Abstract

The detection of radiation with superconducting detectors within the submillimeter frequency regime, which spans approximately the frequencies 300 GHz to 3 THz, is based on two fundamentally different detection principles. Direct-detection devices or incoherent detectors measure the power of the radiation field through a response which is caused by pair-breaking effects in the superconducting material. On the other hand, heterodyne mixers or coherent detectors down-convert the desired signal to orders of magnitude lower frequencies into an instantaneous intermediate-frequency (IF) band where it is analyzed with a spectrometer. This is achieved via a strong nonlinear circuit-element and by superimposing the usually weak signal with radiation from a much stronger reference-frequency local-oscillator (LO) source. Heterodyne-detection techniques are of great importance in radio-astronomical receiver systems due to their high sensitivity and their potential to achieve a high spectral-resolution of order $\nu/\delta\nu \approx 10^5$-$10^6$. Especially the high spectral-resolution is difficult to obtain with a direct-detection device.

This thesis studies novel superconductor-insulator-superconductor (SIS) double-sideband heterodyne mixers and superconducting devices for next-generation astronomical submillimeter receiver-instruments operating in the terahertz frequency regime. It focusses on two projects. In the first project a prototype of a next generation mixer was developed to evaluate the design accuracy, the technology and the ultimate possible performance. The frequency range of 380-520 GHz was chosen to permit the use of mature niobium-based circuit technology. A waveguide-coupled balanced SIS mixer was developed, designed, simulated, fabricated and characterized. In contrast to single-ended mixers, balanced mixers have two independent input ports for the desired signal and the LO radiation and, thus, comparatively simple solutions become possible to arrange these devices to an array of many mixers. The optical setup to couple radiation from the telescope to the mixers is not complicated anymore by the diplexing of signal and local-oscillator radiation. Moreover, optical diplexers limit the instantaneous IF bandwidth and the low power of local oscillators working at terahertz frequencies limits the number of the mixers in an array. Important advantages of balanced mixers are that the noise contribution of the LO, that might significantly lower the receiver sensitivity, is cancelled in the balanced IF output and that the low LO output power for terahertz frequencies can be used more efficiently.

The balanced mixer devices in this thesis are fabricated on 9 μm thick silicon membranes on which the various radio-frequency (RF) components of the device are integrated. This includes in particular two tapered-slotline waveguide antennas, a 90° RF hybrid coupler, two separate SIS junction circuits used as mixing devices and a RF blocking filter. We find that the balanced-mixer devices have quantum-limited sensitivity over 70 % of the RF detection bandwidth of 380-520 GHz while providing an instantaneous IF bandwidth of 4-8 GHz. This is the first time an integrated balanced-mixer is reported with these specifications

reaching quantum-limited sensitivity. Measurements are reported which show the functionality and symmetry of the devices in different operation modes when the two separate SIS junction circuits are biased with either same or opposite polarities.

Furthermore, we show for the first time a quantitative measurement of the noise contribution of various LOs using the integrated balanced SIS mixer. Although it is known that LO sources can add noise to a heterodyne receiver, mainly due to amplitude and phase fluctuations of the LO signal, until now this noise contribution was not unambiguously quantified. In single-ended mixers during the frequency-mixing process, any noise from the LO sidebands is downconverted and is at the end indistinguishable from the desired IF signal. Presently there are only few sensitive balanced mixers reported in the terahertz regime that are capable of these measurements. We present a measurement method where any LO noise-level can be quantified in terms of an equivalent noise temperature. We show that the noise level of LO sources is largest close to the carrier frequency and can exceed the quantum noise. Therefore, the sensitivity of a heterodyne receiver using mixers with low IF, such as hot-electron bolometer mixers, is particularly lowered by LO noise.

In the second project, we studied the device physics of mesoscopic NbTiN/Nb/Al-AlO_x/Nb/Au/NbTiN contacts. These devices are a promising technology for future terahertz SIS mixers in the frequency range above 700 GHz where the niobium transmission-line technology becomes lossy. Most importantly, they still use the high-quality niobium-trilayer technology resulting in very low subgap-current tunnel junctions. We expect that these tunnel junctions will function as mixers up to frequencies of 1.3 THz. Low-loss transport of RF signals up to about the same frequencies is now provided by the material niobium-titanium-nitride. Earlier reported heating of the electron system in the niobium due to the *Andreev* trap formed at the interface between the niobium and the niobium-titanium-nitride, is removed by adding a normal-metal layer of gold. We show that dependent on the gold-layer thickness and shape, the effective electron temperature in the niobium can be lowered to values close to the phonon bath-temperature, a process which we call *geometrically assisted cooling*. Additionally, we discuss the influence of the proximity effect in the gold on tuning-circuit designs. For the balanced mixers developed in the first project of this thesis, this new junction technology is important for realizing the next generation of these mixers, preferably operating at 1 THz.