An On-chip Homodyne Detector for Generating Quantum Random Numbers and Measuring Coherent States

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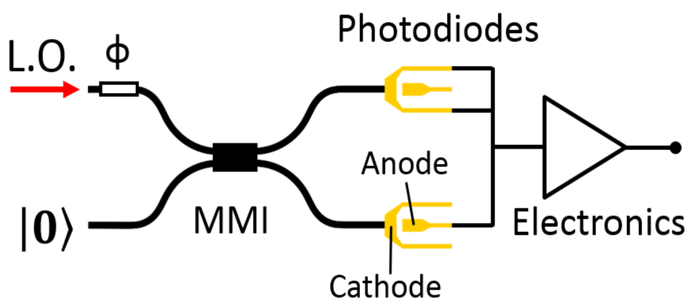
Here we demonstrate the design and operation of a homodyne detector integrated in silicon-on-insulator photonic platform. We generate high rate quantum random numbers and perform quantum state tomography of coherent states, showing a compact and monolithic device readily available for cryptographic applications and continuous-variable QKD.

Introduction

The homodyne detector is a primitive element in many quantum optics experiments. Used primarily as a characterization device for measuring the quantum state of the electromagnetic field [1], homodyne detection has more recently become integral part of continuous-variable quantum photonics. Homodyne detectors are widely used in continuous-variable QKD [2] and to generate certified random numbers at the Gbps rate [3]. Quantum integrated photonics [4], in which optical sources, circuits, and detectors are monolithically integrated on a semiconductor chip, provides an ideal platform in which to implement quantum devices such as the homodyne detector. Moreover, small size, scalable, CMOS compatible and low-cost devices in different platforms, from InP to silicon-on-insulator, have been successfully used to perform quantum key distribution [5,6].

A homodyne detector consists of an optical beamsplitter and a pair of balanced photodiodes. A strong coherent state and the signal field of interest are input onto the beamsplitter and a measurement of the difference in the photocurrents of the two photodiodes is proportional to a measurement of the quadrature of the quantum electromagnetic field Q, where $Q(\theta) = a^{\dagger}e^{-i\theta} + ae^{+i\theta}$, and θ is the optical phase difference between the signal and the local oscillator fields. For a sufficient number of different local oscillator phases, it is possible to reconstruct the full state of the quantum optical signal field [7]. When the signal field is the electromagnetic vacuum the measurement outcome of the quadrature operator, regardless of local oscillator phase, is a Gaussian-distributed random variable. If the quantum noise (derived from the shot noise associated with the local oscillator beam) can be distinguished from the classical noise present in the detector (derived from electronic sources), a stream of quantum random numbers can be extracted from the output of the homodyne detector [3]. Trustworthy random numbers of this type can then be used for applications like cryptography



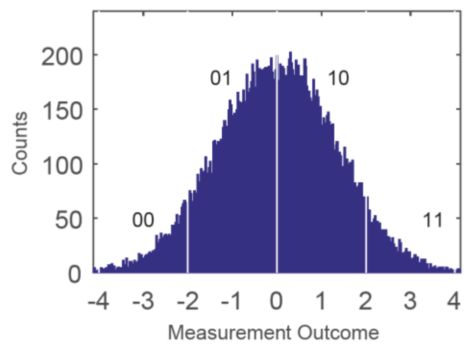


Figure 1: (a) Scheme of the integrated device. The LO is injected on the top waveguide, while the signal is injected in the bottom one. Here is represented the vacuum states measurements used to generated random numbers. (b) Gaussian distribution obtained by measuring the vacuum states. As an example, here it is divided into four bins. See [8] for details

where the security of random numbers is a concern.

When squeezed or coherent states are used as a signal field, homodyne detector can be exploited to perform quantum protocols in the continuous-variable regime. This is of particular relevance to continuous-variable QKD, which allows exchange of secure keys at a high rate, by taking advantage of homodyne measurements of coherent states without any need of single photon generation and single photon detection [2].

Experiment

The homodyne detector (see Fig. 1(a)) was fabricated on a silicon-on-insulator wafer, using IMEC foundry services. Two single mode slab waveguides are coupled to a multi-mode interference device (MMI) which performs the balanced beamsplitting operation necessary for homodyne detection, while Germanium is grown on silicon to form a PIN photodiode. The waveguides, MMI, and detectors are extremely compact, measuring just 1x0.25mm. As shown in Fig. 1(b), the output of the device is Gaussian distributed, and the ratio between the quantum noise and the electronic noise was 11 dB, with a 150 MHz homodyne detector bandwidth.

To obtain a signal of random numbers that is uncorrelated with the classical source of noise, we perform post-processing in the form of a randomness extraction after acquiring the samples of vacuum states. The total rate of random number generation after post-processing is 1.2 Gbps, and these quantum random numbers pass all the tests for unbiased random numbers from the NIST statistical test suite.

To perform quantum state tomography of coherent states, a strongly attenuated coherent beam is coupled into the bottom waveguide shown in Fig. 1(a). In our experiment, we performed full state tomography of coherent states for a few different amplitudes, reconstructing the Wigner function with fidelity above 99%.

The ability to scale up these integrated circuits and incorporate micro-electronics opens the way to new and advanced integrated quantum communication technologies and larger adoption of quantum-secured communications. We anticipate this compact, high-speed, homodyne detector will find application in a wide range of tasks that require secure random numbers, characterisation of coherent states, and continuous-variable quantum key distribution.

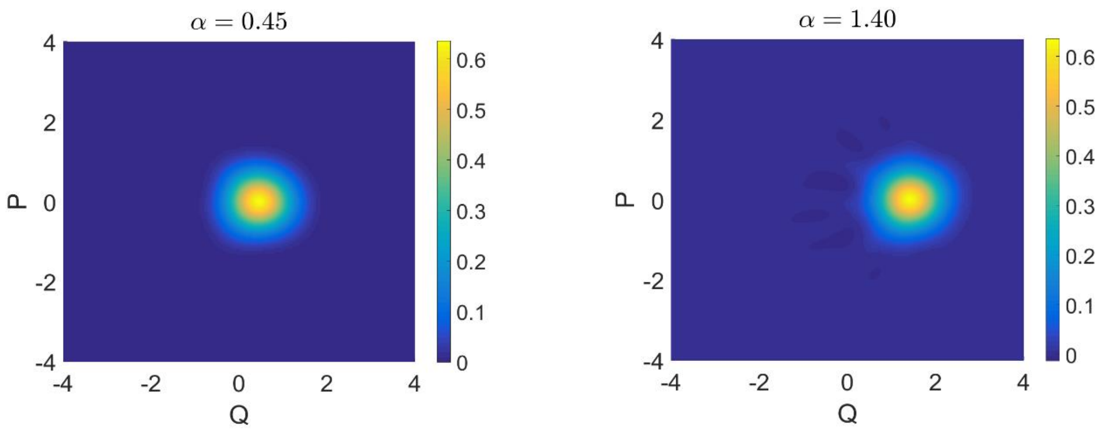


Figure 2: Reconstructed Wigner function for coherent states of different amplitudes.

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