Development of an Optical Phase-Locked Loop for 1-THz Optical Beat Signal Generation

by Takasaka Shigehiro*, Yasuyuki Ozeki*2, Shu Namiki*3, Misao Sakano*4 and Yu Mimura *

ABSTRACT To support larger telecommunications capacities, the speed of optical transmission is increasing apace, and coming transmission rates in excess of 160 Gbit/s raise hopes for all-optical signal processing technologies that make possible high-speed signal processing. Accordingly, as the clock signal source that is indispensable for signal processing, we have developed an optical phase-locked loop (OPLL) that can generate a high-speed optical beat signal of 1 THz. The OPLL consists of an optical beat signal source and an all-optical phase detector, and to realize a simple construction has a pair of 3-electrode distributed feedback (DFB) laser diodes for the optical beat signal source and an all-optical phase detector based on two-photon absorption in a silicon avalanche photodiode. As a result of measurement of the synchronization characteristics with respect to a pulse train of 40-GHz repetition rate, it has been confirmed that this OPLL can synchronize 160-GHz and 1-THz beat signals with low timing jitter of 126 fs (0.016 rad ^{2}) and 28 fs (0.03 rad ^{2}) respectively.

1. INTRODUCTION

The technology for the extraction and recovery of the clock signal from the data signal is one of the essential technologies for telecommunications systems. This is because the clock signal applies a timing reference, making possible data signal retiming at the relay point and data confirmation at the receiving station to be carried out accurately. In today's optical telecommunications systems optical signals are first converted by photodiodes into electrical signals and clock recovery is accomplished by electrical signal processing.

But optical transmission speeds are increasing to permit transmission of ever higher volumes of data, and at the coming transmission speeds in excess of 160 Gbit/s, electrical signal processing will not be feasible. To achieve the all-optical signal processing required by higher-speed operation will necessitate an optical clock signal, giving great importance to techniques for optical clock signal recovery.

Proposals for optical signal sources that will result in technologies for generating an ultrafast optical clock signal in excess of 160 Gbit/s include a method using a mode-locked laser diode 1) and a method for optical time-division multiplexing a mode-locked laser at a low repetition rate 2). Each of these methods, however, presents problems in terms of the need for sophisticated techniques for fabricating the laser diodes (LDs), the complexity of its structure and the large optical loss involved.

There is also, however, a technique whereby the optical beat signal is generated by interference in a continuous combined signal of two continuous waves with different wavelengths. This technique has the advantage of structural simplicity, plus the fact that it can generate an optical beat signal with a high repetition rate, not limited the bandwidth of electrical devices. There are reports of experiments taking advantage of the features of this technology, that have applied optical pulse compression techniques using optical devices to generate an optical pulse train with repetition rates as high as 1 THz 3)~5).

In order to use an optical beat signal as the clock signal it is necessary that the beat signal be synchronized with respect to the external optical signal. One method of external synchronization of the optical beat signal uses OPLL technology, but in currently used OPLLs the upper limit of the frequency of the optical output beat signal is determined by bandwidth of its constituent elements--the electrical phase detector and the photodiodes 6). On the other hand, as a phase detector method that is not limited by the bandwidth of electrical devices band, there is an all-optical phase detector, and it has been reported that a 10-GHz RF signal synchronized with an ultrafast optical signal can be generated using an all-optical phase detector 7). Convinced that incorporating this all-optical phase detector into an OPLL would make possible the external synchronization of ultrafast optical beat signals in excess of 160 GHz, we have pursued this technological develop-

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* FITEL Photonics Lab., R&D Div.

*2 PRESTO, Japan Science and Technology Agency (currently with Osaka University)

*3 FITEL Photonics Lab., R&D Div. (currently with National Institute of Advanced Industrial Science and Technology)

*4 Yokohama R&D Laboratory, R&D Division ment[8), 9)].

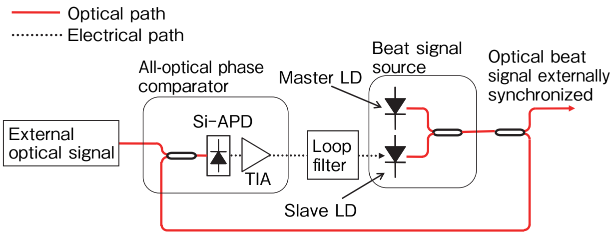
In this paper we demonstrate that external synchronization of an ultrafast optical beat signal is possible by means of OPLL technology using an all-optical phase detector. First we present the operating principle and design guidelines, and then report experiments conducted for external synchronization of a 160-GHz optical beat signal[8), 9)]. In addition, to verify the ultrafast performance of this OPLL, we conducted experiments for external synchronization of a 1-THz optical beat signal[10)]. Through these experimental results it has been demonstrated that this OPLL technology makes possible the generation of ultrafast optical clock signals.

2. OPERATING PRINCIPLE OF OPLL

Figure 1 shows the operating principle of an OPLL using an all-optical phase detector. Broadly speaking it has three component elements: an optical beat signal source comprising master and slave laser diodes; an all-optical phase detector using a silicon avalanche photodiode (Si-APD); and a loop filter. Here the frequency of the optical beat signal source corresponds to the frequency difference between the continuous waves output by the two LDs.

Synchronization of the optical beat signal with the external optical signal proceeds as follows: (1) The all-optical phase detector detects the phase error that is the timing difference between the optical beat signal and the external optical signal, and outputs a phase error signal. (2) The phase error signal is shaped by the loop filter, and, the output wavelength, that is to say the optical beat signal frequency, is controlled through feedback to the slave LD, so that the value of the phase error signal becomes zero.

The operating principle of the all-optical phase detector is as follows: (1) The optical beat signal and the external optical signal, which are of corresponding polarization, are combined and input to an Si-APD. (2) The Si-APD generates a photocurrent in accordance with the amount of phase error, and the current is converted into a voltage at a trans-impedance amplifier (TIA). (3) An offset voltage unrelated to the phase error signal is subtracted from the output voltage of the TIA. The point to be noted here is that since the Si-APD shows virtually no sensitivity to light of 1.5 μm wavelength ranges, it generates a photocurrent solely by means of the two photon absorption (TPA) effect. In addition, since TPA is a non-resonant, non-linear optical effect, it has a response speed of 100 THz or more and for practical purposes places no limitation on the speed of the input signal.



Si-APD: Silicon avalanche photodiode, TIA: Trans-impedance amplifier.

Figure 1 Schematic of OPLL. Red solid and black dotted lines are optical and electric paths, respectively.

As Figure 2 shows, the fact that the photocurrent so generated can be treated as a phase error signal is due to the fact that the amount of photocurrent generated by TPA is at the maximum when the optical beat signal and the external optical signal are input simultaneously, and decreases as the timing difference between two signals becomes larger. This paper reports synchronization experiments that were carried out with the midpoint between the maximum and minimum values of photocurrent set as zero phase error. Note that the frequency of the photocurrent generation in the Si-APD generated by the photocurrent is the same as the frequency of the optical beat signal, being greater than 160 GHz, but since the generated photocurrent is integrated by the electrical capacitance of the Si-APD device and the TIA, the bandwidth of the output phase error signal is sufficiently narrow that it can be processed electrically.

To generate a synchronized optical beat signal of high time accuracy requires a reduction of the timing jitter that serves as its index. For this the OPLL loop bandwidth must be amply large compared to LD linewidth[6)]. To bring this situation about, we have used a 3-electrode DFB LD optical beat signal source. The 3-electrode DFB LD maintains a narrow linewidth, while offering wideband FM response characteristics. At the same time, since it is in effect simply a 3-way split of the top electrode of an ordinary DFB LD, it can be fabricated using substantially the same process as commercially available DFB LDs. Since fabrication is easy, it is suitable for use as a slave LD[11)]. Prototype 3-electrode DFB LDs were fabricated that had a narrow linewidth of 250 kHz and an FM response bandwidth of 100 MHz or more.

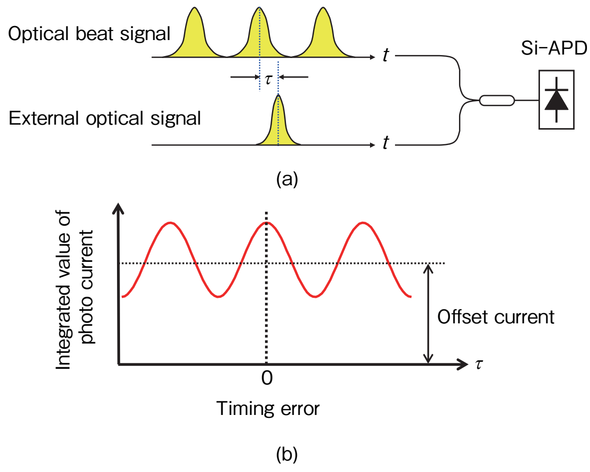


Figure 2 Operation principle of all-optical phase detector using a Si-APD. (a): Definition of timing error τ between optical beat signal and external optical signal, (b): An example of integrated photocurrent as a function of timing error τ.

As shown in Figure 3, 3-electrode DFB LD drive current is effected by connecting a constant-current source to each of the electrodes and controlling the drive current so that the linewidth is reduced the minimum. Modulation of output wavelength is accomplished by a modulation signal stacked on the center electrode. Note also that due to the narrow linewidth of this DFB LD, it was also used as the master LD.

If the linewidth of the LD used as the optical beat signal source is determined, so is the loop bandwidth required to reduce timing jitter. In practice, when an LD with a linewidth of 250 kHz is used as the optical beat signal source, a loop bandwidth in excess of 10 MHz is necessary in order to realize a low timing jitter. This loop bandwidth is three orders of magnitude greater that the 6-kHz loop bandwidth of a PLL using a Si-APD in Reference 7. Expanding the loop bandwidth requires that the bandwidth of the TIA be expanded, but at the same time the wideband thermal noise is stacked on the phase error signal, so the more the bandwidth of the TIA is expanded the greater will be the degradation of the signal-to-noise ratio. Thus in order to expand the bandwidth while maintaining the SNR needed by the synchronization operation, we have adopted a number of approaches to increasing the average power of the optical input signal and raising the efficiency of TPA, such as reducing the spot size of the optical input signal in the Si-APD to 4.3 μm.

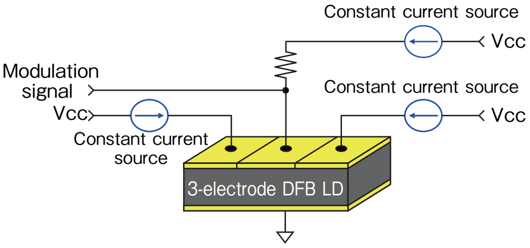
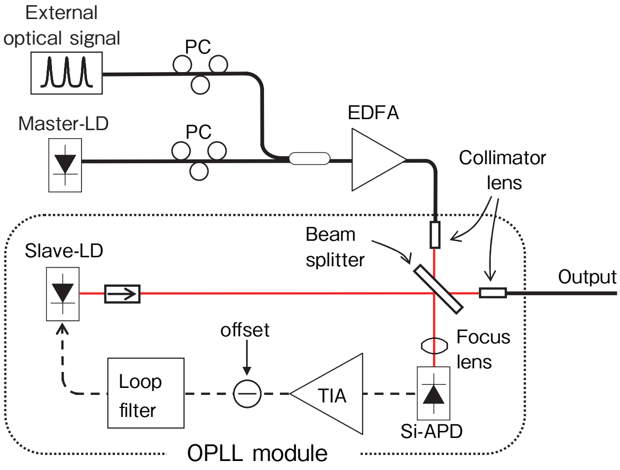


Figure 3 **Wiring diagram of three-electrode DFB LD.**

In addition, since the loop bandwidth is wide, loop delay time is a major factor limiting loop bandwidth and phase margin[6), 12)]. Here loop delay time is that time taken for the phase error signal to propagate around the loop within the OPLL. In this OPLL the elements comprising the loop surrounded by the broken line in Figure 4 have been fabricated using free-space optics into a module measuring 145×44×110 mm. Figure 5 shows the outward appearance of the OPLL module. The delay time for this module is approximately 1 ns, and for loop bandwidths of 100 MHz or less, loop delay time can be disregarded.



TIA: trans-impedance amplifier,
EDFA: erbium-doped fiber amplifier,
PC: polarization controller.

Figure 4 **Configuration of OPLL.**

3. SYNCHRONIZATION EXPERIMENTS

3.1 External Synchronization of 160-GHz Optical Beat Signal

Using this OPLL we conducted experiments for external synchronization of a 160-GHz optical beat signal to show that this is possible, and to confirm the amount of timing jitter of the optical beat signal[9)].

As the external optical signal we used an optical pulse train with a center wavelength of 1540 nm, a repetition rate of 40 GHz and a pulse width of 2 ps[13)]. The pulse width of this external optical signal matches the pulse width that was used for the 160-Gbit/s optical signal. In order to generate a 160-GHz optical beat signal, the wavelengths of the master and slave LDs were set at 1557.7 and 1559.0 nm respectively. The input power in the Si-APD was a reference optical signal of 200 mW, master LD: 50 mW, and slave LD: 3 mW. TIA impedance was 5 kΩ, and the bandwidth was set at around 80 MHz. We used a lag-lead type loop filter, and loop bandwidth was set to ~ 20 MHz.

To confirm the synchronization operation of the OPLL, we measured the cross-correlation of the optical beat signal and the external optical signal. Figure 6 shows the configuration of the measurement system. To detect the cross-correlation between the 160-GHz optical beat signal and the external optical signal we used an Si-APD. Here the 160-GHz optical beat signal was extracted from the OPLL optical output using a 2-stage optical filter. The rela-

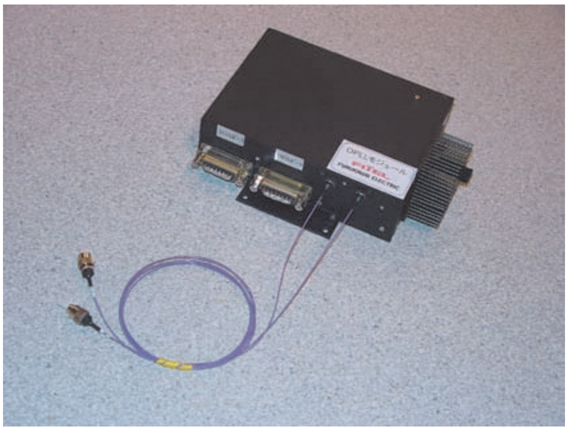
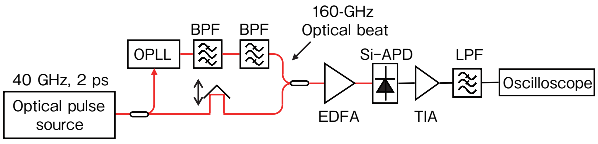


Figure 5 **Appearance of OPLL module.**

tive time of the optical beat signal and the external optical signal is swept by means of the optical delay line. As Figure 7 shows, a sinewave of 6.25-ps period can be clearly perceived, demonstrating that the optical beat signal is synchronized with the external optical signal.

To measure the phase noise of the optical beat signal, we measured the OPLL output signal with a phase error detector using an Si-APD and TIA, and an oscilloscope and RF spectrum analyzer. Figure 8 shows the phase error signal waveforms measured in the 160-GHz optical beat signal. The synchronization operation was also confirmed from the fact that when synchronization was not in effect the phase error signal spread in a random manner, whereas when synchronization was applied phase error converged to zero. Figure 9 shows the phase noise spectrum of the 160-GHz optical beat signal. This is the power spectrum of the phase error signal measured using an RF spectrum analyzer, normalized to the power of the phase error signal under free running. Note that the power used in normalizing was calculated based on the amplitude of the phase error signal as measured using the oscilloscope. The synchronization operation was also confirmed from the fact that the phase noise spectrum showed a decrease in phase noise in the frequency range below 10 MHz with respect to the spectrum under free running as calculated from DFB LD linewidth. The amount of phase noise can be obtained by integrating the phase noise spectrum and multiplying by a constant. By subtracting the value for background noise from the value under synchronized operation, we can find the amount of phase noise that is added by the OPLL. As a result we determined that the variance and the timing jitter for the phase error signal were 0.016 rad^2 and 126 fs, respectively.

Meanwhile, prior to fabrication of the OPLL module, we conducted, as a preparatory measure, a 160-GHz optical beat synchronization experiment using an OPLL with a loop delay time of 5 ns[8]. The timing jitter of the 160-GHz optical beat signal output by this OPLL was 291 fs. By this means it was confirmed that to achieve low timing jitter in an OPLL with a wide loop bandwidth it is important to shorten the delay time.



TIA: trans-impedance amplifier, EDFA: erbium-doped fiber amplifier, BPF: band-pass filter, LPF: low-pass filter

Figure 6 Configuration of a cross-correlation measurement system. Red and black lines are optical and electric paths, respectively.

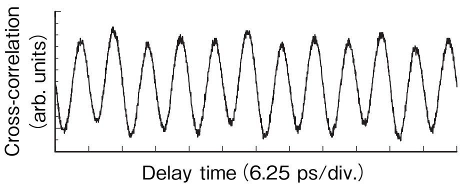


Figure 7 Waveform of cross-correlation between 160-GHz optical beat signal and 40-GHz optical pulse train.

In this way it has been demonstrated that a 160-GHz optical beat signal can be synchronized to an external optical signal by means of an OPLL, and that a low timing jitter of 126 fs can be achieved.

3.2 External Synchronization of 1-THz Optical Beat Signal

Since the frequency of an optical beat signal is determined by the wavelength difference between two continuous waves, it is considered that there is no upper limit to the frequency, and that the response speed of TPA in a Si-APD is 100 THz or more. This holds out the hope that this OPLL can easily synchronize optical beat signals an order of magnitude higher in frequency than 160 GHz. Accordingly, to confirm the ultrafast performance of this OPLL, external synchronization experiments were conducted on 1-THz optical beat signals[10].

Since the experimental configuration is basically the same as that shown in Figure 4, we set forth below the

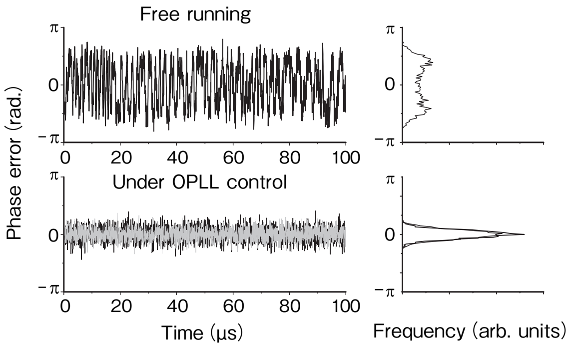


Figure 8 Waveforms of phase error signal in 160-GHz optical beat signal (left hand side) and its frequency graphs (right hand side). Black and gray lines are measured signal and background noise, respectively.

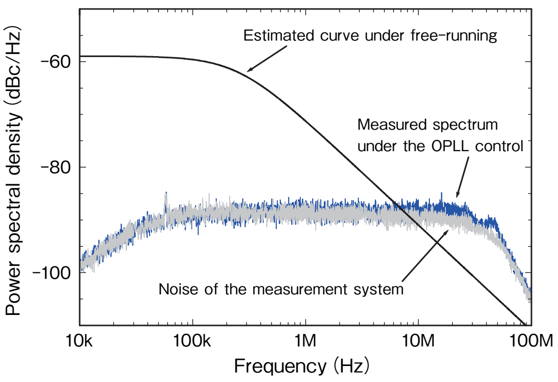


Figure 9 Phase noise spectrum of 160-GHz optical beat signal. Black line: the spectrum under OPLL control, gray line: background noise, and dotted line: estimated line under free running.

points that differ from the 160-GHz optical beat signal synchronization experiments. First of all, to generate a 1-THz optical beat signal we replaced only the master LD used in the experimental system in Section 3.1 above, and the master and slave LDs were set at 1566.3 and 1558.2 nm respectively. Next, we used as the external optical signal a 40-GHz repetition rate 500-fs optical pulse train with a center wavelength of 1540 nm and compressed pulse width [13]. The pulse width of this external optical signal corresponds to the pulse width of the optical signal used for the 1-Tbit/s signal. The power of the various signals in the Si-APD--the external optical signal, master LD and slave LD--were set at 195 mW, 70.8 mW and 4.6 mW respectively, virtually the same values as in the experiments in Section 3.1 above. As a result of the settings described above, the optical spectrum in Figure 10 was obtained at the Si-APD input. Note that since the pulse width of the external optical signal had become shorter, it became more subject to the influence of broadening pulse width due to optical fiber dispersion. Since the amplitude of the phase error signal becomes smaller as pulse width broadens, in these experiments we inserted an external optical fiber to compensate for the dispersion between the optical signal source and the Si-APD. The length of the inserted optical fiber is adjusted so that the amplitude of the phase error signal was maximized.

To confirm synchronization of the 1-THz optical beat signal with the external optical signal, we measured the cross-correlation waveform between the two signals. Without synchronization there is no relationship, but with synchronization a correlation between the two signals appears, so we anticipated being able to measure a waveform of 1-ps period. The configuration of the cross-correlation measurement system was like that shown in Figure 6, but we made re-adjustments so that the wavelength of the optical filter was optimum for these experiments. Figure 11 shows the cross-correlation waveform that we measured. A waveform with a period of 1 ps was observed, confirming that the 1-THz optical beat signal was synchronized with the external optical signal.

Next we measured the timing jitter of the 1-THz optical beat signal. For the purpose of timing jitter measurement, we used the cross-correlation waveform measuring system shown in Figure 6, with an optical delay line fixed so that the average value of the phase error signal becomes the center value of the cross-correlation waveform in Figure 11. In addition to this, the low pass filter (LPF) was detached to achieve accurate waveform measurement. By means of these changes it was possible to measure the cross-correlation signal as a phase noise signal.

Figure 12 shows the result of measuring the phase error signal with a an oscilloscope. The phase error signal, which had random distribution when not synchronized, converged to a phase error value of zero during synchronized operation, and its broadening was suppressed to a level approaching background noise. From this result too, it was possible to confirm synchronization of the 1-THz optical beat signal. Next the phase error signal was measured using an RF spectrum analyzer, and the phase noise spectrum obtained is shown in Figure 13. As in the experiments described earlier, by calculating the variance for phase error and the corresponding timing jitter, it was found that they are 0.03 rad ^{2} and 28 fs respectively. Thus it is clear that a 1-THz optical beat signal can be synchronized with a small timing jitter.

The above discussion demonstrates that this OPLL possesses the ultrafast performance to enable synchronization of even such high-speed optical signals as a 1-THz optical beat signal.

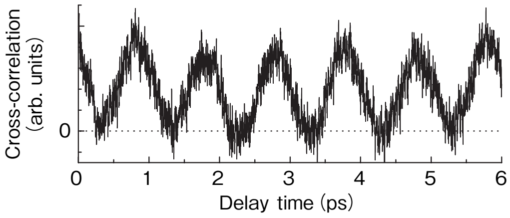


Figure 11 Cross-correlation signal between 1-THz optical beat signal and the external optical signal.

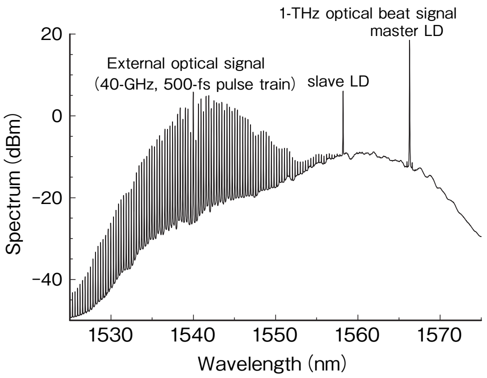


Figure 10 Optical spectrum at Si-APD input port.

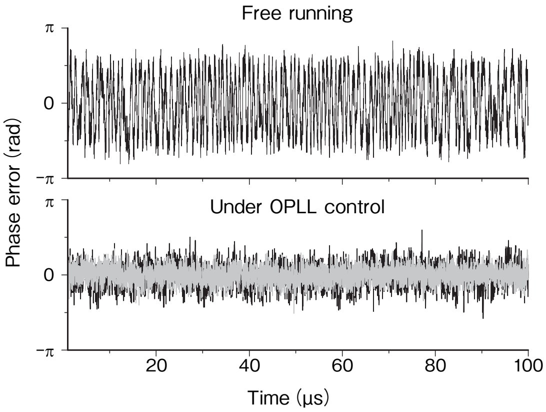


Figure 12 Phase error signals of 1-THz optical beat signal (black line). Gray line is background noise.

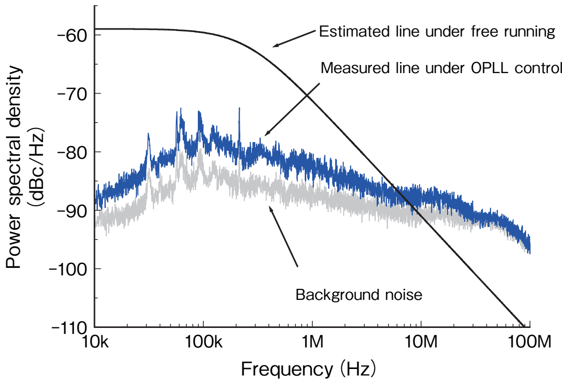


Figure 13 Phase noise spectrum of 1-THz optical beat signal.

4. CONCLUSION

We have demonstrated that an OPLL comprising an optical beat signal source using a 3-electrode DFB LD and an all-optical phase detector using a Si-APD can synchronize a 160-GHz optical beat signal of 40-GHz repetition rate and 2-ps pulse train with a timing jitter of 126 fs, and a 1-THz optical beat signal of 40-GHz repetition rate and 0.5-ps pulse train with a timing jitter of 28 fs. We may therefore say that this OPLL has outstanding characteristics as an ultrafast optical clock signal source capable of coping with future increases in transmission speeds. In future we will add such improvements as will render this OPLL a clock signal source that will support ultrafast all-optical signal processing.

ACKNOWLEDGMENT

This research is the product of a joint research effort with the Japan Science and Technology Agency.

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