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学 位 論 文 題 目　QUANTUM-LIMITED BROADBAND MIXERS WITH SUPERCONDUCTING TUNNEL JUNCTIONS AT MILLIMETER AND SUBMILLIMETER WAVELENGTHS

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論文内容の要旨

On the basis of the quantum theory of mixing and the quasi-five-frequency approximation, at first, the behavior of the mixing with a single SIS junction (or junction arrays in series) is thoroughly investigated in the frequency range of 100~650 GHz (i.e., below the gap frequency of Nb junctions), particularly in regard to the junction characteristic (i.e., the $\omega R_n C_j$ product) and the embedding impedances (seen by the SIS junction) at both the RF and IF frequencies. The optimum operating conditions of SIS mixers and their frequency dependences are studied. The conclusions provide general guidelines for the designing of SIS mixers, though being not necessarily limitations. In addition, some interesting results are described. As the quantum theory of mixing cannot be directly employed in simulating the performance of SIS mixers with parallel-connected twin junctions (PCTJ, separated by a tuning inductance), which is a tuning means for SIS junctions, both the large- and small-signal equivalent circuit models of the PCTJ are constructed in a general form of multi-sideband frequency ports. The mixing behavior of the PCTJ is then compared to that of a single junction.

Because SIS junctions of a relatively low critical current density are adopted to develop SIS mixers in this thesis, it is essential to resonate out the junction geometric capacitance to realize good mixer performance. Therefore, suitable tuning circuitry must be integrated with the SIS junction. Three types of junction tuning circuits, namely the parallel inductance, end-load (i.e., serial inductance), and PCTJ are thus compared, regarding to mainly the tuning bandwidth, input impedance at resonance, and fabrication easiness. As a result, the PCTJ appears a good first choice for submillimeter-wave SIS mixers.

To suit the PCTJ of a $\omega R_n C_j$ product equal to four and an equivalent normal state resistance equal to 10 Ω, a novel waveguide mixer mount, which is associated with a diagonal horn, is proposed. One of the key components of the mixer mount is the waveguide-to-microstrip transition (of a half-reduced-height waveguide) featuring an integrated dc/IF return and an offset coupling probe adopted to extend the working bandwidth. The RF and LO signals are transmitted from the input waveguide to a 75-Ω microstrip line via this transition, and then coupled to the PCTJ via two sections of 1/4-wavelength impedance transformer. The waveguide-to-microstrip transition is simulated by making use of the finite element method. The simulated and scaling (at Ka-band) experimental results, demonstrating a return loss (at the input port of the transition) of less than −15 dB over a 30% relative bandwidth (for a fixed backshort), are in good agreement. According to the proposed junction device and mixer mount, the performance of the 500-GHz waveguide SIS mixer is theoretically predicted. The predicted mixer performance is rather promising, giving an SSB conversion gain of −4.5~1.5 dB and an SSB mixer noise temperature of less than 45 K in the frequency range of 430~570 GHz. Hopefully, this mixer design can be scaled from 100 GHz up to 1 THz.

In terms of the design of the 500-GHz waveguide SIS mixer, four real SIS mixers at 100, 200, 270, and 500 GHz respectively, are constructed and measured. The 100-GHz SIS mixer exhibits a DSB receiver noise temperature of less than 40 K in the frequency range of 80~120 GHz, with a minimum value just four times as large as the quantum limit (i.e., $4h\nu/k$), which is comparable or superior to the state-of-the-art SIS mixers at this frequency band. In addition, two interesting mixing behaviors including one related to the ac Josephson effect are first observed at this frequency band, and they are discussed in detail. The experimental results of the 100-GHz SIS mixer are analyzed qualitatively. The analytical results support the experimental results in general. The 200- and 270-GHz receivers are both tested in a real radiometric system which employs a relatively high IF frequency (5~7 GHz) and a folded Fabry-Perot diplexer situated in front of the SIS mixer to combine the RF and LO signals. The receiver noise temperatures (DSB) calibrated before the SIS mixer, are approximately five times as large as the quantum limit for both receivers. The 500-GHz mixing experiment, carried out only around 482 GHz (for lack of LO sources), is associated with an SIS junction of a fairly large subgap leakage current. In spite of that, photon-assisted tunneling steps are clearly observed and the receiver noise temperature calibrated before the mixer's feed horn is only 176 K (~$8h\nu/k$). The experimental results are analyzed quantitatively, by evaluating the subgap leakage effect and breaking down the receiver noise performance. If corrected the effect of the subgap leakage current, which accounts for a 67-K noise contribution at the input port of the quasi-optical system and a 7-dB conversion-gain degradation, the mixer conversion gain (DSB) and noise temperature (DSB) would turn out to be only −0.5 dB and 35 K, respectively. Furthermore, the embedding impedance of the 500-GHz SIS mixer is extracted at 482 GHz using those LO-pumped dc I-V characteristics related to different LO power levels, and the extracted value is in good agreement with the simulated one. Likewise, the measured performance of the 500-GHz SIS mixer is compared to the quantum mixing theory, by simulating the mixer performance with the real dc I-V characteristic of the 500-GHz junction. Again, the experimental results agree with the theoretical predictions.

A very compact dual-frequency (100/230-GHz) SIS receiver is developed. The system design, particularly those related to the quasi-optical and 4-K cooling systems, is described in detail.

論文の審査結果の要旨

本学位論文は、ミリ波・サブミリ波による宇宙観測で基本的に重要となるＳＩＳミクサ型検出器において、優れた広帯域性能を実現できるデザインとして提案された対結合型トンネルジャンクション(PCTJ)の定量的解析法をはじめて確立し、試作実験によってその有効性を確認するとともに、検出感度においても従来のシングルジャンクション型の最高感度と同等の高い性能を実現できることを示したものである。

超伝導状態下でのトンネル効果を利用したSISミクサは、ミリ波・サブミリ波による星や惑星系の形成、原始銀河、星間物質の観測などの宇宙観測において広く用いられている検出器であり、各国の第一線の天文研究機関でその開発が競われている。国立天文台野辺山宇宙電波観測所では純ニオブを用いた安定なＳＩＳミクサを開発してきたが、さらにその広帯域化が可能な対結合型トンネルジャンクション（PCTJ）を野口らが提案した。これは２つのジャンクションを並列に置くことによって広い周波数にわたるインピーダンスの適正化を実現し、バックピストンによる機械的調整なしに広い帯域幅を確保できる方式である。機械調整なしでの広い観測波長域の確保は、波長が短く機械調整が困難になるサブミリ波や、現在世界的に進みつつあるマルチミクサ／マルチビーム受信器への前進、またスペースからのミリ波・サブミリ波観測など、今後の電波観測の中心を担う分野において、重要な意義を持つ方式と考えられる。

この新しいPCTJミクサをサブミリ波において世界で初めて実用化することを目的として、その基本的な解析手法の開発から着手し、実器の試作により性能の実証を行ったのが、申請者による本学位論文である。

本論文の中心となる研究とその成果は、全八章のうち第三章～第六章に述べられている。申請者はまずPCTJミクサの解析とモデリングをはじめて詳細に行い、さらにPCTJと導波管との結合回路構造をＦＥＭ（有限要素法）を用いて最適化することにより、観測波と中間波のよいカップリングが広い帯域にわたって実現できることを具体的に示した。これに基づいて100GHz～500GHzの導波管型ＳＩＳミクサの設計を行い、シミュレーション計算により目的とする性能の達成が可能なことを示した。ついで100GHz、210GHz、270GHz、及び500GHz帯のミクサの試作とそれらの性能の測定を研究協力者との共同で行い、その結果について解析を行った。100GHzミクサでは、80～117GHzの広い帯域にわたり受信器雑音25～40Ｋ（固定ピストン）という、雑音温度で世界トップレベル、帯域では最高の性能が実現された。210GHzおよび270GHz帯でもそれぞれ極めて優れた性能が達成され、PCTJ型ミクサの優位性を実証する結果を得た。500GHz帯では制作されたジャンクションの性能が十分でなかったが、雑音測定値の要因分析の結果、ジャンクション性能の改善でミクサ雑音温度100～200Kを達成する見通しを得た。

本審査委員会は、本研究が宇宙観測の上で重要なミリ波・サブミリ波の観測に大きな前進をもたらす新しい検出器の開発に成功したものであり、申請者はその過程においてオリジナリティを発揮し国際的に誇るべき優れた成果を導いたものとして、本論文を高く評価し、博士論文として十分な内容を備えたものであると判断した。