Locking Bandwidth of Actively Mode-Locked Semiconductor Lasers

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***Abstract*—The locking bandwidth of an actively mode-locked semiconductor laser is a measure of its tolerance to variations in the input drive frequency. At frequencies outside the locking bandwidth, the output pulses from the laser exhibit large amplitude fluctuations and timing jitter. This paper investigates the locking bandwidths of fundamentally driven and harmonically driven high-repetition-rate actively mode-locked semiconductor lasers. We show that the locking bandwidth is maximized when the cavity length is minimized. The locking bandwidth is related to an important constant, the "pull-in time". Experimental data and numerical modeling show that the pull-in time is a function of the optical bandwidth of the system and the RF drive level.**

I. Introduction

Actively mode-locked semiconductor lasers are attractive as sources of periodic trains of short optical pulses. Applications of mode-locked semiconductor lasers include very high bit-rate communications [1], instrumentation [2], and optical clock distribution [3]. One of the most important features of actively mode-locked lasers is that the optical pulses are phase locked to an external electrical reference through the RF drive signal that modulates the active device. This is clearly an essential feature in communications and other systems in which synchronization to an external clock is required. Of practical interest in the design of systems using actively mode-locked lasers is the range of RF drive frequencies over which the laser will produce stable optical pulses with low-amplitude fluctuations and low timing jitter [4]–[13].

An actively mode-locked semiconductor laser comprises a gain region which is driven by an external RF source. The active region is coupled to a passive external cavity. The emission wavelength of the laser can be controlled using a wavelength-selective component, such as a bulk grating [14], [15], or an integrated Bragg reflector in the cavity. The gain region is biased above threshold, and an RF drive current modulates the gain. The RF drive frequency is set close to the cavity resonance frequency or a harmonic of this frequency. Thus, the output pulse repetition frequency is close to the cavity resonance frequency or a harmonic of this frequency. It is important to recognize that small differences between the RF drive frequency and the closest harmonic of the cavity resonance frequency (the "detuning") significantly affect the behavior of the laser in terms of pulsewidth, amplitude fluctuations, timing jitter, optical wavelength, and spectral width [4], [6], [7], [9], [11], [13], [16]–[28].

The actively mode-locked laser is similar in some respects to an injection-locked oscillator in which the output signal is frequency and phase-locked to an external reference signal. One important parameter of injection-locked oscillators is the "locking bandwidth" [29]–[33]. Outside this bandwidth, the output of the injection-locked oscillator does not phase lock to the input, and large phase (hence timing) jitter occurs. Within the locking bandwidth, the phase is tightly controlled. Mode-locked lasers exhibit a similar phenomenon in that the RF phase of the detected output pulses is locked to the RF drive signal. Thus, the timing jitter is low within the locking bandwidth and high outside it [9]. Zhai *et al.* have shown that fundamentally driven lasers have a larger locking bandwidth than harmonically driven lasers [9], and have demonstrated locking bandwidths on the order of 60 MHz at a pulse repetition frequency of 4 GHz.

This paper presents measurements of locking bandwidths of fundamentally and harmonically driven semiconductor mode-locked lasers employing different cavity lengths and operating at pulse repetition frequencies from 1 to 12 GHz. We show that the locking bandwidth is maximized when the cavity length is minimized. In addition, we identify important parameters that affect the locking bandwidth. Simple empirical expressions are developed for these parameters to allow the performance of a mode-locked laser to be optimized for a particular application. We show that the locking bandwidth is related to an important constant, the "pull-in time." Experimental data and numerical modeling show that the pull-in time and the locking bandwidth are functions of the optical bandwidth of the laser and the RF drive level applied to the active device. Some of our results qualitatively agree with earlier work on a variety of mode-locked laser systems [20], [34]–[40]. We believe that the present paper gives the first extensive study of the locking bandwidth properties of fundamentally and harmonically driven mode-locked

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semiconductor lasers operating at multigigahertz rates. Our work concentrates on grating-controlled external cavity devices, but the general conclusions also apply to any actively mode-locked system where bandwidth limitation is achieved by an intracavity dispersive element [27], [41], including monolithic external cavity lasers incorporating DBR regions [25], [42] and lasers employing fiber grating cavities [43].

Section II presents measurements of the locking bandwidth for different cavity lengths and drive frequencies. Section III presents a simple analytical theory of the locking bandwidth, and introduces a parameter "pull-in time" using a simple quantitative approach. Section IV presents measurements and numerical simulations that show that pull-in time is a function of the drive current and the optical bandwidth of the system.

II. Experimental Results

Fig. 1 is a schematic of the bulk-optical external cavity actively mode-locked semiconductor laser used in our experiments. It uses a 1300 nm laser with an anti-reflection-coated (better than 0.1% reflectivity) rear facet coupled to an external cavity using a 2 mm diameter anti-reflection-coated sphere lens. The external cavity mirror is formed with a 1200 line/mm diffraction grating with a blaze wavelength of 750 nm and had lengths between 1.5 cm (10 GHz resonance) and 15 cm (1 GHz resonance). This grating controls the lasing wavelength and system bandwidth. The system bandwidth was estimated to be approximately 120 GHz, based on a measurement of the beam spot size on the grating surface. The RF drive to the laser is superimposed on a constant dc bias using a commercial bias tee. The drive signal is supplied by a Hewlett-Packard synthesized signal generator (8341B) with a Mini-Circuits amplifier (ZHL-42) to boost the power for frequencies up to 4 GHz or a Microwave Power Inc. amplifier (LHJ-105) for frequencies above 6 GHz.

Coupling between the laser and the grating was optimized by adjusting for minimum threshold current. Similarly, the grating angle was adjusted to minimize the threshold current, thereby ensuring that the device was operated close to the gain peak wavelength. This is not necessarily the wavelength for minimum pulsewidth because higher differential gains are possible at shorter wavelengths [14]. Operating conditions were optimized to produce the shortest pulses possible (as measured on the sampling oscilloscope) by adjusting the RF drive power to about 28 dBm and selecting a dc bias level about 120% of threshold.

The pulses were monitored using a high-speed p–i–n photodetector (risetime < 12 ps) closely coupled to a Tektronix sampling oscilloscope (CSA 803) with an SD-26 sampling head (risetime < 18 ps). No attempt was made to deconvolve the detector response. The average pulsewidth and the rms timing jitter were measured using the built-in functions of the oscilloscope. The RF spectrum of the detected pulses was measured with a Hewlett-Packard optical signal analyzer (HP70000) with a lightwave section (HP70810A).

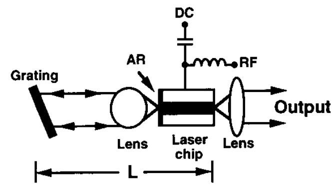

Fig. 1. Actively mode-locked semiconductor laser.

We considered the following mode-locked configurations: 1) a 1 GHz cavity (15 cm long) operated with the RF drive frequency near its eighth harmonic, 2) a 2 GHz cavity (7.5 cm) operating near its fourth harmonic, 3) a 4 GHz cavity (3.75 cm) operated near its second harmonic, and 4) an 8 GHz cavity (1.88 cm) operating near its fundamental. The output pulse repetition frequency in each case was about 8 GHz. Fig. 2(a) shows the average pulsewidth as a function of detuning for these lasers. Detuning in these figures is the frequency offset of the RF drive frequency from the frequency where the shortest stable pulses were obtained.

The measured minimum pulsewidths were similar for all cavities. However, the detuning for a short pulse is much more critical with a longer cavity laser driven at a harmonic (3.75 cm to 15 cm cavities) than with a shorter cavity laser driven at its fundamental (1.88 cm cavity). An explanation of this behavior is as follows. The pulse shaping by the gain modulation is critically dependent on the time difference between a pulse entering the gain medium and the peak of the gain modulation waveform. In a laser driven at its nth harmonic, there are n pulses circulating in the external cavity at a time, and each circulating pulse passes through the gain medium only once every n modulation periods. Thus, the time difference builds up over n modulation periods. Therefore, the laser is n times as sensitive to detuning as a fundamentally driven laser.

Fig. 2(b) shows the measured rms timing jitter of the optical pulse trains obtained from the above lasers under similar operating conditions. Each laser exhibits a region where the timing jitter remains low (below 2 ps), indicated by a dotted horizontal line, and outside this region, the timing jitter increases sharply. These measurements show that the range of detunings that give stable pulses (the locking bandwidth) depends on the external cavity length of the laser. The shortest cavity (1.88 cm) gives the largest locking bandwidth. The curves in Fig. 2(b) are not symmetrical about zero detuning. We believe that this is caused by gain compression in the active region. A full explanation will be presented elsewhere. The resolution of the timing jitter measurement was limited by the sampling oscilloscope to about 2 ps. We have also measured the timing jitter using a photodiode and an RF spectrum analyzer [44], and have found similar trends to Fig. 2(b), except that the minimum timing jitter is approximately 300 fs rms in the stable region for all the lasers.

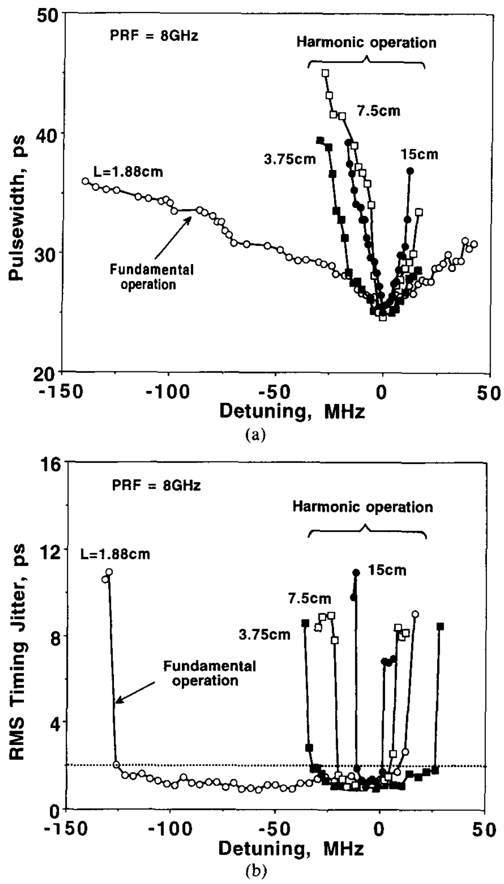

Fig. 2. Measured pulsewidth (a) and timing jitter (b) versus detuning for an 8 GHz pulse-repetition frequency laser with four different cavity lengths.

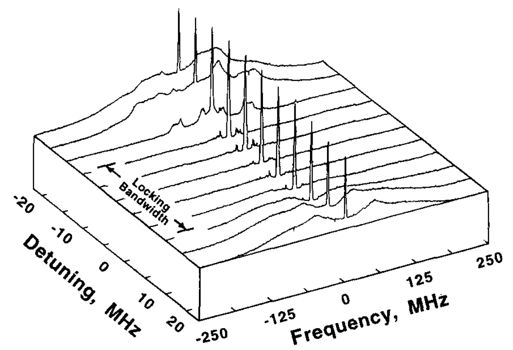

Fig. 3. Measured RF spectrum versus detuning showing spectral broadening outside the locking bandwidth (marked).

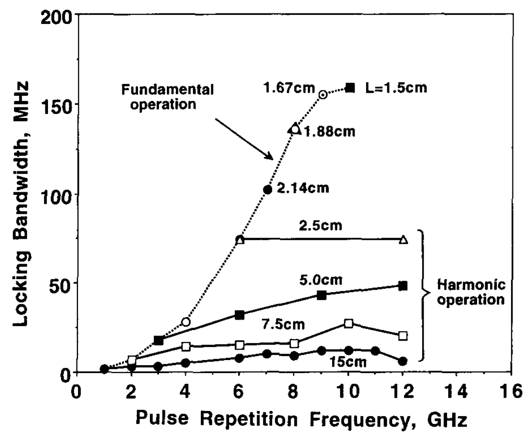

Fig. 4. Measured locking bandwidth versus pulse repetition frequency for a number of cavity lengths and pulse-repetition frequencies.

Fig. 3 shows the RF spectrum of the fundamental component of the pulse-repetition frequency as the detuning is changed for a 1 GHz cavity laser operated at its third harmonic. For detunings within the locking bandwidth of the laser, the spectral peak of the fundamental carrier remains narrow with a low-noise floor around it. Outside the locking bandwidth, several noise sidebands appear in the RF spectrum, indicating the presence of cyclic instabilities [4], [23], [24] and large timing and amplitude fluctuations in the optical pulse train.

We measured the locking bandwidths of several mode-locked lasers operating with the RF drive near the fundamental and harmonics of their cavity resonance frequencies. Fig. 4 shows the measured locking bandwidth of these lasers as a function of the pulse repetition frequency (PRF). There is a quadratic increase of locking bandwidth with the PRF (dotted trace) for fundamentally driven lasers of different cavity lengths, and an approximately linear increase for harmonic operation of fixed cavity length lasers (solid traces). This figure also shows that the largest locking bandwidth for a particular pulse repetition frequency is always obtained with a fundamentally driven laser.

III. Simple Model

The behavior of an actively mode-locked laser can be explained by considering the action of the modulated gain on the pulses circulating the laser cavity. Fig. 5 illustrates the effect of the modulated gain [curve (a)] on pulses returning to the laser chip (thick lines) from the external cavity to give reshaped pulses (thin lines). For pulses arriving early, but within t^- of the gain peak, the gain modulation is able to resynchronize the pulse by amplifying the trailing edge more than the peak [curves (b)]. This results in phase-locked pulses with a low timing jitter. Pulses arriving after the gain peak, but within t^+, will also be resynchronized [curves (c)]. For pulses arriving well before the gain peak [curves (d)], a double peak is formed. This is because the gain at the incoming pulse's peak is low, but the gain during the tail of the incoming pulse is high, and the rate of change of the gain near the gain peak is larger than the rate of decay of the tail of the pulse. The new peak will be preferentially amplified on successive round trips to become the dominant peak [23], [24], [28], [40]. However, the two peaks will coexist for a number of round trips. The time displacement between the old peak and the new peak will give a large timing jitter. Similarly, pulses arriving too late also have large

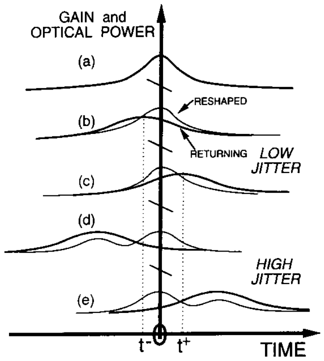

Fig. 5. Reshaping of optical pulses returning to the laser chip by the modulation of the gain of the laser chip (a) for four detunings (b)–(e).

timing jitters [curves (e)]. Thus the locking is only effective over a limited range of time delays between the incoming pulse and the gain peak, which we term the "pull-in time" T_{pi} where [9]

$$T_{pi} = t^+ + t^- \quad (1)$$

To develop a relation between locking bandwidth and pull-in time, we assume that the pull-in time is constant for a constant rate of change of the gain. The rate of change of gain is the exponential of the rate of change of the carrier density. Because the optical pulse is brief compared with the modulation period, the carrier dynamics are dominated by spontaneous rather than stimulated recombination during the majority of the modulation period. Thus, for modulation periods shorter than the carrier lifetime, the carrier density modulation depth is inversely proportional to the RF drive frequency. Therefore, for frequencies above approximately 1 GHz, the rate of change of the carrier density, hence the pull-in time, is independent of the RF drive frequency. The locking bandwidth f_{lock} is the maximum RF drive frequency $(T_{cav} - t^+)^{-1}$ minus the minimum RF drive frequency $(T_{cav} + t^-)^{-1}$, where T_{cav} is the round-trip time of the cavity:

$$f_{lock} = T_{pi}/[(T_{cav})^2 + T_{cav}(t^+ - t^-) - t^-t^+]. \quad (2)$$

By substituting $f_{RF} = 1/T_{cav}$, and for $t^+, t^- << T_{cav}$, this simplifies to

$$f_{lock} = T_{pi}(f_{RF})^2. \quad (3)$$

Thus, for constant pull-in time and for fundamentally driven lasers, the locking bandwidth is proportional to the square of the RF drive frequency (equivalent to the square of the cavity resonance frequency).

Because pulses are only resynchronized when they pass through the laser chip, pulses in an nth-harmonic driven laser will be resynchronized only once every n RF periods. This means that the locking bandwidth will be a factor of n less in lasers driven at the nth harmonic of the cavity resonance frequency, that is,

$$f_{lock} = T_{pi}(f_{RF})^2/n. \quad (4)$$

This analytical result explains the quadratic dependence on the pulse repetition frequency or drive frequency seen for fundamentally driven lasers ($n = 1$) in Fig. 4, and also the linear dependence on drive frequency for fixed cavity length harmonically driven lasers (f_{RF}/n = constant). The experimentally observed reduction of locking bandwidth from that expected in (4) at frequencies above 8 GHz can be attributed to chip and package parasitics reducing the gain modulation depth. Thus, our assumption that pull-in time is constant if the rate of change of gain is constant appears to be valid.

In high-frequency circuit applications, it is often the fractional or normalized bandwidth of a circuit that is more useful than the absolute bandwidth. A fractional bandwidth for the mode-locked laser can be found by dividing the locking bandwidth by the RF drive frequency (i.e., the pulse repetition frequency). Since $f_{RF} = nf_{cav}$, where f_{cav} is the cavity resonance frequency, the fractional bandwidth is

$$f_{lock}/f_{RF} = T_{pi}f_{cav}. \quad (5)$$

The fractional locking bandwidth, gained from the results in Fig. 4, is plotted in Fig. 6 against cavity resonance frequency. The fractional locking bandwidth is proportional to the cavity resonance frequency of the laser, and the pull-in time is the constant of proportionality, as shown in (5). The solid line is a theoretical curve obtained by plotting (5) for T_{pi} = 2.0 ps. The different symbols represent experimentally measured locking bandwidths for lasers described in Fig. 4. This figure demonstrates that the pull-in time is an important parameter that is independent of the harmonic drive number and the pulse repetition frequency, and shows the importance of a large pull-in time and short cavity in giving a large fractional locking bandwidth. The results in Fig. 6 indicate that fractional locking bandwidths of more than 1.7% are possible with fundamentally driven 9 GHz external cavity lasers.

IV. Factor Affecting Pull-In Time

The above experiments show that pull-in time is an important constant associated with mode-locked lasers [9]. For a laser that is tolerant to tuning, the pull-in time should be maximized. Ausschnitt *et al.* have described the effects of system bandwidth on the stable mode-locking range for CW dye lasers [20]. In their system, an intracavity filter was used to control the system bandwidth. In this section, the effects of the optical system bandwidth (controlled by external grating) and the RF drive current on pull-in time are investigated experimentally and numerically. The numerical simulations use the Transmission Line Laser Model (TLLM) [23], [24]. The TLLM is a time-domain numerical model based on modeling the traveling optical fields within the laser. The use of optical fields allows the laser system to be modeled over a wide, continuous bandwidth, and allows dispersive elements such as filters to be easily included into the algorithm. Previous work on

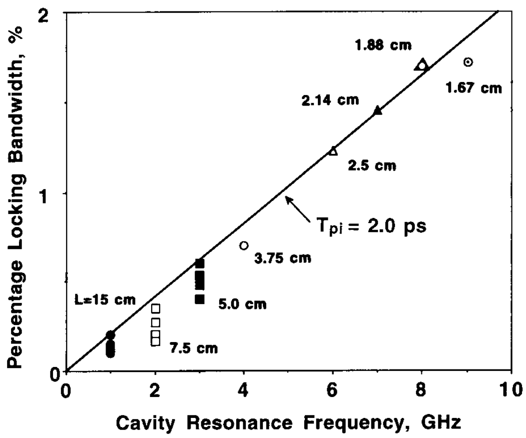

Fig. 6. Percentage locking bandwidth versus cavity resonance frequency for fundamentally and harmonically driven lasers.

mode-locked lasers has shown the TLLM to give results in excellent agreement with those observed experimentally [4], [9]. The parameters used in the numerical model are presented in Table I.

A. System Bandwidth

The bandwidth of the optical system has previously been shown to affect the minimum pulsewidth of mode-locked lasers [45]–[47], [20]–[21], and extensive simulation results using external grating as the bandwidth limiting element were presented in [23]. In this paper, the TLLM has been used to predict the effect of the system bandwidth on locking bandwidth, hence the pull-in time, by simulating the timing jitter versus detuning curves for a number of system bandwidths, and then measuring the locking bandwidth. The dispersion caused by the grating was modeled as a truncated Gaussian impulse response FIR digital filter [26]. The modeled laser was operated near the second harmonic of its 1 GHz cavity resonance with a dc bias at 126% of threshold, and was driven with a 200 mA peak-to-peak sinewave RF drive signal. Our experimental studies show that the locking bandwidth is relatively insensitive to bias level, so the discrepancy between the experimental and numerical bias levels (120 and 126%, respectively) is unimportant.

Fig. 7 shows simulated timing jitter versus detuning for system bandwidths of 25, 50, and 100 GHz (FWHM). The behavior of the timing jitter is similar to that observed experimentally, with rapid increases in timing jitter at the edges of the locking bandwidth, confirming the validity of the model for this purpose. The largest pull-in times were obtained for the narrowest system bandwidths. Fig. 8 shows the simulated pull-in times versus system bandwidth. These points are a good fit to a straight line, indicating an inverse relationship between pull-in time and system bandwidth. Thus, to obtain a large pull-in time requires a narrow system bandwidth. However, narrow bandwidth systems give wider pulses [20]–[21], [23], [46]. Also plotted are experimental pull-in times for a laser

TABLE I
LASER PARAMETERS USED IN SIMULATIONS (UNLESS STATED OTHERWISE)

Symbol	Parameter Name	Value	Unit
λ	Lasing Wavelength	1.3	μm
L	Laser Chip Length	300.0	μm
w	Active Region Width	2.0	μm
d	Active Region Depth	0.15	μm
L_e	External Cavity Length	150	mm
Δf	System Bandwidth	60.0	GHz
N_0	Transparency Carrier Density	1.0×10^{18}	cm^{-3}
a	Gain Cross Section	3.5×10^{-16}	cm^2
Γ	Waveguide Confinement Factor	0.35	
α	Linewidth Enhancement Factor	5.6	
n_e	Group Index of Waveguide	4.0	
α_{sc}	Waveguide Attenuation Factor	30.0	cm^{-1}
R_f	Front Facet Reflectivity	30.0	%
R_r	Rear Facet Reflectivity	0.1	%
R_e	External Cavity Coupling	10.0	%
A	Monomolecular Recomb. Coef.	1.0×10^8	s^{-1}
B	Bimolecular Recomb. Coef.	8.6×10^{-11}	cm^3 · s^{-1}
C	Auger Recomb. Coef.	4.0×10^{-29}	cm^6 · s^{-1}
β	Spontaneous Coupling per Laser Chip Mode	4.0×10^{-5}	

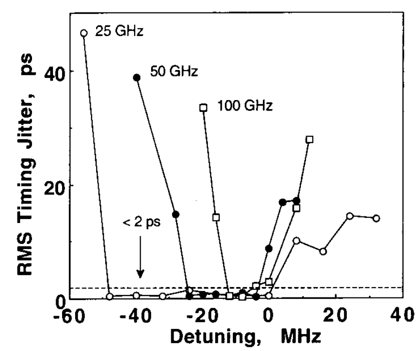

Fig. 7. Simulated timing jitter versus detuning for system bandwidths of 25, 50, and 100 GHz.

driven close to the fourth harmonic of its 1 GHz cavity resonance frequency and employing 30, 70, and 120 GHz system bandwidths. These experimental results confirm the inverse relationship between system bandwidth and pull-in time.

The dependence of pull-in time on system bandwidth can be explained using the gain-modulation model, shown in Fig. 9. Wider pulses arriving early, with respect to the gain modulation, will be reshaped by the gain to give a single-peaked pulse synchronized with the gain. Wider bandwidth systems will have less dispersion, and so will return narrower pulses from the grating to the gain medium. Because of the relative steepness of the trailing edge of the narrow pulse, narrow pulses at the same detuning cannot be reshaped without the growth of a secondary pulse peak. The secondary peak will be amplified on successive passes through the laser chip to become the dominant peak. As before, the time difference between the old and the new peaks causes a large timing jitter. Thus, for the same detuning, wider pulses in a narrow-bandwidth system are more likely to be within the locking bandwidth than narrow pulses from a wide-bandwidth system.

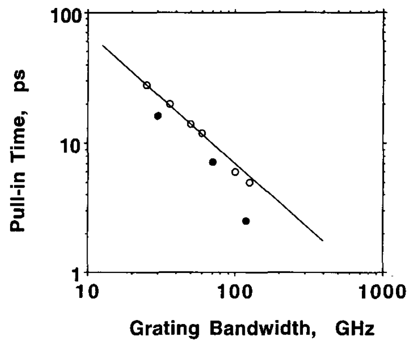

Fig. 8. Measured (●) and simulated (○) dependence of pull-in time on system bandwidth. The line indicates an inverse dependence.

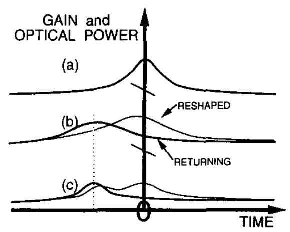

Fig. 9. Shaping of wide (b) and narrow (c) returning optical pulses by the modulated gain (a).

B. RF Drive Level

The effect of RF drive level on locking bandwidth has been studied experimentally and numerically. Fig. 10 shows the measured and numerical pull-in time versus the RF drive level for a laser system with a 30 GHz system bandwidth as determined by the grating. The RF current in Fig. 10 was determined by measuring the RF drive power into a 50 Ω microwave power meter, and using this power level and the known laser input impedance. The measured results fit to a straight line, indicating that the pull-in time is proportional to the log of the RF drive current over practical levels of drive power. Also plotted is the pull-in time for a number of RF drive levels simulated using the TLLM. The numerical results were obtained by simulating a 60 GHz bandwidth system, and then scaling by multiplying the pull-in time by 2 to allow comparison with the 30 GHz system used in the experiments. The numerical results are in excellent agreement with the measurements, and also show a logarithmic dependence of pull-in time on RF drive current.

A simple physical explanation for the increase in pull-in time with RF drive level is as follows. A higher drive level leads to a greater depth of gain modulation. Because the gain at the optical pulse peak is clamped close to the threshold gain of the laser, increased modulation will cause the losses to increase at either side of the peak of the gain waveform. Thus, pulse peaks before and after the original peak will be prevented from building up, and the timing jitter will be lower over a wider range of detunings.

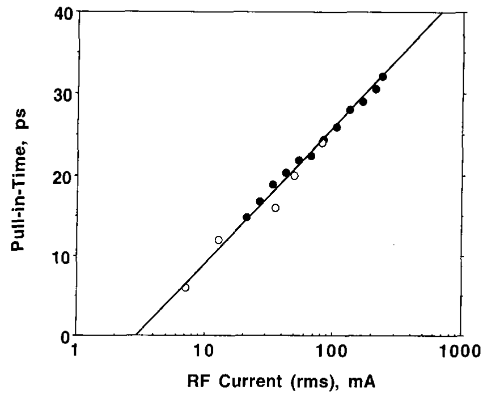

Fig. 10. Measured (●) and simulated (○) dependence of locking bandwidth on RF drive level. The line indicates a logarithmic dependence.

V. Conclusion

The locking bandwidth is a measure of the tolerance of actively mode-locked lasers to changes in the RF drive frequency. Within this locking bandwidth, the output pulses from the laser have low amplitude and timing jitter. At frequencies outside the locking bandwidth, the output pulses from the laser exhibit large amplitude and timing jitter. We have investigated the locking bandwidths of fundamentally driven and harmonically driven high-repetition-rate mode-locked semiconductor lasers, and have shown that the locking bandwidth is maximized when the cavity length is minimized. We have demonstrated the importance of the pull-in time in describing the locking bandwidth performance of actively mode-locked lasers. A simple analytical model has been used to explain the physical mechanisms of pulse shaping and the origin of pull-in time. This model shows that the locking bandwidth of a laser with any cavity length driven at either the fundamental or harmonics of the cavity resonance frequency can be calculated from a knowledge of the pull-in time. Experimental data and numerical modeling have shown that the pull-in time and the locking bandwidth can be maximized using a narrow optical system bandwidth set by, for example, a grating in the external cavity, and by driving the laser with a high RF current.

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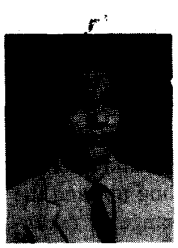

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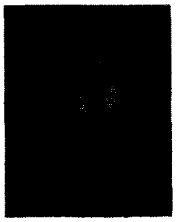

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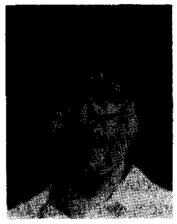

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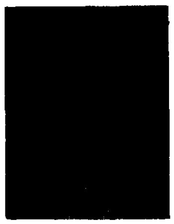

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