Microwave and Millimeter Wave Signal Generation
Using Mode-Locked Semiconductor Lasers
with Intra-Waveguide Saturable Absorbers

D. J. Derickson, R. J. Helkey, A. Mar,

J. G. Wasserbauer, Y. G. Wey, and J. E. Bowers

ECE Dept. MS 172, University of California, Santa Barbara, CA 93106

Abstract

Microwave and millimeter wave signals can be generated using mode-locked semiconductor lasers with intra-waveguide saturable absorbers. Monolithic and external cavity devices optimized for electrical and optical signal generation are discussed along with measurements of amplitude noise, phase noise, output power, and repetition rate tunability.

Introduction

Mode-locked semiconductor lasers are capable of generating ultra-short optical pulses at repetition rates from tens of MHz to 350 GHz. [1,2,3,4]. Because of their small size, low power requirements, and ease of use, semiconductor lasers are useful in many applications which would not be feasible or economical with solid state or dye laser systems. When the optical pulses from mode-locked lasers are detected in high-speed photodetectors, electrical signals can be generated over these same frequency ranges. This work demonstrates electrical and optical signal generation techniques using passively and hybridly mode-locked semiconductor lasers with intra-waveguide saturable absorbers. Intra-waveguide saturable absorbers are efficient photodetectors which allow electrical signals to be simultaneously generated along with the optical signals in the same integrated structure [5]. The electrical and optical signals from mode-locked semiconductor lasers are useful in many microwave applications. Optical pulses as short as 2 ps can be easily generated which have a corresponding bandwidth well over 100 GHz. When semiconductor lasers are passively mode-locked, optical and electrical pulses at microwave frequencies are directly generated using only DC power supplies. The optical pulses are a convenient source for electrooptic sampling measurements of microwave signals [6]. Optical signals from mode-locked lasers can be used to injection-lock photosensitive electronic devices [7]. The electrical and optical output power, repetition rate tunability, and noise properties of mode-locked semiconductor lasers are examined in this work.

Figure 1 illustrates the external and monolithic cavity mode-locked laser structures that are studied. The top metalization of the laser in each case is broken up into three sections, allowing non-uniform electrical pumping of the structure. Section B is forward biased to provide the overall gain necessary for lasing. Section A is reverse-biased to act as an intra-waveguide saturable absorber [5]. Reverse-biased section A also acts as an integrated photodetector which provides an electrical output port from these devices. Section C serves as a gain modulation segment. Figure 1c shows a scanning electron micrograph of a multi-section mode-locked semiconductor laser structure. There are three techniques that are commonly used to produce short pulses in the laser structures of Figure 1: active, passive, and hybrid active-passive mode-locking.

In active mode-locking, a repetitive electrical pulse stream with a period equal to the round trip time in the laser cavity is applied to the gain modulation segment. The electrical pulses create a narrow time window of net gain in the device and a favored time for light to pass through the laser. After many round trips in the laser cavity, an optical pulse which is very much narrower than the electrical pumping waveform is formed. In order to get very short optical pulses from an actively mode-locked laser, the electrical modulation pulses should be narrow in time and of large amplitude. The laser segments must also have small electrical parasitics so that the high frequency content of the electrical signal is not attenuated. Pulses as short as 1.4 ps with 0.28 pJ of energy have been created using active mode-locking [8]

Passive mode-locking makes use of the pulse shortening properties of a saturable absorber. When an optical pulse enters the reverse-biased saturable absorber/photodetector segment, the leading edge of the optical pulse is absorbed, creating free carriers in the saturable absorber. The carrier density in the saturable absorber increases until the absorber becomes transparent at high carrier density levels. This selective removal of the leading edge of the optical pulse causes pulse shortening. On each pass around the laser, the pulse becomes narrower until the pulsewidth becomes limited by the bandwidth of the optical amplifier (which can be several THz). The free carriers are swept out of the saturable absorber due to the built-in electric field and a photocurrent pulse is generated. Only DC electrical power supplies are necessary for passive mode-locking, with optical and electrical pulses produced at the output. Passively mode-locked lasers are capable of operating at repetition rates well over 100 GHz [4]. Hybrid mode-locking combines the pulse shaping functions of active and passive mode-locking simultaneously.

Mode-locked semiconductor lasers designed for microwave signal generation are different than those designed for short optical pulse generation. Since optical output signals are not required, laser coatings can be applied and bias conditions modified to maximize the electrical signal output instead of the optical signal output. Figure 2 shows the pulsewidth versus optical output power for several values of the output facet reflectivity. Lower facet reflectivities extract larger optical outputs from the laser at the expense of slightly wider optical pulsewidths.

(a) monolithic cavity device
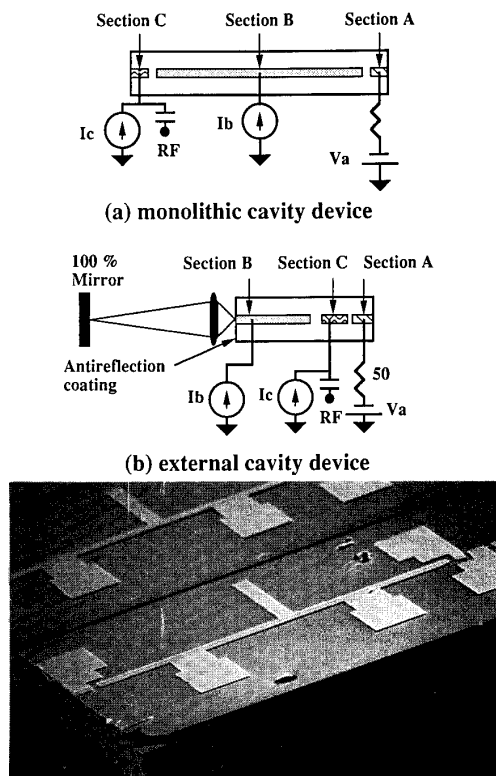

(b) external cavity device

Figure 1. Monolithic cavity (a) and external cavity (b) mode-locked semiconductor lasers. Segment A is the saturable absorber segment, segment B is the gain section, and segment C is the gain modulation segment. (c) Scanning Electron Micrograph of a multi-section mode-locked semiconductor laser.

Performance Characteristics

Figure 3 shows the electrical output pulse from a passively mode-locked external cavity laser (like that of Figure 1b) at a repetition rate of 2.5 GHz as detected in the integrated saturable absorber/photodetector, and from an external 20 GHz bandwidth p-i-n photodetector. Integrated photodetectors offer higher coupling efficiency and mechanical stability compared with external detection schemes. The integrated photodetector shows a 22 ps rise time, limited by the R-C response time of the

capacitance of the photodetector and the 50 Ω input impedance of the measuring sampling oscilloscope. The integrated photodetector shows a much slower fall time. The slower fall time is due to saturation effects in the photodetector in which the spatially separated holes and electrons create an opposing electric field to that of the internal photodetector field resulting in slow carrier removal. The response time of the integrated photodetector can be substantially improved if the functions of photodetection and saturable absorption are separated so that the photodetector is not operated at saturation carrier density levels [9]. The external photodetector shows a much faster response time since it is not operating in a saturation condition. Photodetectors can be made with an extremely fast response time, nearly equal to the optical pulsewidth. Figure 4 shows the impulse response time versus input optical pulse energy for a ultra-high speed graded double heterostructure GaInAs/InP p-i-n photodetector [10]. The impulse response at low input pulse energies is 3.9 ps with the impulse response degrading to 12 ps for 0.22 pJ of input energy. The responsivity of this photodetector is 0.2 implying that 0.013 pC of charge with a 5 ps pulsewidth can be extracted from these devices.

The output power of these intra-waveguide devices can be increased by placing multiple saturable absorbers in the cavity and combining the outputs. We have combined the output of two integrated saturable absorbers to double the electrical output signal from the mode-locked laser. The photodetectors can also be summed in series using artificial transmission lines in a similar manner to travelling wave MESFET amplifiers.

The performance of the mode-locked laser is very dependent on the saturable absorber design. Increasing the saturable absorber length increases the total saturable absorber photocurrent but there is an upper limit on absorber length. Increased saturable absorber length requires more gain from the semiconductor gain segment and eventually gain saturation (typically a few pJ of output energy) in the semiconductor laser amplifier will be reached. Long saturable absorber lengths are also more susceptible to a self-pulsation mode of operation in which the laser pulsates at a rate much lower than the round trip time in the laser [11]. The optimal absorber length for shortest optical pulse width is discussed in reference 12.
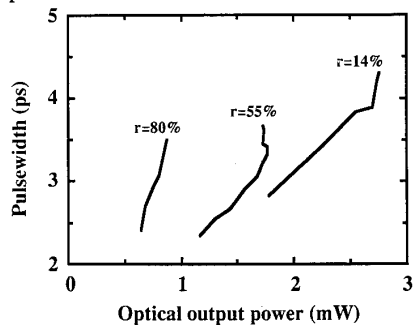

Figure 2. Output power versus facet amplitude reflectivity for a two-section passively mode-locked external cavity laser. The repetition rate is 2.5 GHz.

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For use as a microwave source, the phase and amplitude noise at the mode-locking frequency is critically important. The phase noise of the optical and electrical pulses were measured using the experimental set up shown in Figure 5 [13]. When the switch is in the 'A' position, the absolute phase noise contributed both by the mode-locked laser and the modulation source is measured. When the switch is in the 'B' position, the residual phase noise of the mode-locked laser independent of the modulation source is measured. The electrical phase noise characteristics of a 1.25 mm long monolithic cavity device (1.55 μm) passively and hybridly mode-locked at 36 GHz are shown in Figure 6. The figure shows $\mathcal{L}(f)$, the single sideband noise level in a 1 Hz bandwidth. The device was hybridly mode-locked with the frequency doubled output from an HP 8340B synthesizer which was amplified to 26 dBm with a travelling wave tube amplifier. The phase noise from the mode-locked laser is very similar to that of the driving source below 10 kHz but the mode-locked laser makes a significant contribution above this offset frequency. When the laser is passively mode-locked using only DC power supplies, a higher level of phase noise is seen due to the fact that the mode-locked laser is a free running electrical oscillator with moderate device Q. The integrated r.m.s. timing jitter is 0.2 ps (100 Hz- 100 MHz) for the electrical driving source, 0.6 ps (100 Hz- 100 MHz) for the hybridly mode-locked laser, and 3.3 ps (100 kHz-100 MHz) for the passively mode-locked laser. A more thorough description of the phase noise properties of mode-locked semiconductor laser is given in reference 14.

The repetition rates in external cavity mode-locked lasers are tunable by mechanically varying the external cavity length, producing rates to 20 GHz. The repetition rate for external cavity lasers is limited by the finite size of the external cavity optical components. Monolithic cavity mode-locked lasers are well suited for repetition rates over 10 GHz (corresponding to maximum device length of 3.5 mm) up to 350 GHz [1]. For a fixed cavity length, mode-locked lasers can be slightly tuned from the resonance with minimal degradation in device performance. The pulsewidth versus repetition rate of actively and hybridly mode-locked monolithic and external cavity lasers is compared in Figure 7. The repetition rate is varied by adusting the modulation signal frequency. The monolithic cavity device is a 2.75 mm long bulk GaAs active region device [15] operating at 13 GHz. The external cavity device is 500 μm long, operates at a 6.5 GHz repetition rate and comes from the same wafer as the monolithic cavity device. The tuning range limits in Figure 7 represent the points at which the mode-locked laser exhibits significant phase or amplitude instabilites as measured in an electrical spectrum analyzer with a photodiode input. Monolithic cavity devices show a greater tunability than external cavity devices. This is due to the lower cavity Q of the long monolithic cavity devices with all-active waveguides (the semiconductor waveguide losses are 30 dB/cm) as compared to long air external cavities. Active waveguides also offer additional tunablity because the carrier density and thus the index of refraction can self-adjust to keep the cavity in resonance.

Mode-locked lasers which incorporate distributed Bragg reflectors in the cavity have shown a larger tuning range due to the frequency dependence of the effective reflection point [16]. In passive mode-locking, the device's repetition rate can be electrically tuned using segment 'C' of Figure 1. The tuning characteristics for a passively mode-locked external cavity device are shown in Figure 8. The tuning is accomplished by varying the current in a 16 μm long tuning section.
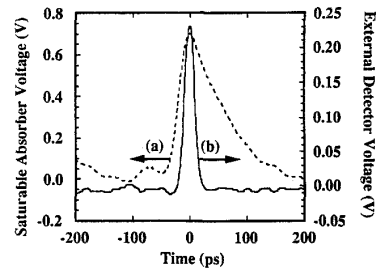

Figure 3. Photocurrent generated voltage as measured in a high speed sampling oscilloscope with 50 Ω input impedance (AC coupled). (a) Photocurrent measured from the internal saturable absorber/photodetector. (b) Photocurrent measured from an external 20 GHz bandwidth p-i-n photodetector.
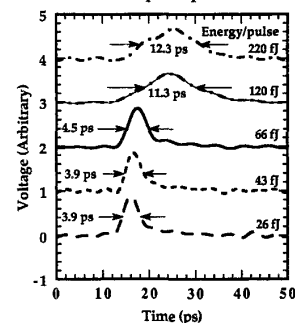

Figure 4. Impulse response versus input optical pulse energy for a high-speed graded double-heterostructure GaInAs/InP photodiode [9].
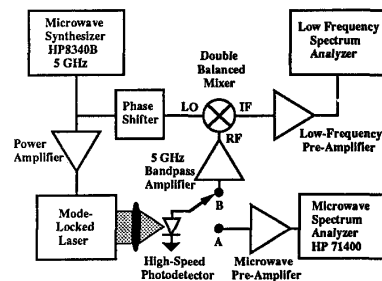

Figure 5. Experimental configuration for measuring residual (switch in position B) and absolute (switch in position A) phase noise from mode-locked semiconductor lasers.
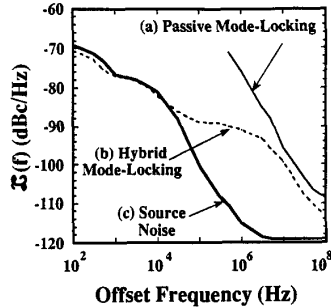
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Offset Frequency (Hz)

Figure 6. The single sideband phase noise normalized to a 1 Hz bandwidth for a monolithic mode-locked laser with a repetition rate of 36 GHz. The laser is a 1.25 mm long quantum well laser operating at 1.55 μm. (a) The phase noise under passive mode-locking conditions. (b) The phase noise under hybrid mode-locking conditions. (c) The phase noise of the modulation source.

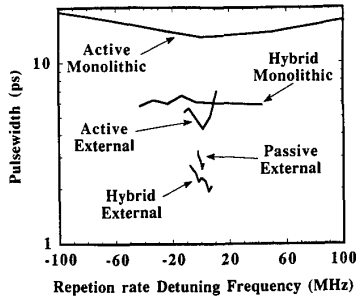**Repetion rate Detuning Frequency (MHz)**

Figure 7. Pulsewidth versus repetition rate detuning in monolithic and external cavity mode-locked semiconductor lasers. The external cavity is at a center repetition rate of 6 GHz and the monolithic cavity device is at a center repetition rate of 13 GHz. The limits of detuning are points where substantial amplitude and phase instability results.
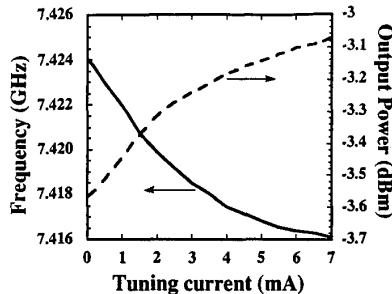

Tuning current (mA)

Figure 8. Repetition rate detuning versus current in a 16 μm long tuning section for a passively mode-locked semiconductor laser. The elecrical power from the saturable absorber is also shown versus tuning current.

In summary, external and monolithic cavity passivelyand hybridly mode-locked lasers offer a simple means of microwave and millimeter wave electrical signal generation. Integrated saturable absorber/photodetectors provide a convenient electrical

output port which is coordinated with the optical output signals. External photodetectors provide narrower electrical pulsewidths at the expensive of increased mechanical complexity. The timing jitter of the electrical and optical pulse streams is very low in hybridly mode-locked systems and much higher when the passive mode-locking operation is used. The repetetition rates of hybridly mode-locked lasers can be modulation frequency tuned over a small frequency range (0.5 %) with minimal degredation in device performance. Passively mode-locked devices are electrically tunable for phase-locking applications and offer moderate output power levels.

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