Short-Pulse Generation with Broad-Band Tunability from Semiconductor Lasers in an External Ring Cavity

Bor-Lin Lee and Ching-Fuh Lin

***Abstract*—Short optical pulses are generated by actively mode locking semiconductor lasers in an external ring cavity with a very broad tuning range from 795 to 857 nm. The wide tunability is possible because the gain bandwidth is broadened by the use of asymmetric dual quantum wells for the semiconductor laser material. Assuming a Gaussian shape, the generated pulses have pulsewidths of 13–21 ps and spectral widths of 2–4.5 Å for the tuning range. The mode-locked spectrum contains almost no amplified spontaneous emission noise.**

***Index Terms*—Asymmetric dual quantum wells, ring cavity, semiconductor laser, short-pulse generation.**

OPTICAL pulses generated from semiconductor lasers have potential applications in areas such as optical communications, physics measurement, and photonic switching, due to their compact sizes and low costs. In short-pulse generation, wide-gain bandwidth of laser materials is usually desired because it provides the possibility of achieving ultrashort pulses and broad-wavelength tunability. So far, wide-gain bandwidth has not been fully utilized to achieve ultrashort-pulse generation. In contrast, it could easily offer broad-band tunability. For example, the corresponding spectral width of mode-locked pulses in semiconductor lasers is usually less than 20 nm [1], [2], while the tuning range of mode-locked semiconductor lasers could easily reach over 25 nm [3], [4]. In other words, wide-gain bandwidth of semiconductor laser materials is more promising in broad-band tunability than in extremely short pulse generation. Recently, the gain bandwidth of semiconductor laser materials is further broadened using multiple quantum wells (MQW's) of different widths [5]–[9]. Its broad-band tunability on single-wavelength oscillation has already been experimentally demonstrated [7]–[10]. In this work, we further report that extremely wide-range tunability can also be achieved for short-pulse generation from semiconductor lasers using asymmetric dual quantum wells. The tuning range could be as large as 62 nm and the pulsewidth is 13–21 ps.

The semiconductor laser material used for the experiment has two QW's with widths of 40 Å and 75 Å, respectively. The gain bandwidth can then be broadened more than two times. Design consideration on the QW structure had been given in [5]. Semiconductor laser amplifiers (SLA's) were fabricated on such material using standard processing techniques. The SLA's have a ridge waveguide tilted at 7° from the normal of the cleaved facet. The waveguide is approximately 6 μm wide and 500 μm long. Fig. 1 schematically shows the experimental setup for short-pulse generation using such an SLA, in which the Fabry–Perot resonance of the SLA chip is significantly reduced [11]. Also, a ring cavity was used in this experiment for the following reasons. First, because the tilted-stripe SLA has both facets with very small retro-reflectivity, the linear-cavity configuration typically needs two arms. In order to synchronize the RF modulation with the pulse train, the lengths of the two arms should be equal or with a ratio of rational number, which is very difficult to align. In contrast, it is relatively easy to synchronize the RF modulation signal with the pulse train in the ring cavity. Second, even though the two arms of the linear cavity is aligned at the required lengths, the small fluctuation of each arm will cause spectral instability due to the coherence interference effects [12]. For stability consideration, a ring cavity is also better than a linear cavity. Third, amplified spontaneous emission (ASE) noise of output (a) in the ring-cavity configuration is significantly suppressed [10].

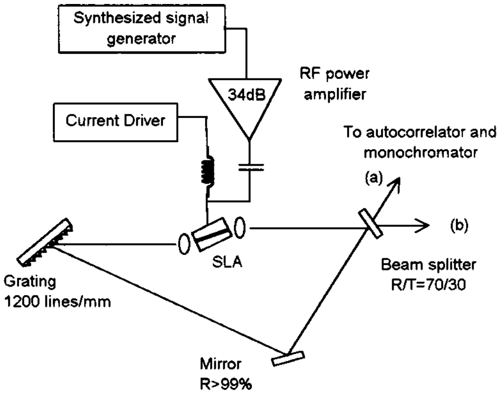

Fig. 1. A schematic diagram of the setup for actively mode-locking experiment.

Using an SLA with both facets of small reflectivity has the advantage of suppressing the secondary pulses [12], but it also has a drawback. Because the counterpropagating pulses collide in the SLA, gain competition exists between the pulses. However, because the two pulses usually have quite different energy in the semiconductor gain medium, the pulse-colliding effect is not significant. Therefore, the actively mode-locked pulses

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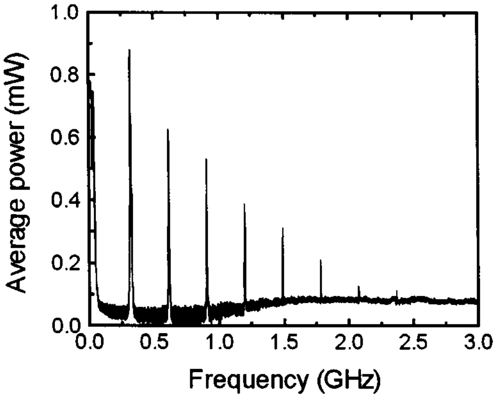

Fig. 2. The measured average power of the laser output (a) versus RF modulation frequency.

[12] are not obviously worse than conventional ones using laser diodes with one AR-coated facet.

Fig. 2 shows the measured laser output power versus the modulation frequency for RF power fixed at 16 dBm and dc bias at threshold. This figure shows the overall frequency response of the laser. Very strong response at the harmonics of the cavity frequency (295.3 MHz) is observable. High frequency of RF modulation could usually result in shorter pulsewidths [13] because it provides a narrower gain range in the time domain. However, as shown in Fig. 2, the frequency response decreases with the increasing harmonics. The reason is twofold. First, because the device was not well impedance-matched, the high-frequency RF power could not be delivered well to the SLA. Second, in the external-cavity configuration, the frequency of relaxation oscillation is usually reduced to less than 1 GHz due to the long cavity length, leading to rapid roll-off of response at high modulation frequencies. In order to have a sufficient modulation depth, TIA 900-10 was used to amplify the RF signal from the HP 83732B synthesized signal generator. Because TIA 900-10 has a fixed amplification gain of 34 dB within the frequency range 100–900 MHz, the third harmonic, ~886 MHz, was used.

In the beginning, the grating was adjusted to have the laser oscillating near 830 nm. The measured autocorrelation shape and width are not strongly affected by the dc biased level as long as it is between $0.6I_{\rm th}$ and $I_{\rm th}$. On the other hand, the RF modulation frequency has a very significant influence. In order to maintain the measured autocorrelation trace with a well-behaved shape, the RF modulation frequency can only be varied within 0.3 MHz, as shown in Fig. 3. Because the modulation frequency coincides with the cavity round-trip characteristics and the pulses sensitively vary with the frequency change, the short pulses are most likely generated by a mode-locking mechanism instead of gain-switching.

The above behavior is similar for the tuning range from 810 to 857 nm. Tuning was achieved by rotating the grating angle, which inevitably changed the cavity length. As a result, the round-trip frequency was slightly different, therefore the modulation frequency had to be changed. Fig. 4 shows the RF modulation frequency, dc bias, and lasing threshold versus tuning wavelength in the experiment. The lasing threshold for 810–857 nm is approximately between 45 and 70 mA. The RF modulation depth was maintained at $\sim 0.5I_{\rm th}$ for the entire tuning range.

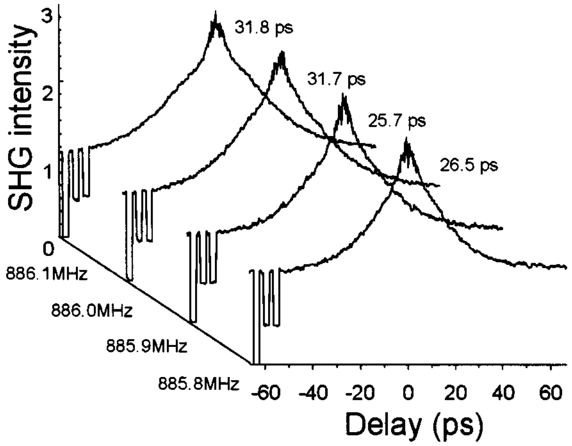

Fig. 3. The autocorrelation trace of the mode-locked pulses at different modulation frequencies.

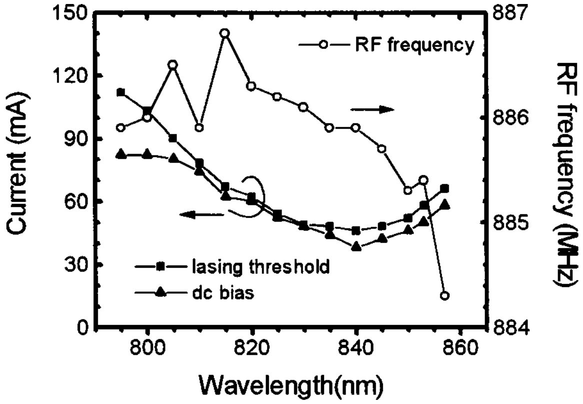

Fig. 4. The RF modulation frequency, dc biased current, and threshold current versus tuning wavelength for the actively mode-locked lasers in the experiment.

Under the above biasing condition, the output power is around 2 mW, measured from the output beam (a). For wavelengths below 810 nm, the lasing threshold increases to above 70 mA. The RF modulation depth at $0.5I_{\rm th}$ then causes an extra gain for the tail of the pulses, leading to significant broadening of the pulses. The extra gain could be reduced by lowering the dc biased level. Therefore, the experiment has shown that the well-behaved autocorrelation trace is retained by decreasing the dc bias.

Although the tuning is demonstrated only for 795–857 nm, a wider tuning range for such actively mode-locked pulses is possible with a proper adjustment of dc bias and RF modulation depth. The wide tuning range is because of the broad gain bandwidth provided by the asymmetric dual QW structure. In addition, unlike passive mode-locking using saturable absorbers, active mode-locking does not require a broad-band absorption spectrum, so it is particularly suitable for mode-locking of semiconductor lasers with a wide tuning range.

Fig. 5 shows the mode-locked pulsewidth and spectral width versus the tuning wavelength. The pulsewidth is calculated by assuming the Gaussian pulse shape. The pulsewidth is 13–21 ps and, in general, decreases with decreasing laser wavelength. One reason for the tendency may be due to the increasing differential gain with decreasing wavelength [14]. The corresponding spectrum from beam (a) contains almost no ASE noise [10]. The

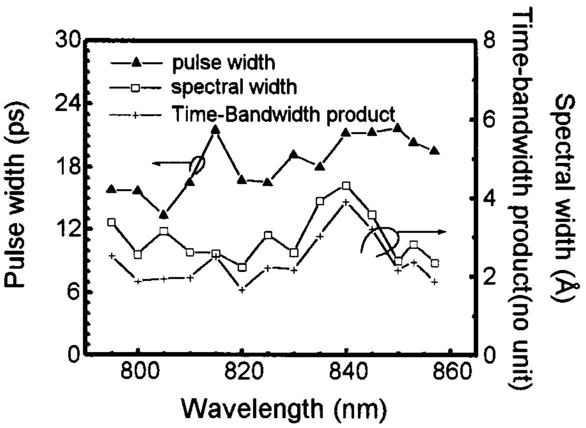

Fig. 5. The mode-locked pulsewidth, spectral width, and the time–bandwidth product versus the tuning wavelength.

FWHM of the spectrum is between 2 and 4.5 Å, showing no obvious spectral dependency. This spectral width is much wider than that of single-wavelength operation of the ring laser cavity without RF modulation [10]. The spectra are slightly undulated by the Fabry–Perot resonance of the SLA chip. With the RF modulation, because the instantaneous gain is larger near the peak of the modulation cycle, the Fabry–Perot resonance of the SLA chip is probably enhanced, leading to the undulated spectrum. The measured spectrum may cover either more convex than concave features or vice versa, depending on the tuning of the grating. As a result, the spectral width randomly varies with the tuning wavelength.

The variation of the time–bandwidth product is also shown in Fig. 5. The excess bandwidth more than transform limit is common in active mode-locking [13] due to the existence of chirp. Because the mode-locking force is not strong enough for the present modulation frequency, increasing the spectral width does not result in a reduced pulsewidth. Instead, it only increases the time–bandwidth product. Therefore, the variation of this product with the tuning wavelength is almost the same as the spectral width. This variation also shows that there is no evidence of decreased chirp with decreasing lasing wavelength. This is different from the past observation [3]. The reason is probably because the spectral width randomly varies with the wavelength. The broad gain bandwidth provided by the asymmetric dual QW's may also reduce the spectral dependence of the chirp.

To see if a wider spectrum of the laser with asymmetric dual QW's could be actively mode-locked, the grating was also replaced with a mirror. The spectral width then significantly increased to about 50 Å when the modulation signal was applied. However, no well-behaved auocorrelation shapes were measured as a result of insufficient mode-locking force for such a broad spectrum.

In conclusion, short optical pulses are generated from semiconductor lasers in an external ring cavity with a tuning range as large as 62 nm. To our knowledge, this is the broadest tuning range for actively mode-locked semiconductor lasers near the 0.8-μm wavelength range. The wide tuning range is possible due to the broadened gain bandwidth using asymmetric dual QW's for the laser material. The pulsewidths are between 13 and 21 ps with the spectral width 2–4.5 Å. The beam is accompanied with almost no ASE noise.

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