Phase Noise Power Spectral Density Measurement of Narrow Linewidth CW Lasers Using an Optical Phase-Locked Loop

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***Abstract*—A novel technique for continuous-wave (CW) laser phase noise power spectral density measurement, useful for coherent communications, is proposed. It employs a homodyne optical phase-locked loop. Experimental results are compared with a self-heterodyne linewidth measurement and the comparison shows how the proposed measurement method gives more accurate results for coherent transmission system applications.**

***Index Terms*—Homodyne detection, phase-locked loops, phase measurement, phase noise.**

I. Introduction

RECEIVER sensitivity limit in coherent optical communications is mainly affected by semiconductor laser phase fluctuations [1], [2]. Also, sensors based on optical fiber interferometer systems have a sensitivity limited by phase noise [3]. For these reasons, many works focused on phase noise characteristics of semiconductor lasers have been published [4], [5]. Measurement methods for laser linewidth characterization were proposed in the past years; most of them are based on interferometric techniques [6], [7].

Here, we propose an accurate measurement technique adequate for testing lasers to be used in optical coherent communications. Such a method is able to retrieve the power spectral density (PSD) of the overall phase noise produced by two lasers, a source laser and a local oscillator (LO) laser. The combined phase noise can then be used for the design and performance estimation of a coherent transmission system. By the way, the CW source laser phase noise PSD could be obtained by this method, if the used LO laser is affected by a negligible phase noise. Our measurement technique is based on an optical phase-locked loop (OPLL) which can be described by a linear model. In this letter, we show experimental results obtained by using an OPLL based on sub-carrier modulation (SC-OPLL) [8]. This way, we are able to characterize CW lasers phase noise; optical oscillators with direct frequency modulation are not required.

Experimental results are also presented in this letter and compared with a common delayed self-heterodyne method.

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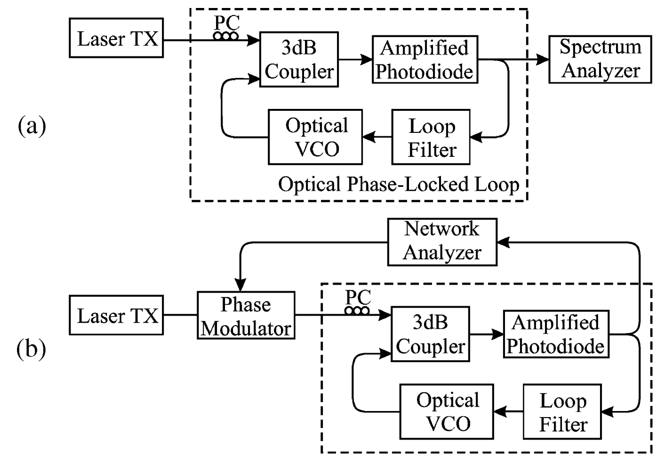

Fig. 1. Setup for measurement of the phase error signal spectrum (a) and the OPLL frequency response (b).

II. Measurement Method

The operation principle is based on a linear OPLL [see Fig. 1(a)] that can be described by a linearized model. An exhaustive study of such a model was presented in [1] and will be used as the starting point of the following treatment. The source laser is not modulated and the phase-lock to data crosstalk will not be taken into account. The signal power level at the OPLL input is set, in order to have shot noise and amplitude electrical noises negligible. This way, the overall phase noise of the source and local oscillator lasers is the only contribution that will be considered. The fundamental equation that allows evaluating the phase noise PSD is

$$V_{\rm PL}(f) = A_{\rm PL} \cdot \phi_N(f) \cdot [1 - H_{\rm PLL}(f)] \tag{1}$$

where $V_{\rm PL}(f)$ is the Fourier transform of the phase error signal, $A_{\rm PL}$ is a constant coefficient, $\phi_N(f)$ is the phase noise Fourier transform, and $H_{\rm PL}(f)$ is the PLL closed-loop transfer function. $A_{\rm PL}$, as defined in [1], depends on photodiode responsivity, transimpedance gain, received signal and local oscillator powers. In the experimental setup, shown in Fig. 1(a), the spectrum analyzer measures the spectrum $S_{\rm VPL}(f)$ of the phase error signal, which can be expressed as

$$S_{\rm VPL}(f) = A_{\rm PL}^2 \cdot S_{\rm PN}(f) \cdot |1 - H_{\rm PLL}(f)|^2 \, B_n \tag{2}$$

where $S_{\mathrm{PN}}(f)$ is the sum of the PSD of the lasers' phase noise, and B_n is the spectrum analyzer resolution bandwidth. The PLL transfer function and the constant A_{PL} can be measured in the experimental setup of Fig. 1(b), where the network analyzer returns the following response:

$$G_{\mathrm{NA}}(f) = \frac{\pi^2}{V_\pi^2} A_{\mathrm{PL}}^2 \cdot |1 - H_{\mathrm{PLL}}(f)|^2. \quad (3)$$

In (3), V_π is the voltage that has to be applied to the phase modulator in order to get a phase deviation of π radians. The function $A_{\mathrm{PL}}^2 |1 - H_{\mathrm{PLL}}(f)|^2$ can be evaluated from (3) and substituted in (2), giving as result the following formula:

$$S_{\mathrm{PN}}(f) = \frac{S_{V_{\mathrm{PL}}}(f)}{B_n} \cdot \left[G_{\mathrm{NA}}(f) \frac{V_\pi^2}{\pi^2} \right]^{-1}. \quad (4)$$

Equation (4) returns the PSD of the phase noise lasers given the measurement results obtained by the experiments shown in Fig. 1.

III. Experimental Results

The previously described technique was implemented for the characterization of two couples of external cavity tunable lasers. The first couple includes two Agilent 81640A, while the second couple consists of two Anritsu MG9638A. Declared linewidths are lower than 100 kHz for the Agilent model, and 700 kHz for the Anritsu model. The OPLL employed for phase noise measurement is an SC-OPLL [8]. The signal power at the photodiode input was set to -16 dBm, while the overall LO power was -3 dBm. The photodiode has responsivity equal to 800 V/W. The optical voltage controlled oscillator (VCO) includes a 10-GHz $LiNbO_3$ intensity modulator and a 6-GHz electrical VCO. The loop filter is a first-order active filter, whose time constants are $\tau_1 = 3.6\ \mu$s and $\tau_2 = 0.46\ \mu$s. Such time constants were chosen in order to get a second-order PLL transfer function with natural frequency $f_0 = 500$ kHz and damping factor $\zeta = 0.707$.

The value of $f_0 = 500$ kHz is the lowest natural frequency that allows OPLL locking, thus it affects the evaluation of $S_{\mathrm{PN}}(f)$ for low-frequency values. At high frequencies, $S_{\mathrm{VPL}}(f)$ is limited by additive white Gaussian noise. At low frequencies, $G_{\mathrm{NA}}(f)$ is not accurate due to the limited network analyzer sensitivity. Thus, our measurement method is only accurate in a limited frequency range around f_0. The upper limit could be overcome by repeating the measurement procedure for higher OPLL natural frequencies. Anyway, the highest OPLL natural frequency that can be set depends on the OPLL loop delay. Our SC-OPLL was affected by a 15-ns feedback loop delay and 8 MHz is the maximum natural frequency for which SC-OPLL can still lock (see [8]). By the way, we were able to measure $S_{\mathrm{VPL}}(f)$ and estimate $S_{\mathrm{PN}}(f)$ on an acceptable range, so we performed the proposed measurement just with $f_0 = 500$ kHz.

The measurement setups shown in Fig. 1 were performed. The electrical spectrum analyzer of Fig. 1(a) was set with a resolution bandwidth equal to 1 kHz and a video bandwidth of 100 Hz. The network analyzer of Fig. 1(b) generates a signal of 4 dBm and drives a $LiNbO_3$ phase modulator with $V_\pi = 5$ V. As previously anticipated, the measurements of $S_{\mathrm{VPL}}(f)$ and $G_{\mathrm{NA}}(f)$ allowed the phase noise PSD evaluation of two Agilent 81640A and two Anritsu MG9638A external cavity tunable lasers. Fig. 2 shows measurement results.

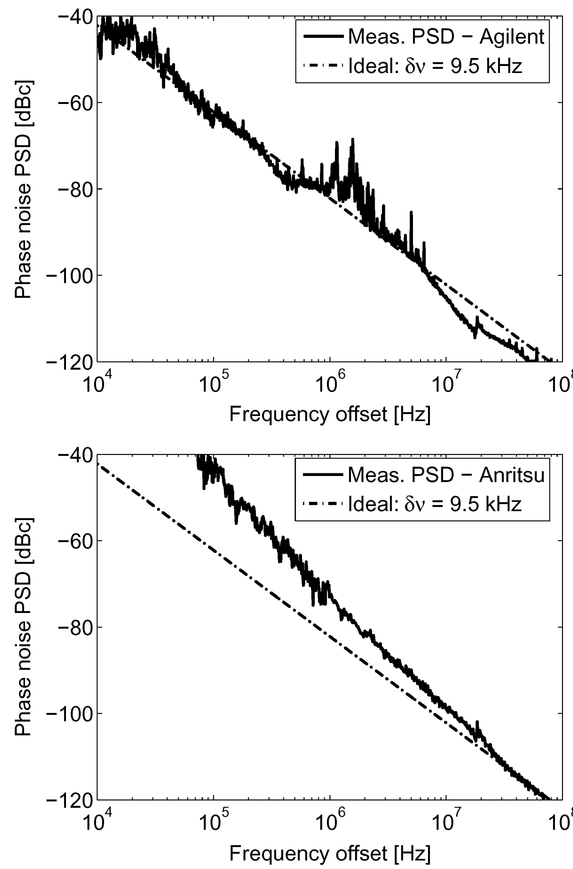

Fig. 2. Measured phase noise PSD of Agilent 81640A (top) and Anritsu MG9638A (bottom) lasers. A theoretical PSD with a linewidth of 9.5 kHz is superimposed.

An ideal phase noise PSD is also plotted in Fig. 2, and it was obtained by considering the combination of two identical white frequency noises, whose one-sided PSD is given by

$$2\frac{\Delta\upsilon}{\pi f^2} \quad (5)$$

where $\Delta\nu = 9.5$ kHz is the laser linewidth that best fits the measured PSD of Agilent 81640A. The same curve is depicted in the lower part of Fig. 2 and compared with the PSD estimate of Anritsu MG9638A. Fig. 2 shows how the first PSD follows the ideal curve and on the measurement frequency range Agilent 81640 is approximately characterized by a white frequency noise. In contrast, the phase noise PSD curve of the Anritsu MG9638A deviates from ideal white frequency noise curve, and is steeper at low frequencies. This suggests worse phase noise performance. To correctly model the behavior of the Anritsu laser, the f^{-n} phase noise contributions—which may arise from flicker noise or random-walk noise—have to be considered [2].

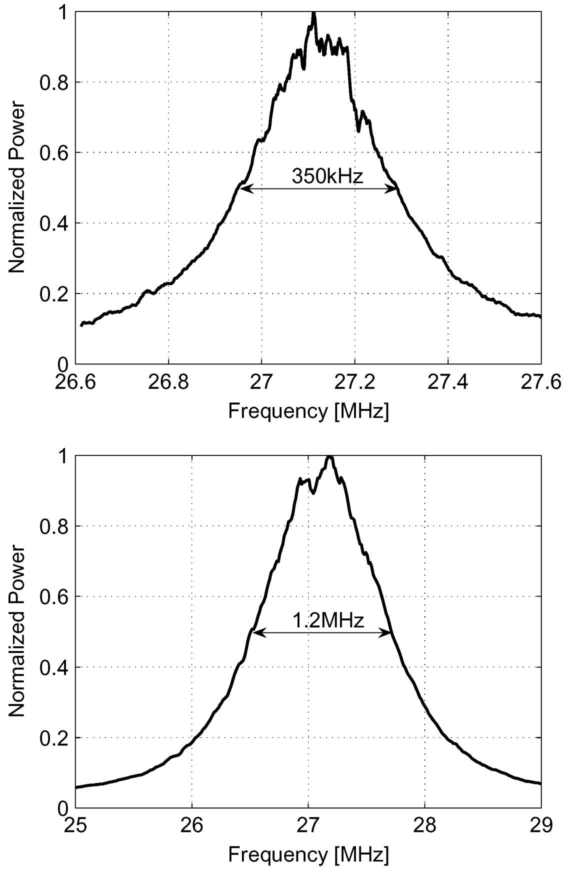

Fig. 3. Delayed self-heterodyne measurement results for Agilent 81640A (top) and Anritsu MG9638A (bottom) lasers, which show respectively $\Delta\nu = \mathrm{FWHM}/2 = 175$ kHz and $\Delta\nu = 600$ kHz.

We calculated the in-band f^{-n} phase noise contributions will increase the phase error standard deviation by 10% with respect to the ideal Lorentzian lineshape, when the natural frequency is set to 3 MHz.

Both source and local oscillator lasers were characterized by a delayed self-heterodyne measurement technique [9]. Such a measurement setup included a 20-km spoon fiber as delay line and an acoustooptic modulator with 27-MHz frequency shift. Fig. 3 shows the detected spectrum, which reveals a linewidth of almost 175 kHz for the Agilent laser and 600 kHz for the Anritsu laser. Such results confirm the worse performance in terms of phase noise of Anritsu lasers.

The considered measurement techniques gave different results. This fact was just observed in [6] during the characterization of DFB lasers and is due to an overestimation of the linewidth when the self-heterodyne method has to deal with deviations of the laser lineshape from the Lorentzian shape, i.e. when the frequency noise spectrum is no longer a flat spectrum because of f^{-n} terms. Such f^{-n} contributions correspond to optical frequency instability and usually have very low speed variation. From an empirical point of view, it can be explained by a frequency shifting, varying with time, of a perfect Lorentzian shape (see Fig. 4). The self-heterodyne (or also self-homodyne) method, being a low-speed measurement, is able to measure only the envelope of the frequency

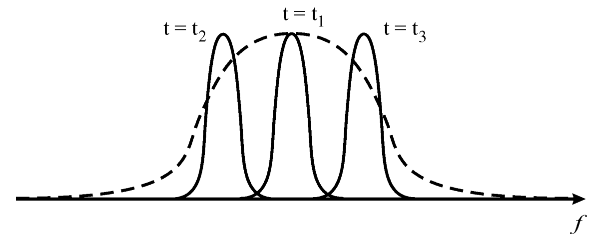

Fig. 4. Instantaneous shots of the drifting Lorentzian spectrum (straight lines) varying with time and long term spectrum (dotted) obtained by a protracted observation.

drifting "perfect" Lorentzian source (see Fig. 4). Since our measurement technique analyzes phase noise contributions on a limited frequency range, it does not take into account f^{-n} contributions at frequencies much lower than the OPLL natural frequency f_0. Such low-frequency contributions are not ignored in the self-heterodyne measurement. Anyway, they do not affect performance in coherent systems applications, so they do not have to be considered in laser phase noise experimental characterizations. For this reason, our method is more reliable for coherent communications because it estimates the "correct" amount of noise that affects the performance. The other mentioned methods overestimate the amount of phase noise for coherent applications.

IV. CONCLUSION

A novel measurement technique for the acquisition of the combined PSD of two lasers was presented. It is able to evaluate the phase noise on a part of the spectrum that determines the influence of linewidth on coherent systems. Other approaches, such as delayed self-heterodyne, give a pessimistic estimation of the linewidth. Therefore, the proposed technique gives the most useful value for linewidth to be used in the performance evaluation and design of coherent optical transmission systems.

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