On-chip, photon-number-resolving, telecom-band detectors for scalable photonic information processing

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Abstract: We demonstrate an integrated photon-number resolving detector, operating in the telecom band at 1550 nm, employing an evanescently coupled design that allows the detector to be placed at arbitrary locations within a planar optical circuit. Up to 5 photons are resolved in the guided optical mode via absorption from the evanescent field into a tungsten transition-edge sensor. The detection efficiency of the absorbing tungsten region is 7.2 %.

OCIS codes: (270.5570) Quantum detectors; (270.5290) Photon statistics; (270.5585) Quantum information and processing

1. Introduction

We demonstrate the operation of a new concept for broadband, efficient, single-photon detection: Evanescently Coupled Photon Counting Detectors (ECPCDs), by merging two well-established technologies: photonic circuits and photon-number-resolving transition edge sensors (TESs). Currently, light from quantum photonics circuits is registered by coupling from the end facet of the device into an off-chip, bulk detector. This is an intrinsically lossy operation, and necessarily restricts the size of the circuits that can be utilized, and thus their complexity. On-chip detectors allow more complex operations, by enabling positioning of the detectors at arbitrary points on the chip. This will allow intermediate measurement stages in cascaded circuits implementing, say, conditional quantum operations. Therefore, development of high-efficiency ECPCDs that are compatible with complex, high-density on-chip optical circuits and that can be placed at arbitrary locations within these circuits is a critical enabling step to fully utilize the processing power of a complex quantum optical circuit.

2. Device Details

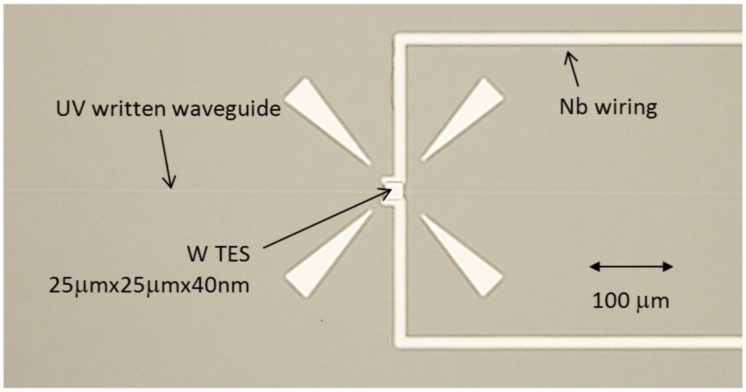

Fig. 1. A micrograph of the fabricated TES on top of a UV-written silica waveguide structure.

Figure 1 shows a micrograph of the fabricated TES placed in the evanescent field of the guided mode of a UV-written silica waveguide passing underneath the detector. As the mode propagates through the detection region, it is coupled continuously into the detector via absorption. The waveguide structure used was written by use of a UV laser writing technique designed to alter the index of a Ge-doped silica core layer, the underclad being a 17 μm layer of thermally grown silicon oxide. No top cladding was fabricated, to maximize the evanescent coupling to the TES. The planar core/cladding layer refractive index contrast is 0.6 % with a core layer thickness of 5.5 μm. The UV written channel had a Gaussian index-profile with a contrast of 0.3 % and a width of about 5 μm. The surface roughness of the intrinsically planarized waveguide structure is typically less than 1 nm. This allows deposition of the TES with only a thin layer of amorphous silicon underneath to relieve the thermal stress at cryogenic temperatures. We used a deposition process that is equivalent to the process used for a fiber-coupled TES used in earlier studies [1] . The TES dimensions were 25 µm x 25 µm x 40 nm with wiring to the tungsten achieved using niobium. The TES is photon-number-resolving, meaning the detector can distinguish the energy correlated to the absorption of not only a single photon ("click detector"), but energy correlated to the absorption of several photons.

3. Experiment and Quantum Efficiency Determination

To test the device and determine its detection efficiency the chip was held at a temperature of about 12 mK inside a commercial dilution refrigerator. The output of a pulsed laser (f_{rep} = 35 kHz, λ = 1550 nm) was attenuated to the single-photon level. The attenuated coherent light pulses are delivered to the device via commercial telecom optical fibers. We connected the telecom fibers by use of two v-groove fiber pigtails to both ends of the waveguide chip. Two power meters were used to measure the overall transmission of the fiber-pigtail-waveguide-TES array. This allowed us to determine the fiber-pigtail-waveguide losses on either side of the TES and the detection efficiency of the TES itself. A fiber optical switch allowed calibration of the input signal before each measurement. Calibration of the input mean photon number was done by use of a calibrated power meter to measure the average input power and to determine the attenuator values, which was done before each measurement. Typically we attenuated the laser pulses by about 60 dB to reach a mean photon number <n> of about 30 at the input fiber after the optical switch. Before the optical switch we used a fiber polarization controller to modify the input polarization into the waveguide chip. The amplified signal from the TES containing the photon traces was recorded with data-acquisition electronics and post-processed to identify the pulse height of each recorded photon event trace to determine the individual photon number.

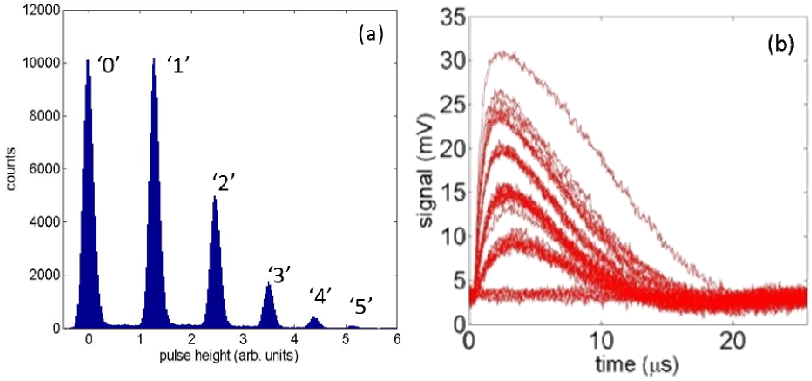

Fig.2. Experimental results. (a) Photon pulse height distribution for a measured coherent state with <n> = 0.986. (b) Electrical TES output traces for different numbers of photons in the weak laser pulse; the photon number resolving capability is clearly visible here.

Figure 2 shows the experimental results when detecting a coherent state with mean photon number of 0.986. When measuring along both possible propagation directions we find a total system detection efficiency (from the input of either end of the fibers at room temperature to the TES) of η_1 = 2.9 ± 0.2 % and η_2 = 3.5 ± 0.2 %, respectively. We can calculate the TES detection efficiency and transmission from either of the fiber ends up to the detector 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 each propagation direction, respectively. 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 along the waveguide will further increase the system's performance. Also, the waveguide core thickness can be reduced to increase the mode overlap of the guided mode with the detector. We are currently pursuing all of these approaches and will present our progress in developing these ECPCD with higher system detection efficiency.

4. Conclusion

We have realized the concept of an evanescently coupled photon-counting detector and demonstrated its operational feasibility by constructing a waveguide-based transition edge sensor, the first implementation of an on-chip, truly photon number-resolving-detector. This wholly integrated solution for detection will be a key component of high efficiency integrated devices functioning in the quantum regime.

5. References

[1] A. E. Lita, A. J. Miller, and S. W. Nam, "Counting near-infrared single-photons with 95% efficiency," Opt. Express **16**, 3032-3040 (2008)