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SIS MIXERS

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Small area superconducting thin film tunnel junctions have properties which make them suitable for high frequency (≳100 GHz) heterodyne receivers. Both pair and single quasiparticle tunneling is present in the devices, but pair tunneling is found to be excessively noisy, whereas quasiparticle tunneling apparently gives hope of near quantum noise limited performance. The physical effect involved is photon assisted quasiparticle tunneling first observed by Dayem and Martin. A recent theory by Tucker has allowed a good understanding of many aspects of the phenomenon so that considerable hope exists for successful application of SIS mixer devices in fields such as millimeter and submillimeterwave astronomy. Some of the laboratory experiments and receiver construction efforts are reviewed in this article.

1. Introduction

In the past few years several advances have been made in the use of low-temperature technology to achieve improvements in microwave and millimeterwave detectors. In particular, the field of astronomical millimeterwave spectroscopy using heterodyne receiver techniques has benefited from the development of superconductor–insulator–superconductor (SIS) thin film junction mixer elements.

Superconducting tunneling effects have been in use for many years for microwave detection, but the most popular effect has been that of Josephson pair tunneling. Traditionally this was developed with point contact (whisker) geometries in order to keep the device capacitance small to allow high-frequency operation. However, it seems that such Josephson devices are intrinsically noisy (see the review article by Richards [3]), although the physical origin for the excess noise is difficult to describe. With the more recent advent of high resolution photolithography and electron beam lithography technologies, it became clear that the well-studied quasiparticle tunneling effects could be useful for detection, since the thin film junctions could be made small enough to reduce the unwanted junction parallel capacitance to negligible values, at least for microwave frequencies. This line of reasoning led to the use of SIS and SIN junctions for receivers [4, 5]. However, independently workers using the familiar Schottky barrier diode receivers concluded that greater sensitivity could be achieved with diodes by replacing the normal metal electrode with a superconducting electrode, in effect using the nonlinearity of the quasiparticle tunneling curve in what is known as the super-Schottky detector [6]. Of these various types of quasiparticle tunneling detectors the most promising seems to be the SIS. Although pair tunneling is allowed in this device, the excess noise associated with Josephson detectors can be avoided by constraining operation to the quasiparticle current dominated regime. The I–V curve nonlinearity is stronger for the SIS than for either the SIN or super-Schottky.

As is clear from the early papers [4, 5], the full

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importance of the photon assisted tunneling process was not immediately grasped. The theoretical discussion of Tucker [2] primarily concerned the super-Schottky diode, which, like the SIN, does not have a very obvious manifestation of the photon assisted tunneling process in the $I-V$ characteristics. However, as soon as clear photon assisted tunneling steps were observed in the SIS $I-V$ characteristics [7] it was obvious that the detection process was the same as for the Dayem–Martin effect [1] and the quantum nature of the devices was established.

It should be pointed out that the requirement of thermal cycling and chemical stability, which is present for computer applications of superconducting circuits, is the same as that for SIS mixers. Thus, another reason for attempting to use SIS mixers for receiver applications is the recent advance in metallurgy for the thin film junctions. A successful high-frequency SIS mixer junction must be of very small area, probably considerably less than 1 μm^2, and be stable and cyclable. With these constraints it is hard to produce a structure with the same sharpness in the $I-V$ characteristics as can be obtained using traditional metal (e.g. Sn) large area junctions. This is the primary reason that the early attempts [4, 5] did not definitively reveal the photon assisted effects.

2. Heterodyne receivers

Before discussing the SIS mixer receivers specifically, some attempt will be made to put them in perspective by briefly describing the current status for high-frequency mixer receivers in general.

To achieve high spectral resolution it is usual in the radio, millimeter and submillimeter wave bands to employ heterodyne receivers in which a local oscillator wave is coherently mixed with the signal. The mixer element is usually a diode-type device providing nonlinear response. The device must be capable of carrying currents at the signal frequency. The difference frequency between the signal and the local oscillator is available as an intermediate frequency (IF) over a somewhat restricted range (usually less than a GHz) depending on the capability of the low noise IF amplifier. Such a receiver is characterized by a noise temperature (T_R) which is contributed to by the noise generated in the mixer, which is equal to or greater than the quantum noise due to fluctuations in the local oscillator power, plus the noise of the IF amplification chain which appears as effectively multiplied by the power conversion loss factor (L) of the mixer. (The case of gain is properly handled by this expression in that L is less than 1 and T_{IF} becomes less important.)

$$T_R = T_M + LT_{IF} . \tag{1}$$

For the purposes of this paper all numbers are quoted for single side band operation (SSB), which is the usual spectroscopic mode. Noise temperature measurements are usually made with white noise, fixed temperature loads applied to the front end of the receiver, which affect both side bands equally. For small values of the IF it is often the case that the double side band values are one-half the SSB values, since both side bands convert power equally. In principle power loss to the unwanted side band can be avoided (image suppression) by differential matching if the IF is large enough, or by the use of a two-element front end. At higher frequencies these techniques are not usually practicable.

Spectroscopy is performed by dividing the IF band into channels of width $\Delta\nu$ and rectifying and integrating the noise in each channel separately. All mixer receivers operating in the Rayleigh–Jeans limit ($h\nu < kT_R$) provide a signal to noise ratio given by the Dicke radiometer equation:

$$\frac{S}{N} = \frac{T_S}{T_R} \sqrt{\Delta\nu\Delta t} , \tag{2}$$

where T_S is the equivalent black body temperature of the signal and Δt is the integration