

Dual-wavelength actively mode-locked laser-diode array with an external grating-loaded cavity

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We report the generation of dual-wavelength picosecond pulses by use of a commercial laser-diode array. The laser cavity incorporated a folded dispersive delay line with a V-shaped double-stripe mirror. The spectral separation of the laser output at the two wavelengths can be tuned from 2 to 11 nm. The actively mode-locked pulse widths at the two wavelengths were both 29 ps. Cross-correlation and power-spectrum measurements indicated that the two-color pulses were synchronized with an absolute timing jitter of less than 1 ps (instrument limited).

Recently we reported a novel cw two-color semiconductor laser system that used a commercial laser-diode array in an external grazing-incidence grating-loaded cavity.¹ The key element of the laser was a V-shaped double slit located at the end mirror. This configuration permitted convenient tuning of the lasing wavelength and the spectral separation of the two wavelengths by movement of the V-shaped double slit horizontally or vertically with respect to the optical axis. It was also demonstrated that the two laser modes utilized different gain regions of the diode array. As a result, the dual-wavelength output could be stably maintained. Synchronized two-color pulses from a single mode-locked laser were also desirable for applications such as two-wavelength pump-probe experiments and difference-frequency generation. Several groups reported femtosecond two-wavelength generation from the cavity of a single Ti:sapphire laser system.²⁻⁵ In this Letter we report, for what we believe is the first time, synchronous dual-wavelength picosecond pulse generation from an actively mode-locked laser-diode array by use of the cw dual-wavelength cavity configuration described previously.¹ A V-shaped double-stripe mirror was used instead of the slit-and-mirror combination used in our previous design. Furthermore, this configuration permits intracavity pulse compensation, as is described below.

Figure 1 shows the laser configuration. A gain-guided 10-stripe phase-locked laser array (Spectra Diode Laboratories SDL-2419C, $\lambda = 0.8 \mu\text{m}$) was used as the gain medium. It has a high-reflectivity coating (reflectivity $R > 95\%$) on the rear facet and an antireflection coating of $\approx 0.1\%$ reflectivity on the front facet. Light emitted by the diode array was collimated and incident at the grazing angle upon a grating (1800 lines/mm). The first-order diffracted light was then focused by a lens ($f = 150 \text{ mm}$) on a V-shaped double-stripe end mirror. The zeroth-order diffraction from the grating, which was 79° with respect to the normal of the grating, was the output of the laser. The two-wavelength output (λ_1 and λ_2) was coaxial, and the wavelength separation

was determined by the V-shaped double-stripe end mirror. The grating-lens-stripe-mirror combination was just a folded dispersive delay line or a grating-pair compressor with an internal telescope. We varied the dispersion of the external cavity by adjusting the distance between the lens and the grating while keeping constant the distance (150 mm) between the lens and the stripe mirror. Thus optimization of the separation of the lens-mirror combination and the grating resulted in compensation of linear chirp in the cavity.⁶ The threshold bias current of the laser was 240 mA.

The inset of Figure 1 is a schematic of the V-shaped double-stripe end mirror. The V-shaped double-striped end mirror was used to select simultaneously the two output wavelengths. The length of each stripe was 15 mm. The angle between the two stripes was $\sim 15^\circ$. The width of each stripe was 0.167 mm, corresponding to an equivalent spectral filter with a bandwidth of 0.27 nm, which is just smaller than the mode spacing of the diode chip. We could tune the spectral separation of the two output wavelengths from 2 to 11 nm by vertically translating the double-stripe end mirror with respect to the optical axis. The corresponding spacing of the two stripe mirrors was 1.2–6.6 mm. The reported maxi-

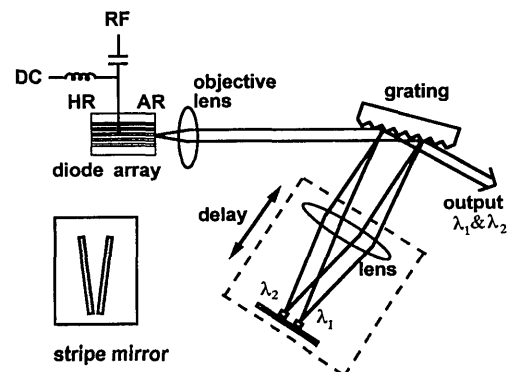


Fig. 1. Laser configuration: HR, high reflection; AR, antireflection. The inset shows a schematic of the V-shaped double-stripe mirror.

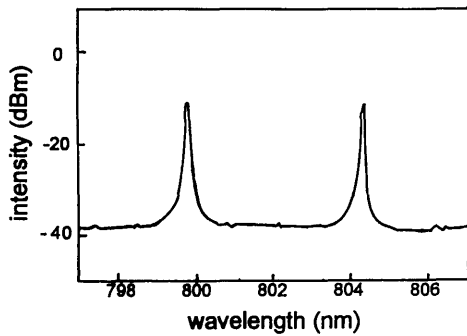


Fig. 2. Spectrum of the two-wavelength laser output for a spectral separation of 4.44 nm

imum spectral separation can be increased somewhat by the injection of a higher dc bias current or the use of a laser-diode structure with an intrinsically higher bandwidth. The laser was actively mode locked by simultaneous injection of a rf sinusoidal modulation signal as high as 1 W at a frequency of 313 MHz and a dc bias current of 180 mA through a bias tee. A monochromator and a noncollinear autocorrelator were used to measure the output spectrum and pulse width. The zeroth-order reflections from the grating—of light at the two wavelengths retroreflected from the end mirror—were angularly separated and served as a useful auxiliary output for monitoring the two resonant wavelengths and the timing jitter of each wavelength separately. We used both the time-domain cross-correlation and the frequency-domain technique^{7,8} for timing jitter measurements. For the latter technique a high-speed photodetector (Antel ps-s2) and a rf spectrum analyzer (HP 8568B, with a resolution bandwidth of 10 Hz) were used to measure the single-sideband phase noise level relative to the carrier per 1-Hz bandwidth.

Figure 2 shows the two-color output spectrum at 804.20 and 799.76 nm. The average output power of each wavelength was 4 mW. The side-mode suppression ratio was found to be better than 20 dB for each wavelength. The full width at half-maximum of the output spectrum at each wavelength was ~ 0.13 nm. The autocorrelation traces of the pulses of each wavelength are shown in Fig. 3. We recorded these by blocking one of the stripe mirrors. It was found that the correlation traces could be fitted best by a sech^2 function. The shortest deconvoluted pulse width was 29 ps for each wavelength at the optimized compression condition, which corresponded to an intracavity dispersion of -0.017 ps/nm.⁹

Figure 4 shows an autocorrelation trace of the dual-wavelength output with both stripe mirrors unblocked. This curve corresponds to a double cross correlation since the two-color pulses were simultaneously sent into each arm of the correlator. The deconvoluted pulse width was also 29 ps, the same as that for each wavelength. The measurement accuracy of our autocorrelator was better than a few femtoseconds. These results indicate that the jitter between the two pulses of each wavelength was of the order of or less than 1 ps. The inset of Fig. 4 shows the magnified view at the peak of the double cross-correlation trace as a function of delay distance.

It is a sinusoidal function with a period of 0.072 mm. This corresponds to half a period of a synthetic wavelength, $\Lambda = \lambda_1 \lambda_2 / |\lambda_1 - \lambda_2|$, at a spectral separation of 4.44 nm. That is, these are interference fringes that are due to the two-color pulses.

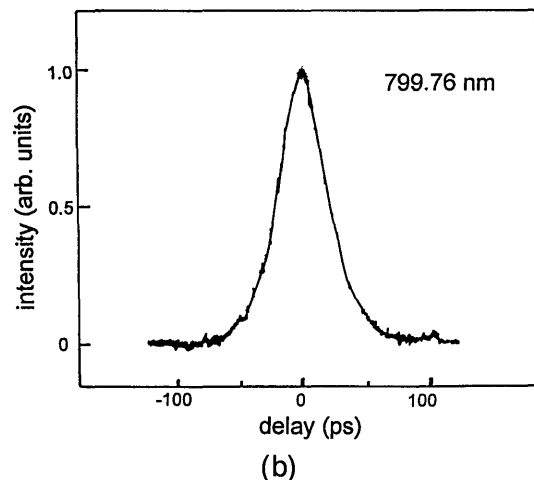
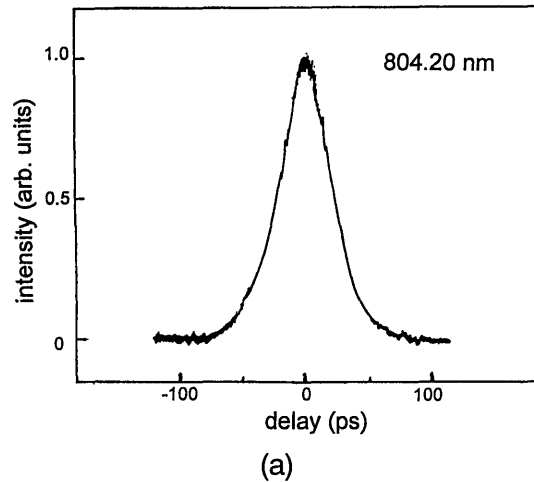


Fig. 3. Autocorrelation traces of the output of the two-color laser at wavelengths of (a) 804.2 and (b) 799.76 nm.

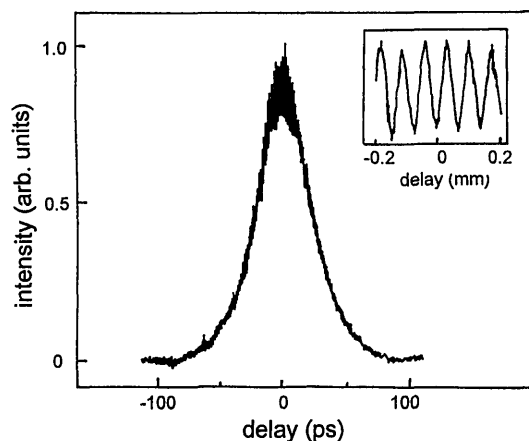


Fig. 4. Double cross-correlation trace of the synchronized two-color pulses. The inset show the magnified view at the peak of the double cross-correlation trace.

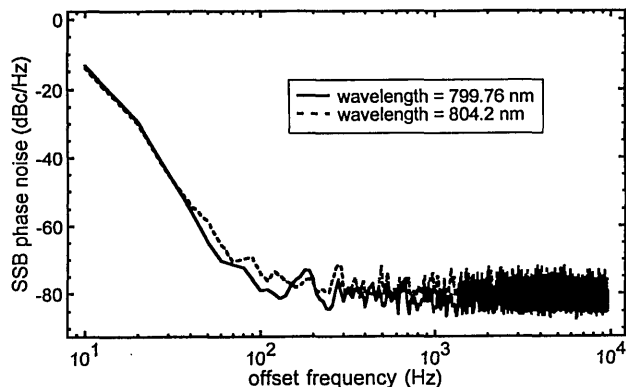


Fig. 5. Single-sideband (SSB) phase noise of the two-color laser output at 799.76 and 804.2 nm.

Figure 5 shows the single-sideband phase noise at the fourth harmonic (4×313 MHz) of the two-color output at 804.2 and 799.76 nm. By use of standard frequency-domain techniques^{7,8} the absolute rms timing jitters of the two-color outputs at 804.2 and 799.76 nm were calculated from Fig. 5 to be 870 and 550 fs (100 Hz to 10 kHz), respectively. In comparison, the absolute timing jitter of an actively mode-locked single-stripe laser diode in an external cavity was 240 fs.⁸

In conclusion, we have demonstrated a new configuration for an actively mode-locked laser-diode array capable of generating tunable synchronized dual-wavelength picosecond pulses. The key element is an intracavity folded dispersive delay line with a V-shaped double-stripe mirror. The shortest

pulse width of each wavelength was 29 ps after optimization of the intracavity dispersion. The spectral separation between the two wavelengths could be conveniently tuned from 2 to 11 nm by translation of the V-shaped mirror vertically. Interference fringes observed in the trace of the double cross correlation of the collinear dual-wavelength output have been identified.

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