Large-scale nanowire camera with a single-photon sensitivity

Superconducting detectors are a leading technology for the detection of single photons, but have been limited in the number of pixels that they can offer. A 400,000-pixel superconducting nanowire single-photon detector camera provides an improvement by a factor of 400 compared with the current state of the art.

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The problem

Superconducting detectors have exceptionally low amounts of noise, are capable of timing resolution in the order of picoseconds, and have unparalleled detection efficiencies across a wide range of wavelengths from X-ray to far-infrared. These detectors are actively being developed by photonic- and ion-based quantum-computing companies[1], are being applied to analyse blood flow in the brain[2] and were the basis of photon detection[3] for the Nobel-prizewinning loophole-free Bell test that established the validity of quantum theory (see go.nature.com/3aj2g2m).

It is often difficult to read out data from large numbers of these detectors efficiently, however. Because they are so sensitive, they are more prone to problems, such as noise and crosstalk between detector pixels, than silicon detectors are. In particular, conventional methods of combining signals from many detectors using only electrical signals necessarily introduce huge amounts of crosstalk. This is because electrical coupling in superconductors is a two-way street; there are no convenient superconducting diodes or transistors that limit signals to travelling in one desired direction.

The read-out architectures of superconducting detectors must therefore be exquisitely tuned, to be sensitive to the faint signals they are detecting and robust enough to not degrade them. This is especially important for superconducting nanowire single-photon detectors, which produce discrete, broadband output pulses that are particularly difficult to combine in a practical manner.

The solution

To collect signals from our superconducting detectors in a way that would vastly exceed current scalability, we used transduction — converting the electrical energy from the detector output into thermal energy. With this thermal coupling, we built one-way communication channels in which the photon-detection signals from a single detector could be passed to a universal read-out line, while keeping signals of the detector highly isolated from those of its neighbours.

This method enabled us to immediately scale to megapixel-size cameras, without affecting individual detector performance: within six months, we had increased the number of pixels in our cameras from 1,000 to 400,000 (Fig. 1). Even with such large detectors, we could retain low timing jitter and a low dark-count rate (background noise), both of which are expected to increase with more pixels and larger detectors.

Future directions

There are several exciting and immediate applications for this technology. For example, it could be used to develop methods for imaging microvascular blood flow in biological tissues. It was previously shown that superconducting detectors can outperform silicon ones in infrared sensitivity, detection efficiency and background noise when doing fast time-domain diffuse correlation spectroscopy of the human brain[2]. Furthermore, there are interesting applications in quantum imaging. These include super-resolution techniques that enable the imaging of objects smaller than the diffraction limit, and sub-shot-noise techniques that enable low-noise imaging at extremely low light levels. These applications typically require the detection of quantum correlations in both time and space and depend heavily on high efficiencies and low background noise.

Our architecture provides as-yet-unbounded scalability in the maximum number of pixels that it can read out, but there is a trade-off with the maximum count rate of photons. After the detection event, a dead time occurs both in the detector and in the read-out, and any other photon detections during this time are lost. Increasing the pixel array size also increases the dead time. However, these count rates are more than sufficient for quantum or biomedical applications, which are typically light-starved.

This initial technology has not yet been optimized for system detection efficiency. Moreover, it was not designed for commonly used wavelengths of light, including 1,064 and 1,550 nanometres. Such wavelengths are required for several applications that we are targeting, such as fast time-domain diffuse correlation spectroscopy of the human brain and sub-Rayleigh super-resolution imaging.

Our research group has extensive experience optimizing detection efficiencies for single detectors[4], and those optimizations can be applied to our camera in a straightforward manner. We intend to use this knowledge to build arrays that are optimized for high system detection efficiency at 1,550-nanometre and other wavelengths.

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EXPERT OPINION

"This work on the operation of a 400,000-pixel superconducting nanowire single-photon detector camera represents an impressive technological achievement as no such camera with a comparable number of pixels has yet been demonstrated. This achievement will certainly inspire the community to further scale up similar arrays, and this will in turn enable a large number of applications in many fields. The work is therefore of interest to a wide audience." (CC BY 4.0)

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FIGURE

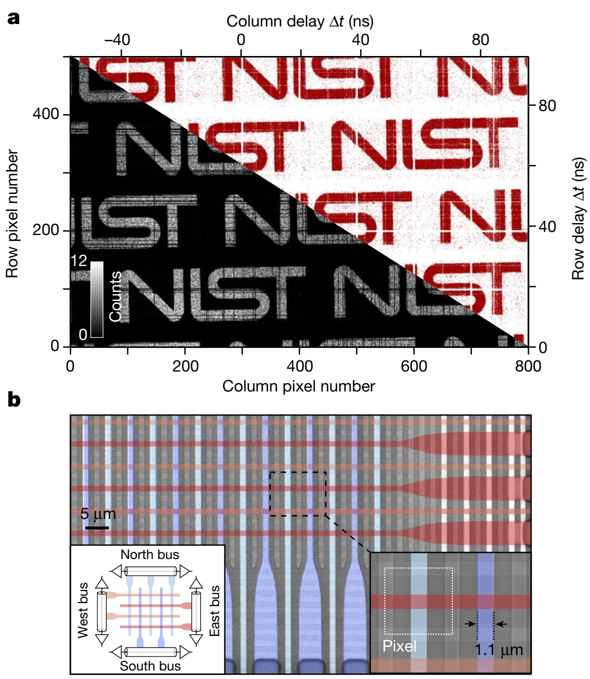

Figure 1 | Overview of the 800-by-500-pixel camera. a, Imaging at 370 nanometres, with raw time-delay data from the communication buses shown as individual dots in red, and binned 2D histogram data shown in black and white. **b**, False-colour scanning electron micrograph of the lower-right corner of the array, highlighting the interleaved row and column detectors. Bottom left inset, schematic of the detector-to-bus connectivity. Bottom right inset, magnification of the 1.1-micrometre detector width and effective pixel sizes of 5 micrometres by 5 micrometres.

BEHIND THE PAPER

The first hurdle in this research was scaling. The usual route in our field is to make dozens of devices, test them and report the best results. But when making a large camera, every single detector must work. Otherwise, a single defective detector will produce dark counts at anomalously high rates, overwhelming the bus and obfuscating true counts.

This meant that we had to meticulously analyse each fabrication step. We received tremendous help for doing this from the research community of the NIST Boulder microfabrication facility. Once we solved all the puzzles, the speed of scaling was astonishing. The paper was initially written for a 10,000-pixel camera, but we kept revising it as new wafers and better results came in. After six months, when we got a working 400,000-pixel device, we decided to stop iterating, and to fully characterize the chip and publish the results.

B.G.O.

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FROM THE EDITOR

The future development of a variety of quantum technologies depends on the efficient generation, manipulation and detection of single photons. The single-photon detector reported in this work redefines the state of the art of these devices, and as such stood out for its potential to have a large number of applications.

Federico Levi, Senior Editor and Team Manager, *Nature*