Broad-Band Optical Clock Recovery System Using Two-Photon Absorption

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***Abstract*—We report a new type of optical clock recovery system that uses two-photon absorption in a silicon avalanche photodiode. Unlike many earlier approaches, the system is compact, broad-band, polarization-insensitive, and scalable to high bit rates. The system was successfully applied at 12.5 Gb/s with wavelengths ranging from 1530 to 1570 nm, and can establish and maintain synchronization for arbitrary input polarization states. The effect of polarization drift on the timing of the recovered clock was investigated and quantified.**

***Index Terms*—Nonlinear optics, optical communication, phase-locked loops, phase noise, photodiodes, polarization, synchronization, timing jitter.**

I. Introduction

THE KEY to the future high-speed time-division-multiplexed networks is the development of techniques for *optical* signal processing at rates that exceed the speed of electronic circuits. One important function that could benefit from optical signal processing is clock recovery. The process of synchronizing a clock signal to a random stream of data is one of the first and most critical stages in any optical receiver, transceiver, 3R regenerator, or optical demultiplexer. One way to overcome the limited speed of electronic clock recovery systems is to measure the timing between the data and optical clock using a nonlinear optical process and utilize a phase-locked loop (PLL) to synchronize the two signals. Many nonlinear processes have been exploited for optical clock recovery including four-wave mixing in fiber [1] or semiconductor waveguides [2], cross-absorption modulation in an electroabsorption modulator [3], and phase modulation in semiconductor amplifiers [4], [5]. Most of these methods are not able to operate over a wide wavelength range and they also suffer different degrees of polarization dependence. These two issues could limit the use of such systems in WDM fiber networks where broad-band optical response is necessary and active control of the polarization state is expensive and impractical.

A number of additional optical clock recovery schemes have been used to generate an optical clock signal from the input data without utilizing a PLL. Most of these methods are based on injection locking of resonant cavities [6], [7] or resonator filters [8]. Such systems can provide broad optical response, but they are often not flexible to the input data rate. In this letter, we report a new type of clock recovery system based on two-photon absorption (TPA) in a silicon avalanche photodiode, and we show that it overcomes some of the disadvantages of earlier approaches.

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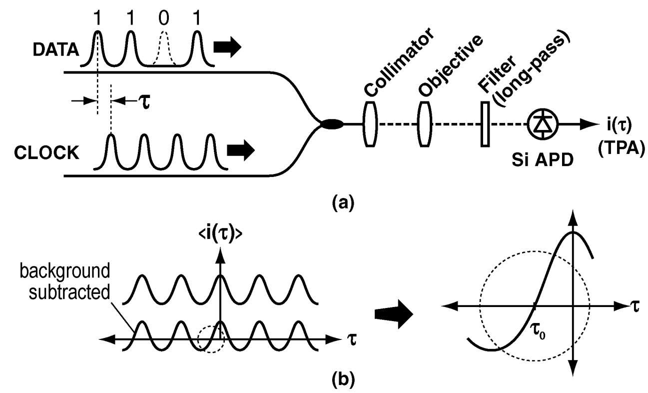

Fig. 1. (a) Setup used to measure timing difference between data and clock signals using TPA in a silicon avalanche photodiode. (b) Time-averaged photocurrent produced through TPA is largest when the clock and data are temporally aligned ($\tau = 0$.) After the background photocurrent is subtracted, the resulting signal can be incorporated in a PLL to synchronize the clock and data. In this example, the clock and data frequency would be locked together with a relative timing offset of τ_0.

TPA in semiconductor photodiodes has emerged as a sensitive and flexible technique for measuring optical autocorrelations and cross-correlations [9], [10]. Unlike sum-frequency generation or four-wave mixing, the mixed product of the two optical signals can be directly measured as a photocurrent without the need for external detection. Because TPA is a nonresonant effect and does not require phase matching between the two input signals, it has a broad spectral bandwidth and ultrafast response time [11]. Recent work shows that it can be polarization-insensitive as well [12]. These features make TPA a very attractive process for optical signal processing applications. TPA has found applications in optical sampling systems [13] and optical demultiplexers [14], but to our knowledge it has not been used for optical clock recovery.

II. Experiment

Fig. 1 illustrates how TPA was used to measure the relative timing between a return-to-zero (RZ) data signal and local clock. The clock and data are combined in a 50/50 coupler and focused to a spot-size of $\sim 3\ \mu$m through a long-pass filter onto the surface of a silicon avalanche photodiode (EG&G C30902E). The photodiode has bandgap larger than the clock and data photon energies, but smaller than their sum (e.g., silicon is a suitable material for the telecommunication band

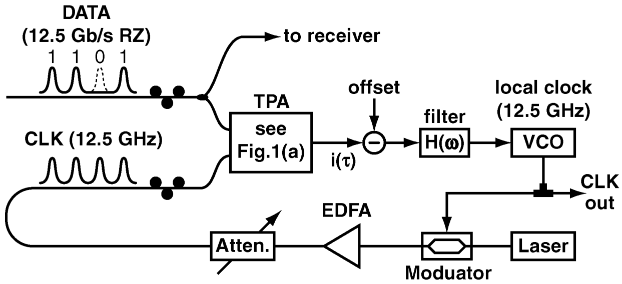

Fig. 2. Experimental setup used in optical clock recovery system based on TPA.

1.3-1.6 μm). Under this condition, the linear absorption is negligible, but a measurable nonlinear photocurrent can be produced by TPA. As shown in Fig. 1(b), the average photocurrent is larger when the data and clock signals are temporally aligned ($\tau = 0$) than when they are misaligned ($\tau \neq 0$.) A relatively slow detector can, therefore, determine the overall timing discrepancy between the clock and the data, averaged over many data bits. The detected photocurrent has a nonzero background level because the data and clock signals can each separately produce TPA even when they are nonoverlapped. After this background level is subtracted, the resulting error signal can be used in a feedback loop to synchronize the clock and data.

Fig. 2 shows the experimental system used to demonstrate optical clock recovery using TPA. The RZ data signal was generated by external electrooptic modulation of a tunable laser (not shown). An electrical circuit (Vitesse VSC7992) was used to convert the 12.5-Gb/s nonreturn-to-zero (NRZ) data produced by a pattern generator into an RZ electrical signal which in turn drives the electrooptic modulator. The optical clock signal was similarly generated by driving an electrooptic modulator with a sinusoidal radio-frequency (RF) signal produced by a voltage-controlled oscillator (VCO). The average optical power impinging on the detector was 2.8 mW for both clock and data signals, and the pulsewidth for both signals was $\sim$30 ps. A constant offset voltage was subtracted from the output of the TPA detector and the resulting error passes through a feedback filter and is used to control the frequency of the VCO. The feedback filter was designed so that the closed-loop transfer function would have a third-order low-pass response with a bandwidth of $\sim$10 kHz.

III. Measurements

Fig. 3 shows the measured performance of the TPA clock recovery system. Bit-error-rate (BER) measurements were performed with a 13-GHz amplified PIN diode photoreceiver (New Focus 1544-B), and a pattern length of $2^{31} - 1$ bits. The noise-equivalent power of the receiver was approximately 33 pW/Hz$^{1/2}$. The BER was measured both with the original and the recovered clock, with no measurable power penalty. When measuring the error rate, the optical power used for clock recovery was fixed while the power entering the receiver was varied using an attenuator.

Fig. 4 plots the measured RF spectrum of the original and recovered clock, as well as the corresponding single-sideband

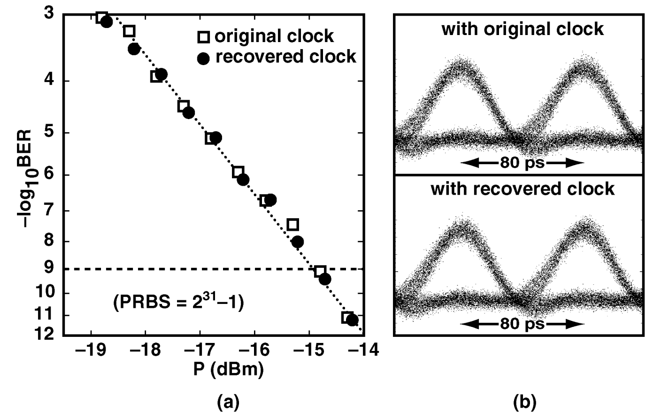

Fig. 3. Measured performance of clock recovery system based on TPA. (a) BER shows no appreciable power penalty when compared with back-to-back measurements using the original clock signal. (b) Measured eyes diagrams at BER $= 10^{-9}$ triggered with the original clock (upper) and with the recovered clock (lower).

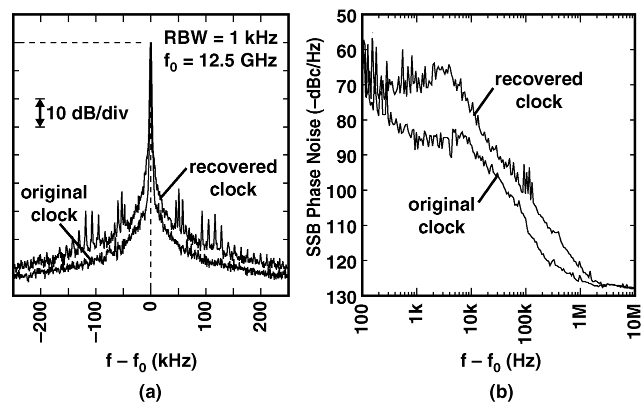

Fig. 4. (a) Measured RF spectrum and (b) single-sideband phase noise of original and recovered clock signals.

phase noise. By integrating the phase-noise pedestal from 100 Hz to 10 MHz, we estimate the timing jitter to be 700 fs for the recovered clock compared to 170 fs for the original clock. We believe that the spikes seen in the spectrum of the recovered clock are generated from the RF circuits in the system including the NRZ-to-RZ converter and the pattern generator. The contribution of these spikes to the calculated timing jitter is less than 20 fs.

For the representative measurements shown in Figs. 3 and 4, the data wavelength was 1555 nm and the clock wavelength was 1543 nm. We have confirmed that the clock recovery system shows similar behavior when the input wavelength is adjusted from 1530 to 1570 nm. The range of wavelengths tested was limited only by the bandwidth of the erbium-doped fiber amplifier, and we expect that the system could operate over a much wider range of wavelengths than we could produce in our laboratory.

To investigate the polarization sensitivity, we used a fixed circular polarization state for the clock signal and varied the the polarization state of the data signal. A recent study of TPA in silicon photodiodes [12] has shown that by maintaining a fixed circular polarization state for the clock signal, the effect of data

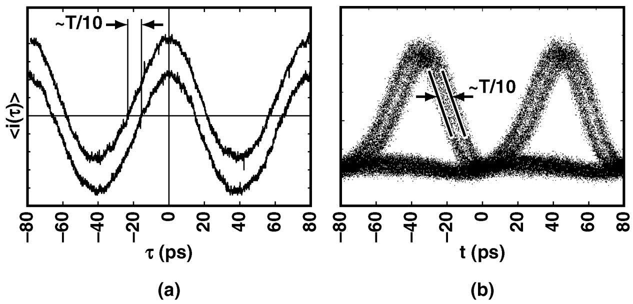

Fig. 5. When the polarization state of the data signal varies, the background nonlinear photocurrent changes, leading to a shift in the timing of the recovered clock. (a) Output of detector versus delay τ for two extremal cases obtained by adjusting the input polarization state. (b) Superposed eye diagrams for the two extremal cases considered in (a) showing the timing shift due to polarization changes.

polarization drift is simply to change the background photocurrent. Under these conditions, we found that the clock recovery system was able to both acquire and maintain synchronization even when the input polarization state was arbitrarily adjusted. However, as shown in Fig. 5, the change in background photocurrent causes a shift in in the timing of the recovered clock.

The data plotted in Fig. 5(a) were obtained by measuring the output of the detector on a slow oscilloscope with the PLL disabled, after setting the free-running frequency difference to 5 kHz. The two periodic signals shown in Fig. 5(a) correspond to the minimum and maximum background levels obtained by adjusting the data polarization. When the PLL was enabled, we observed a corresponding shift in the observed eye diagrams as a result of adjusting the polarization of the data signal, as shown in Fig. 5(b). For the 12.5-Gb/s system reported here, the timing shift could be as large as 8 ps, but we expect that at higher data rates the timing shift should be proportionately smaller. Based on the degree of eye closure in Fig. 5(b), we estimate a power penalty of 0.3 dB due to polarization fluctuations. If the polarization state fluctuates, this would cause the timing jitter to increase beyond the figure estimated from Fig. 4. This polarization-dependent timing shift could be eliminated by using dithering [4] or differential detection to remove the background level instead of simply subtracting a fixed offset.

Although these measurements were performed at 12.5 Gb/s, recent reports of femtosecond-scale autocorrelation measurements using TPA in silicon photodiodes [15] suggest that the timing extraction process could be easily scaled to higher data rates. It would also be possible to use the system for subharmonic clock recovery, provided the clock and data pulses have similar durations. In this application, the signal and clock powers will need to be adjusted to optimize the ratio between the cross correlation and background.

IV. Conclusion

We have reported the first experimental demonstration of an optical clock recovery system that uses TPA. Unlike many other clock recovery systems based on nonlinear processes, our approach can be used over a very wide optical bandwidth without sacrificing performance or efficiency. We successfully tested the clock recovery system at data rates up to 12.5 Gb/s, with optical wavelengths ranging from 1530 to 1570 nm and arbitrary polarization states, and we believe the system could be extended to much higher rates and wider wavelength ranges than we can presently generate. The system operates with average optical powers in the milliwatt range, and does not require low duty-cycle pulses with high peak power. The broad bandwidth, and high speed of the system make it an attractive candidate for future high-speed optical time-division-multiplexed systems. The small size and silicon composition make the device especially suitable for integration with other silicon optoelectronic components such as waveguides and modulators.

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