Supplementary Data for: A Homodyne Detector Integrated onto a Photonic Chip for Measuring Quantum States and Generating Random Numbers

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I. ELECTRONICS

Description of the design

Figure S1: Schematic of the electronics. The amplification stage of our detector was based on a OPA847 operational amplifier used in a transimpedance amplifier (TIA) configuration. The photodiodes were integrated on the silicon chip and wirebonded to the PCB with the electronics. R2 is the feedback resistor, which sets the gain of the TIA, and determines the bandwidth of the homodyne detector.

The design of the detection electronics is based on the design developed in [1]. Figure S1 shows a schematic of the electronics: the subtraction signal generated by the two photodiodes (PD1 and PD2) is amplified by a OPA847 operational amplifier in transimpedance configuration. The output signal is collected from the board by means of an SMA cable. The voltages supplying it have been stabilised by means of two fixed voltage regulators (LM78L05 and LM79L05). Each photodiode has been reverse-biased with a voltage provided by an adjustable voltage regulator (LM317LM and LM337LM). These two voltages are independent and can be tuned by changing the values of the resistors R7 and R8, this allows control
on the time response of the photodiodes. For the acquisition of the data reported in this paper, their values were both chosen at 1 V. The device is powered by two 9 V batteries (V+ and V-) in order to avoid power supply instabilities and improve compactness. The ground signal is carried on the board by the external shielding of the output SMA cable and provided by the same instrument used to measure the output signal. In our characterisation we used a Keysight DSOV134A oscilloscope for time response measurements and a N1996A Agilent RF spectrum analyser for spectral response measurements.

**Bandwidth limitations**

The bandwidth of a transimpedance amplification circuit is mainly affected by the capacitances of the electronic components involved. In our case, its value is given by [2]:

$$f_{-3dB} = \sqrt{\frac{GBW}{2\pi C_{tot} R_F}},$$

where GBW is the gain-bandwidth product of the operational amplifier and $R_F$ is the feedback resistor. $C_{tot}$ is the equivalent capacitance of the circuit, ideally obtained as the sum of the intrinsic capacitances of the photodiodes $C_{PD}$, and the differential $C_D$ and common mode capacitance $C_{CM}$ of the operational amplifier. The printed circuit board (PCB) hosting the components can also introduce a parasitic capacitance $C_L$, which is dependent on the geometry of the design and might have to be taken into account.

The quoted values for the common-mode and differential capacitances of the OPA847 are respectively 1.7 pF and 2.0 pF [3], while the feedback resistor is $R_F = 4.7$ kΩ. The quoted bandwidth of each integrated photodiode is 23 GHz [4], which corresponds to an intrinsic capacitance of $C_{PD} \sim 0.2$ pF. Assuming the parasitic capacitance of the PCB was negligible, we would expect a bandwidth of $\sim$180 MHz. The measured value of the bandwidth is $f_{-3dB} \sim$150 MHz, meaning that the estimated parasitic capacitance of the PCB is $\sim$ 2 pF.

**II. CHARACTERISATION OF INTEGRATED PHOTODIODES**

The integrated photodetectors included in the device are Ge p-i-n photodiodes. As the current signal detected by the homodyne detector is a subtraction between the currents
generated by the photodetectors, we can identify as "positive photodiode" the one that generates the positive contribution in the subtraction and as "negative photodiode" the other. Since the optical chip is monolithic, it was not possible to decouple the two photodiodes from the MMI coupler in order to characterise them separately. For this reason, each of the photodiodes has been characterised by means of an effective responsivity taking into account loss in the MMI. These measurements have been obtained by injecting a CW laser in the LO waveguide and measuring the two currents generated by the photodiodes. The transmissivity of the LO channel leading to the MMI is known to be $0.31 \pm 0.03$. Details on how this value has been measured are reported in the methods section of the main text.

Fig. S2 shows the effective responsivity curves of the two photodiodes. The values of the powers on the photodiodes were calculated assuming a perfectly balanced splitting ratio of the MMI. The two graphs show a responsivity of $(0.80 \pm 0.07) \, \text{A/W}$ for the positive photodiode and $(0.78 \pm 0.06) \, \text{A/W}$ for the negative one.

![Figure S2](image)

**Figure S2:** (a) *Response of the photodiode generating a positive current, showing a responsivity of $0.80 \pm 0.07 \, \text{A/W}$.* (b) *Response of the photodiode generating a negative current, showing a responsivity of $0.78 \pm 0.06 \, \text{A/W}$.*

### III. ESTIMATION OF COMMON MODE REJECTION RATIO

The common mode rejection ratio (CMRR) of a homodyne detector is defined as the ratio between the signal measured when only one of the photodiodes is illuminated and when both
the photodiodes are illuminated. This quantifies how well the balanced signals from the two photodiodes can suppress technical noise in the LO. The graph in Fig. S3 shows the spectra of both subtracted and unsubtracted signals that were measured with our device using a pulsed LO with a repetition rate of 50 MHz. The difference between the heights of the two peaks at 50 MHz corresponds to the CMRR. We found this to be 28 dB.

Figure S3: Measurement of the CMRR. Red line: Power spectrum of the signal with 18 µW of pulsed LO provided by a Pritel FFL-50 laser. Blue line: Power spectrum of the signal with the same LO, but with one photodiode disconnected from the circuit. The difference in height between the peaks is a measurement of the CMRR.

IV. TESTU01 STATISTICAL TESTS

In addition to the statistical tests NIST SP800-22 reported in Table I of the main text, we also applied the Small Crush Test included in the test suite TestU01 [6], to a different sample of ~1.8 Gbits in accordance with the different requirements of format and size of the input data. The results for the Small Crush Test are shown in Table S1. Our generator passed all the test provided. Here the P-value test is a double tailed test, which implies that the P-values must be such that 0.01 < P < 0.99. Details on the different tests applied can be found in [6].
| Test name                          | P-value |
|----------------------------------|---------|
| BirthdaySpacings                 | 0.75    |
| Collision                        | 0.16    |
| Gap                              | 0.94    |
| SimpPoker                        | 0.50    |
| CouponCollector                  | 0.59    |
| MaxOft                           | 0.06    |
| MaxOft Anderson-Darling          | 0.73    |
| WeightDistrib                    | 0.40    |
| MatrixRank                       | 0.97    |
| HammingIndep                     | 0.04    |
| RandomWalk1 Statistic H          | 0.24    |
| RandomWalk1 Statistic M          | 0.19    |
| RandomWalk1 Statistic J          | 0.63    |
| RandomWalk1 Statistic R          | 0.39    |
| RandomWalk1 Statistic C          | 0.53    |

Table S1: **TestU01 statistical tests on the random data.** For the Small Crush Test the results of the statistical tests on the hashed data are reported. In this case the validity range for the P-values is $0.01 < P < 0.99$, shown on the second column of the right hand table.

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