

Peer Review File

Manuscript Title: A superconducting-nanowire single-photon camera with 400,000 pixels

Reviewer Comments & Author Rebuttals

Reviewer Reports on the Initial Version:

Referees' comments:

Referee #1 (Remarks to the Author):

The work reported by Oripov et al. on the operation of a 400,000 pixel SNSPD camera represents an impressive technological achievement as no SNSPD camera with a comparable number of pixels has yet been demonstrated.

The readout challenge for large numbers of pixels is what has kept the community from reaching the sizes achieved here.

The main innovation is a new readout process based on readout buses that couple thermally to individual SNSPDs and by reading out from both ends, the pixel can be identified. This technique is convincingly demonstrated and a very large number of pixels operate with very low dark count levels and seem to reach high detection efficiencies for visible wavelengths. A system detection efficiency would be very useful for the readers instead of the detection count rate given in figure 1b.

The fill factor is another cause of concern, while the first paragraph talks about 'cameras with 100% fill factors', the fill factor is given on page 8 at 13.7% leaving ample room for improvement.

SNSPDs have several strong advantages over other single photon detectors with time resolution being crucial. With jitter values measured on the order of 336 ps, a trade off is being made with this design where the time resolution is two orders of magnitude below the state of the art.

this work is a very impressive technological achievement and will certainly inspire the community to further scale up SNSPD arrays, this will in turn enable a large number of applications in many fields, the work is therefore of interest to a wide audience.

Referee #2 (Remarks to the Author):

This paper reports an improvement in the number of pixels of an imaging system with superconducting nanowire single-photon detectors (SNSPDs). The authors have demonstrated a 400,000-pixel SNSPD camera, while the maximum number of pixels demonstrated so far was around 1,000. This paper will be of interest to researchers developing highly sensitive photodetectors, but also to many researchers involved in advanced research and development using photodetectors. However, the authors need to benchmark the performance of a single-photon avalanche diode (SPAD) (<https://doi.org/10.1109/IEDM19574.2021.9720605>). The photon detection efficiency of around 70% has been already achieved for the visible wavelength range in the 3.2-megapixel SPAD camera and the timing resolution of 100 ps is also demonstrated. On the other hand, the 0.4-megapixel SNSPD camera has a quantum efficiency of 100% in the visible wavelength region, but the filling factor is as low as 13.7%, indicating that the photon detection efficiency of SNSPD camera is much lower than that of SPAD. The authors need to describe more clearly what is required for

SNSPD to outperform SPAD.

One of the advantages of using SNSPDs is their high photon detection efficiency at 1550 nm, but 0.4-megapixel SNSPDs have relatively large linewidths of around 1.1 μm , resulting in low quantum efficiency. The authors should describe how to achieve both high quantum efficiency and filling factor at 1550 nm.

This paper is highly valuable for demonstrating the operation of 400,000-pixel SNSPD imager, which is a factor of 400 improvement for the previously demonstrated SNSPD imager. However, since this paper has not been able to convince readers that SNSPD imager has a potential to outperform SPAD, I have to conclude that this paper is not suitable for publication in Nature.

Referee #3 (Remarks to the Author):

This manuscript presents the development and characterization of a 400 kpixel SNSPD array. To my knowledge, this is the largest number of SNSPD-based pixels ever fabricated. This new development offers high quantum efficiency, extremely low dark counts, and high resolution due to the spacing and size of the Nanowires. The presented array will be useful for the development of large-format SNSPD-based cameras, which will speed up the development of quantum technologies such as sub-Rayleigh super-resolution imaging or sub-shot-noise imaging among others.

The manuscript is well written, however, more detailed information could be given in the following points.

1. It is mentioned that, due to the plateau region observed for different wavelengths, the quantum efficiency should be 1 for a wide range of bias current. Have you quantified the quantum efficiency of the detector more accurately? If yes, please give the values.
2. How was the detector dead time measured? Please provide more details.

Author Rebuttals to Initial Comments:

Dear Editor and reviewers,

We thank the reviewers for the constructive comments and the positive review. The individual points have been addressed inline below. One commonality of those comments was the desire for expanded information about the camera's efficiency, and we agree that it should be better described in the main text of the paper. As expected from this initial design which has not yet been optimized for system detection efficiency (low fill factor, excess dummy material, no antireflection coating), the overall optical absorption efficiency will be relatively low. As we worked on scaling the camera size up, our primary concern was verifying that the internal quantum efficiency was high to guarantee that any photon that is absorbed produces a measurable output, so that in future work when we begin to optimize the absorption efficiency we are not limited by the intrinsic detector performance.

In the interest of clarity, we have performed RWCA simulations that show the as-fabricated camera to have peak absorptions at 550nm and 1300nm of ~26%, with half of those photons being absorbed in leftover dummy material between the detectors, yielding a final optical absorption of ~13% in the detectors. This is further compounded by the low-fill factor limiting the 4-way-coincidences between rows and columns. These data can potentially be experimentally verified, but we believe that these low-efficiency data will not be particularly interesting until future implementations—with optical stacks and denser fill factors—approach higher efficiencies that require careful measurement for validation. Regardless, we agree it should be made clearer in the text that this initial implementation has a low overall efficiency and so we have modified the main text to include this information, adding a paragraph dedicated to .

In terms of future designs, the process will follow the same trajectory as our previous work optimizing single-pixel SNSPDs and comprehensively measuring their end-to-end system detection efficiencies. Our simulations indicate that to optimize the material stack for 1550nm photons, we can achieve a >90% optical absorption efficiency using a standard TiO₂/SiO₂ AR stack, gold mirror, and $\lambda/4$ cavity structure, with wide ranges of options for the wire widths and pitches (e.g. 1 μ m wires with $\leq$ 2 μ m pitch, 0.75 μ m wires with $\leq$ 1.75 μ m pitch, 0.5 μ m wires with $\leq$ 1.5 μ m pitch), and these wires can be meandered as in previous work if desired. As an aside, during this review we also realized that our use of the term "fill factor" is unnecessarily confounding in the context of these nanowire arrays – it is not clear whether "100% fill factor" means multiple detector wires with essentially no separation (width=pitch), or whether it means 100% optical absorption. To clarify, we have removed this language and replaced it with more specific language such as "optical absorption efficiency".

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- We thank the reviewer for their comments. Please see the initial discussion above for how we have modified the text to include more information about efficiency and fill-factor.
- We agree the jitter is an area for improvement in this architecture. In any single-ended readout scheme like that presented here, the jitter is necessarily a product of the large imaging area the wires need to cover – each wire is several millimeters long, resulting in a large geometric jitter contribution. There are however strategies that can be employed to overcome this – for instance, breaking the imaging area into smaller sections with shorter wires, or implementing a differential detector readout (e.g. each detector wire is connected to two buses, one on either side). We have added this additional context to the main text.

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- We thank the reviewer for their comments. Above, we have further information about the efficiency in this initial implementation, which as the reviewer correctly points out, is much lower than SPAD state-of-the-art. We have added additional discussion to the main text to make sure this is very clear.

One of the advantages of using SNSPDs is their high photon detection efficiency at 1550 nm, but 0.4-megapixel SNSPDs have relatively large linewidths of around 1.1 μ m, resulting in low quantum efficiency. The authors should describe how to achieve both high quantum efficiency and filling factor at 1550 nm.

- We agree this is a very useful context for readers, as much of the interest in SNSPDs is in their infrared performance. Please see our discussion above, where we have described a 1550nm-optimized material stack and computed simulation results for its total optical absorption efficiencies, in the same manner we have done (and validated) for single-pixel SNSPDs. We note that at visible wavelengths, we believe SPAD implementations will remain the leading technology for the foreseeable future, due to their high performance and room-temperature operation, and we have noted so in the conclusion.

This paper is highly valuable for demonstrating the operation of 400,000-pixel SNSPD imager, which is a factor of 400 improvement for the previously demonstrated SNSPD imager. However, since this paper has not been able to convince readers that SNSPD imager has a potential to outperform SPAD, I have to conclude that this paper is not suitable for publication in Nature.

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1. It is mentioned that, due to the plateau region observed for different wavelengths, the quantum efficiency should be 1 for a wide range of bias current. Have you quantified the quantum efficiency of the detector more accurately? If yes, please give the values.

- We thank the reviewer for their comments. Since the quantum efficiency only describes the probability of generating an output click from photons which are absorbed in the detector, we would need an accurate, calibrated system detection efficiency measurement to make an accurate, quantitative measurement of the quantum efficiency. However, in such an end-to-end system measurement other factors (such as low optical absorption efficiency in this initial implementation) would be much more limiting than quantum efficiency. In our other work on single SNSPDs with the same detector material, we have observed that having such large plateau regions does in fact correspond to near-unity quantum efficiencies (measured end-to-end as a system detection efficiency to at least 98%). We plan to examine this aspect in much greater detail in future implementations which will have optical stacks and significantly higher overall efficiencies.

2. How was the detector dead time measured? Please provide more details.

- We measured the detector dead time in two ways and reported the more conservative (larger) of those values in the original text. The first way was to measure the autocorrelation of the pulses emitted from the readout bus. This autocorrelation indicated that the bus remained insensitive for 4.4 μ s after a detection event. The second way was to measure the 3dB compression point of 1.09×10^5 counts/s as shown in Fig. 4a and take its inverse as the dead time (= 9.16 μ s). We originally reported the longer/worse value in the interest of being conservative, but it makes sense to include both values. Per the reviewer's suggestion, we have added these additional details to the main text.

Sincerely,

Dr. Adam McCaughan

Dr. Bakhrom Oripov