Integrated optical platform for photon-number resolving, telecom-band detectors for photonic information processing

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***Abstract*— We report the development of the optical substrates for the demonstration of an integrated photon-number-resolving detector, operating in the telecom band at 1550 nm, employing an evanescently coupled design that allows it to be placed at arbitrary locations within a planar circuit. Up to five photons are resolved in the guided optical mode via absorption from the evanescent field into a tungsten transition-edge sensor. The detection efficiency is 7.2 ± 0.5%. The polarization sensitivity of the detector is also demonstrated.**

Keywords-photon-number resolving detector; telecom-band; integrated

I. INTRODUCTION

Quantum information processing has seen a steady drive towards an integrated format in order to achieve increasingly complex circuit designs. Currently detection of low photon number signals is accomplished off-chip. However there is a drive to add this functionality on-chip to allow scalability, reduce loss and maintain the quantum optical state. Here we present an on-chip integrated photon-number resolving detector using evanescent coupling to a transition edge sensor (TES) [1].

These Evanescently Coupled Photon Counting Detectors (ECPCD's) display the low noise and single-photon sensitivity required to operate in the quantum regime, are compatible with complex, high-density on-chip optical circuits and can be placed at arbitrary locations. In addition the TES is photon-number-resolving, implying the detector can distinguish the energy correlated to the absorption of not only a single photon as in a 'click detector', but energy correlated to discern the absorption of several photons.

TESs are highly sensitive detectors that use the electrical and thermal properties of a superconducting thin film to distinguish the energy of a discrete number of photons. They function across a very broad range of wavelengths and have been used to demonstrate the highest recorded detection efficiencies and photon number resolution. By biasing the material at its superconducting transition temperature via voltage biasing, absorbed photons create a temperature change that can be measured via the resulting change in resistance. To resolve this temperature change, the device's heat capacity must be carefully specified, which in turn limits the volume of superconducting material that may be used. The choice of detector geometry is therefore critical to ensure good energy resolution and high-efficiency absorption. Device operation relies on a number of key factors that can be achieved by use of UV written silica-on-silicon waveguides and will be reported in this work.

II. DEVICE FABRICATION

The photon absorber, in this case a tungsten TES, is placed in the evanescent field of the guided mode of a waveguide passing underneath the detector, as shown in Figure 1. As the mode propagates through the detection region, it is coupled continuously into the detector via absorption. The confinement of the waveguide mode allows potential for extended interaction regions, providing a straightforward way to increase

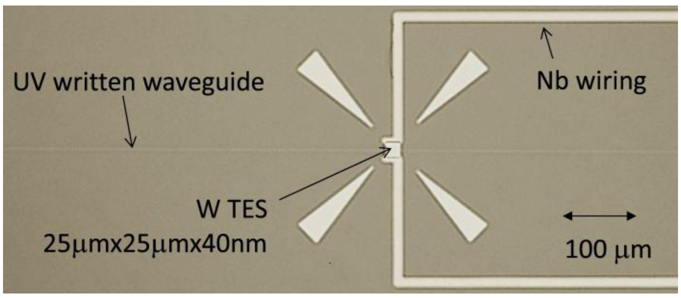

Figure 1. A micrograph of the fabricated TES on top of a UV-written silica waveguide structure.

efficiency without limiting the detector's spectral bandwidth.

The high real and imaginary refractive index of tungsten results in a large polarization dependent absorption while reducing scatter into other modes. The absorption coefficients for the TE and TM modes were measured to be 3 ± 2 cm^{-1} and 55 ± 2.4 cm^{-1} which is in good agreement with our predicted modelled values of 2.3 cm^{-1} and 54.6 cm^{-1}.

The waveguide structure used in this work was fabricated via direct UV writing, where illumination locally increases the refractive index of the silica core layer. The silica core was deposited by flame hydrolysis deposition and contained germanium and boron to induce photosensitivity [2]. The substrate was silicon with a 17 μm thermal oxide layer which acted as the underclad. An over cladding was not fabricated in order to maximize the evanescent coupling to the TES. The planar core/cladding layer refractive index contrast was 0.6% with a core layer thickness of 5.5 μm. The UV written channel was Gaussian in profile with a contrast of 0.3% and a width of ~ 5 μm. A usually minor, but in this case a key feature of the waveguide is the low surface roughness of the planar waveguide structure, which is typically less than 1 nm (R_a). This allows deposition of the TES with only a thin layer of amorphous silicon underneath to relieve the thermal stress at cryogenic temperatures. This deposition process is equivalent to the process used for fibre-coupled TES used in earlier studies [3]. To fabricate the TES detector, a 40 nm thin film of tungsten was DC sputtered onto a thin layer of amorphous silicon. The tungsten layer was patterned and etched such that a 25 μm x 25 μm pad remained directly in contact with the core layer of the silica waveguide. Wiring to the tungsten was established by use of niobium, which was sputtered and lifted off.

III. CHARACTERISATION

Optical measurements were performed in a commercial dilution refrigerator at a temperature of 12 mK to test the device and determine its detection efficiency. Pulses of a laser (f_{rep} = 35 kHz, λ = 1550 nm), attenuated to the single-photon level, were delivered to the device via commercial telecom optical fibers (SMF-28). Both ends of the waveguide chip were pigtailed to provide coupling loss information. The detector was voltage biased within its superconducting transition region, and the electrical output was fed into a dc-superconducting quantum interference device (SQUID) circuit. The SQUID output is then amplified at room temperature, and the signal is measured with data acquisition electronics. Full details of the measurement technique can be found elsewhere [1].

Figure 2 shows the experimental results when detecting a coherent state with mean photon number of 0.986. The main plot shows the pulse-peak histogram when light with TM polarization is coupled into the device and illustrates the photon resolving ability of the detector. The TM data shows pulses with up to 5 photons just resolvable. The insert data shows a similar plot for the TE polarization. When measuring along both possible propagation directions we find a total system detection efficiency of 2.9 ± 0.2 % and 3.5 ± 0.2 %. Using this data the TES detection efficiency and insertion loss can be calculated using the known total device transmission and the total system detection efficiency. We found a TES detection efficiency of 7.2 ± 0.5 % and a fiber-pigtail-waveguide transmission of 39.8 ± 4.6 % and 47.9 ± 5.2 % for both propagation directions, respectively. We observe a reduction in the coupling efficiency from the room temperature state and is thought to be a consequence of the thermal contraction of the adhesive used to connect the launch fibre assembly to the chip. The detection efficiency of these devices can be improved by elongating the detector along the waveguide structure to increase the absorption length. In addition, multiplexing several TESs and modifying the waveguide core thickness will further increase the system's performance.

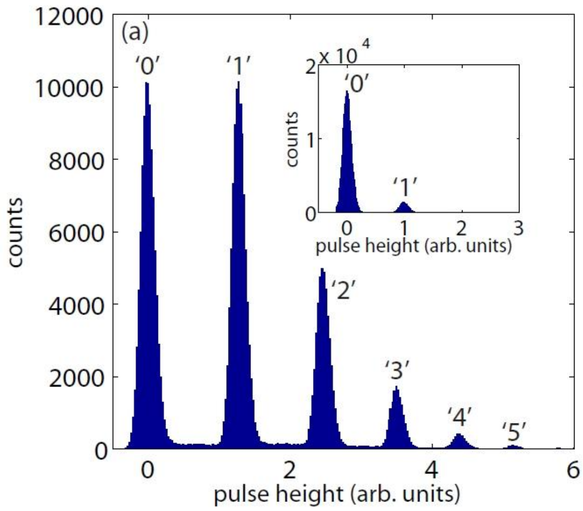

Figure 2. Photon pulse height distribution for a measured coherent state with mean photon number of 0.986. The inset shows the photon pulse height distribution for the anti-optimal TE polarization.

IV. CONCLUSIONS

Here we have presented the concept of an evanescently coupled photon-counting detector and demonstrated the first implementation of an on-chip, truly photon number resolving detector. We shall discuss the fabrication and design of the devices in more depth, direct measurement of the absorption of the tungsten layer and considerations when working at extreme cryogenic temperatures.

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