A 1-2 K Cryogenic System With Light Weight, Long Life, Low Vibration, Low EMI and Flexible Cooling Capacity for the Superconducting Nanowire Single-Photon Detector

Haizheng Dang, Han Tan, Tao Zhang, Rui Zha, Jun Tan, Yongjiang Zhao, Bangjian Zhao, Renjun Xue, and Jiaqi Li

***Abstract*—This paper presents a 1-2 K cryogenic system for cooling the superconducting nanowire single-photon detector (SNSPD). The system is based on the Stirling-type pulse tube cryocooler (SPTC) and the Joule-Thompson (JT) cryocooler technologies and thus named as the hybrid cryogenic system. It eliminates any moving component at the cold end which endows it with evident advantages over the Gifford-McMahon (GM) cryocooler in terms of low vibration, low electromagnetic interference (EMI) and long life. It can operate at 1-2 K and has an expected mean-time-to-failure of 10 years. The overall weight is below 30 kg, which makes it an attractive cryocooler candidate for the space applications. Furthermore, the operating temperature can be adjusted conveniently for the SNSPD other than being at a fixed temperature as the superfluid helium does. The design approaches and system integration are described in detail, and the performance characteristics presented and discussed. The cooling system has an experimental cooling temperature of 1.52 K. It is also expected to reach 1 K and below provided that the further performance improvement is conducted.**

***Index Terms*—Superconducting nanowire single-photon detector, Hybrid cryogenic system, 1-2 K, Stirling-type pulse tube cryocooler, low vibration.**

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I. Introduction

RECENTLY, the superconducting nanowire single-photon detector (SNSPD) advances rapidly and is expected to be used in many fields such as quantum key distribution, optical quantum computing and laser communications [1], [2] due to its high detection efficiency, low dark count rate, high counting rate, and low time jitter. For space applications, the SNSPD needs a demanding reliable cryogenic system which features light weight, long lifetime, low vibration and low EMI. The operating temperature of SNSPD is usually around 2 K and a lower temperature often results in a better performance [3]. Meanwhile, there are always irreversible losses while SNSPD coupled with cryocooler, and thus a cryocooler capable of lower temperatures would make sure SNSPD works at desirable temperatures. The superfluid helium cryostat was ever used, but the drawback that the cryogen needs regular filling prevents it from the long-time operation. The emphasized light weight, long lifetime and oil-free makes GM cryocooler impossible to be used in space environment.

In the authors' laboratory, a 1-2 K hybrid cryogenic system based on the Stirling-type pulse tube cryocooler (SPTC) and Joule-Thompson (JT) cryocooler has been developed. The SPTC, driven by a linear compressor is a well-proven cryocooler which eliminates any wear-outs at both warm and cold ends and thus achieves high reliability and long operating time [4]. The JT cryocooler, driven by DC-flow linear compressors, is another type of long-life cryocooler which also has no moving part at both warm and cold ends [5].

The hybrid cryocooler has many advantages over the GM cryocooler. First, the expected mean-time-to-failure (MTTF) of the hybrid cryocooler is 10 years, which is about five times that of GM cryocooler. Second, the vibration level and the electromagnetic interference noise of the hybrid cryocooler are much lower than those of GM cryocooler. Third, the overall weight of the hybrid cryocooler is below 30 kg, which is much more compact and lightweight than GM cryocooler.

This paper conducts the design and performance characteristics of the hybrid cooling system. The configuration details will be described and the cooling performance discussed as well. The test results of the vibration level of the system will be presented.

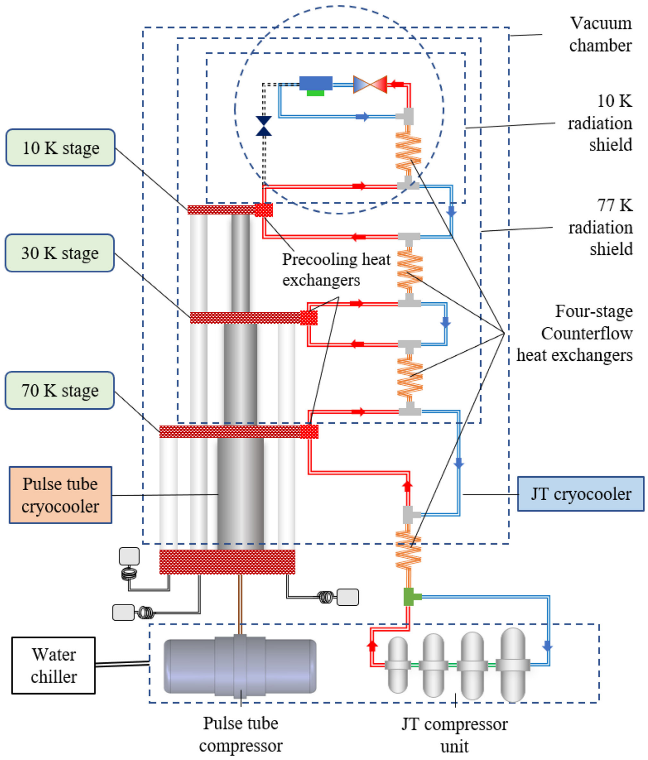

Fig. 1. Schematic of the overall system.

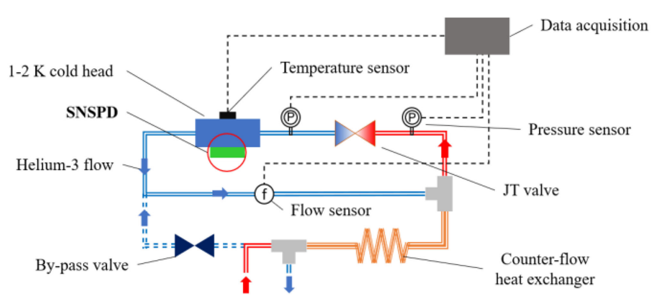

Fig. 2. Details of the coupling structure of the cold head and SNSPD.

II. Design of the Overall System

A. Description of the Cryogenic System

The schematic of the overall system is shown in Fig. 1. The system contains four parts: the three-stage SPTC system, the JT cryocooler, the four-stage JT compressor unit and the SNSPD. The three-stage SPTC system provides precooling for the JT cryocooler and also cools the two radiation shields at 77K and 10 K. The main effect of the radiation shields is to reduce the cooling consumption caused by thermal radiation and the EMI noise from the compressors. The JT cryocooler is driven by the JT compressor unit consisting of four compressors, and the JT cold head directly cools SNSPD. The coupling structure details are shown in Fig. 2. The SNSPD mount is directly mounted on the copper block of the cold head.

The hybrid cryocooler is a three-stage SPTC plus a JT cryocooler. Fig. 3 indicates the detailed design of the three-stage SPTC. Due to the gravity has little effect on the cooling performance of the developed SPTC [6], it is expected that the

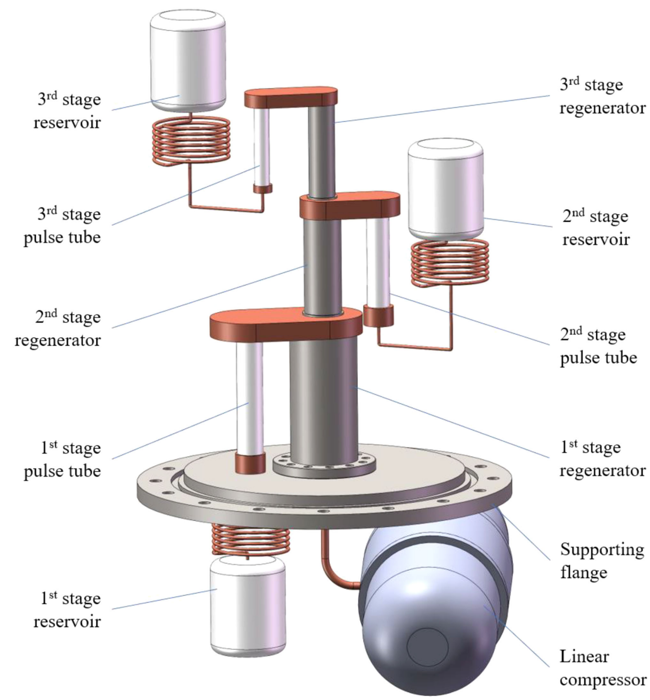

Fig. 3. Design of the three-stage SPTC.

reduction of gravity will not lead to a loss of cooling power in the future space applications. The three-stage SPTC is driven by an Oxford-type linear compressor with a maximum input power of 500 W. The three-stage SPTC has a gas-coupled arrangement. Compared with the thermally-coupled arrangement, the gas-coupled one eliminates all the external thermal links between stages and thus avoids the potential irreversible losses, which might result in a more compact configuration and a higher cooling efficiency as well. In addition, considering the strict requirements while used in practical applications, the gas-coupled arrangement has more advantages over the thermally-coupled one in weight, size, reliability and lifetime. In our previous work, the multi-stage gas-coupled SPTCs have achieved 3.3 K for space applications [7]–[9]. In this work, we designed a new three-stage SPTC. The main difference is that the new one can provides three cooling temperatures of 70 K, 30 K and 10 K, and also has much larger cooling powers because it needs to cool the JT loop as well as the radiation shields simultaneously.

As shown in Fig. 1, the JT cryocooler has a four-stage arrangement, which means it contains four counterflow heat exchangers (HEXs). Between the counterflow HEXs, there are three precooling HEXs which are connected to the SPTC. In the cold end, there are a throttle valve and a cold head. The cold head is an evaporator which provides cooling powers by evaporating the liquid helium. The throttle valve is a perfect round orifice and the designed upstream and downstream pressures at both ends of the orifice are 800 kPa and 6.6 kPa, respectively. To achieve such a large pressure ratio, high-efficiency DC-flow linear compressors are employed, which are similar to the AC-flow linear compressor used for driving the SPTC. The coolant in the JT loop is Helium-3, which has better cooling performance than Helium-4 below its critical temperature. At

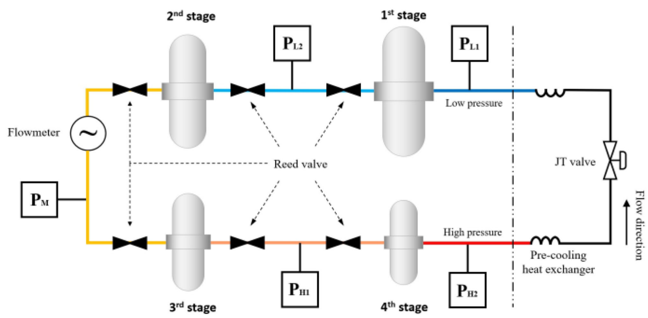

Fig. 4. Schematic of four-stage JT compressor unit.

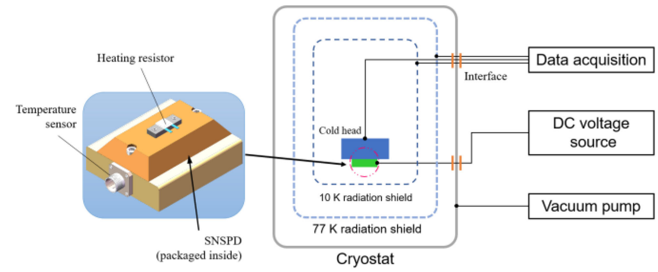

Fig. 5. Schematic of the coupling design.

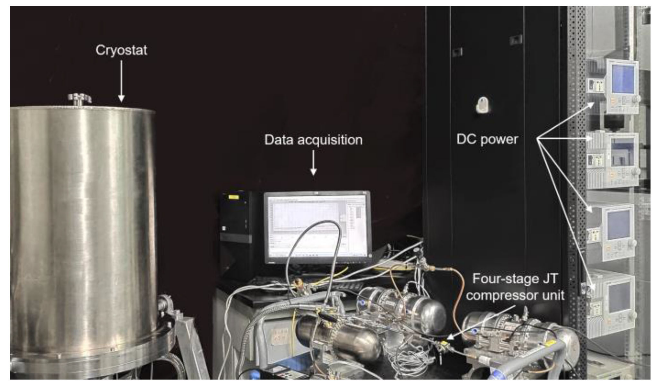

Fig. 6. Experimental setup.

first, the high-temperature and high-pressure gas pass through the four-stage counterflow HEXs, the three precooling HEXs and the bypass pipe. In this process, the gas is cooled down to 10 K step by step. After that, the bypass valve is closed and the JT cycle starts. When the gas goes through the orifice, the throttling effect happens. In this process, the gas pressure drops sharply and the temperature further reduces. The Helium-3 gas is liquified and flows into the cold head. After evaporation, the gas is still cold and can cool the upstream flow through the counterflow HEXs.

The JT loop has no moving component and thus achieves low vibration and long life. In addition, the main components of the JT loop are pipes and then can be coiled around the three-stage SPTC to make the whole system more compact. The maximum outer dimension of the developed hybrid cryocooler is 400 × 460 × 680 mm and the total weight only about 28.8 kg. By comparison, for a typical GM cryocooler currently used to cool the SNSPD detectors, the size of the compressor alone is about 591 × 450 × 588 mm and the overall mass of the GM cryocooler up to about 90 kg. Therefore, the developed hybrid cryocooler has the obvious advantages of being much more compact and lightweight.

B. Four-Stage JT Compressor Unit

As shown in Fig. 4, there are four DC-flow linear compressors for driving the JT loop. The low-pressure compressor actually acts as a vacuum pump to maintain the required saturation pressure in the evaporator and the high-pressure compressor produces a high-pressure gas flow through the compression process.

The DC-flow linear compressor is a new type of compressor developed based on the Oxford AC-flow linear compressor. By adding a reed valve at the outlet of the linear AC compressor, a stable high and low pressure is formed to achieve the purpose of DC output. The pressure ratio of a single DC-flow linear compressor can usually reach a level of about 3∼4, but the pressure ratio required by the JT cryocooler is much greater. Therefore, in practical applications, the JT compressor unit of the JT cryocooler is usually composed of four DC-flow linear compressors in series, and the gas is compressed step by step to achieve the actual required pressure ratio.

The linear compressor has a pair of moving pistons which have reciprocating motions. The pistons are the leading cause of vibration. In order to reduce the vibration level, the compressors are cleverly designed to have a dual-opposed structure. The JT compressors also have low noise and high reliability. Furthermore, by adjusting the input power of the JT compressor unit, high and low pressure of the JT loop can be adjusted to achieve flexible cooling capacity.

C. System Integration

The coupling structure with the SNSPD is shown in Fig. 5, which consists of the cold head of the hybrid cryocooler and the temperature measurement subsystem. Note that we here only focus on the thermal characteristics of the coupling. The SNSPD will be packaged into an oxygen-free copper block, which is directly mounted on the cold head of hybrid cryocooler with Au-plated surface to enhance the thermal conductivity. To reduce radiant heat loss and EMI noise, two radiation shields with temperatures of 10 K and 77 K were used to surround the coupling components and to be placed together in the cryostat. The heat load, which is used to measure the cooling power of the hybrid cryocooler, is provided by a heating resistor controlled by an external DC power supply, while the cooling temperature of the cold head and radiation shields is measured by the temperature sensors attached to their surface and monitored with a data acquisition.

III. Performances of the System

A. Cooling Performance

The experimental setup of the hybrid cryocooler is shown in Fig. 6. The results are shown in Fig. 7. The temperature of the two radiation shields, the cold head of JT loop is measured by using

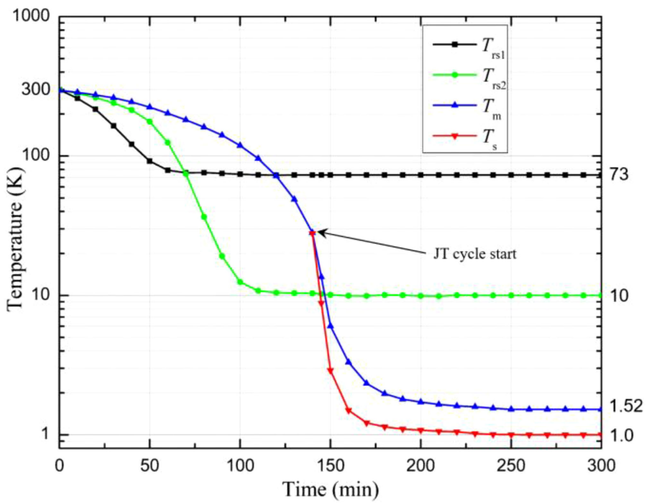

Fig. 7. Cooling performance of the hybrid cryocooler. $T_{\rm rs1}$ is the temperature of the first radiation shield. $T_{\rm rs2}$ is the temperature of the second radiation shield. $T_{\rm m}$ is the temperature of the JT cold head. $T_{\rm s}$ is the temperature of simulations.

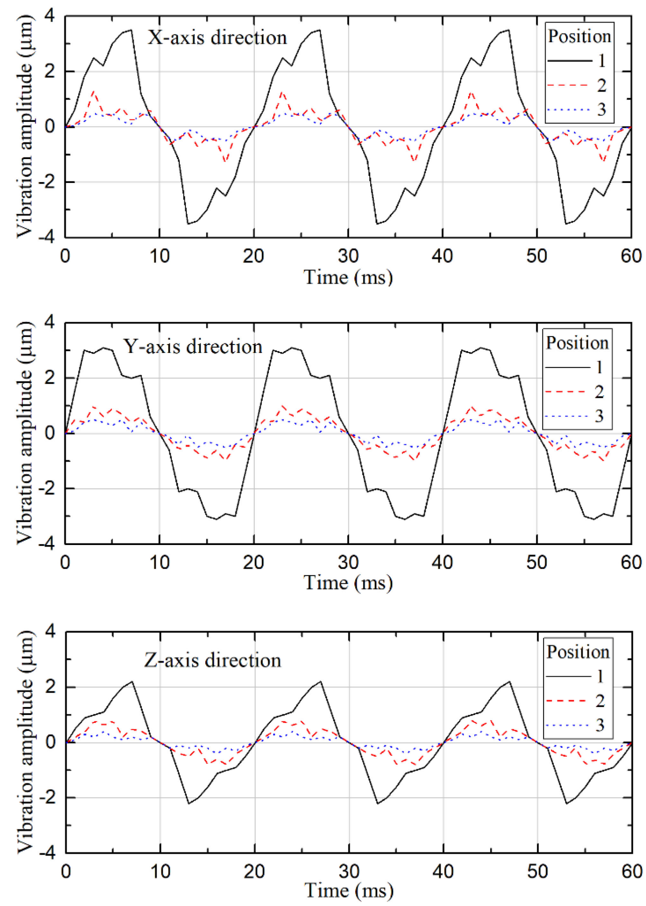

Fig. 8. Vibration level of the cooling system. The three figures present the vibration amplitudes of the X-, Y- and Z-axis directions, respectively. Position 1 is on the baseplate of the compressors, position 2 is on the cold head of the JT loop, and position 3 is on the SNSPD.

ceramic Rh-Fe resistance thermometers. When the temperature of the cold head drops to 30 K, close the bypass valve and start the JT cycle. It takes about 3.5 hours for the whole system to be steady. The temperatures of the two radiation shields are 73.2 K and 10.5 K, respectively, which are very close to the designed results. Moreover, the temperature of the cold head is 1.52 K. A CFD model has been developed to simulate the internal flow mechanism in SPTC and the heat and mass transfer process in JT as well. Based on the established CFD model, the developed hybrid cryogenic system can further reach a minimum no-load temperature of 1.0 K by improving compressor performance and reducing the low pressure of JT loop. The above results indicate that the hybrid cryocooler has the ability to cool the SNSPD to below the critical temperature.

B. Vibration Level and EMI Noise

Generally speaking, to any cryocooler for practical applications, the vibration level is an essential parameter because a large vibration output will have a significant effect on the signal noise ratio (SNR) of the cooled devices [11], [12]. The vibration level of three positions in the developed cooling system is tested. The first position is on the baseplate of the compressors, the second position is on the cold head of the JT loop, and the third position is on the SNSPD. The results are shown in Fig. 8. In the X-axis direction, the vibration amplitude of position 1 is much larger than those of position 2 and position 3. The maximum value of vibration amplitude of position 1 is about 1.7 μm, while the ones of position 2 and position 3 are 0.6 μm and 0.3 μm, respectively. In the Y-axis direction, the vibration amplitude of position 1 is slightly smaller than that in the X-axis direction. The maximum values of vibration amplitude of the three positions are 1.5 μm, 0.5 μm and 0.3 μm, respectively. In the Z-axis direction, the vibration amplitudes of the three positions are 1.1 μm, 0.4 μm and 0.2 μm, respectively, which are smaller than those of both the X- and Y-axis directions. The above results indicate that the vibration level is effectively reduced at the SNSPD while compared with the one near the compressors. The vibration amplitudes of the three directions are all significantly smaller than the typical values of the commercial GM cryocoolers [12]-[14], and hence it is acceptable for the SNSPD.

IV. Conclusion

This paper presents a 1-2 K cryogenic system developed for cooling the SNSPD. The structure design and system integration of the hybrid cryocooler are introduced in detail. The performance of the hybrid cryocooler is also presented and discussed.

The hybrid cryocooler consists of a three-stage SPTC and a JT cryocooler. The three-stage SPTC provides three cooling powers for the JT cryocooler at temperatures of 70 K, 30 K and 10 K, respectively, and also cool the two radiation shields. The JT cryocooler reaches the lowest temperature of 1.52 K. It is also expected to reach a no-load temperature of 1 K according to the simulations.

During the test, the feasibility of the cryogenic system for cooling the SNSPD is verified. The system is compact and simple, and the vibration level as well as the EMI noise level can also meet the requirements. The overall weight of the cryogenic system is about 28.8 kg.

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