Detection efficiency of large-active-area NbN single-photon superconducting detectors in the ultraviolet to near-infrared range

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We report our studies on spectral sensitivity of meander-type, superconducting NbN thin-film single-photon detectors (SPDs), characterized by GHz counting rates of visible and near-infrared photons and negligible dark counts. Our SPDs exhibit experimentally determined quantum efficiencies ranging from ~0.2% at the 1.55 μm wavelength to ~70% at 0.4 μm. Spectral dependences of the detection efficiency (DE) at the 0.4 to 3.0-μm-wavelength range are presented. The exponential character of the DE dependence on wavelength, as well as its dependence versus bias current, is qualitatively explained in terms of superconducting fluctuations in our ultrathin, submicron-width superconducting stripes. The DE values of large-active-area NbN SPDs in the visible range are high enough for modern quantum communications. © 2002 American Institute of Physics [DOI: 10.1063/1.1487924]

Single-photon detectors (SPDs) represent the ultimate quantum limit for any radiation-type detectors. Visible-light photons can be successfully counted using commercial silicon avalanche photodiodes. Counting rates, however, typical for Si photodiodes are roughly two orders of magnitude too low for practical quantum cryptography implementations, especially in the case where the Vernam, single-pass cipher is required. There is also urgent need for the development of infrared (IR) SPDs.

Very recently, we demonstrated a picosecond, superconducting SPD consisting of an ultrathin, 0.2-μm-wide, and approximately 1-μm-long NbN stripe. The detection mechanism of the device was based on photon-induced, supercurrent-assisted hotspot formation of a resistive barrier across a superconducting stripe, kept at a temperature well below the superconducting transition of the material $T_C$, and current biased just below the critical current $I_C$. Our SPD had an intrinsic quantum efficiency (QE) reaching 20% for 0.8 μm photons, speed of response <100 ps, jitter <20 ps (both limited by the bandwidth of the signal amplifier), and negligible dark counts. Unfortunately, due to its very small active area (a single, submicron-wide stripe), the detector had a detection efficiency (DE) that was too low for widespread practical applications.

The aim of this letter is to present the performance of large-active-area, meander-type NbN SPDs, excited by photons within the 0.4-μm- to 3.0-μm-wavelength range, coming from both pulsed and continuous wave (cw) optical sources. We concentrate our effort on the spectral sensitivity of SPDs with the fixed, 0.2-μm-wide stripes. We note that in our case, the DE corresponds to the experimentally measured probability of detection of a single-photon incident on the device, or equivalently, it is the counting rate of light pulses, containing on average one photon per pulse. On the other hand, the intrinsic QE is obtained by normalizing the DE to the physical, active area of the detector, including the optical spot size. We calculated the QE for our best $10\times10 \mu m^2$ SPDs, for several characteristic wavelengths, primarily to provide meaningful comparison with semiconductor single-photon detectors, but our experimental data are presented and discussed in terms of the DE.

Our device fabrication process and the experimental testing setup were similar to that described in Ref. 3. Briefly, our meander-type devices consisted of $w=0.2-\mu m$-wide and $d=10-\mu m$-thick stripes, patterned using electron-beam lithography from NbN films, deposited on sapphire substrates by reactive dc magnetron sputtering in an Ar+N₂ gas mixture. The meander microstructures covered either 4 μm by 4 μm or 10 μm by 10 μm active areas with the line pitch of 0.4 μm or 1.2 μm, respectively. The devices exhibited $T_C\approx10.5 \mathrm{K}$ and the critical current density $j_C>5\times10^6 \mathrm{A/cm^2}$ at 4.2 K, ruling out any granularity of our NbN films.

The NbN SPDs were connected to a cryogenic, low-noise amplifier and isolator (both characterized by 30 dB gain and 1 to 2 GHz bandwidth), and the entire system was mounted on an optical cryostat cold plate and maintained at 4.2 K. Outside the cryostat, the photodetector signal was again amplified and fed to a 200 MHz variable voltage-level threshold pulse counter for real-time event recording and statistical analysis. Optical excitation sources were either 100-
fs-wide, 82-MHz-repetition-rate pulses at 405, 810, or 1550 nm wavelengths from a titanium-sapphire laser, coupled with a parametrical optical amplifier, or 560, 670, 940, 1260, and 1550-nm-wavelength photons generated by cw laser diodes. In addition, the broadband DE dependence on wavelength was measured using a grating spectrometer and a cw blackbody radiation source. In the case of laser sources, optical radiation was delivered to the SPD as a free-propagating beam, using a long focal length (working distance 49.5 mm) microscope objective outside the dewar. The beam spot was typically ~100 μm in diameter, in order to assure uniform illumination of our devices. The beam intensity was attenuated using banks of neutral-density filters, and inside the cryostat we placed the cold-glass filters to cut the parasitic room-temperature background radiation.

Figure 1 shows the counting rate (CR) as a function of the average number per pulse of 405, 810, and 1550 nm photons from a femtosecond laser, incident upon a 10 ×10-μm²-area SPD. The CR corresponds to the number of detector counts per second (equivalently, per 82×10⁵ incident laser pulses), based on the average number of counts detected by the SPD over a 60 s counting period. The device was biased at the constant current level $I/I_c = 0.8$, which, we must stress, was the value far below the one corresponding to the maximal DE (see the later discussion on the influence of $I/I_c$ on the DE). It allowed us, however, to maintain the same bias level for light intensities spanning over 11 orders of magnitude and avoid problems associated with thermal suppression of $I_c$ at the highest light intensities. We note that the CR dependences shown in Fig. 1 are very similar to those presented earlier in Ref. 3 for 810-nm-wavelength pulses with a 10⁵ Hz repetition rate. For 405 nm photons, at very low photon fluxes, we clearly observe a single-photon detection regime with the slope exponent $m = 1$ (see Ref. 3 for details). The same linear dependence extends, however, into higher photon intensities, suggesting that over the entire studied light intensity range, the presence of at least one 405 nm photon in the optical pulse was sufficient to trigger the detector response. At wavelength $\lambda = 810$ nm, we observe the linear, single-photon response at very low photon counts and the quadratic law for higher photon fluxes. The latter suggests that for 810 nm photons, the two-photon ($m = 2$) absorption mechanism was more efficient for high light intensities. Finally, for $\lambda = 1550$ nm, the CR dependence is highly nonlinear, showing also multiphoton ($m \geq 3$) absorption. This behavior is a consequence of both the increase of the probability of a many-photon detection process with the increase of the photon flux and the device limited spectral sensitivity at longer wavelengths. At extremely low photon fluxes, our experimental data points, for every wavelength, level off at the same ~0.1 counts’s value, which must be associated with the accidental absorption of high-energy photons by our detector and regarded as the laboratory photon background radiation level. On the other hand, the saturation observed at the highest incident power level corresponds to all optical pulses are being recorded and represents the transition of our quantum detector into a classical optical intensity detector.

In Fig. 2, we present a DE versus $I/I_c$ for 4×4 μm² devices illuminated with different-wavelength single photons from cw laser sources. The DE follows the activation-type exponential law and shows a change of slope at some biasing threshold current. The position of the slope change point depends on the photon wavelength. Assuming the cylindrical shape of a hotspot, the crossover points, indicated by arrows in Fig. 2, allow us to estimate the hotspot area from the value of the crossover current. Figure 3 shows the hotspot area versus the corresponding photon energy $h\nu$ (the top axis shows the corresponding $\lambda$). As predicted in Ref. 5, this dependence is linear with the extrapolated “zero-size” hotspot for $h\nu \approx 0.5$ eV ($\lambda \approx 2.5$ μm). This latter value can be regarded as the lower bound of the spectral sensitivity for our 0.2-μm-wide NbN single-photon detector.

Finally, in Fig. 4, we present DE spectral dependences for all 4×4 μm² and 10×10 μm² SPDs that we tested. The
Below than average DE values, especially for shorter wavelengths. The two-dimensional regime, with the coherence length, in which case \( D \) may contribute to dark counts. If a photon enters the fluctuation characteristic time, thermal fluctuations cause the total phase change along the superconducting wire of the superconductor order parameter to jump by \( 2\pi \). The inverse fluctuation characteristic time (frequency of attempts) is proportional to the factor \( \exp(-\Delta F/kT) \), where \( \Delta F \) is the free-energy barrier for a particular transition in the Langer and Ambegaokar model. Our devices are in the two-dimensional regime, with \( w \) noticeably larger than the coherence length, in which case \( \Delta F \) can be viewed as the superconducting condensation energy in the relevant volume of the strip. In the absence of the photon flux, fluctuations may contribute to dark counts. If a photon enters the fluctuation area where the free energy barrier is significantly suppressed, the probable formation of a sufficiently large resistive hotspot increases. The larger the energy of the incident radiation quantum, the greater the probability of a normal-state hotspot appearance. As a result, the linear increase of the photon energy leads to the activation-type exponential increase of the superconducting SPD response probability, as indeed we observe in our experimental data.

In conclusion, the experimental DE at 405 nm for a 10 \( \times 10 \) \( \mu \text{m}^2 \) SPD is about 3%, a quite reasonable value for free-space quantum communication applications, taking into account the GHz-range counting rate of those devices. The corresponding QE is calculated as \( \sim 70\% \), the value favorably comparable with modern, fast semiconductor photodetectors. Despite the drop of the QE to \( \sim 10\% \) and \( \sim 0.2\% \) at 0.67 \( \mu \text{m} \) and 1.55 \( \mu \text{m} \) wavelengths, respectively, the NbN superconducting single-photon detector has already been demonstrated to exhibit at least 100 times better performance in very large scale integrated circuit testing, as compared to the top semiconductor competitors. The improvements, leading to larger DEs should be focused on the increase of the radiation-matching factor, meander filling factor, and, finally, on the optimization of the optics that delivers photons to the device (fiber-based delivery is preferred). The devices with narrower (\( w < 0.2 \mu \text{m} \)) and thinner (\( d < 4 \text{ nm} \)) meander stripes are expected to exhibit a significantly larger DE and should be more efficient in counting IR photons.

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4. In semiconductor single-photon counters, the detector active area is usually larger that the incident photon beam cross section, thus, the QE coincides with the DE.