Demonstration of a low-noise near-infrared photon counter with multiphoton discrimination

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We have demonstrated a system capable of directly measuring the photon-number state of a single pulse of light using a superconducting transition-edge sensor microcalorimeter. We verify the photon-number distribution of a weak pulsed-laser source at 1550 nm. Such single-photon metrology at telecommunication wavelengths provides the foundation for ensuring the security of photon sources used in implementations of quantum cryptography. Additionally, this system has the lowest noise equivalent power of any single-photon detector and combines high efficiency near-infrared photon counting with the ability to resolve multiphoton absorption events. © *2003 American Institute of Physics.* [DOI: 10.1063/1.1596723]

The ultimate security of a quantum cryptography (or quantum key distribution) system based on single photon sources can be destroyed by a host of eavesdropping attacks if the source departs from ideal operation by emitting more than one photon in the same quantum-bit state. As a result, researchers have put increased effort into the development of true single-photon sources.[1–3] However, the security of quantum cryptography systems can also be compromised if the detectors used in the receiving system have high error rates.[4,5] As a result, very low-noise single-photon detectors are also needed. Additionally, the realization of long-distance (>100 km) quantum cryptographic networks requires sources and detectors that operate at near-infrared wavelengths ($\lambda > 1.3$ μm) to ensure a minimum of photon loss due to absorption in the optical fibers.[6] Conventional near-infrared detector systems are severely limited by low sensitivity and high dark-count rates[7,8] and cannot, even in principle, provide photon number-state discrimination, a capability essential for directly measuring the multiphoton error rate of a single-photon source. Conventional detectors meet very few of the above requirements. Although a silicon-based photon-number resolving detector has been demonstrated,[9] it suffers from a high dark-count rate and only operates at visible wavelengths. In this letter we describe a system built to specifically enable the efficient measurement of photon-number states at the ideal telecommunication wavelengths ($\lambda = 1310$ and 1550 nm) with negligible dark-count rate.

Our system is based on the superconducting transition-edge sensor (TES) microcalorimeter technology originally developed for high-performance astronomical spectrophotometers.[10] The TES device produces an electrical signal proportional to the heat produced by the absorption of a photon. The increase in temperature of the absorber is measured by an ultrasensitive thermometer consisting of a tungsten film with a very narrow superconducting-to-normal resistive transition ($T_c \sim 125$ mK, $\Delta T_c \approx 1$ mK). Applying a voltage across the metal film causes it to self-bias in the resistive transition allowing its temperature to be determined by measuring the electrical current flow through the metal. In this configuration the integral of the current pulse is proportional to the optical energy deposited in the absorber.[11] The tungsten devices are fabricated on a silicon substrate and are electrically connected with patterned aluminum wires. The tungsten acts as both the photon absorber and the thermometer and has an area of 25 μm$\times$25 μm and a 35 nm thickness. The superconducting aluminum wires ($T_c \approx 1$ K) are thermally insulating at the device operating temperature thereby ensuring that heat generated by the absorption of photons is confined to the thermometer.

The device is optically and electrically configured as shown schematically in Fig. 1. For the light source we use pulsed fiber-coupled lasers coupled to a single-mode fiber and then heavily attenuated. The light is coupled to the TES

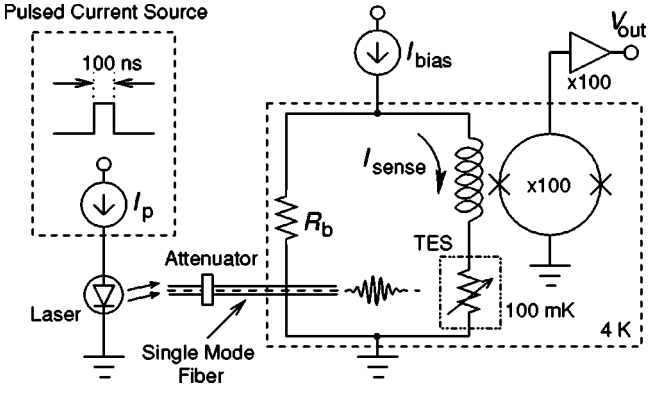

FIG. 1. Schematic of TES device biasing, readout, and optical coupling. The optical source is a pulsed telecommunication laser (1310 or 1550 nm) coupled to a single-mode fiber. The pulses are attenuated with an in-line fiber attenuator and then coupled to the TES. The voltage bias for the device is provided by a room-temperature current source (I_{bias}) and a 100 $\mu\Omega$ shunt resistor (R_b) at 4 K. The device signal I_{sense} is amplified by a 100-element array of dc–SQUID amplifiers and processed with room-temperature pulse-shaping electronics.

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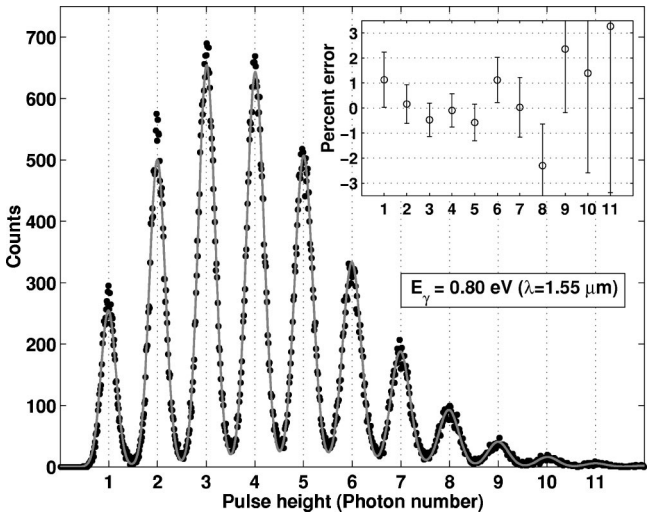

FIG. 2. Comparison of the measured pulse-height distribution of a pulsed-laser source using a TES calorimetric photon counter with the expected photon-number distribution. The source was 100 ns wide pulses of 1550 nm laser light at a repetition rate of 500 Hz containing an average photon number of $\mu \approx 4$. Total acquisition time was 4 min. Shown are the data (●) and best fit (–) Poisson distribution convolved with the measured device response. Inset shows the difference between measured and fit probability distributions. Error bars show the expected $\sqrt{N}$ standard deviation due to counting statistics.

device at 125 mK using a telecommunications fiber-coupling ferrule by centering the end of the fiber over the detector at a distance of ≈ 125 μm. The sub-Kelvin operating temperature for the device is provided by a portable adiabatic demagnetization refrigerator.[12] The detector is voltage biased using a room-temperature current source (I_{bias}) shunted through a small resistor (R_b) at a temperature of 4 K. The device signal (I_{sense}) is amplified by a 100-element series array of dc-superconducting quantum interference device (SQUID) amplifiers[13] at 4 K and finally processed with room-temperature pulse-shaping electronics. The rise and fall times of the sensor are approximately 100 ns and 15 μs, respectively, allowing event count rates up to 20×10^3 counts/s.[14]

The optical efficiency of the device is limited by the absorptivity of the W film, which gives a quantum efficiency of 40%–50% across the entire near-UV to near-IR band ($\lambda = 200$–1800 nm).[10] The combination of moderate energy resolution and high quantum efficiency enables broadband spectroscopy to be performed down to the single-photon level. Conventional single-photon detectors, such as avalanche photodiodes or photomultiplier tubes, have little or no photon-number measurement ability due to the saturating avalanche-amplification process. In contrast, the output of an ideal calorimetric photon counter is proportional to nE_γ, where n is the photon number-state measured ($n=1,2,\ldots$) and E_γ is the single-photon energy ($E_\gamma = hc/\lambda$). Shown in dots (●) in Fig. 2 is the pulse-height distribution from our TES photon counter in response to a periodically gated $\lambda = 1550$ nm ($E_\gamma = 0.80$ eV) telecommunication laser attenuated to give an average of about four absorbed photons per gate interval. This interval is short enough (~ 100 ns) to ensure that the system counts multiple photons within each interval as a single energy-absorption event. The total acquisition time was 4 min with the source running at a repetition rate of ~ 500 Hz. These and similar data demonstrate that the response of the system is linear with photon number to within 5% up to $n=15$. In addition to $\lambda = 1550$ nm we have demonstrated photon counting at wavelengths (energies) of 670 nm (1.85 eV), 830 nm (1.49 eV), 1310 nm (0.95 eV) with the photon-number discrimination ability improving at lower source wavelength (higher energy) because the separation between adjacent photon-number peaks increases with higher energy while the peak width (device energy resolution) is constant with energy.

The pulsed-laser source measured here is typical of the weak coherent sources used in many implementations of quantum cryptography to date.[15,16] In such sources the probability of producing an n-photon state $|n\rangle$ is a Poisson distribution $P(n) = (\mu^n/n!)e^{-\mu}$, where $\mu = \langle n \rangle$ is the mean number of photons per pulse.[17] The solid line in Fig. 2 is the result of a fit of the data to this Poisson distribution convolved with the energy resolution of the device (a Gaussian with standard deviation σ_E). The fit has a total of two free parameters and results in $\mu = 4.02 \pm 0.16$ and $\sigma_E = 0.120 \pm 0.017$ eV. The inset in Fig. 2 shows the difference between the measured distribution (integrated for each photon number) and the fit Poisson distribution. The two distributions agree to within the expected deviations due to photon-counting statistics (error bars show the expected 1-σ standard deviations).

False detector triggers (dark counts) are determined solely by the intrinsic 125 mK thermal fluctuations of the device. Assuming a Gaussian distribution appropriate for this type of thermal noise, the expected dark-count rate is less than 1 event per 1000 s, corresponding to a dark-count probability of lower than 10^{-10} per gate interval.[18] In addition to this negligible dark-count probability, we have demonstrated near-infrared detection efficiencies comparable to present technologies. Our measured absolute quantum efficiency is typically 20 % at 1310 and 1550 nm. The two main sources of loss are the fiber-to-detector alignment and the reflectivity of the tungsten devices. Through better alignment and the use of antireflection coatings on the detector[19] we expect to easily achieve efficiencies over 80%, a significant improvement over typical infrared photon-counter efficiencies of 20% or less.[7,20,21]. The common figure of merit that combines the dark-count rate and detection efficiency is the noise-equivalent power defined as $\text{NEP} = (h\nu/\eta)\sqrt{2R}$, where $h\nu$ is the photon energy, η is the detection efficiency, and R is the rate of dark counts. Our measured values of $\eta = 20\%$ and $R = 1 \times 10^{-2}$ counts/s (limited by stray background light) give a NEP for our system below 1×10^{-19} W/Hz$^{1/2}$, three orders of magnitude better than the best NEPs achieved with traditional telecommunication-wavelength photon counters and over one order of magnitude better than even the best silicon-based single-photon detectors can achieve at visible wavelengths.[20]

It is now clear how this system can be used to quantitatively evaluate the security of emerging single-photon sources for use in secure quantum cryptography systems. A quantum communication channel can be compromised if the optical sources used in the system emit multiple photons instead of single photons.[4,5] Significant progress has been made toward practical realizations of a single-photon source

designed to specifically address this security loophole.[1] The non-Poisson behavior of these devices is typically observed in the second-order coherence of emitted light by use of two detectors in a Hanbury Brown-Twiss (HBT) configuration.[22] Although very successful at allowing the characterization of non-Poisson sources at the two-photon level, the HBT configuration has a maximum theoretical efficiency of 50% and cannot provide information about photon-number states with $n>2$. Because all photon-number states can be directly measured with a single TES device, the full probability distribution for a source can be observed using just one channel of this system with no fundamental limit to the quantum efficiency.

These detectors are exciting not only for their unique ability to perform characterization of low-flux sources, but also for the improvements they promise as receivers in quantum cryptography systems. The implementation of long distance (>100 km) fiber-based quantum cryptographic networks requires sources and detectors that operate at near-infrared wavelengths ($\lambda>1.3$ μm) to signal degradation due to absorption and dispersion. The high efficiency and negligible dark-count rate of our system will enable unconditional secure key transmission over a distance of 100 km.[23] With conventional detectors, the same assumptions allow unconditional security only over distances less than 40 km due to the high probability of recording a false detector trigger instead of a signal photon.

In summary, we have directly verified the photon-number distribution of a Poisson source using a high-efficiency, low-noise photon-number resolving detector operating at near-infrared wavelengths. We expect this system to significantly impact unconditionally secure quantum cryptographic systems by providing quantitative validation of the security of emerging single-photon sources and by extending the useful transmission distance to greater than 100 km using standard optical fiber.

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