Development of a 0.5 W/40 K Pulse Tube Cryocooler for an Infrared Detector

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ABSTRACT

A Stirling-type pulse tube cryocooler (PTC) has been developed to provide cryogenic cooling for very long wavelength infrared detectors such as GaAs/AlGaAs Quantum-Well infrared photodetectors (QWIPs)[1] that require the cooling power of 0.3 W at 40K and are sensitive to vibrations.

The U-shape prototype cryocooler driven by a flexure bearing compressor is optimized with an inertance tube and a double-inlet compound configuration. A cooling performance of 420 mW at 40 K has been achieved with 240 W electrical power input at a rejection temperature of 290 K, provided by water cooling.

Several matching experiments between the PTC and the infrared detectors have been performed. The results of these experiments show that the infrared focal plane array (FPA) detectors can work at 38.5 K with the single-stage Stirling-type pulse tube cryocooler.

INTRODUCTION

Along with the commercialization of High Temperature Superconductor (HTS) detectors in the fields such as mobile communications and the development of very long wavelength infrared devices for space and military applications, a strong demand has arisen for a simple and highly reliable cryocoolers working from 40 K to 80 K.[2] The Stirling-type pulse tube cryocooler has the potential to achieve high reliability and long-life time because it operates without a moving displacer at the cold end. Based on the linear Oxford-type compressor, its operating frequencies is from 30 to 60 Hz, and it provides cooling power at the temperature range of 30-150 K.

Cryocoolers for cooling normal long wavelength infrared detector usually work at 80 K or slightly higher temperature and the cooling power is usually from a few milliwatts to a few watts. With the development of very long wavelength infrared devices such as QWIPs, lower temperatures such as 40 K are required for these devices to work properly. Conventionally, cryogenic fluid (such as liquid nitrogen, or liquid helium) have been used to cool the infrared devices. However, this method has a disadvantage for controlling the temperature of infrared detectors; the consumption of a large quantity of liquid helium due to its inefficiency. In addition, handling cryogenic fluid can be troublesome in some instances.

PTCs are the attractive candidates for cooling QWIPs because of the absence of moving parts at low temperatures. PTCs bring less vibration and electromagnetic interference (EMI) than other cryocoolers.

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For example, acceleration measurement has shown that the vibration generated by PTCs is an order of magnitude less than Gifford-McMahon (G-M) cryocoolers and Stirling cryocoolers.[3]

QUANTUM-WELL INFRARED PHOTODETECTORS

Infrared is a portion of the electromagnetic spectrum. It is convenient to subdivide the infrared into the four parts shown in Table 1.

An infrared detector is simply a transducer of radiant energy. It converts radiant energy into another measurable form; this can be an electrical current, a change in some physical property of the detector, or blackening of a photographic plate. The detectors are grouped into two classes that differ by the physical mechanism involved in the detection process, one group is called thermal detectors and the other group is called photon or quantum detectors.[4]

Most quantum detectors have the detectivity of one or two orders of magnitude greater than that of thermal detectors. This greater detectivity does not come for free, however, since many quantum detectors will not function unless they are cooled to cryogenic temperatures. Because of the direct interaction between the incident photons and the electrons of the detector material, the response time of photon detectors is very short; most have time constants of a few microseconds, rather than a few milliseconds, typical of thermal detectors. Finally, the spectral response of photon detectors, unlike that of thermal detectors, varies with wavelength.

The very long wavelength (~15¼ mm) quantum-well infrared photodetectors (QWIPs) require moderate cooling (below 40 K). Figure 1 shows the I-V characteristics of QWIPs. When the cooling temperature is below 40K, the current of the QWIPs increase little changes in temperature. The current of QWIPs increases with temperatures obviously above 40 K. For example, the performance of a QWIP at 45 K is half of that at 40 K. Specially, the performance of QWIPs at 50 K are almost invalid.

Table 1. Subdivision of the Infrared Spectrum

Designation	Abbreviation	Wavelength range (μ m)
Short wavelength infrared	SWIR	1 to 3
Middle wavelength infrared	MWIR	3 to 5
Long wavelength infrared	LWIR	8 to 13
Very long wavelength infrared	VLWIR	>13

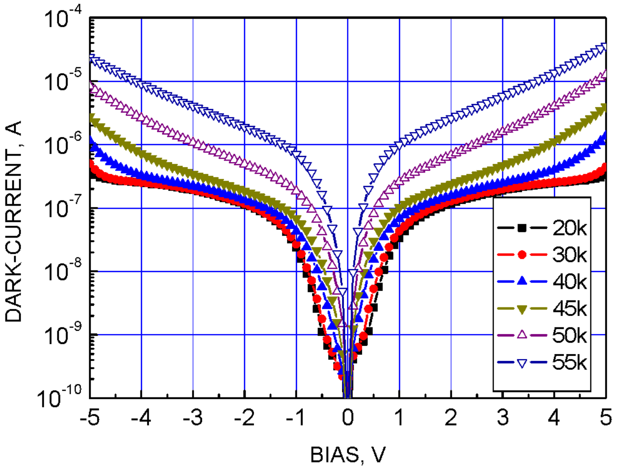

Figure 1. I-V characteristics of QWIPs vary with Temperature

PULSE TUBE CRYOCOOLER

Experimental System

A schematic diagram of a system specially designed for cooling very long infrared detectors is shown in Figure 2. A Leybold Polar SC7 linear compressor with a maximum input power of 250 W is used to drive the cooler. A U-shaped configuration has been used for the cooler. The cooler was designed to achieve the lowest temperature at the cold tip. The dimensional layout of the pulse tube and regenerator was guided by a one-dimensional numerical simulation program that extends a previous numerical model, and by previous experience gained from the development of miniature high frequency pulse tube coolers for 0.5W/80K.[5]

As indicated in Figure 2, the pulse tube is equipped with an inertance tube, a buffer volume and a double-inlet flow resistance for adjustment of the phase shift between pressure and mass flow oscillation. For control of DC flow, the double-inlet flow resistance consists of a needle valve arrangement made in-house with adjustable flow symmetry. The length of transfer line connecting the compressor and the cold head is about 20 cm. A copper tube for water cooling is wrapped and soldered around the warm end of the cold head.

In the experiments, the temperature of the cold tip is measured by means of a calibrated iron-rhodium resistance thermometer. The net cooling power is measured by use of a resistive heater attached to the cold tip. Several layers of aluminized mylar foil are wrapped around it to reduce radiation losses.

Based on the optimization of the pulse tube and the regenerator geometry, several PTC were fabricated and tested systematically to optimize the working parameters. The optimization took place for different operating frequencies, charge pressures, input powers, and hot end temperatures. We have chosen some representative experimental test data for presentation in the following paragraphs.

Experimental Optimization of the Working Parameters

Figure 3 shows the frequency dependence of the cold-head no-load temperature for the coolers. No local minimum exists in this figure. However, the temperature increases monotonically with operating frequency. The optimum operating frequency of the miniature pulse tube coolers for 0.5 W at 80 K in the same laboratory is usually around 45-50 Hz. The lower optimum operating frequency is attributed to the smaller thermal penetration depth and the smaller thermal capacity of stainless steel screens at the cold end below 60 K.

Figure 4 shows the temperature dependence of the cooling power below 40 K. The charge pressure is 2.5 MPa and the operating frequency is 38 Hz.

Figure 5 shows the cooling power of the PTC at 40 K under different temperature of the hot end. The cooling power at 40 K rises evidently with a decrease in the hot end. Cooling the hot end is important to the optimization of the PTC for cooling infrared detectors at 40 K.

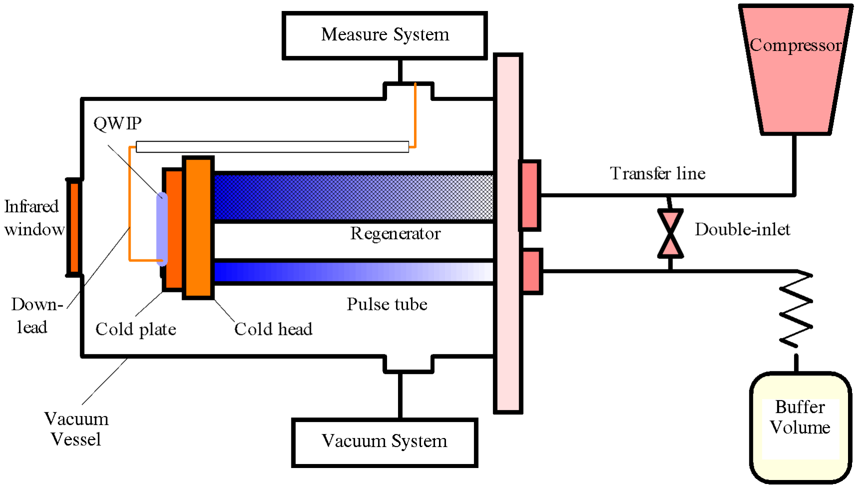

Figure 2. Schematic diagram of experimental system.

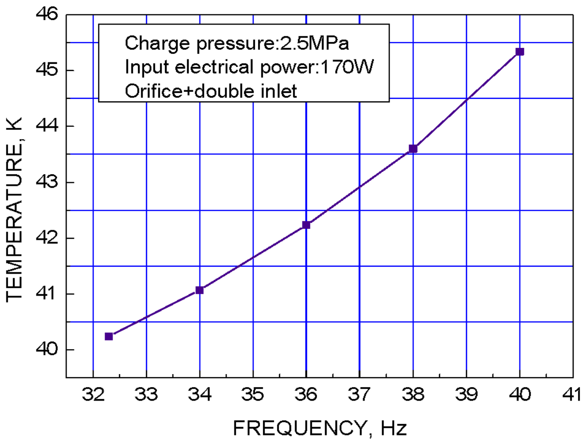

Figure 3. Frequency dependence of the no-load temperature.

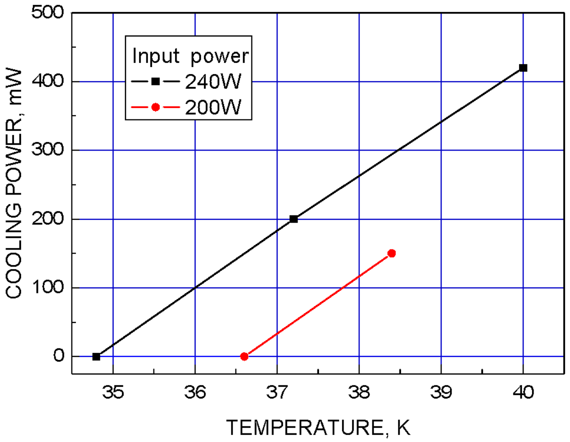

Figure 4. Temperature dependence of the net cooling power of the PTC.

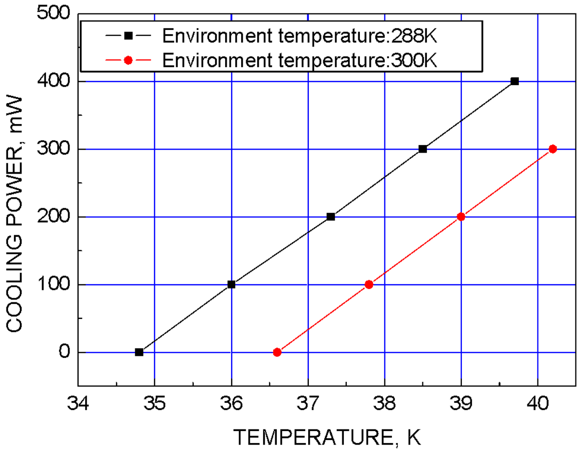

Figure 5. Variation of the cooling power with the temperature of the hot end.

Table 2 shows the variation of cold head no-load temperature with the different phase shift methods for the PTC. The key measure to reach the minimum temperature of the cold head below 40 K is to optimize the double-inlet. The inertance tube is more useful than an orifice as a phase shift resistance.

EXPERIMENTAL RESULTS OF COUPLED TEST

A schematic diagram of the system specially designed for cooling QWIP FPA is shown in Figure 2. The QWIP FPA is fixed on a cooling plate which is connected to the cold head by bolts. Figure 6 shows the cool down curves for cooling a QWIP FPA. The QWIP FPA can be cooled down to 37.2 K in 2 hours, and the QWIP FPA can work at 38.5 K successfully. Table 3 shows the experimental results of the temperature distribution at different steps of the coupling test. We can discover that the heat loss through conduction and radiation from the cold plate and the QWIP FPA to ambient is about 150 mW and the heat production of the QWIP FPA is about 100 mW. Figure 7 shows the imaging of an iron by the QWIP FPA.

Table 2. Minimum temperature reached of three phase shifts

Input Power Phase shift	150W	180W	240W
orifice	59.1K	56.1K	54.8K
inertance	54.2K	51.3K	47.8K
Inertance + double inlet	41.2K	38.3K	34.8K
Orifice + double inlet	43.2K	40.1K	36.5K

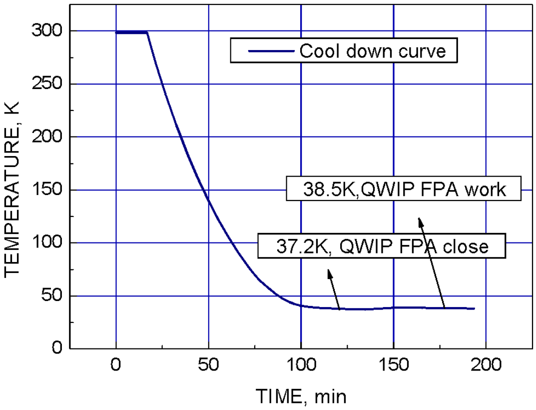

Figure 6. Cooling down curve for cooling the QWIP FPA

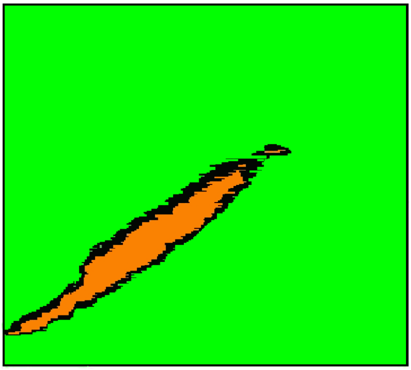

Figure 7. Imaging of the iron

Table 3. Experimental results of the coupled test

Location Steps	Cold tip temperature (K)	Cold plate temperature(K)	QWIP temperature(K)
No load	35		
Cold plate installation	36	36.9	37
QWIP work		38.5	38.5

CONCLUSIONS

Based on the compound configuration with inertance tube and double-inlet, a Stirling-type U-shaped PTC has been developed and tested systematically to optimize the cooler geometry and working parameters. The PTC can reach a lowest temperature of 34.8 K and provide a cooling power of 420 mW at 40 K.

Some coupled experiments between PTC and infrared detectors have been performed, which show that the Quantum-Well infrared photodetectors (QWIPs) focal plane array (FPA) can work below 40 K temperature successfully with the single-stage Stirling-type pulse tube cryocooler.

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