Simultaneous multiwavelength generation from a mode-locked all-solid-state Cr:forsterite laser

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We demonstrate a multiple-channel, mode-locked, all-solid-state Cr:forsterite laser. By inserting an etalon into the laser cavity, we have generated 12 phase-locked channels with 9–19-ps pulse width near 1230 nm with 280-mW average output power from a single laser oscillator. By tuning the etalon bandwidth we can shorten the pulse width in a specific channel to 1.8 ps.

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Multiwavelength generation of ultrashort and highly synchronized pulses is of great interest for novel photonic networks that use a combined optical wavelength-division-multiplexed and time-division-multiplexed data format. To date, most approaches achieve multiple-wavelength operation by using semiconductor lasers, either in arrays of independent gain media[1] or with a frequency-control system on a single gain medium.[2,3] These approaches require precise wavelength controllers as well as one independent gain medium for each channel,[1] have difficulty in establishing a power balance between channels,[2] or require complex management techniques for different output couplers.[3] Recently, synchronized multiwavelength generation directly from a mode-locked laser oscillator based on semiconductor lasers was demonstrated by several research groups. Shi *et al.* used a GaAs–AlGaAs semiconductor optical amplifier to generate four wavelengths simultaneously with 0.3-mW channel power and 12-ps optical pulse width for each channel.[4] Vlachos *et al.* employed an InGaAsP/InP semiconductor optical amplifier and a Fabry–Perot filter in the cavity to produce 10 channels of 7-ps pulses with 580-μW total power.[5] These actively mode-locked, multiwavelength lasers not only preserve the advantage of relative wavelength stability among all oscillating modes but also result in simpler experimental configurations, however with relatively low output power of less than 1 mW.[4,5] To improve the output power level and increase the number of channels for telecommunication applications, it is desirable to develop multiwavelength, solid-state-laser technologies based on high-power broadband laser crystals.[6] Recently Chudoba *et al.* generated 14-fs pulses at 80-mW average power from a Cr:forsterite laser cavity with a spectrum covering the whole 1.3–1.55-μm communication band.[7] A multichannel, mode-locked Cr:forsterite laser will have the potential to satisfy both bandwidth and power requirements. In the research reported here, an etalon was inserted into a mode-locked Cr:forsterite laser cavity to produce Fabry–Perot modes for simultaneous multiwavelength generation. We tuned the pulse width by modifying the interface reflectivity. We used a second-harmonic-generation (SHG) based frequency-resolved optical gating (FROG) technique to investigate the properties of multichannel output.

The structure of the laser resonator is shown schematically in Fig. 1. The laser constructed for this study used a 19-mm-long Brewster-cut Cr:forsterite crystal with a 5×10^{18} cm^{-3} chromium(IV) ion concentration. The crystal was oriented with its *b* axis in the horizontal plane, resulting in horizontal laser polarization. The laser was pumped with 8.5 W of 1064-nm light from a diode-pumped Nd:YVO_4 laser (Spectra-Physics Millennia IR). The Cr:forsterite crystal absorbed 75% of the 1064-nm pump, corresponding to an absorption coefficient of $\sim$0.73 cm^{-1}. The crystal temperature was kept near 2 °C, and a nitrogen purge prevented water condensation. A 10-cm lens was used to focus the pump beam through cavity mirror M2 onto the Cr:forsterite crystal. The laser cavity had a folded configuration with a 5% output coupler, three laser mirrors (M1–M3), and a semiconductor saturable-absorber mirror (SESAM). In our study the SESAM consisted of 25 periods of GaAs/AlAs quarter-wave layers, followed by an $Al_{0.48}In_{0.52}As$ quarter-wave layer with two embedded $Ga_{0.47}In_{0.53}As$ quantum wells. To provide saturable-absorber nonlinearity for initiating and stabilizing the Cr:forsterite laser, we designed the

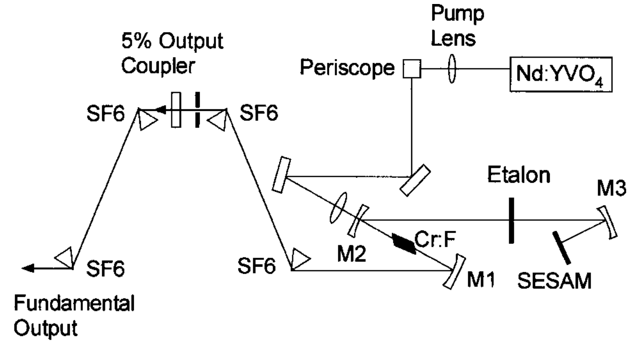

Fig. 1. Schematic diagram of the experimental setup.

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quantum-well structure to have heavy-hole excitonic resonance at 1232 nm at room temperature. The insertion loss of the SESAM was 2.5%, with a saturation energy fluence of $\sim 50\ \mu J/cm^2$. Mirrors M1 and M2 had 10-cm radii of curvature, and mirror M3 had a 20-cm radius of curvature. All mirrors were high-reflection coated (>99%) for a spectral range of 1200–1270 nm. An SF6 prism pair was placed inside the cavity to provide compensation for intracavity group-velocity dispersion. We used another SF6 prism pair outside the cavity to achieve both beam shaping and dispersion compensation of the laser output. The etalon used in the cavity was a 0.15-mm cover glass (Matsunami Glass) with a 1.5 refractive index, mounted upon a rotary stage to provide control of the incidence angle. We used an optical spectrum analyzer (OSA; Anritsu Model MS9710B) with 0.07-nm spectral resolution to monitor the spectrum. A fiber collimation lens with 7.5-cm focal length was employed to couple the laser beam into the connector of a single-mode fiber, which was connected to the OSA. We used a beam splitter after the external prism pair to direct a portion of the output to an autocorrelator. We also used this beam to make SHG FROG measurements with a 300-μm-thick β-barium borate crystal. The FROG signal was recorded by a CCD-based spectrometer.

Without the etalon, the Cr:forsterite laser generated 130-fs pulses (assuming a $sech^2$ profile) at 81 MHz. The lasing pump threshold power was ~3.2 W. Because of the narrow reflection bandwidth of the SESAM, the FWHM of the output spectrum was limited to only 13 nm, which resulted in a 0.334 time–bandwidth product. After insertion of the etalon, simultaneous multichannel generation from the laser was observed in the OSA. With the etalon at normal incidence, the output power was 280 mW. The corresponding spectrum in shown in Fig. 2(a). Twelve channels with a 0.2-nm channel bandwidth and a 3.36-nm free spectral range (FSR) were observed. The average optical power of each channel ranged from 0.13 to 100 mW, which is sufficient for communication applications. With a $sech^2$ fit, the peak envelope of the spectrum has a 6.5-nm FWHM near 1227 nm. The corresponding autocorrelation trace [Fig. 2(b)] showed dense modulation over an envelope of 18.5-ps FWHM [Fig. 2(b), dotted curve] with 1.52-ps spacing and 390-fs FWHM of each modulation peak. We also performed SHG FROG to investigate the phase relations among different channels. Figure 3 illustrates the measured SHG FROG signal with a linear scale interpretation, showing both temporal and spectral modulation. The signal at wavelengths 602.5–612 and 617–622.5 nm can be observed easily only in log scale figures, in agreement with the measured spectrum, and is not visible in Fig. 3 because of dynamic-range limitation. Figure 4 shows the FROG-retrieved intensity and phase of the laser spectrum (both in linear scale). Strong phase correlation among channels is shown. A wider retrieval spectrum displayed strong dispersion for each channel as a result of the spectral resolution limitation in the SHG measurement and of retrieval uncertainty caused by measurement noises. Nevertheless, good agreement with the OSA measured spectrum in peak position and in magnitude relation was observed. We used a Fourier transformation to investigate the characteristics of each channel. The channel pulse width ranged from 9 to 19 ps, calculated with data obtained from the FROG measurements.

Reduction of interface reflectivity is required for broadening the transmission bandwidth for each etalon's longitudinal mode and to shorten pulse widths. We achieved this reduction by turning the incidence angle on the cover glass. When the angle was turned 50° from normal incidence, the channel bandwidths were broadened to 0.8–1.56 nm [Fig. 5(a)] with a 3.96-nm FSR. The corresponding autocorrelation trace shows a shorter, 5.4-ps FWHM [Fig. 5(b),

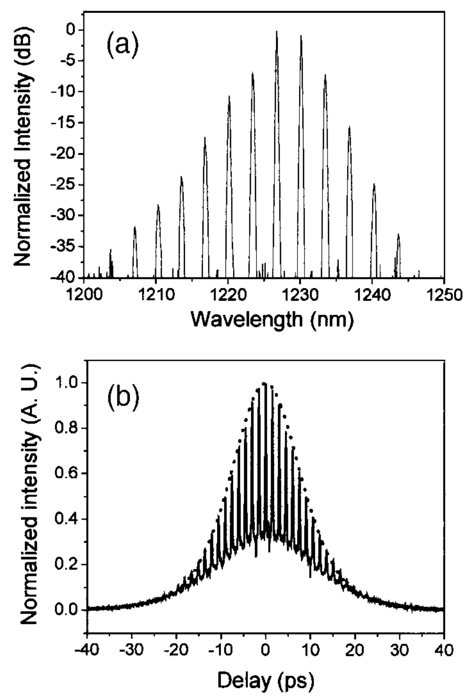

Fig. 2. (a) Output spectrum and (b) its corresponding autocorrelation trace of the multiwavelength Cr:forsterite laser output when the cover glass is inserted normally to the laser beam. The dotted curve in (b) is a $sech^2$ fitting.

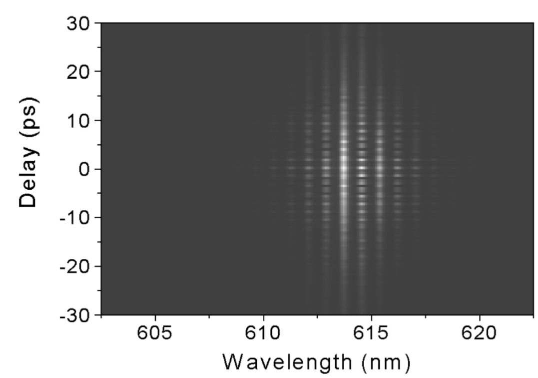

Fig. 3. SHG FROG trace of the multiwavelength Cr:forsterite laser output when the cover glass is inserted normally to the laser beam.

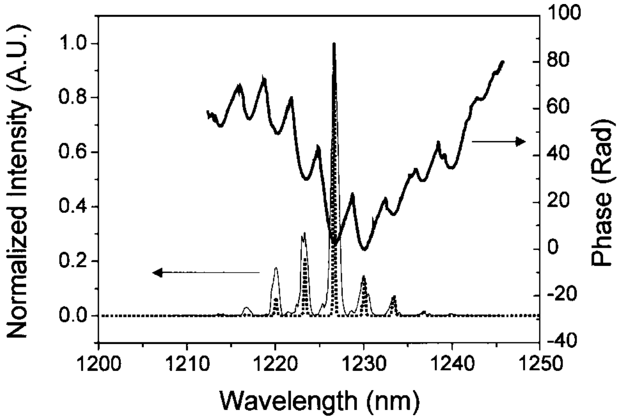

Fig. 4. Recovered intensity and phase spectra for the condition of Fig. 3. Dotted curve, the measured spectrum.

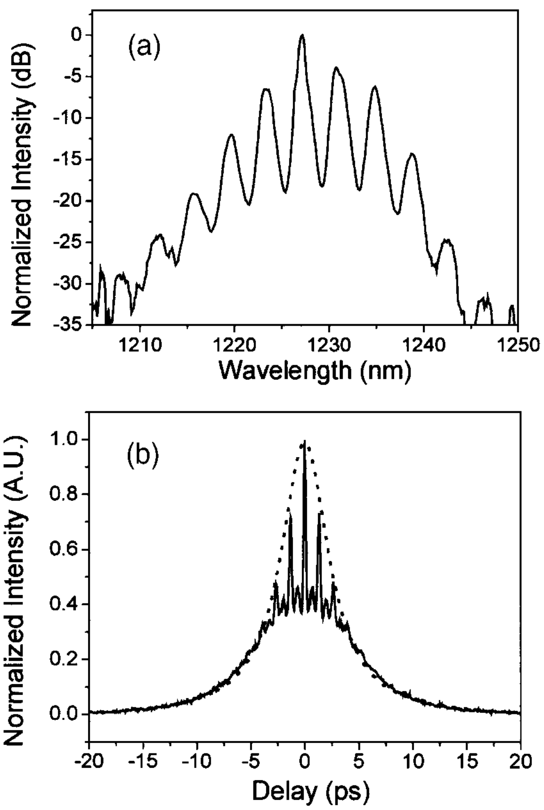

Fig. 5. (a) Output spectrum and (b) its corresponding autocorrelation trace of the multiwavelength Cr:forsterite laser output when the cover glass is turned 50° from normal incidence. The dotted curve in (b) is a Lorenzian fit.

dotted curve] than in Fig. 2(b). SHG FROG was also performed, and the pulse width for each channel was found to be reduced to 1.8–3.4 ps. Additionally, with given parameters (thickness, $d = 0.15$ mm; refractive index, $n = 1.5$; center wavelength, $\lambda = 1226$ nm; refractive angle, θ) the FSR calculated from Fabry–Perot theory,

$$\Delta\lambda = \lambda^2/2nd \cos\theta\,, \tag{1}$$

showed good agreement with the experimental results, which indicates that one can manage the mode spacing by changing the thickness of the etalon.

In conclusion, we have demonstrated high-power, simultaneous multiple-wavelength generation from a mode-locked Cr:forsterite laser. By inserting a cover glass into the laser cavity, we generated 12 phase-locked channels with 9–19-ps pulse width near 1230 nm with 280-mW average output power from a single laser oscillator. By changing the interface reflectivity and the thickness of the etalon, we can manage the pulse width of each channel and the mode spacing. Even though the achievable aggregate data transmission rate with this laser is relatively low (~1 Gbit/s), one could improve it by increasing either the repetition rate or the number of channels. One could greatly enhance the repetition rate either by shortening the cavity length or by using a harmonic mode-locking technique. We can increase the number of channels by decreasing the channel spacing with a smaller FSR or by increasing the total laser bandwidth with a better SESAM mirror coating. With the recent broadband demonstration of Cr:forsterite lasers covering the whole telecommunication wavelength from 1200 to 1580 nm, our study shows the potential for use of Cr:forsterite lasers as high-power multiwavelength sources for a hybrid optical-wavelength-division and time-division-multiplexed communication system.

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