# Multicolor Single-Wavelength Sources Generated by a Monolithic Colliding Pulse Mode-Locked Quantum Well Laser

Y. K. Chen, M. C. Wu, T. Tanbun-Ek, R. A. Logan, and M. A. Chin

*Abstract*—**Multicolor single-wavelength laser sources are generated by narrow-band spectral filtering of a 300 GHz monolithic colliding pulse mode-locked semiconductor laser. Experimentally, the selected longitudinal mode shows a 10-dB reduction of low-frequency relative intensity noise, compared to that of the selected mode from the same laser in continuous-wave (CW) lasing condition. The strong phase coherence among the passively mode-locked longitudinal modes reduces the partition noise of the unlocked CW laser.**

MODE-LOCKED semiconductor lasers provide very stable optical pulses in the time domain for many applications such as ultrahigh speed electrooptical sampling systems and optical solitons in fiber communication systems, which require short pulsewidth and pure spectral properties [1], [2]. However, the spectral properties of the mode-locked lasers were not widely exploited. One potential application is to utilize the multimode nature of the mode-locked laser to produce multicolor single-wavelength sources by narrow-band spectral filtering with Fabry–Perot etalons or gratings. Because of the strong phase locking among the longitudinal modes, the fluctuations of the total intensity and linewidth of a mode-locked laser are similar to those of a single-mode laser [3]–[6]. The linewidth of the selected mode depends only on the total intensity of the mode-locked source rather than the individual modal intensity [7]–[9]. On the other hand, the modal intensity fluctuation of the mode-locked laser is more complicated and not studied as extensively as the well-known mode partition noise of an un-locked continuous-wave (CW) laser [10]–[13]. The low-frequency intensity fluctuation of the selected mode is very important because it would be up-converted to the modulated signal bandwidth once the selected mode is modulated externally [14]. In this letter, we report on the separation of single longitudinal modes from the mode-locked spectrum of a 300 GHz monolithic colliding pulse mode-locked (CPM) semiconductor quantum well laser. Experimentally, a 10 dB reduction of the relative intensity noise of the selected mode is obtained by operating the quantum well laser in the CPM mode as compared to the same laser in the unlocked CW operation.

The experimental layouts are illustrated in Fig. 1. A 300 GHz monolithic colliding-pulse mode-locked semiconductor laser is used for this work. The 300-$\mu$m-long laser is passive mode-locked by applying 49.4 mA dc current to the 265-$\mu$m-long saturable gain sections and 0.45 V to the 15-$\mu$m-long saturable absorber section. The mode-locked spectrum is centered at 1538 nm and the laser oscillates in single lateral mode. Detailed descriptions of this monolithic CPM semiconductor laser were reported elsewhere [15], [16]. The average optical power coupled into the optical fiber from this mode-locked CPM laser is $-5$ dBm, which is low for further spectral filtering and noise analysis. To increase the signal power of these 300 GHz optical pulses, a 1480 nm diode pumped erbium-doped fiber amplifier (EDFA) is used. The long spontaneous emission lifetime ($\sim 10$ ms) and the wide gain spectra of the EDFA are well suitable for amplifying picosecond optical pulses [17], [18]. The EDFA used in this experiment provides 10 dB gain and has a noise figure of 9 dB. The average power of the amplified pulses is $+5$ dBm, and the peak power of the pulses is 10 mW. Fig. 2 shows the autocorrelation trace of the amplified pulses recorded by a background-free noncollinear second-harmonic generation (SHG) autocorrelator. The residual 1480 nm pump light are filtered out from the SHG trace by the phase-matching condition of the $LiNbO_3$ SHG crystal. The full-width-at-half-maximum (FWHM) pulsewidth of the amplified pulses is broadened slightly to 1.0 ps by the EDFA, assuming a hyperbolic-secant pulse shape. From the time-average spectral bandwidth (FWHM) of 3.4 nm, the time-bandwidth product of the amplified pulses is 0.43, which is very closed to the transform-limited value of 0.31.

Fig. 3(a) shows the spectrum of the unlocked CW laser and (b) shows the spectrum of mode-locked pulses with the same average output power. The longitudinal mode spacing of the mode-locked spectrum in (b) is 2.47 nm, which is twice of that of the CW laser in (a). The amplitude of those suppressed fundamental modes are more than 25 dB below the CPM modes near the center lasing wavelength. This reflects the distinctive dual-pulse CPM operation inside this linear cavity laser. The individual longitudinal mode of the amplified pulses is selected by a narrow-band Fabry–Perot

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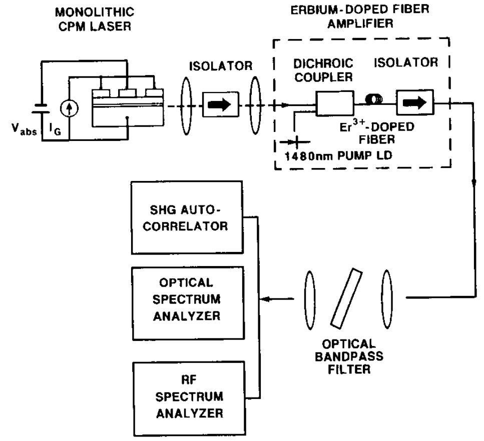

Fig. 1. The schematic diagram of the experimental setup.

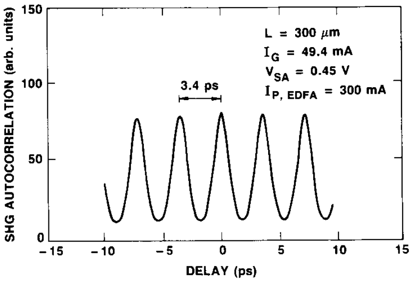

Fig. 2. The second-harmonic generation (SHG) autocorrelation trace of the amplified optical pulses generated by a 300 GHz monolithic colliding pulse mode-locked quantum well laser. The cavity length of the laser is 300 $\mu$m and the length of the saturable absorber is 15 $\mu$m.

etalon with 1 nm bandwidth. The side-mode rejection ratio of the bandpass filter is more than 25 dB. By adjusting the tilt angle of the Fabry–Perot etalon, the central wavelength of the narrow-band filter is shifted, and each longitudinal mode is selected accordingly, as shown in Fig. 3(c).

The modal intensity fluctuation of the selected longitudinal mode is detected by a low-noise, high-speed p-i-n detector and a radio-frequency electronic spectrum analyzer (HP71400A). The optical power coupled into the detector is maintained at −7 dBm with an optical attenuator. The measured modal relative intensity noises (RIN) of the amplified strongest longitudinal mode at 1538 nm for both the CW and mode-locked cases are shown in Fig. 4. The relative intensity noise is defined as the ratio of the square of the optical intensity noise to the average detected optical power per unit bandwidth. The resolution bandwidth of the RF spectrum analyzer is 3 MHz. In Fig. 4, the measured RIN values fall to a noise floor of −141 dB/Hz for frequencies beyond 2.5 GHz. This noise floor represents the shot noise from the detector-preamplifier and the measurement system of −144 dB/Hz. The RIN of the collective intensity fluctuation under uniform injection without EDFA is also recorded in Fig. 4 for comparison. Both of the modal partition noise of the uniformly injected laser and the modal intensity noise of the mode-locked laser exhibit a Lorentzian-like dependence at low frequency. For the unlocked laser, the modal RIN is 16 dB higher than the RIN from all modes at zero frequency, after deducting the 9 dB noise figure from EDFA. This large increase of the excess low-frequency intensity fluctuation agrees well with many other published experimental data and analysis on the mode partition noise [11], [12]. When the same laser operates in the CPM condition, a 10 dB reduction of the low-frequency modal relative intensity noise is obtained.

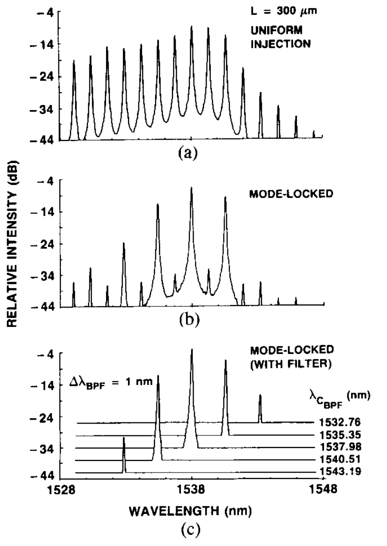

Fig. 3. (a) The spectrum of the unlocked CW laser uniform injection. (b) The spectrum of the mode-locked CPM laser. (c) The selected longitudinal modes from the mode-locked spectrum of (b) with a narrow-band spectral filter at various center wavelength ($\lambda_c$).

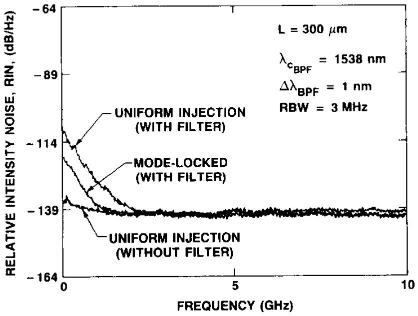

Fig. 4. Measured relative intensity noise (RIN) spectra of the modal intensity fluctuations of the selected single modes ($\lambda_c$ = 1538 nm) from the amplified mode-locked and CW spectra of Fig. 3(a) and (b). The RIN of total intensity fluctuation of the uniformly injected laser without the EDFA is also plotted.

Because the locked modes behave collectively as a single mode, most of the published theoretical studies adapted the *supermode* approach to analyze the total noise fluctuation of a mode-locked laser [4], [5]. The frequency dependence of the modal intensity noise under the mode-locked conditions can be illustrated by the mode-lock equations of an active mode-locked laser [6], [7]. From these formulations the relative intensity noise of all locked modes, $\mathrm{RIN}_T$, is

$$\mathrm{RIN}_T(\omega_o) = \frac{C}{1+\omega_o^2} \tag{1}$$

where $C$ is the RIN of the total modes at zero frequency (dc). The relative intensity noise of the central locked mode, $\mathrm{RIN}_o$, is

$$\mathrm{RIN}_o(\omega_o) = C\left[\frac{1}{1+\omega_o^2} + \sum_{p=0}^{N} H_p^2(0) \cdot \frac{1}{2^p p!}\,\frac{N}{\pi}\,\frac{1}{(pk)^2+\omega_o^2}\right] \tag{2}$$

where $k$ is the phenomenologic coupling coefficient between two adjacent modes, $H_p$ is the $p$th Hermite polynomial, $2N+1$ is the total number of locked modes, and $\omega_o$ is the normalized frequency. Fig. 5 shows the calculated relative intensity noise of the peak mode for various intermode coupling strength of the mode-locked laser. The half-power bandwidth of the modal RIN is a function of the mode coupling constant $k$. When the longitudinal modes are loosely coupled ($k = 0.05$), the modal RIN shows a Lorentzian-like behavior. With very tight coupling among longitudinal modes ($k = 2$), the modal RIN follows the total intensity fluctuation, as expected. Equations (1) and (2) qualitatively describe the general low-frequency noise characteristics of mode-locked lasers. However, the detailed expressions of the passive model-locked lasers need further investigations.

In summary, we have successfully separated an individual locked longitudinal mode from the mode-locked spectrum of a 300 GHz passive colliding mode-locked semiconductor laser with a bandpass filter. With filters of different center wavelengths, multicolor single wavelength sources are generated. The intensity fluctuation of the single-wavelength source exhibits a Lorentzian-like spectral behavior at low frequency. This measured excess low frequency intensity noise is 10 dB lower than what is obtained from a selected mode of the same laser operated in the unlocked CW oscillation. These single-wavelength sources are also capable of injection locking other single frequency lasers such as distributed feedback (DFB) lasers or distributed Bragg reflector (DBR) lasers.

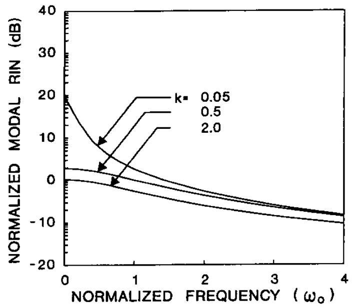

Fig. 5. The calculated relative intensity noise spectra of the peak mode of a mode-locked laser for various coupling strength $k$.

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