40-GHz subharmonic optical clock recovery using an injection-locked optoelectronic oscillator

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Abstract: 40-GHz subharmonic optical clock recovery has been demonstrated using an optoelectronic oscillator (OEO) injection locked by 160-Gb/s data streams. The data streams are coupled to a photodetector in the OEO feedback loop after transmitted through a LiNbO₃ intensity modulator, which enhances the residual subharmonic clock component in the data streams. The pulse width and root-mean-square timing jitter of the recovered clocks are 9.03 ps and 221 fs (10 Hz – 40 MHz), respectively.

Keywords: clock recovery, optoelectronic oscillator, injection locking, optical time division multiplexing, phase noise

Classification: Photonics devices, circuits, and systems

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1 Introduction

All-optical clock recovery is one of the key technologies for realizing optical time-division-multiplexed (OTDM) networks that require synchronous operations such as demultiplexing, add-drop and 3R (reamplification, retiming, and reshaping) regeneration. Subharmonic clock recovery is indispensable for demultiplexing and add-drop operations and was demonstrated using optoelectronic oscillator (OEO) [1, 2], mode-locked lasers [3, 4], and phase-locked loops [5, 6]. OEO-based clock recovery [1, 2, 7, 8] is advantageous in simultaneously extracting both electrical and optical clocks with high spectral purity. In a previous work [2] we demonstrated 40-GHz subharmonic optical clock recovery, in which 160-Gb/s data streams were directly coupled to a photodetector (PD) in the OEO feedback loop. The mechanism responsible for subharmonic clock recovery was the residual 40-GHz component in the 160-Gb/s data streams, which was produced by the imperfection of the OTDM multiplexer. The pulse width and root-mean-square (rms) timing jitter of the recovered clocks were 11.3 ps and 782 fs (10 Hz – 18.6 MHz), respectively, which was limited by the small amplitude of the residual subharmonic component.

This paper describes improvements in the performance of subharmonic optical clock recovery at 40 GHz using a modified OEO configuration. 160-Gb/s data streams are coupled to the PD after transmitted through a LiNbO₃ intensity modulator in the OEO feedback loop, which enhances the amplitude of the subharmonic clock component. This modification results in shorter pulse width and smaller timing jitter as well as the more than 10 dB reduction in the power of the injected data streams.

2 Experimental Setup

Figure 1 (a) shows schematic diagram of the OEO for 40-GHz subharmonic clock recovery used in the previous work [2]. The OEO is comprised of a continuous-wave (CW) laser, LiNbO₃ intensity modulator, variable optical

Fig. 1. Schematic diagram of optoelectronic oscillators for subharmonic optical clock recovery used in (a) previous and (b) present works.

delay line (VDL), PD, electrical amplifier, and high-Q electrical bandpass filter (BPF). The output light from the CW laser is input to the modulator and is converted to an electrical signal by the PD. The PD output signal is fed back to the modulator through the amplifier and BPF. The OEO is designed to oscillate around 40 GHz and it is assumed that 160-Gb/s data streams contain subharmonic component at 40 GHz. Recovered optical clocks are extracted just after the modulator, while 160-Gb/s data streams are directly coupled to the PD, which is advantageous for achieving wavelength-independent and polarization-insensitive operation [2].

In the absence of injected data streams, the OEO supports self-sustained oscillation at the frequency determined by the BPF and transit time of the feedback loop. The oscillation frequency can be tuned by adjusting the VDL. With data streams injection, the OEO is forced to synchronize with the subharmonic component in the data streams. Therefore, the performance of clock recovery strongly depends on the amplitude of the subharmonic components, which was a main limiting factor in the previous work [2].

To improve the performance of clock recovery a modified OEO shown in Fig. 1 (b) is used in the present work. 160-Gb/s data streams are input to the modulator together with the CW light and are modulated by the 40-GHz electrical clock signal, which is expected to enhance the amplitude of the subharmonic component. 40-GHz optical clocks are extracted just after the VDL using a directional coupler and optical BPF. Although this configuration sacrifices the merit of wavelength-independent and polarization-insensitive operation, it drastically improves the performance as will be shown below.

159.25248-Gb/s data streams are generated from an actively mode-locked fiber laser (AML-FL) with a repetition frequency of 9.95328 GHz. The pulse width and center wavelength of the AML-FL output are 2.0 ps and 1550.3 nm, respectively. The AML-FL output pulses are encoded by a $2^7 - 1$ pseudorandom

dom bit sequence (PRBS) pattern using a LiNbO₃ intensity modulator, and are multiplexed into 159.25248-Gb/s data streams. The four-stage fiber-optic OTDM multiplexer has the delays of 6.4, 3.2, 1.6 and 0.8 ns, respectively, which ensures a PRBS pattern at the output. Although an ideal 160-Gb/s data stream contains no subharmonic components, imperfection in the multiplexer produces residual 40-GHz tone, which enables injection-locking at the subharmonic frequency [1, 2].

As shown in Fig. 1 (b), the 1560.0-nm CW light and data streams are combined and detected by the PD after transmitted through the modulator. The center frequency and Q factor of the BPF are 39.81291 GHz and 961, respectively. The transit time of the feedback loop is 20.0 ns corresponding to the free spectral range of 50 MHz, which ensures single-mode oscillation. To evaluate the performances, optical clock waveforms are observed with an optical sampling oscilloscope (Yokogawa, AQ7750) whose trigger signal is derived from a frequency synthesizer used to mode-lock the AML-FL. Phase noise of the optical clocks is measured using a signal source analyzer (Agilent, E5052A) after electrical down-conversion [9].

3 Results

By adjusting the VDL the OEO oscillation frequency can be continuously tuned between 39.8008 and 39.8382 GHz when the average power of the CW light incident upon the PD is -7.77 dBm. Injection locking is achieved for the OEO frequency detuning between -0.55 MHz and 0.19 MHz from the nominal clock frequency of 39.81312 GHz. The average powers of the 159.25248-Gb/s data streams required for achieving stable injection locking are -7.12 , -18.1 and -8.27 dBm for the frequency detuning of -0.55 , -0.01 and 0.19 MHz, respectively.

Figure 2 shows the optical sampling traces of the 159.25248-Gb/s data streams and 39.81312-GHz optical clocks. Figure 2(a) corresponds to the input data streams. The amplitude of the residual 40-GHz clock component contained in the data streams is estimated to be 0.054 % of the average intensity [10]. Figure 2(b) shows the result from the previous work representing the waveform of optical clocks obtained with the configuration shown in Fig. 1 (a). The average optical powers incident upon the PD are -6.54 and -4.12 dBm for the CW light and data streams, respectively. A relatively large pulse width of 11.3 ps is attributed to the smaller amplitude of the subharmonic clock component in the data streams.

Figure 2(c) corresponds to the optical clocks obtained with the configuration shown in Fig. 1 (b). The average powers incident upon the PD are -7.74 and -16.1 dBm for the CW light and data streams, respectively. The observed waveform can be well fitted to Gaussian shape with the full width at half maximum (FWHM) of 9.03 ps. The FWHM of the spectral envelope is measured to be 0.437 nm giving the time-bandwidth product of 0.486. By comparing Figs. 2 (b) and (c), it can be seen that the present configuration is effective for reducing the pulse width. The improvement can be attributed

Fig. 2. Optical sampling traces: (a) 160-Gb/s input data streams, (b) 40-GHz clocks obtained in the previous work [2], (c) 40-GHz clocks obtained in the present work, and (d) 160-Gb/s data streams after transmitted through the modulator.

Fig. 3. PN-PSD $S_{\phi}(f)$ (curves A and B) and root-mean-square (rms) timing jitters σ_J (curves C and D) of the 39.81312-GHz optical clocks. Curves A and C were obtained in the previous work [2], while curves B and D represent the results obtained in this work.

to the increased amplitude of the subharmonic clock component, which is verified from the waveform of the data streams after transmitted through the modulator shown in Fig. 2(d). It can be seen that the data streams are transformed into twin pulses with a period of 25.12 ps, which contain larger subharmonic clock component than those before modulation. It should be also noticed that the average power of the data streams incident upon the PD is reduced by 12 dB as compared with the previous work [2].

Figure 3 shows the phase noise power spectral density (PN-PSD) $S_{\phi}(f)$ (curves A and B) and rms timing jitters σ_J (curves C and D) calculated by

using the relationship

$$\sigma_J = \frac{1}{2\pi f_{\text{rep}}} \sqrt{\int_{f_l}^{f_h} S_\phi(f) df}, \quad (1)$$

where $f_{\text{rep}} = 39.81312$ GHz represent the clock frequency, f_l and f_h denote the lower and upper limits of integration, respectively. The value of σ_J is calculated for fixed f_h and is plotted as a function of f_l . Curves A and C represent the results obtained in the previous work [2]. The rms jitter amounts to 728 fs (10 Hz – 18.6 MHz), which is about 2.8 times larger than that obtained in 40-Gb/s line rate clock recovery [2]. Curves B and D represent the results obtained with the configuration shown in Fig. 1 (b). By comparing curves A and B, it can be seen that the noise above 100-Hz Fourier frequency is considerably reduced. The rms jitter amounts to 221 fs (10 Hz – 40 MHz) corresponding to 0.88% of the nominal pulse period. These values are comparable to those obtained in 40-Gb/s line rate clock recovery [2].

4 Summary

In summary, 40-GHz subharmonic optical clock recovery from 160 Gb/s data streams was demonstrated using an injection-locked OEO. To enhance the residual clock component, 160 Gb/s data streams were coupled to the PD after transmitted through the modulator in the OEO feedback loop. The pulse width and rms timing jitter of the recovered clocks were 9.03 ps and 221 fs (10 Hz – 40 MHz), respectively. The minimum average power of the data streams required for stable injection locking was –18.1 dBm. These performances are much better than those obtained in the previous work and are comparable to the those of 40-GHz line rate clock recovery [2].