Linewidth Measurements of MEMS-Based Tunable Lasers for Phase-Locking Applications

Ezra Ip, Joseph M. Kahn, *Fellow, IEEE*, Doug Anthon, and Jeff Hutchins

***Abstract*—We have used two techniques—the beat spectrum method and the frequency noise spectrum method—to measure linewidths of microelectromechanical systems (MEMS)-based tunable external cavity lasers (ECLs) in the C-band (1527–1567 nm). The two techniques yield similar results, but the latter is able to measure narrow linewidths more accurately in the presence of frequency jitter. The MEMS-based ECL linewidths are found to be inversely proportional to output powers over a wide range of powers. At output powers of 12 dBm, the beat linewidth is no more than 30 kHz, corresponding to per-laser linewidths of about 15 kHz. We show that these lasers are suitable for coherent detection of quadrature phase-shift keying.**

***Index Terms*—Frequency stability, laser measurement, laser tuning, microelectromechanical devices, phase jitter, phase-locked loops, phase noise, synchronous detection.**

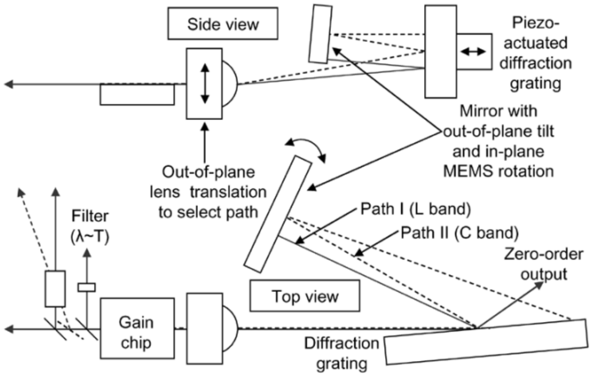

Fig. 1. Schematic of MEMS-tuned semiconductor external-cavity lasers.

I. INTRODUCTION

FUTURE optical communication systems will seek to increase spectral efficiency beyond the 1 bit per symbol offered by binary ON–OFF keying (OOK) and binary differential phase-shift keying (DPSK). In order to maximize both spectral efficiency and receiver sensitivity, it is necessary to use nonbinary modulation, such as quadrature phase-shift keying (QPSK) or M-ary quadrature-amplitude modulation, in conjunction with coherent detection[1] [1]. Laser phase noise is an important potential impairment to coherent receivers. In lasers whose lineshape is well-modeled as Lorentzian, frequency noise is a white Gaussian process whose power-spectral density (PSD) is proportional to laser linewidth. Many lasers exhibit additional nonwhite frequency-noise components at low frequencies, often referred to as “frequency jitter.” Both white and nonwhite frequency noises impact the performance of a coherent receiver’s phase-locked loop (PLL). In this letter, we use two well established techniques—the beat spectrum method and the frequency noise spectrum method—to characterize the linewidths of tunable external cavity lasers (ECLs) based on microelectromechanical systems (MEMS). We find that the two methods yield similar results, but the latter method can measure narrow linewidths more accurately in the presence of frequency jitter. We show that these lasers achieve linewidths as small as 15 kHz with low frequency jitter, and are suitable for coherent QPSK detection.

II. ECL DESIGN

Fig. 1 shows the schematic of a MEMS-tuned external-cavity semiconductor laser. These devices, optimized for either ITU channel grid locking or continuous mode-hop-free tuning, have been described in detail elsewhere [2], so only a brief description will be given here. The beam emitted by the antireflection-coated intracavity facet of the gain chip is collimated by the lens, diffracted by the grating, and frequency-selected by the requirement that the beam be retroreflected to the gain chip along the path (Path II in these measurements) selected by the out-of-plane mirror tilt and lens position. Varying the virtual pivot MEMS actuator voltage changes the cavity length and in-plane mirror angle, giving substantial mode-hop-free tuning ranges that can be extended by cavity length adjustment using the grating piezoelectric transducer (PZT) actuator voltage. Excellent long-term stability results when the MEMS and PZT voltages, as well as the gain chip current, are controlled by servos based on the relative intensities of the zeroth-order, linear-filter-sampled, and etalon-sampled outputs. For the measurements reported here, however, low jitter is more important than long-term stability, and best results are obtained by eliminating the servos and driving the gain chip and actuators directly by low-noise dc sources.

III. LINEWIDTH MEASUREMENT TECHNIQUES

A. Beat Spectrum Method

The setup for both techniques is depicted in Fig. 2. The outputs of the two lasers are combined using a 3-dB coupler and

Manuscript received March 25, 2005; revised June 10, 2005. The work of E. Ip and J. M. Kahn was supported by National Science Foundation Grant ECS-0335013.

E. Ip and J. M. Kahn are with the Department of Electrical Engineering, Stanford University, Stanford, CA 94305-9515 USA (e-mail: wavelet@stanford.edu; jmk@ee.stanford.edu).

D. Anthon and J. Hutchins are with Iolon, San Jose, CA 95131 USA (e-mail: danthon@iolon.com; jeff_o_hutchins@yahoo.com).

Digital Object Identifier 10.1109/LPT.2005.856435

---

[1] “Coherent detection” denotes synchronous detection by a phase-locked local oscillator, and should be distinguished from noncoherent detection (e.g., of OOK) and differentially coherent detection (e.g., of DPSK) [1].

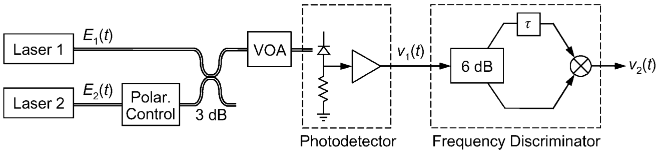

Fig. 2. Measurement setup. In the beat spectrum method, $v_1(t)$ is measured by a spectrum analyzer, while in the frequency noise spectrum method, $v_2(t)$ is measured.

a photodetector measures the signal at one of the coupler outputs. In the absence of frequency noise, the photodetector output voltage $v_1(t)$ is a sinusoid at the difference frequency $\Delta f = \Delta f_2 - \Delta f_1$. In the presence of white frequency noise, the one-sided PSD of $v_1(t)$ is a Lorentzian centered at Δf

$$S_{v_1v_1}(f) = K\left(1+\left(2\frac{f-\Delta f}{\Delta\nu}\right)^2\right)^{-1}. \tag{1}$$

The beat linewidth $\Delta\nu = \Delta\nu_1 + \Delta\nu_2$ is equal to the sum of the two linewidths. K is a scaling constant that depends on the laser powers, the photodetector responsivity, and the beat linewidth. In the beat spectrum method, $v_1(t)$ is directly measured by a spectrum analyzer. Approximating the analyzer's internal narrow-band filter by a rectangular function of width B, the one-sided spectrum displayed is [3]

$$\begin{aligned} S_{v_1v_1,\text{meas}}(f,\Delta\nu,B) &= \int_{f-B/2}^{f+B/2} S_{v_1v_1}(f')df' \\ &= \frac{K\Delta\nu}{2}\left[\tan^{-1}\left(\frac{2(f-\Delta f)+B}{\Delta\nu}\right)\right. \\ &\qquad \left. - \tan^{-1}\left(\frac{2(f-\Delta f)-B}{\Delta\nu}\right)\right]. \end{aligned} \tag{2}$$

For a given resolution bandwidth B, we compute a set of functions $S_{v_1v_1,\text{meas}}(f,\Delta\nu,B)$ corresponding to different values of $\Delta\nu$, in order to estimate the value of $\Delta\nu$ best fitting the measured spectrum. The value of B must be chosen carefully. A large value of B reduces sweep time, which is necessary in the presence of frequency jitter, but B must be chosen sufficiently small that the shape of (2) is sensitive to $\Delta\nu$. Typically, accurate measurement of $\Delta\nu$ requires $\Delta\nu$ to be at least of the same order as B. As a result, the beat spectrum method cannot measure very narrow linewidths in the presence of large frequency jitter.

B. Frequency Noise Spectrum Method

In the frequency noise spectrum method [4], we pass $v_1(t)$ through a frequency discriminator that converts frequency fluctuations into intensity fluctuations. The discriminator output signal $v_2(t)$ is measured by a spectrum analyzer, yielding an estimate of the beat frequency noise spectrum. If the beat spectrum $S_{v_1v_1}(f)$ is Lorentzian, the beat frequency noise is a white Gaussian process with one-sided PSD given by

$$S_{v_2v_2}(f) = \frac{K_v^2}{Z}\frac{\Delta\nu}{\pi}. \tag{3}$$

In (3), Z is the termination impedance of the spectrum analyzer and K_v is the slope of the frequency discriminator (volts/hertz).

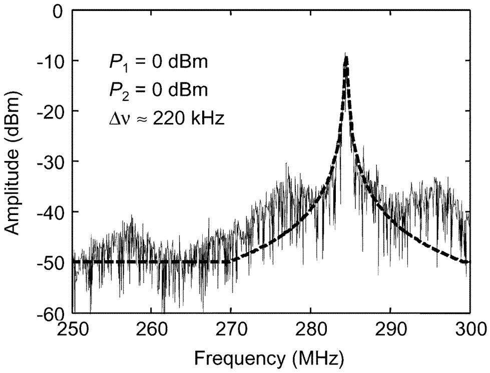

Fig. 3. Estimating beat linewidth from beat spectrum. Dashed line is an evaluation of (2) with the best-fit linewidth $\Delta\nu = 220$ kHz.

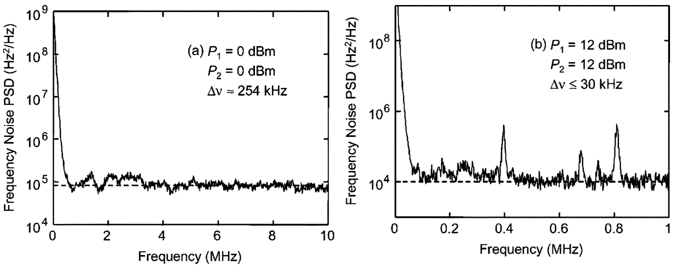

Fig. 4. Estimating beat linewidth from frequency noise spectrum. (a) $P_1 = P_2 = 0$ dBm, 0–10 MHz. (b) $P_1 = P_2 = 12$ dBm, 0–1 MHz. Dashed lines denote the white frequency noise level $\Delta\nu/\pi$.

Provided that the analyzer thermal noise floor is well below $S_{v_2v_2}(f)$, the frequency noise spectrum method can measure small beat linewidths $\Delta\nu$ in the presence of frequency jitter, since there is no requirement that the beat linewidth $\Delta\nu$ be at least of the same order as the resolution bandwidth B.

IV. EXPERIMENTAL RESULTS

We measured the linewidth of two MEMS-based ECLs emitting in the C-band (1527–1567 nm) using the methods outlined. The results presented below were taken at 1544 nm. No significant differences in linewidth were observed at other wavelengths in the C-band, within measurement error.

Fig. 3 shows a typical measurement of the beat spectrum $S_{v_1v_1}(f)$ recorded with resolution bandwidth $B = 300$ kHz. The laser output powers were set to 0 dBm. The dashed line in Fig. 3 shows an evaluation of $S_{v_1v_1,\text{meas}}(f,\Delta\nu,B)$, given by (2), for the best-fit linewidth $\Delta\nu = 220$ kHz.

In order to implement the frequency noise spectrum method, we constructed a frequency discriminator using a delay line and mixer, as shown in Fig. 2. The discriminator transfer function is a sinusoidal function of frequency that is approximately linear near its zero crossing at 200 MHz (the delay element was an 8-in coaxial cable). The slope K_v is proportional to the squared amplitude of $v_1(t)$. As the laser powers were varied, a variable optical attenuator was adjusted so the power of $v_1(t)$ was fixed at 10 dBm, so that the discriminator had a fixed slope of $K_v = -1.66$ mV/MHz.

Fig. 4(a) shows a measurement of the frequency noise PSD under conditions similar to Fig. 3. A flat spectrum is observed from below 1 MHz to above 10 MHz. The PSD rises at low

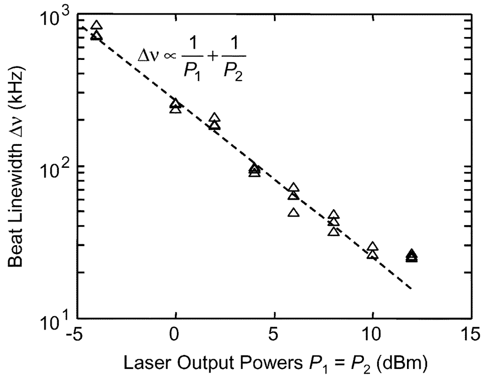

Fig. 5. Beat linewidth versus laser output powers.

frequencies due to the nonsuppression of the spectrum analyzer local oscillator feedthrough signal. The analyzer video bandwidth was set to 10 kHz. The white frequency noise component $\Delta\nu/\pi = 8.1 \times 10^4$ Hz^2/Hz corresponds to a beat linewidth $\Delta\nu = 254$ kHz, in good agreement with the result $\Delta\nu = 220$ kHz obtained by the beat noise spectrum method.

The frequency noise spectrum method was used to measure the beat linewidth $\Delta\nu$ as a function of laser output power, holding the two output powers equal, $P_1 = P_2$. Results are shown in Fig. 5. If each laser has a linewidth proportional to the inverse of its output power, then the beat linewidth is proportional to the sum of the inverses of output powers. We observe that this trend is obeyed over a wide range of output powers. At the highest output powers of 12 dBm, the beat linewidth is less than or equal to 30 kHz, suggesting that each laser has a linewidth of about 15 kHz. Since frequency jitter makes it difficult to measure beat linewidths under 30 kHz, it is difficult to determine conclusively whether the lasers exhibit linewidth rebroadening at the highest output powers.

Fig. 4(b) shows a frequency noise spectrum recorded at 12-dBm output powers between 0 and 1 MHz. At high powers, several peaks emerge above the noise floor, caused by spurious frequency modulation (FM) of the lasers. While we were unable to identify the origin of the spurious FM, we can model it as sinusoidal modulation at 400, 700, and 800 kHz. The instantaneous phase of the beat signal can be written as

$$\varphi(t) = 2\pi f_{\mathrm{IF}} t + 2\pi \int_{-\infty}^{t} \Delta f(\tau) d\tau + \sum_{n=1}^{N} 2\pi a_n \cos(2\pi f_n t + \phi_n) \quad (4)$$

where f_{IF} is the mean difference frequency between the signal and LO laser and $\Delta f(t)$ is the white component of frequency noise. The last term represents modulation by N sine waves having amplitudes a_n radians and FM frequencies f_n. The instantaneous frequency of the beat signal is

$$f_{\mathrm{inst}}(t) = f_{\mathrm{IF}} + \Delta f(t) + \sum_{n=1}^{N} 2\pi a_n f_n \sin(2\pi f_n t + \phi_n) \quad (5)$$

and its spectrum consists of delta functions centered at the f_n with powers proportional to $(a_n f_n)^2$. The magnitudes a_n can be extracted from Fig. 5, but our measurements are not able to determine the phases ϕ_n.

V. DISCUSSION

In this section, we briefly consider using the MEMS-based ECLs for coherent detection of QPSK.

We first consider the effect of the white frequency noise. In a coherent receiver for QPSK, the phase error standard deviation should be less than 2.97° for a power penalty below 0.5 dB [5]. Assuming a beat linewidth $\Delta\nu = 30$ kHz and a bit rate of 10 Gb/s, this can be achieved by a second-order PLL having natural frequency $\omega_n = 57$ Mrad/s and damping constant $\zeta = 0.707$ [6]. The PLL propagation delay must not exceed $\tau = 5.8$ ns, which requires careful PLL design.

We now consider the effect of the spurious FM components. For small phase errors, we can model a PLL as a linear system with transfer function $H(f)$. The third term of (4) gives rise to a phase error of

$$\varepsilon(t) = \sum_{n=1}^{N} \pi a_n [H(f_n) \cdot e^{j2\pi f_n t} + H(-f_n) \cdot e^{-j2\pi f_n t}]. \quad (6)$$

The error $\varepsilon(t)$ is a sum of N sine waves, and maximum phase deviation occurs when the sine waves add in phase (ϕ_n equal), resulting in a peak phase shift of $\varphi_{\max} = 2\pi \sum_{n=1}^{N} a_n |H(f_n)|$. For the second-order PLL parameters given above, the observed spurious FM components would lead to $\phi_{\max} = 0.16°$. We can upper bound the resulting power penalty by assuming this effect is equivalent to a static phase error of 0.16°, which would have negligible impact on detection of QPSK [5].

VI. CONCLUSION

We have measured the linewidths of MEMS-based tunable ECLs in the C-band. At output powers of 12 dBm, a pair of lasers exhibits a beat linewidth no more than 30 kHz. We have shown that these lasers should be able to support coherent detection of QPSK.

REFERENCES

[1] J. M. Kahn and K. P. Ho, "Spectral efficiency limits and modulation/detection techniques for DWDM systems," *IEEE J. Sel. Topics Quantum Electron.*, vol. 10, no. 2, pp. 259–272, Mar./Apr. 2004.

[2] J. D. Berger and D. Anthon, "Tunable MEMS devices for optical networks," *Opt. Photon. News*, vol. 14, no. 3, pp. 43–49, Mar. 2003.

[3] R. A. Linke and K. J. Pollock, "Linewidth versus length dependence for an external cavity laser," in *Proc. 10th IEEE Int. Semiconductor Laser Conf.*, Kanazawa, Japan, Oct. 1986.

[4] D. Derickson, *Fiber Optic Test and Measurement*. Englewood Cliffs, NJ: Prentice-Hall, 1998, pp. 194–201.

[5] V. K. Prabhu, "PSK performance with imperfect carrier phase recovery," *IEEE Trans. Aerosp. Electron. Syst.*, vol. 12, no. 2, pp. 275–285, Mar. 1976.

[6] J. R. Barry and J. M. Kahn, "Carrier synchronization for homodyne and heterodyne detection of optical quadriphase-shift keying," *J. Lightw. Technol.*, vol. 10, no. 12, pp. 1939–1951, Dec. 1992.