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Fundamental limitations of THz and Niobiumnitride SIS mixers

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Document Version
Publisher's PDF, also known as Version of record

Publication date:
1998

Link to publication in University of Groningen/UMCG research database

Citation for published version (APA):
Dieleman, P. (1998). *Fundamental limitations of THz and Niobiumnitride SIS mixers*. [Thesis fully internal (DIV), University of Groningen]. University of Groningen.

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Chapter 1

Submm radiation detection

1.1 Understanding the universe

Since the emergence of consciousness, mankind has gone in search of the origin of our surroundings and ourselves to find meaning and purpose of life. Simultaneously, understanding of the evolution of man as well as the birth and evolution of our earth has significantly evolved during the past millennia. Still, the mechanisms behind the actual emergence of life as well as the occasion to the ”big bang” are unknown. A detailed knowledge of the circumstances at the beginning of time and space may clarify these old but still actual issues.

A central question in the study of the early universe is when and how galaxies were formed. Studies of stars in nearby galaxies indicate that the first stars were formed in a dust-free environment, but since the formation of stars involves rapid production of heavy elements and dust, the radiation in the optical regime is obscured. This makes young galaxies difficult to observe at optical wavelengths, but very bright at submillimeter wavelengths (THz frequencies) where the radiation absorbed by the dust is re-emitted. During the initial starburst, copious amounts of warm molecular gas are also expected to be present, emitting a rich spectrum of rotational lines in the submillimeter range. When later in the lifecycle gas clouds cluster around stars to form planets or new stars, much heavier elements, like iron, are formed than the originally present hydrogen and helium atoms. The presence of these molecules have been indispensable for the origin of life on our planet[1]. For these reasons, observations at submillimeter wavelengths are essential to un-

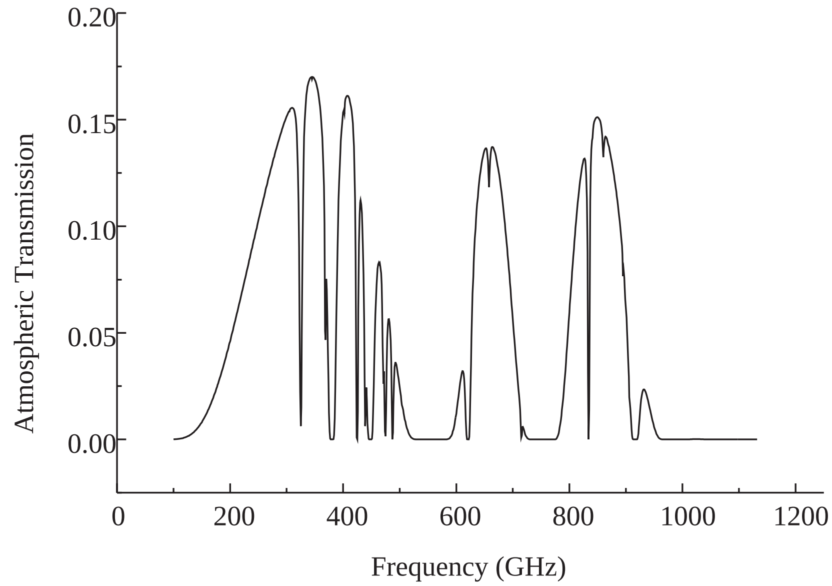

FIGURE 1.1. The transmission of the atmosphere at an altitude of 4200 m for average humidities. Atmospheric windows are present at 345, 690, and 850 GHz. (Calculated by Q. Kleipool).

derstand the origin of the universe.

1.2 Atmospheric research

More down to earth, observations of rotational transitions of gases in the atmosphere provide a wealth of information on the origin and progress of the greenhouse effect. Key frequencies are 215 GHz for the detection of chlorine monoxide and ozone, 640 GHz for hydrochloric acid[2] and at a frequency of 2522 GHz the rotational line of the hydroxyl radical is found. Once the distribution and abundance of chlorine monoxide and other molecular species, involved in the destruction of the Earth's ozone layer are accurately measured, the atmospheric chemical reaction scheme can be completed.

1.3 Radiation detection at THz frequencies

A thorough exploration of the submillimeter wavelength band is now on the way. Large aperture telescopes are needed to have high sensitivity and good angular resolution. These telescopes must be placed on high altitude dry sites since water is mostly responsible for the absorption as shown in Fig. 1.1.

The first ground-based submillimeter telescope, the Caltech Submillimeter Observatory, started in 1987 followed shortly by the Maxwell Telescope, both on Mauna Kea, Hawaii at an altitude of 4200 m. The Institut de Radioastronomie Millimétrique (IRAM) operates a submillimeter telescope in Spain at an altitude of 2560 m, and the European Southern Observatory (ESO) operates in Chili at an altitude of 2300 m. More recent developments focus on airborne observatories (flying at an altitude of 13.7 km) such as the Kuiper Airborne Observatory (KAO)[3] and the Stratospheric Observatory for Infrared Astronomy (SOFIA)[4]. Future plans involve satellite missions, such as the European plan for the Far Infrared & Submillimeter Space Telescope (FIRST)[5], and multidisk ground-based observatories such as the 64 telescope US Millimeter Array (MMA)[6] and European Large Southern Array (LSA) combination and the Japanese 50 telescope Large Millimeter and Submillimeter Array (LMSA) both planned to be constructed in Chili, (See Fig. 1.2).

1.3.1 Detector requirements

To obtain information on the variety and abundance of gases present in galaxies or the atmosphere, a spectrum of the incoming signal is required. A clear example of what the final result of a measurement may look like is shown in Fig. 1.3

The following introduction on the requirements for THz radiation detection and to what extent these have been met by current detectors is not meant to be complete. Excellent reviews have been written which offer a thorough overview of the current status in the field of submillimeter radiation detection[7–11].

Depending on the purpose of the research, emphasis of the requirements can be on the sensitivity, spectral resolution, and bandwidth. Obviously, a gas cloud far away containing molecular species with faint rotational transition lines lying closely together will require both high sensitivity and high resolution. Another point of attention is the bandwidth of detection. Most objects in the universe have a strong angular momentum, causing gases, e.g. in outer rings of newly forming

FIGURE 1.2. An artist's impression of the millimeter array (MMA). Current plans involve a joint US European effort to build up to 64 antenna's each focusing the signal onto about 6 detectors with 2 polarizations, meaning that a total of 640 superconducting detectors will operate simultaneously.

stars, to have a large difference in velocity upon movement towards or away from the observer. This causes Doppler shifts in the frequency, like the well known ”redshift” caused by the expansion of the universe. For this reason, rotational lines can be broadened and, since the shape provides information on the velocities with which the object is moving, the entire line shape which can be broadened with several GHz must be measured in a single scan. This poses a lower limit to the bandwidth of detectors when used for astrophysical observations.

1.3.2 Coupling of radiation to the detector

Two methods are in use to couple the signal to the detector: quasioptically and by means of a waveguide. The first method shown in Fig. 1.4 uses an antenna usually glued to a lens. The advantage here is that the fabrication of the antenna is relatively simple; it can be done in the same fabrication run and with the same technique as with which the detector is made. The method employing a wave-

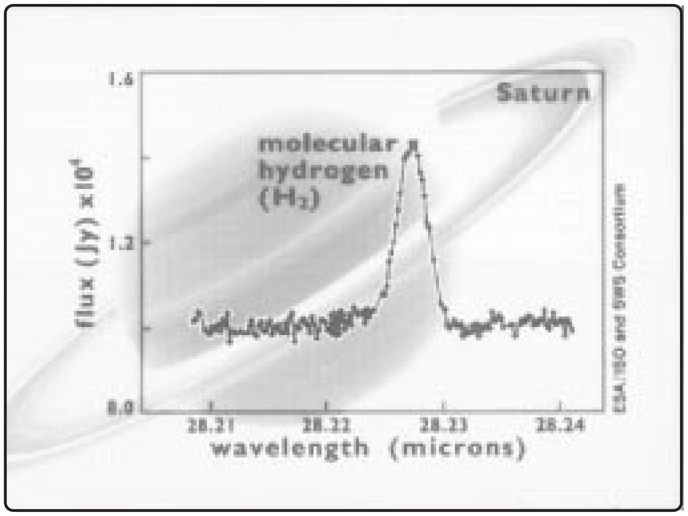

FIGURE 1.3. A spectrum of the atmosphere of Saturn, taken with the Infrared Space Observatory (ISO). The background is formed by a photograph in the visible regime of the planet.

guide is from a fabrication point of view more difficult, fabricating a waveguide with minimum dimensions of 50 μm as needed for THz frequencies is state of the art mechanical machining. The substrate with probes between which the detector is placed is mounted in the middle of the waveguide as shown in Fig. 1.5. The advantage of waveguide systems over quasi-optical coupling is that a tuning element, the backshort, which is a movable rod in the waveguide can be used to change the impedance the detector ”sees”. A match between the detector and its environment can be obtained even though the detector impedance is different from the intended one. In addition the frequency range at which the detector can be used is increased. In practice, although a mechanical tuning element is very convenient in the laboratory, it is prohibited in space applications since a movable mechanical element is intrinsically vulnerable.

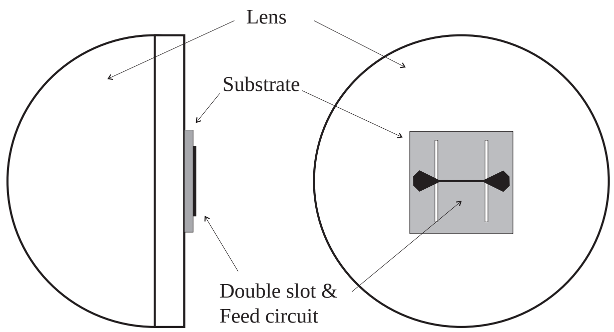

FIGURE 1.4. A simplified side- and front view respectively of the quasioptical coupling scheme; a lens with double slot antenna and coupling circuit

1.3.3 Submm radiation detection modes

Two basic methods of detection are the optical technique of direct detection such as bolometric detection, and the radio technique of heterodyne mixing.

Direct detection is a process in which a photon either raises the temperature of a bolometer element or causes an electron current to flow in a photoconductor. This is a *power* detection process in which the fundamental noise limiting the

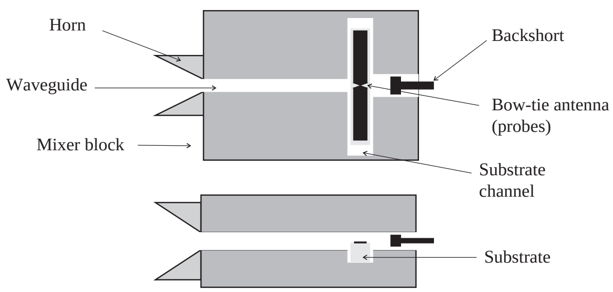

FIGURE 1.5. A schematic crossectional top- and side view of the mixer block with horn, backshort, substrate channel and mounted junction.

sensitivity is the noise in the signal. Since the detector does not actually follow the applied AC power, frequency selectivity is obtained by placing a filter in front of the device such as in a Fabry-Perot interferometer system. The system resolution and frequency band is determined by the input filter.

A heterodyne measurement is one in which a strong local oscillator (LO) is combined with the weak astronomical signal by means of a beam splitter or directional coupler, so that the superposed waves are incident on a nonlinear detector. This detector then mixes the incoming waves and provides an intermediate frequency (IF) at the output of typically a few GHz. The components of the downconverted signal can be spectroscopically separated and integrated to obtain the signal frequency spectrum. A simple way to illuminate the concept of heterodyne mixing is to consider a non-linear element which has a current-voltage characteristic given by $I(V) = V^2$. The incoming radiation and local oscillator signals can be represented by sinusoidal voltages: $V_{sig}(t) = V_S \sin \omega_S t$ and $V_{lo}(t) = V_{LO} \sin \omega_{LO} t$. If these voltages are both applied to the nonlinear element, a little trigonometry shows that the resulting current is given by $I(t) = V_L O \sin \omega_{LO} t + V_S \sin \omega_S t + V_{LO} V_S \sin{(\omega_{LO} - \omega_S)} t + V_{LO} V_S \sin{(\omega_S - \omega_{LO})} t$ and higher order terms. The terms including $\omega_S - \omega_{LO}$ and $\omega_{LO} - \omega_S$ appear at the IF output. This process is schematically depicted in Fig. 1.6 in which radiation in a band at 1 THz $\pm$ 1.5 GHz is downconverted into the same band with the IF frequency as center frequency. Since both the frequency above as well as below the LO frequency are downconverted into the same IF band, the detector is said to operate in double side band (DSB) mode, as opposed to single side band (SSB) mode, where the image frequency is filtered out. Three bandwidths and frequencies can be identified:

- The RF bandwidth, in which frequency range the detector is sensitive and couples radiation in. A detector operates at a certain center frequency, e.g. 1 THz with an RF bandwidth of for instance 20 %, so from 900 – 1100 GHz.

- The IF bandwidth determines how many times the LO frequency must be changed to map the entire RF bandwidth. If the RF bandwidth is 400 GHz around 1 THz and the IF band is 1 GHz, the LO frequency must be set 400 times, from 800, 801, 802, . . ., 1200 GHz to obtain the complete RF spectrum obtainable. A broad IF band reduces the number of LO steps, speeding up the measurement and enabling broad lines to be measured in one scan. The bandwidth is set by a bandpass filter at the IF output of the

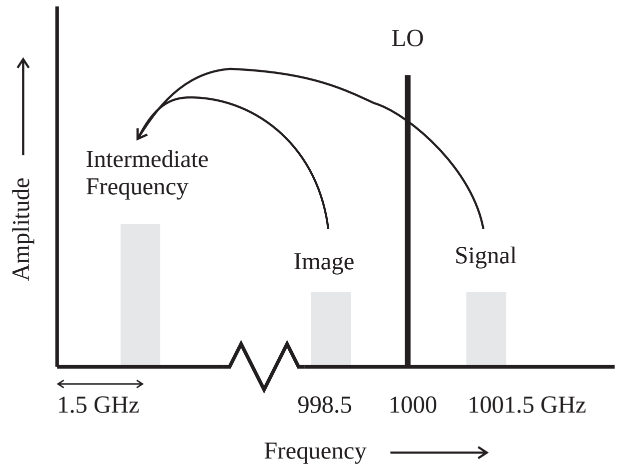

FIGURE 1.6. Both the signal ($\omega_{LO} + \omega_{IF}$) and the image ($\omega_{LO} - \omega_{IF}$) band are down-converted in the heterodyne mixing process.

detector.

- The IF frequency is the center frequency to which the signal is downconverted. This frequency is sometimes confusingly called the IF bandwidth, which it indeed determines, but it is not identical to it. For example, if the IF frequency is 1.5 GHz and the IF bandwidth is 0.5 GHz, RF radiation in the frequency ranges from 998 to 999 GHz and 1001 to 1002 GHz are down-converted to a signal band with a center frequency of 1.5 GHz. To avoid disturbance of the IF spectrum by low frequency LO noise or $1/f$ noise in the spectrum, the IF bandwidth must be smaller than the IF frequency, as can be understood from Fig. 1.6.

The heterodyne noise component is primarily quantum noise from the uncertainty principle, caused by simultaneous measurements of amplitude and phase of the signal[12–14]. Other contributions like shot noise from currents flowing without applied radiation (leakage currents) or Johnson noise from some resistance in the circuit can occur in direct as well as heterodyne detection. The combination of resolution and sensitivity requirements determine which type of detector is favored.

In general for dust continuum observations low resolutions suffice and direct detection beats the heterodyne receiver with an order of magnitude in sensitivity. If the required resolution becomes larger, as in the case for galaxies or molecular clouds, the heterodyne instrument rapidly outperforms the direct detector with increasing sensitivity at THz frequencies. Since astrophysical research currently focuses on detection of high frequency radiation from nearby to very distant gas clouds, we concentrate our efforts on the development of a heterodyne instrument for THz radiation detection.

1.4 Heterodyne detectors

Heterodyne mixing requires a nonlinear electronic element. Three devices, the Schottky-barrier diode (SBD), Superconductor-Insulator-Superconductor (SIS) junction, and Hot Electron Bolometer (HEB), with each having their own advantages and disadvantages are currently under development and in use.

1.4.1 Schottky-barrier diode

SBD junctions exhibit a non-linear current-voltage (I-V) characteristic originating from a Schottky barrier which exists between a metal point contact and a semiconductor. An advantage is that these operate at room temperature, although the performance is improved upon cooling to 20 – 30 K, a temperature accessible with commercially available cryocoolers. The low capacitance (4 fF/μm^2) provides reasonable matching of the radiation coming from a real impedance environment like vacuum or a waveguide to the junction. A disadvantage is the large LO power required which is hard-to-get at THz frequencies, and moreover the sensitivity is beaten by an order of magnitude by the two competing detectors since these have much sharper nonlinearities.

1.4.2 SIS junctions

SIS tunnel junctions have been in use since 1979 for their unequaled nonlinearity and low leakage current[15,16]. The junction consists of two superconducting layers of 200 nm separated by an oxide layer of a few atoms thick, through which a current can flow via quantum mechanical tunneling of electrons. The superconductor commonly used is niobium, with a superconducting transition temperature of 9.2 K. The major advantage is the sensitivity, which is unbeaten so far. Limitations are mainly posed by the large intrinsic capacitance, which calls for impedance matching methods which can introduce large absorption losses. The LO power required is much smaller than for Schottky diodes, enabling compact lightweight LO supplies for space applications. A further disadvantage is that the device needs to be cooled to 4 K to become superconducting and sufficiently nonlinear. This poses an upper limit on the lifetime in space operations, since the liquid helium used to keep the device at 4 K will last only 2 to 3 years.

1.4.3 HEB junctions

Hot electron bolometer junctions[17,18] are a hot topic these days since the sensitivity is close to that of SIS. The device merely consists of a thin short superconducting strip between two thick normal metal pads. The electron temperature in the strip is raised to the critical temperature T_c of the superconductor. At this temperature the resistance of the strip is extremely sensitive to the power impinging on the device. Since the resistance of a superconductor around T_c depends in an nonlinear fashion on the temperature, the device acts as a heterodyne power mixer. A major advantage of the device is that the intrinsic capacitance is negligible which greatly facilitates matching of the incoming radiation to the junction. This mainly comes into play at high frequencies, where most materials suitable for make impedance matching structures required for SIS detectors exhibit large absorption losses. A disadvantage, on which most of the scientific effort is concentrated, is the IF bandwidth, which is only a few GHz. By making the superconducting strip shorter ($<$ 100 nm) or thinner ($<$ 5 nm) this can be improved. An advantage of thin and short bridges is that the required LO power which is proportional to the bridge volume is an order of magnitude smaller than that required for SIS junctions. For this reason the HEB is the most promising detector for the frequencies above which the SIS needs an unpractically large LO power and exhibits a rapid decrease in sensitivity. The research described in this thesis is concerned with the development of detectors in the range of 700 to 1500 GHz, where the SIS detector is likely to be competitive in terms of sensitivity and bandwidth.

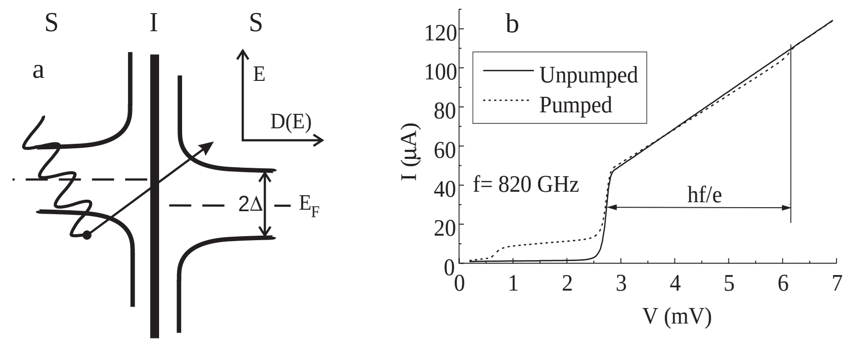

FIGURE 1.7. **a**. Energy band diagram of the SIS structure with an applied voltage. In the horizontal plane the density of states is depicted, which becomes infinite at $|E| = \Delta$. An incoming photon can raise the energy of a quasiparticle enabling photon assisted tunneling. **b**. The resulting current-voltage characteristics with and without 820 GHz radiation of a Nb junction.

1.5 SIS heterodyne detectors

The current- voltage characteristics of an SIS junction can best be explained by means of an energy band diagram as depicted in Fig. 1.7. Since a superconductor exhibits an energy gap of magnitude 2Δ, a quasiparticle with an energy $|E| < \Delta$ with respect to the Fermi energy in the superconductor on the left cannot tunnel into the right superconductor. Therefore no current can flow until the voltage is large enough for the quasiparticles to overcome the gap. At this voltage, the infinite densities of states are aligned, causing a steep current rise. From this voltage on the current increases approximately linear with voltage since the density of states also falls off rapidly to its normal state value for energies $|E| > \Delta$. The energy gap of Nb at 4.2 K is about 1.4 meV, therefore the ”gap voltage” $2\Delta/2e$ at which the current rise occurs is 2.8 mV.

The operation of the device as detector becomes clear in Fig. 1.7. If the applied voltage is just below the gap voltage, an incoming photon can raise the energy of a quasiparticle in order to enable tunneling into the other superconductor[19]. This is what happens if LO power is applied to the receiver which functions as a direct detector for the LO radiation. If on top of the relatively strong AC voltage

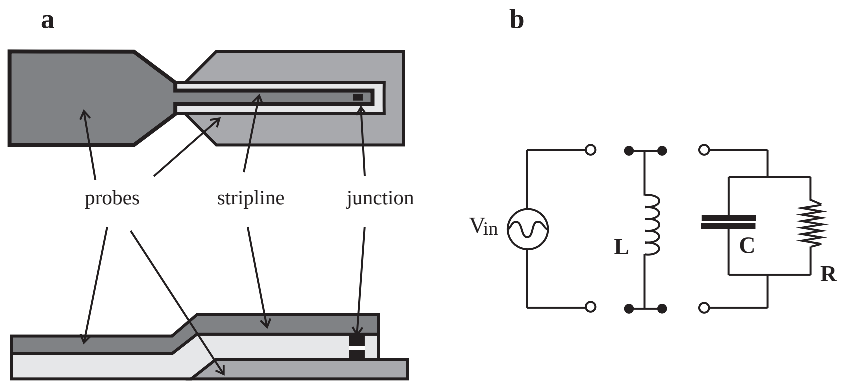

FIGURE 1.8. **a.** Top and crossectional view of a junction embedded in a stripline. The left probe is stretched via a narrow line over the right probe, forming a stripline. The SIS junction is situated at the end of this line. **b.** The circuit schematically shows the electrical equivalent of a stripline; the stripline acts as an inductor which cancels out the junction capacitance leaving only the real part R of the impedance.

modulation by the LO radiation of the junction the RF signal to be detected is applied, the signals are mixed.

Since the SIS consists of two (super)conductors separated by an insulator, an intrinsically large capacitance is formed which tends to shunt the incoming high frequency signal. To overcome this capacitance, an impedance transformation is used to convert the junction impedance with the large capacitive part to the real impedance (50 – 100 Ω) of the probes. This is done with a transmission line technique, in our case a stripline[20]. The stripline is formed by extending part of the layer contacting the top side of the junction over the layer contacting the lower side of the junction. An example of such a structure is shown in Fig. 1.8. The transmission line transforms the probe impedance to the complex conjugate of the junction impedance. This means that the junction looking into the stripline sees an impedance which is equal to the junction resistance plus an inductive term equal in magnitude to the capacitance. Therefore the resulting impedance is simply the junction resistance since the inductive and capacitive parts cancel each other. This is valid for one frequency only, since with varying frequency the transformation of the stripline changes. The analogous electronic circuit is a resonant RLC circuit, which has a certain bandwidth around a center frequency. Obviously the larger the RF bandwidth, the better. Since the bandwidth depends on the impedance mismatch, the junction area is chosen as small as practically possible to decrease the capacitance.

1.6 Frequency range of SIS operation

In the early days of SIS, frequencies of interest were in the range of 85 – 115 GHz. Since then detectors have been developed for increasing frequencies, mostly corresponding to the transmission windows in the atmosphere, at 230, 345, 490 and 650 GHz (See Fig. 1.1). The question of up to what frequency the SIS would function competitively was theoretically answered already in 1979[21]. However the major limitation to the attainable upper frequency comes from the tuning circuit.

1.6.1 Tuning circuit characteristics

The fortunate properties of superconductors for SIS mixing are the existence of an energy gap and a nearly infinite density of states at the gap edges. An equally important property for the success of SIS detectors is that superconductors are superconducting, that is, have near zero absorption of radiation when used as stripline material to guide the signal towards the junction. However, this property of lossless transport is frequency dependent. Once the applied frequency exceeds the superconductor energy gap, the radiation has enough energy to destroy the superconducting properties of the material. In a superconductor electrons are coupled in pairs, so called Cooper pairs, which flow without dissipation. The coupling strength is equal to the gap energy 2Δ. The energy of the incoming radiation is expressed as $\hbar\omega$. At 700 GHz, the signal energy is equal to the gap energy of niobium, and Cooper pairs are split into individual electrons, which experience resistance when accelerated by an (AC) voltage and are therefore dissipative. From this frequency on, the absorption in the superconductor sharply rises[22]. As shown by de Lange *et al*[23,24] a large part of the incoming signal is absorbed before it reaches the junction, resulting in a severely decreased sensitivity of the receiver. Two solutions have been devised to enable use of SIS with striplines at frequencies beyond 700 GHz: use of a superconductor with a larger energy gap which extends the upper frequency limit, and use of a normal highly conductive metal. The first solution seemed the easiest. The only candidate sufficiently developed in the past years to be of direct applicability is NbN with a gap of 5 meV, almost twice as large as that of Nb, extending the upper frequency of lossless coupling to 1300 GHz. However, for reasons mentioned in Section 2.5.3 this material has a rather large absorption even in superconducting state. A very recent development is the use of NbTiN, which has shown to exhibit low RF losses, most likely due to its higher DC conductivity in normal state[25]. A promising solution with potential beyond 1500 GHz will be shown in Ch. 3 to be the use of clean, highly conductive aluminum[23,26]. Of course, since the aluminum is not a superconductor at the operation temperature of 4.2 K, the losses are non-zero and the sensitivity of SIS receivers above 700 GHz drops with nearly an order of magnitude.

1.6.2 Junction frequency range limitations

Clearly, the material of which a junction is made is not necessarily the same as that of the stripline. In theory, an SIS junction operates as a heterodyne instrument until it is no longer nonlinear with respect to the radiation. When the voltage modulation applied by the impinging signal is larger than the voltage nonlinearity of the SIS junction, the junction stops mixing. Since the I-V characteristic of an SIS junction is symmetric, the effective width of the nonlinearity is 4Δ. Hence the Nb junction will in principle operate as a mixer up to 1400 GHz, twice the gap frequency of Nb. From the discussion in the previous paragraph it is clear that the junction has an upper frequency limit twice that of the stripline when made from the same material. At frequencies beyond 1400 GHz, the *junction* material has to be replaced by a superconductor with a larger energy gap and therefore a larger voltage nonlinearity. For this purpose NbN or NbTiN comes into play, which, with its large energy gap should be able to operate up to 2600 GHz. Therefore three SIS frequency regimes can now be identified:

100 – 800 GHz	Nb SIS junction with Nb tuning structure.
800 – 1200 GHz	Nb SIS junction with Al or NbTiN tuning structure.
1200 – 2600 GHz	NbN SIS junction with Al tuning structure.

Anticipating the results reported in this thesis we will show that Nb SIS junctions outperform NbN junctions up to 1200 GHz, at which frequency the Nb stops functioning as a heterodyne mixer.

1.7 Conclusions

An abundance of information can be obtained from submillimeter observations of gas clouds in space or of our own atmosphere. Various ways to detect this radiation are currently under development. Nb SIS junctions are currently unlimited in noise performance up to 1000 GHz. Beyond this frequency, Nb and NbN HEB's as well as NbN SIS junctions are promising competitors.

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