Submillimeter Receivers for Radio Astronomy

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Invited Paper

The state of development of receivers for submillimeter-wave radio astronomy is reviewed. Bolometers for continuum observation, hot-electron mixer receivers for narrow-band spectral line observation, and heterodyne receivers, both Schottky diode and superconducting tunnel junction, are presented. At the lower frequency end of the submillimeter band, standard waveguide techniques, scaled from millimeter wavelengths, prevail. At wavelengths shorter than about 0.5 mm quasioptical designs are preferred: in the case of Schottky diode receivers, corner cube designs are used almost exclusively, whereas integrated mixer designs are the focal point of research for SIS receivers at these wavelengths. Although such designs are extensively reviewed, it is nevertheless the Schottky diode mixer remains the element of choice at the shortest submillimeter wavelengths.

I. Introduction

Until, recently, the only method used to examine the universe was through observations made at optical wavelengths. It is now more than a century since electromagnetic waves were first generated at wavelengths other than optical. For some time, scientists had predicted that observations at wavelengths in other parts of the electromagnetic spectrum would add to the knowledge of the physical processes occurring in the universe. However, it is only about 60 years since the first successful radio astronomy observation was made [1]. A similar, but smaller, time lag occurred between the prediction that the rotational transitions of some of the light molecules should fall into the millimeter region of the electromagnetic spectrum [2] and the first observations of millimeter-wave molecular transitions. The observations of the transitions of CO and CN at 115 and 113.5 GHz respectively, representing the birth of millimeter-wave radio astronomy, were made by a group from Bell Laboratories [3], [4] using a specially designed receiver. This was mounted in the 36 ft radio telescope which had recently been completed by the National Radio Astronomy Observatory (NRAO) at Kitt-Peak, Arizona.

Since the beginning of millimeter-wave radio astronomy, a little over two decades ago, we have witnessed an enormous expansion in the number of radio observatories dedicated to millimeter-wave observations of astronomical sources. The first decade was mainly a period of experimentation and saw the completion of a number of the millimeter radio telescopes. Largely driven by the great success of these pioneering instruments—a single antenna at Kitt-Peak, Arizona, followed by the radio interferometers at Hat-Creek and Owens-Valley, California—a number of millimeter-wave observatories are now in operation and millimeter-wave radio astronomy has reached a certain level of maturity. It is partly for this reason that submillimeter astronomy is now emerging as the focal attraction of radio astronomy. Indeed, the submillimeter wave band (λ = 1–0.1mm) is one of the last frontiers of the electromagnetic spectrum to be explored for astronomy. Although submillimeter observations have been made using radio telescopes designed primarily for millimeter-wavelength operation, there are only two specially designed ground-based submillimeter telescopes currently in operation: the James Clerk Maxwell Telescope (JCMT) and the Caltech Submillimeter Observatory (CSO). Both are situated on Mauna Kea, Hawaii. A number of submillimeter radio telescopes are now under construction (e.g., the SubMillimeter Telescope, a joint project between the University of Arizona and the Max Planck Institut für Radioastronomie, and the SubMillimeter Array of the Smithsonian Astrophysical Observatory).

Finally, it is reasonable to assess the state of submillimeter receiver instrumentation as being in a similar stage of development to that of millimeter receivers of about a decade ago. In the sections that follow, we discuss the continued development of such instrumentation—of vital importance in the advancement of submillimeter radio astronomy.

II. Receiver Types

Given the diversity of astronomical requirements (see the paper by Phillips and Keene in this issue), it is not surprising that several types of receiving systems have evolved to fulfill those requirements. For broadband continuum detection, the sensitivity of a receiving system increases as its added noise is reduced and as the receiving bandwidth,

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B, is increased, scaling as $B^{1/2}$. Thus inherently wideband systems, such as bolometric receivers, are often employed. For spectral line observations, the lowest spot-noise systems consistent with spectral line width requirements are preferred. Heterodyne receivers incorporating either a Schottky diode or a superconductor-insulator-superconductor (SIS) tunnel junction mixer are usually employed. However, when only narrow spectral line width observations are to be made (up to a few MHz), a hot electron mixer receiver may be employed.

Traditionally, radio astronomy facilities have limited resources so that not all types of receiver systems are generally available at any single observatory. Although broadband bolometeric systems offer the best continuum sensitivity and InSb hot electron bolometers offer low noise over limited bandwidths, the most common compromise is to install heterodyne receivers of the Schottky or SIS type as facility instruments.

III. Bolometric Receivers

Mainly as a consequence of their inherently large detection bandwidth, bolometric, or direct detection, instruments offer the best sensitivity for continuum observation at submillimeter wavelengths. The sensitivity of a bolometer is usually quoted in terms of its noise equivalent power, NEP, defined as the input signal power that results in a signal to noise ratio of unity at the detector output [5]. For a given background noise level, this is approximately inversely proportional to the square of the physical temperature of the bolometer element. To achieve the highest sensitivity, it is therefore desirable to cool the element to as low a temperature as possible. A dilution refrigerator has been proposed to cool arrays of bolometers to 0.1 K [6] and adiabatic demagnetization has been used to cool bolometers to $\sim$ 0.2 K [7]. However, it is more usual to cool to $\sim$ 0.3 K using ^{3}He as the refrigerant [8].

At the heart of a typical bolometer system lies the detector element, made from either doped germanium or silicon. This is bonded to an absorbing surface which is usually mounted in a small cavity at the end of a Winston cone feed. The signal input to the bolometer is often defined by a series of band-pass mesh-type filters, cooled to reduce losses. For ground-based observations, these are matched to the atmospheric windows which offer reasonable transmission and may be selected individually via a rotating wheel so that a single bolometer may operate through several observing bands. The Winston cone feed, like the bolometer element, is insensitive to polarization so that all of the filtered radiation is available for detection. For polarization measurements, two bolometers may be operated simultaneously and a simple wire grid may be used to define and separate the polarizations. Since the incoming signals are now polarized, waveguide horns may be substituted for the Winston cones, offering an improved beam shape. This also has the advantage that low-pass filters may be used to define the operating bandwidth, since the lower frequency cutoff is now set by the waveguide dimensions.

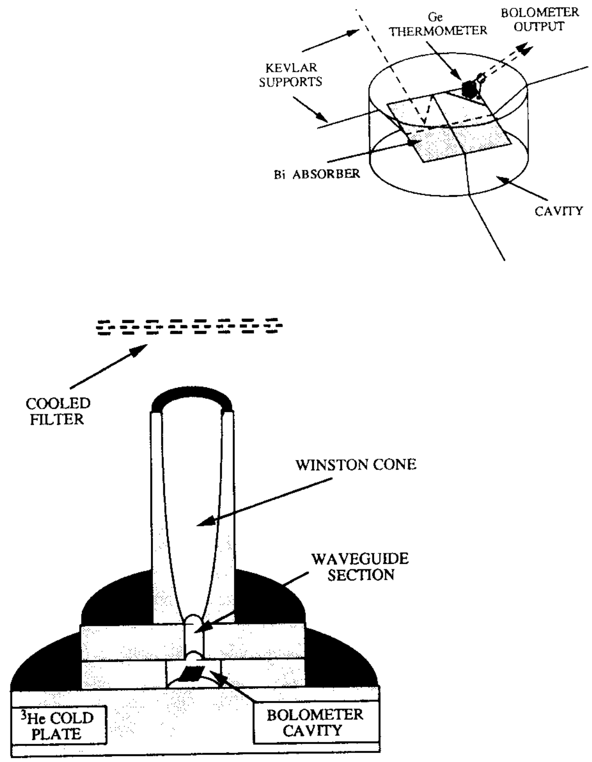


Fig. 1. Signal input to the bolometer passes through cooled filters before entering the Winston cone feed, which is fixed to a ^{3}He cold plate. The insert shows an expanded view of the cavity housing the detector element, a Ge thermometer soldered to a sapphire substrate supporting the Bi absorber.

A typical bolometer receiver is described with reference to Fig. 1. The detector element is fabricated from neutron-transmutation-doped germanium and has low current-noise ohmic contacts made using boron ion implantation [9]. This is directly soldered with indium to a thin layer (1000 Å) of gold deposited on the back surface of a sapphire substrate which essentially provides a large increase in absorbing area with only a modest increase in heat capacity. The front surface of the substrate is coated with a thin layer of bismuth, which acts as the absorbing element. Although bismuth films are known to be fragile and may even degrade with time, bismuth is preferred for use with the lowest background bolometers because of its low heat capacity, typically a factor of 10 lower than that of the nichrome, which has superior mechanical properties. The sapphire substrate is mounted at the base of cylindrical cavity using thin Kevlar threads, and is coupled to a Winston cone feed via a short section of circular waveguide which also acts as a high-pass filter. A low-pass filter made up of free-standing resonant meshes is used to define the observing band. Additional layers of fluorogold and black polyethylene are used to cut out unwanted infrared radiation. Cooling of the bolometer assembly is provided by a small ^{3}He cyrostat with a hold time of about 30 h at 0.27 K. With this system, the beam switching necessary to cancel fluctuations in atmospheric emission is achieved either with a focal plane chopper arrangement or, if the radiotelescope is so equipped, with a nutating subreflector.

In order to evaluate the effectiveness of the bolometer system, we now compare its sensitivity with that of a heterodyne receiver operating at the same wavelength. The signal to noise ratio obtained by the bolometer [10] is given by

$$(S/N)_D = P\Delta t^{1/2}\mathrm{NEP}^{-1}, \tag{1}$$

where P is the signal power received through a submillimeter bandwidth, B_D, defined by the band-pass filter and Δt is the integration time. Assuming that the source temperature, T_s, is high enough for the Rayleigh–Jeans limit to apply, we may write the signal input power as

$$P = mkT_sB_D, \tag{2}$$

where k is Boltzmann's constant, and $m = 1$ or 2, depending on whether single or dual polarizations are detected. Substituting for P in (1) gives

$$(S/N)_D - mkT_sB_D\Delta t^{1/2}\mathrm{NEP}^{-1}. \tag{3}$$

The signal-to-noise ratio for the heterodyne receiver is given by the Dicke radiometer equation:

$$(S/N)_H = T_sT_{H^{-1}}(B_H\Delta t)^{-1/2}, \tag{4}$$

where T_H is the noise temperature of the receiver itself and B_H is its final detection bandwidth.

Assuming that we observe the same source and integrate over the same time period, we may write

$$(S/N)_H/(S/N)_D = \mathrm{NEP}\cdot B_{H^{1/2}}/(mkT_HB_D). \tag{5}$$

Suppose now that the two systems, bolometer and heterodyne receiver, are operating at 1 mm wavelength. A typical state-of-the art bolometer may have an NEP $= 3.10^{-16}\mathrm{W}\cdot\mathrm{Hz}^{-1/2}$ and an input bandwidth of 35 GHz [12], well matched to the atmospheric window from about 320 to 360 GHz. The heterodyne system may have a noise temperature of 100 K and an instantaneous bandwidth of about 2 GHz. Substitution of these numbers into (5) shows that the bolometer system is more sensitive by about a factor of 3.5, and by a factor of about 7 if both polarizations are detected. In fact, the first, and so far the only, radiodetection of Pluto was made with a bolometer system [13]. Also, partly because of their relative simplicity, they may be preferred to heterodyne systems for use as focal plane array receivers. Indeed a submillimeter common-user bolometer array (SCUBA) of 91 pixels for 650 GHz and 37 pixels for 350 GHz is being constructed for the JCMT [6].

The bolometer receiver described above offers essentially no spectral resolution. However, bolometers may be incorporated into a Fourier transform spectrometer (FTS) and used to observe rotational transitions of either extragalactic origin (Doppler broadened) or planetary origin (pressure broadened) with limited resolution. An FTS based on the Martin–Puplett interferometer, using free-standing wire grids as beam splitters, has been tested at 1 mm wavelength on the 30 m radio telescope of the Insitut de Radio Astronomie Millimétrique (IRAM) [14]. It incorporates two ^{3}He cooled bolometers as the detector elements and, depending on the choice of input filter, can be used throughout several of the atmospheric windows, up to about 600 GHz. In this configuration, the FTS is a dual-channel, polarization-sensitive instrument, and can also be used to measure the polarization of continuum sources when set to the central fringe position. The spectral resolution of this instrument, limited by the maximum path length difference obtainable in the interferometer, is about 100 MHz. However, when used to measure spectra, its (per channel) sensitivity is degraded by the ratio of the bolometers pass band to its spectral resolution. An FTS offering 100 MHz spectral resolution and equipped with a pair of bolometers described above would therefore have a signal to noise ratio about 50 times worse than that of the heterodyne receiver used in the continuum sensitivity comparison above. Alternatively, bolometers or photoconductive elements may also be used in conjunction with a grating for similar spectral resolution, or with a Fabry–Perot interferometer for resolutions approaching $\nu/\Delta\nu \sim 10^5$ [15]. Clearly, for high-resolution spectral line measurements, the heterodyne receiver is more powerful than the direct detection instruments at all but the highest frequencies.

IV. The Hot Electron Mixer Receiver

When cooled to liquid helium temperatures, pure InSb exhibits hot electron effects: the temperature of the conducting electron gas, T_e, is only weakly coupled to that of the lattice and can therefore be raised above it. Unlike Schottky diode and SIS mixers, which respond to the applied local oscillator (LO) and signal voltages, and hot-electron mixer element responds to power at the LO and signal frequencies. An increase in detected power results in an increase in T_e, which in turn increases the mobility, μ_e of the electron gas, since this is limited by impurity scattering at low temperatures ($\mu_e \alpha T_e^{3/2}$). Under constant-current operation, therefore, the voltage change across the mixer is a function of the temperature change. At submillimeter frequencies, the mixer does not respond directly at the incident frequency since the effective hot electron energy relaxation time constant $\tau_e(\sim 10^{-7}\mathrm{s})$ is significantly longer than the period of the incident radiation. However, in the presence of LO power, mixing can occur, yielding a voltage output at frequencies up to $1/\tau_e$, typically a few MHz. The mixer is therefore inherently narrow band, but may be operated in the double-side band (DSB) mode with the two sidebands separated by only a small fraction of the IF. Spectra can be measured by stepping the LO across the band of interest and collecting data at each frequency point in the band. This type of receiver offers excellent noise performance when used to observe narrow spectral lines (< 5 MHz). However, the receiver noise performance is effectively degraded for broader spectral observation by $N^{1/2}$, where N is the number of narrow-band spectral channels observed.

The InSb hot electron mixer receiver [16] was first used for spectral line observations of CO at 115 GHz

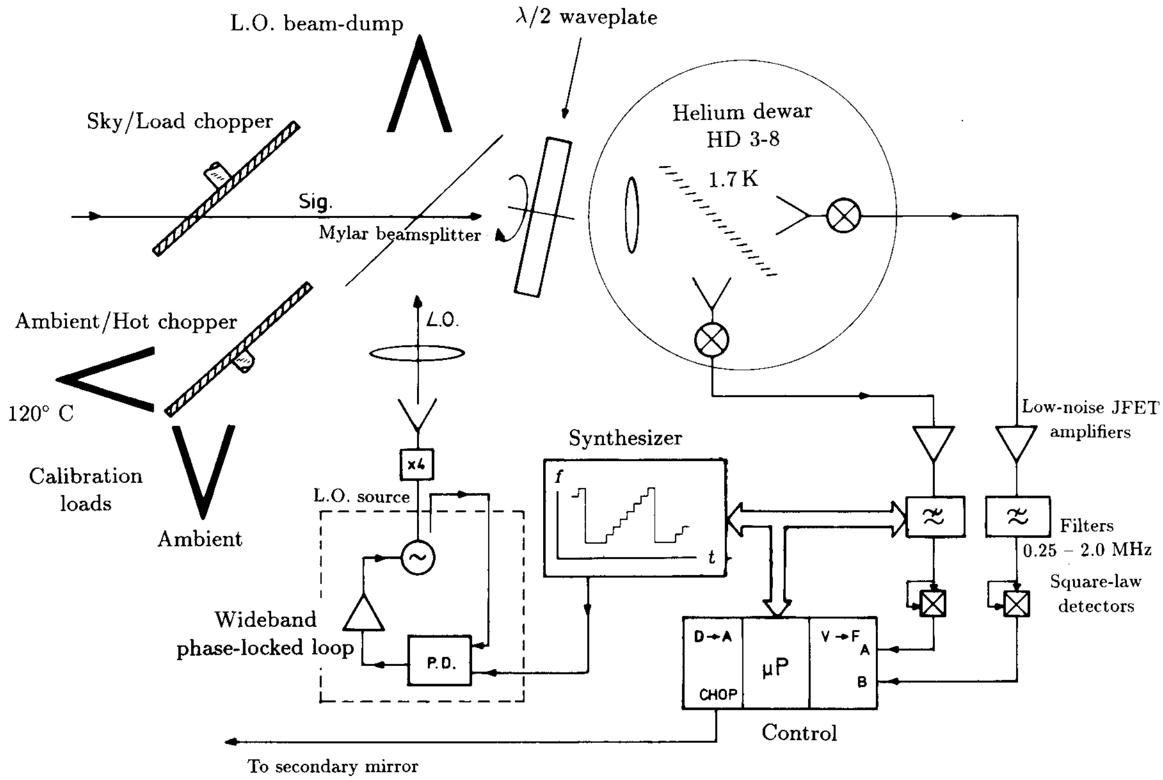


Fig. 2. Block diagram of the InSb hot electron mixer receiver installed at the JCMT. Signal input to the mixers is via a sky/load chopper, a Mylar beam splitter for LO injection purposes, and a half-waveplate used to equalize the LO drive to the mixers.

by Phillips and Jefferts [17]. Their system achieved a DSB noise temperature of ~ 250 K at 120 GHz and had an operating bandwidth of about 4 MHz. Fig. 2 shows the general optical arrangement of a dual-channel InSb receiver, recently constructed for the JCMT, for operation at 461 GHz and 492 GHz [18]. The beam coming from the telescope is sent through a series of beam chopping assemblies and matched loads at known, fixed temperatures for amplitude calibration purposes. The LO source consists of a single varactor diode quadrupler fed by interchangeable InP Gunn oscillators operating at ~ 115 GHz and ~ 123 GHz. The LO power output from this assembly is ~ 100–200 μW, more than adequate to pump the mixers, which typically require 1 μW each. For this reason, coupling of the LO power to the mixers is made using a simple Mylar beam splitter. Since the LO is of a single polarization, a simple rotatable half-wave plate is used to equalize the LO power on the two mixers without affecting the signal input.

Signal is input to the cryostat, housing two InSb detectors cooled to 1.7 K and set to receive orthogonal linear polarizations, via a high-density polyethylene (HDPE) window, not shown, a cooled HDPE lens, and a simple wire grid polarizer. Smooth-walled conical horns are used to feed the orthogonal signals onto their respective detectors, each of which is made from a section of n-type InSb and mounted across the narrow dimension of a rectangular waveguide section 0.54 x 0.30 mm. Output from the individual mixers is first amplified in a low-noise video amplifier, and is then coupled out through a dc block to reject LO noise close to the carrier. The resolution bandwidth of the receiver is defined by selectable low-pass filter networks whose output is sampled at the same time as the LO is stepped across the band of interest.

With receiver noise temperatures of ~ 500 K at 461 GHz and ~ 1100 K at 492 GHz, this dual polarization instrument is competitive with the broader heterodyne systems for observations requiring fewer than about 50 spectral channels. However, this situation is unlikely to persist since an SIS mixer receiver designed to operate in the same wave bands, offering much reduced noise and an instantaneous bandwidth of 1 GHz, has recently been installed at the CSO [19]. Similar low-noise performance has been achieved in the laboratory at the SRON (Laboratory for Space Research, Gröningen) [109].

In order to achieve increased instantaneous bandwidth, comparable to that of current SIS or Schottky diode mixers, a number of groups have begun to investigate the possibility of using two-dimensional electron gas (2DEG) devices as hot electron mixers [20], [21]. Values of τ_e for 2DEG heterostructures of 10^{-9}–10^{-11} s have been measured over the temperature range 4.2–300 K. This suggests that instantaneous bandwidths in excess of 10 GHz may be possible for the 2DEG mixer [22]. Recently, mixing experiments made at 94 GHz with an $\mathrm{Al}_x\mathrm{Ga}_{1-x}\mathrm{As/GaAs}$ heterostructure, grown by organometallic chemical vapor deposition, have demonstrated an instantaneous bandwidth of 1 GHz [23]. Although the measured conversion loss of

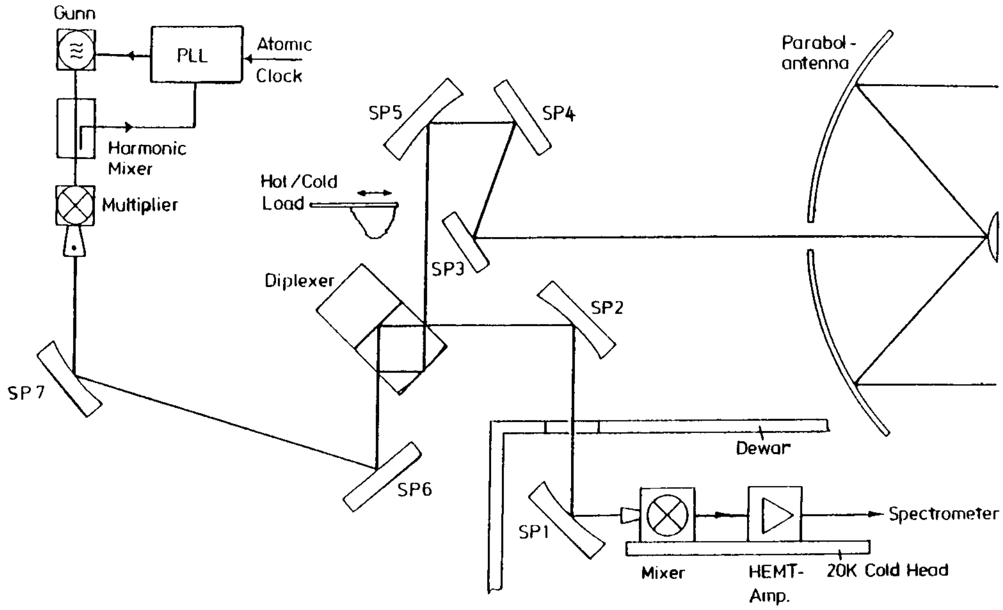


Fig. 3. Schematic illustration of a cooled Schottky diode mixer receiver built for operation at 345 GHz. This receiver is easily divided into three subsystems: the input optics which includes several off-axis mirrors, the LO system, and the mixer and first IF amplifier cooled to 18 K.

these devices is poor at this initial stage of development, there is no fundamental reason forbidding the scaling and refining of this type of device for submillimeter operation.

V. Schottky Diode Mixer Receivers

In Schottky diode mixer receivers, the incoming signal is mixed with the LO signal in a barrier diode possessing a nonlinear *I–V.* relation. This type of receiver has so far been the mainstay for radio astronomy observations from the millimeter to the far-infrared. Receiver designs incorporating waveguide are favored at the lower frequencies (< 600 GHz), whereas quasioptical designs are favored for higher frequency operation.

Fig. 3 is a schematic illustration of a Schottky diode receiver system designed to have optimum sensitivity for observing the $CO_{J=3\rightarrow 2}$ rotational transition at 345 GHz [24]. Referring to this figure, the receiver may be conveniently separated into three subsystems: the LO assembly, the input quasioptics, and the mixer and IF amplifier assembly. The output signal-to-noise ratio of such a receiver was expressed previously, through (4), in terms of receiver noise temperature, T_H. Reference to (4) indicates that in order to achieve high sensitivity, T_H should be kept to a minimum. For the heterodyne receiver, T_H is made up of noise arising from losses at the receiver input, losses in the mixer, and multiplied mixer and IF noise. The individual contribution of these noise sources may be written as

$$T_H = T_{li} + L_i T_M + L_i L_M T_{\mathrm{IF}}, \qquad (6)$$

where T_{li} is the noise arising from losses, L_i, in the quasioptics at the receiver input (at a physical temperature T_i), T_M is the mixer noise temperature, L_M is the mixer conversion loss, and T_{IF} is the noise temperature of the IF amplifier chain. In order to achieve low receiver noise, it is clear that losses arising in signal coupling and LO injection schemes, often quasioptical, should be kept small. Cooled input optics and the use of mirrors instead of lenses may be used to reduce the input noise contributions. For a complete discussion on quasioptical components, see the paper by Goldsmith in this issue. From the above equation, it is also clear that mixer noise and mixer conversion losses should also be kept small for low receiver noise. The fundamental limitations on mixer performance are discussed in papers by Crowe and by Wengler also in this issue.

We now examine the receiver, shown in Fig. 3, in more detail. The LO source consists of a phase-locked Gunn oscillator which delivers about 40 mW of power at 115 GHz to a frequency multiplier. The multiplier ($\times 3$) incorporates a varactor diode from the University of Virginia (type 6P4) and, with an efficiency of 8%, can deliver 3.2 mW at 345 GHz. Gunn oscillator–varactor multiplier chains are commonly used as receiver LO's to about 600 GHz. (For an up-to-date review of LO sources, see the paper by Räisänen in this issue). Both LO and signal input are coupled to the mixer using a folded Fabry–Perot resonator. This has a maximum signal transmission loss of ~ 0.5 dB and a relative signal degradation of only 2% at the IF band edges. This quasioptical design incorporates a number of off-axis elliptical mirrors. These are phase corrected and are designed to truncate the beam at a radius equal to 1.5 times its waist radius, i.e., at the -19 dB level. Some small loss of signal is therefore inevitable. The total signal transmission loss through the input optics and LO diplexer is about 1 dB and is responsible for somewhat less than 140 K, or about one third, of the receiver's total DSB noise temperature of 350–380 K. Amplitude calibration of the receiver is

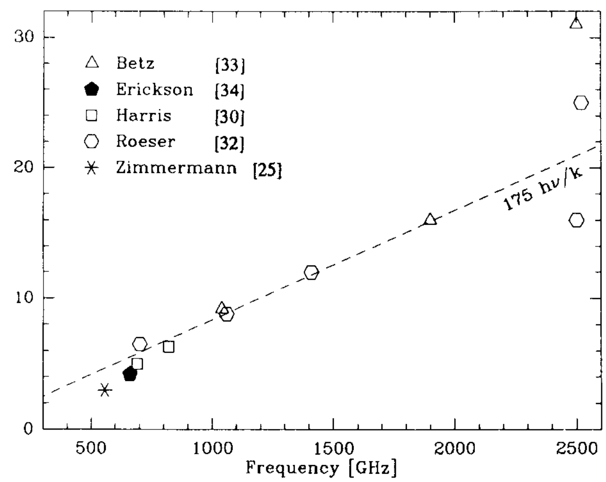


Fig. 4. The single sideband receiver noise temperature for the best reported Schottky mixer receivers is plotted as a function of frequency across the submillimeter waveband. The dashed line represents a receiver noise equal to 175 times the quantum limit of mixer noise.

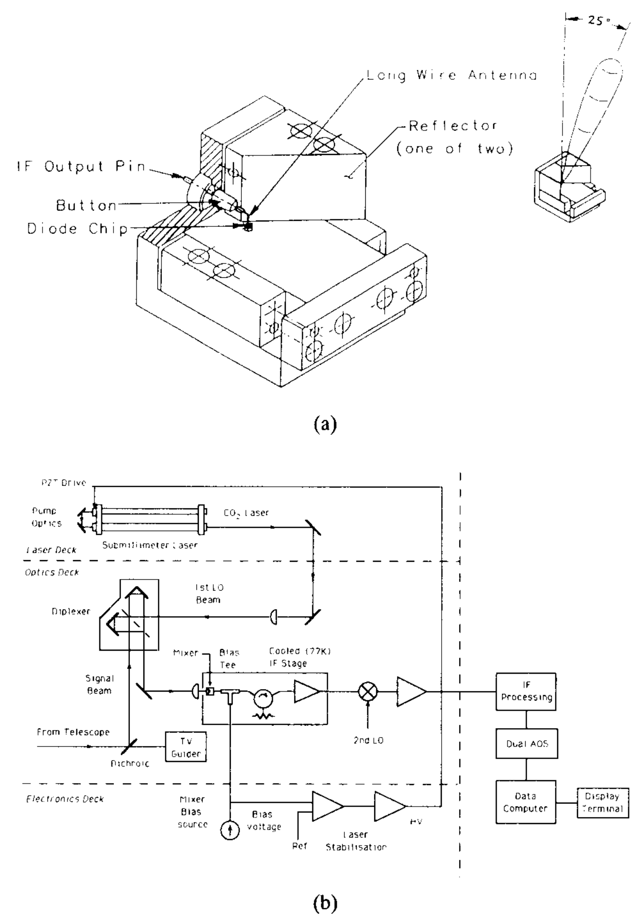


Fig. 5. (a) Mechanical layout of the corner-cube mixer. This mixer includes adjustable corner reflectors so as to produce a symmetrical beam pattern at 25° to the axis of the long wire antenna. (b) Block diagram of the complete receiver system used for observations of CO at 806.6 GHz [30].

achieved using a sliding mirror that can be displaced so as to direct either a hot (300 K) or cold (40 K) load towards the receiver input. Input to the mixer diode, a 2I1-150 diode from the University of Virginia, is made via a dual-mode Potter horn connected to a short waveguide section housing the diode. A coaxial choke filter is used to output the IF. This is amplified using a high electron mobility transistor (HEMT) amplifier with center frequency 1.4 GHz, bandwidth 800 MHz, and noise temperature ~10 K. This is cooled with the horn–mixer assembly to about 18 K using a commercially available two-stage refrigerator. Output from the receiver passes to an acousto-optical spectrometer (AOS), a fourth subsystem that may be switched to analyze data from different receivers.

Fig. 4 gives a brief summary of the noise performance of Schottky mixer receivers designed to operate in the frequency range 500–2500 GHz. It is largely due to the reliability and to the ease and efficiency of signal coupling that waveguide remains the best choice of medium in which to build a low-noise heterodyne mixer at the longer submillimeter wavelengths, up to about 600 GHz. The high frequency limit arises because as the wavelength is further decreased it becomes increasingly difficult to machine fundamental waveguide and back-short tuners of the appropriate dimensions. At the lower frequencies, we should note the excellent low-noise performance of the room-temperature Schottky mixer receiver at 557 GHz [25], built for a balloon experiment to detect the water molecule in giant molecular clouds. A more complicated receiver using subharmonically pumped Schottky mixers, radiatively cooled to about 150 K, is now under development for the Submillimeter Wave Astronomy Satellite [26]. With a projected single-sideband (SSB) system noise temperature of about 2500 K, this will be used to detect O_2 at 487 GHz, C(I) at 492 GHz, $H_2^{18}O$ at 547.5 GHz, ^{13}CO at 551 GHz, and H_2O at 557 GHz. (For more information, see the paper by Erickson in this issue).

Above about 700 GHz, a different type of coupling technology is preferred. In particular, the corner cube open structure mixer is most widely employed. The theory for calculating the approximate beam patterns for this type of antenna structure is relatively straightforward. The long wire traveling wave antenna produces a hollow cone-shaped beam pattern concentric with the wire. Placed in a 90° corner reflector, the antenna and its electrical images form an array which produces a beam with a well-defined main lobe (see Fig. 5(a)). There exist many variations of the basic corner cube design and the antenna length–spacing ratio has been investigated extensively [27], [28]. A typical design, producing a symmetrical beam about 15° wide at the half power points, may include an antenna of length 4λ placed 1.2λ from the apex of the cube [29]. The corner cube designs are polarized with the E field along the antenna length and offer good on-axis cross-polarization ~ 1%. Unfortunately, corner cubes have large side lobes off their main axes. These reduce the beam efficiency to about 50%—considerably less than well-designed waveguide feeds which achieve beam efficiencies of ~ 90%. However, in the absence of improved designs, the corner cube mixer still reigns supreme at frequencies above ~ 600 GHz.

Fig. 5 is a schematic representation of one of the most successful corner cube mixer receivers used for ground-based radio astronomy [30]. Since beam shape and efficiency depend critically on the placement of the antenna within the corner-cube structure, the mixer design includes individually adjustable reflectors (shown in Fig. 5(a)). The Schottky diode is soldered onto the end of a diode post which is inserted through the base of the corner cube assembly. Contact to the top of the diode is made via the long-wire antenna, the other end of which is soldered to an IF pin used to couple the IF out of the mixer. The IF pin, a glass/metal feedthrough chosen for reasons of mechanical stability, is rigidly mounted to the mixer block so that the reflectors may be adjusted without disturbing the antenna-diode assembly.

Referring to Fig. 5(b), both signal and LO are input to the mixer via a Martin–Puplett type interferometer. The LO is a submillimeter molecular laser which is optically pumped with a CO_2 laser. This type of LO system is common to most submillimeter receivers since it offers several advantages over competing systems. Firstly, solid-state sources, typically varactor multiplied Gunn oscillators delivering about 50 μW, fall short of the power required to correctly pump the Schottky diode mixer by about half an order of magnitude. Secondly, backward wave oscillators (carcinotrons) are notoriously unreliable and expensive, and are often short-lived. Finally, since the laser only oscillates on discrete molecular lines, the LO frequency is well defined; typically within 1 MHz after tuning for maximum power output. Therefore, for a single receiver system, the laser need not be phase-locked and the system electronics may be simplified considerably. However, one consequence of using a fixed frequency LO is that, in order to observe different molecular lines, the receiver IF must be flexible—covering different bands for different astronomical lines. The IF output from the mixer (Fig. 5(b)) passes to one of several low-noise amplifier networks which is cooled to 77 K. Note that wideband, low-noise HEMT amplifiers of the type described by Pospieszalski [31] can be used to eliminate the need to switch between different amplifier networks as the observing frequency is changed. Finally, after amplification the signal undergoes a second down-conversion before final processing with an AOS.

A similar receiver, designed to operate in the wavelength range 500–100 μm and flown successfully on the Kuiper Airborne Observatory (KAO), was developed at the Max Planck Institut für Radioastronomie. Once again, the LO source incorporates an optically pumped submillimeter laser of compact design—especially configured for use in flight [32]. The performance of this receiver is given in Fig. 4 as 16 000 K (SSB) at 2500 GHz. Also shown in the same figure are data from Betz and Boreiko [33] for their receiver system designed to operate from $\sim$ 1000–2500 GHz. This system has also been used successfully with the KAO to observe molecular spectra.

As discussed above, the sources of receiver noise arise from losses in quasioptics, mixer noise, and multiplied IF noise. With the ever improving HEMT IF amplifiers, the majority of receiver noise in Schottky mixer systems is due to the mixer. This mixer noise, a function of frequency, is particularly elevated at submillimeter wavelengths and strongly depends on the diode parameters. Until recently, small-area, low-capacitance diodes for submillimeter operation have been available from only two laboratories [35], [36]. However, due to the ever increasing activity at submillimeter wavelengths, a consortium has recently been established in an effort to further the diode technology. Initial room-temperature noise measurements made on devices from this consortium are promising: a mixer noise temperature of 2000 K and a mixer conversion loss of -7.5 dB have been measured at 649 GHz [37].

Given that, at the present time, there exists no viable alternative to the Schottky mixer type of receiver for operation above about 1000 GHz, it is likely that these receivers will represent the state of the art for some time to come.

VI. SIS Receivers

A. Background

It is now about 30 years since Dayem and Martin [38] observed a step structure in the current–voltage (I–V) curve of an SIS tunnel junction when subjected to microwave radiation at 38 GHz. This step structure was later explained by Tien and Gordon [39] in terms of the photon-assisted tunneling of single electrons across the tunnel barrier. Fifteen years later, Tucker developed a quantum mechanical treatment of heterodyne mixing in the SIS tunnel junction [40]. His theory was used to predict a number of interesting features. In particular, it predicted quantum limited mixer noise and the possibility of mixer conversion gain [41], not possible through the classical treatment of mixing, and hence the possibility of extremely low-noise receivers. It also predicted that the LO power required for optimum noise performance, typically 10^{-7} W, is several orders of magnitude lower than that required to operate the Schottky diode mixers usually employed for heterodyne mixing.

The features predicted by Tucker's theory were extremely attractive to the receiver engineer. A number of groups had access to the required technology which was largely developed for Josephson junction applications, including low-noise mixing. Josephson junction mixers however were found to be both noisy and unstable, so the possibility of low-noise frequency conversion using a similar device was quickly seized upon [42]–[44]. The first SIS mixer receivers to be used on radio telescopes were described by Olsson *et al.* [45] and by Woody *et al.* [46]. The first complete demonstration of quantitative agreement between the theory and experimental measurements was made by Feldman *et al.* [47] in 1983. Tucker's theory is now well established and both mixer conversion gain and mixer noise close to the quantum limit ($T_M = h\nu/k \sim 0.05$ K/GHz) have been observed in a number of laboratories [48]–[52]. There have also been major advances in the development of SIS junction fabrication technology, the general level of our understanding of the SIS mixer has improved, and receiver noise performance of only several times the quantum limit has now been measured. Because of their lower noise performance at millimeter wavelengths, SIS receivers have now replaced the more traditional cooled Schottky diode receivers at many radio observatories. However, at wavelengths shorter than 0.5 mm SIS receivers are still under development.

Although SIS receivers are now the obvious first choice for lowest noise operation, we should note that their exploitation is not without added complexity particularly in the domain of cryogenics. In the case of Schottky diode mixers, low-noise receiver operation is achieved by cooling the mixer to either 77 K using liquid nitrogen or to $\sim$ 20 K using standard two-stage refrigeration techniques. SIS mixer receivers only operate when the SIS tunnel junction is cooled below the critical temperature of its superconducting electrodes. For the commonly used superconductors, low-noise mixer operation is obtained at or below about 4 K. Many different cooling schemes have been developed for use with SIS receivers. These include the classical wet-cryostat requiring both liquid nitrogen and liquid helium and the hybrid cryostat [53] in which a liquid helium chamber is surrounded by radiation shields at $\sim$ 70 K and $\sim$ 20 K cooled using a standard two-stage refrigerator. A number of closed-cycle 4 K refrigerators have also been developed for this purpose [54]; these usually rely on a Joule–Thomson expansion circuit precooled using a standard two-stage refrigerator.

In the subsections that follow, we first present the current state-of-the-art performance of waveguide SIS receivers. We then examine various quasioptical designs for shorter wavelength operation.

B. Waveguide Receivers

The first SIS mixers were made by simply replacing the Schottky diode in a waveguide mixer with an SIS tunnel junction deposited onto a quartz substrate. Because the SIS junction has an inherently large geometric capacitance, typically 50 fF for a 1 μm^2 device compared with about 10 fF for submillimeter Schottky diodes, a second tuning element was sometimes added to the waveguide circuit. More recent designs have included resonant integrated tuning structures [55], deposited at the same time as the SIS element, to further improve impedance matching.

In Fig. 6 we display some of the best reported receiver noise temperatures as a function of operating frequency for waveguide SIS systems built to operate up to 500 GHz. For completeness, and partly because of the lack of true submillimeter data, we extend the frequency scale down to 200 GHz. At lower frequencies, not shown in the figure, the fixed tuned mixer receivers of Kerr and Pan [56] and Winkler *et al.* [57] offer low-noise performance throughout most of the 3 mm atmospheric window. Low noise is also offered by the single tuned mixer receivers installed at the interferometer of the IRAM on the Plateau de Bure in the French Alps. We should also note the excellent receiver noise performance, about four times the quantum limit of mixer noise, offered by the double tuned mixer receivers

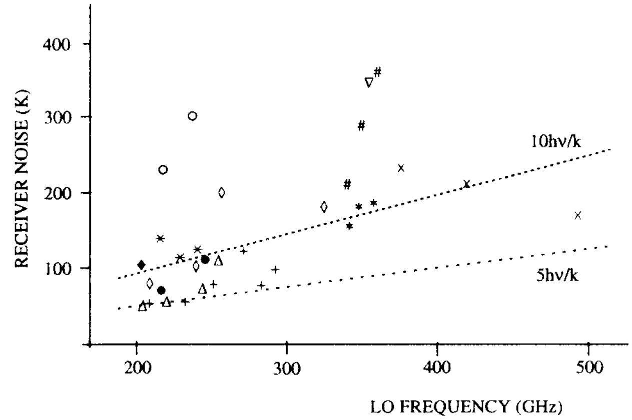


Fig. 6. The double sideband receiver noise temperature for the best reported SIS waveguide mixer receivers is plotted as a function of frequency. Dashed lines are drawn at 5 and 10 times the quantum limit of mixer noise. Data plotted in this figure are after references: × [19]; • [65]; ⋇ [66]; △ [67]; + [68]; ○ [69]; * [72]; # [73]; ◇ [74]; ▽ [75]; ♦ [108].

described by Kerr and Pan [58] and, more recently, by Ogawa *et al.* [59]. These receivers are of similar design and both incorporate a double-tuned waveguide mixer similar to that first described by Pan *et al.* [60]. This type of mixer allows almost any desired embedding admittance to be presented to the SIS junction, hence the low-noise performance.

The 2 mm wavelength range has received attention in only two laboratories, those at the IRAM and the University of Cologne. The SIS receivers built and tested at these laboratories offer improved performance [61]–[63] over Schottky diode mixer receivers built for this wavelength range, about ten times the quantum limit of mixer noise.

The first SIS receiver specifically designed for the 1.3 mm atmospheric window was built and tested by Sutton in 1983 [64]. Its noise performance was comparable to or better than that of Schottky diode receivers operating in the same waveband. Largely in response to the success of this receiver, many laboratories have now developed similar, but lower noise, receivers operating in this wavelength range. The receiver noise offered by the best of these is also reproduced as a function of LO frequency in Fig. 6. The waveguide receivers built at the IRAM and Caltech have been in use for several years now. Both offer good, low-noise performance [65]–[66], about ten times the quantum limit of mixer noise. More recently, excellent low-noise performance, about four times the quantum limit, has been obtained using a receiver constructed at the NRAO [67] and, for the CSO, at Caltech [68]. The first of these makes use of a broadband waveguide mixer which incorporates a series array of inductively shunted SIS junctions. The mixer also has two short circuit plungers to ensure optimum tuning at the signal frequency. LO power is input to the receiver via a cooled waveguide coupler. An extremely low noise HEMT IF amplifier completes the receiver. The other receiver incorporates a small-area, low-leakage, Nb/Al-oxide/Nb SIS trilayer junction as the mixer element. It also has two RF tuning elements: a regular back-short tuner and an E-plane tuner. The mixer output impedance was carefully matched to the 50 Ω input of the IF network: a cooled HEMT amplifier with a noise temperature of about 5 K. The designers claim that the impedance transformation at the IF was an important factor in achieving low receiver noise.

The results of experiments made with a superconductor-insulator-normal metal (SIN) mixer receiver are also shown in Fig. 6 [69]. In this case, an SIN tunnel junction was simply substituted for an SIS tunnel junction in the measurement setup described in [65]. The increase in receiver noise of about 30% for the SIN mixer receiver should be considered as encouraging for higher frequency operation. More recently, results of computer simulations have shown that both reasonable gain and low-noise mixing should be possible with SIN junctions made using current technology to above 500 GHz [70]. A subharmonically pumped SIN mixer has been developed for operation at 500 GHz. However, laboratory tests indicate high conversion loss [71].

Most of the development work done at wavelengths below 1.3 mm has been aimed at the production of systems to operate specifically at 345 GHz, in the 0.87 mm atmospheric window. Since little work has been published at these wavelengths, the majority of available SIS receiver noise data is included in the figure. Only two receivers have been used on a regular basis for the collection of radio data, those of Ellison [72] and Sutton *et al.* [73]. The most successful receiver, offering the lowest noise, is that of Ellison. This is installed as a facility instrument at the CSO. The mixer used in this receiver is a scaled version of one previously built for 230 GHz operation and is shown schematically in Fig. 7. Referring to the figure, the mixer is made up from a single lead alloy SIS junction mounted across a full-height rectangular waveguide. Input to the mixer is through a corrugated feed horn and tuning at the signal frequency is made using a regular noncontacting backshort and an E-plane tuner. The output from the mixer, at 1.5 GHz, passes along a low-pass filter network which provides more than 20 dB rejection over the required signal bandwidth to an IF matching circuit. This is used to match the mixer's IF output impedance, typically 150 Ω real, to the 50 Ω IF amplifier input.

Above 350 GHz, only two sets of receiver noise data have been published. The first of these, a single measurement yielding 620 K at 490 GHz, was made using a laboratory test system previously developed for lower frequency operation [76]. The other data were measured using a receiver specifically designed for operation in the atmospheric windows at 460 and 490 GHz [19]. This receiver was recently installed at the CSO and has a receiver noise temperature of only 170 K (DSB), measured at 492 GHz. Excellent noise performance is also achieved at 420 and 376 GHz with this receiver (see Fig. 6).

C. Integrated Mixer Receivers

1) Alternatives to Waveguide Structures: As in the case of Schottky receivers, the difficulties in fabricating ultrasmall

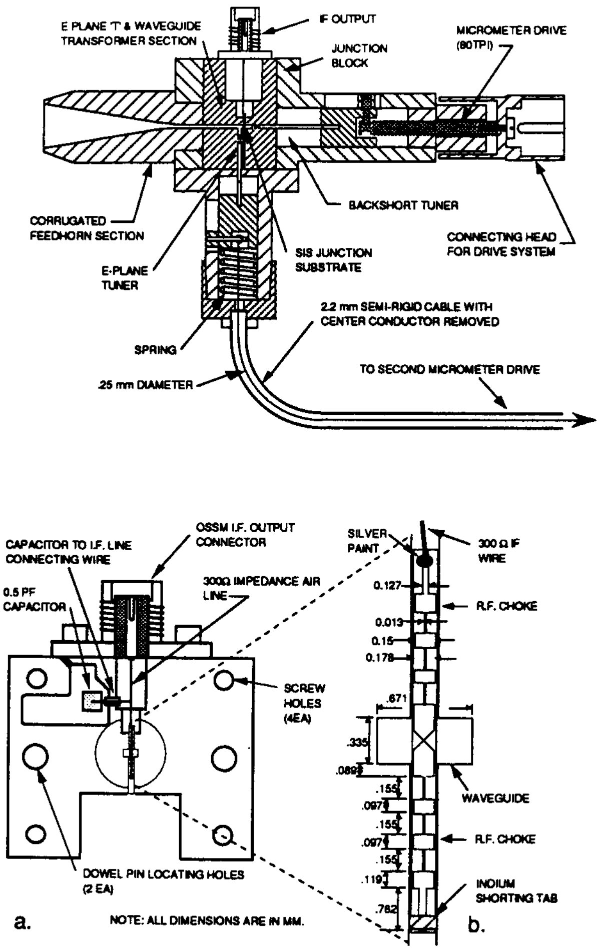


Fig. 7. Detail of the 345 GHz mixer of Ellison *et al.* [72] showing the corrugated feed input and the E-plane and back-short tuners. Also shown are the IF matching network and details of the low-pass filter circuit used to pass the IF and reject the input signal frequency.

waveguide for the high-frequency end of the submillimeter wave band have driven SIS receiver builders to look for other alternatives. Among the different possibilities proposed, the planar printed antenna type receiver, in which the SIS junction and a printed antenna coupling structure are integrated on the same substrate, stands out as a viable alternative. The incentives to pursue such a development are as follows.

1. In the waveguide technology, it is common practice to fabricate the SIS junction and the associated RF choke on the same substrate. Given that the dimensions of a submillimeter microantenna are compatible with the monolithic technology, it seems only natural to try to include a planar antenna in the same circuit.
2. The monolithic approach inherently guarantees reproducibility and reliability.
3. While a waveguide receiver has a maximum bandwidth of about half an octave, certain wideband printed radiating elements can function over several octaves in frequency. It has been hoped that an ultrawideband quasioptical receiver, covering several

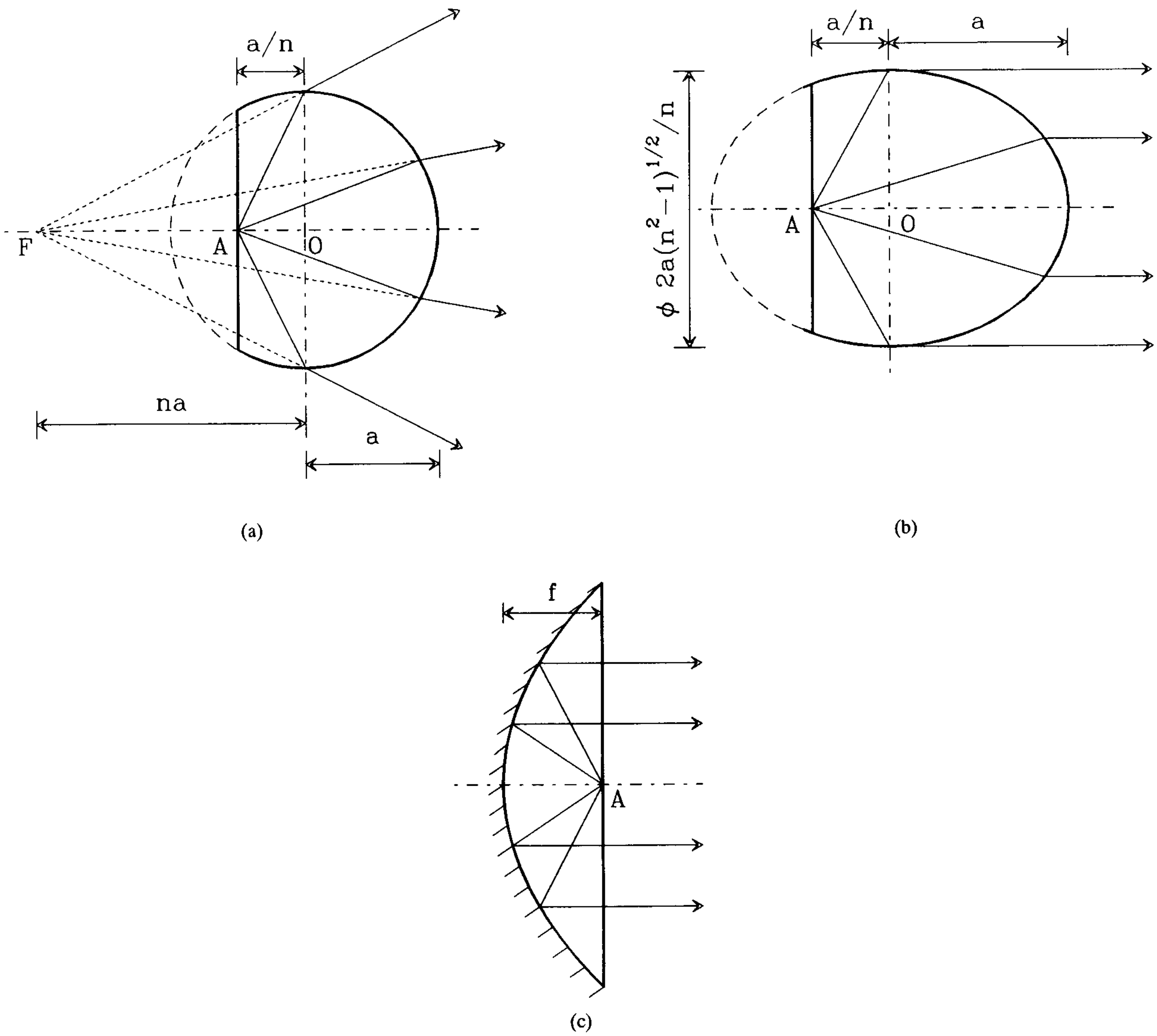


Fig. 8. Substrate lens designs for integrated receivers. In each case, the antenna feed point is positioned at A. (a) The hyperhemispherical lens generates a virtual focus at F behind the lens. (b) The ellipsoidal lens collimates the radiation from A into a parallel beam. (c) The dielectric-field paraboloid transforms the radiation of the printed antenna into a diffraction-limited beam upon reflection at the metallized surface.

atmospheric windows, can be constructed using the planar technology.

4. The use of arrays of planar receivers opens the horizon for low-cost, compact multibeam systems. In fact, many proposals concerning quasioptical receivers have been derived from optical imaging work [77].
5. Integration may eventually be extended to incorporate some IF circuitry, thus forming a fully integrated receiver. It is this possibility that is extremely attractive to receiver engineers and astronomers alike.

At microwave frequencies, a large variety of low-profile radiating elements are being exploited. However, direct scaling of these designs to submillimeter is not often feasible for a number of reasons:

1. In order to reduce power loss to surface wave modes, the substrate thickness, t, needs to be scaled with the operating frequency. Typically, $t < 0.1\lambda_0$ is used. This means that for $f > 600$ GHz, the substrate should be less than 50 μm thick. Such thin substrates are difficult to handle.
2. The gain of printed antennas is usually very low. It is in general difficult to efficiently couple the incoming signal to the broad radiation pattern of these antennas. To date, this beam coupling problem remains the major obstacle in the design of integrated antenna type receivers.
3. In a waveguide mount, the mixer block acts as a heat sink so that it is relatively easy to cool the superconducting tunnel junction to the correct operating temperature, typically that of liquid helium. In a typical quasioptical design, the junction may be at the feed point of a wideband antenna having a broad radiation pattern. As a consequence, a more elaborate design is necessary to ensure that the junction is

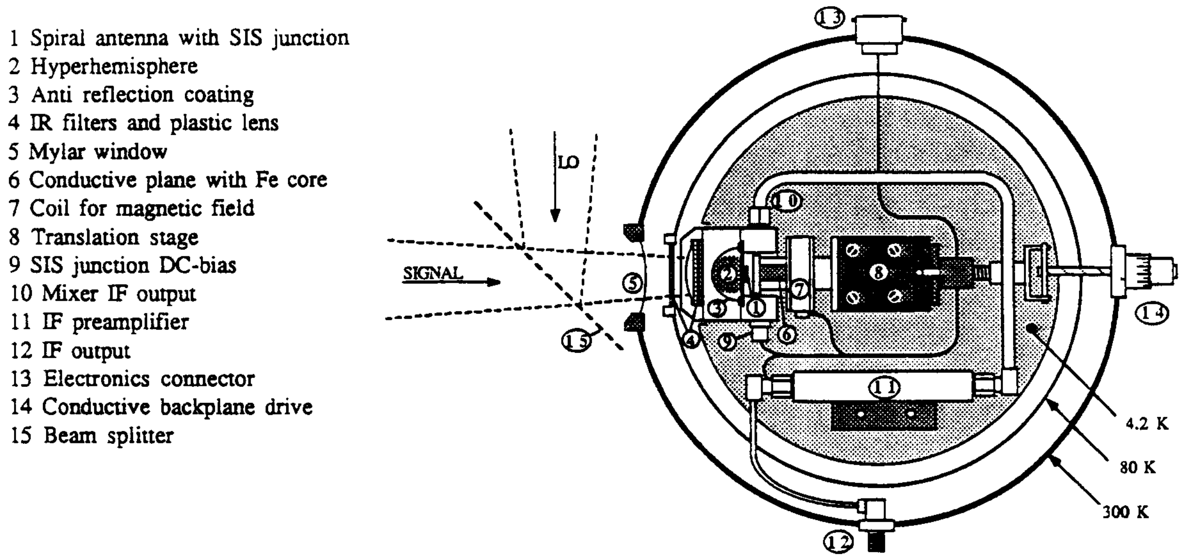


Fig. 9. Typical layout of an integrated mixer receiver incorporating a substrate lens mixer design, after [87].

properly cooled and that saturation problems arising from out-of-band signals are taken care of.

4. Unlike waveguide mixers, it is very difficult to incorporate a movable tuning element in an integrated receiver to vary the mixer's embedding impedance. Furthermore, the radiation impedance of all broadband microantennas as well as narrow-band antennas at resonance is real. As a consequence, additional measures are required to tune out the junction capacitance for optimum performance.

2) The Substrate Lens: Most of the integrated receivers tested so far employ a substrate lens [78], [79] (or immersion lens). This helps to alleviate some of the problems listed above. In a typical setup, the substrate carrying the microantenna is pressed against the planar surface of the immersion lens so that the antenna radiates predominately into the lens.

There are multiple advantages to this design. First, surface wave effects can be completely eliminated. The power radiated into the lens is mostly coupled forward onto the signal path. The forward radiation power is about n^3 times the backward radiation into free space, where n is the refractive index of the lens [80]. Hence, even normally bidirectional radiating antennas can also be utilized. The front surface of the lens may be shaped to improve the coupling between the incoming signal beam and the microantenna. In addition, since the lens and the substrate carrying the microantenna form a single unit, thicker substrates present no problem. The lens lends itself as an excellent mechanical support for the substrate. Microantenna designs requiring a very thin dielectric layer are in fact possible because the dielectric layer may be sputtered or grown epitaxially onto the back of the thick substrate.

The majority of the experimental submillimeter receivers described below incorporate a hyperhemispherical lens. Referring to Fig. 8(a), this type of lens produces a virtual focus at a distance na behind the center, O, of the equivalent sphere. In this case the beam width of a printed antenna, placed at A, is decreased by a factor of n [81]. An increasingly popular alternative, shown in Fig. 8(b), is the ellipsoidal lens. In this case, the radiation of the printed antenna is transformed further into a diffraction limited beam [82]. Alternatively, largely for ease of fabrication, the front portion of the elliptical surface may be approximated by a spherical surface resulting in an extended hyperhemisphere with elliptical focus. The dielectric-filled paraboloid, shown in Fig. 8(c), is derived from the substrate lens [83]. In this case, the curved surface is reflecting and focuses the radiation from the printed antenna into a parallel beam in the same way as a parabolic dish. Fig. 9 gives the layout of a receiver incorporating a printed spiral antenna coupled to a hyperhemispherical lens, and Fig. 10 is a photograph of another substrate lens mixer designed to operate at 350 GHz.

Two types of antenna have been used to feed the substrate lens: the broadband antenna and the resonant antenna. Receivers incorporating these two types of antenna feed are now described in more detail. The performance of these receivers is summarized in Table 1.

3) The Broadband Substrate Lens Receiver: The bow-tie receiver was the pioneering integrated receiver for submillimeter frequencies [84]. In this type of receiver, a bow-tie-shaped planar antenna (Fig. 11(a)) is printed on a quartz substrate. An SIS junction is incorporated at the center of the bow tie and the substrate is pressed onto a quartz hyperhemisphere. The beam emerging from the hyperhemisphere is further focused by a second focusing element (lens or mirror) to yield a narrower beam width suitable for feeding the radio telescopes. This receiver has been tested in the laboratory from 100 to 500 GHz, giving DSB noise temperatures from 200 K at 100 GHz to 800 K at 500 GHz.

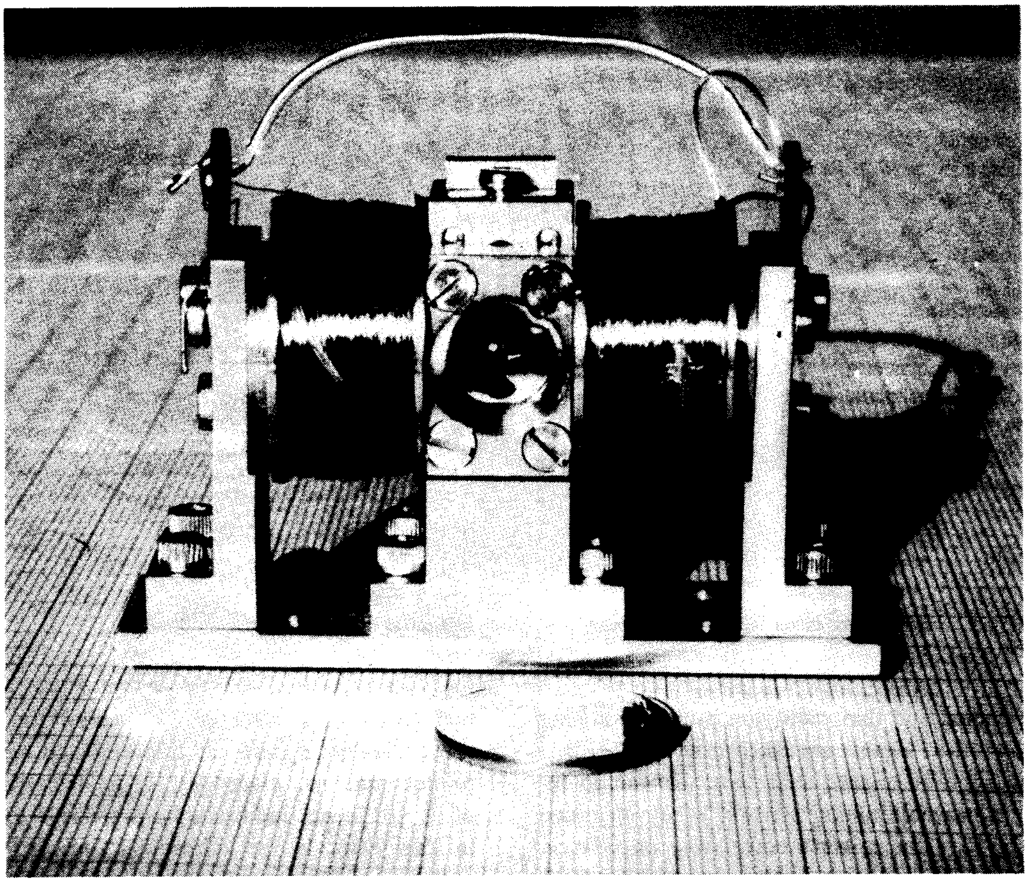


Fig. 10. Front view of a substrate lens mixer design (courtesy Rothermal [102]). The substrate lens carrying the printed antenna structure is placed at the center of the mixer block. The coils at either side of the block are used to generate a magnetic field to suppress unwanted noise from the Josephson effect.

Although the bow-tie antenna coupled to a quartz substrate lens presents a convenient impedance level of 120 Ω to the SIS junction, the antenna's front radiation lobe does not coincide with the optical axis. Such radiation characteristics have been confirmed by both theoretical and extensive experimental studies [85], [86]. Consequently, coupling with the incoming signal is low so that the bow-tie receiver has never seriously been considered for use as a facility instrument at a radio telescope.

The second broadband antenna to be explored is the two-arm logarithmic spiral antenna (Fig. 11(b)) [87]. Again, the SIS junction is placed at the center of the antenna, and the IF output is taken from one of the truncated ends of the spiral. The planar spiral antenna provides a number of attractive features: By using a self-complementary pattern on a quartz hyperhemispherical lens, a radiation impedance of 114 Ω can be obtained. The antenna also possesses a proper broad side radiation lobe with nearly symmetrical E- and H-plane patterns and low side lobes. Furthermore, the bandwidth of the receiver can be controlled easily by a simple rule of thumb: if r_1 and r_2 are respectively the radius of the smallest feature of the spiral and the outer radius of the spiral, the operating bandwidth is simply given by $10r_1 < \lambda_0 < r_2/2$. Nevertheless, contrary to most other receivers, the spiral antenna is circularly polarized. In order to insert quasioptical components in front of the microantenna, a linear-to-circular polarizer is usually needed.

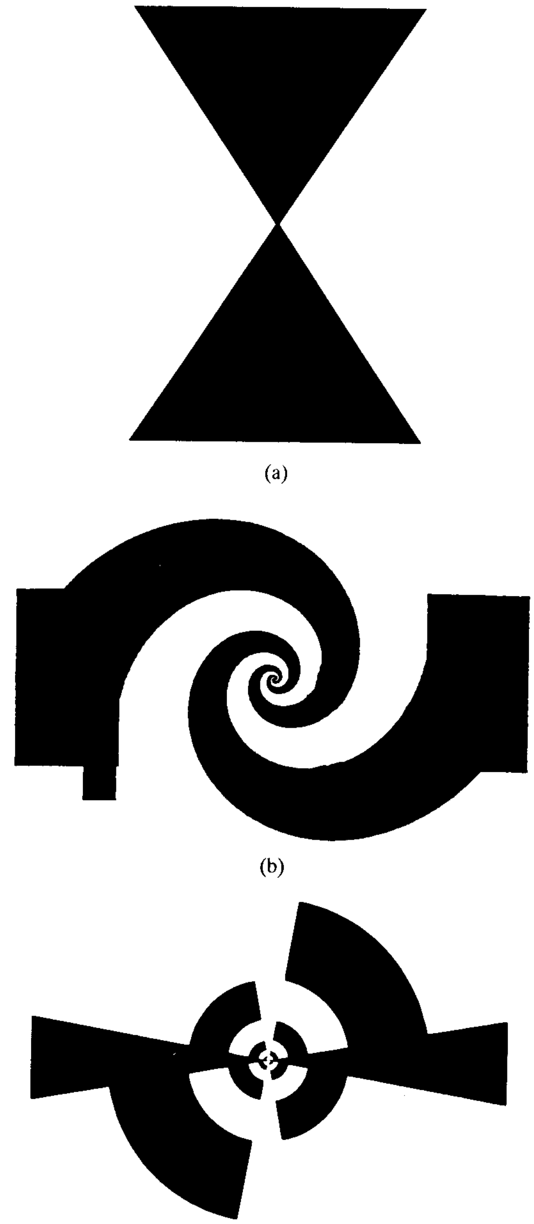
This receiver has been tested in the laboratory between 115 and 762 GHz, giving excellent noise performance. It is in fact the widest band SIS receiver ever tested. The receiver has also been operated at the CSO. However, the on-telescope performance of the receiver appeared to be somewhat poorer than in a laboratory test. This problem is attributed to poor coupling of the signal beam to the telescope. Recently, an extended hyperhemisphere was used to replace the hyperhemisphere and more promising results have been obtained [88].

Apart from the bow-tie and the spiral antennas, the planar log-periodic (Fig. 11(c)) [89] has also received considerable attention. A harmonic mixer using the planar log-periodic antenna and a beam-lead Schottky diode on a silicon substrate lens has been developed for the frequencies 90/180 GHz [90]. SIS receiver development is also in progress. Although the log-periodic antenna is linearly polarized, it has been found that the plane of polarization rotates with frequency. This is certainly a hurdle for its use in a fully integrated receiver.

Another class of integrated receiver that falls into the broadband category uses the traveling slotline antenna.

Table 1 Noise Performance of All Published Integrated SIS Mixer Receivers

SIS Mixer Receiver	Noise Temperature of IF Stage, (T_{IF}) (K)	LO Frequency (GHz)	DSB Receiver Noise Temperature (K)
Bow-Tie Antenna [84]	19	115 230 345 460	200 275 375 800
Bow-Tie Antenna with Integrated Tuning Stub [85]	20	100	200
Dipole Array on Paraboloid [96]	6	230	259
Twin Dipole on Elliptical Lens [98]	4	110 400	145 220
Spiral Antenna on Hyperhemi-spherical Lens [87]	2	115 230 345 525 761	33 116 215 470 1100
Modified Spiral Antenna Integrated Receiver [88]	—	345 426 492	200 220 500
Twin Slot Antenna [100]	11	490	420
Linear Array of Patches on Elliptical Lens [103]	—	345	~200



(a)

(b)

(c)

Fig. 11. Broadband traveling-wave antennas for integrated SIS receivers: (a) the bow-tie antenna; (b) the logarithmic spiral antenna (after [87]); and (c) the log-periodic antenna.

A number of designs exist [91]: the Vivaldi antenna, in which the slot opens up exponentially toward the radiation space; the linear-taper slot antenna (LTSA), in which the transition between the slot line and radiation space is linear instead of exponential; and the constant width slot antenna (CWSA), in which the radiating section is a constant width slotline. The SIS junction can be easily integrated across the slot in front of a quarter-wave fixed tuned short circuit. Originally, these antennas were developed to function as free-standing configurations. At millimeter wavelengths, they are printed on thin substrates that radiate in the end-fire direction, and focal plane arrays of SIS receivers at 100 GHz have been tested with this design. However, for submillimeter applications, the substrate thickness needed to avoid surface wave effects becomes unrealistically small: $t < 0.03\lambda_0\{\varepsilon_r - 1\}^{-1/2}$ [91]; for 600 GHz and $\varepsilon_r = 4, t < 15\mu$m!

Recently, it has been suggested that the slot antenna may be printed on a very thick substrate. In this case, a superstrate is added so that the antenna is embedded in a sandwich of dielectric material [92]. In this configuration, the substrate lens approach can easily be adopted by placing the immersion lens in contact with the front face of the sandwich. Laboratory model tests show that using an elliptical lens, such a design can be easily exploited at submillimeter wavelengths [93].

Attractive as a multioctave element, the broadband antenna–substrate lens combination is, nevertheless, not without problems.

So far, all integrated SIS receivers have employed a quartz substrate lens. The underlying reasons for this are compatibility with the substrate bearing the SIS junction and the relatively low permittivity. However, $\varepsilon_r \sim 4$ means that the reflection coefficient at the front surface of the lens is 1/3 at normal incidence; that is to say, more than 11% of the forward radiation power is scattered backward. In order to eliminate this unwanted reflection a quarter-wave antireflection sheet is usually deployed over the lens surface [94]. A thin Teflon sheet ($\varepsilon_r \sim 2.1$) of the right thickness is sufficient. However, this means that for each frequency range of interest, a different matching sheet has to be employed. Since it is not practical to swap matching layers, this requirement effectively counterbalances the initial wideband advantage offered by this type of receiver.

Moreover, it has been pointed out that the radiation impedance of all broadband antennas is real. For the SIS mixer, optimum performance can only be obtained when the susceptance associated with the junction's geometrical capacitance is tuned out by the RF circuit. The receiver designer can adopt two different strategies for optimization. First, as is the case of waveguide mixer designs, an integrated tuning element which tunes out the junction susceptance at the frequency of interest may be included. This is a particularly attractive approach for the monolithic mixer, given that the driving point impedance of the microantenna might not be of the desirable value and that some sort of impedance transformation is needed. The spiral antenna receiver was found to have better performance when an impedance transformer and tuner was introduced [88]. Obviously, this approach limits the operating bandwidth of the original design. The second possibility is to use very small area junctions with negligible capacitance. However, small-area junctions are prone to harmonic effects. It has been shown by a five-port model analysis that harmonic effects are undesirable [95]. Given that the receiver is very broad band, the conversion from harmonic sidebands is likely to be significant. Furthermore, in a laboratory hot/cold load noise temperature measurement, harmonic degradation may not be readily observed because the harmonic sidebands are terminated with the same load as the fundamental sidebands; the mixer behaves as if it has improved conversion gain. When operated on the telescope, harmonic conversion effectively raises the noise temperature of the receiving system. In other words, for spectral line measurements, in order to achieve a given signal to noise ratio, more observing time is required. This effect is similar to calibration difficulties that sometimes arise in receivers operating with unknown sideband ratios (see Section VII). It should also be noted that small-area junctions suffer more from Josephson effects, usually undesirable in low-noise systems.

4) The Resonant Substrate Lens Receiver: The problems associated with the broadband substrate lens receiver have led workers to look into resonant antennas that cover a limited bandwidth around the resonant frequency of the antenna. At microwave frequencies, resonant patch antennas are very popular but they generally have too narrow a bandwidth and too high an input impedance to be of interest for submillimeter radio astronomy applications. Printed dipoles and printed slots are the natural candidates. The behavior of these elementary radiating elements when printed on a substrate lens was first studied about ten years ago [79].

It is well known that the radiation pattern of a resonant dipole on a dielectric half-space peaks at the Brewster angle in the H-plane, and has a null at the same angle in the E-plane [80]. Hence, a single dipole on a dielectric hemisphere might not be an appropriate choice. Dipoles printed on paraboloidal and elliptical lenses have been reported.

A 2×5 array of half-wave dipoles was printed on a quartz dielectric-filled paraboloid [96]. The features of this design are: coplanar strip IF lines with integrated balun impedance transformers and LO injection via a hole at the back of the mixer block. This receiver has been tested at 230 GHz. A DSB receiver noise of 259 K and conversion loss of 10 dB have been obtained.

The second configuration involves a twin half-wave dipole sandwich between an HDPE elliptical lens and a quarter-wave HDPE slab, backed by a metallic reflector [97]. The two dipoles are connected by a pair of coplanar strips across the midpoint of which lies the junction. Laboratory measurements show that the design is quite wideband. The 100 GHz version of the design functions from 96 to 122 GHz. Preliminary measurements at 400 GHz show a best receiver noise temperature of 220 K [98].

The Yagi–Uda antenna is derived from the dipole antenna. Using a half-wave dipole with a conveniently positioned director [99], this setup has been employed for imaging work at millimeter frequencies. It may also turn out to be a promising candidate for an integrated submillimeter receiver. However, the feed lines appear to induce undesirable structure in the H- plane radiation pattern.

When compared with the dipole antenna, the printed slot has the advantage of providing isolation between the feeding structure and the forward radiation—for an observer in front of the substrate lens, the feeding structure can be made invisible. However, the radiation pattern does not show a null at the dielectric–air interface in the E-plane [80]. This dictates the use of twin slots separated by half a wavelength along their length so that a more symmetrical beam can be produced.

A receiver noise temperature of 420 K (DSB) was measured at 500 GHz using an experimental twin slot antenna–hyperhemispherical lens combination [100]. The length of the slot antennas is chosen for the antiresonant frequency of the slot so that a relatively low radiation impedance of 35 Ω and a wider bandwidth ($1.6:1$) can be achieved. Contrary to all of the other integrated receivers mentioned above, this receiver features thin-film superconducting microstrip feed lines fabricated in an all integrated process. This novel configuration indicates that thin-film microstrip technology [101] can be applied at submillimeter wavelengths and that true submillimeter planar circuitry can be conceived. However, the superconducting lines are only lossless up to the gap frequency of the superconductor (700 GHz for niobium). Therefore, unless a high-energy-gap material is used, the superconductor has to be overlaid with a gold film in order reduce circuit losses.

Finally, a 350 GHz receiver incorporating a planar antenna structure mounted on an ellipsoidal immersion lens, shown in Fig. 10, has been designed [102]. In this case, the printed antenna structure is simply the IF filter section of an early waveguide mixer design [65]. The true radiating element is the linear array of patches constituted by the low-impedance sections of the filter. As a result, the beam pattern is highly elliptical [103]. Initial observations with this receiver mounted on the 30 m radio telescope of the IRAM indicate a receiver noise temperature of about 200 K.

VII. Calibration of Data

One of the areas in which a number of radio telescope–receiver systems fall short is that of calibration, in particular the ability to correctly calibrate the receiver output in amplitude.

The bolometric receivers, which are wideband for continuum observation, and the narrow-band InSb receivers are readily calibrated by measuring the power at their output with different fixed temperature loads (290 K and 77 K) placed at their input. Other heterodyne receivers that operate in a pure DSB mode can also be calibrated using the same procedure. It is common practice to check the receiver calibration frequently, just before and just after an observation, because of possible receiver gain and noise temperature variations. A radio source with an accurately known flux can also be used for calibration purposes. Assuming that the source completely fills the main beam of the telescope, the calibration temperature is simply given by

$$T_{\rm cal} = A_e S/2k, \tag{7}$$

where A_e is the effective aperture of the antenna and S is the source flux density. We should note that at high frequencies, low-temperature calibrators may not obey the Rayleigh–Jeans limit so that the full Planck quantum expression may be required.

For spectral line observations it is generally preferable to observe in the SSB mode, lines from the image sideband being of no interest. Waveguide receivers generally have either a single or two back-short tuners permitting some sort of image rejection. However, proper calibration requires that the ratio of the USB receiver gain to that of the LSB be known. Since this ratio generally varies with receiver tuning and frequency, accurate calibration is often difficult. Pure SSB operation is possible using only a single tuner placed approximately $\lambda_{\rm IF}/4$ away from the mixer element. However, most single-tuner mixer designs are such that this is not possible. Receivers incorporating mixers with two tuning elements are regularly operated in the SSB mode [60]. Neither corner cube nor printed antenna mixers have tuners that allow SSB tuning, so that image rejection is often provided using a quasioptical diplexer similar to those used for LO coupling. The inclusion of such a diplexer or filter, before the mixer, results in some degradation in receiver noise and adds somewhat to the complexity of the receiver system. Also, some caution is necessary when employing such a filter as the exact rejection varies across the IF band. This is particularly noticeable in systems with a high fractional bandwidth. This problem can be alleviated somewhat by using the reflective polarizing interferometer, described by Erickson [104], since this has increased fractional bandwidth capability over standard designs.

Although spectral line observers often require SSB operation, DSB measurements are sometimes preferred because of difficulties in obtaining pure SSB operation. Amplitude calibration is then relatively straightforward and band identification is often possible by making a separate observation with a small LO offset. Features belonging to the different sidebands move in opposite directions. Recently, a group at the NRAO Kitt-Peak observatory have implemented a technique, known as sideband smear, through which sideband discrimination is readily achieved. This technique requires that the first and a second LO be under computer control. Since this is generally the case at most radio observatories and no other additional hardware is required, this technique, at least in principle, may be readily employed. A block diagram of a system through which both sidebands may be recovered independently is given in Fig. 12. Operation of this system essentially requires that the first and second LO's be swept in frequency at the same rate. Since the system is symmetrical after the first down-conversion, it is sufficient to consider the recovery of only a single sideband, the lower sideband (LSB). In this case, both the first and second LO's are swept in frequency at the same rate and in the same direction. Signals from the LSB that appear at the input of the second mixer will gradually appear to increase in frequency. Since the second LO is also increasing in frequency, and at the same rate, the LSB signals appear as fixed-frequency signals at the output of the second mixer. USB signals, however, appear to move downward in frequency at the input of the second mixer and therefore, at the output, appear to move at twice the sweep rate. At the output of the spectrometer these signals appear to be smeared or washed out. The amount of sideband smearing depends on a number of factors. Also, a number of practical considerations have to be addressed before such a sideband smearing scheme may be implemented; these are fully addressed by Payne *et al.* [105].

A sample spectrum taken at 115 GHz obtained with sideband smear in operation is also given in Fig. 12. The first and second LO's were stepped by 2 MHz over the entire spectrum. For the wanted sideband the oscillator steps cancel out so that the desired spectrum is integrated properly in the USB spectrometer. For the unwanted sideband (LSB), the oscillator shifts cause an effective convolution of the original CO spectrum with a comb function of characteristic spacing 4 MHz, i.e., the sum of the shifts of the first and second LO's. In this test, the 4 MHz is greater than the half-width of the unwanted spectrum, so the residual shows overlapping images of the original emission spectrum, each reduced to approximately 3% of the original strength, and separated by 4 MHz. In regular operation, the oscillator steps would be made one half of the basic spectrometer channel spacing. This would cause the residual images to be completely smeared out, leaving only a small dc offset which is easily removed.

VIII. SIS Receiver Development Prospects

The first planar SIS mixer receiver was tested in 1985 [84]. We have summarized a number of different devel-

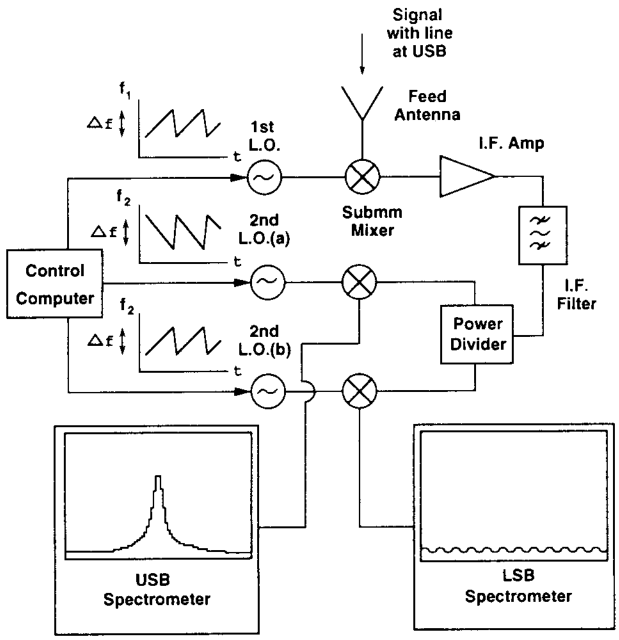


Fig. 12. Block diagram of a scheme through which sideband smearing may be implemented. Sweeping the second LO's in opposite directions, but at the same rate as the first LO, ensures that LSB and USB signals are independently recovered. Also shown are the spectrometer outputs with the $CO_{J=1-0}$ emission from Orion A appearing at the USB.

opments that have taken place since then. Clearly, there is still a large amount of development to be done before a fully integrated receiver will be available on a routine basis for observational astronomy. It appears certain that integrated receivers will outperform waveguide receivers over a large fraction of the submillimeter wave band. However, the exact crossover frequency below which waveguide receivers will prevail is still far from certain. Waveguide receivers, basically scaled from millimeter technology, are now offering excellent performance up to about 500 GHz. Above about 700 GHz, it is likely that an integrated receiver technology will be preferred. While waveguide receiver development will rely on simply pushing the limits of micromachining capabilities, the integrated receiver development calls for new ideas.

We have focused our attention on the substrate lens type of integrated receiver, of which many different configurations have been tested. However, other configurations should not be neglected. One such example is the integrated horn structure, etched from silicon [106] (although it has not yet been shown that an SIS junction can be fabricated on a free-standing membrane). The Fresnel zone plate configuration is another interesting alternative [107]. At the present moment, the greatest challenge seems to be the coupling problem between the signal beam coming from the telescope and the integrated feed structure. It is believed that, once this problem is solved, integrated receivers will inevitably arrive for installation at radio telescopes.

So far, SIS receivers have not been used at the shorter submillimeter wavelengths. This is partly because this technology first emerged at millimeter wavelengths and submillimeter developments were not of the highest priority. Also, SIS mixers have a fundamental upper frequency limit beyond which their performance is significantly degraded. This limit is set by the gap frequency of the superconductors forming the junction. So far NbN appears as the material of choice for higher frequency operation. Although NbN should permit low-noise mixing to above 1 THz, its development is in an early stage and mixing experiments have only been made to about 200 GHz [108].

IX. Summary

We have examined the wide variety of receivers currently used and under development for submillimeter radio astronomy. In order to achieve the lowest noise and highest sensitivity, the majority of these are cryogenically cooled. For wideband continuum observation, the bolometric receivers continue to offer the highest sensitivity. This is largely due to their wide detection bandwidth. Despite the difficulties in cooling the bolometer elements to below about 0.3 K, they are of relatively straightforward construction and a large focal plane array is being built. For narrow-band spectral line observations, the InSb hot electron mixer receiver offers low-noise performance. However, unless the instantaneous bandwidth of the hot electron mixer receiver can be increased, through for example the use of an $Al_xGa_{1-x}As/GaAs$ heterostructure mixer, it is unlikely that this type of receiver will enjoy increased popularity.

The most versatile of the low-noise receivers designed for submillimeter operation is the Schottky diode mixer receiver. Designs incorporating either waveguide or corner-cube mixers are used throughout the whole of the submillimeter band, from about 1 mm to 0.1 mm wavelength. These receivers generally have instantaneous bandwidths of about 1 GHz and, with the possibility of SSB operation, may be used for both continuum and spectral line observation. In fact at wavelengths shorter than about 0.5 mm, line observations of high, or even moderate, spectral resolution ($> 10^3$) are made almost exclusively with this type of receiver. It is likely that Schottky diode mixer receivers will remain the first choice at the shorter submillimeter wavelengths for some time to come. Improvements in this type of receiver are likely to come from better materials technology with the development of lower noise diodes, and from future developments in the area of wideband, frequency agile, higher power solid-state LO sources.

At the low frequency end of the submillimeter band, < 500 GHz, the lowest-noise receiver systems incorporate SIS mixers, under development since about 1979. During the last ten years, we have witnessed a steady increase in the number of laboratories investing in this technology and many observatories now have SIS mixer receivers in operation where Schottky diode mixer receivers used to be. This is particularly so at millimeter wavelengths. The high-frequency limitations of SIS mixers have not been addressed here. However, it is believed that receivers incorporating Nb-based SIS elements should offer low-noise performance to at least 700 GHz and that NbN SIS elements have the potential of low-noise operation to about 1200 GHz. Mixer designs for these frequencies are not yet developed; however it is likely that they will be of an open structure type. Such structures were discussed extensively in Section VI.

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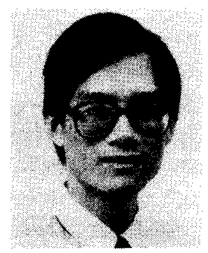

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