

Universality of Mode-Locked Jitter Performance

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Abstract—It is shown experimentally that the jitter of actively mode-locked laser pulses is determined by two factors: first, by spontaneous noise associated with cavity loss, and second, by round-trip propagation time. As the round-trip time is increased, a characteristic frequency which defines the high-frequency limit of phase noise decreases. For a comparable round-trip time and cavity loss, the jitter of mode-locked lasers based on diverse gain media, whether semiconductor or erbium ion is universal and independent of the upper-state transition lifetime.

Index Terms—Active mode locking, jitter, semiconductor lasers.

I. INTRODUCTION

COMPACT sources of high-frequency low-jitter picosecond pulses are desired for applications such as optical time-division-multiplexing [1], optical switching [2] and sampling [3], and high-resolution photonic analog-to-digital conversion [4], [5]. Compared to sources utilizing other gain media, such as rare-earth-doped fibers, semiconductors offer substantially smaller size and weight, low power requirements, and potentially low cost. They can combine functions such as gain, modulation, saturable absorption, and optical filtering in one monolithic component and are the only practical source capable of fundamental mode locking at repetition rates in the multiten of gigahertz.

Though substantial literature exists on mode-locking phenomena, noise performance remains inadequately addressed. This is especially so with respect to active harmonically mode-locked lasers where time-domain simulations are exceedingly consumptive of computational resources. Jitter can be inferred experimentally, however, by integrating measured phase-noise spectra offset from the carrier. To date, the lowest reported values have come from erbium-ion fiber lasers with jitter of 10 fs (specific to a phase noise integration range 100 Hz–1MHz) and 16 fs (integration range 100 Hz–100 kHz) [6], [7]. By comparison, for semiconductor lasers 65 fs (integration range 150 Hz–50 MHz) and 43 fs (integration range 10 Hz–10 MHz) [8], [9] are reported. It is widely accepted that the source of jitter is spontaneous emission coupled into the lasing mode. The level of spontaneous emission is determined by the needed cavity gain and by the degree of

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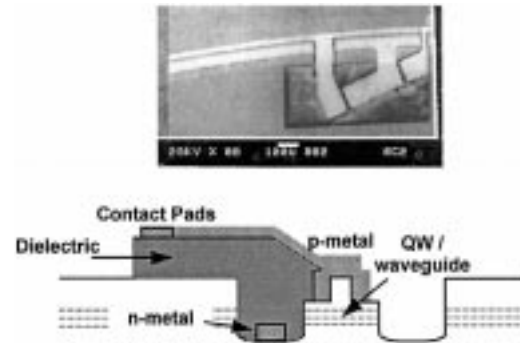


Fig. 1. Micrograph and schematic of the low-capacitance two-section curved-waveguide gain element used in the mode-locked laser. Active harmonic mode locking at 10-GHz was achieved.

inversion. A prior assumption has been that the larger jitter of diode lasers relates to the short upper-state carrier lifetime ($\tau_{\text{semiconductor}} \approx 1$ ns) as compared to the erbium ion ($\tau_{\text{erbium}} \approx 10$ ms); a factor of 10^7 times shorter. Indeed, a short upper state lifetime impacts linearity and the conditions needed to obtain maximal inversion, however, it does not have a direct impact on noise. In this letter, we present a detailed experimental study which demonstrates for the first time that the jitter performance of mode-locked lasers is determined by the same physical mechanisms, independent of the transition lifetime, and that semiconductor mode-locked sources compare favorably to that of erbium fiber lasers. This study shows that jitter is determined by net cavity loss and cavity Q .

II. DEVICE

The mode-locked laser gain element (Fig. 1) consists of a low-capacitance, curved, two-section InGaAsP active waveguide, and saturable absorber/modulator. It is coupled to an external end-mirror by high numerical aperture lenses. The gain element contains three compressively strained quantum wells. A parasitic capacitance of ~ 0.4 pF obtains from fabricating deeply etched trenches parallel to and ~ 15 μm from the ridge. The trenches reach the n-substrate and allow electrical contact from the p-side. A patternable dielectric isolates contact pads from the semiconductor device and mitigates capacitance. Waveguide curvature enables the integration of a high-reflectivity facet mirror with a low effective-reflectivity output to control intracavity reflections and prevent spectral modulation. The waveguide makes an angle of $\sim 6^\circ$ to the output facet normal, providing a reflection $< 10^{-5}$ [10]. A $\sim 3\%$ coating reduces reflections further. The HR-coated facet integrates a low-loss cavity end mirror. The p-cap layer etched from the ridge defines two active sections of the device, a short section

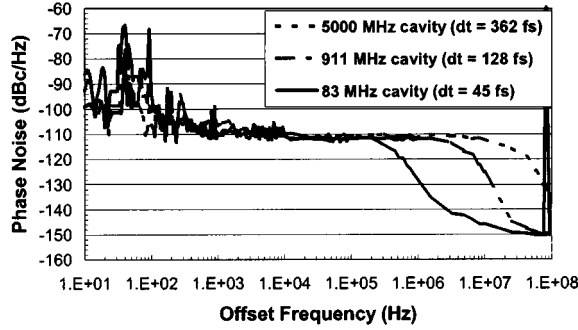


Fig. 2. Phase noise as a function of cavity length for 10-GHz mode locking. Phase noise is at a constant level up to a characteristic frequency f_{knee} related to the cavity length. For clarity, data corresponding to three cavity lengths is shown.

abutting the HR-coated facet functioning as modulator and saturable absorber, and a longer section providing gain. The laser is mode locked by simultaneously applying reverse and RF signal biases to the modulator. Only 38 mA of dc bias is required at the gain section.

III. JITTER

At 10 GHz, the harmonically mode-locked laser emits pulses of 6-ps duration as measured by autocorrelation. They are detected with a 20-GHz bandwidth photodiode with the 10-GHz frequency component amplified electronically. When coherently detected, the residual phase noise is obtained as a function of offset frequency from the carrier tone. We employ an Agilent E5501 phase-noise test set for this purpose. The term *residual phase noise* refers to the added contribution of phase noise of the mode-locked laser over and above that of the 10-GHz drive signal [11].

Phase noise was measured versus offset frequency for cavity lengths corresponding to 5000-, 3300-, 910-, 160-, and 83-MHz mode spacings (Fig. 2). In all cases, phase noise is characterized by a white-noise plateau at ~ -110 dBc/Hz. The phase noise rolls off as $\sim 1/f^2$ above a characteristic “knee” frequency f_{knee} which decreases inversely with cavity length, consistent with the theory of Hjelle and Mickelson ([12]). The narrow-band spur at 83 MHz corresponds to cavity-mode beat noise, and being extrinsic, it is excluded from the jitter calculation. (Spur suppression has been demonstrated in which the low frequency phase-noise is unaffected [13].)

Jitter is inferred by integrating the phase noise using the expression [14], [15]

$$\Delta t = \frac{1}{2\pi f_m} \sqrt{2 \int L(f) df} \quad (1)$$

where $L(f)$ is the single-sideband phase-noise spectral density and f_m is the modulation frequency. The upper integration limit is $\sim f_{\text{knee}}$ (Fig. 2), yielding

$$\Delta t \approx \frac{1}{2\pi f_m} \sqrt{2L_{J_Plateau} f_{\text{knee}}} \propto \frac{1}{2\pi f_m} \sqrt{\frac{2L_{J_Plateau}}{L_{\text{cavity}}}} \quad (2)$$

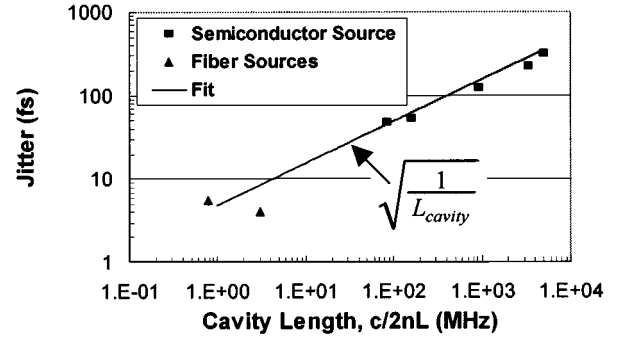
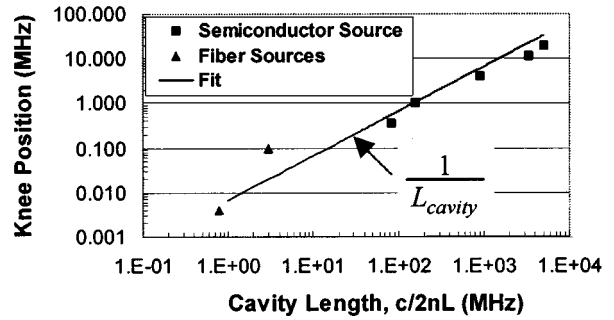


Fig. 3. Knee frequency and jitter (integration range 10 Hz–100 MHz) versus cavity length. The data fits well to the cavity-length dependence as shown in (1) and (2). Extrapolating to longer cavities, the semiconductor laser jitter approaches that of erbium fiber lasers.

where L_{cavity} is resonator length. Root-mean-square (rms) jitter, Δt , (integration range 10 Hz to 100 MHz) and f_{knee} are plotted versus cavity length (Fig. 3), following the cavity length fit quite well.

Extrapolating to longer cavities, one may compare semiconductor to erbium fiber mode-locked sources. Jitter data for fiber sources is available (References [6], [7]) for 190 and ~ 50 -m cavities. In these references, absolute phase noise was measured, yet it is possible to extract the position of the phase-noise knee by noting where the measured phase-noise deviates from that of the driving synthesizer. This data confirms that the relationship between cavity length and jitter is obeyed too for mode-locked fiber lasers, consistent with the theory of [12] considering the case of low-frequency phase-noise extended to active harmonically mode-locked lasers.

As seen, round-trip time, related to cavity Q , plays a strong role in determining the frequency profile of the phase noise, and hence timing jitter. Another factor influencing jitter is the optical loss within the cavity, which above lasing threshold clamps the gain.

Our next experiment measures the influence of cavity loss on phase noise for a fixed cavity length, with loss adjusted at the end mirror using output couplers of reflectivity 50%, 75%, and 90%. The phase noise plateau, formerly fixed, decreases by 5 dB as the output coupler is varied from 50% to 90% (Fig. 4). This can be understood by noting the connection between stimulated and spontaneous emission expressed by the Einstein relations. As the spontaneous emission rate is related to gain, smaller losses lead to a reduced spontaneous emission power. Since spontaneous emission causes phase noise, lower cavity losses leads to reduced jitter.

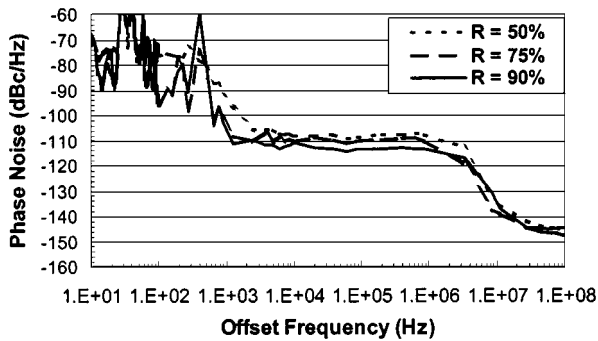


Fig. 4. Phase noise versus mirror loss. Additional cavity losses cause an increase in phase noise.

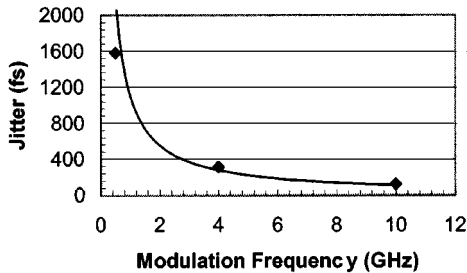


Fig. 5. Jitter versus drive frequency. Jitter (integration range 10 Hz–100 MHz) follows the $1/f_m$ trend predicted by (1) and (2).

Phase noise is characterized, finally, as a function of drive frequency while maintaining a fixed cavity length. Jitter is measured (integration range 10 Hz–100 MHz) with the cavity actively mode locked at 0.5, 4.0, and 10 GHz. As phase noise is determined by the photon lifetime, the measured phase-noise profile is similar for all mode-locking rates. Therefore, upon integration, the jitter is found to vary as the inverse of the drive frequency f_m consistent with (1) and (2) (Fig. 5).

IV. CONCLUSION

Low jitter in mode-locked lasers is obtained through a high- Q low-loss cavity, regardless of gain medium. The longer photon lifetime associated with higher Q mitigates against pulse-to-pulse phase fluctuation, and leads to low jitter. As spontaneous emission is related to the gain required to achieve lasing threshold, lower cavity losses lead to lower values of phase noise and, hence, lower jitter. Cavity losses in erbium

fiber lasers are similar to those of semiconductor lasers owing to the losses of high-speed modulators required in the erbium designs. Jitter performance is universal and, to first order, independent of upper-state carrier lifetime. Indeed, by extrapolating to long cavities, the jitter of mode-locked semiconductor lasers can compare favorably to that of the erbium fiber sources.

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