Polarization-Insensitive Optical Clock Recovery at 80 Gb/s Using a Silicon Photodiode

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***Abstract*—We report an optical clock recovery system that uses two-photon absorption in a conventional silicon photodiode to synchronize a 10-GHz optical clock to an 80-Gb/s data stream. Compared to many other clock recovery techniques, the system is economical, polarization-insensitive, and can operate over a broad range of optical wavelengths. The system was tested back-to-back and in a 110-km transmission experiment, achieved error-free performance in all cases, and exhibits a root-mean-square timing jitter of 120 fs. Low timing jitter is maintained even in the presence of slow or fast polarization fluctuations.**

***Index Terms*—Nonlinear optics, optical communication, optical signal processing, phase-locked loops (PLLs), photodiodes, polarization, synchronization, timing jitter.**

I. Introduction

FOR DATA rates up to 40 Gb/s, clock recovery is accomplished using high-speed photodetection and electronic signal processing. In future time-division-multiplexed systems, the data rate could exceed the speed of conventional electronics, and the process of clock recovery can be better accomplished in the optical domain. One promising approach for clock recovery is to utilize a fast optical nonlinearity to measure the timing difference without directly detecting the data.

In this letter, we describe an 80-Gb/s optical clock recovery system that uses two-photon absorption in a conventional silicon photodiode as the timing detection mechanism. Unlike many other nonlinear processes, two-photon absorption is simple, inexpensive, broad-band, and ultrafast. As an example of the ultrafast speed and bandwidth of this process, two-photon absorption in a silicon photodiode was recently used to measure 20-fs optical pulses which have a bandwidth over 200 nm [1]. In theory, two-photon absorption can be observed whenever the photon energy lies between the half-bandgap and full-bandgap energy.

Many optical clock recovery systems have been reported in the past, primarily based on injection-locked laser cavities [2], electrical ring oscillators [3], or optical phase-locked loop (PLL) systems. Reference [4] provides a review of the most commonly used techniques. Among the PLL methods, many nonlinear processes have been employed for timing detection, including four-wave mixing in fiber [5] or semiconductor waveguides [6], cross-absorption modulation in an electroabsorption modulator (EAM) [7], cross-phase modulation in semiconductor amplifiers [8], and optoelectronic mixing in modulators [9]. Few techniques have been reported that offer a polarization- and wavelength-insensitivity comparable to what is routinely obtained in slower electrical clock recovery systems.

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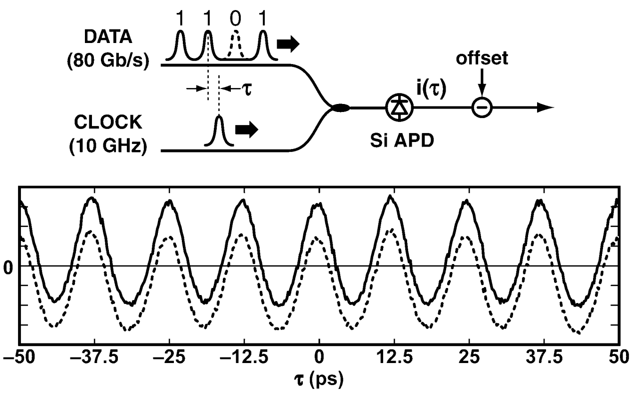

Fig. 1. Cross-correlation between 80-Gb/s RZ data and 10-GHz clock, measured using two-photon absorption in a silicon avalanche photodiode. The two curves shown here represent the minimum and maximum signals obtained by adjusting the data polarization state.

We reported the first experimental demonstration of optical clock recovery at 12.5 Gb/s using two-photon absorption [10], and we showed that the system has low polarization sensitivity and broad optical bandwidth. In the present work, we show that the scheme can also be used for subharmonic clock recovery at data rates beyond the speed of current electronic circuits, and we apply the system in a 110-km 80-Gb/s transmission and demultiplexing experiment.

The principle of clock recovery using two-photon absorption can best be described in reference to Fig. 1, which shows the cross-correlation between an 80-Gb/s return-to-zero (RZ) data stream and a 10-GHz optical clock signal, measured using two-photon absorption in a silicon avalanche photodiode. The cross-correlation signal ordinarily exhibits a background level caused by two-photon absorption of the clock and data separately. For clock recovery, an offset was subtracted to produce a bipolar cross-correlation signal that can serve as the error signal in a PLL to synchronize the clock and data. The background level depends on the data polarization state, but as shown in Fig. 1 the cross-correlation exhibits a zero-crossing for all possible polarization states.

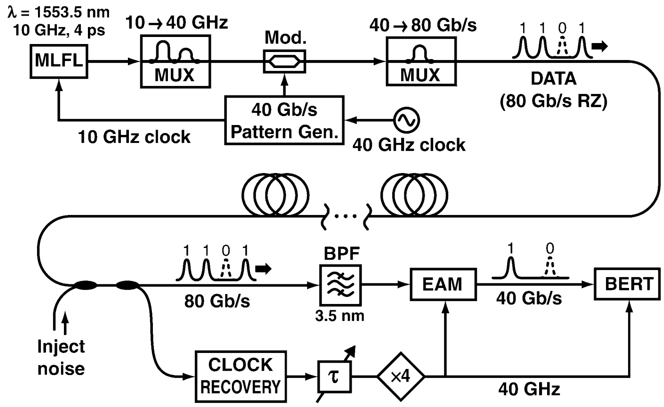

Fig. 2. Transmitter and receiver used to test optical clock recovery system.

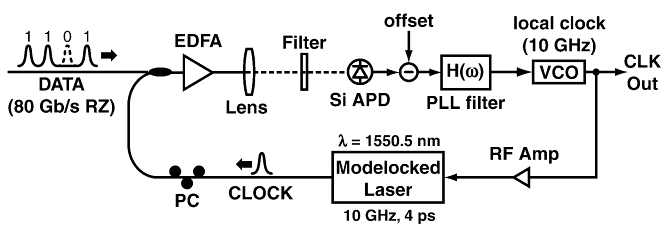

Fig. 3. Diagram of optical clock recovery system. The 10-GHz optical clock and 80-Gb/s RZ data are combined and focused on a silicon avalanche photodiode. The resulting cross-correlation signal is used in a feedback loop to synchronize the clock and data.

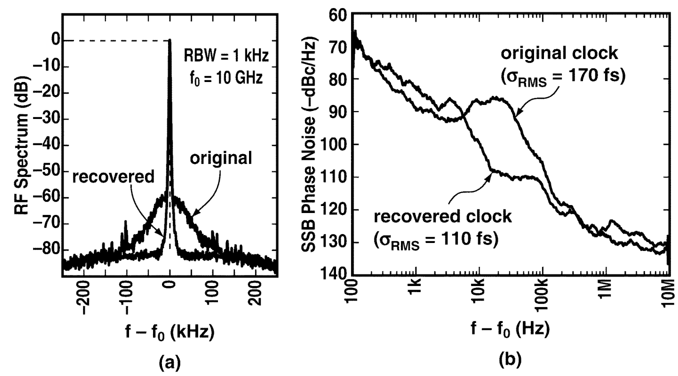

Fig. 4. (a) Spectrum and (b) single-sideband phase noise of the recovered clock compared to the original clock.

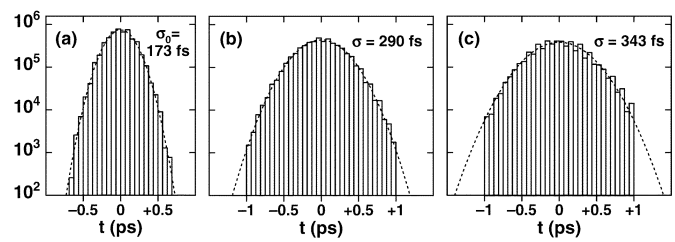

Fig. 5. Histograms showing temporal deviation in zero-crossing point. (a) Self-triggered clock signal exhibits a jitter of 173 ps, which shows the resolution of the instrument. (b) Recovered clock signal, triggered with original clock, and (c) recovered clock, with 5-kHz polarization scrambling enabled.

II. Experiment

The experimental setup used to demonstrate the clock recovery system is shown in Fig. 2. Fig. 3 shows the clock recovery system that synchronizes a 10-GHz optical clock to the 80-Gb/s data. The optical clock signal was produced by a hybrid-mode-locked semiconductor laser diode, driven by a voltage-controlled 10-GHz microwave oscillator. The clock and data were combined and focused onto the surface of the silicon photodiode. The spot-size of the focused light is about 3 μm and the long-pass filter shown in the diagram is used to block any shorter wavelengths that would otherwise generate a linear photocurrent. The loop filter $H(\omega)$ was designed so that the closed-loop transfer function would have a bandwidth of 6 kHz. In this experiment, both the clock and data pulses were each approximately 4 ps in duration, and the average signal powers were 6 mW for the clock and 3 mW for the data. The center wavelength for the clock was 1550.5 and 1553.5 nm for the data. At the receiver, the frequency of the recovered clock is first multiplied by four using two frequency doublers and bandpass filters. The resulting 40-GHz clock is then applied to an EAM, which demultiplexes the 80-Gb/s data into the 40-Gb/s data, which was directed to the receiver and bit-error-rate (BER) tester.

III. Measurements

Fig. 4 shows the spectrum and single-sideband phase noise of the recovered 10-GHz electrical clock signal, in comparison to that of the original clock used in the transmitter. By integrating the phase noise pedestal from 100 Hz to 10 MHz, a root-mean-square (rms) timing jitter of 110 fs is measured for the recovered clock compared to 170 fs for the original (transmitter) clock.

We also investigated the relative timing jitter of the two clocks by observing the recovered clock on a high-speed sampling oscilloscope that was triggered with the original clock. We used a precision time base system (Agilent 86 107A) to reduce the effect of intrinsic sampling jitter. The histograms shown in Fig. 5 show the statistical distribution of timing variations, observed near the zero-crossing point. To estimate the resolution of this technique, we first performed the measurement on a self-triggered clock signal, which gave an intrinsic rms sampling jitter of 173 fs, as shown in Fig. 5(a). Fig. 5(b) shows the timing histogram of the recovered clock, from which we calculate an rms deviation of 290 fs. Assuming the two sources of jitter are uncorrelated, we estimate the relative rms timing jitter to be 230 fs.

Polarization dependence in the clock recovery system is complicated by the fact that both the cross-correlation and background level depend upon the clock and data polarization states. We earlier demonstrated that by fixing the polarization state of the clock to circular, the cross-correlation component becomes independent of the polarization state of the data, whereas the background changes slightly [11]. We therefore made the clock circularly polarized to obtain the least amount of change in the amplitude of our error signal. The effect of changes in the background level can be seen in Fig. 1, which plots the cross-correlation for the two extremal cases obtained by adjusting the data polarization state. One can see that even if the polarization changes, the cross-correlation signal exhibits a zero-crossing, which allows the clock recovery system to function. Indeed, we observed that with the clock circularly polarized, the system was able to both acquire and maintain lock for any input data polarization state.

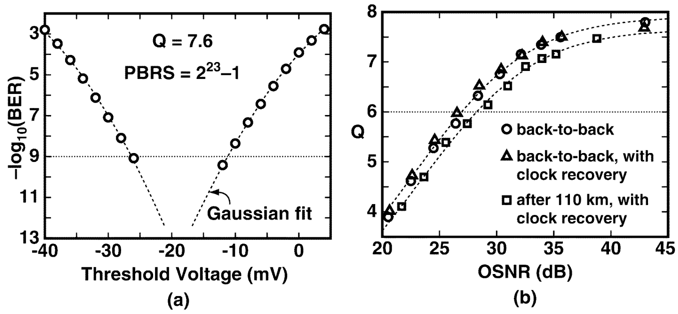

Fig. 6. (a) Mesaured BER versus threshold level for data after propagating through 110 km of fiber, using clock recovery at receiver, and (b) Q versus OSNR for back-to-back transmission without clock recovery, back-to-back with clock recovery, and over 110 km with clock recovery.

To quantify the effect of polarization fluctuations, we used a variable-speed polarization scrambler to vary the data polarization state prior to clock recovery. When the scrambling frequency was set much higher than the loop bandwidth, we observed no measurable increase in the timing jitter. This result is expected because for high frequencies, the clock recovery system responds only to the time-averaged cross-correlation signal. However, when the speed of scrambling was decreased to within the loop bandwidth, the fluctuations in the background level can produce a corresponding variation in the timing of the recovered clock. We observed this effect by measuring the relative timing jitter and phase noise for several scrambling frequencies ranging from 10 Hz to 12 kHz. Fig. 5(c) plots the timing histogram for one of the worst-case settings (5 kHz). Under these conditions, the rms timing jitter was observed to increase from 230 to 290 fs (both figures corrected for sampling jitter.) This implies that about 185-fs timing jitter is introduced by the polarization scrambling. A similar increase in timing jitter was observed through phase-noise measurements.

The clock recovery system requires a prescribed input optical power in order to maintain the cross-correlation amplitude needed for proper operation. Therefore, rather than measuring the BER as a function of power, we instead maintained a fixed optical power and injected broad-band amplified spontaneous emission to vary the signal-to-noise ratio. We emphasize that the noise was introduced *prior* to clock recovery, demultiplexing, and detection. The Q-value was estimated by measuring the BER as a function of the threshold level [12], as shown in Fig. 6(a).

Fig. 6(b) plots the measured Q versus optical signal-to-noise ratio (OSNR) for three different cases. The open circles correspond to back-to-back transmission without clock recovery, i.e., the original transmitter clock was also used for demultiplexing and error detection. The triangles were obtained for back-to-back transmission using the 10-GHz optical clock recovery system described here. These curves show no appreciable penalty introduced by the clock recovery system, even for low OSNR. We also confirmed that polarization fluctuations introduced by the scrambler do not cause a measurable power penalty.

The final curve in Fig. 6(b) plots the measured Q versus OSNR after the data was transmitted over 110 km of fiber, comprised of alternating spans of dispersion-shifted and conventional fiber, with distributed Raman amplification. A detailed description of the fiber span can be found in [13]. We attribute the Q-penalty to uncompensated chromatic dispersion in the span. The rms phase noise of the recovered clock was measured to be 120 fs (from 100 Hz to 10 MHz), almost identical to the result obtained for back-to-back clock recovery.

IV. Conclusion

We report the first experimental demonstration of an 80-Gb/s subharmonic optical clock recovery system based on two-photon absorption. The system offers several advantages over earlier approaches, including simplicity, broad optical bandwidth, ultrafast response time, and polarization insensitivity. We successfully employed the system after transmission through 110 km, and we show that the system exhibits sufficiently low timing jitter even in the presence of polarization fluctuations.

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