated a femtosecond Cr:forsterite laser with high output power and high pump efficiency. Stable and self-starting mode-locking operation is achieved. Under the pump power of 7.9 W, the output pulse power as high as 760 mW is obtained, yielding a record pump power slope efficiency of 12.3%. It demonstrates the highest slope efficiency up to date in mode-locking Cr:forsterite lasers. The pulse width is measured to be 46 fs with a spectral bandwidth of 45 nm.

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