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40 K single-stage coaxial pulse tube cryocoolers

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Several 40 K single-stage coaxial high frequency pulse tube cryocoolers (PTCs) have been developed to provide reliable and low-noise cooling for GaAs/AlGaAs Quantum-Well infrared photodetectors (QWIPs). The inertance tubes together with the gas reservoir become the only phase shifter to guarantee the required long-term stability. The mixed regenerator consisting of three segments has been developed to enhance the overall regenerator performance. At present, the cooler prototype has achieved a no-load temperature of 29.7 K and can typically provide 860 mW cooling at 40 K with 200 W electric input power rejecting at 300 K. The performance characteristics such as the temperature stability and ambient temperature adaptability are also presented.

1. Introduction

In recent years, more and more space applications such as weather monitoring, Earth observation systems, astronomy, etc. require high performance large format long wavelength infrared (LWIR) detector arrays in the range of 13–16 μm [1]. Traditionally, longer wavelengths could be accessed by narrowing the band-gap of the most common photon detectors such as $Hg_{1-x}Cd_xTe$ by changing its alloy composition *x*. However, very narrow bandgap materials are difficult to grow and process into devices, which often reduce the yield and also increase the cost of the arrays [1]. These difficulties motivate the exploration of low effective material systems such as GaAs/AlGaAs. As a result, the significant efforts have been devoted in developing GaAs-based Quantum-Well infrared photodetectors (QWIPs) and rapid advances have been achieved in the past decade. Such a GaAs-based QWIP benefits from the highly mature GaAs growth and processing technologies, which becomes critical at the very long wavelengths where narrow band-gap materials become very difficult to work with. Besides the high production yield, low cost, and very long wavelength capability, the GaAs/AlGaAs QWIPs also have other important advantages in large uniform FPAs, mature III–V technology, high speed, and radiation hardness, etc.

Recently, the GaAs/AlGaAs QWIPs with the response wavelength of longer than 15 μm have been worked out in the same institute [2], and the practical applications are underway. They require about 0.5–1.0 W of cooling power at around 40 K. The conventional cooling method using the cryogens brings some intrinsic inconvenience in transportation, maintenances, the dependence of orientations, etc., and thus a turnkey mechanical cryocooler is desirable. However, while a cryocooler is employed instead of a cryogen cryostat to cool the infrared sensors, the low vibration and EMI have to be especially emphasized in order to bring the minimum additional interferences [3]. The absence of any moving mechanical component at the cold end of the pulse tube cryocooler (PTC) endows it the intrinsic advantages such as minimum vibration and EMI, which have a strong appeal to GaAs/AlGaAs QWIPs applications.

2. Development goals

Several single-stage coaxial PTC prototypes have been developed in our group to meet the cooling requirements of the developed GaAs/AlGaAs QWIPs applications.

Traditionally, the two-stage or multi-stage arrangement for the high frequency PTC is often employed to realize the applications below 40 K [4–7]. However, obviously, the single-stage arrangement will definitely minimize the complexity of the cooler system and also reduce the research cost, which is also one of the key reasons for our development. In fact, the development of single-stage PTCs working at 30–40 K has a longer history. For instance, TRW demonstrated its single-stage high efficiency 35 K flight-like PTC even in 1993, which provided 1 W cooling at 35 K for 200 W into the compressor with a 20 cc of swept volume [8]. A new scaled-down model named TRW 3503 had been developed in 1995, which provided 0.3 W at 35 K for 82 W into a compressor with a 10 cc swept volume [9]. Both of the above coolers adopted the in-line

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Table 1
A summary of key development goals of the SITP's 40 K PTC.

Parameters	Design goal
Stage arrangement	Single-stage
Geometrical arrangement	Coaxial
Phase shifting mechanism	Without double-inlet
Cooling capacity	⩾0.8 W@40 K (at 300 K reject)
Power consumption (electric input)	⩽200 W
No-load temperature	⩽30 K
Mass (including control electronics)	⩽8.0 kg
Ambient temperature adaptability	243–323 K
Temperature stability	±0.1 K
Vibration output of cold head	⩽0.1 N (rms)
Vibration output of compressor	⩽0.5 N (rms)
Expected lifetime	⩾50,000 h

geometrical arrangement and achieved the remarkable thermodynamic efficiencies. In recent years, single-stage in-line PTCs working below 40 K have achieved some new progresses in both no-load temperature and cooling ability [10].

In some specific applications, the coaxial instead of in-line geometrical arrangement is often chosen to ease the integration between the cold head and the cooled devices [11,12]. Recently, the single-stage high frequency coaxial PTC working below 40 K was also developed, which achieved a no-load temperature below 30 K and achieved a 0.5 W cooling at 35 K for about 200 W into the compressor [13]. In our PTC development program, the coaxial geometrical arrangement is determined considering the final mounting of the cooled QWIPs.

For the abovementioned developed single-stage in-line or coaxial Stirling-type PTCs working below 40 K, the double-inlet mechanism is often employed as an effective means to evidently enhance the thermodynamic performance of the abovementioned developed PTCs [8–10,13]. However, the potential instability induced by the possible DC effect will leave behind a hidden peril for the special application fields such as in space [3,14]. Therefore, for our developments, the double-inlet mechanism is excluded, while the phase shifting mechanism at the warm end only uses the inertance tubes together with the corresponding gas reservoir in order to guarantee the required long-term stability.

Table 1 gives a summary of key development goals. In the practical applications, the net refrigeration power of the PTC has to include irreversible losses and parasitic heat losses, thus the refrigeration requirement is to provide at least 0.8 W cooling power at 40 K. An electric input power of less than 200 W into the compressor is required, and the reject temperature is at 300 K. The overall mass including cooler control electronics will be kept below 8.0 kg. The other parameters such as the ambient temperature adaptability, temperature stability, vibration output of the cold head and compressor, and expected lifetime are very important for the practical applications.

Table 2
Key parameters of the three-segmented mixed regenerator and a single regenerator.

Regenerator	Segment	Inner diameter	Length	Regenerator matrix
No. 1	Regenerator I	21 mm	15 mm	250-mesh SS
	Regenerator II		45 mm	400-mesh SS
	Regenerator III		15 mm	500-mesh SS
No. 2		21 mm	75 mm	400-mesh SS

3. Design and optimizations

The schematic of the developed single-stage coaxial inertance PTC is shown in Fig. 1. The cooler system is addressed as the split arrangement because the cold finger is connected the linear compressor with a 25 cm flexible metallic connecting tube. The linear compressor adopts the dual-opposed piston configuration to minimize the generated vibration.

The inertance tubes, which consist of two sections with different inner diameter and length, as the Inertance tube I and II shown in Fig. 1, are optimized at 40 K to obtain desirable phase relationship since a single inertance tube with a constant diameter has great difficulty in obtaining the desired phase relationships. During the optimization, an inertance tube with a constant inner diameter of 3.5 mm has been attempted firstly based on the same pulse tube finger. The no-load temperature can only reach 41.6 K and there is no any cooling power at 40 K with a 200 W into the compressor, no matter how the tube length varies. With the same operating conditions, the other inertance tube with a diameter of 4.5 mm has been tested, the no-load temperature reaches 38.9 K and only about 50 mW of net cooling power at 40 K has been achieved. However, when the abovementioned tube diameters are combined to optimize the performance, the no-load temperature of below 30 K and a net cooling power of more than 800 mW at 40 K have been achieved. The detailed performances of the PTC with the double-segmented inertance tube will be presented in the following paragraphs. The double-segmented inertance tube, together with a gas reservoir, serves as the only phase-shifting components in order to guarantee the reliable performance of the system. The two straighteners at the warm and cold ends try to keep the laminar working gas in the pulse tube.

An important feature of the 40 K PTC different from other types developed in the same group for providing coolings above 50 K [15–17] is that the former employs a mixed regenerator, which consists of three segments with the same diameters (as the regenerators I, II and III shown in Fig. 1). The three-segmented regenerator is filled into the stacked stainless steel screens made of the same material while with the different meshes, respectively. Table 2 gives the key dimensional parameters of the three-segmented mixed regenerator (regenerator No. 1), and a single regenerator filled with the

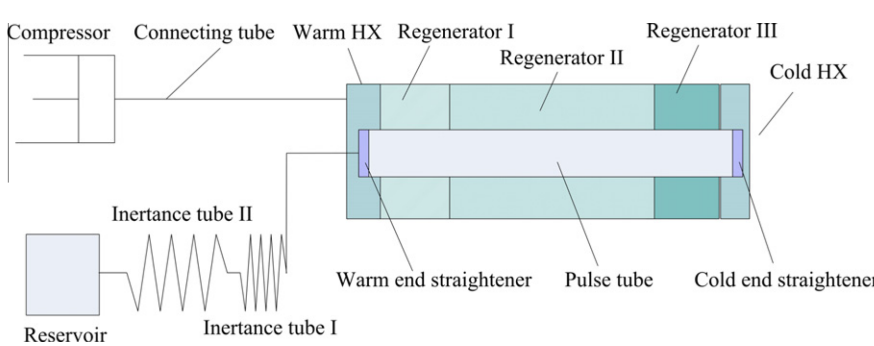

Fig. 1. Schematic of the developed single-stage coaxial inertance 40 K PTC.

Table 3
Key parameters of the double-segmented regenerators for additional experiments.

Regenerator	Segment	Inner diameter (mm)	Length (mm)	Regenerator matrix
No. 3	Regenerator I′	21	15	250-mesh SS
	Regenerator II′		60	400-mesh SS
No. 4	Regenerator II″		60	400-mesh SS
	Regenerator III″		15	500-mesh SS

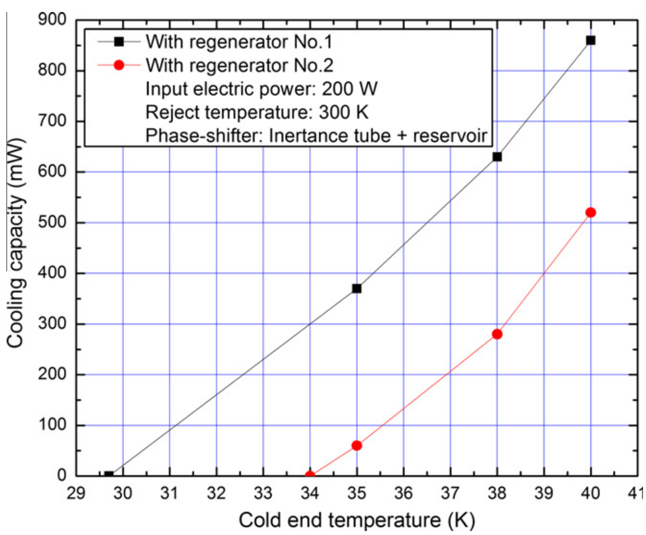

Fig. 2. Cooling performance of the developed PTC with regenerator No. 1 at several typical temperatures (performance with regenerator No. 2 is also shown for comparisons).

constant 400-mesh SS (regenerator No. 2) is also shown for comparisons.

The optimization of the three-segmented regenerator is based on the principle of minimizing the flow resistances while keeping the necessary thermal penetration depths of the regenerator matrix along the whole regenerator. The comparison experiments have been conducted, and it shows that the development of the mixed regenerator is an important optimization measurement to enhance the refrigeration performance in the range of 30–40 K. Fig. 2 shows the cooling performance of the developed PTC with regenerator No. 1 at several typical temperatures, while the performance of the PTC with regenerator No. 2 is also shown as comparisons. For the PTC with a single regenerator, when other cooler components are kept the same except that the inertance tubes have been optimized for the corresponding regenerator geometry, a no-load temperature of 34 K and a net cooling power of 0.52 W at 40 K have been achieved with an electric input power of 200 W and at 300 K reject temperature. However, when the three-segmented regenerator is used, the no-load temperature goes down to 29.7 K and the cooling capacity at 40 K increases evidently to 0.86 W.

In order to investigate which segment of the three-segmented mixed regenerator, of the 500-mesh one on the cold end and 250-mesh one on the warm end, makes a greater contribution to the enhancement of the cooling performance of the PTC, the additional comparison experiments have been performed. Two double-segmented regenerators have been made, which cancel the 250-mesh or 500-mesh

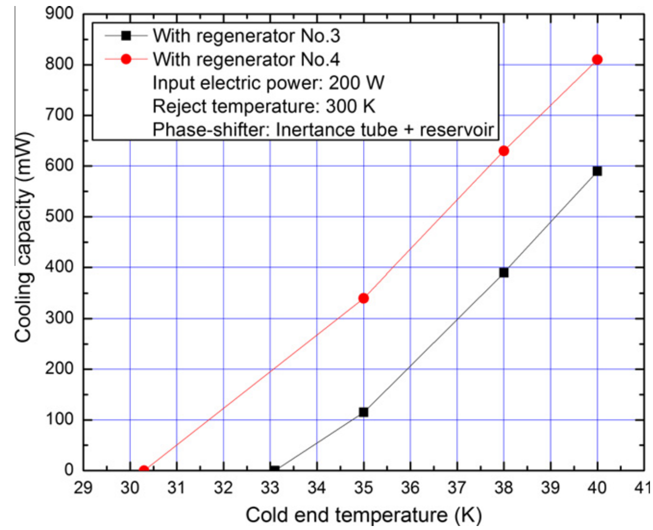

Fig. 3. The comparison experiments with regenerators No. 3 and No. 4.

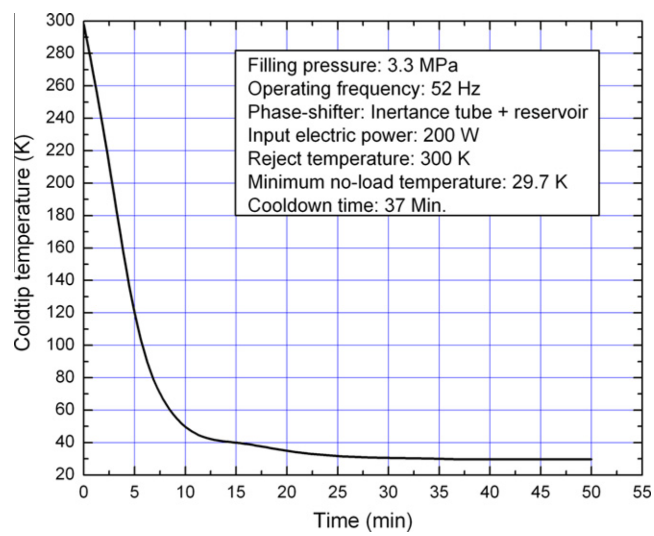

Fig. 4. Typical cool-down curve of the developed 40 K PTC.

segments while prolonging the 400-mesh to keep the same length, respectively. The key dimensional parameters of the regenerators are shown in Table 3. However, it should be pointed out that the inertance tubes for the two PTCs have to be optimized again to achieve the optimal phase relationships, since the flow resistances in the regenerators are changed. As shown in Fig. 3, under the optimal operating conditions, the PTC with regenerator No. 3 achieves a no-load temperature of 33.1 K and a cooling power of 0.59 W at 40 K, while the PTC with regenerator No. 4 achieves a no-load temperature of 30.3 K and 0.81 W at 40 K. In the preliminary analysis, it shows that the 500-mesh segment makes the main contribution on improving the PTC performance by enhancing the regenerative capacity at the lower temperature, while the 250-mesh segment also makes partial contributions by reducing the flow resistance at the warm end.

The fine slot heat exchanger has become an effective optimization means in designing the high frequency single-stage PTC operating above 50 K in the same group [15–17]. The fine slots increase the effective heat exchange area for the given dimensions, and also become additional straighteners at both ends to suppress the turbulence introduced by the flow reversal. As the operating working

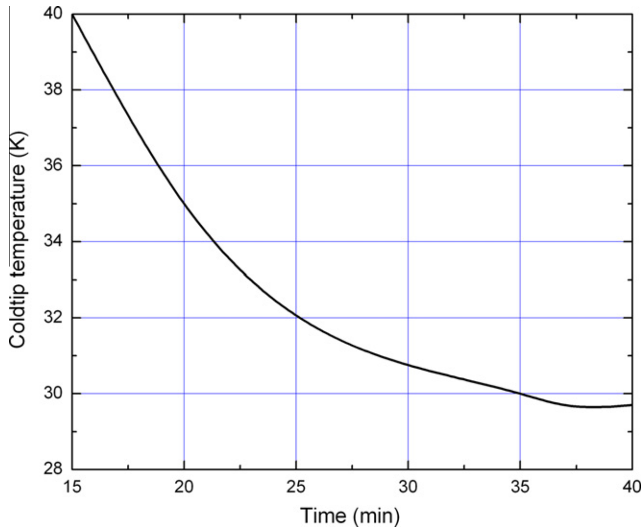

Fig. 5. Detailed cool-down process below 40 K.

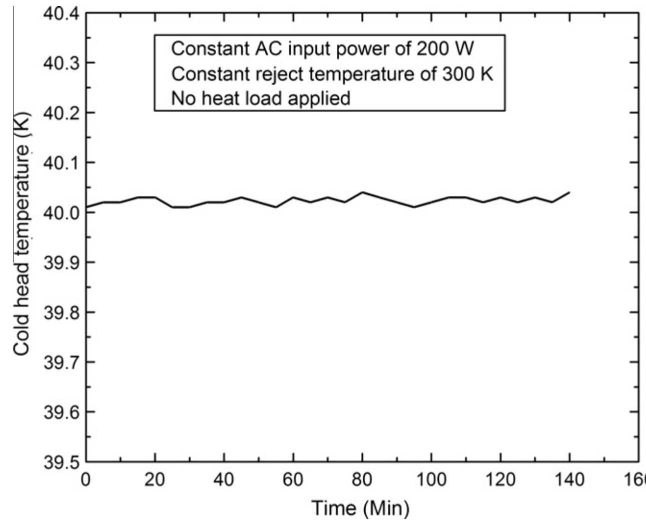

Fig. 7. Temperature stability of the developed 40 K PTC during 150 min.

temperature goes down to 40 K or below, there will be much more demanding requirements on the high efficiency of the cold and warm-end heat exchangers to exchange the heats as soon. Therefore, for both exchangers, each slot is fabricated by the EDM technology into with the slot width as narrow as 0.15 mm, instead of the 0.2 mm used in the 60 K PTCs [16]. The determination of the slot width is a tradeoff between the pressure drop and heat transfer. By narrowing the width and increasing the number of slots, one can effectively enhance the heat transfer, however, it also increases the flow resistance through the slots correspondingly. In the optimization, it is found that the slot width of narrower than 0.15 mm (but still wider than 0.1 mm) has no evident impact on the improvement of the overall performance. It is difficult for our present technology to cut the smooth and straight slots smaller than 0.1 mm. Therefore, the experiments on the much finer slots have not been attempted and their effects are not clear presently.

The typical cool-down curve of the developed 40 K PTC is shown in Fig. 4. It takes about 37 min for the cold tip to cool down from 298 K to the no-load temperature of 29.7 K. The more detailed cool-down process below 40 K is shown in Fig. 5 as a supplement.

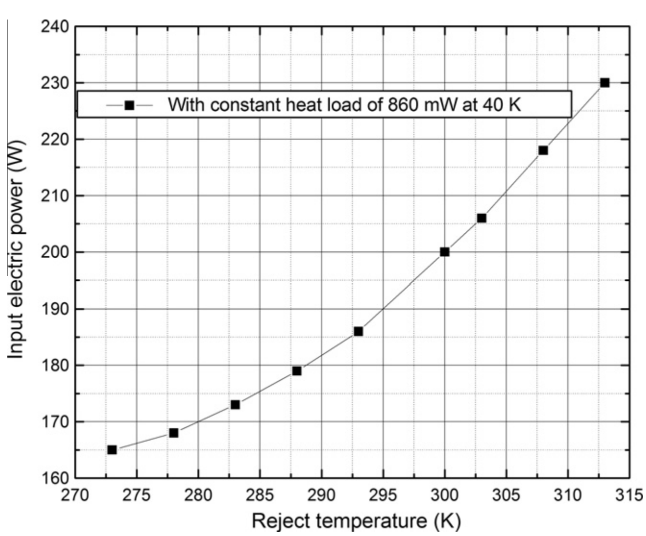

Fig. 6. Cooler's sensitivity to heat sink with constant heat load of 860 mW at 40 K.

4. Ambient temperature adaptability

The investigation on the temperature adaptability of the developed 40 K PTC is conducted. An experiment is performed to examine the cooler's sensitivity to the heat sink with the constant heat load of 860 mW at 40 K, as shown in Fig. 6. It shows that with a reject temperature of 273 K, the aimed cooling capacity is achieved with only an input electric power of 165 W. However, a 230 W input electric power has to be applied in order to keep the same cooling performance when the reject temperature increases to 313 K. The dramatic change of the input power with the reject temperature will bring very adverse effect on the PTC operating in a fluctuating source temperature environment. The investigations on suppressing the effect are underway.

5. Temperature stability

The developed 40 K single-stage PTC system only adopts the inertance tube together with a reservoir to realize the stable performance. Before the acceptance tests are conducted, the cold head temperatures have been monitored over a relatively longer period to examine the temperature stability at 40 K. The measurements are performed in open loop, with no heat load is applied, and the Ac input power into the compressor and the reject temperature are kept at constant 200 W and 300 K, respectively. Fig. 7 shows the experimental results of the stability of the cold tip temperature during 150 min. The fluctuations are far below the required ±0.1 K.

6. Discussions and conclusions

The 40 K single-stage coaxial high frequency pulse tube cryocooler (PTCs) have been developed to provide reliable and low-noise cooling for GaAs/AlGaAs QWIPs, which have a potential space application to replace some $Hg_{1-x}Cd_xTe$ based IR detector arrays in the range of very long wavelength (such as >15 μm).

The single-stage arrangement is employed instead of two-stage to minimize the complexity of the cooler system. Furthermore, in order to avoid the potential instability induced by the possible DC effect, the double-inlet mechanism is excluded while the phase shifting mechanism only uses the inertance tubes together with the corresponding gas reservoir. The coaxial geometrical arrangement is chosen instead of the in-line type to ease the integration between the cold head and the cooled detectors.

A mixed regenerator, which consists of three segments filled into with the different meshes stainless steel screens, respectively, has been developed to enhance the regenerator performance at the coldest end and also to minimize the overall flowing resistance along the tube.

At present, the developed cooler prototypes, which weights 7.5 kg including the cooler control electronics, has achieved a no-load temperature of 29.7 K, and can typically provide 860 mW cooling at 40 K with 200 W electric input power at 300 K reject temperature. The preliminary experiments show that the long-term temperature stability (<150 min) of the cold head is also within the required limit.

In the practical experiments, it is found that the developed QWIPs shows better performance when the cold head temperature decreases by 2 K. Therefore, the performance of the developed PTC will be further optimized correspondingly at the temperatures of 38 K or even lower in the next step.

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References

[1] Kukkonenb CA, Sirangelo MN, Chehayeb R, et al. Commercialization of quantum well infrared photodetector focal plane arrays. Infrared Phys Technol 2001;42(3–5):397–405.
[2] Li N, Guo FM, Zhen H, et al. Detection wavelengths and photocurrents of very long wavelength quantum-well infrared photodetectors. Infrared Phy Technol 2005;47(1):29–36.
[3] Radebaugh R. Pulse tube cryocoolers for cooling infrared sensors. In: Proceedings of SPIE 4130; 2000.
[4] Nast TC, Olson J, Evtimov B, et al. Development of a two-stage pulse tube cryocooler for 35 K cooling. Cryocoolers 2003;12:213–8.
[5] Jaco C, Nguyen T, Harvey D, et al. High Capacity Staged Pulse Tube Cryocoolers 2005;13:109–13.
[6] Nguyen T, Colbert R, Durand D, et al. 10 K pulse tube cooler. Cryocoolers 2007;14:27–31.
[7] Dietrich M, Thummes G. Two-stage high frequency pulse tube cooler for refrigeration at 25 K. Cryogenics 2010;50(4):281–6.
[8] Burt WW, Chan CK. Demonstration of a high performance 35 K pulse tube cryocooler. Cryocoolers 1995;8:313–9.
[9] Burt WW, Chan CK. New mid-size high efficiency pulse tube coolers. Cryocoolers 1997;9:173–82.
[10] Ren J, Dai W, Luo E. Experimental investigation on a single-stage Stirling-type pulse tube cryocooler working below 30 K. Cryocoolers 2011;16:51–5.
[11] Petach M, Waterman M, Tward E, et al. Pulse tube microcooler for space applications. Cryocoolers 2007;14:89–93.
[12] Jaco C, Nguyen T, Tward E. High capacity two-stage coaxial pulse tube cooler. Adv Cryo Eng 2008;53:530–7.
[13] Yang LW, Xun YQ, Thummes G, et al. Single-stage high frequency coaxial pulse tube cryocooler with base temperature below 30 K. Cryogenics 2010;50(5):342–6.
[14] Gedeon D. DC gas flows in stirling and pulse tube refrigerators. Cryocoolers 1997;9:385–92.
[15] Dang HZ. High frequency coaxial pulse tube cryocoolers for cooling infrared focal plane arrays. In: Proceedings of SPIE 7854, 2010.
[16] Dang HZ, Wang LB, Wu YN, et al. Performance investigation on SITP's 60 K high frequency single-stage coaxial pulse tube cryocoolers. Cryocoolers 2011;16:149–56.
[17] Dang HZ. Development of high frequency pulse tube cryocoolers for space applications. Adv Cryo Eng, 2012; 57, in preparation.