Oscilloscopic capture of 100 GHz modulated optical waveforms at femtowatt power levels

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Abstract: Time-domain sampling oscilloscopic capture of ultra-high bandwidth modulated optical waveforms at 1550 nm is demonstrated at ultra-low power levels below -100dBm, with eye SNR varying from 13dB at 30 GHz to 6dB at 100 GHz.

OCIS codes: (030.5260) Photon counting; (130.4110) Modulators; (320.7100) Ultrafast measurements

1. Introduction. Commercially-available optical oscilloscopes achieve a front-end bandwidth of about 100 GHz, with a noise floor of about 0.9 Vrms (+12 dBm) [1]. There are many applications which require comparably high bandwidth but much weaker photon flux levels such as in long-distance communications [2], testing and qualification of pre-packaged photonic modulators and detectors [3], in space and underwater communications [4], in quantum communications, or in surveillance and diagnostics. Traditional oscilloscopic methods are fundamentally inhibited due to the standard quantum limit (SQL), which can be calculated, for 100 GHz bandwidth at 1550 nm, to be -43 dBm.

The ultimate low-power limits of optical waveform capture are, by definition, obtained by detecting single quanta i.e., photons. In the single-photon regime, it is not possible to generate copies for replica-based [5] or nonlinear-based [6] capture techniques. However, useful information can be obtained using direct detection; for example, time-correlated single-photon counting (TCSPC) has been demonstrated for imaging [7] and pulse-position modulation communications [8]. Previously, methods for sampling acquisition (see e.g., [9], [10]) have achieved only about 11 GHz of effective measurement bandwidth which is on par with standard oscilloscopes. Here, capture at an unprecedented (high-bandwidth, low-power) operating point is shown to be feasible when two conditions are met: (i) very high bandwidth and low jitter components are used in the hardware, and (ii) the system operates in a regime where there is either no detection event or a single detector firing event, which is time-stamped, in each time window between clock pulses.

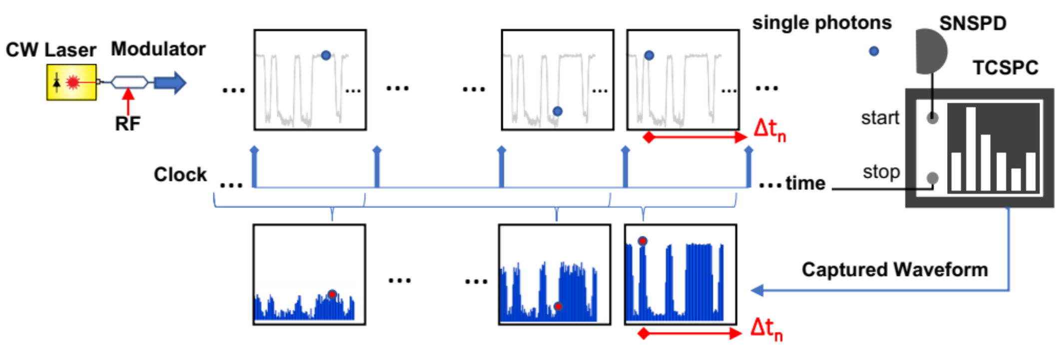

Fig. 1. Working principle: A continuous-wave (CW) laser provides 1550 nm light to the modulator, which imprints the test (RF) waveform on the optical carrier. Detection using a superconducting nanowire single-photon detector (SNSPD) is performed in the ultra-low power regime with, on average, less than one detected photon per clock tick. Histograms of the start (photon detection) to stop (clock reference) time difference Δt_n, performed, e.g., by a time-correlated single-photon counter (TCSPC), reproduce the RF waveform, over a few seconds or minutes.

2. Experimental setup. As shown in Fig. 1, light from a continuous-wave fiber-coupled laser was modulated using an electro-optic modulator, which was driven by high-frequency RF signals, which could be either sinusoidal waves or data waveforms depending on the application. The modulated lightwave signal was attenuated down to an average power level around 100 femtowatts (-100 dBm) and detected using a single-pixel superconducting nanowire single-photon detector (SNSPD). Each photon detected by the SNSPD generated a "start" pulse for a time-correlated single-photon counting (TCSPC) card. A periodic electrical clock (here, at 80 MHz) was sent to one of the electrical inputs of the TCSPC card, and generated the trigger of the "stop" signal. The histogram of the start-stop time difference Δt_n, acquired repeatedly (n=1,2, … enumerates the clock pulses) over about 2 minutes, reproduces the waveform to be measured. (In these experiments, each photon detection event was also time-stamped, in order to characterize the build-up of the histogram over time; however, this is not required in routine operation.)

Fig. 2 reports on an experiment demonstrating the concept using standard, commercially-available instruments: a conventional 10 Gbit/s lithium niobate electro-optic modulator (EOM), tungsten silicide (WSi) SNSPDs operated in a cold cryostat at 0.8K (PhotonSpot Inc.) and TCPSC card (TimeHarp 260 PCIe board, PicoQuant GmbH). To study the highest modulation frequencies that could be captured, the EOM device used in the results reported in Fig. 3 was a recently-reported hybrid silicon photonic device, in which unetched thin-film lithium niobate was oxide-bonded to silicon photonic waveguides, achieving phase-matched operation with >100 GHz 3-dB electrical modulation bandwidth (V_π = 6.5V) [11]. Millimeter-wave (>70 GHz) test signals were generated using a multiplier chain consisting of an RF synthesizer and amplifiers [12,13]. For lower RF frequencies, a commercial RF synthesizer and amplifier instrument were used. The modulated optical signals were detected using a niobium nitride SNSPD with cryogenic amplification of the detector signal [9]. The combination of the SNSPD, amplifier and (room temperature) TCSPC card (SPC-150NXX, Becker and Hickl GmbH) was measured to have an instrument response function (IRF) of 6.3 ps full-width at half-maximum at 1550 nm.

3. Results. Since the random selection of single photons from attenuated laser light (with Poisson statistics) itself results in a Poisson process, the entire waveform is sampled fairly and uniformly, and the histogram-reconstructed waveforms reproduce the original RF waveform, without clipping of either end of the acquisition window or bias towards the center. An experiment was performed to show this. Fig. 2 shows the capture of a data-carrying (modulated NRZ pattern) optical waveform using two different methods: Fig. 2(a) shows capture using a standard optical front-end of a sampling oscilloscope (Keysight DCA-X with 86105 module), whereas Fig. 2(b) shows the accurate capture of the same waveform with about 100 dB additional attenuation (thus resulting in an average power level of only 6.3 fW for the NRZ data stream) using single-photon detection. Fig. 2(c) shows the cross-correlation between the two traces was normalized by the square root of the product of the autocorrelations at zero time difference; correlation coefficients thus calculated were between 99.5% to 99.8%. This shows that the two waveforms are accurate replicas over both short and long time spans, up to the full memory (800 ns) of the TCPSC capture card that was used in this measurement.

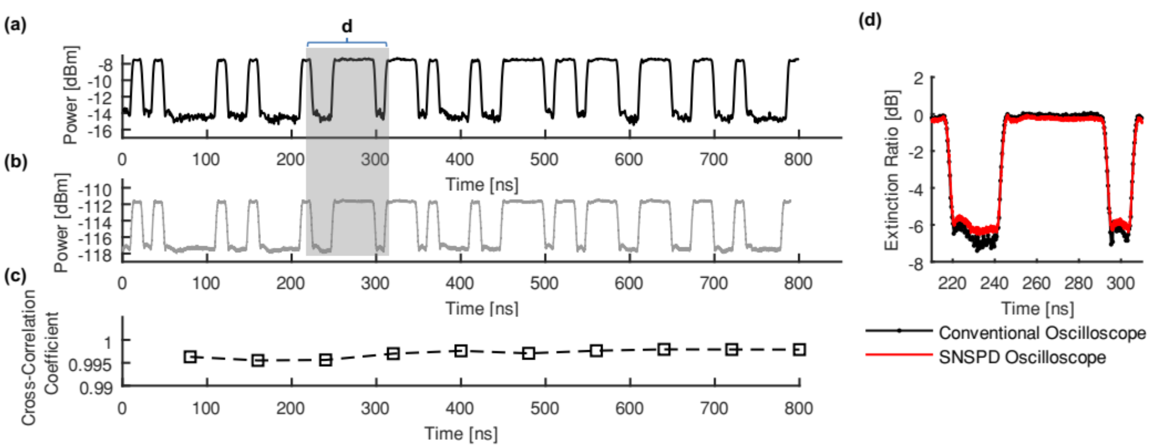

Fig. 2(a) A 20 GHz bandwidth optical module in a conventional sampling oscilloscope was used for capture of an NRZ encoded binary data message at -7 dBm average power at the receiver front-end. **(b)** After 105 dB additional attenuation, the same message was detected, error-free, using the scheme described in Fig. 1. **(c)** Cross-correlation between the two recorded messages shows high correlation for both short windows and long windows, spanning the entire message length. **(d)** Magnified view of a short section of panels (a) and (b), showing the close agreement of the waveforms (including the overdrive), despite the greater-than-100 dB difference in the received power level.

Fig. 3(a) reports on the signal-to-noise ratio (SNR) calculated for the recorded waveforms as the ratio of the mean signal power over twice the standard deviation of the noise power. Each SNR data point and corresponding eye diagram represents the data acquired over 120 seconds. Given the high mm-wave frequencies involved, sinusoidal rather than square-shaped drive waveforms were used. Noise power was calculated from a time domain fit after phase-drift removal (e.g., a residual several-second-scale drift in the unpackaged EOM microchip bias point for the Mach-Zehnder structure) and correcting for time-bin nonlinearity of the TCSPC card. After verifying the subtraction of the raw data from the line of best-fit did not result in any observable periodicity or identifiable skew in the residual trace, the remaining signal from best-fit subtraction was taken as a noise signal for the purpose of calculating the SNR, reported in Fig. 3(a). The eye diagrams in Fig. 3(b)-(e) were obtained by stacking the adjacent periods of the recorded waveforms in off-line data processing using MATLAB.

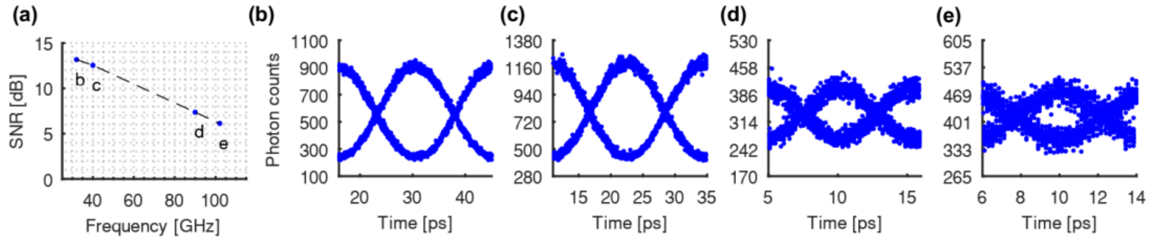

Fig. 3. Signal to noise ratio (SNR) calculation and eye diagram reconstruction, using data acquired over 120 seconds, at a detected average power of 64 femtowatts, in each case. **(a)** SNR of 13.2 dB at 32 GHz, 12.5 dB at 40 GHz, 7.36 dB at 90 GHz, 6.13 dB at 102 GHz sinusoidal modulation of the optical carrier. **(b)-(e)** Eye diagrams at 32 GHz, 40 GHz, 90 GHz, and 102 GHz modulation.

4. Discussion. Results already achieved here can be further scaled in the future to continuous detection coverage windows. A simple parallel stacking of eight TCSPC cards with 3.2 ps time bins (adequate for 100 GHz) would cover around 102 ns, greater than the dead time of a single detector (100 ns). Once the TCSPC record window exceeds the dead time of the photodetector, triggering each card in a round-robin manner will cover the acquisition window without dead times. Single-chip-based multi-channel time-to-digital converter systems with adequately-low jitter have been developed [14], which could reduce the cost of a multi-channel SNSPD system and synchronization complexities. Although the SNSPD detector is cryogenically cooled, the cost and complexity of closed-cycle ~1K cryocoolers is rapidly dropping, and more than a dozen detectors can be housed in a single system [15]. Thus, we believe that the technology exists today, building upon the present demonstration, to use state-of-the-art ultra-high-bandwidth electro-optic modulators, low-jitter single-photon detectors, and commercially-available electronics and cryogenics and achieve breakthrough performance in optical sampling oscilloscope technology.

5. Conclusion. Ultra-wideband (>100 GHz) waveform capture of modulated telecommunication (1550 nm wavelength) optical signals is demonstrated at extremely low (<100 femtowatt, -100 dBm) average optical power, with an acquisition time of 2 minutes. This demonstration presents a viable solution to high speed waveform capture, particularly in situations where the optical power levels available are many orders-of-magnitude lower than those required by any other technique.

This work was partially supported by the NSF (ECCS 1201308, EFMA-1640968) and NASA (NNX16AD14G, and the Space Technology Research Fellowship, 80NSSC17K0166), and the DARPA Defense Sciences Office, through the DETECT program. Part of the research was performed at the Jet Propulsion Laboratory, California Institute of Technology, under contract with NASA.

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