High-efficiency optical detectors that can determine the number of photons in a pulse of monochromatic light have applications in a variety of physics studies, including post-selection-based entanglement protocols for linear optics quantum computing and experiments that simultaneously close the detection and communication loopholes of Bell’s inequalities. Here we report on our demonstration of fiber-coupled, noise-free, photon-number-resolving transition-edge sensors with 88% efficiency at 1550 nm. The efficiency of these sensors could be made even higher at any wavelength in the visible and near-infrared spectrum without resulting in a higher dark-count rate or degraded photon-number resolution.

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FIG. 1. (Color online) Calorimeter operation. Energy is deposited in the absorber and the thermometer reads out the change in temperature. The absorber cools down quickly and slowly cools through the weak thermal link to the thermal heat sink. The tungsten transition-edge sensors described here, the electron subsystem in a thin film of tungsten plays the parts of both the absorber and thermometer. The detector is cooled below its superconducting transition temperature and a voltage bias is applied to increase the electron temperature above that of the substrate. At low temperatures, the electrons in tungsten have anomalously low thermal coupling to the phonons, providing the weak thermal link, and the rapid change in resistance near the superconducting critical temperature results in a very sensitive measure of temperature. The temperature change due to energy deposition by a photon results in a change in resistance, and the current change in the voltage-biased detector is measured with a superconducting quantum-interference device (SQUID) array [17].

1In order to be practical, quantum lithography requires the development of a bright source of entangled photons.

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The sensor was illuminated with a 1550-nm (0.8-eV) gain-switched laser diode pulsed at 50 kHz with a pulse duration of 4 ns. The pulses from the detector were shaped with a 2-μs semi-Gaussian filter and the maximum value for each pulse was determined. (For events in the zero-photon peak, the amplitude of the signal was measured at the expected arrival time of the photon.) The relationship between filtered pulse height and energy was determined by measuring the mean of each histogram peak, and the data were then corrected to linearize the response of the detector. The full width at half maximum of the zero-, one-, two-, three-, and four-photon peaks are 0.13, 0.20, 0.25, 0.34, and 0.45 eV, respectively. The inset shows typical unfiltered pulses for zero-, one-, two-, three-, and four-photon events.

The change in temperature (and thus current) is proportional to the photon energy, so the sensor can resolve the number of photons in a pulse of monochromatic light.

The detection efficiency of a bare thin-film tungsten sensor 20-nm thick is 15 to 20% at visible and near-infrared wavelengths and is limited by reflection from the front surface and transmission through the film. However, every photon that is absorbed by the tungsten leads to a change in temperature of the electrons, so the detection probability can be increased by embedding the tungsten detector in a stack of optical elements that enhance the absorption of the light in the tungsten. The TESs discussed in this paper measure 25 × 25 μm² and are approximately 20-nm thick with superconducting critical temperatures of 110±5 mK. The full width at half maximum of the zero-, one-, two-, three-, and four-photon peaks are 0.13, 0.20, 0.25, 0.34, and 0.45 eV, respectively. The inset shows typical unfiltered pulses for zero-, one-, two-, three-, and four-photon events.

The increase in the FWHM of the peaks with increasing energy is due to the device nonlinearity mentioned above. Measurements and simulations of the optical properties of the various layers indicate that the total expected efficiency of the sensor, neglecting system losses, is 92%.

Photons were coupled to the detector through a 9-μm core single-mode fiber with an antireflective coating for 1550 nm. The fiber was held 50–75 μm above the detector and aligned at room temperature by backside through-chip imaging. Focusing the light from the fiber was not necessary because the spot size was small enough at this distance, that greater than 99% of the light was incident on the detector. The housing holding the fiber was clamped in place and the detector was then cooled to less than 100 mK in an adiabatic demagnetization refrigerator. Because the applied voltage bias keeps the electrons in the superconducting-to-normal transition, the detector is not sensitive to slight fluctuations in the cryostat temperature as long as the temperature is well below the superconducting transition temperature of 110±5 mK.

Coupling and alignment losses reduce the measured efficiency of the detector from the expected 92%. To minimize connection losses, the fiber from the detector and the fiber going to room temperature were fused together in the cold space of the cryostat. The typical loss for a fiber fuse is approximately 0.5%. We measured the room-temperature loss from outside the cryostat to the sample space to be 2.3%. Tests to determine the loss in a loop of fiber that passes through the cold space of the refrigerator indicated that the loss does not change when the fiber is cooled. Thermal cycling of the fiber-coupled detector did not change its efficiency, and we measured greater than 80% efficiency for several different detectors, indicating that our alignment method is robust and that the fiber-to-detector alignment does not degrade when cooled.

Measuring the efficiency of the detectors is nontrivial due to the low power levels involved and the introduction of loss through fiber connectors. The relatively slow pulse decay (several microseconds) and the desire to avoid pulse pileup requires the use of subfemtowatt average optical power levels. At present, commercial power meters do not have the sensitivity required to measure such low levels. To circumvent this problem, we calibrated a series of programmable optical attenuators using a calibrated power meter well within its linear regime, as shown in Fig. 3. The attenuator was calibrated at point A to ensure that the laser power did not drift. All measurements were performed within the linear range of the power meter.
calibration and efficiency measurements were performed using a laser with a center wavelength of 1550 nm and FWHM of 0.05 nm.

The efficiency measurements presented here were performed in continuous-wave operation at several different power levels to ensure that there was no dependence of measured efficiency on power level, as shown in Fig. 4. Power levels were adjusted by means of the calibrated programmable attenuators. The number of pulses with pulse heights within ±3σ (σ = 0.07 eV) of the one-photon peak was recorded at each power level for 100 s. The background rate in the same energy range, which was approximately 400 Hz and was due to blackbody radiation from room-temperature surfaces [19], was measured periodically between data sets and subtracted from the raw count rate. The procedure outlined above provides a measure of the number of single-photon events from the laser. At the higher power levels, counts were present at energies greater than 3σ above the mean energy of the one-photon peak. The spectral weight at these energies results from pulse pileup, the arrival of a second photon before the system has recovered from a previous event. To correct for this effect, we included the high-energy counts as two-photon events. This correction is smallest (1% of the total counts) at the lowest power levels and remains below 2% at even the highest power level.

Figure 4 shows the detection efficiency as a function of power level, with error bars given by the uncertainties due to Poisson statistics. Not shown are the uncertainties resulting from fiber bends at room temperature. We have observed that small bends in the fiber can easily lower the measured efficiency by up to 3%, and the scatter in efficiency measurements is most likely due to slight shifts in the fiber position. All the efficiency values presented are relative to the amount of light in the fiber at point A in Fig. 3.

The measured system efficiency of 88.6±0.4% is consistent with measurements and simulations of the optical elements and the system losses. This detection efficiency exceeds the threshold of 83% required to close the detection loophole in an experiment testing Bell’s inequalities. This enables an experiment that would simultaneously close both the detection and communication loopholes, decisively refuting a local realism interpretation of quantum mechanics.

Increasing the detection efficiency beyond 88.6% at 1550 nm is in principle simple and involves fabricating an optical structure with more layers and finer control over layer thickness. Similarly, it should be possible to produce near-unity-efficiency detectors at any wavelength in the ultraviolet to near-infrared frequency range with this technique. Simulations indicate the possibility of increasing the efficiency well above 99% at any given wavelength in this spectrum, making these detectors an extremely valuable tool for quantum optics and quantum-information processing.

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Note that the background counts were not from detector noise; rather, they resulted from photons from the low-energy tail of the blackbody distribution propagating through the optical fiber.

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