Investigation of a 1.6 K Space Cryocooler for Cooling the Superconducting Nanowire Single Photon Detectors

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

Abstract—**The superconducting nanowire single photon detectors (SNSPD) are now widely used in space quantum communication, satellite laser ranging, and quantum key distribution, etc. However, a very low temperature around 2 K is required for its operation and performance improvement. We are developing a 1.6 K hybrid cryocooler to meet this demand, which is composed of a three-stage Stirling-type pulse tube cryocooler (SPTC) and a Joule-Thomson cryocooler (JTC). The hybrid cryocooler has no moving component at the cold end and is driven by the long life linear compressor, thus realizing high reliability, low vibration and long operation life time. The cryogenic system, including the coupling structure with the SNSPD, is descripted in detail. The thermodynamic enthalpy analysis of the last-stage of the hybrid cryocooler is carried out, by which the upstream pressure and precooling temperature are optimized to meet the required base temperature and cooling capacity with less input power. The model is described and the experiments coupling with a SNSPD simulated load are carried out. The results show that the hybrid cryocooler can achieve 16.3 mW at 1.6 K, 20 mW at 1.8 K and 25 mW at 2.1 K, respectively, and thus suggests a promising space cryocooler for cooling the SNSPDs.**

Index Terms—**1.6 K, Superconducting nanowire single photon detector, Space cryocooler, Stirling-type pulse tube cryocooler, J-T cryocooler, System Integration.**

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I. Introduction

IN RECENT years, the superconducting nanowire single photon detectors (SNSPD) have been attracting a great deal of attention due to the superior characteristics of high system detection efficiency (SDE), low dark count rate (DCR), fast repetition rate and low timing jitter [1]–[3]. Now the SNSPD is playing an important role in a wide range of fields, such as space quantum communication, satellite laser ranging, and quantum key distribution, etc. [4], [5]. For practical applications, the very low temperatures of around 2 K and below are required to achieve its high performance and further improvement [6]. For example, at 2.1 K, the SDE of a NbN-SNSPD is 90.2% at a wavelength of 1550 nm (at dark count rate of 10 Hz). When the temperature is less than 1.8 K, the saturated SDE reached 92.1% [7].

The demanding temperature requirement makes it a serious challenge for the suitable cryogenic system. In particular, when used in space, the cryogenic system is emphasized with high reliability, long operation life time, limited room occupation and power consumption, which make the challenge more formidable.

So far, most studies on the performance of SNSPD are based on the cooling of the commercial two-stage Gifford-McMahon (GM) cryocooler. However, the lowest temperature of the two-stage GM cryocooler is around 2.1 K, which restricts the further improvement of the SNSPD performance. In fact, some attempts have been made by using a GM-type cryocooler plus a Joule-Thomson (JT) stage to reach around 1 K [8]. Nevertheless, the intrinsic characteristics of the GM or GM-type cryocooler, such as massive compressor, high power consuming and moving displacement leading to several drawbacks: heavy weight, mechanical wear, loud noise and vibrations, which make it unrealistic to be used in space.

In contrast to the GM cryocooler, the pulse tube cryocooler (PTC) eliminates any moving component at the cold end, from which it gains the obvious advantages in high reliability, long life and low vibration at the cold end. The Stirling-type PTC (SPTC) [9] driven by the linear compressor further achieves the long continuous operation time at the warm end, and thus results in an attractive cryocooler candidate for space applications. Besides, for the multi-stage SPTC used to obtain temperatures below 10 K, the cold fingers of each stage can be closely arranged, which makes the cooling system very compact [10], [11]. However, as a regenerative cryocooler, the SPTC generally has limited efficiency in obtaining temperatures below liquid helium (4.2 K), even the multi-stage arrangement used.

By contrast, the Joule-Thomson cryocooler (JTC), due to a type of recuperative cryocooler and using the throttling effect, is much easier to achieve the required cooling at liquid-helium temperature and even 1K-class provided that it is precooled by the regenerative cryocoolers such as GM, Stirling or PTC [12]–[14]. Several compact hybrid cryocoolers had already been developed for cooling the SNSPD. For example, V. Kotsubo *et al.* [15] developed a compact 2.2 K SPTC/JTC cooling system for SNSPD, and N. R. Gemmell *et al.* [16] also reported a miniaturized Stirling/JTC platform for cooling SNSPD with a base temperature of 4.2 K. In addition, similar to SPTC, the JTC also has no moving part at the cold end and is driven by the linear compressors at the warm end. Therefore, a proposal is put forward in which a three-stage SPTC precooling a JTC forms a hybrid one to achieve 1.6 K and provide effective cooling capacity for the SNSPD. Our preliminary work aiming to achieve around 2 K with a similar hybrid cryocooler reported in Ref. [17] now has been upgraded and improved.

In this paper, the structural design of the upgraded cryogenic system and its integrated layout with the SNSPD are presented. He-3 is used as the working fluid and the four-stage linear compressors are applied to drive the JTC with more than a pressure ratio of 100. The thermodynamic enthalpy analysis is carried out to optimize the upstream pressure and precooling temperature to achieve 1.6 K with less input power and higher efficiency, as well as to provide control strategy for the SNSPD temperature control system. Furthermore, the experimental tests coupling with a SNSPD simulated heat load are carried out and the cooling performance is evaluated and discussed.

II. System Configuration with Hybrid Cryocooler

A. Structural Design of the Hybrid Cryocooler

The hybrid cryocooler is composed of a three-stage SPTC and a JTC, as shown in Fig. 1. The former is thermally coupled with the latter and provides three-stage precooling. In the three-stage SPTC, each stage cold finger consists of a pulse tube (PT), a regenerator, an inertance tube, a reservoir and a cold head. For space applications, the inertance tube and reservoir are employed together as the phase-shifter to achieve the stable and reliable performance. All the three stages of the SPTC adopt U-type arrangement. The three fingers are completely gas-coupled and driven by only one linear compressor.

For the JTC, the major components are the four-stage counter flow heat exchangers (CHEX), three precooling heat exchangers (PHEX) a JT valve and an evaporator. The CHEX is made of stainless steel and adopts tube-in-tube design. The high-pressure gas flows through the inner tube while the low-pressure gas does along the annular space between the two tubes. The PHEX is

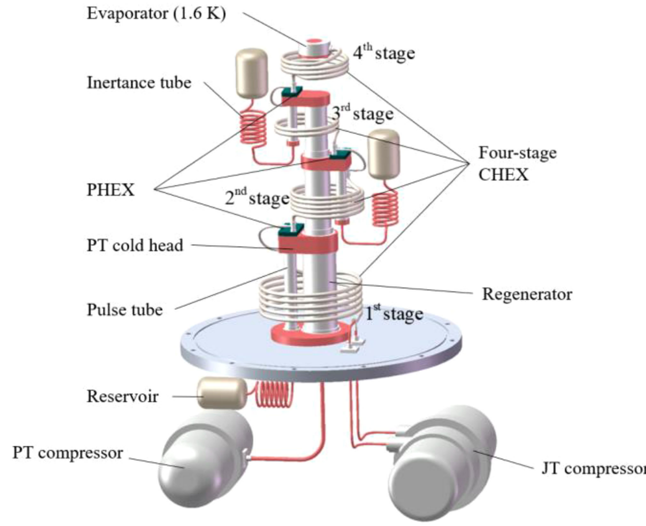

Fig. 1. Configuration of the three-stage SPTC/JTC hybrid cryocooler.

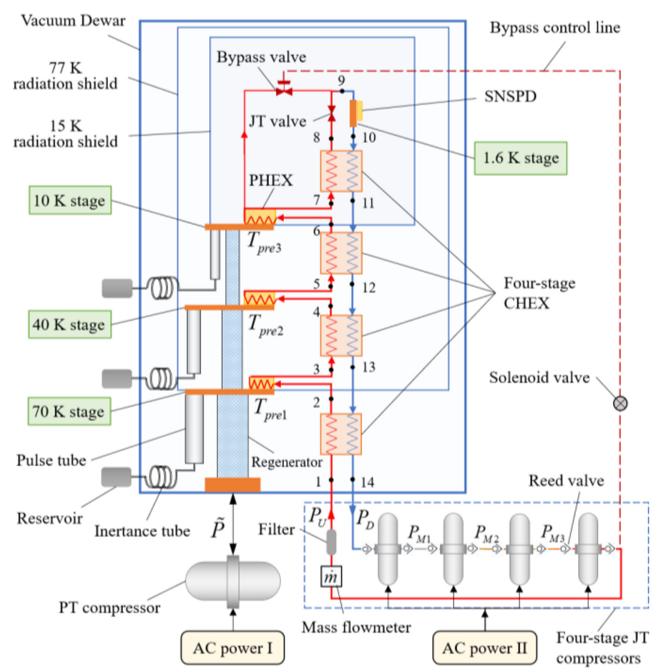

Fig. 2. Schematic of the three-stage SPTC/JTC hybrid cryocooler.

tightly mounted on the PT cold head and the both are made of oxygen-free copper (OFC) with good thermal conductivity. The cold finger of the JTC is driven by the four-stage JT compressors. In Fig. 1, only one JT compressor is showed and the JT valve with a fixed orifice is integrated inside the evaporator.

Fig. 2 is the schematic of the three-stage SPTC/JTC hybrid cryocooler, which shows the structure and operating mechanism of the cryogenic system. The working fluid of the three-stage SPTC and the JTC are He-4 and He-3, respectively. The AC power I is supplied to the PT compressor to generate the sinusoidal oscillation flow for the three-stage PT cold fingers. The temperatures of the three PT cold heads are 70 K, 40 K and 10 K, respectively. In addition to providing precooling for the PHXE, the first and third stage PT cold heads are also separately

TABLE I
DESIGN SPECIFICATIONS OF THE 1.6 K HYBRID CRYOCOOLER

Items		Specifications
Hybrid cryocooler	Cooling capacity Power consumption Total weight	15 mW@1.6 K <500 W <50 kg
Three-stage SPTC	Cooling capacity Power consumption Operating frequency	0.05 W@10 K 0.2 W@40 K 1 W@70 K <350 W (AC I input) 30 Hz
Four-stage JT compressors	Compression ratio Pressure Mass flow rate Power consumption	>3.2 for each stage P_U=0.55 MPa, P_D=5 kPa >2.5 mg/s <150 W (AC II input)

connected to a 77 K and a 15 K radiation shields through thermal links to reduce the radiation heat loss.

The AC power II is supplied to the four-stage JT compressors to drive the closed JT cycle. The oscillation flow generated in the four-stage compressors is turned into the direct current (DC) flow by the reed valves installed at the inlet and outlet of each stage compressor. A mass flowmeter is used to measure the He-3 mass flow rate of the JT circuit and a filter applied to ensure the cleanliness of the gas, which is critical to the long-term operation of the JTC.

A bypass route is designed to shorten the cooling time in the precooling process. The open/close of the bypass valve in the bypass route is pneumatically controlled by the control line connecting to the outlet of the JT compressors, in which a solenoid valve is placed at the ambient environment to handle the pressure for the pneumatic actuator. As the bypass valve is opened in the precooling process, the He-3 gas cooled by the first three stage CHEXs and PHEXs is diverted through the bypass route directly to cool the evaporator and the SNSPD. When the evaporator temperature approaches far below the highest inversion temperature of He-3, that is 34 K, the bypass valve is closed and all He-3 gas is introduced to the fourth stage CHEX and the JT valve.

At this point, due to the resistance of the JT valve (orifice), the pressure of the working fluid is lifted by the four-stage JT compressors thus forming stable high and low pressures in the upstream and downstream flow paths. When going through the JT valve, the working fluid experiences isenthalpic expansion with both temperature and pressure dropping at the same time. A fraction of liquid is produced in the evaporator, which is called the cooling capacity of the hybrid cryocooler. The design specifications of the developed hybrid cryocooler are summarized in Table I.

B. *System Integration With SNSPD*

The integrated system is composed of the SNSPD measurement subsystem and the hybrid cryocooler setup, as shown in Fig. 3. The 1.6 K stage of the JTC is made of the OFC with gold-plated surface, which has good thermal conductivity. The SNSPD package is directly mounted on the copper block. The

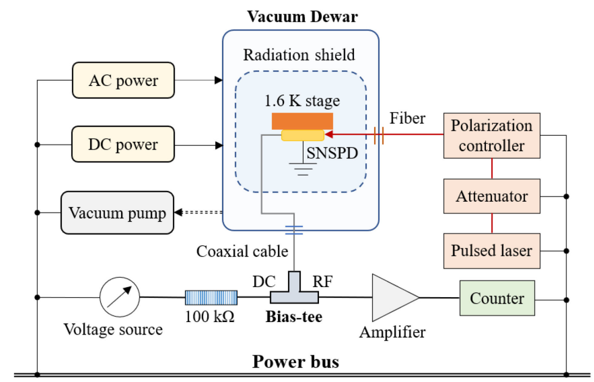

Fig. 3. Schematic diagram of the integrated system including the SNSPD measurement subsystem and the hybrid cryocooler setup.

coupling component which contains the SNSPD package and the last stage of the JTC is covered by a radiation shield with a temperature of about 15 K. The vacuum in the small Dewar is kept below 10^{-5} Pa by a vacuum pump.

In the SNSPD measurement subsystem, a fiber coupled picosecond pulsed laser is used to generate photons. By varying the attenuation, the incident power was adjusted close to one photon per pulse. The polarization controller is employed to obtain the maximum count rate. To measure the SNSPD, the device is current-biased through the DC branch of the bias-tee while the output response is transferred through the RF port and amplified by a low-noise amplifier (LNA). The amplified response signals are counted by a photon counter. Both the fiber and the coaxial cable are connected to the SNSPD via the interface reserved on the vacuum Dewar.

The SNSPD temperature is adjusted by a feedback control system, which includes several temperature and pressure sensors, a data acquisition and a controller. The temperature of the SNSPD, with pressures and precooling temperatures of the hybrid cryocooler, are measured and then transmitted to the data acquisition. The controller regulates the input power of the cryocooler according to an embedded control strategy to change or stabilize the temperature of the SNSPD. The control strategy is based on the theoretical optimization model which is presented in the next section.

III. PERFORMANCE OPTIMIZATION AND TESTS

A. *Theoretical Optimization Model*

The last-stage of the hybrid cryocooler (including the fourth stage CHEX, the JT valve and the evaporator) is the core unit that produces cooling performance at 1.6 K. Therefore, in the first step, the specific cooling capacity of the last-stage cooling unit is focused on. Through thermodynamic enthalpy analysis, the boundary values of the operating parameters that affect specific cooling capacity are determined, of which the upstream pressure P_U and the precooling temperature T_{pre} are set as two independent key variables. The enthalpy analysis indicates that there are a series of (P_U, T_{pre}) parameter pairs to meet the designed cooling capacity of 15 K. In order to achieve this goal with less input power and higher efficiency, the coefficient of performance (COP) of the hybrid cryocooler is optimized

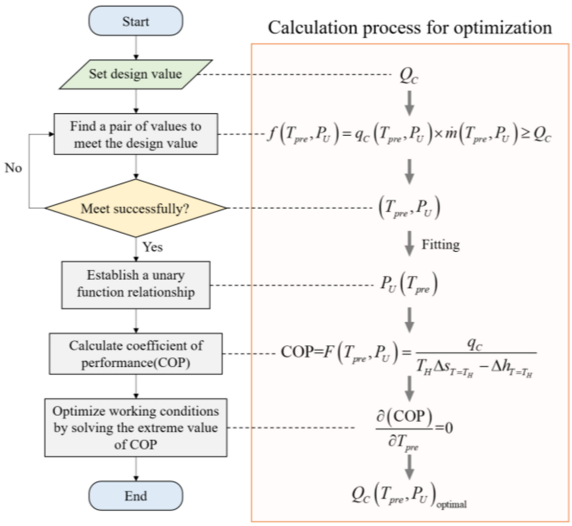

Fig. 4. Flowchart of the parameters calculation process of the theoretical optimization model (Q_C: cooling capacity, q_C: specific cooling capacity, P_U: upstream pressure, T_{pre}: precooling temperature, $\dot{m}$: mass flow rate, s: entropy, h: enthalpy).

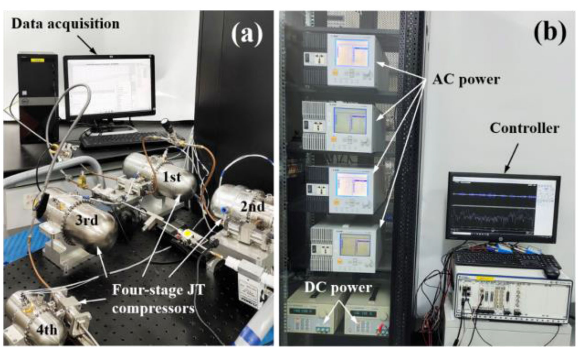

Fig. 5. Experimental setup of the integrated system.

to determine the best operating parameters of P_U and T_{pre}. The calculation process of the theoretical optimization model is shown as the flowchart in Fig. 4.

B. Experimental Tests

The prototype of the three-stage SPTC/JTC hybrid cryocooler has been developed and its cooling performance is tested. Fig. 5 shows the layout of the experimental setup and Fig. 6 presents the developed prototype of the 1.6 K space cryocooler inside the vacuum Dewar. A heat exchanger with a heating resistor is mounted on the 1.6 K stage serving as the SNSPD simulated load to measure the cooling capacity of the hybrid cryocooler.

The cooling process of the second and third stage of the SPTC and the evaporator of the JTC is shown in Fig. 7. With 320 W input power the second and third stage cold heads of the SPTC is able to achieve 40 K and 10 K respectively in about 1.2 hours. When the input power of the JTC is 146 W, the lowest temperature reaches 1.6 K. Then the heat load is applied to the evaporator to test the cooling performance. The results show that the cooling capacity of 16.3 mW at 1.6 K is achieved, which is beyond the design specifications. With more heat load applied, the cooling capacities of 20 mW and 25 mW

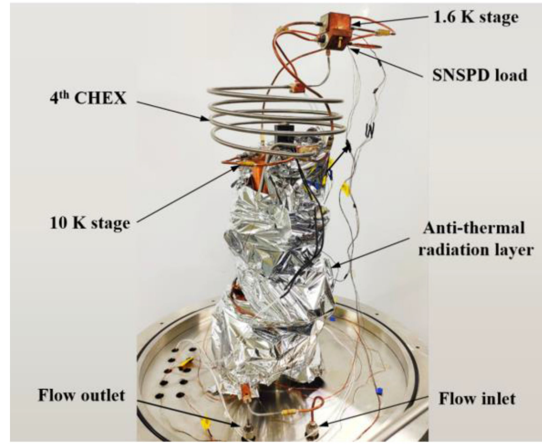

Fig. 6. Prototype of 1.6 K space cryocooler inside vacuum Dewar.

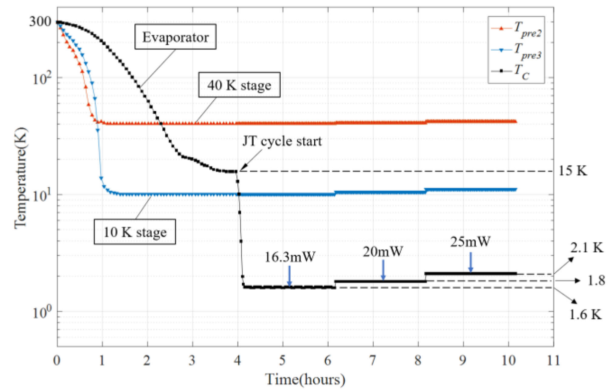

Fig. 7. Cool-down curves of each stage of the three-stage SPTC/JTC hybrid cryocooler.

are obtained at 1.8 K and 2.1 K, respectively. During the tested six hours, each base temperature is maintained for 2 hours with temperature fluctuations of ± 5 mK, which indicates that the cooling temperature has a good stability.

So far, the outer size of the hybrid cryocooler is 400 mm $\times$ 460 mm $\times$ 680 mm and the total weight is around 30 kg. There are still much room to further reduce its volume and weight for space applications. For example, the CHEX could be made into a more compact spiral shape with a smaller volume and the linear compressors made of titanium alloy other than of stainless steel to make them lighter.

IV. Conclusion

A hybrid cryocooler, which consists of a three-stage SPTC and a JTC, is developed to cool the SNSPD to 1.6 K for space applications. The structural design of the cryocooler and its integrated arrangement with the SNSPD are described in detail. A theoretical optimization model is established to improve the performance of the hybrid cryocooler and provide control strategy for the SNSPD temperature control system. The experimental results show that, with 320 W input power for the three-stage SPTC and 146 W for JTC, the hybrid cryocooler can achieve a cooling capacity of 16.3 mW at 1.6 K, which meets the design performance of 15 mW at 1.6 K. In conclusion, the 1.6 K hybrid cryocooler is a promising candidate for cooling SNSPD in space.

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