Characterization of Semiconductor-Laser Phase Noise with Digital Coherent Receivers

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Abstract: We develop a method of characterizing semiconductor-laser phase noise using a digital coherent receiver. The field spectrum, FM-noise spectrum, and phase-error variance can completely describe phase-noise characteristics.

OCIS codes: (060.1660) Coherent communications; (140.5960) Semiconductor Lasers; (300.3700) Linewidth

1. Introduction

With the recent development of digital coherent receivers [1], multi-level modulation formats have been attracted large attention because of their spectrally-efficient transmission characteristics in wavelength-division multiplexed (WDM) systems [2,3]. In such systems, phase-noise characteristics of lasers for the transmitter and the local oscillator (LO) determine the bit-error rate performance, and we are usually concerned about 3-dB linewidths of the lasers for the system design. However, the 3-dB linewidth is dependent on the measurement method, and is not necessarily a good measure of phase noise of lasers.

In this paper, we present a systematic method of fully characterizing laser phase noise using a digital coherent receiver: The digital coherent receiver acquires the complex amplitude of a beat between two lasers, from which we evaluate the field spectrum, FM-noise spectrum, and phase-error variance though offline digital signal processing. We find that the 3-dB linewidth of distributed feedback (DFB) semiconductor lasers has a strong dependence on the measurement time, whose origin can well be analyzed by using the FM-noise spectrum, the phase-noise variance, and time-resolved field spectra.

2. Phase-Noise Characterization Method

A digital coherent receiver measures a beat between the transmitter laser and LO expected to have the same characteristics. The real part and the imaginary part of the beat signal constitute the complex amplitude $E(t)$ in the digital domain, which is sent to a personal computer for offline phase-noise analyses. The sampling rate of analog-to-digital converters (ADCs) in the receiver is $1/\tau_s = 1.25\ \text{GS/s}$ or $12.5\ \text{MS/s}$, and the number of samples $n = 1.25\times10^5$ in our experiments.

Since the AM noise of semiconductor lasers operating well above threshold is negligibly small, the phase noise $\Delta\phi_n(t)$ is given as the argument of $E(t)$. We employ the following three functions for phase-noise characterization: (1) the field spectrum $S(f)$ obtained as the power spectral density of $E(t)$, (2) the FM-noise spectrum $S_F(f)$ that is the power spectral density of instantaneous-frequency fluctuations approximately given as $\left(\Delta\phi_n(t+\tau_s)-\Delta\phi_n(t)\right)/\left(2\pi\tau_s\right)$, and (3) the phase-error variance within a time interval τ defined as $\sigma_\phi(\tau)^2 = \left\langle\left(\Delta\phi_n(t+\tau)-\Delta\phi_n(t)\right)^2\right\rangle$. Relations among the three functions are illustrated in Fig.1 [4, 5]. The phase-noise characterization can be done by analyzing these three functions.

It is worthy of mentioning the ideal case usually assumed in the coherent system design: The FM noise is white and its spectral density is given as $\delta f/\pi$. In such a case, $S(f)$ has a Lorentzian lineshape, whose 3-dB bandwidth is δf , and $\sigma_\phi(\tau)^2 = 2\pi\delta f\tau$ [4, 5].

3. Experimental Results and Discussions

We measured the phase-noise characteristics of narrow-linewidth DFB semiconductor lasers used for coherent optical communications. Center wavelengths are around 1550 nm. Black curves in Figs.2 (a), (b), and (c) show the

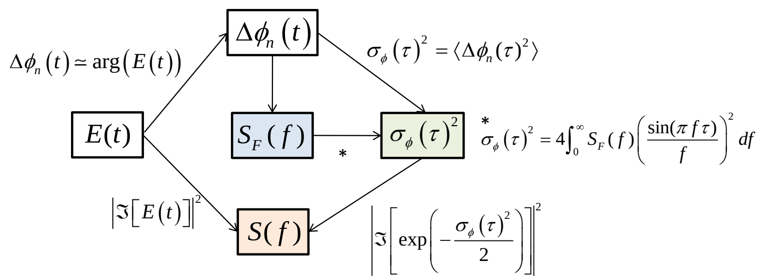

Fig.1 Relations among the field spectrum $S(f)$, the FM-noise spectrum $S_F(f)$, and the phase-error variance $\sigma_\phi(\tau)^2$. $\Im$ represents the Fourier transform.

field spectrum, the FM-noise spectrum, and the phase-error variance of the beat between the transmitter and LO, respectively, when $1/\tau_s = 1.25$ GS/s and $n = 1.25 \times 10^5$. Then the measurement time $\tau_s n$ equals 10^{-4} s. From Fig. 2(c), we find that the phase-error variance is proportional to the delay time τ, as shown by the red broken line fitted to the experimental result. Noting that the slope of the red broken line is $2\pi\delta f$ in the ideal case, we can estimate that δf =170 kHz. Then, we can draw a Lorentzian shape with δf =170 kHz in Fig.2 (a) by the red curve, which is in good agreement with the experiment. On the other hand, Fig.2 (b) shows that the FM-noise spectrum is approximately white, and the red line represents its spectral density obtained from the linewidth as $\delta f / \pi$, which is also in good agreement with the experimental result.

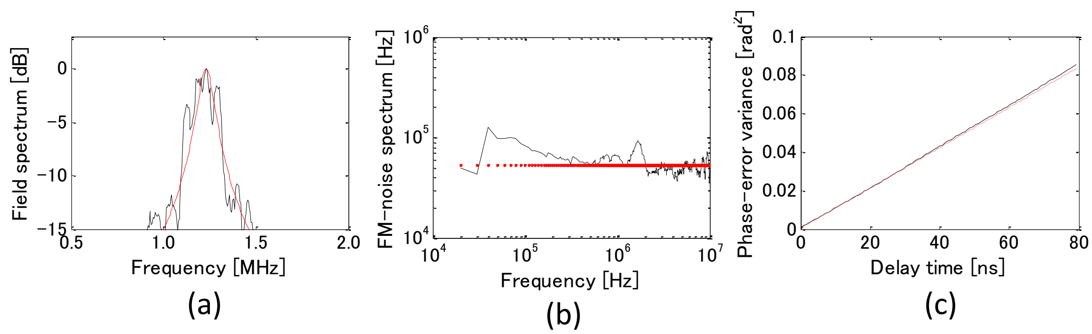

Fig.2 Field spectrum (a), FM-noise spectrum (b), and phase-error variance (c) of the beat between the transmitter and LO, when $1/\tau_s = 1.25$ GS/s and $n = 1.25 \times 10^5$.

Black curves in Fig.3 show the phase-noise characteristics measured when $1/\tau_s = 12.5$ MS/s and $n = 1.25 \times 10^5$. The measurement time $\tau_s n$ is extended to 10^{-2} s. In such a case, we clearly find that the phase-noise characteristics deviate from the ideal ones shown in Fig.2 due to low-frequency FM noise [6]. The red broken line in Fig.3 (c) represents the linear fit to the experimental phase-error variance in the small delay-time region. The red line in Fig.3 (b) is the spectral density of the FM noise obtained from the slope of the fitted line in Fig.2(c). It is seen that the FM-noise spectral density increases in the lower frequency side, whereas it is flat in the high-frequency side and is in good agreement with the red line. The Lorentizan spectrum calculated from the flat FM-noise component in Fig.3 (b) is shown by the red curve in Fig.2 (a), which differs from the measured one significantly.

In order to examine the effect of the low-frequency FM-noise more clearly, we calculate time-resolved field spectra as follows: The total measurement time of 10^{-2} s is divided into ten sections having 10^{-3}-s time intervals, and the field spectrum in each section is calculated in time order from 1×10^{-3} s to 10×10^{-3} s. Figure 4 shows such time-resolved field spectra, where the horizontal scale is MHz, and the vertical one dB. We find that the center frequency measured in the shorter time interval of 10^{-3} s fluctuates significantly, resulting in a broadened Gaussian-like spectrum measured in the longer time interval of 10^{-2} s.

In high bit-rate systems, the white FM-noise component mainly determines the bit-error rate performance; however, the 3-dB spectral width does not necessarily correspond to it. For complete characterization of phase noise, it is important to evaluate the field spectrum, FM-noise spectrum, and phase-error variance simultaneously, changing measurement time intervals.

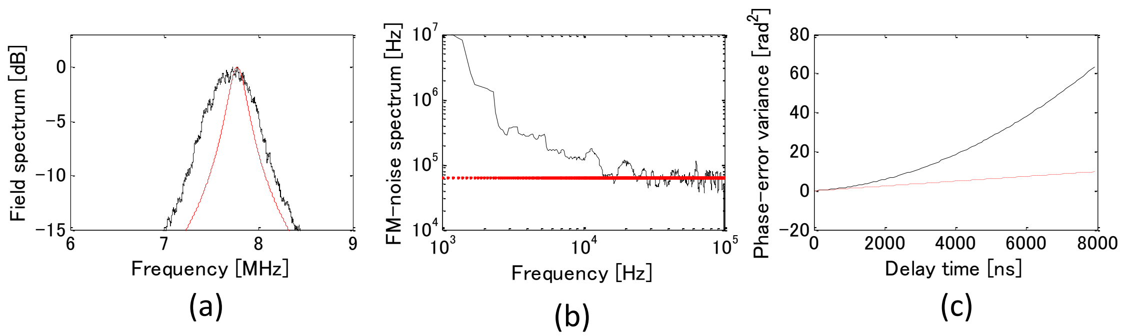

Fig.3 Field spectrum, FM-noise spectrum, and phase-error variance of the beat between the transmitter and LO, when $1/\tau_s = 12.5$ MS/s and $n = 1.25\times10^5$.

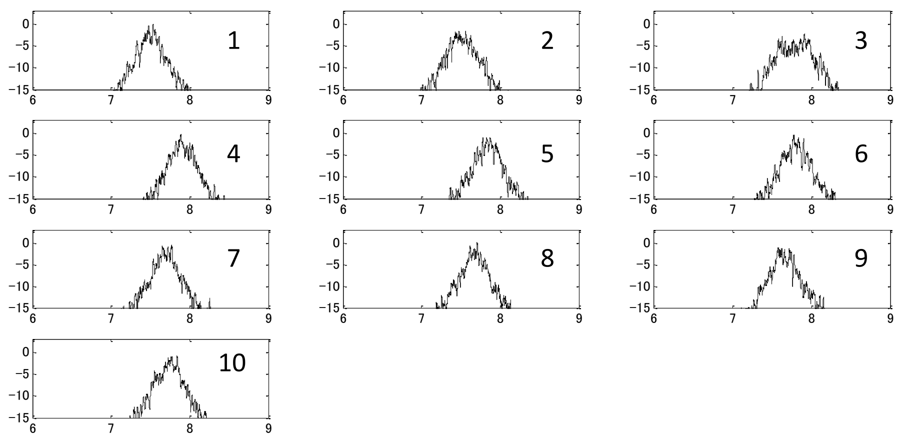

Fig.4 Time-resolved field spectra. The total measurement time of 10^{-2} s is divided into ten sections having 10^{-3}-s time intervals, and the field spectrum in each section is calculated in time order from 1×10^{-3} s to 10×10^{-3} s. The horizontal scale is MHz, and the vertical one dB.

4. Conclusions

We have presented a systematic method of characterizing phase noise of semiconductor lasers for coherent optical communications by using a digital coherent receiver. We evaluate the field spectrum, FM-noise spectrum, and phase-error variance for different measurement time intervals, which give us full information about the phase-noise characteristics necessary for the coherent system design.

Acknowledgements

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