Characterization of Electro-Optical Devices with Low Jitter Single Photon Detectors – Towards an Optical Sampling Oscilloscope Beyond 100 GHz

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Abstract We showcase an optical random sampling scope that exploits single photon counting and apply it to characterize optical transceivers. We study single photon detectors with a jitter down to 40 ps. The method can be extended beyond 100 GHz.

Introduction

Single photon counting 1 has found broad applications within quantum technologies, such as quantum sensing², quantum information³ and quantum communication⁴. More recently it was proposed⁵ that low jitter single photon detectors could be used to realize optical random sampling scopes with a bandwidth well beyond 100 GHz, a range not accessible with existing measurement instrumentation. Such instrumentation is suitable to support research on next generation electrooptical devices such as EOMs and VCSELs. In this demo session paper, we showcase a proof of principle measurement and characterize commercial SFP+ modules using both Single Photon Avalanche Detectors (SPADs) and Superconducting Nanowire Single Photon Detectors (SNSPDs) with down to 40 ps jitter (FWHM). Both detectors are capable of detecting signals in the femtowatt regime. The SPAD provides an effective measurement bandwidth of about 11 GHz. The SNSPD provides a measurement that is free of typical detector artefacts, such as ringing and non-linearity. With the jitter of current SNSPDs reaching into the few picosecond regime⁵ the method holds promise to enable a measurement bandwidth well beyond 100 GHz. This research is timely and innovative and will appeal to the audience. All data shown below will be measured live at the demo session setup. Visitors will have access to a modern graphical touch interface that will enable them to control all measurement parameters and experience the single photon optical sampling technique on site.

Measurement Setup

Fig.1 illustrates the measurement setup as presented in the ECOC demo session. setup measures the modulation response and eye diagram of an 850 nm MMF (FINISAR FTLX8574D3BCL, 10 Gbit/s) and a 1310 nm SMF (Juniper EX-SFP-10GE-LR-C-UL, 10 Gbit/s) SFP+ module, simultaneously with the single photon counting approach exploited herein and with a state-of-the-art test system (30 GHz InGaAs photodiode, Thorlabs DXM30BF, and 50 GHz oscilloscope, Keysight Infiniium). Each optical output of the SFP+ modules is split with fiber splitters. One arm of each output is directed to a photodiode (PD) and oscilloscope. The second arm is left open and the light is allowed to travel through about 20 cm air gap after which a fraction of the intensity is picked up with an optical fiber again and directed to the SPAD (Silicon APD, IDQ 100) and SNSPD (Scontel) for 850 nm and 1310 nm, respectively. The air gap provides an attenuation on the order of 100 dB and the distance and coupling efficiency of the gap is used to adjust the photon count rates on the detectors under CW illumination to about 1 Mcounts/s. This count rate ensures that the average time between two photon detection events is much larger than the detector dead times (about 50 ns) such that the single photon detectors are operated in the linear range well below saturation. The outputs from the single photon counters are connected to two independent channels of a multichannel time-to-digital converter (TDC), that is implemented in a Kintex 7 FPGA by exploiting carry chains of the dedicated adders as tapped

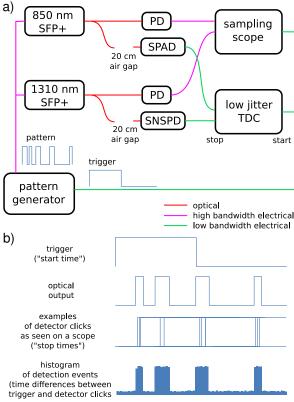


Fig. 1: a) optical and electrical setup, b) measurement principle.

delay lines⁶. A low jitter pattern generator delivers two synchronous output patterns: one output generates the 10 Gbit/s pattern that is applied to the SFP+ modules. A second output generates a trigger pulse for each bit pattern that is applied to the oscilloscope and to a third channel of the TDC. The random sampling measurements proceeds as follows (see Fig. 1b). The optical pattern and the trigger pulses are generated repeatedly with a rate on the order of 10 MHz. The triggers are used as "start" clicks and detected photons are used as "stop" clicks. Note that with the given photon count rates (imposed by the detector dead times), on average less than one photon is detected per cycle. The TDC measures the time differences between "start" clicks and "stop" clicks and accumulates them in a histogram, thereby providing a random sampled representation of the optical intensity. It is instructive to consider the analog bandwidth of distinct signal paths of the system (see also Fig. 1a). The photodiodes are connected to the oscilloscope via suitable 2.92 mm coaxial lines that provide 40 GHz analog bandwidth. By contrast, the analog bandwidth of the electrical pulses that are output by the single photon detectors is only a few GHz. Thus, simple RG316 SMA cables and input discriminators with moderate bandwidth (Texas Instruments LMH7322, maximum toggle rate 3.9 GHz, jitter 572 fs) are enough to deliver the detector signals to the TDC. This aspect is important: in an

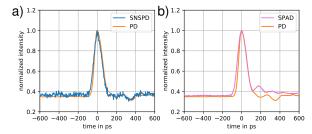


Fig. 2: Optical pulse response for isolated 1 bit pulses (duration 100 ps). Single photon counting results (orange) are compared to the SNSPD (blue) and SPAD (pink).

optical sampling scope based on single photon detectors, the measurement bandwidth is determined by the *jitter* of the single photon detectors and *not* by the analog bandwidth of the receiver. This enables us to conceive an optical sampling scope with a bandwidth that could reach into the THz regime without the need of handling high frequency electrical signals.

Results

We first characterize the pulse response of both single photon detectors by applying isolated 1 bit pulses to the SFP+ modules, providing nominally 100 ps long optical output pulses. Fig. 2 shows the measured optical pulses. The results obtained with single photon counting are compared to the measurements with the photodiodes and they are generally in good agreement. At the same time, distinct measurement artefacts are apparent. In case of the photo diode the main peak is slightly skewed and weak ringing is observed, seen as a shoulder at about +100 ps. The single photon counting measurements provide an ideal Gaussian pulse shape and are free of ringing and electrical reflections. On the other hand, the SPAD is subject to afterpulsing⁷, which unfolds as a weak exponential tail with a time constant of about 2 ns, here modulated with weak oscillations from the VCSEL itself. The response function of the SNSPD is artefact free: an ideal symmetric pulse response is obtained that is only limited by the Gaussian broadening induced by the detector jitter. Please note that the weak dip at about +270 ps is a true intensity dip that is present in the optical signal.

To better illustrate the effects of the afterpulsing present with the SPAD, we proceed to measure optical square pulses with increasing period (see Fig. 3). The afterpulsing tails are now more apparent. Since the detector pulse response enters the measurement via a convolution, for pulses with longer period, the afterpulsing tail, respectively ringing is accumulated over a longer range and distorts the signal more strongly. For the SNSPD, an artefact free measurement is obtained. Note that the noise on the single photon counting measurements are purely due to shot

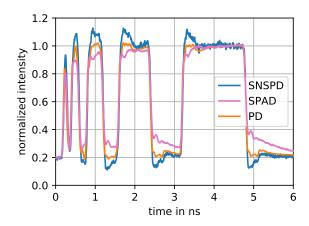


Fig. 3: Pulse patterns. The nominal pulse widths are 100, 200, 400, 800 and 1600 ps (from left to right).

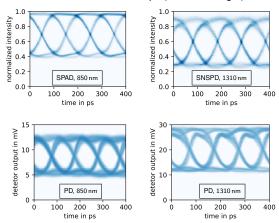


Fig. 4: Eye diagrams.

noise and can be improved to the desired precision by averaging for a longer time. For the present proof of principle demonstration, we proceed and measure the eye diagrams of the SFP+ modules (see Fig. 4). For this measurement, we apply random 8b10b symbols to the SFP+ modules. To acquire this data with single photon counting, one histogram is accumulated for each 8b10b symbol and the data is combined to a twodimensional histogram. With this measurement, the effect of the skewed pulse response of the photodiode becomes apparent. It unfolds as a distortion of the respective eye diagrams. By contrast, the single photon counting measurements are free of distortions due to their inherent Gaussian pulse responses.

Conclusions

We have demonstrated a proof-of-principle optical sampling scope based on low jitter single photon detectors and have applied it to measure the pulse response and eye diagram of two commercial SFP+ modules. Thereby, we have studied the performance of two types of modern single photon counting detectors, one, a Si-SPAD, that is operated at room temperature and useable in the visible wavelength range, and a sec-

ond one, an SNSPD, that requires cryogenic operation and that is optimized for the 1310 nm and 1550 nm telecom bands and useable over an extended optical wavelength range. We observed that both detectors provide accurate and undistorted eye diagram measurements, which we explained with their nearly ideal Gaussian pulse responses. We found that the SPAD results in significant distortion when measuring a step response, which we attributed to the afterpulsing tail. The SNSPD, which does not suffer from afterpulsing, provided an ideal step response measurement. The measurement scheme allows for the detection of very low optical powers down to the femtowatt regime and can provide very high optical measurement bandwidth without requiring high bandwidth electrical signals. The measurements presented herein are limited by the litter of the photodetectors, which is 40 ps (FWHM) for the SPAD and 50 ps (FWHM) for the SNSPD, respectively. This translates into an effective measurement bandwidth of 11 GHz, respectively 9 GHz. Recently SNSPDs with 2.7 ps jitter (FWHM) were reported⁵, translating into an effective measurement bandwidth of about 160 GHz. At present, there is no technical limit known for the jitter achievable with single photon detectors and it is expected that it will be significantly further reduced within the next few years. This opens the perspective for optical sampling scopes with a bandwidth well beyond 100 GHz. The TDC used in the present study has an RMS jitter of 8 ps and will be the limiting factor in future optical sampling scopes. This calls for the implementation of low jitter multichannel TDCs with short dead times (no more than few ns) that will enable a novel class of single photon based optical sampling scopes.

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