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博士学位论文摘要选登

# 太赫兹频段氮化铌超导隧道结混频特性研究及天文应用

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高灵敏度超导混频技术是推动天体物理前沿领域 — 太赫兹天文观测研究发展的重要因素之一. 目前, 已被广泛应用的铌超导隧道结的灵敏度已接近量子极限, 但其能隙频率仅为 0.7 THz. 高于该频率, 超导体会吸收光子能量拆散其中 Cooper 对 (能量耗散过程), 进而导致探测灵敏度恶化. 因此, 研究基于更高能隙超导体的太赫兹混频技术具有特别重要的意义. 氮化铌超导隧道结的能隙频率是铌的 2 倍, 其制备技术近年来取得很大进展, 但较于铌隧道结的优势尚未显现, 也未实现天文观测应用.

基于上述背景, 论文开展了太赫兹频段氮化铌超导隧道结量子混频特性的系统研究, 并利用研制的 0.5 THz 频段氮化铌超导隧道结混频器开展天文试验观测. 取得的主要研究成果包括: (1) 实现基于高介电常数 MgO 基板的 0.4∼0.6 THz 宽带波导型信号耦合回路的数值模拟; (2) 成功制备能隙电压高达 5.6 mV 、质量因子高达 15 的全氮化铌超导隧道结; (3) 研制的 0.5 THz 频段波导型氮化铌超导隧道结混频器的实测接收机噪声温度低达 5 倍量子极限, 是同频段氮化铌超导隧道结实现的最好噪声性能; (4) 首次实验展示了氮化铌超导隧道结在高达 10 K 温区仍有接近量子极限的噪声性能以及不易受 Josephson 效应干扰 (更高稳定性) 的独特优势; (5) 在国际上首次实现应用氮化铌超导隧道结的天文观测.

论文研究工作对氮化铌超导隧道结的太赫兹频段量子混频特性有了更深入的理解, 实现了接近量子极限探测灵敏度以及天文试验观测, 并展示了其宽工作温度区间和高稳定性等独特优势, 为将来实现 1 THz 以上频率氮化铌超导混频技术的应用 (特别是空间及大规模系统) 打下重要基础.

# Terahertz Mixing Characteristics of NbN Superconducting Tunnel Junctions and Related Astronomical Observations

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High-sensitivity superconducting SIS (superconductor-insulator-superconductor) mixers are playing an increasingly important role in the terahertz (THz) astronomical observation, which is an emerging research frontier in modern astrophysics. Superconducting SIS mixers

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with niobium (Nb) tunnel junctions have reached a sensitivity close to the quantum limit, but have a frequency limit about 0.7 THz (i.e., gap frequency of Nb tunnel junctions). Beyond this frequency Nb superconducting films will absorb energetic photons (i.e., energy loss) to break Cooper pairs, thereby resulting in significant degradation of the mixer performance. Therefore, it is of particular interest to develop THz superconducting SIS mixers incorporating tunnel junctions with a larger energy gap. Niobium-nitride (NbN) superconducting tunnel junctions have been long known for their large energy gap, almost double that of Nb ones. With the introduction of epitaxially grown NbN films, the fabrication technology of NbN superconducting tunnel junctions has been considerably improved in the recent years. Nevertheless, their performances are still not as good as Nb ones, and furthermore they are not yet demonstrated in real astronomical applications.

Given the facts mentioned above, in this paper we systematically study the quantum mixing behaviors of NbN superconducting tunnel junctions in the THz regime and demonstrate an astronomical testing observation with a 0.5 THz superconducting SIS mixer developed with NbN tunnel junctions. The main results of this study include: (1) successful design and fabrication of a 0.4∼0.6 THz waveguide mixing circuit with the high-dielectric-constant MgO substrate; (2) successful fabrication of NbN superconducting tunnel junctions with the gap voltage reaching 5.6 mV and the quality factor as high as 15; (3) demonstration of a 0.5 THz waveguide NbN superconducting SIS mixer with a measured receiver noise temperature (no correction) as low as five times the quantum limit ($5\hbar\omega/k_B$ ), which is the best among NbN superconducting SIS mixers developed in this frequency band; (4) demonstration of high sensitivity for NbN superconducting SIS mixers operated at temperatures as high as 10 K, and demonstration of much less interference resulting from the Josephson effect; (5) demonstration of the first astronomical observation ever done with an NbN superconducting SIS mixer.

This study has provided further understanding of the quantum mixing behaviors of NbN superconducting SIS mixers. It has been demonstrated that NbN superconducting SIS mixers can reach nearly quantum-limited sensitivity and have good stability. Furthermore, NbN superconducting SIS mixers have less stringent requirement for cooling and magnetic field compared with Nb ones. Hence they can be used in astronomical applications, especially for space-borne projects and complex systems such as multi-beam receivers.