# High-Speed Broadband Polarization-Independent Optical Clock Recovery in a Silicon Detector

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**Abstract:** We have recently successfully used a silicon detector for optical clock recovery at 1.55 μm and speeds up to 80 Gb/s. We report here a novel optical dithering scheme that eliminates polarization dependence in the system and improves the dynamic range without introducing additional jitter in the recovered clock.

**OCIS codes:** (060.4510) Optical communications; (070.4340) Nonlinear optical signal processing; (190.4180) Multiphoton processes; (190.4360) Nonlinear optics, devices; (190.5970) Semiconductor nonlinear optics; (190.7110) Ultrafast nonlinear optics;

The conventional method for clock recovery in optical networks uses a fast photodiode and electrical signal processing. While this approach is wavelength- and polarization-independent, the maximum data rate is limited by the speed of the electronic components. Optical clock recovery systems can overcome this limitation by replacing the critical electronic components with a nonlinear optical process. Optical techniques for clock recovery include injection-locked laser cavities [1], optoelectronic ring oscillators [2], and optical phase-locked loops [3–6]. Although these methods have enabled sub-harmonic clock recovery at speeds up to hundreds of Gb/s, few of these techniques provide polarization- and wavelength- independence comparable to what is routinely attained in slower electronic clock recovery systems.

We report here a simple and effective clock recovery system that uses two-photon absorption in an inexpensive silicon avalanche photodiode as the nonlinear mechanism. We have developed a new optical time dithering system which eliminates the polarization dependence and provides over 10 dB of dynamic range without introducing excess jitter in the recovered clock signal.

Fig. 1(a) is a simplified diagram of a recently reported 80 Gb/s optical clock recovery system based on two-photon absorption in a silicon photodiode [7]. The high-speed data and clock are combined and focused onto the surface of a silicon photodiode, which produces an average photocurrent proportional to the cross-correlation of the two signals. Fig. 1(b) plots the measured cross-correlation signal between the 80 Gb/s data and the 10 GHz optical clock, showing that the photocurrent is highest when the clock and data pulses are temporally aligned ($\tau = 0$) and smallest when there is no overlap between clock and data. After subtracting a DC offset, the resulting bipolar error signal is used in a phase locked loop to synchronize the clock and data. Under normal operation, the phase-locked loop drives this error signal to zero, which ensures that the clock and data remain synchronized with a relative time delay determined by the position of the zero-crossing.

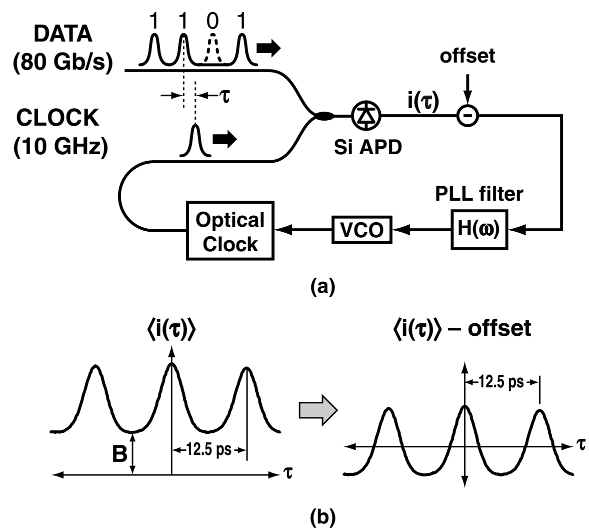


**Fig. 1**: (a) Schematic of the 80 Gb/s TPA-based clock recovery and (b) the cross-correlation signal used as PLL error signal after offset subtraction. $\tau$ is the delay between data and clock.

One disadvantage of this approach is that the background level, denoted $B$ in Fig. 1(b), depends on the wavelength, polarization-state and power of the data signal. Changes in any of these parameters can therefore cause the zero-crossing to shift or even disappear altogether. This problem is endemic to all phase-locked loop systems that rely on unipolar cross-correlation signals for synchronization.

One solution to this problem is to generate the bipolar error signal using balanced detectors [3, 5]. This would require two matched silicon detectors with identical avalanche gain, which adds to the cost and complexity of the system. An alternative technique that can track the peak of the cross-correlation without requiring two detectors is to intentionally dither the timing of the clock signal by modulating the phase of the voltage-controlled oscillator (VCO) [8, 9]. When the resulting cross-correlation signal is mixed with the dithering signal and low-pass filtered, it produces a bipolar error signal that approximates the slope of the original cross-correlation function. The only disadvantage of this technique is that the recovered electrical and optical clock are dithered and exhibit distinct spectral sidebands at the dither

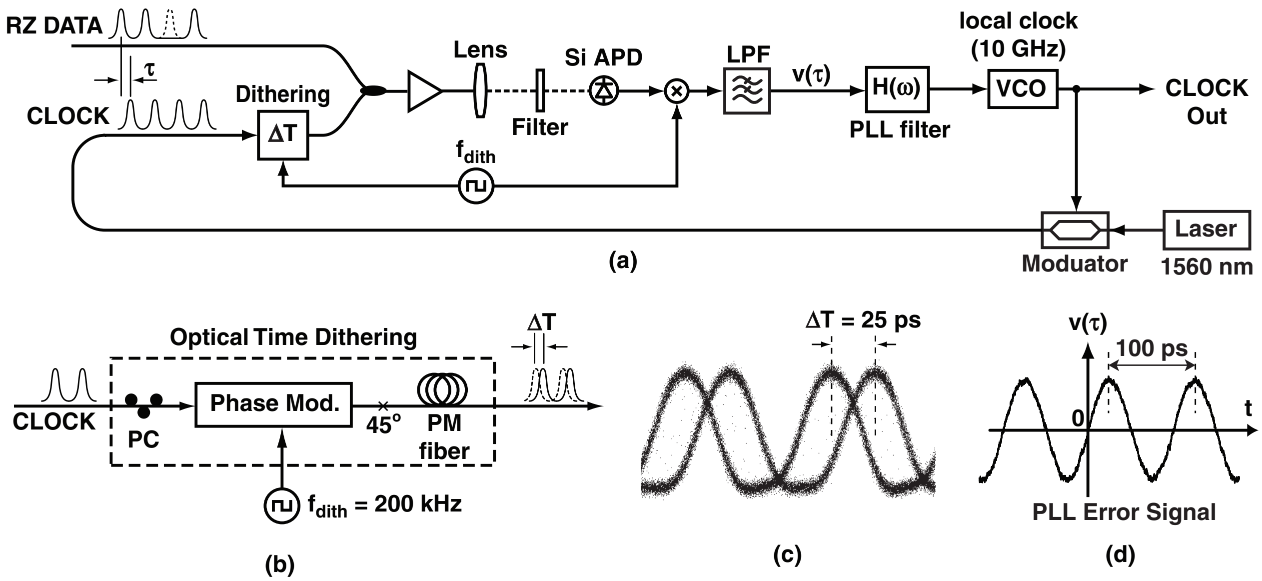


**Fig. 2**: (a) Clock recovery system employing optical time dithering, (b) optical dithering system in detail, (c) eye diagram of the dithered optical clock and (d) the offset-free error signal after low-pass filtering.

frequency. Because of this, the recovered clock is unsuitable for later use in optical regeneration or retransmission.

Fig. 2 depicts our solution to this problem. Instead of dithering the electrical clock signal, we have developed an external technique for dithering the timing in the optical domain. This allows access to the undithered electrical and optical clock signals for later use in demultiplexing or regeneration. The dithering system was tested in a prototype 10 Gb/s system, although it should also be applicable at higher speeds.

The 10 Gb/s RZ data signal was generated by electrooptic modulation of a tunable laser (not shown.) The optical clock was similarly produced by driving an electrooptic intensity modulator with a 10 GHz electrical VCO. The clock and data were combined and focused to a 3 µm spot on the silicon avalanche photodiode. The average clock power on the detector was 5 mW, and the data power was varied from 0.8 to 8 mW.

The optical dithering system is comprised of an electrooptic phase modulator followed by a length of birefringent (PM) fiber, as depicted in Fig. 2(b). The clock polarization is adjusted so that the signal entering the phase modulator is linearly polarized at 45 degrees to the z-axis of the modulator. The phase modulator is driven with a square wave at frequency $f_{\mathrm{dith}} = 200$ kHz. When the amplitude of the square wave is adjusted properly, the signal emerging from the modulator is periodically switched between two orthogonal polarization states at ±45 degrees. The axes of the PM fiber are also oriented at ±45 degrees with respect to the modulator, so that the signal enters into the fast or the slow axis of the fiber, depending on the applied voltage. The amplitude of the timing dither is then entirely determined by the length and birefringence of the PM fiber.

Fig. 2(c) shows the dithered optical clock measured on a sampling oscilloscope in eye diagram mode. The timing of the optical clock signal is switched by about 25 ps, which was achieved by using 18 m of PM fiber. The error signal as a function of delay shown in Fig. 2(d) was obtained by mixing the detected photocurrent from the silicon photodiode with the original dithering frequency and low-pass filtering. Unlike the orig-

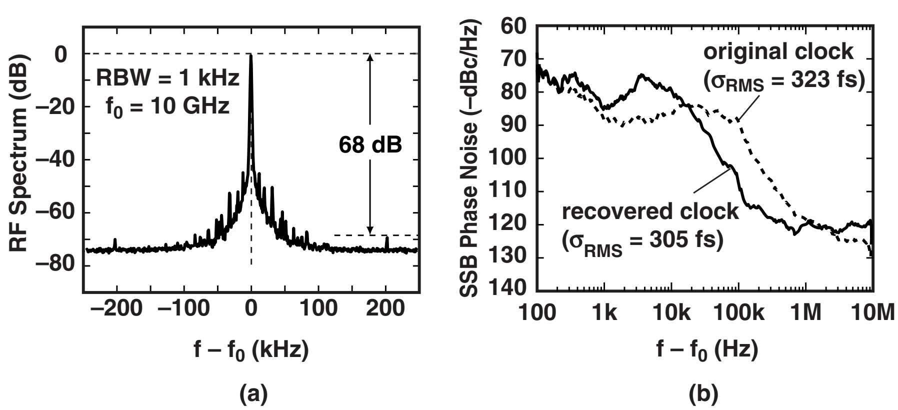


**Fig. 3**: (a) Electrical spectrum of the recovered clock, showing 68 dB suppression of tones at dithering frequency, (b) Single-sideband phase-noise of original (dashed) and recovered (solid) clock.

inal cross-correlation of Fig. 1(c), the resulting error signal exhibits a symmetric zero-crossing at $\tau = 0$, regardless of the background level.

Unlike the electrical dithering method used by others, the optical and electrical clock recovered with our system is not contaminated by the timing dither. Fig. 3(a) plots the electrical spectrum of the recovered clock, showing the suppression of the 200 kHz dithering tones by $-68$ dB relative to the carrier. We estimate that these small residual sidebands increase the timing jitter of the recovered clock by only 9 fs. When we instead produced the same 25 ps timing dither through electronic phase modulation, the sidebands rise to $-8$ dB below the carrier.

Fig. 3(b) plots the phase-noise of the original transmitter clock along with the phase-noise of the recovered clock. By integrating the phase-noise from 100 Hz to 10 MHz, we found the RMS timing jitter of the recovered clock to be about 305 fs versus 323 fs of the original clock.

An immediate advantage of using time dithering as opposed to offset subtraction is improved tolerance to power and wavelength variations. To quantify this improvement, we varied the power of the data signal while keeping clock average power fixed at 5 mW. The ratio of the data to the clock power was varied from $-8$ dB to $+2$dB and the system was able to acquire and maintain lock at all of these power levels. The system was also observed to operate without adjustment over the entire wavelength range from 1534 nm to 1568 nm, a range limited only by the bandwidth of our EDFA.

The dithering detection method also greatly reduces the polarization sensitivity of the system. Fig. 4 plots the measured eye diagram of the data signal, using the recovered clock as a trigger. The polarization state of the data was randomly varied during each measurement. Fig. 4(a) shows that when the offset-subtraction method is used, the eye becomes distorted as a result of polarization-induced timing fluctuations. This occurs because changes in the polarization state produce a predictable change in the background photocurrent, which in turn leads to a shift in the zero-crossing time [10]. Fig. 4(b) depicts the same experiment using the optical time dithering system reported here, showing no significant increase in the timing jitter.

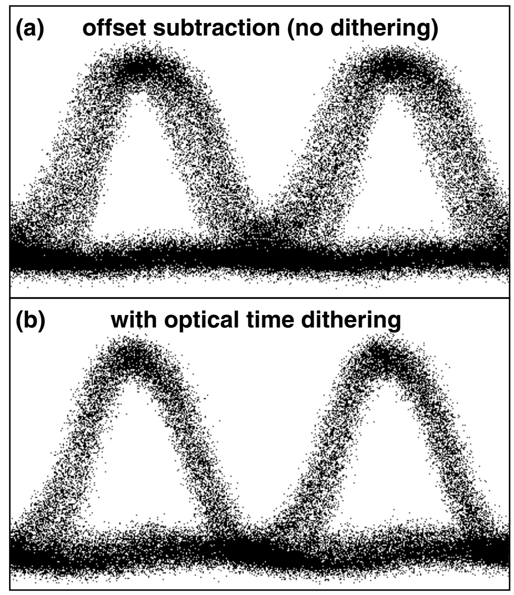


**Fig. 4**: Data eye diagram measured using recovered clock in the presence of polarization fluctuations (a) without dithering and (b) with dithering.

In summary, we report a clock recovery based on two-photon absorption in silicon that is both polarization and wavelength insensitive. The system uses a novel optical dithering system that provides an offset-free error signal with no balance detection. At least 10 dB of data power dynamic range is reported using this system.

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