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Optimization of an 8K Level High Frequency Pulse Tube Cryocooler

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Abstract. As very low temperature high frequency pulse tube cryocooler is the precondition of many space detection researches, it has been a hot topic in the field of pulse tube cryocooler. Improving the cryocooler’s performance is a common goal of researchers. In this paper, the regenerator material and the compressor of the second-stage pulse tube cryocooler as well as the first-stage pulse tube cryocooler are experimentally optimized using a new thermally coupled high frequency pulse tube cryocooler. Finally, more than 20mW of cooling power is achieved at 8K and the electric power decreases from 450W to 300W. The results increase the reliability of the space application of NbN terahertz detectors.

1. Introduction

As the increasing demands of superconducting devices, THz space detection and 2K hybrid JT cooler are urgent, very low temperature high frequency pulse tube cryocooler has become a focus in the field of pulse tube. Since G-M pulse tube cryocooler can’t meet the demands of space because of its size and input power, Lockheed Martin’s Advanced Technology Center (LMATC), Northrop Grumman Space Technology (NGST), National Institute of Standards and Technology (NIST), the Institute of Refrigeration and Cryogenics in Zhejiang University and Technical Institute of Physics and Chemistry(TIPC), Chinese Academy of Sciences(CAS) have been working on multi-stage high frequency pulse tube cryocooler to meet the low temperature needs [1-9].

Our laboratory has been doing the research on very low temperature high frequency pulse tube cryocooler. In 2014, we successfully coupled the THz component studied by the Purple Mountain Observatory (PMO), CAS and our two-stage high frequency pulse tube cryocooler. The THz component worked well at 8K with total 450W input power [9]. In this paper, we do some research on optimizing the first-stage pulse tube cryocooler, the compressor and the regenerator material of the second-stage pulse tube cryocooler with a two-stage thermally coupled high frequency pulse tube cryocooler by experiments. By the optimization, we successfully decrease the electric power and increase the cooling efficiency.

2. Experimental apparatus

A two-stage thermally coupled high frequency pulse tube cryocooler designed by our laboratory is used for the optimization. The schematic of the cryocooler is shown in figure1. The cryocooler includes two parts: the first-stage (part B shown in figure1) and the second-stage (part A shown in figure1). Every stage includes a cold finger and a compressor. Both of the two cold fingers are coaxial...
configuration. Cold iner-tance tube, cold gas reservoir, cold double inlet and cold mid-bypass are used as phase shifter in the cold finger of the second-stage, while phase shifters for the cold finger of the first-stage are iner-tance tube and gas reservoir. According to the variation of temperature in different regenerator sections, different regenerative materials are filled in the regenerator. Regenerator material in the first-stage regenerator is stainless steel mesh. For the second-stage regenerator, above 30K, stainless steel mesh is used, while below 30K, magnetic regenerator materials are used to reach lower temperature [9-12].

![Figure 1. Schematic of the two-stage pulse tube cryocooler](image)

3. Optimization results
In 2014, the cryocooler can provide 31mW cooling power at 8K with total 450W compressor electrical power [9]. After that, we manufactured a new two-stage thermally coupled high frequency pulse tube cryocooler and optimized the regenerator material of the second-stage, the compressor of the second-stage and the working efficiency of the first-stage. The experimental results of the optimization are shown as follows.

3.1. The optimization of regenerator material
Based on our previous research, ErNi is suitable as regenerative material above 8K while HoCu2 is better than ErNi below 6K. During our optimization, we used ErNi as the regenerative material in the cold end of the second-stage to enhance the cooling power in 8K. The optimization results is shown in figure 2. From the experimental results, the no load temperature is lower when HoCu2 is used as regenerative material while the cooling efficiency in 8K and 15K is larger when the regenerative material in the cold end is ErNi. Since we hope to gain more cooling power at 8K and 15K, we use the optimization solution that ErNi is used as the regenerative material in the second-stage cold end.
3.2. **The optimization of compressor**

In 2014, the compressor of the second-stage was manufactured by Leybold Company and plunger spring was used in the compressor. As the large radial stiffness of flexure bearings provides a support for piston to ensure it works in a non-contact way with cylinder and the working efficiency of the Leybold’s compressor is very low at about 20Hz, we designed a new compressor with the flexure bearings to improve the compressor’s efficiency of operations and reliability. The new compressor was coupled to the second-stage’s cold finger for experiment and the working frequency was optimized. The experimental results are shown in figure 3.

From figure 3 we can conclude that the new designed compressor’s working efficiency is higher than the Leybold’s compressor at working frequency of 16Hz. The lowest temperature is 5.6K when the new designed compressor with 170W input power is used. As the new compressor is improved in spring stiffness, its working efficiency at about 20Hz has been increased. From the experimental results of the no load temperature, the electric efficiency has been increased about 30%.
3.3. *The optimization of the first-stage*

Our laboratory is working on single-stage high frequency pulse tube cryocooler. In 2017, a high efficiency single-stage coaxial pulse tube cryocooler which operated at 60 K was manufactured. It provides a cooling power of 7.7 W at 60 K with an input power of 200 W, and achieves a relative Carnot efficiency of around 15\%[13]. Base on the research results, we optimized the design parameters of the first-stage, the experimental results of the optimization are shown as below. From figure 4 we can conclude that the optimized first-stage cryocooler can provide a cooling power of 5 W at 62.5 K with 180 W electric power while the old first-stage cryocooler only provides 2.8 W at 60 K with 250 W input power. The cooling efficiency at 60 K of the first-stage cryocooler raise substantially.

![Figure 4. Cooling power of the first-stage pulse tube cryocooler](image)

![Figure 5. Cooling capacity of the optimized two-stage pulse tube cryocooler](image)

After the optimization of the first-stage, the electric power of the first-stage is decreased to 150 W, and the cooling power of the optimized two-stage pulse tube is shown in figure 5. More than 22 mW of cooling power is achieved at 8 K with total input power of 300 W. The results meet the requirements of the application of NbN Superconductor-Insulator-Superconductor (SIS) mixers used for terahertz detection. More than 120 mW cooling power is achieved at 15 K with an input power of 300 W which
meet the needs of 2K hybrid cryocooler. The optimized two-stage thermal coupled high frequency pulse tube cryocooler has been used at a 2K hybrid cryocooler which successfully coupled with Superconducting nanowire single photon detector (SNSPD) [14].

4. Conclusion

Based on the results of our optimization and experiments, more than 22mW of cooling power is achieved at 8K with the new two-stage thermal-coupled high frequency pulse tube cryocooler used. The input power at same working operation has decreased from 450W to 300W, the cooling efficiency at 8K increases about 50% after the optimization. The results of the high frequency pulse tube cryocooler achieve the requirements of the application of NbN SIS mixers and 2K hybrid cryocooler, so it paves a way for the space application of terahertz technologies and SNSPD.

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References

[1] Nast T, Olsen J, Champagne P, et al. Development of 4.5 K pulse tube cryocooler for superconducting electronics 2008 Advances in cryogenic engineering 53 pp 881-886
[2] Webber R J, Dotsenko V V, Delmas J, et al. Evaluation of a 4 K 4-stage pulse tube cryocooler for superconducting electronics 2009 Cryocoolers 15 (Springer Science and Business Media, New York, NY ) pp 657–664
[3] Vladimir V D, Jean D, Robert J W, Integration of a 4-Stage 4 K pulse tube cryocooler prototype with a superconducting integrated circuit 2009 IEEE T Appl. Supercond. 19 1003-1007
[4] Jaco C, Nguyen T, Raab J., 10 K Pulse Tube Cooler Performance data 2009 Cryocoolers 15 (New York:Kluwer Academic/Plenum Publishers) pp 1-6
[5] Kotsubo V, Radebaugh R, Hendershot P, et al , Compact 2.2 K Cooling System for Superconducting Nanowire Single Photon Detectors 2017 IEEE T Appl. Supercond. 27 1–5
[6] Cao Q, Investigation on refrigeration mechanism of multi-stage stirling pulse tube cryocoolers working at liquid helium temperature, 2012 Doctor Dissertation Zhejiang Zhejiang University (in Chinese)
[7] Chen L, Wu X, Liu X, et al. Numerical and experimental study on the characteristics of 4 K gas-coupled Stirling-type pulse tube cryocooler. 2018 International Journal of Refrigeration 88
[8] Chen L, Wu X, Wang J, et al. Study on a high frequency pulse tube cryocooler capable of achieving temperatures below 4 K by helium-4. 2018 Cryogenics 94 pp 103-109
[9] Quan J, Liu YJ, Liu D, et al. 4K high frequency pulse tube cryocooler used for terahertz space application, 2014 Chinese Science Bulletin 59 pp 3490-3494
[10] Quan J, Liu Y J, Liang J T, et.al. Experimental investigation of regenerative material on performance of a 10K multi-stage high frequency pulse tube cryocooler 2012 Cryocoolers17 (ICC Press, Boulder, Colorado) pp 309-314
[11] Quan J, Liu Y J, Zhao M G, et.al. Investigation on the influence of pre-cooler for thermal-coupled multi-stage high frequency pulse tube cryocooler 2012 Advances in Cryogenic Engineering pp 359-362
[12] Liu Y J, Theoretical and experimental investigation on 10K level high frequency multi-stage pulse tube cryocooler, 2011 Doctor Dissertation, Beijing, University of Chinese Academy of Sciences (in Chinese)
[13] Wang N, Zhao M, Ou Y, et al. A high efficiency coaxial pulse tube cryocooler operating at 60K. 2018 Cryogenics 93 pp 48-50
[14] You L, Quan J, Wang Y, et al. Superconducting nanowire single photon detection system for space applications. 2018 Optics Express 26 pp 2965-2971.