Ultra-long-time (0.8 s) characterization of laser phase noise with high temporal resolution (800 ps) based on heterodyne reception with FPGA data acquisition

Hayato Kiwata [(1)], Masahiro Kikuta [(2)], Masahiro Shigihara [(2)], and Koji Igarashi [(1)]

[(1)] Graduate School of Engineering, Osaka University, iga@comm.eng.osaka-u.ac.jp
[(2)] NEC Platforms, Ltd.

Abstract *Laser phase noise can be measured for 0.8 s with a time resolution of 800 ps using coherent detection with FPGA data acquisition, and illustrated by field spectrogram and very wide FM noise spectra from near DC.*

Introduction

In optical coherent transmission systems, the bit-error ratio (BER) strongly depends on the phase noise characteristics of semiconductor lasers for transmitters and local oscillators (LOs) [1,2]. Although the 3-dB spectral linewidth of a laser is widely used for characterizing the magnitude of laser phase noise, it strongly depends on the measurement time. In particular, it cannot be used to evaluate the slow fluctuation of laser phase and frequency, which determine the long-term stability of digital signal processing (DSP) in optical coherent systems.

The field spectrum and FM noise spectrum are suitable measure of laser phase noise, although they are rather laborious to measure because optical interferometers are required [3]. Recently, a phase noise characterization method using a digital coherent receiver has been reported [4]. The field spectrum and FM noise spectrum are constructed offline from the stored data using digital coherent receivers. Although it is an easy and flexible method, there is difficulty in long-term measurement because the number of measured data samples is limited to approximately 10M. Therefore, components with frequencies of near DC cannot be evaluated. Even if long-term data such as 1 Gsamples could be measured, it is very difficult to deal with the huge amount of data on common personal computers (PCs).

In this work, we measure and characterize ultra-long-period laser phase noise with high temporal resolution. Laser phase noise is measured using coherent reception with data acquisition implemented by field programmable gate array (FPGA) circuits. To characterize phase noise for a long period with high temporal resolution, we propose the field spectrogram and very wide FM noise spectrum from near DC constructed from huge-size (1 Gsamples) measured data.

Laser phase noise measurement

Figure 1 shows the configuration of our method. We evaluated the phase noise characteristics of two types of semiconductor lasers, i.e., a distributed feedback laserdiode (DFBLD) driven with a handmade circuit and an external cavity laser (ECL) from a commercially available product (LS-601A) provided by Koshin Kogaku. The linewidths of the DFBLD and ECL as indicated in the specification sheets were larger than 300 kHz and smaller than 10 kHz, respectively. CW light generated from the DFBLD or ECL was measured by heterodyne detection with a LO. The IF frequency was set to approximately 300 MHz. The detected electrical signals were acquired and stored by a Xilinx Vertex 7 FPGA board with an analog-digital converter (ADC) with 10-bit resolution at the sampling rate f_s of 1.25 Gsample/s. In the FPGA board, a 1-Gbyte DDR3 memory was embedded, and the measured data were stored with 1 Gsamples and 8-bit resolution. The stored data were transferred to a PC via Gigabit Ethernet.

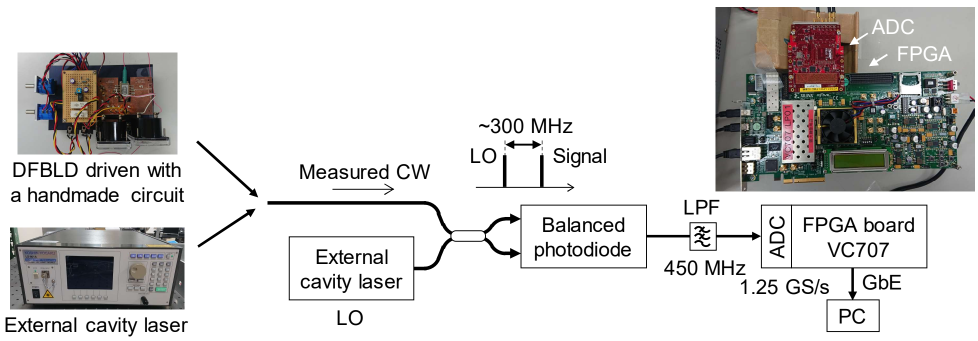

Fig. 1: Configuration of our method for measuring laser phase noise.

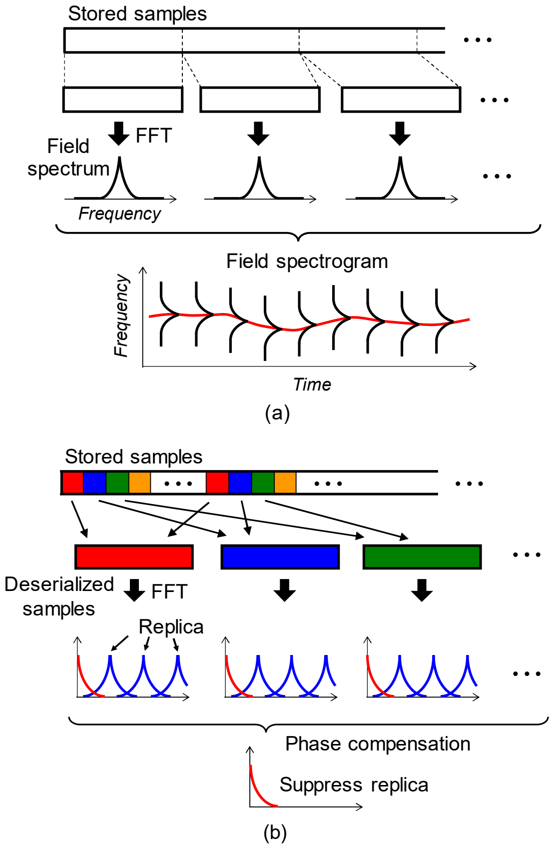

Fig. 2: DSPs to calculate (a) field spectrogram and (b) very wide FM noise spectrum.

It is difficult to calculate the field spectrum and the FM noise spectrum from the acquired 1G data because common PCs cannot perform an FFT on such a large amount of data. We propose the field spectrogram and very wide FM noise spectrum to evaluate the long-term and high-resolution phase noise characteristics.

(1) Field spectrogram: Figure 2(a) shows the DSP to calculate the field spectrogram. The large samples are divided into multiple moderate-size blocks of consecutive samples for a short time, for which the frequency drift is negligible. By aligning multiple field spectra for a short time range, the field spectrogram (time-resolved field spectra) can be constructed.

(2) FM noise spectrum from near DC: To evaluate slow fluctuation (below 1 kHz) of the FM noise, we need large samples for the long-term range of longer than 1 ms. Such large samples cannot directly undergo FFT. We propose phase-compensated FFT using deserialized samples. Figure 2(b) shows the DSP to calculate the very wide FM noise spectrum with high-frequency resolution. The huge-size samples of instantaneous frequency $s(k)$ are temporally deserialized (demultiplexed) into multiple interleaved samples $s(Nk-i)$, where N is the deserializing degree and i is an integer from 0 to $N-1$. Note that the FFT data of the

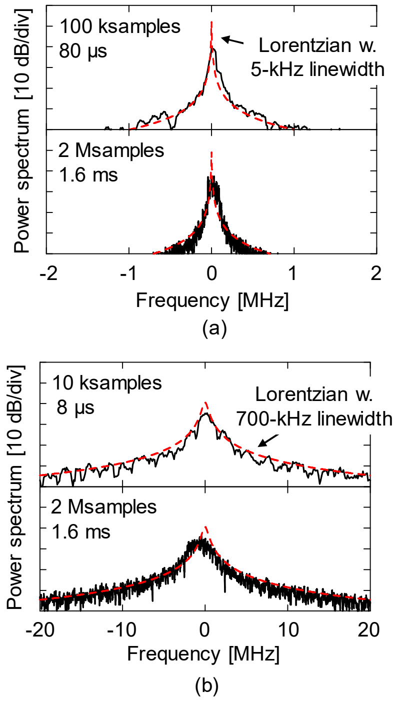

Fig. 3: Field spectra of (a) ECL and (b) DFBLD.

deserialized samples suffer from unideal replica because the sampling theorem is not satisfied. To suppress the replica, we use the phase-compensated FFT data of the deserialized samples, as follows.

$$S(f)=\sum_{i=1}^{N}\Im\{s(Nk+i)\}\exp(-j2\pi fi/f_s) \quad (1)$$

where f_s is the sampling rate of the ADC, and $\Im\{\bullet\}$ indicates the FFT of $\{\bullet\}$. If the stored 1G data are divided into 500 deserialized samples, the FFT block size is reduced to approximately 2M, on which it is easily possible to perform an FFT on common PCs.

Measured field spectrogram

To investigate the time range (FFT block size) for which the frequency drift is negligible, we first measured the short-term and long-term field spectra of lasers. Figure 3(a) shows the field spectra of the ECL calculated from the short-term data composed of 100 ksamples for 80 μs and the long-term data of 2 Msamples for 1.6 ms. Red dashed lines indicate Lorentzian-shaped spectra with linewidths of 5 kHz. There is a good agreement between the short-term spectrum and the 5-kHz Lorentzian, although the long-term spectrum shows fluctuations caused by the frequency drift. The drift is negligible over a time interval of 80 μs. By aligning the short-term field spectra calculated from 2^{16} samples for the time range of approximate 50 μs, we constructed the field spectrogram for 0.8 s, as shown in Figs. 4(a). The inset indicates the field spectrogram for

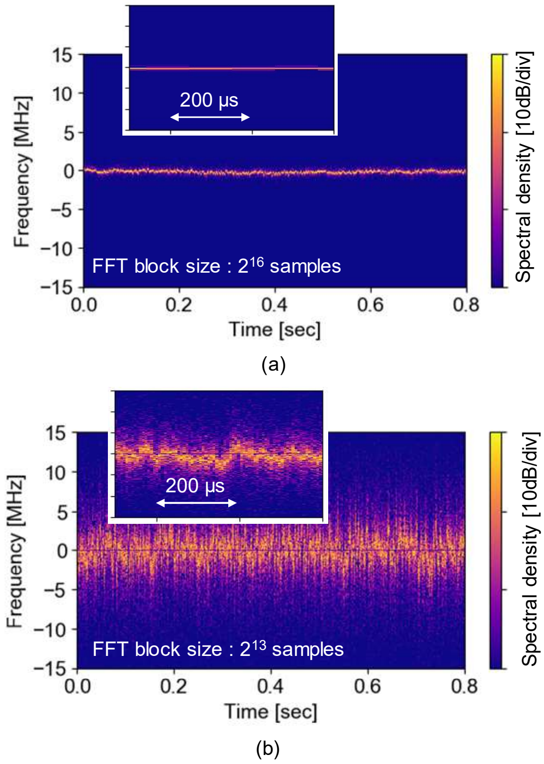

Fig. 4: Field spectra of (a) ECL and (b) DFBLD.

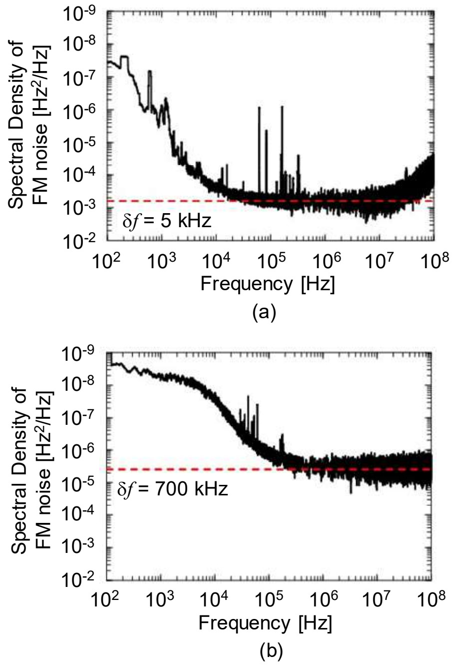

Fig. 5: FM noise spectra of (a) ECL and (b) DFBLD.

500 μs. We found that the long-term frequency drift of the ECL was well stabilized with fluctuations less than ±1 MHz for 0.8 s.

The short-term and long-term field spectra of the DFBLD are shown in Fig. 3(b), which are calculated from 10 ksamples for 8 μs and 2 Msamples for 1.6 ms. Although the long-term spectrum fluctuated because of the frequency drift, the short-term spectrum agrees with the Lorentzian with 700 kHz linewidth, as indicated by red dashed line. The frequency drift was negligible for 8 μs. With the field spectra of 2^{13} samples for 6.5 μs, we constructed the field spectrogram of the DFBLD, which is shown in Figs. 4(b). We observed a large frequency drift of over ±10 MHz for 0.8 s. The inset illustrates the field spectrogram for 500 μs. We found a frequency drift speed of several tens of μs. The field spectrogram is effective for measuring the frequency fluctuation for both short and long time ranges.

Measured FM noise spectra from near DC

Next, we constructed the FM noise spectrum with phase-compensated FFT. Figure 5(a) shows the very wide FM noise spectrum from 100 Hz to 100 MHz. The FM noise components lower than 50 MHz were constructed from deserialized data using Eq. (1), and the higher-frequency FM noise components were calculated from consecutive 2 Msamples of the stored data. Red dashed line indicates ideal random-walk phase noise with a linewidth of 5 kHz. We found a good agreement between the flat density of the FM noise spectrum and phase noise with 5 kHz linewidth. In the ECL, the FM noise components lower than 10 kHz were suppressed. The results are consistent with those of the field spectra and spectrogram, as shown in Figs. 3(a) and 4(a). The frequency components higher than 10 MHz were enhanced. This is due to the limitation of the bit resolution of the stored data.

Figure 5(b) shows the FM noise spectrum of the DFBLD. The flat spectral density agrees with the ideal random-walk phase noise with a linewidth of 700 kHz, as indicated by red dashed line. In addition, significantly large FM noise components were observed for frequencies lower than 100 kHz, which is consistent with the field spectrogram, as indicated in Fig. 4(b).

These results show that the very wide FM noise spectrum is effective for evaluating the laser phase noise over very wide frequency range.

Conclusions

We demonstrated the characterization of laser phase noise in the ultra-long term with high temporal resolution using heterodyne detection with FPGA data acquisition. We proposed the field spectrogram and very wide FM noise spectrum from near DC to illustrate the laser phase noise.

Acknowledgements

We thank Prof. Kyo Inoue of Osaka University for the fruitful discussions. A part of this work was supported by the KAKENHI Grant Number 18H03231.

References

[1] K. Robert *et al.*, "Performance of Dual-Polarization QPSK for Optical Transport Systems," *J. Lightw. Technol.*, vol. 7(16), 3546–3559, 2009.

[2] K. Kikuchi, "Fundamentals of Coherent Optical Fiber Communications," *J. Lightw. Technol.*, vol. 34(1), 157–179, 2016.

[3] K. Kikuchi and T. Okoshi, "Measurement of FM Noise, AM Noise, and Field spectra of 1.3 μm InGaAsP DFB Lasers and Determination of the Linewidth Enhancement Factor," *IEEE. J. Quantum. Electron.*, vol. QE-21(11), 1814–1818, 1985.

[4] K. Kikuchi, "Characterization of Semiconductor-laser Phase Noise and Estimation of Bit-error Rate Performance with Low-speed Offline Digital Coherent Receivers," *Opt. Express*, vol. 20(5), 5291–5302, 2012.