第42卷第2期
2023年4月

红外与毫米波学报
J. Infrared Millim. Waves

Vol. 42, No. 2
April,2023

文章编号：1001-9014(2023)02-0188-05

DOI：**10. 11972/j. issn. 1001-9014. 2023. 02. 006**

Research on the adaptability of space environment about NbN superconducting SIS mixer for high sensitivity terahertz detection module

ZHANG Kun[1,2], YAO Ming[1], LIU Dong[1], LIU Bo-Liang[1,2], LI Jing[1], YAO Qi-Jun[1], SHI Sheng-Cai[1*]

(1. Purple Mountain Observatory, Chinese Academy of Sciences, Nanjing 210034, China;
2. School of Astronomy and Space Sciences, University of Science and Technology of China, Hefei 230026, China)

Abstract: The high sensitivity terahertz detection module (HSTDM) is one of the scientific instruments of the China Sky Survey Telescope. HSTDM is a high-resolution spectrometer and the first space heterodyne receiver using niobium nitride (NbN)-based superconducting tunnel junction (Superconductor - Insulator - Superconductor (SIS)) mixer (the NbN SIS mixer). The NbN SIS mixer must meet the specification requested for a space environment, such as high operation reliability, robustness to vibration, cosmic irradiation, and thermal variation. This paper presents the space qualification tests performed on the NbN SIS mixer, including sine and random vibration tests, single-particle irradiation test, total dose radiation test, and thermal cycling test. The mixer's performance analysis confirms that it can meet the space application requirements of HSTDM.

Key words: terahertz(THz), superconducting, superconductor - insulator – superconductor(SIS) mixer, space-qualified

高灵敏度太赫兹探测模块氮化铌超导SIS混频器空间环境适应性研究

张　坤[1,2]，姚　明[1]，刘　冬[1]，刘博梁[1,2]，李　婧[1]，姚骑均[1]，史生才[1*]

(1. 中国科学院紫金山天文台,江苏 南京210034;
2. 中国科学技术大学,天文与空间科学学院,安徽 合肥 230026)

摘要:高灵敏度太赫兹探测模块(High Sensitivity Terahertz Detection Module, HSTDM)是中国巡天望远镜的科学载荷之一。HSTDM是一台工作频段为410~510 GHz的高灵敏度高频率分辨率的外差混频接收机,其核心是工作在10 K温区的氮化铌(NbN)基超导隧道结(Superconductor - Insulator – Superconductor, SIS)混频器。HSTDM将首次实现氮化铌(NbN)基超导SIS混频器的空间应用。NbN基超导SIS混频器应适应空间环境的特殊要求,如高可靠性,对振动、宇宙辐照和热变化的适应性。对NbN基超导SIS混频器进行的鉴定试验测试,包括正弦振动试验、随机振动试验、单粒子辐照试验、总剂量辐照试验和热循环试验。研究结果表明氮化铌(NbN)基超导SIS混频器能够满足HSTDM的空间应用需求。

关　键　词:太赫兹;超导;超导隧道结(Superconductor – Insulator – Superconductor, SIS)混频器;空间适应性

中图分类号:P16　　**文献标识码**:A

Introduction

The China Sky Survey Telescope (CSST) is an optical broadband space observation instrument that co-orbits with the China Space Station, as shown in Fig. 1. CSST is scheduled for launch in 2024 and should operate in orbit for more than ten years. When operational CSST will provide unprecedented astronomical observational opportunities in the optical and THz bands and study cosmic dark matter, dark energy, compact celestial bodies, and the formation and evolution of galaxies [1]. Carrying out THz astronomical observations in space can eliminate the influence of the earth's atmosphere on the absorption

---

Received date: 2022-08-29, **revised date**: 2022-12-23　　**收稿日期**:2022-08-29,**修回日期**:2022-12-23

Foundation items: Supported by National Natural Science Foundation of China (11925304, 12020101002, 11903086, 11903087, 11973095), Foundation of the Chinese Academy of Sciences (QYZDJ-SSW-SLH043, GJJSTD20210002)

Biography: ZHANG Kun(1985-), male, Zhangjiakou China, senior engineer, master. Research area involves integration and testing of THz superconducting receiver systems. E-mail: zhangkun@pmo. ac. cn

[*] **Corresponding author**: E-mail: scshi@pmo. ac. cn

of THz signals [2-3] and obtain remarkable scientific achievements in THz astronomy [4-7]. CSST will provide a good opportunity for China's THz astronomical observation.

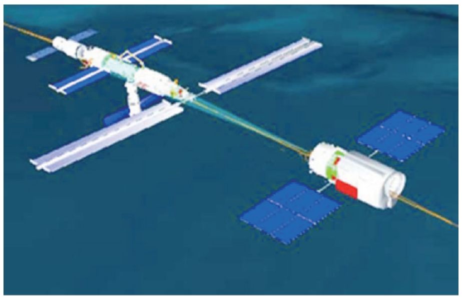

Fig. 1 Schematic diagram of the co-orbit flight between CSST and China Space Station
图1 中国巡天望远镜与中国空间站共轨飞行示意图

High sensitivity terahertz detection module (HSTDM) is one of the scientific instruments onboard the CSST. HSTDM is a high-resolution spectrometer and the first space heterodyne receiver using NbN SIS mixers with nearly five times quantum-noise limited sensitivity. The specifications of HSTDM compared with HIFI band 1[8] and Odin are shown in Table 1. Covering a frequency range from 410 GHz to 510 GHz and a 2 GHz wide intermediate frequency (IF) and with a spectral resolution higher than HIFI and Odin, HSTDM will probe many astrophysical sources via their rotational molecular lines. HSTDM will detect many molecular spectral lines in the 410–480 GHz for the first time in space.

HSTDM is another device that uses SIS mixer receivers in space after Herschel HIFI and JEM/SMILES [9]. The HIFI and JEM/SMILES have realized the space application of Nb superconducting SIS mixers, and HSTDM will achieve the space application of NbN SIS mixers for the first time. The superconducting transition temperature (Tc) of NbN is about 16 K, so the NbN SIS mixer can work at 10 K temperature region [10], which can significantly reduce the difficulty of space cooling. For the space application of HSTDM, NbN SIS mixers should meet the requirements of high operation reliability and adaptation to the space environment. This paper studies the space environment adaptability of NbN SIS mixers from three aspects: vibration, cosmic irradiation, and thermal variation.

1 Design and characterization of NbN SIS mixer

The NbN SIS mixer chip is installed in a mixer block (as shown in Fig. 2), which provides mechanical, optical, electrical, and thermal interfaces for the chip. The size of the mixer block is 59 mm×43 mm×25 mm, and it is composed of a local oscillator signal horn, a radio frequency signal horn, a waveguide directional coupler, and a base cover. The LO and RF signals are combined by the directional coupler and then transmitted to the chip through the waveguide. The chip is installed in the chip-packaging slot with hot melt wax and connected to the bias-T circuit and block by ultrasonic spot welding with Φ25 μm aluminum wire. The IF SMA connector, DC bias connector, and DC bias circuit board are mounted on the cover of the block. To meet the specified connection interfaces of the mixer block, an orthogonal transition was needed between the IF output SMA connector and the bias-T board. We have chosen the low transmission loss and flexible POGO connectors between the IF SMA connector and the bias-T board and between the DC bias board and the bias-T board [11]. The POGO pins are pressed on the DC and IF pads via spring to transmit the signals. We use permanent magnets to suppress the Josephson effect of the NbN SIS mixer, which are mounted in the block on both sides of the mixer.

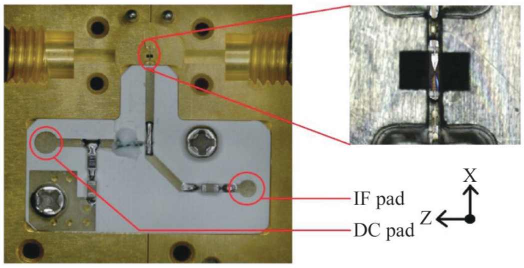

Fig . 2 Images of the SIS chip and bias-T board in the block
图2 混频器腔体内SIS芯片和bias-T电路照片

We have characterized the performance of the NbN SIS mixer before the mechanical vibration and particle irradiation test. Figure 3 shows the I-V curves of the NbN SIS mixer at room temperature and low temperature. According to the calculation, we can obtain that the room temperature resistance of the NbN SIS mixer is about 225 Ω, and the mixer energy gap voltage V_{gap}=5. 5 mV, normal resistance R_n=30. 1 Ω. The receiver noise temperature was derived by the Y-factor method, monitoring the receiver IF output with hot (300 K) and cold (77 K) loads presented at the receiver input. Figure 4 shows the LO-pumped I-V curve along with the IF power output for the hot and cold loads at 490 GHz. The receiver noise temperature at 490 GHz is about (170±5) K.

Table 1 Specifications of HSTDM, HIFI band1, and Odin
表1 HSTDM,HIFI band1 和Odin的技术参数

	Frequency/GHz	Angular resolution /arcsec	Noise temperature /K	Spectral resolution /kHz
Odin	486~504/541~580	120	3 000	1 000
Herschel HIFIband 1	480~640	40	70~110	125
HSTDM	410~510	<100	<250	<100

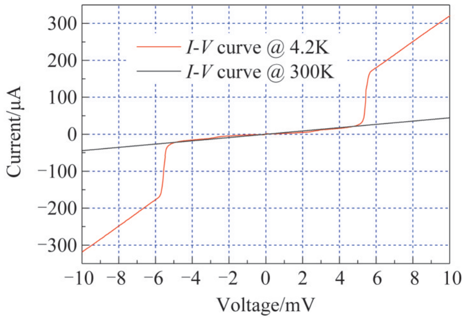

Fig. 3 *I-V* curves of NbN SIS mixer at room temperature and 4. 2 K
图3 NbN SIS混频器在常温和4. 2 K时的*I-V*曲线

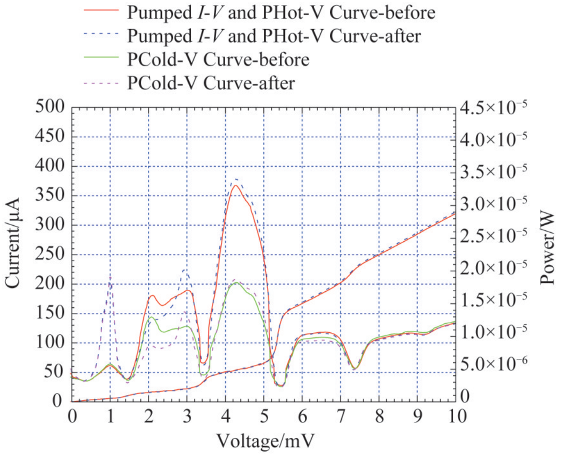

Fig. 4 LO-pumped *I-V* curve and IF power curves at 490 GHz
图4 混频器在本振信号为490 GHz时泵浦*I-V*曲线和中频功率曲线

2 Vibration test

The size of the NbN SIS mixer chip is 2 000 μm×102 μm×51 μm, and the weight is about 27 μg, the tunnel junction area is about 1 μm^2. The chip itself is not sensitive to mechanical vibration. The POGO connectorc and fixation of the mixer chip or bonding might fail after repeated thermal cycling test or due to the strong vibrations during launch. HSTDM can use POGO connectors because it has been proven on HIFI, but environmental tests still need to verify its reliability. Sticking and fixing tiny chips with hot-melt wax has been widely used in the packaging of superconducting mixers on ground-based telescopes, but HSTDM will apply this method in space for the first time, so it is necessary to verify the reliability of the mixer chips through mechanical tests. To prevent the bonding wires from breaking or the welding spots from falling off due to vibration during the launching process, wax was used to seal the bonding wires and the welding spots at both ends of the mixer chip to improve the mechanical resistance. Therefore we vibration-tested at room temperature, at the Technical Institute of Physics and Chemistry (TIPC), CAS, a complete demonstration model (DM) containing a real NbN SIS mixer. The tests include sine vibration and random vibration. The vibration specifications from the decomposition of CSST qualification vibration conditions in the three directions of *X*, *Y*, and *Z* are listed in Table 2.

The mixer block was bolted on an interface plate and then installed on the vibration table, in different configurations to test all three axes *X*, *Y*, and *Z*. One accelerometer was fixed on the plate for monitoring the mechanical response of the mixer block during the vibration process.

First, there was no major resonance during the vibration test at low frequencies(<200 Hz). One small (1 g) resonance showed up near 1 260 Hz in the random test for the *X* axes, and one small (0. 5 g) resonance showed up near 1 790 Hz in the random rest for the *Z* axes. It could be a resonance in the interface plate bolting, or in the mixer unit itself. Furthermore, such a high-frequency resonance presents no threat to the mixer.

Second, these tests were an opportunity to test the reliability of the SIS mixer mounting and gluing techniques, the POGO connectors, and the circuit boards soldered on the aluminum block. We found no damage on any mechanical part after the vibration tests, and the mixer chip is not loose.

Table 2 Vibration specifications in *X*, *Y*, and *Z*
表2 X/Y/Z方向的振动量级参数

X		*Y*、*Z*	
Sine Vibrations			
Frequency/Hz	Qualified level	Frequency/Hz	Qualified level
10~15	8. 83 mm	5~15	6. 62 mm
15~30	8 g	15~70	6 g
30~100	6. 5 g	70~100	4. 44 g
Sweep rate	2 oct/min	Sweep rate	2 oct/min
Random Vibrations			
Frequency/Hz	Qualified level	Frequency/Hz	Qualified level
10~20	9 dB/oct	10~20	9 dB/oct
20~200	0. 075 g^2/Hz	20~200	0. 031 5 g^2/Hz
200~2 000	−3 dB/oct	200~2 000	−3 dB/oct
Duration	2 min	Duration	2 min

Third, we tested the unpumped and LO-pumped *I-V* curves and the IF power for the hot and cold loads at 490 GHz to study the effect of mechanical vibration on the performance of NbN SIS mixer. The IF power outputs are basically the same before and after the vibration tests with the same pumping current of the mixer. Comparison of the NbN SIS mixer characteristics before and after the vibration test demonstrates no loss of function or performance degradation. The test results show that the fixation of the NbN SIS mixer chip and the bonding wire connection is reliable, and the POGO connector can adapt to the mechanical vibration environment.

3 Radiation test

CSST operates at Low-Earth Orbit (LEO) with an orbital altitude of about 400 km. The main sources of LEO charged particle radiation are: (1) Galactic cosmic rays (charged particles from outside the solar system); (2) Electrons and protons captured by the Earth's radiation belts; (3) Solar cosmic rays [12]. High-energy heavy ions and protons in galactic and solar cosmic rays, as well as high-energy protons in the Earth's radiation belts, can induce single-event effects in microelectronic devices. The long-term accumulation of electrons and protons on the device may affect the performance of optoelectronic devices and cause device damage. The orbital height of CSST is about 400 km, and it will operate in orbit for 10 years. The components must be anti-single-event flipping and anti-single-event locking and can withstand a total ionizing dose of not less than 20 krad (Si).

According to the influence of particle irradiation on the ESA-ISO detector, the probability that particles hit a 1 μm^2 tunnel junction is about once every 10^7 seconds [13], so the probability of the NbN SIS mixer in orbit being affected by charged particles during operation is very low. The single event effect on the NbN SIS mixer may be the breakdown of the tunnel junction barrier layer caused by the bombardment of high-energy particles, thereby affecting the energy gap voltage and leakage current of the mixer. Total dose radiation exposure may cause damage to the mixer, resulting in deterioration of its performance or loss of function. Therefore it is important to assess the resistance to ionizing radiation of SIS mixers. We conducted single-particle irradiation and total dose irradiation experiments on NbN SIS mixers to study the effect on the performance of NbN SIS mixers. The cover of the mixer block was opened so that the particles can radiate on the mixer chip. The bias voltage and current were monitored during the irradiation test. We use three heavy ions to radiate the NbN SIS mixer for the single-particle irradiation test. Table 3 shows the parameters of single-particle irradiation. The bias voltage and current of the NbN SIS mixer are changeless during single-particle irradiation. The test results show that the single-event effect threshold value of the NbN SIS mixer is greater than 37.31 MeV·cm^2/mg.

We performed 20 krad (Si) irradiation test on the NbN SIS mixer using Co60, while the irradiation time was 56 hours. The bias voltage and current of the NbN SIS mixer were changeless during the test. Figure 4 shows the LO-pumped *I*-*V* curves of the NbN SIS mixer before and after the irradiation test at 490 GHz and the IF power output for the cold and hot loads. The test results show that the mixer's gap voltage and normal-state resistance did not change after irradiation, and the particle irradiation did not cause loss of function to the NbN SIS mixer. The differences in *P*-*V* curves between 0 mV to 3 mV are due to the Josephson effect caused by different magnetic fields of the test system.

According to the IF power corresponding to the cold and heat load, we can obtain the receiver noise temperature using the Y-factor method in the bias voltage range of 3.8–4.4 mV shown in Fig. 5. The results show that the receiver noise temperature does not deteriorate significantly after irradiation with a total dose of 20 krad (Si), but there are some differences in the noise temperature before and after irradiation. Combined with the characterization of the DC and mixing characteristics of the NbN SIS mixer before and after irradiation, the main reason might be the differences in the measurement system and test environment between the twice experiments. When CSST works in orbit, the block, cryostat, HSTDM structure frame, and CSST shell can provide effective shielding for the mixer chip to reduce the total ionizing dose and the energy of high-energy particles reaching the chip. The NbN SIS mixer chip's external structure has an equivalent aluminum thickness of about 8 mm, and the effective total dose reaching the chip is about 840 rad (Si), which is much smaller than 20 krad (Si). The test results show that the NbN SIS mixer is insensitive to single-particle irradiation and can withstand irradiation with a total dose of 20 krad (Si).

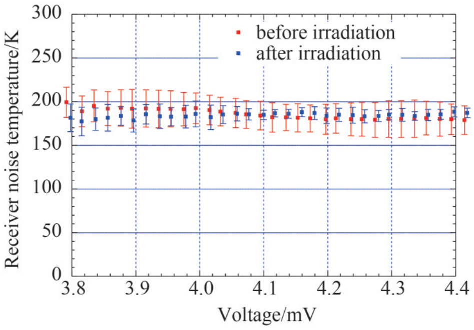

Fig. 5 Receiver noise temperature before and after irradiation at 490 GHz
图5 接收机在辐照前后的噪声温度(本振为490 GHz)

4 Thermal cycling and bake-out test

Thermal cycling test could evaluate and validate thermal design safety margins and accelerate exposure to potential defects in products, eliminate early failures, and improve product reliability. The thermal cycling test conditions of NbN SIS mixer are from 4 K to 300 K, with 20-30 cycles [11,13]. Extensive experience exists from laboratory dipstick measurements and indicates that no prob-

Table 3 Parameters of the single-particle irradiation
表3 单粒子辐照参数

Particle type	Energy/MeV	LET/(MeV·cm^2/mg)	Range in silicon/μm	Irradiation time/mins	Total particles
$^{48}Ti^{10,15+}$	169	21.8	34.7	4	2.9×10^6
$^{35}Cl^{11,14+}$	160	13.05	46.03	3	6.1×10^6
$^{74}Ge^{11,20+}$	208	37.31	30.3	4	6.8×10^5

lem is to be expected. We have tested the integrated block for more than 20 cycles in the laboratory. The results showed that the thermal cycling test did not affect the performance of the NbN SIS mixer chip. The POGO connectors, wax fixation, and electronic components adapt to the thermal cycling test.

The internal structures of the HSTDM cryostat need to be baked at 80 ℃ before launching to remove the internal contamination gas. However, during junction fabrication, higher temperatures are used for baking the photoresist, and SIS mixer chips are heated at about 120 ℃ when mounted, so the bake-out test is OK for the NbN SIS mixer. We will test the mixer for its resistance to a 140-hour long, 80 ℃ bake-out in a thermal vacuum chamber.

Through the performance test of the NbN SIS mixer after the thermal cycling test, the results show that the mixer can adapt to the working thermal environment.

5 Conclusion

This paper has described the tests space qualification of NbN SIS mixers, including mechanical vibration test, particle irradiation test, and thermal cycling test. The DM has successfully passed these tests. Properties characterization of the mixer before and after the tests demonstrates that the mixer and the integrated block can adapt space environment. The research results in this paper have guiding significance for the qualification model development of HSTDM.

Acknowledgment

We acknowledge the vibration tests done by LIU Yan-Jie and QUAN Jia at TIPC, CAS.

References

[1] Gu Y D. The China Space Station: a new opportunity for space *science* [J]. *National Science Review*, 2022, **9**(01):6.

[2] De Lucia F C. Science and technology in the submillimeter region [J]. *Optics & Photonic News*, 2003, **14**(8):44-50.

[3] Shi S C, Paine S, Yao Q J, *et al.* Terahertz and far-infrared windows opened at Dome A in Antarctica[J]. *Nature Astronomy*, 2016, **1**(1): 0001.

[4] Hjalmarson Åke, Bergman P, Biver N, *et al.* Recent astronomy highlights from the Odin satellite[J]. *Advance in Space Research*, 2005, **36**(6):1031-1047.

[5] Fixsen D J. The temperature of the cosmic microwave background [J]. *The Astrophysical Journal*, 2009, **707**(2):916.

[6] Costa A A, Xu X D, Wang B, *et al.* Testing the interaction between dark energy and dark matter with Plank data[J]. *Physical review D*, 2014, **89**(10): 103531-1 ~ 103531-13 .

[7] González-Alfonso E, Fischer J, Isaak K, *et al.* Herschel observations of water vapour in Markarian 231[J]. *Astronomy & Astrophysics*, 2010, **518**(1):L43.

[8] Doyle D, Pilbratt G, Tauber J. The herschel and planck space telescopes[J]. *Proceedings of the IEEE*, 2009, **97**:1403-1411.

[9] Manabe T. Development of Superconducting Submillimeter-Wave Limb-Emission Sounder (JEM/SMILES) aboard the International Space Station[J]. *Journal of the Communications Research Laboratory*, 2002, **49**(2):17,.

[10] Jing Li, M. Takeda, Z. Wang, *et al.* Low-Noise 0.5 THz All-NbN Superconductor -Insulator- Superconductor Mixer for Submillimeter Wave Astronomy[J]. *Appl. Phys. Letts.* 2008, **92**:222504.

[11] Delorme Y, Salez M, Lecomte B, *et al.* Space-qualified SIS mixers for Herschel Space Observatory's HIFI Band 1 instrument[C]. In: 16th International Symposium on Space Terahertz Technology, May, 2005.

[12] Benton E R, Benton E V. Space radiation dosimetry in low-Earth orbit and beyond[J]. *Nuclear Instruments and Methods in Physics Research B*, 2001, **184**(1-2):255-294.

[13] van de Stadt H, Gao J R, de Graauw T, *et al.* Assessment of Submillimeter Heterodyne Mixers for Space applications[C]. In: Proc. 30th ESLAB Symp., Submillimeter and Far-Infrared Space Instrumentation, Sep.1996.