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A single-stage high frequency 40 K pulse tube cryocooler

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Abstract

To develop a long-wavelength infrared detector, a 40 K pulse tube cryocooler is needed to provide reliable and low-noise cooling power. Traditionally, it is generally believed that to improve efficiency, a 40 K pulse tube cryocooler needs to operate at around 40 Hz. However, low frequency cryocoolers are heavier and are not preferred for use on satellites. In this paper, a lightweight pulse tube cryocooler working at 76 Hz is designed. The inertance tubes, along with the reservoir, serve as the only phase-shifter to guarantee the stability. Currently, the cryocooler has achieved a no-load lowest temperature of 26 K. It has a cooling capacity of 9 W at 40 K while operating at 500 W of electrical power, and it weighs only 7.8 kg. The efficiency relative to the Carnot efficiency was approximately 11.1%. The performance characteristics of the designed cryocooler are presented in detail.

Introduction

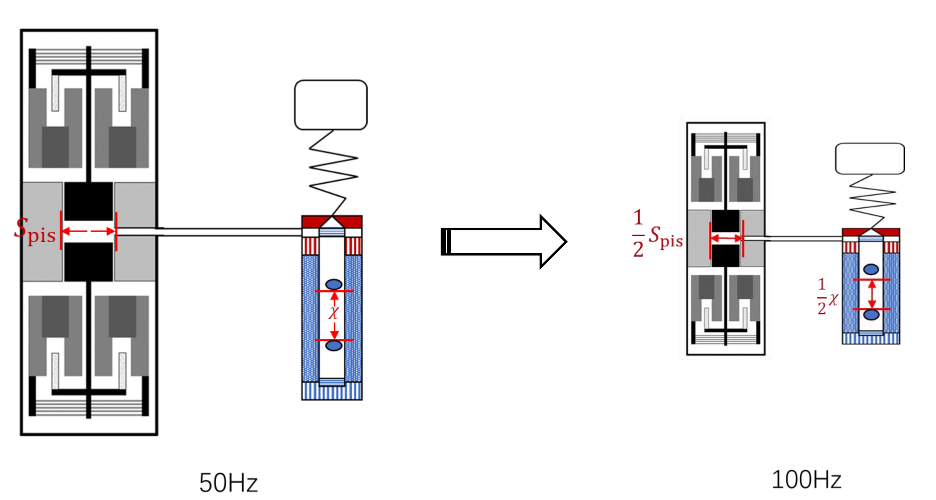
- **The Key Laboratory of Space Energy Conversion Technologies of TIPC**, CAS has conducted the research on PTCs for **over twenty years**. Several PTCs working at **4 K to 180 K** have been manufactured.
- In recent years, we have developed several single-stage low-temperature pulse tube cryocooler. In 2021, we designed a **2.1 W/40 K** single-stage PTC, the relative Carnot efficiency was up to 8.8%. In 2023, we further optimized this PTC to obtain a minimum **no-load temperature** of **20.3 K**.
- In order to reduce the weight, the high frequency technology is applied to the 40 K PTC. Finally, we have successfully developed a lightweight 40 K PTC.

High frequency technology

- The lightness of a cryocooler can be measured in terms of its specific mass. The specific mass of a PTC can be defined as the ratio of its mass to its cooling capacity. Research indicates that the **specific mass** of PTC is related to its **efficiency**, operating **frequency**, and charging pressure. As shown in Equation 1.

$$\beta_{ptc} = \frac{Q_{c_{PTC}}}{M_{PTC}} \propto \eta_{cf} f P_0 \qquad (1)$$

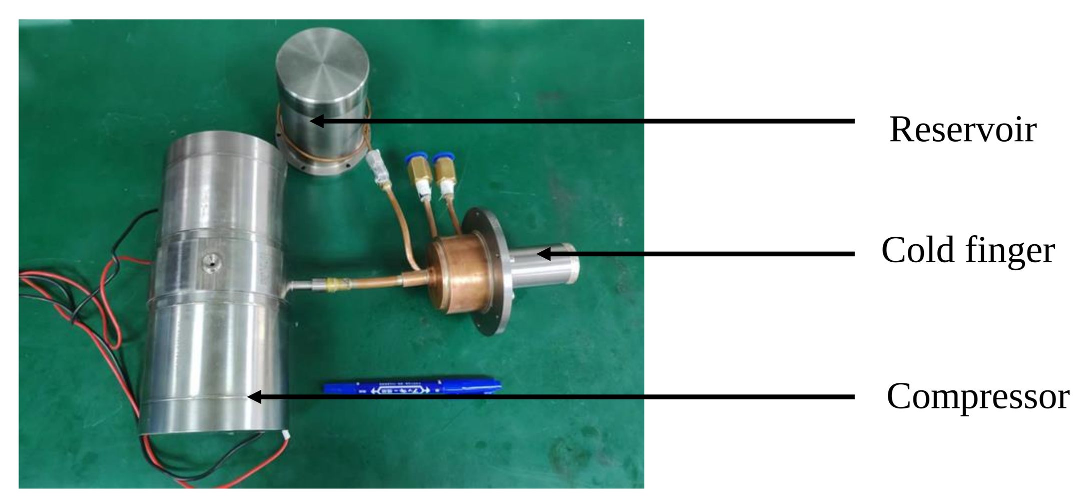
- The term M_{PTC} is the PTC mass, $Q_{c_{PTC}}$ is the cooling capacity, η_{cf} is the efficiency of the cold finger, f is the frequency, P_0 is the charge pressure.



Schematic of high-frequency technology

PTC parameters

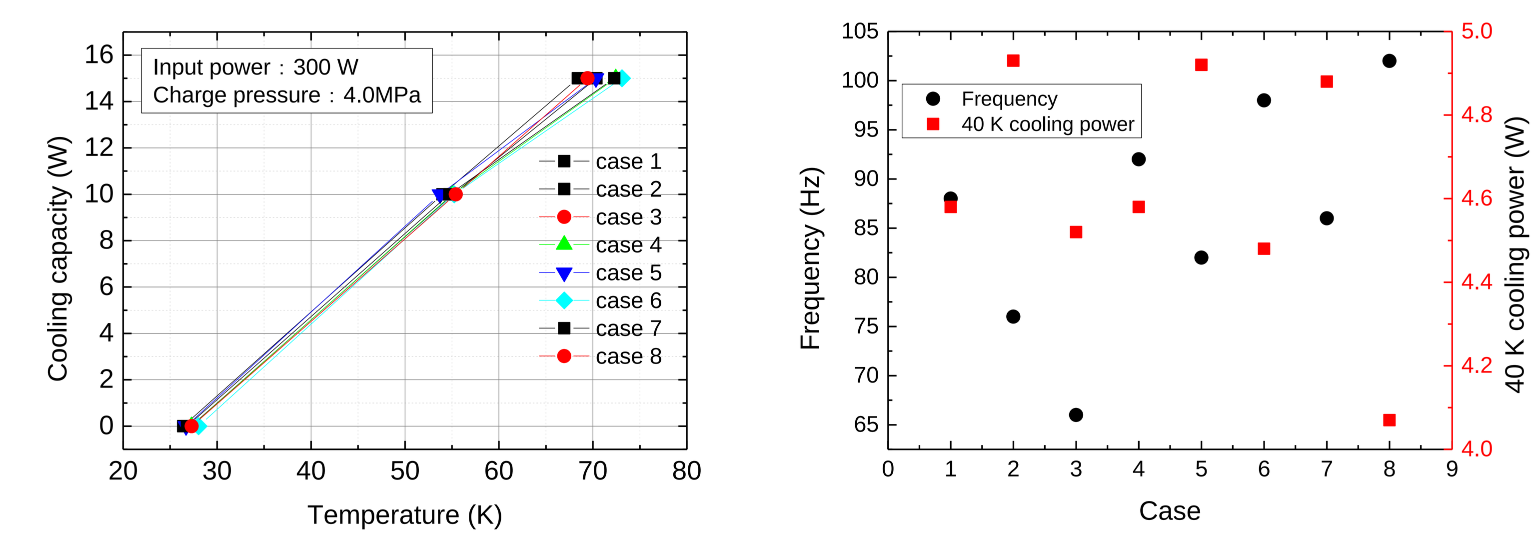
Components	Values
Length of REG	55 mm
Diameter of REG	31 mm
Swept velum of compressor	10.6 cc
Charge pressure	4.0 MPa
Mesh	#500&#600stainless steel screen
Hot end temperature	288 K
Mass	**7.8 kg**



The photo of the 40 K PTC

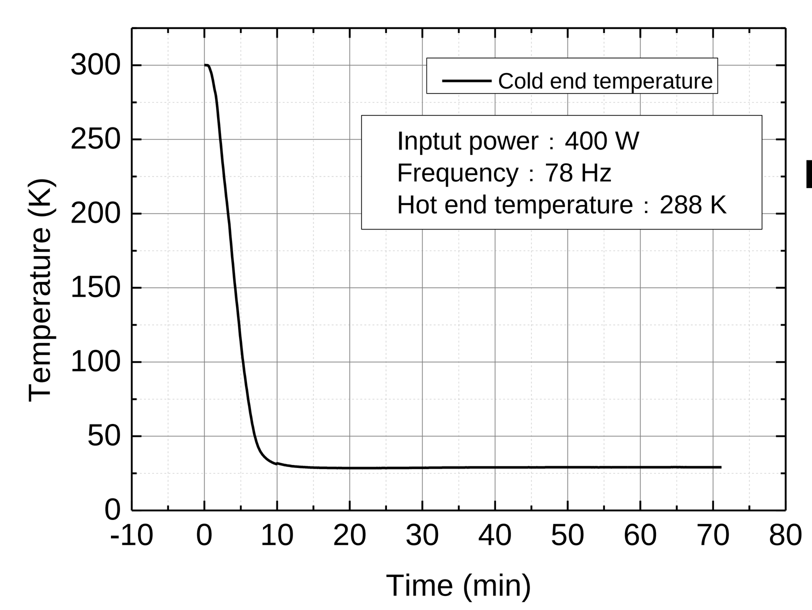
Phase shifter optimization

No.	The combination of inertance tubes
Case 1	Φ4 mm×1.5 m
Case 2	**Φ4 mm×2 m**
Case 3	Φ4 mm×2.5 m
Case 4	Φ4 mm×1.0 m+Φ5 mm×0.5 m
Case 5	Φ4 mm×1.0 m+Φ5 mm×1.0 m
Case 6	Φ4 mm×0.5 m+Φ5 mm×1 m
Case 7	Φ4 mm×0.5 m+Φ5 mm×1.5 m
Case 8	Φ5 mm×1.5 m



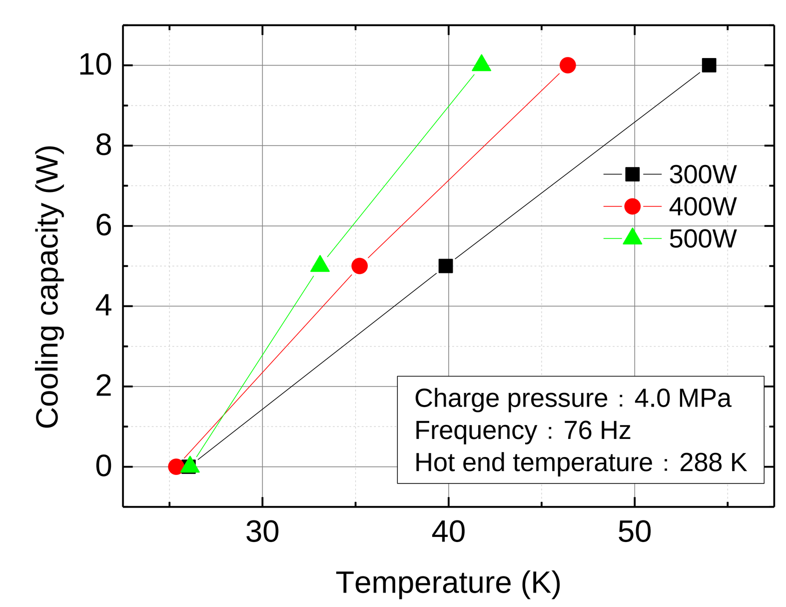
The optimization of phase shifter

Performance



Typical cool-down cure

- It takes about **7 min** for the cold head to cool down from 300 to 80 K, and about **10 min** to below 40 K.



Input power	Cooling capacity	Relative Carnot efficiency
300	5.0	10.4%
400	7.1	11.1%
500	**9.0**	**11.1%**

The cooling performance of this cooler prototype

Conclusions and future work

- **Conclusions :** By adopting high-frequency technology, the operating frequency of the 40 K cryocooler is increased from the conventional 40 Hz to 76 Hz. At present, this cooler prototype has a cooling capacity of 9 W at 40 K while operating at 500 W of electrical power, and it weighs only 7.8 kg. Compared to the conventional 40 K cryocooler, the efficiency is basically the same, but the weight is significantly reduced.
- **Future work:** It is expected that by optimizing the cold finger parameters, the operating frequency can be higher than 100 Hz, and the weight of the cryocooler can be further reduced.