Fundamental and Subharmonic Hybrid Mode-Locking of a High-Power (220 mW) Monolithic Semiconductor Laser

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***Abstract*—We report on the generation of stable optical pulses at 1.55-μm wavelength via fundamental and subharmonic hybrid mode-locking of a high-power electrically pumped semiconductor diode laser with a slab-coupled optical waveguide structure. The highest average power measured in mode-locked operation was 220 mW. This is the highest power reported for a hybrid mode-locked monolithic semiconductor laser. We also measure the phase (or timing) noise during fundamental and subharmonic operation and our measurements show good agreement with theory.**

***Index Terms*—Laser noise, optical pulses, semiconductor lasers.**

I. Introduction

HIGH-POWER electrically pumped monolithic semiconductor mode-locked lasers offer an economical, compact, and power-efficient alternative to existing solid-state and fiber mode-locked lasers. For application areas such as high bit rate return-to-zero-format optical time-division-multiplexed systems, high-speed photonic analog-to-digital conversion, and radio-frequency (RF) signal generation, compact, stable, low noise, high-power, monolithic semiconductor mode-locked lasers, which can be synchronized to external clocks, are expected to play an important role [1], [2]. Whereas both solid-state and fiber mode-locked lasers can produce subpicosecond pulses with energies in the tens of nanojoule range, conventional semiconductor mode-locked lasers produce pulses that are typically less than a few picojoules. Since the phase (or timing) noise of mode-locked pulses is inversely proportional to the pulse energy [3], it is desirable to have high-power semiconductor mode-locked laser sources.

Pulse gain saturation energies in conventional semiconductor lasers are generally small and in the 0.3- to 3.0-pJ range. Recent experiments have shown that in a slab coupled optical waveguide geometry the gain saturation energies can be scaled up to 30–100 pJ by increasing the optical mode area and by reducing the overlap of the optical mode with the active region [4]–[7]. Passive mode-locking in slab-coupled waveguide laser structures was recently demonstrated by Plant *et al.* and by [4], [5], and [7]. Previously, we have also reported a 100-mW power actively mode-locked monolithic laser [8].

In this letter we demonstrate fundamental and subharmonic hybrid mode-locking of a high-power (220 mW) InGaAsP–InP monolithic slab-coupled waveguide laser operating at 1.55-μm wavelength with a fundamental repetition rate of ~5.2 GHz. This, to the best of our knowledge, is the highest power monolithic hybrid mode-locked laser reported. In hybrid mode-locking the dominant pulse shaping mechanism is still dynamic gain saturation and slow saturable absorption. The externally applied RF gain or loss modulation locks the timing of the pulses and reduces the phase noise (or timing noise) at small frequency offsets from the carrier. We present results from measurements of the phase noise of the pulse train for both fundamental and subharmonic mode-locking.

II. Device Fabrication and Experimental Setup

The laser structure, similar to the one reported in [7], was grown via metal–organic vapor phase epitaxy on an n-type InP substrate. The mode guiding layer is a lightly doped [$n = 6.5 \times 10^{16}$ cm^{-3}, 4 μm thick, InGaAsP slab ($\lambda_g = 1.03$ μm)]. This is followed by a five-quantum-well active region. The active region is followed by a 1.1-μm graded doped p-type InP cladding. The top contact layer is a heavily p-doped 0.2-μm-thick InGaAs layer. Fabrication of the lasers followed a procedure similar to the one described in [7]. The width and height of the waveguide ridge were approximately 4.5 and 1.9 μm, respectively. The calculated gain confinement factor Γ of the optical mode was ~0.01. After cleaving and coating the facets (with 85%/10% coatings), the lasers were mounted on a gold plated copper chuck using indium solder. The chuck was maintained at 10 °C. The gain section was forward biased using a pair of dc probe tips. The reverse biased saturable absorber section was also used for providing the RF modulation. A high-frequency ground-signal probe was used for RF modulation. The RF ground contact was fabricated right next to the saturable absorber contact (see Fig. 1). Electrical isolation of greater 40 kΩ was achieved between the gain and the absorber section by etching the highly doped InGaAs contact layer. The polyimide-planarized laser structure provided low capacitance for high-frequency RF modulation. The lasers used in the experiments reported here had a total cavity length of ~8.3 mm. The length of the saturable absorber section was ~200 μm. To mode-lock the laser, current in excess of 800 mA was injected into the gain section. Light from the laser was coupled to a high-speed 26-GHz New Focus RF detector (and an autocorrelator) via an aspheric lens and an optical isolator. The electrical signal from the photodetector was measured

Manuscript received January 31, 2008; revised May 1, 2008. This work was supported by the National Science Foundation (NSF) Career grant 0348501, by NSF grant 0334986, ILX Lightwave Co., and by Infotonics Inc.

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Digital Object Identifier 10.1109/LPT.2008.926911

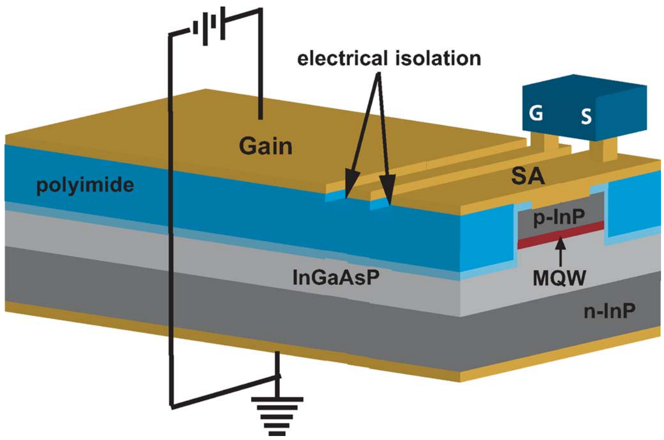

Fig. 1. Schematic of the cross section of the laser. The mode resides mainly in the InGaAsP waveguide layer. The figure also shows the scheme used to reverse bias the saturable absorber (SA) section using a G-S probe.

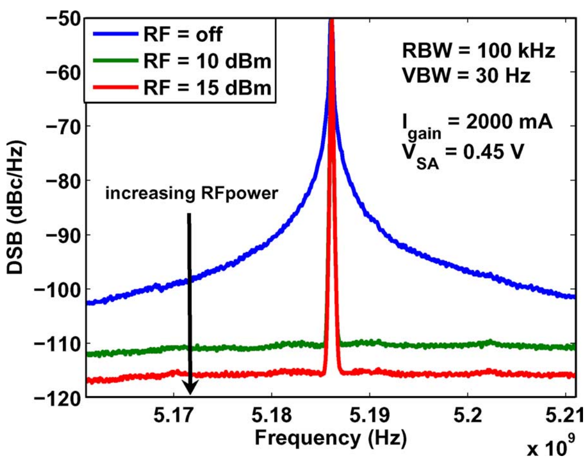

Fig. 2. Double sideband (DSB) noise spectrum for hybrid mode-locking for an average power > 200 mW. Increasing the applied RF power results in a reduction in the measured noise.

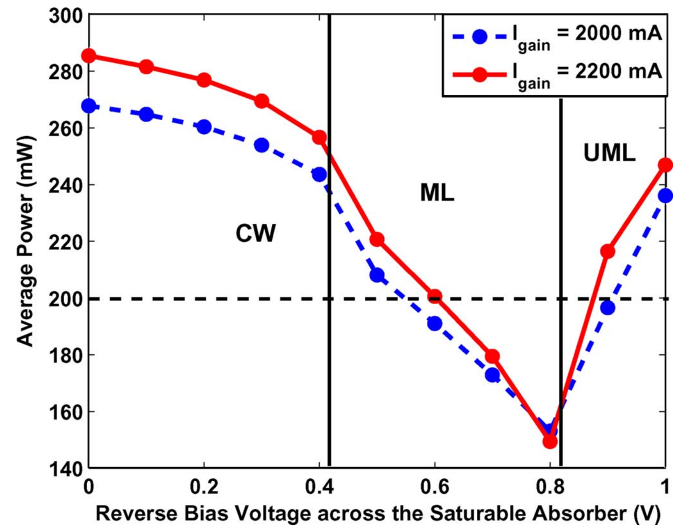

Fig. 3. Measured average optical power as a function of the reverse bias voltage across the saturable absorber for two different gain currents. CW, ML, and UML indicates continuous wave, mode-locked, and unstable mode-locked operations, respectively.

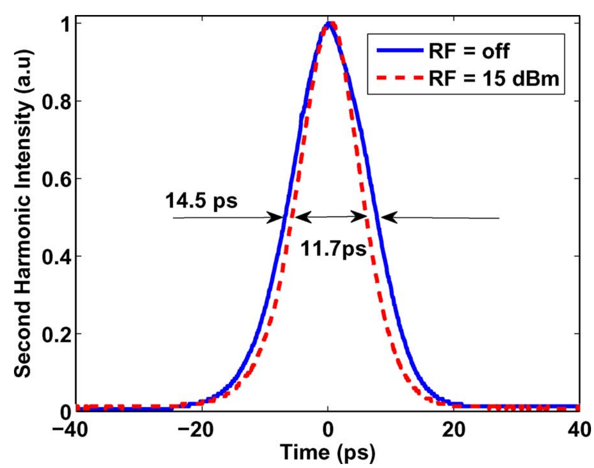

Fig. 4. Measured pulse intensity autocorrelation. The extracted pulsewidths in the absence and presence of the RF signal are indicated. The pulsewidth is reduced slightly when the RF signal is switched ON. The gain current is 1000 mA and the reverse bias voltage across the saturable absorber is 0.8 V.

using an RF spectrum analyzer. The reverse bias voltage across the saturable absorber section was increased until passive mode-locking was achieved. An external RF signal was then capacitively coupled in using a bias-tee. The frequency of the RF source was adjusted until the RF spectrum analyzer signal was stable.

III. Results and Discussion

Fig. 2 shows the behavior of the measured noise near the fundamental frequency as a function of the applied RF signal power for an average output power exceeding ~200 mW. In order to obtain high average powers under hybrid mode-locked operation, the gain current was increased to a maximum value of 2200 mA and the reverse bias voltage on the saturable absorber was maintained just above 0.4 V. Fig. 3 shows that the maximum power obtained from the laser when mode-locked was 220 mW. The pulse energy at this point was approximately 44 pJ. This to our knowledge is the highest power reported for a monolithic hybrid mode-locked laser. Fig. 3 also shows the region of stability for mode-locked operation. The full-width at half-maximum spectra of the pulses increased from 4 to 8 nm with the increase in reverse bias on the saturable absorber section. The corresponding pulsewidths varied between 25 and 10 ps.

Fig. 4 shows the pulse intensity autocorrelation and the extracted pulsewidths in the absence and presence of the RF signal when the gain current was 1000 mA and the reverse bias voltage was 0.8 V. Assuming a Gaussian pulse shape, the pulsewidth for the passively mode-locked case was 14.5 ps. The pulsewidth reduced to 11.7 ps when a 15-dBm RF signal was applied.

According to the theory, the pulse timing noise Δt obeys the following equation [3]:

$$\frac{d\Delta t(T)}{dT} = -\gamma \Delta t(T) + F(T) \tag{1}$$

where γ represents a damping term that is proportional to the applied RF signal strength and the square of the modulation signal frequency [3]. $F(T)$ is a delta-correlated noise source. Consequently, the measured phase noise spectral density $S_\phi(\omega)$ at a

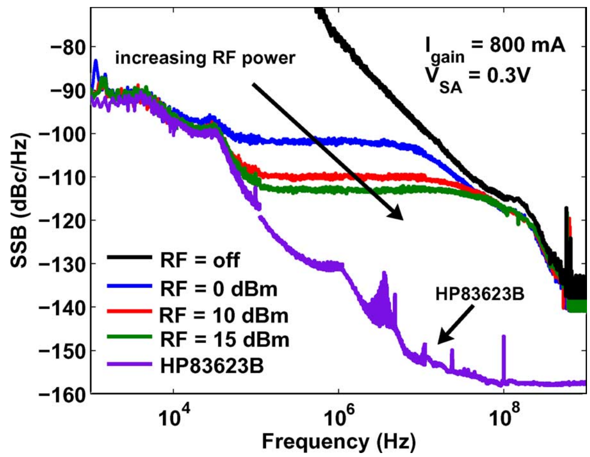

Fig. 5. SSB phase noise for various applied RF powers. Also seen in the plot is the SSB for the case when the RF signal is switched OFF (passive mode-locking). The SSB for the RF source shows that beyond 50 kHz, the timing noise is mainly due to the laser.

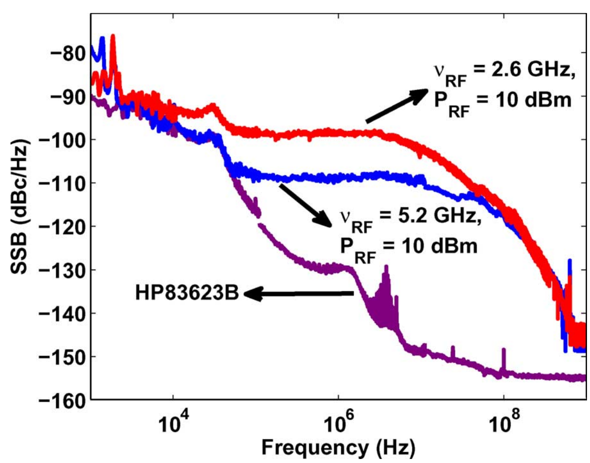

Fig. 6. Applying a 2.6-GHz external RF signal results in subharmonic hybrid mode-locking. The SSB phase noise shows an increase in the timing noise compared to the case of fundamental hybrid mode-locked operation. The gain current was 1000 mA and the reverse bias voltage was 0.3 V.

frequency offset ω is expected to scale as $S_\phi(\omega) \propto 1/(\omega^2 + \gamma^2)$. The phase noise was measured using the technique described in [9] and the results presented here thus represent an upper limit on the actual phase noise. Fig. 5 shows the measured single sideband (SSB) phase noise when the gain current was 800 mA and the reverse bias on the saturable absorber was 0.3 V. The measured phase noise exhibits the scaling characteristics predicted by the theory. When the RF signal is OFF, the phase noise exhibits a $1/\omega^2$ dependence characteristic of passive mode-locking. When the RF signal is present, the phase noise spectral density has a Lorentzian shape with a knee frequency that increases in proportion to the strength of the applied RF signal. In addition, the phase noise at frequencies smaller than the knee frequency decreases in proportion to the applied RF signal strength. At frequencies smaller than $\sim$50 kHz, the measured phase noise is dominated by the phase noise of the RF signal source (HP83623B).

Subharmonic mode-locking was achieved by tuning the frequency of the RF signal to one-half the fundamental frequency. Fig. 6 shows the measured phase noise for fundamental and subharmonic mode-locking for an RF signal power of 10 dBm. Since the damping γ of the pulse timing noise is proportional to the square of the modulation frequency, one would expect the knee frequency of the phase noise spectral density to decrease by a factor of four and the low-frequency phase noise to increase by 10 dBc/Hz when going from fundamental to subharmonic mode-locking. The measured results shown in Fig. 6 display the expected scalings.

IV. Conclusion

In this letter, we demonstrated hybrid fundamental and subharmonic mode-locking of a high-power slab-coupled semiconductor laser. The maximum measured output power of 220 mW is the highest reported for a hybrid mode-locked monolithic semiconductor laser. We also presented results on the pulse timing (or phase) noise spectral densities.

Acknowledgment

The authors would like to thank Dr. F. Bartoli for NSF Career grant 0348501.

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