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Viewpoint: Compact Cryogenics for Superconducting Photon Detectors

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Superconducting detectors capable of registering single light quanta - single photons - are highly sought after in a host of emerging 21st century technologies [1]. Superconducting nanowire single-photon detectors (SNSPDs or SSPDs) [2] operating in the telecommunication wavelength range outperform conventional semiconductor detectors in the following metrics: dark count rate, system detection efficiency (SDE), photon counting rate and timing jitter [3, 4, 5, 6]. SNSPDs have been deployed in many important emerging photon-counting applications including single photon LiDAR [7, 8], quantum key distribution [9, 10], optical quantum computing [11], life sciences [12, 13], fibre sensing [14, 15], exoplanet spectroscopy [16] and free space optical communication [17].

Over the past decade multiple companies worldwide have successfully commercialized high-performance SNSPDs mounted in Gifford McMahon(GM) or Pulse Tube(PT) closed-cycle regenerative cryocoolers for laboratory settings [18]. The advent of reliable and affordable PT and GM platforms has eliminated reliance on liquid cryogens (liquid helium and nitrogen), which previously deterred many potential users from adopting superconducting detector technologies. Worldwide sales of cryogenic SNSPD systems exceed hundreds per year [19], however the development of SNSPDs in applications outside laboratory settings is limited by the Size, Weight and Power (SWaP) of available cryocooler platforms.

A typical cryogenic system for SNSPDs consists of a commercial regenerative cryocooler driven by an air-cooled helium gas compressor. Temperatures below 3 K can be reached with this setup, with a power consumption >1 kW. Below 4 K the efficiency of these cryocoolers diminishes due to real gas effects [20, 21]. Also, the regenerative alternating flow cycle produces temperature oscillations, affecting the performance metrics mentioned above. Steady base temperatures below 1 K can be achieved by the addition of a ^{4}He closed-cycle sorption cooler into the cryogenic setup [22]. Current ^{4}He sorption coolers are engineered to achieve hold times of 24 hours or greater before cycling is necessary. This combination of the significant SWaP of the cryogenic system, limited hold time and poor efficiency have prevented the use of SNSPDs in more portable applications.

If the SWaP of the cryogenic systems could be reduced further, this would dramatically expand the range of applications for SNSPDs outside of research laboratories. A particularly exciting prospect is deploying SNSPDs in space, either as instrumentation satellites for communications and earth monitoring, or next-generation space telescopes. Weight is a major constraint for spaceborne applications. Even using the most efficient current launch platforms, the cost of delivery of a payload to Low Earth Orbit (LEO) is estimated in US dollars at \$2,750/kg [23, 24]. Due to the limitations in current cooling options, there is a demand for a low SWaP, efficient cryogenic system with a steady base temperature. The realisation of such a compact, reliable and efficient cryogenic system will allow the integration of SNSPDs into future satellites or space telescopes.

In the past 5 years several international groups (UK, USA and China) have attempted to meet these requirements through proof-of-principle demonstrations [25, 26, 27, 28], an example of which is displayed in Figure 1. Each has a similar cryogenic architecture of a closed cycle regenerative cryocooler which pre-cools a Joule-Thomson Cryocooler (JTC) that provides the base temperature for the SNSPDs. A ^{4}He JTC is an attractive option as it can provide a steady base temperature below 4 K. To produce cooling the JTC stages must be pre-cooled to below 45 K, and at least 20 K for a base temperature of 4 K and 10 K for 2.5 K. JTCs suffer from low efficiencies, however this is acceptable as the required cooling power per SNSPD detector channel is around 0.1 mW at 4 K. The main bottleneck for this approach is the JTC compressor. The base temperature of a JTC cryocooler is determined by the suction pressure of the compressor. For a ^{4}He JTC a suction pressure of one atmosphere (1 atm = 101,325 Pa in SI units) provides a base temperature of 4.2 K, while 1/10 atm gives 2.5 K. These suction pressures place the compressor in the vacuum category. Widely used scroll vacuum compressors can easily provide the required pressures, but they are not commercially available in low SWaP form.

Figure 1. The viewpoint authors with a compact cryogenic system for SNSPDs, as reported by Gemmell *et al.* SUST 2017 [25].

The new Superconductor Science and Technology paper by Hu *et al.* [29] reports a compact cryocooler designed for space that operates at 2.4 K with an integrated high performance SNSPD. At this temperature the authors achieved an SDE of 93% at 1550 nm wavelength. The SNSPD device is a twin layer superconducting nanowire design, embedded in a tailored optical cavity, based on a design first reported in Ref [30]. Its performance approaches the best reported SDE measurement of 99% at 1550 nm performed in a standard cryogenic platform [31]. This work [29] presents optimisation made to a cryogenic system consisting of a two-stage PT cryocooler that pre-cools a ^{4}He JTC previously reported on [32]. A new four-stage compression cycle for the JTC improved the base temperature from 2.8 K to 2.4 K by reducing the suction pressure by 10 kPa. The new cryogenic system is 10 kg lighter, reducing its launch cost to LEO by more than $25,000. Both iterations of this cryogenic system run on approximately 320 W of input power, an order of magnitude less than commercially available alternatives. Additionally, the flow rate was reduced to improve heat exchange in the JTC, allowing it to reach the extremely low base temperature.

The work of Hu *et al.* [29] details important steps towards realising the next generation of space-ready 4 K coolers. State-of-the-art SNSPD detector performance is demonstrated at 1550 nm wavelength in a low SWaP cryogenic platform. Further advances in reducing the SWaP of cryogenic systems for superconducting detectors depends on innovative engineering and sustained investment in solutions to this important problem. There has been significant progress in micro-cooling research in recent years [33], opening pathways to mass production of high performance, low SWaP cryogenic platforms for wider commercial applications.

Data availability statement

No new data were created or analysed in this study.

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