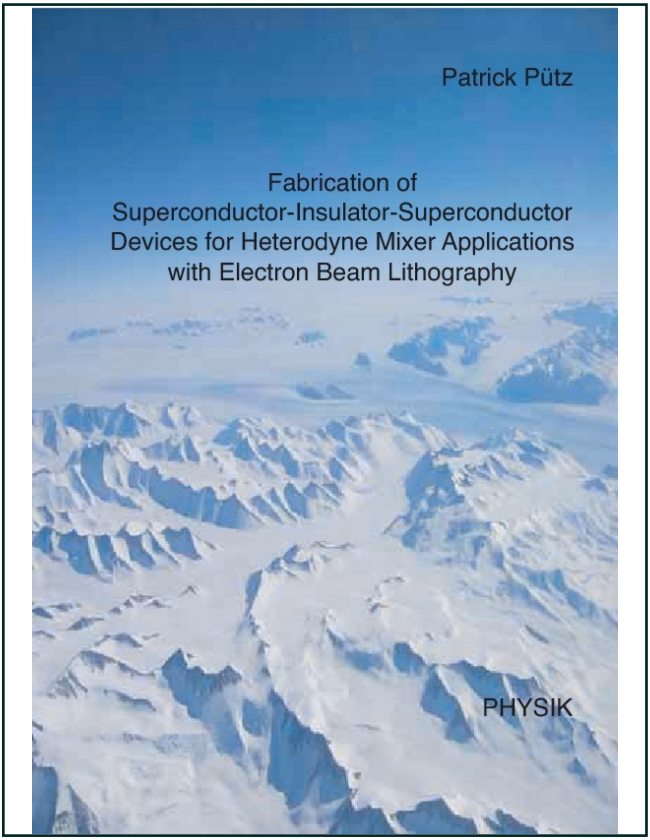
Patrick Pütz (Autor)

Fabrication of Superconductor-Insulator-Superconductor Devices for Heterodyne Mixer Applications with Electron Beam Lithography



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Introduction

The last twenty years has seen a great increase of our knowledge about the "cold" (2.7–100 K) regions of the interstellar matter (ISM) and the mechanisms of star birth. Due to the low temperatures this matter can gravitationally attract each other to form giant molecular clouds which contain a large amount of molecules and dust. These regions harbor star birth and, consequently, planet formation. In particular, the thermally excited electromagnetic radiation emitted from the atoms and molecules and its subsequent spectral analysis have contributed significantly to our understanding of the physical properties (temperature, density, mass) of these clouds. In case of the molecules the radiation predominately comes from rotational transitions and is emitted in the millimeter and submillimeter wavelength region, i. e. at frequencies of approx. 100 GHz upwards.

The linear molecule carbon monoxide is a good example. The lowest $J = 1 \rightarrow 0$ transition at 2.6 mm (115 GHz), was discovered back in 1970 by Wilson et al. and marks the beginning of modern radio astronomy of the ISM [86]. CO is the most common observable molecular species and exhibits a very simple rotational transition ladder with lines approx. every 115 GHz.[1] Up to the present day more than 130 different molecular species including simple amino acids have been clearly identified using their millimeter and submillimeter wavelength spectroscopic fingerprint [87].

Groundbased astronomical measurements towards higher frequencies are increasingly limited by transmission of our atmosphere to frequency bands where water vapor does not absorb the extraterrestric signals. Non-continuous transmission windows exist up to frequencies of 1.5 THz and can be observed from dry, high altitude sites. Well-known observatories are the IRAM[2] 30-m telescope at the Pico Veleta in Spain for millimeter wavelengths (< 300 GHz), and, for the submillimeter region (< 1 THz), the HHSMT[3] on Mt. Graham in Arizona and the

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[1] The most abundant molecule H_2, with relative quantities of over 90% (by mass), is very light-weight and has not dipole moment. It thus does not emit any radiation at submillimeter wavelengths.

[2] Institut de Radioastronomie Milllimétrique. http://www.iram.fr/

[3] Heinrich Hertz Submillimeter Telescope. http://aro.as.arizona.edu/

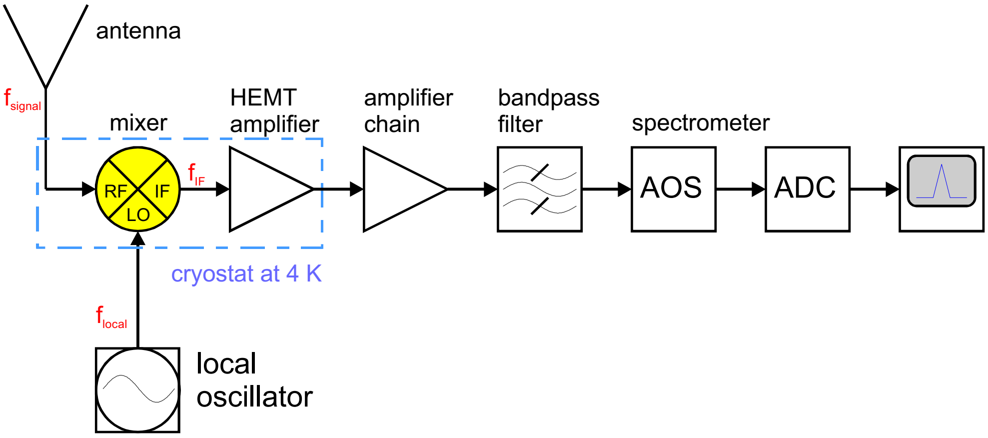

Figure 1.1: Block diagram of a principal heterodyne receiver setup for astronomical measurements at submillimeter wavelengths. The extraterrestric signal is fed from the telescope's antenna to the mixing element where it is combined with the local oscillator signal. The resulting intermediate frequency is amplified and and spectrally analyzed.

CSO[4] on Mauna Kea in Hawaii. KOSMA[5] operates its own observatory on the Gornergrat in Switzerland which is equipped with 230, 345, 490 and 810 GHz receivers. Additionally, 810 GHz mixers from KOSMA are used at AST/RO[6] at the Amundsen-Scott South Pole Station in the Antarctic.

Future groundbased observatories will be situated in the Atacama desert in Chile and, possibly, in the Antarctic. These special sites should enable measurements up to 1.4 THz. For even higher frequencies, air-borne observatories such as SOFIA[7] or space-based such as the HSO[8] are currently being built. Research of our atmosphere itself also profits from submillimeter measurements. Investigation of the ozone layer, for example, relies on measurements of the density of the radical chlorine monoxide (ClO) at 204 GHz.

1.1 Heterodyne receivers for radio astronomy

Progress in detection at submillimeter frequencies is directly correlated to advancement of receiver technology. Extraterrestric lines are very weak, line integrated powers for molecule detection are well below 10^{-15} W, and thus require very sensitive detectors. Additionally, the typical relative velocities between 0.1 km/s and 100 km/s of the cloud matter require a high spectroscopic resolution

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[4] Caltech Submillimeter Observatory. http://www.submm.caltech.edu/cso/

[5] Kölner Observatorium für Submillimeter Astronomie. http://www.ph1.uni-koeln.de/gg/

[6] Antarctic Submillimeter Telescope and Remote Observatory. http://cfa-www.harvard.edu/∼adair/AST_RO/

[7] Stratospheric Observatory for Infrared Astronomy. http://sofia.arc.nasa.gov/index.html

[8] Herschel Space Observatory. http://astro.estec.esa.nl/SA-general/Projects/First/first.html

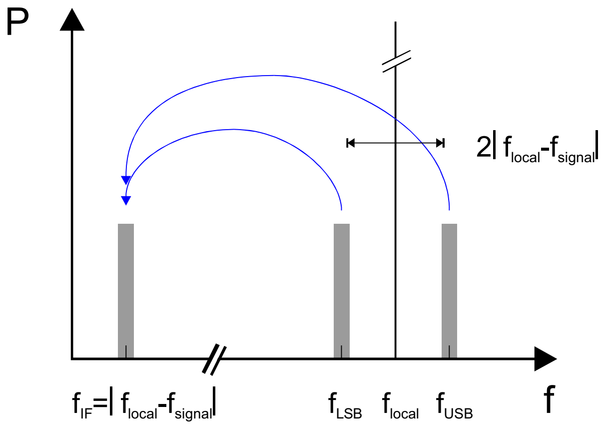

Figure 1.2: Visualization of the frequency conversion and spectral sensitivity of a heterodyne receiver.

of 10^3–10^6 in order to resolve the line profiles [29]. Coherent detection techniques originate from longer wavelength radio astronomy and are the best method for high resolution spectroscopy. In contrast to incoherent detection methods, thousands of frequency channels can be simultaneously measured with a spectrometer without RF input losses due to bandpass filtering [90]. Basis technology is a heterodyne receiver system which uses frequency downconversion of the extraterrestric signal with the help of a nonlinear device as frequency mixer. The mixer is the first active receiver component of such a receiver and with it the incoming signal is heterodyned with a many magnitudes stronger and slightly offset (typically 1–4 GHz) local oscillator signal (Fig. 1.1). Among others the mixer generates a signal at an intermediate frequency (IF) that is the difference between local oscillator (LO) and signal frequency. In this way a signal containing full phase and amplitude information of the extraterrestric signal is yielded at a 2–3 orders of magnitude lower frequency which then can be adequately boosted by state of the art low-noise HEMT amplifiers. As depicted in Fig. 1.2 the heterodyne receiver intrinsically detects power in two frequency bands, i. e. the sidebands, which lie symmetrically to the LO frequency position. For an unambiguous spectral line to frequency relation one sideband has either to be removed by filtering or determined by slightly de-tuning the LO or other means.

Fig. 1.1 shows that a heterodyne receiver consists of series connection of the components mixer, amplifiers, bandpass filter and spectrometer. Sensitivity of the total system is limited by the noise it adds to the signal. Noise contribution of every individual component is usually expressed by its noise temperature T_i which is defined as the equivalent noise power added by this component at the component's input divided by $k_B B$ (with bandwidth B). The total noise temperature of the receiver then is given by the generalized expression

$$T_{rec} = T_1 + \frac{T_2}{G_1} + \frac{T_3}{G_1 G_2} + \frac{T_4}{G_1 G_2 G_3} + \cdots \ , \tag{1.1}$$

where G_i is the gain (transmission) of each component. T_1 is the noise temperature and G_1 the gain of the first component. The equation can be simplified to

$$T_{rec} = T_m + \frac{T_{IF}}{G_m} \ , \tag{1.2}$$

where T_m is the mixer noise temperature, G_m the mixer gain and T_{IF} the summarized noise temperature of the remaining components. Because usually $G_m < 1$ and $G_i > 1$ (for $i \geq 2$) it is clearly evident that the noise and gain contribution of the mixer is crucial for receiver performance.

Calculation of the total system sensitivity of the telescope needs to include the contributions of the optical components and, in case of a groundbased (and to less extend airborne) observatory, the atmospheric transmission. For this the same formalism as in Eq. 1.1 can be applied for calculation of the system noise temperature T_{Sys}. Particularly at submillimeter wavelengths atmospheric transmission becomes the dominant contribution to noise temperature with increasing frequency.

The minimum detectable signal temperature ΔT^A_{min} then is a measure of detection sensitivity:

$$\Delta T^A_{min} = \frac{T_{Sys}}{\sqrt{\Delta\nu\tau}} \ . \tag{1.3}$$

Here $\Delta\nu$ is the detection bandwidth (usually the bandwidth at the IF) and τ the integration time of the measurement[9] [28]. τ is limited by receiver stability (amplifier gain fluctuations, mixer stability, etc.), which is characterized by the Allan stability time, and typically is a few seconds. [1, 65]. Consequently, this creates a practical lower limit for ΔT^A_{min} for a system.

1.2 Superconducting mixer devices

Superconductor-Insulator-Superconductor (SIS) tunnel junctions at present are the mixing devices of choice for millimeter and submillimeter heterodyne receivers. Their first application for millimeter wave mixing was by Richards et al. at 36 GHz in 1979 [61]. SIS mixers now are used for observations in all atmospheric frequency windows up to 950 GHz as standard instrumentation. They provide more than a factor 5 lower noise temperatures than their predecessors, the Schottky diodes, and have two orders of magnitude lower LO power requirements (which is a very important factor for higher frequencies). The reason for this lies in the extremely non-linear characteristic of the quasiparticle branch visible in the I-V curve (Fig. 2.2) and the lack of series resistance in superconducting wiring material [81, 82]. As a matter of fact, the practically achieved double sideband (DSB) mixer noise temperatures lie close to the quantum limit [41]

$$T^{quantum}_{limit} = \frac{h\nu}{k_B} \quad \text{(i. e. 4.8 K/100 GHz)} \ , \tag{1.4}$$

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[9] Strictly speaking, this equation only applies to uncorrelated white noise.

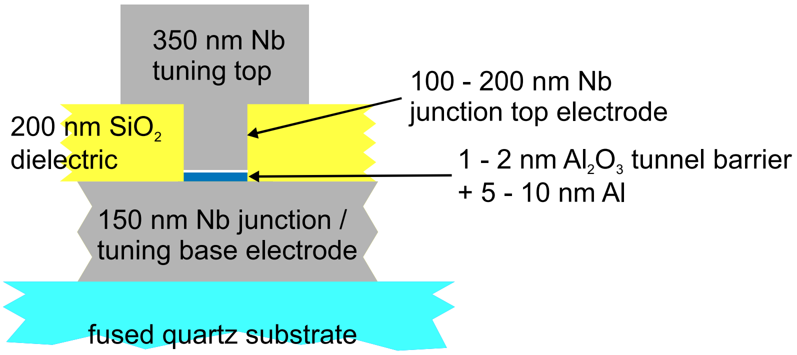

Figure 1.3: Schematic cross-section of a Superconductor-Insulator-Superconductor (SIS) device with standard Nb-Al/Al_2O_3-Nb trilayer including the integrated tuning circuit, e. g. as used for the 475 GHz SMART devices. In case the signal path uses a waveguide in front of the mixer element (as all SIS mixers built at KOSMA do) fused quartz is used as material for the wafer.

with reported DSB mixer noise only 2–3 times higher for frequencies $\nu \leq 700$ GHz (the material dependent gap frequency for niobium junctions) [22]. The remaining discrepancy is mainly due to imperfections in the barrier (leakage currents) and non-perfect matching to the SIS junction.

SIS mixer devices are fabricated with thin film, microfabrication methods as used in the semiconductor industry. In particular, this involves evaporation or sputtering based layer deposition, lithography to define features with submicrometer precision and reactive-ion etch processes. Typical layer thicknesses are 100–150 nm for the junction electrodes and only 1–2 nm for the tunnel barrier. Two developments concerning fabrication of the SIS mixer devices have significantly improved performance in the past and are now used as standard.

First, is the introduction of the Nb-Al/Al_2O_3-Nb junction trilayers [62, 24, 34] as a replacement for the lead based tunnel junctions (Fig. 1.3). The niobium junctions use a 5–10 nm thin aluminum base layer which is thermally in-situ oxidized before the counter electrode is deposited. Because aluminum has the property to completely wet the niobium surface, it leaves a very smooth interface and consequently very high quality tunnel junctions with low subgap currents can be fabricated.

Second, is the integration of a superconducting, thin film microstrip tuning circuit into the device which compensates for the SIS junction shunt capacitance by realization either of a series or parallel inductance and, additionally, yields a broadband match to the antenna (Fig. 1.4). A SIS junction forms a parallel-plate capacitor with large specific capacitances of around 90 fF/μm^2 which effectively short circuits the RF power when not compensated for. The frequency dependent characteristic of the resonant tuning circuit poses limitations on the SIS device RF input bandwidth. While the tuning circuit top electrode is fabricated as a microstrip line on top of the junction insulation layer, the tuning base electrode of an simple all-niobium device is already defined together with the junction base electrode and the RF chokes (Fig. 1.3, Fig. 1.4). The best achieved fractional input

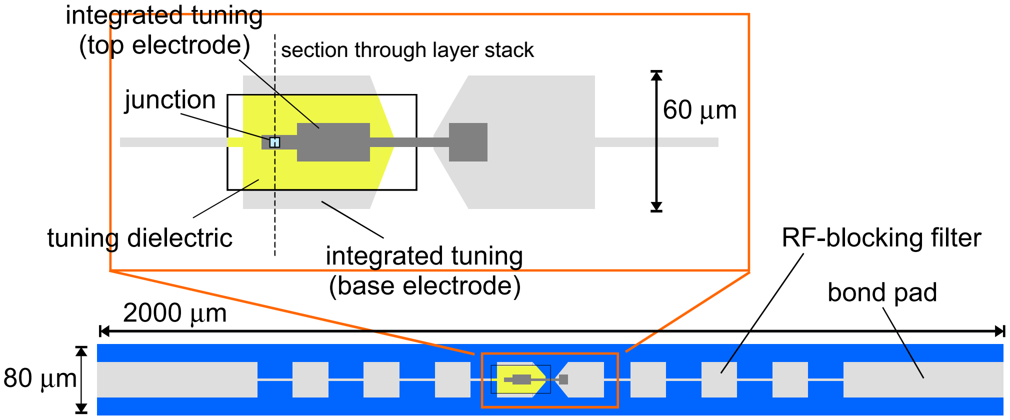

Figure 1.4: Schematic overview of a SIS waveguide device (not to scale). Dimensions are typical for a 800 GHz device. The magnified view of the junction area given in the inset shows a typical integrated tuning circuit with series inductor for compensation of junction capacitance and two $\lambda/4$ transformers for impedance match of the junction to the waveguide.

bandwidths are approx. 30% (this will be discussed more thoroughly in Sec. 2.2 and in Chap. 2.3) [40].

Quasiparticle mixing is limited by the combined double energy gaps $2\Delta_1 + 2\Delta_2$ of the SIS junction electrodes which, for a standard niobium SIS junction, is theoretically 1.4 THz ($4\Delta/h$), but practically limits operation to about 1.2 THz (see Sec. 2.1.2). RF losses in the tuning circuit electrodes deteriorate mixer performance already above the gap frequency $2\Delta/h$ of the used superconducting material (see Sec. 2.2). Therefore latest SIS mixer developments, e. g. SIS device development for HIFI Band 4 (960–1120 GHz) and 5 (1120–1250 GHz), incorporate hybrid superconducting junction electrodes with AlN instead of Al_2O_3 tunnel barriers and one or two normal conducting tuning circuit electrodes (see Sec. 6.5) [39, 47, 11]. For fabrication reasons only one niobium junction electrode is usually replaced by the higher energy gap superconductor NbTiN. Theoretically, the mixing limit of such a Nb-Al/AlN-NbTiN junction SIS device 1.9 THz. To date the highest operation frequency of a SIS mixer reported is 1.13 THz and a best receiver noise temperatures of 400 K was measured [37].

At frequencies above $(2\Delta_1 + 2\Delta_2)/h$ superconducting hot-electron bolometer mixers (HEB) are presently the best choice. These devices are made up of very thin (≤ 10 nm) and small ($< 1 \times 1\,\mu m^2$) superconducting microbridges and thus also require microfabrication. Unlike SIS tunnel elements, a HEB does not generate the IF signal through frequency multiplication but is sensitive to the amplitude modulation of the incident RF power. Due to the non-linearity of the R-T characteristics of the superconducting microbridge material, the modulation generates an oscillation of device resistance and thus the IF signal [57, 18, 71, 17, 72]. The upper limit for frequency mixing is not determined by the gap frequency of the

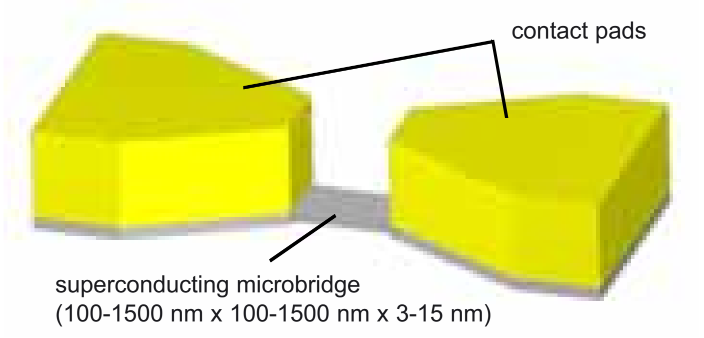

Figure 1.5: Schematic view of a superconducting hot-electron bolometer (HEB, drawn to scale). The normal conducting contact pads (gold) have a thickness of typically less than 100 nm. Phonon-cooled HEB species use thinner microbridges with larger lateral dimensions than their diffusion-cooled counterpart. Illustration adapted from [72].

material.[10]

The speed of a HEB, i. e. the highest possible IF frequency it can generate, is determined by the relaxation time of the hot electrons in the microbridge which are created by absorption of the RF power. Devices with two different types of cooling mechanisms are used. One kind of device relies on phonon-cooling (NbN or NbTiN microbridge) through the substrate while the other employs diffusion-cooling (Nb or Ta microbridge) through normal-conducting contact pads. Although HEB mixers have only been around for about 10 years their performance is significantly better than competing Schottky diodes up to the highest presently evaluated frequencies of 2.5 THz [22].

The phonon-cooled HEB species show better noise temperatures but somewhat limited IF bandwidth performance, e. g. 800 K at 1.6 THz with approx. 4 GHz IF bandwidth, whilst the diffusion-cooled HEB species display higher IF bandwidths with the penalty of worse noise temperatures, e. g. 1800 K at 2.5 THz with $\geq$ 9 GHz IF bandwidth [13, 88]. To date most of the development efforts focus on the phonon-cooled species.

Nevertheless much is still unclear concerning the practical operation of HEB devices (e. g. receiver stability issues) and presently only one observatory is running a HEB receiver for astronomical observations, namely the RLT in the Atacama desert in Chile.[11] [12] Nevertheless HEB devices will play a crucial role for important upcoming projects, like for the HIFI[13] Band 6 mixers (1410–1910 GHz) of

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[10] At very high frequencies approaching near infrared wavelengths, the bridge at one point will become transparent for incoming photons.

[11] Receiver Lab Telescope. http://cfa-www.cfa.harvard.edu/srlab/

[12] In February 1999 and January 2000 the CO $J = 7 \rightarrow 6$ and CO $J = 9 \rightarrow 8$ transitions at 807 GHz and 1037 GHz, respectively, have been detected with a phonon-cooled HEB mixer during observing runs at the HHSMT.

[13] Heterodyne Instrument for FIRST. http://www.sron.nl/divisions/lea/hifi/