Superconducting Nanowire Single-Photon Detectors

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Abstract: Superconducting nanowire single-photon detectors show exceptional performance for quantum information processing, but several developments promise further progress, including new signal-amplification methods and efficient devices in the mid-infrared.

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Existing Superconducting Nanowire Single-Photon Detector (SNSPD) technology achieves simultaneously high device detection efficiency (as high as 57% at 1550 nm optical wavelength [1]), ultrashort jitter performance (30 ps), and a short reset time (~ 3 ns). Dark counts for well-shielded detectors can be 100 counts per second or less. These devices perform well across a broad spectral bandwidth in the UV, visible and (with gradually decreasing efficiency) infrared, although to achieve optimum performance they must be optimized for a particular wavelength range.

These remarkable performance specifications can meet the diverse requirements for a variety of applications in quantum information science, each of which may require a different set of specifications. In quantum cryptography, the requirements depend on the range of communication desired: for high-rate, short-range communication over low-loss channels, the low jitter, short reset time, and high efficiency are useful. For lower-rate longer-range communication (or over higher-loss channels) reset time is less important than efficiency, but jitter remains important. In this limit where photon arrival rate is low, the low dark counts of the device are particularly important. Finally, for quantum-information processing, the system efficiency of the device is key. Device efficiencies above 65% are quite feasible, and perhaps even higher efficiencies—enabling efficient post-selection of photon states—might be realized.

Figures 1 and 2 show new results that are designed to provide improved performance of detectors. Figure 1 shows narrower nanowires that are expected to provide more robust photodetection performance further into the infrared, and figure 2 shows the electrical schematic required to read out this device with appreciable signal.

Nanowire detectors have also been developed or are in development that have some interesting and unique properties: (1) the ability to count photon number; (2) the ability to amplify the signal internally, to present a more robust signal to the outside world (and thus couple less noise into the device); and (3) the as yet unproven ability to detect single photons with acceptable efficiency in the mid-infrared.

Photon-number-resolving detectors have been devised using two distinct approaches: (1) by using multiple electrically distinct but interwoven nanowires that overlap with the optical mode; and (2) by using an electrically connected parallel array of nanowires that generate a voltage pulse proportional to the number of absorbed photons. We will primarily discuss the first approach, which we have used successfully to measure high-order coherences of a variety of optical sources.

A major challenge to efficient photodetection is the electromagnetic coupling of the light to the nanowire. This problem is greatly facilitated by the fact that these devices have optical impedances that are intrinsically well-matched (within a factor of 10) of the free-space impedance. Coupling by adapting standard microwave-antenna techniques (*e.g.*, a quarter-wave stub, or feed gap) to the nano-optical domain is thus possible. Furthermore, these wires are narrow enough to be seamlessly integrated into on-chip optical waveguides, offering the potential of integrated quantum optics and photodetection. Given this possibility, a compact high-speed superconducting nanowire quantum-optical receiver seems like a future possibility.

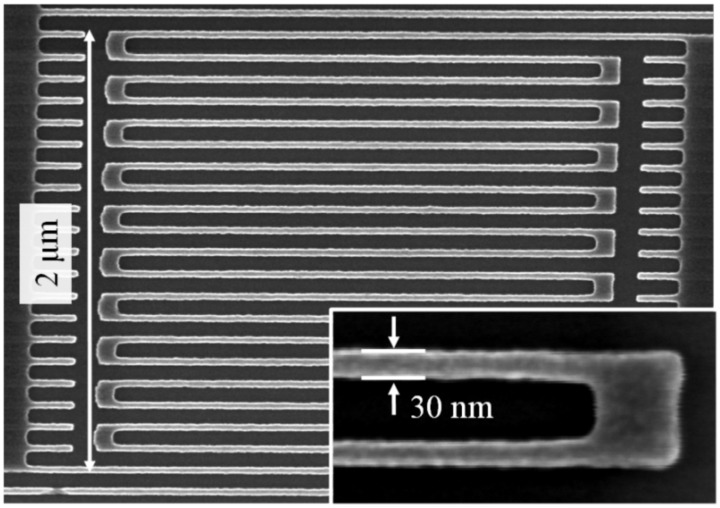

Fig. 1, SEM image showing single 30 nm-wide superconducting nanowire single-photon detector. This image shows the exposed and developed electron-beam resist (hydrogen silsesquioxane) on top of a NbN substrate prior to etching. After etching, the image quality via SEM is generally poor due to charging in the substrate. These devices have successfully been tested, and yield detection efficiencies of a few percent at near-infrared wavelengths. Such ultranarrow devices (relative to the standard device width of 100 nm) are expected to show improved performance for detection of light further into the infrared range ($\lambda > 2\ \mu$m). They are also expected to provide more robust (i.e. higher fabrication yield and higher efficiency) detection for conventional 1.5 µm wavelengths.

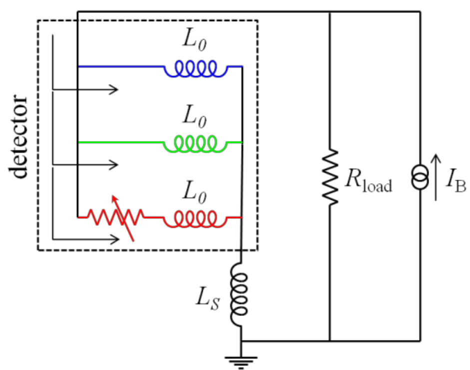

Fig. 2, Schematic showing designed architecture of Superconducting Nanowire Avalanche Photodetector, or “SNAP” device. The device is designed to amplify the signal from a single detector, permitting much narrower nanowires (*e.g.*, down to the 30 nm-width dimensions shown above, and even smaller) to be used.

[1] K. M. Rosfjord, "Nanowire Single-photon detector with an integrated optical cavity and anti-reflection coating", Opt. Express **14**, 527 (2006).