Delayed Self-Heterodyne Phase Noise Measurements With Coherent Phase Modulation Detection

Tam N. Huynh, Lim Nguyen, and Liam P. Barry

***Abstract*— We present coherent phase modulation detection for laser phase noise measurements with delayed self-heterodyne method. The technique is demonstrated for the first time with the distributed feedback laser and external cavity laser. The results are within 15% of self-homodyne measurements using an optical coherent receiver.**

***Index Terms*— Delayed self-heterodyne method, linewidth, phase modulation detection, phase noise measurement.**

I. Introduction

THE phase noise of laser sources has been identified as a crucial characteristic that affects the performance of coherent optical communications for Dense Wavelength Division Multiplexing systems [1], [2]. This has lead to extensive measurement efforts to determine the phase noise characteristic of lasers for transmitters and local oscillators in these systems [3]–[5]. Among the various measurement techniques for phase noise characterization, delayed self-heterodyne method has been widely employed to determine the laser linewidth from the full-width half-maximum (FWHM) of the electrical spectrum of the modulating carrier frequency [5]–[7]. However, as it only measures the 3-dB linewidth, conventional self-heterodyne measurements can not fully characterize the laser phase noise [3], [5], [7].

In this letter, we propose a novel PM detection technique for laser phase noise measurements using delayed self-heterodyne method. The proposed technique can determine the differential phase coherently, thus allowing a more complete characterization of the phase noise for different lasers.

II. Measurement Method

A. Analytical Model

The electric field of the optical output signal from a single-mode laser with negligible amplitude noise can be expressed in complex notation as follows:

$$E(t) = \sqrt{P} \times e^{j(\omega_o t + \phi(t))} \tag{1}$$

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where P is the optical output power, ω_o is the angular optical frequency and $\phi(t)$ is the laser phase noise. Fig. 1(a) shows the block diagram of the proposed method with a phase modulator. The incident E-field on the photo-detector can be written in terms of the delayed and phase-modulated signals:

$$E_i(t) = 0.5\left[E(t-\tau) - E(t) \times e^{j[b\sin(\omega_c t + \phi_c)]}\right]. \tag{2}$$

Here τ is the delay of the fiber spool, b is the PM index, ω_c and ϕ_c are the modulating carrier frequency and phase of the driving signal at the phase modulator input, respectively.

It can be shown that the electrical current from the detector output is proportional to the intensity of the incident field as:

$$\begin{aligned} i_{pd}(t) = \ & 0.5\Re P[1 - \cos[\omega_o\tau + \phi(t) - \phi(t-\tau) \\ & + b\sin(\omega_c t + \phi_c)]] \end{aligned} \tag{3}$$

where $\Re$ is the photodiode responsivity. The delay τ should be much larger than the coherence time of the laser, so that $\phi(t)$ and $\phi(t-\tau)$ are statistically uncorrelated. Ignoring the DC term $0.5\Re P$, and expanding (3) with $\Delta\phi(t) = \phi(t) - \phi(t-\tau)$:

$$\begin{aligned} i_{pd}(t) = & -0.5\Re P\cos[\omega_o\tau + \Delta\phi(t)]\cos[b\sin(\omega_c t + \phi_c)] \\ & + 0.5\Re P\sin[\omega_o\tau + \Delta\phi(t)]\sin[b\sin(\omega_c t + \phi_c)]. \end{aligned} \tag{4}$$

Using the Bessel coefficient expansions, the in-phase and quadrature components $I(t)$ and $Q(t)$ of the differential phase noise, $\Delta\phi(t)$, can be found at even and odd harmonics of the photo-detector electrical signal in (4). In particular at the first and second harmonics:

$$\begin{aligned} Q(t) = \ & J_1(b)\Re P\sin[\Delta\phi(t) + \omega_o\tau]\sin(\omega_c t + \phi_c) \\ I(t) = \ & -J_2(b)\Re P\cos[\Delta\phi(t) + \omega_o\tau]\cos[2(\omega_c t + \phi_c)] \end{aligned} \tag{5}$$

where $J_k(b)$ is the Bessel function of the first kind with integer order k. $I(t)$ can also be found from the base-band term as $-0.5J_o(b)\Re P\cos[\Delta\phi(t) + \omega_o\tau]$.

Equation (5) shows that $i_{pd}(t)$ can be coherently demodulated to recover the differential phase $\Delta\phi(t)$ plus a constant phase offset $\omega_o\tau$. In off-line digital signal processing (DSP), the captured data of $i_{pd}(t)$ are demodulated by $-\cos[2(\omega_c t + \phi_c)]$ and $\sin(\omega_c t + \phi_c)$. A simple carrier phase recovery algorithm estimates ϕ_c prior to demodulation. Notice that the modulation index b should be adjusted so that $J_1(b) = J_2(b)$, or $b \sim 2.63$, for balanced I/Q outputs. The phase noise analysis evaluates (i) the E-field power spectral density (PSD), (ii) the phase-error variance, and (iii) the frequency modulation (FM) noise spectrum [3].

Due to the nature of self-heterodyne method, these measures will be twice the actual values of the laser linewidth. For example, the estimated 3-dB, FWHM Lorentzian linewidth

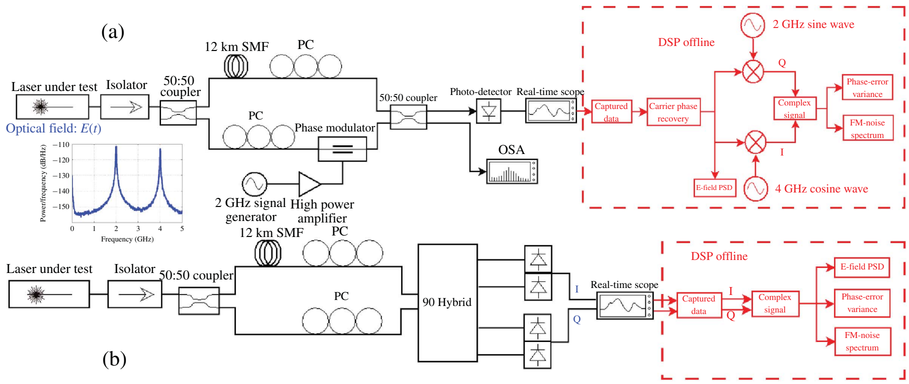

Fig. 1. Experiment setups for (a) self-heterodyne PM detection method and (b) self-homodyne optical coherent receiver method.

$\Delta\nu$ of the laser is one-half of the 3-dB, FWHM bandwidth of the one-sided PSD measured at the first or second harmonic of the modulating carrier. The phase-error variance over a time interval τ_i is one-half of the results determined from the self-heterodyne (or self-homodyne) measurements. Thus, if the laser phase noise was ideally described by a random walk, the measured phase-error variance,

$$\sigma^2_{\Delta\phi}(\tau_i) = \left\langle (\Delta\phi(t) - \Delta\phi(t-\tau_i))^2 \right\rangle \tag{6}$$

would increase linearly with τ_i and the slope from a linear fit to the measurements will be given by $2\pi(2\Delta\nu)$.

The FM-noise spectrum is defined as the PSD of the instantaneous frequency which can be obtained by differentiating the phase noise. The estimated 3-dB linewidths from the FM-noise spectra could be determined from the white noise region, S_o, of the measurements as: $\Delta\nu = \pi(S_o/2)$[4].

B. Experiment Setup

Fig. 1(a) shows the experiment setup in which the laser under test was optically isolated and then split into two arms by a coupler. The delayed arm was set to $\tau \sim 60$ μs with a 12 km single-mode fiber. The other arm went through a 12.5 Gb/s EOspace phase modulator driven by a 2 GHz signal generator. The light from the delayed and phase modulated arms were recombined via a second coupler. An 11 GHz photo-detector with an integrated transimpedance amplifier (TIA) detects the incident light from the coupler output. An Agilent real-time scope captured the TIA output signal at 20 GSa/s for 200K samples that were then fed into a computer for post-processing. The signal generator output was amplified to provide sufficient drive (PM index b) to the modulator in order to achieve balanced power at the first and second harmonics on an RF spectrum analyzer, as indicated by Fig. 1(a) inset.

In order to evaluate the PM detection technique, we also implemented the self-homodyne method with an optical coherent receiver, which is an extension of the approach in [3], as shown in Fig. 1(b). The two arms from the coupler outputs were now fed into an optical 90° hybrid whose outputs were detected by a pair of 43 Gbps balanced receivers with integrated TIAs.

III. Measurement Results

We performed the experiments with a DFB laser operating at 1540nm and an ECL laser. Figs. 2 and 3 show the results of the DFB laser analysis for PM detection and coherent receiver methods. The one-sided PSDs of E-fields at 2 GHz with PM detection and at base-band with the coherent receiver are shown in Figs. 2(a) and 3(a), respectively, yielding the estimated 3-dB linewidths of 6.5 MHz and 6 MHz. Figs. 2(b) and 3(b) plot the measured phase-error variance over a 50 ns time interval. The linear fits to the variance plots yield about 6.7 MHz and 5.9 MHz for $\Delta\nu$. The insets in Figs. 2(b) and 3(b) further extend the time delay to 400 ns and 50 μs. The linear fits over the 50 ns time interval have been plotted against the variance curves in the insets to show that the DFB laser is dominated by white FM noise. This is also evident from the FM-noise spectra in Figs. 2(c) and 3(c) that demonstrate white noise characteristics corresponding to 5.7 MHz and 6.4 MHz for $\Delta\nu$, respectively.

The high frequency difference with PM detection in Fig. 2(c) is from low-pass filtering the demodulated I/Q components in order to reduce spurious harmonics of the 2 GHz PM carrier. The PM frequency could be increased should higher frequency characterization be desired. The high frequency peaking in Fig. 3(c) is an artifact from sub-sampling the 43 Gbps balanced detectors at 20 GSa/s without filtering.

The experimental results demonstrate the random walk in phase characteristics of the DFB laser. The slight deviation of the phase-error variance from linearity over the extended delay intervals suggests that the broadening of the E-field PSD would be observed over a longer time scale. In contrast, the ECL has additional random-walk frequency fluctuation [3], [5]. This low-frequency noise behavior could be observed in Fig. 4 with PM detection at the reduced sampling rate of 20 MSa/s. The phase variance in Fig. 4(a) deviates significantly from linearity over the 50 μs delay interval. A polynomial fit to the variance in Fig. 4(a) yields the asymptotic slope at zero delay that corresponds to $\Delta\nu \sim 130$ kHz.

The FM-noise spectrum in Fig. 4(b) shows $1/f^2$ noise below 6 kHz that corresponds to a random walk in frequency, in addition to the dashed line approximation to the white FM noise that corresponds to $\Delta\nu \sim 168$ kHz. In comparison, the 3-dB linewidth estimate from the PSD was nearly twice as large at 350 kHz due to random-walk fluctuation of the optical carrier as shown by the PSD inset in Fig. 4(a), and by the broadening of the averaged electrical spectrum in Fig. 4(b) inset. Similar measurements with the coherent receiver have yielded linewidth estimates of 150 kHz, 155 kHz and 300 kHz

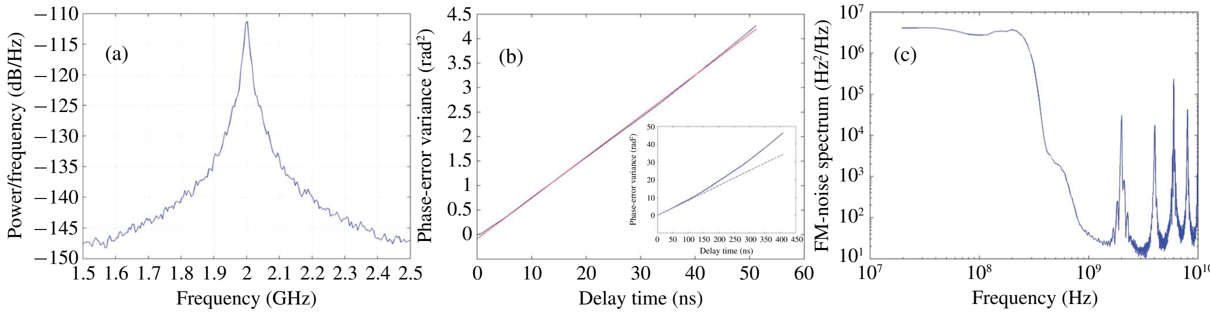

Fig. 2. DFB laser with PM detection. (a) PSD of E-field. (b) Phase-error variance. (c) FM-noise spectrum.

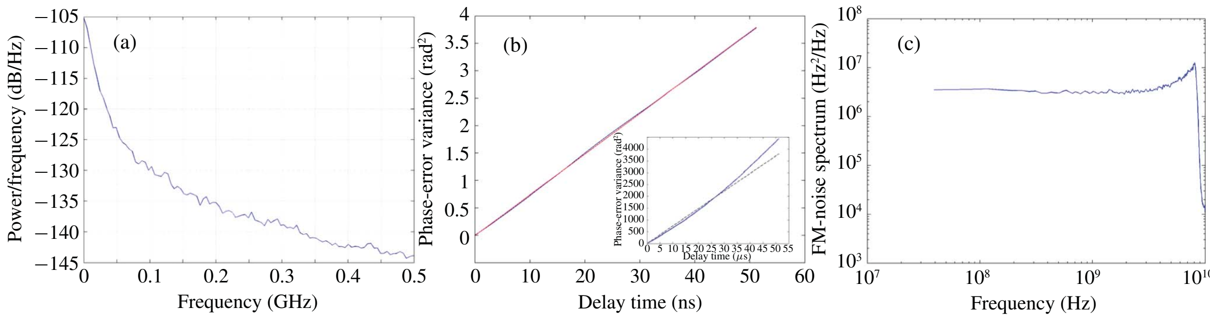

Fig. 3. DFB laser with coherent receiver. (a) PSD of E-field. (b) Phase-error variance. (c) FM-noise spectrum.

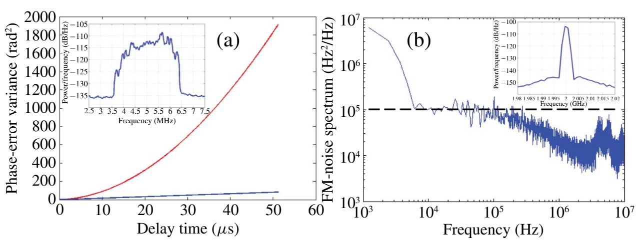

Fig. 4. ECL with PM detection. (a) Phase-error variance. (b) FM-noise spectrum.

TABLE I
ESTIMATED 3-dB LINEWIDTHS

Laser	Estimated method	Coherent receiver	PM detection
DFB	E-field PSD	6 MHz	6.5 MHz
	Phase-error variance	5.9 MHz	6.7 MHz
	FM–noise spectrum	5.7 MHz	6.4 MHz
ECL	E-field PSD	300 kHz	350 kHz
	Phase-error variance	150 kHz	130 KHz
	FM–noise spectrum	155 kHz	168 kHz

that have been determined in the same manner from the phase-error variance, FM-noise spectrum and E-field PSD.

Table I lists the results of the analysis which shows good agreements between the linewidth estimates for the DFB laser. For the ECL, however, the E-field PSD overestimates the linewidth because the phase noise deviates from the ideal random walk model. This shows that the 3-dB linewidth is not a complete measure of the laser phase noise [3]. The results from the PM detection and the optical coherent receiver are within about 15% of one another and validate the proposed method.

IV. CONCLUSION

We have presented a novel coherent PM detection for the delayed self-heterodyne method and have shown that the in- phase and quadrature components of the self-heterodyne signal can be demodulated at the first and second harmonics of the PM carrier. The proposed technique was demonstrated for the first time with the DFB laser and ECL. The experiment results have been shown to be consistent with self-homodyne measurements from the optical coherent receiver. Coherent PM detection thus extends the capability of the delayed self-heterodyne technique for laser phase noise measurements.

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