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Ultra-high system detection efficiency superconducting nanowire single-photon detectors for quantum photonics and life sciences

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Abstract: Ultra-high system detection efficiency (SDE) s uperconducting nanowire single-photon detectors are demonstrated for a broad range of wavelengths, from UV to mid-infrared, opening novel possibilities in the fields of quantum photonics, neuroimaging and astronomy.

1. Background

Superconducting single-photon detectors (SNSPDs) are among the best single-photon detection technologies with promising applications in space optics, optical communications, biophotonics, light detection and ranging (Lidar) and quantum key distribution. SNSPDs have been fabricated and used in many material platforms, among these, NbTiN based SNSPDs can operate at higher temperatures (e.g. 7K operation has been demonstrated [1]) and simultaneously achieve high time resolution, ultrahigh efficiency and low dark count rates [1].

High performance SNSPDs are exceedingly desired for characterizing bright single-photon sources. A promising class of such emitters are III-V quantum dots which typically emit at 800-1000 nm wavelength range. Increasing the collection efficiency of quantum dots and the system detection efficiency of detectors are major challenges in current quantum photonic technologies.

Due to the increasing demand on single-photon detectors in communication applications, the highest efficiencies also have been reported for telecom detectors, between the O-band (1310 nm) and the C-band (1550 nm). In recent works, over 98 % SDEs have been demonstrated on different platforms [2–4]. Meanwhile, efforts were made to extend the working wavelenghts of SNSPDs into the mid-infrared range. In 2019, Hui Zhou et al. [5] demonstrated 63% SDE at 2000 nm with 102 ps time resolution using NbN films and Verma et al demonstrated WSi SNSPDs with sensitivity up to 10 μm [6].

2. Our works

2.1. UV and visible range: 350 nm - 800 nm

For the lower part of this wavelength range, our work has been focused on the use of superconducting single-photon detectors in conjunction with scintillators for gamma ray detection. For the visible and near infrared (500-800 nm) range, multimode fiber coupled detectors were developed [7]. The high detection efficiencies, between 405 nm and 650 nm that were achieved ($70-80\%$ for 550-650nm range and $> 60\%$ for 405nm)) and the demonstrated high timing resolution ($<$ 20 ps for a multimode fiber coupled detector) can improve the performance of experiments in quantum optics, bio-imaging and space optics.

2.2. Near infrared: 800 nm - 1000 nm

Our current work is focusing on combining fiber-coupled semiconducting quantum dots, with emission at 800-950 nm wavelength range, and high SDE SNSPDs that are specially tuned (by tuning the design of their distributed bragg reflectors) for corresponding wavelengths. The fiber-detector airgap was controlled by employing non-deformable metal spacers to maximize the absorption in the desired wavelengths. Fig. 1a shows a detector with a maximum system detection efficiency of $> 95\%$ at the wavelength of 940 nm, which is, to the best of our knowledge, the highest reported single-photon detection efficiency for a non-telecom detector.Inset of Fig. 1a, shows a time resolution of 10.5 ps for another high performance device in similar wavelength range. Typical jitter values were in the range of 10-18 ps for the majority of the detectors.

2.3. *Single-photon detection at 1300 nm - 1900 nm for deep tissue imaging:*

Beside demonstrating $> 98\%$ detection efficiency at telecom wavelength [4] we also investigated the potentials of high performance SNSPDs for neuroimaging. Two available, less explored, high transmission windows for deep mouse brain imaging are around 1300 nm and 1700 nm. Within this range, we show $> 90\%$ efficiency at 1500 nm (fig. 1b). Our SNSPDs were used to experimentally demonstrate, in a single-photon microscopy setup, deep imaging of mouse brains [8]. Non-invasive confocal fluorescence imaging can also benefit from high performance detectors at longer wavelength e.g. $> 1880\,nm$. Our detectors were recently used in a non-invasive neuroimaging experiment [9] in the wavelength range of 1600-1900 nm.

2.4. *Single-photon detection at 2 μm and beyond*

One of the most important aspects about this wavelength range is the presence of unique molecular fingerprints of many chemicals and greenhouse gasses such as carbon dioxide and methane among others. High SDE mid-infrared detectors could give birth to new technologies to monitor harmful gases on Earth using Lidar or provide space telescopes with power instruments for applications such as exoplanet spectroscopy. On the other hand, low scattering in the human skull and biological tissue in parts of the mid-IR range, make this area appealing for next generation brain imaging technologies. In our recent work [10], SNSPDs with different nanowire widths (40/60/80 nm) and diameters (8/9/10 μm) were fabricated on NbTiN films and achieved high performance for the wavelength range of $2-4\mu m$. An example is shown in Fig.1c together with its low jitter (inset).

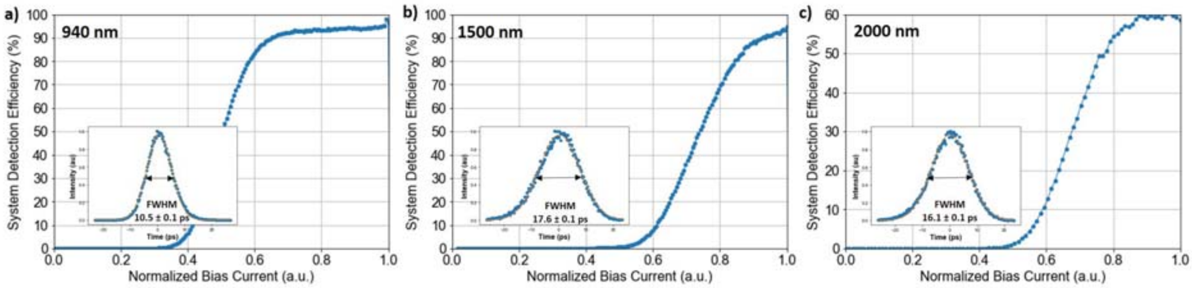

Fig. 1. SDE of SNSPDs at a) 940 nm, b) 1500 nm and c) 2000 nm.

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