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# Scalable single-photon detection on a photonic chip

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**Abstract:** We developed a scalable method for integrating sub-70-ps-timing-jitter superconducting nanowire single-photon detectors with photonic integrated circuits. We assembled a photonic chip with four integrated detectors and performed the first on-chip  $g^{(2)}(\tau)$ -measurements of an entangled-photon source.

**OCIS codes:** (040.5570) Quantum detectors; (270.5290) Photon statistics; (250.5300) Photonic integrated circuits

## 1. Introduction

Photonic integrated circuits (PICs) enable manipulation of light at the wavelength scale with excellent stability, compactness and cost. To avoid significant coupling losses, on-chip integration of detectors with PICs is desirable. Superconducting nanowire single photon detectors (SNSPDs [1]) have emerged as viable candidates, combining high detection efficiency [2] and sub-50-ps timing jitter [3] in the near-infrared. However, to date the integration of more than one SNSPD [4, 5] within the same PIC has yielded sub-0.2% system detection efficiency [6] due to the low nano-fabrication yield [7] of these detectors. Here we demonstrate [8] a micron-scale flip-chip integration process which allowed us to overcome the yield problem.

## 2. Detector integration on photonic chip

The detector, comprising 80-nm-wide  $\sim$ 4-nm-thick niobium nitride nanowires, was fabricated on top of a  $\sim$ 200-nm-thick-SiN<sub>x</sub>-on-Si substrate. The underlying silicon was then removed in subsequent etch processes, leaving free-standing SiN<sub>x</sub> membranes that carried superconducting single-photon detectors [9]. We used tungsten microprobes coated with adhesive (PDMS) and mounted on 3-axis translation stages to remove the detector membranes from the bulk substrate. As shown in Fig. 1(a) the detector membranes were flipped to enable tight contact of the detector with the silicon waveguide and then transferred to the desired waveguide region. The electrical contact pads on the membrane matched pre-fabricated gold pads on the photonic chip and were used to read out the transferred detector signals. Since we could pre-select the detector membranes for subsequent transfer steps, we did not require high-yield fabrication to generate scalable systems. Using this method we assembled a photonic chip, shown in Fig. 1(b) with four integrated detectors.

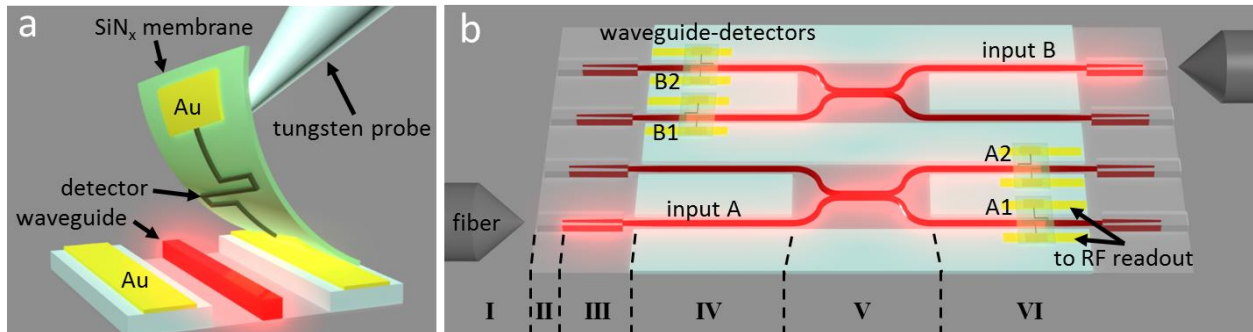


Fig. 1. (a) Schematic sketch of integration of superconducting single-photon detectors with photonic waveguides via physical transfer of the detector fabricated on top of a thin carrier membrane. (b) Sketch of photonic chip with four waveguide-integrated detectors assembled using the concept shown in (a). Infrared light was coupled from a lensed fiber (I) with a spot diameter of  $2.5\mu\text{m}$  into a  $2\mu\text{m} \times 3\mu\text{m}$  polymer coupler (II). The polymer coupler overlapped with a 50- to 300-nm-wide tapered portion silicon waveguide (III), evanescently coupling the mode into the waveguide. The mode traveled along the 500-nm-wide waveguide (IV) over a distance of 2mm before reaching a beamsplitter (directional coupler in section V) and waveguide-integrated detectors (VI).

### 3. On-chip correlation measurements

The high efficiency of our integrated detector system (up to 19% system detection efficiency including all losses) enabled the on-chip single-photon detection of a non-classical source with multiple detectors within the same photonic circuit. The experimental apparatus is shown in Fig 2(a). Using spontaneous parametric down-conversion (SPDC) we generated time-energy entangled photon pairs with center wavelength at 1560 nm that were highly correlated in time and highly anticorrelated in frequency [10]. We used a polarizing beam splitter to separate signal (sent to PIC input B) and idler photons (sent to PIC input A). With this system we collected  $g^{(2)}(\tau)$ -statistics shown in Figs. 2(b). When measuring the time delay  $\tau$  between a count from B1 and a count from one of the other three detectors, the entangled-photon-pair source resulted in coincidence peaks for A1 and A2 but not for B2. As a comparison, a mode-locked pulsed laser yielded coincidence peaks for all detector pairs.

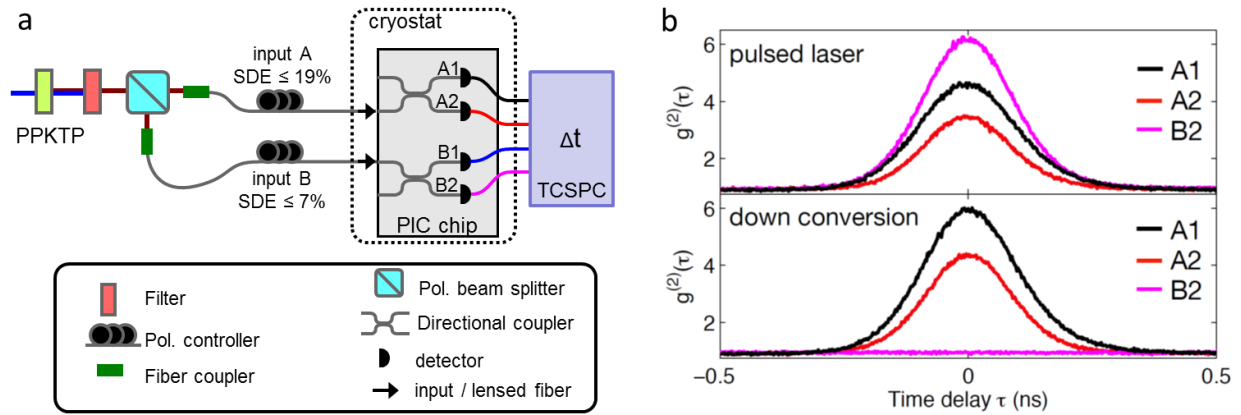


Fig. 2. (a) Experimental setup for on-chip  $g^{(2)}(\tau)$  measurement of an entangled-photon source coupled into the photonic circuit via two inputs. The photonic chip was cooled to 3 Kelvin in a closed-cycle cryostat and the lensed fibers were aligned to the polymer couplers in-situ. (b) Coincidence counts vs. time delay between A1 and B1, B2 and A2 for a pulsed laser and the source shown in (a). The system detection efficiency SDE was  $19 \pm 2\%$  for input A and  $7 \pm 1\%$  for input B.

### 4. Outlook

We have demonstrated the first on-chip  $g^{(2)}(\tau)$ -measurements of an entangled-photon source using four low-jitter high-efficiency detectors and showed the scalability of our micron-scale flip-chip integration approach. Since the detector fabrication was performed on a separate chip, our integration approach was independent of the PIC material and complexity. Combined with electrical multiplexing schemes [11, 12], this approach enables the integration of large numbers of detectors on a photonic chip without complicating the PIC fabrication. Eventually, with progress in scalable integration of on-chip quantum sources [13], PIC chips could become a fully-integrated compact platform for the generation, manipulation and detection of quantum states.

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