OVERVIEW OF THE UNIVERSITY OF MICHIGAN SPACE TERAHERTZ TECHNOLOGY PROGRAM

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ABSTRACT

In June 1988, NASA established nine university-based Space Engineering Research Centers for the purpose of enhancing and broadening the nation's engineering capabilities to meet the growing demands of the space program. The newly formed centers--which cover a wide range of specialties extending from robotics and propulsion to solid-state electronics--will perform research and develop technologies relevant to the establishment of operational bases on the moon, to manned and unmanned operations on Mars, to space flight missions to other parts of the solar system, and to observations of the Earth's environment from space platforms.

The University of Michigan's NASA Center for Space Terahertz Technology (NASA/CSTT) will focus on the development of terahertz devices, circuits, antenna arrays and heterodyne receiver systems in support of molecular line spectroscopy with particular emphasis on planetary atmospheres, including the Earth's upper atmospheric layer. During Phase I of the program (1988-93), most of the activities will be conducted at frequencies in the 0.1 to 1 THz range, corresponding to the 3 mm to 300 μm wavelength range. The research activities of the Center are divided into three areas: (1) terahertz device modeling fabrication and performance evaluation, (2) terahertz receiver development, including antenna fabrication and integration with the mixer/local oscillator components, and (3) the use of terahertz technology for the study of the Earth's upper atmosphere, astrophysical investigations, and industrial applications.

1. INTRODUCTION

The THz region is one of the least explored segments of the electromagnetic spectrum. Although a number of applications have been identified, primarily in astrophysics and for the study of planetary atmospheres, the potential of the THz region for scientific and industrial applications is yet to be explored. The primary factor that has impeded such an exploration has been technology. The construction of high sensitivity spectral receivers at frequencies above 0.1 THz, and particularly in the 0.3 to 3.0 THz band, is both very difficult and expensive. To detect the presence of a given molecule in interstellar space or to study ozone depletion in the Earth's upper atmosphere, for example, it is necessary to perform spectral line observations with spectral resolutions on the order of 1 MHz or narrower. Moreover, most of the molecules of interest are characterized by weak emission lines with typical antenna temperatures of a few kelvins (Figures 1 and 2), thereby imposing an additional constraint on the required performance sensitivity of THz receivers.

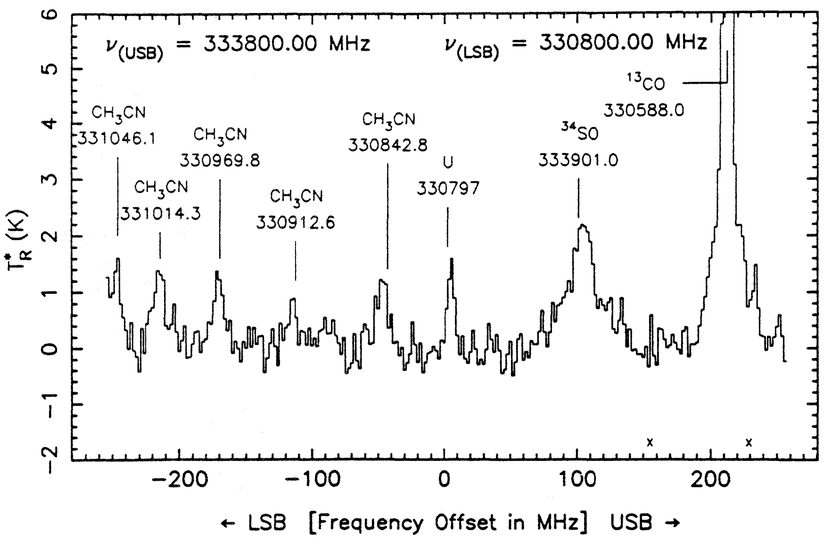


Figure 1. Spectrum of Orion A near 330 GHz measured by the NRAO telescope. (From [1], original data reported in [2].)

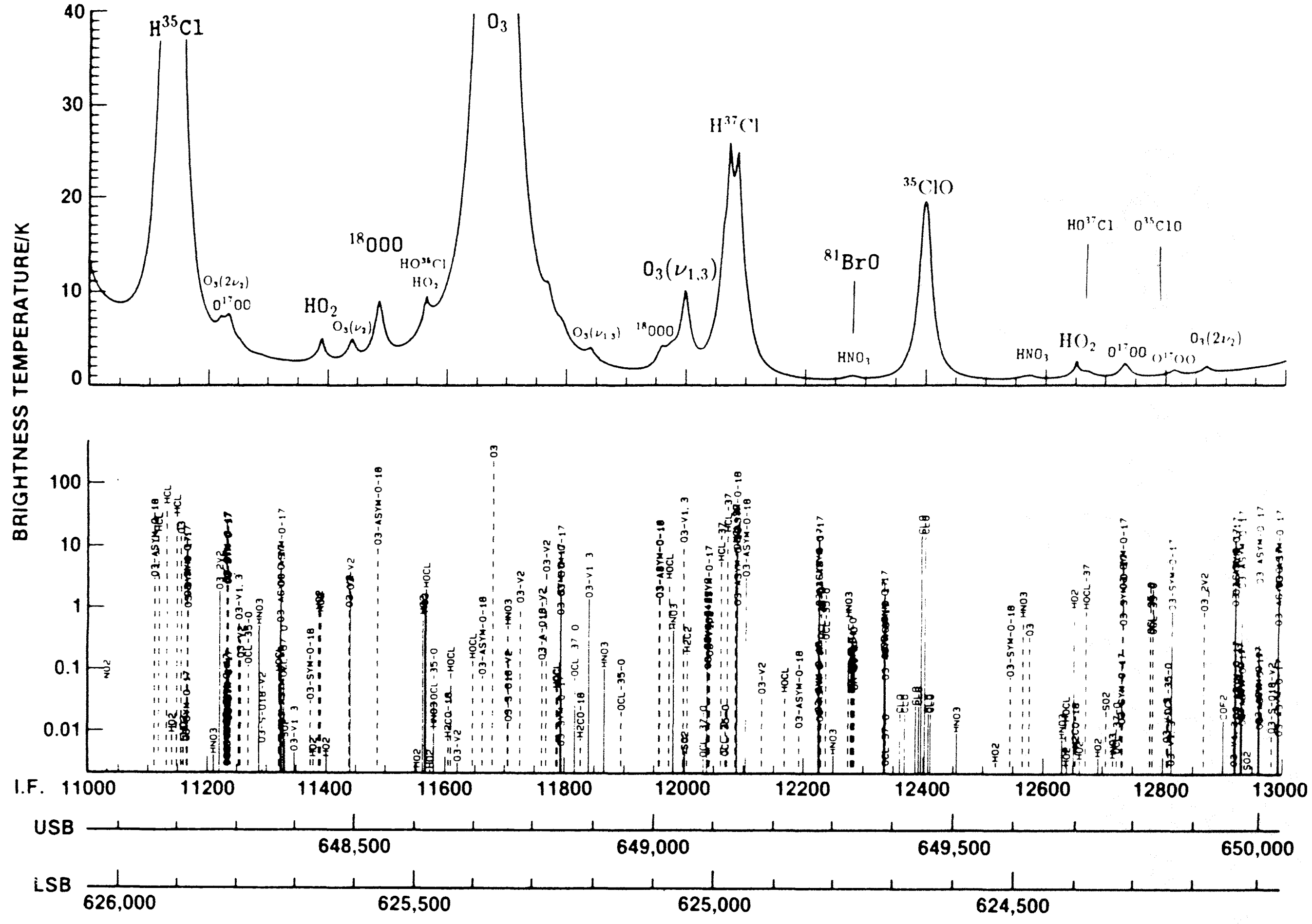


Figure 2. Calculated atmospheric limb emission spectra. The vertical scale is the emission brightness temperature. The horizontal scale is frequency; the calculation is for a radiometer with local oscillator frequency at 637,050 MHz equally receiving radiation from both upper (USB) and lower (LSB) sidebands at 11,000 to 13,000 MHz intermediate frequency (F). The top panel gives results of a full radiative transfer calculation for a limb path with 36 km tangent height; the bottom panel, with much compressed vertical scale, shows all spectral lines from the JPL catalog with the line intensities scaled to account for the limb measurement path and expected abundances for the middle stratosphere. Solid lines in the bottom panel indicate upper sideband; dashed lines indicate lower sideband.
(From [3].)

Although successful millimeter and submillimeter spectral observations of the emission from some galaxies and interstellar clouds have been made from Earth telescopes at mountain tops, the attenuating effects of the Earth's atmosphere (Figure 3) impose a major limitation to observations in the THz region. Furthermore, in order to perform these observations, it has been necessary to use

SIS mixers cooled to liquid-helium temperatures or Schottky-diode mixers cooled to 10° to 15° K to achieve the required receiver sensitivity. To circumvent the opacity of the Earth's atmosphere, we need to conduct the observations from space platforms. However, providing very-low temperature refrigeration on board of a space platform is a major, although not impossible, constraint.

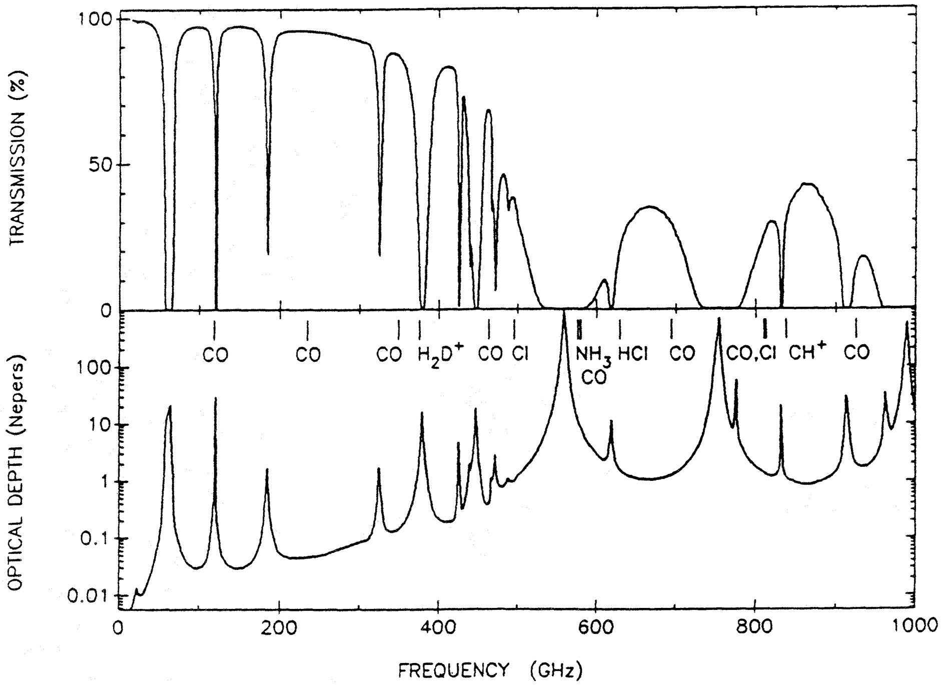


Figure 3. Atmospheric transmission at Mauna Kea at an altitude of 4,200 m, with 1 mm of precipitable water. The 850 GHz (350 μm) window is the highest frequency one available in the submillimeter. Te next window is in the middle infrared at about 30 μm. Also shown are some molecule rotation and atomic fine structure lines. (From [4].)

NASA's Office of Aeronautics and Space Technology (OAST) is supporting an intensive program for the development of THz receiver technology. One component of this program has been to establish a Center for Space Terahertz Technology (CSTT) at The University of Michigan through the University Space Engineering Research Centers Program. The goals of the CSTT are:

a. *To accelerate the development of solid-state receivers--including local oscillators, detectors, mixers, and antenna arrays--at THz frequencies, with particular emphasis on room-temperature performance; and*

b. *To train graduate students in this field.*

This paper provides an overview of the research program conducted by CSTT. To place the program in proper perspective from the standpoint of its intended contribution to the development of space THz technology, we will start with a brief review of the present capability of today's receiver technology.

2. REVIEW OF HETERODYNE RECEIVER TECHNOLOGY

Heterodyne detection is the most commonly used technique for making spectral line observations at millimeter and submillimeter frequencies. A traditional heterodyne receiver (Figure 4) uses a local oscillator and a double-ended balanced mixer to downconvert the frequency of the input signal, ω_S, to an IF frequency $\omega_{IF} = |\omega_S - \omega_{LO}|$. The IF output signal is then amplified, and sometimes mixed down again to a still lower frequency, and then fed to a bank of filters to obtain the spectrum of the input signal. The noise performance of the receiver is governed primarily by the RF amplifier, and to a lesser extent by the mixer. Thus, to insure low-noise performance, the RF amplifier should have high gain and low noise. Metal waveguide is used as the standard line for RF connections between the antenna and the RF amplifier, the RF amplifier and the mixer, and the local oscillator and the mixer.

This arrangement works well at frequencies below 100 GHz. As we increase the frequency above 100 GHz, we start to encounter a number of problems. These include:

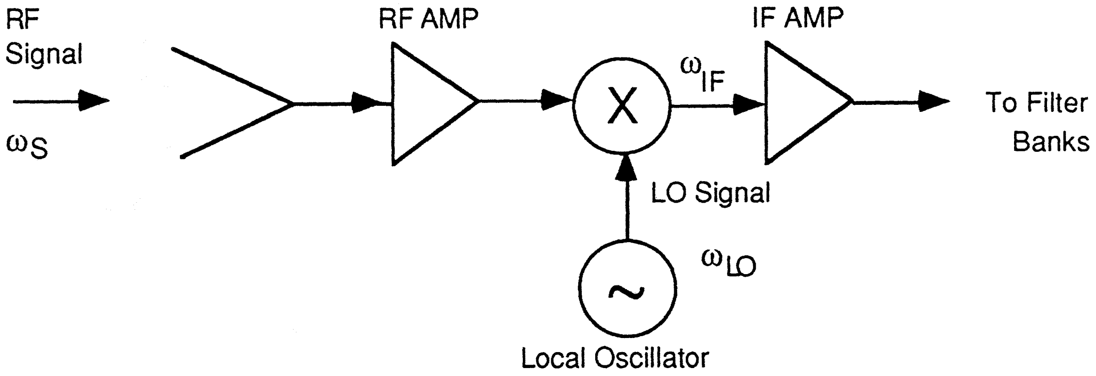


Figure 4. Block diagram of a traditional heterodyne receiver.

a. *Unavailability of RF amplifiers.* In this situation, the noise performance of the receiver becomes dictated by the noise characteristics of the mixer and IF amplifier.

b. *Unavailability of double-ended balanced mixers.* With single-ended mixers, we have to use a quasi-optical diplexer to combine the LO signal with the input RF signal prior to reaching the mixer. An example is shown in Figure 5.

c. *Poor mixer noise performance.* This necessitates cooling the mixer environment to a low temperature. The mixer elements most commonly used today at frequencies above 0.1 THz are the SIS diode and the Schottky barrier diode. Usually, SIS diodes are cooled to liquid-helium temperatures to realize super conductivity, and Schottky diodes are cooled to 15° K to reduce their mixer noise. With the recent advances made in high T_C superconductivity materials, it is hoped that SIS mixers can be made to operate at higher temperatures in the future. Figure 6 shows a plot of typical receiver noise temperatures for SIS mixers, Schottky diode mixers at 20° K and at 300° K, and InSb bolometer mixers. Both the SIS and InSb bolometer mixers were cooled to liquid-helium temperature. The InSb mixers exhibit good noise performance, but they are not desirable for making spectral

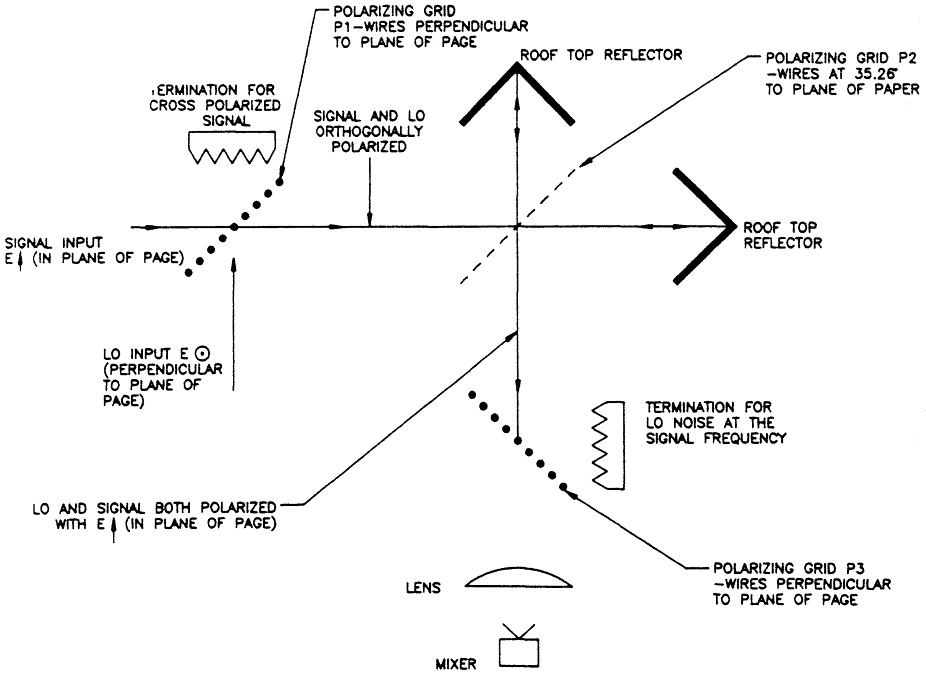


Figure 5. Martin-Puplett interferometer used as diplexer. (From [1].)

observations because they have narrow instantaneous band widths on the order of 1 MHz, which would necessitate scanning the local oscillator frequency in order to cover the desired spectrum.

d. *Unavailability of low-noise solid-state oscillators with sufficient output power to drive the mixer.* Gunn oscillators are now available up to about 120 GHz [5]; and by using doublers and triplers, the frequency range can be extended to about 360 GHz. Quadruplers and quintuplers have also been examined for solving this problem, but the output power of a harmonic multiplier is on the order of $1/n^2$ of the input power (where n is the harmonic order). IMPATT diodes can provide more power than Gunn diodes (Figure 7); but they are far noisier which has detracted from their use in millimeter and submillimeter heterodyne receivers. Using doublers and triplers with Gunn oscillators can provide sufficient power to drive cooled Schottky diode mixers up to about 360 GHz. To extend the range to

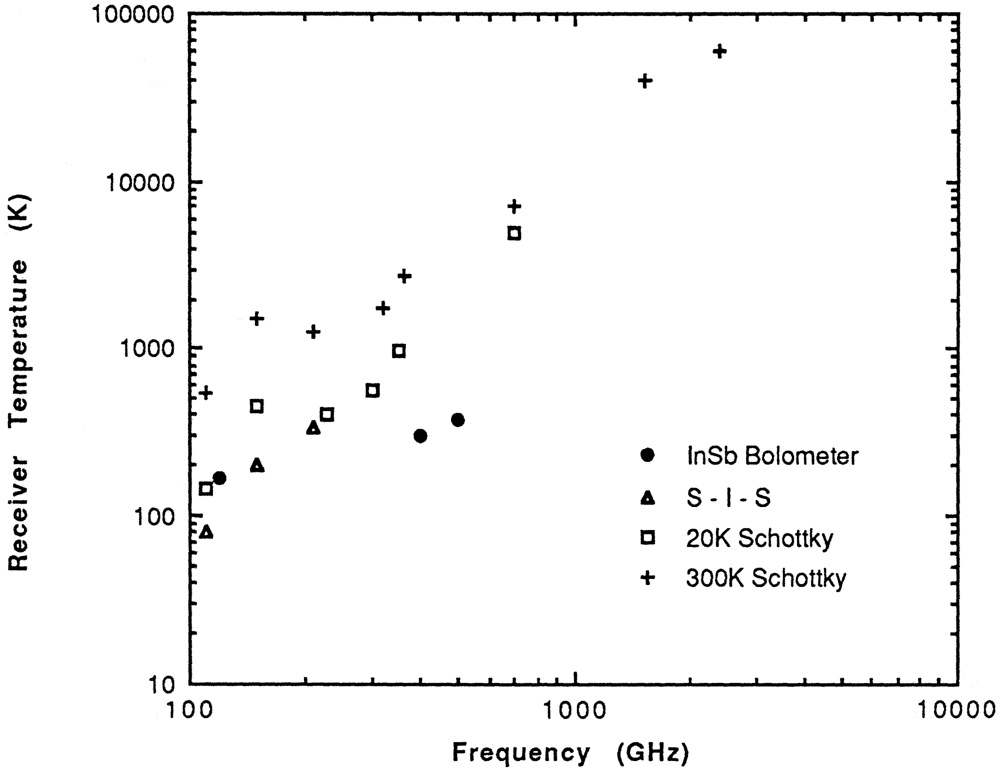


Figure 6. Typical receiver performance in the near millimeter-wavelength band for a number of different types of mixer receivers. (From [5].)

higher frequencies requires the availability of low-noise local oscillators that can produce more than 1 mW of output power at frequencies in the 100 to 400 GHz range. As we will discuss in Section 3, this is one of the major goals of CSTT.

Although SIS mixers require much lower levels of local-oscillator power to function (10^{-7} W, compared to more than 10^{-4} W for Schottky diodes [4]),the liquid-helium refrigeration requirements for superconductivity limit the use of SIS receivers to ground operations. (Schottky diode mixers can operate at room temperature, albeit with poorer noise performance.)

Subharmonic mixing is an alternate technique for operating at frequencies above the fundamental oscillation frequency of available local oscillators. A pair of balanced mixers is used to mix the local oscillator signal with a subharmonic of the

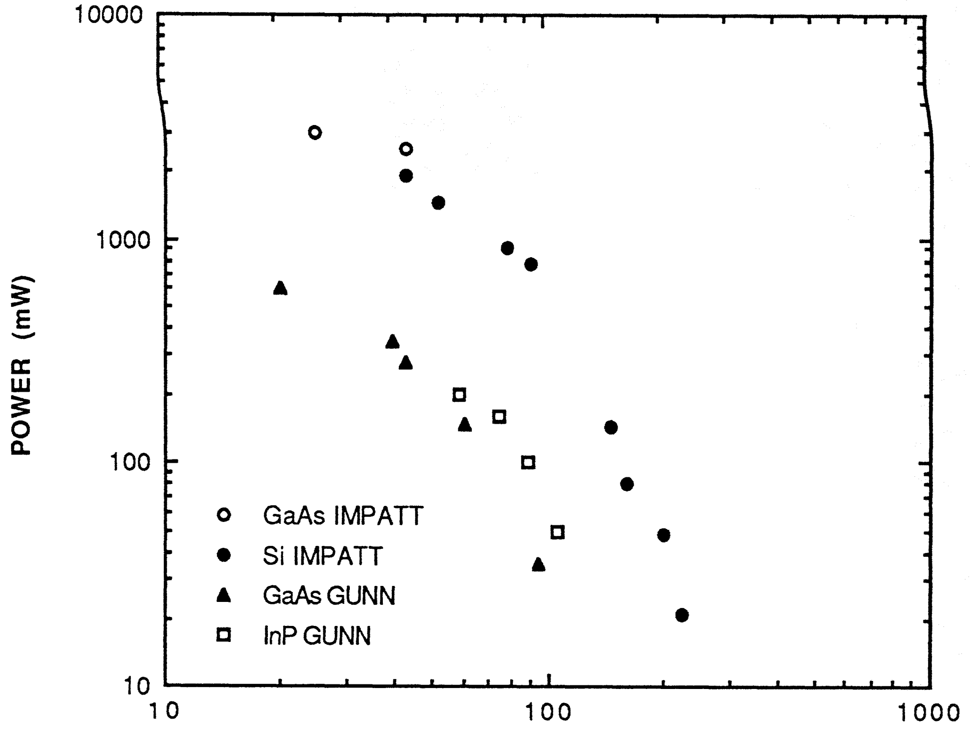


Figure 7. CW performance for IMPATT and Gunn-diode oscillators at near-millimeter frequencies. (From [5].)

input signal to produce an IF output. In general, the signal-to-noise performance of this technique is not as good as that realized with the harmonic-multiplication technique.

e. *Increased ohmic losses in conducting waveguides and increased difficulty of constructing components inside the guide.* For fundamental-mode operation at 300 GHz, for example, the internal dimensions of the waveguide have to be no more than 1 mm x 0.5 mm, and even smaller if it is necessary to reduce the guide height in order to match its wave impedance to a low-impedance component such as a diode detector [5]. A case in point is the Schottky diode mixer (Figure 8); the height of the waveguide carrying the input signal usually is tapered down to about 1/4 of its nominal value as it approaches the diode.

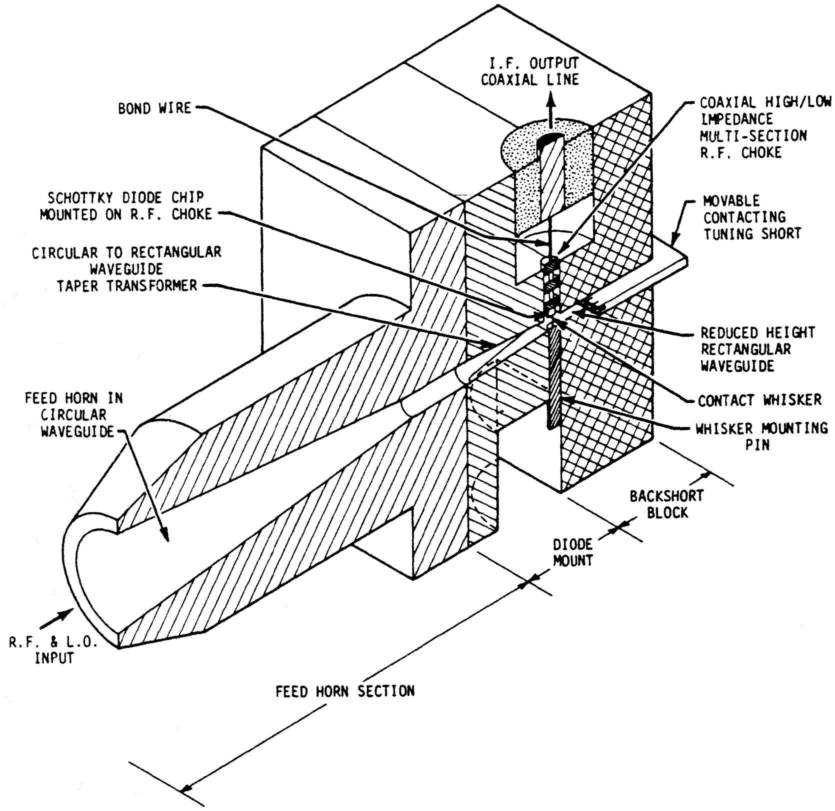


Figure 8. Typical mixer block for millimeter-wave applications. (From [1].)

To avoid the problems associated with waveguides, alternate approaches have been used for coupling RF energy to the mixer, including the planar thin-film antenna configuration shown in Figure 9, and the corner-cube antenna shown in Figure 10. It is also possible to use a half-wave dipole on a thin membrane placed inside a horn antenna and to connect the detector or mixer across the dipole input terminals (Figure 11). This type of configuration is particularly useful for imaging applications, as discussed further in Section 3.3.

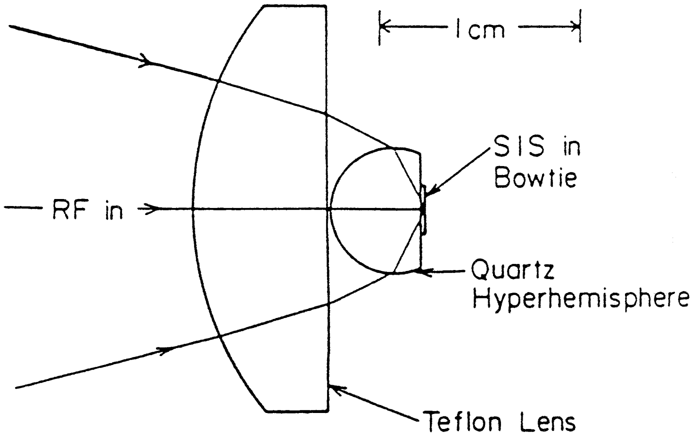


Figure 9. SIS optical-mode coupling for bow-tie antenna structure. (From [4].)

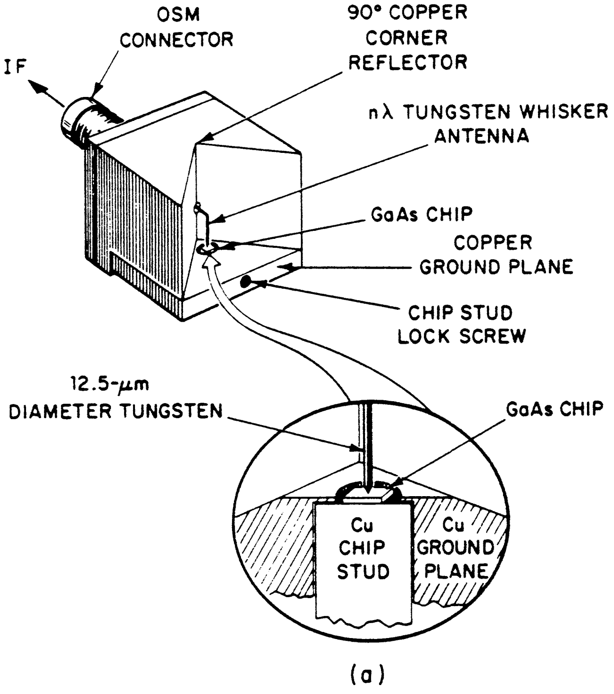


Figure 10. Corner-reflector antenna with quasi-optical mixer mount. (From [6].)

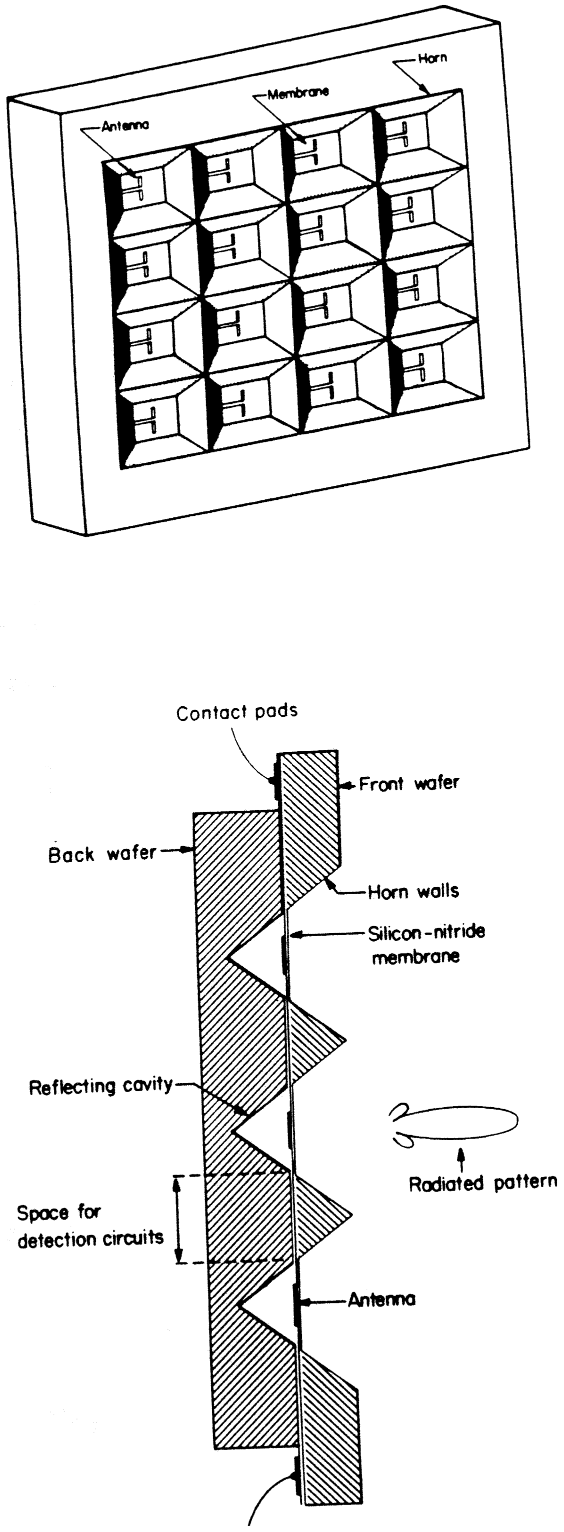


Figure 11. Monolithic antenna horn array. (From [7].)

To incorporate the various aspects peculiar to heterodyne detection at millimeter and submillimeter wavelengths, the receiver is more likely to look like the system shown in Figure 12 than like the traditional configuration shown in Figure 4. This system, which is part of the James Clerk Maxwell Telescope (JCMT) constructed by Cambridge University for operation in Hawaii [8], uses a 75.5 GHz Gunn oscillator and a third harmonic multiplier to provide the local oscillator signal at 226.5 GHz. A quasi-optical diplexer is used to combine the LO and RF signals, and additional optics, including a polarizer, are used to separate the horizontal and vertical polarization components of the input signal and to feed them into the two channels shown in the figure. The mixer elements are Schottky diodes cooled to 20° K.

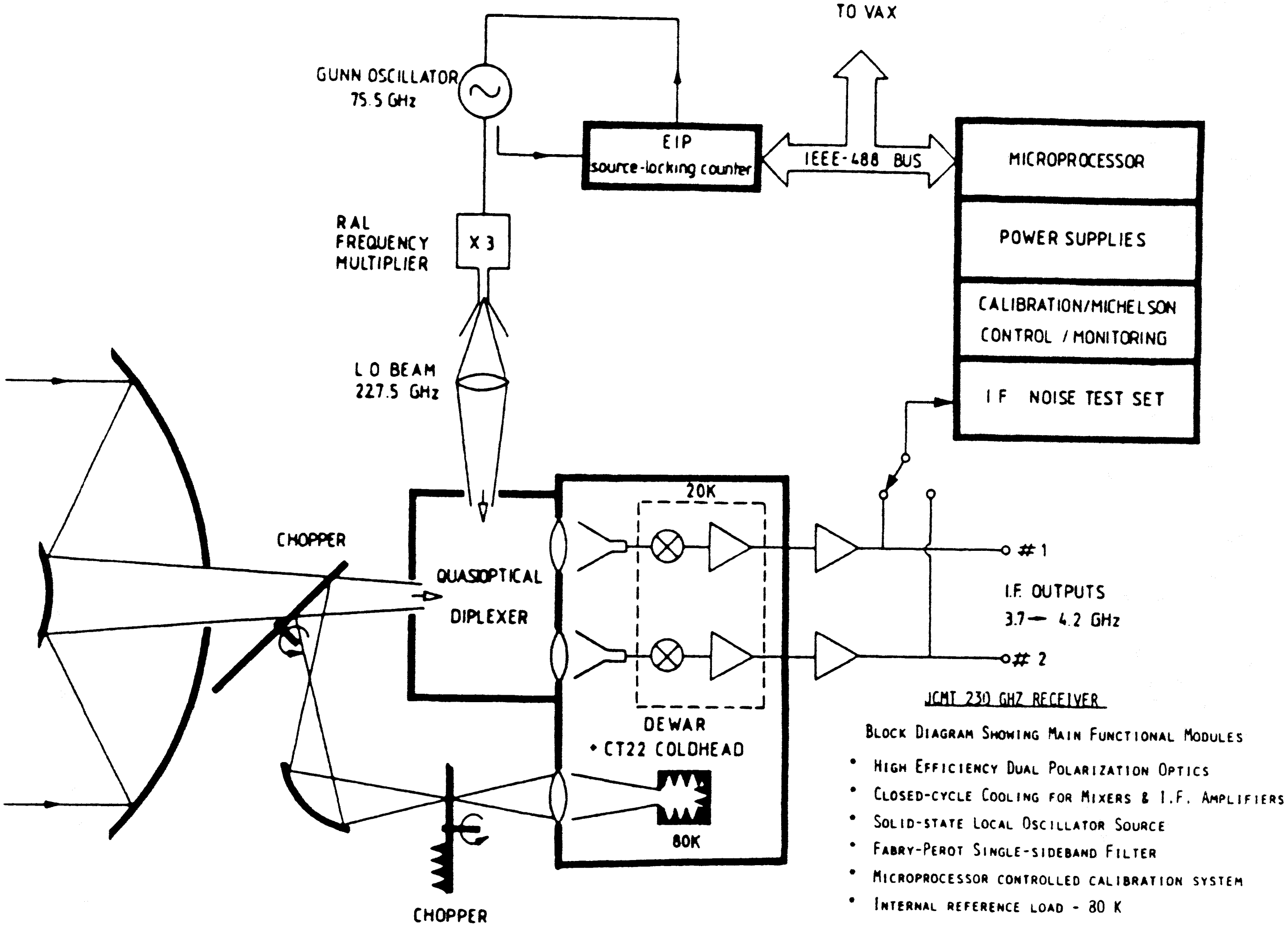


Figure 12. Block diagram of the 230 GHz receiver of the James Clerk Maxwell Telescope. (From [8].)

The cursory review of THz heterodyne receivers given in this section is by design brief in extent and general in scope; for more detailed reviews, the reader is referred to the articles by Archer [5], Payne [1]. Phillips [4], White [8], Goldsmith [9], and other [10-17]. The intent of the review is to provide a framework against which to describe the goals and research activities of the program sponsored by NASA/CSTT at The University of Michigan.

3. NASA/CSTT PROGRAM

3.1 Program Objectives

The program has three inter-related objectives, each of which is of fundamental importance to the program and its long-term viability.

Technology

The goal is to develop the capability to design and fabricate solid-state heterodyne receivers at THz frequencies, with emphasis on room-temperature operation using fundamental local oscillators, but not to the exclusion of liquid-nitrogen cooled receivers or harmonic multiplication and subharmonic mixing techniques. The program will focus on the 0.1 to 1 THz frequency range during Phase I (1988-1993), with the intent to extend the range to higher figures in later phases. The development will be guided by system specifications appropriate for observations of molecular line spectra from space platforms.

Scientific Applications

The use of the technology being developed by NASA/CSTT will be made available to the scientific community at large, including NASA, industry, and other academic institutions. At The University of Michigan, we are exploring the THz spectrum for studying the height profile of the OH number density in the Earth's upper atmosphere, the emission spectra of ^{12}CO, ^{13}CO, and HCN in the Martian atmosphere, and submillimeter-wave interaction with water and ice clouds. These studies are important in and of themselves, as well as for maintaining a firm connection between the technology component of space THz technology and the scientific-application component.

Academic Objectives

The presence of a broad-based research program in THz science and technology provides graduate students with exposure to many facets of this field through seminar courses, visits by scientists from other institutions, symposia, and interaction with other graduate students in the program. One of the objectives of the program is to produce graduate students who have strong experience with THz instrumentation and measurement techniques, in addition to a firm theoretical foundation in their specific area of specialization. An additional academic objective of the program is to create an atmosphere conducive to novel ideas and interdisciplinary research.

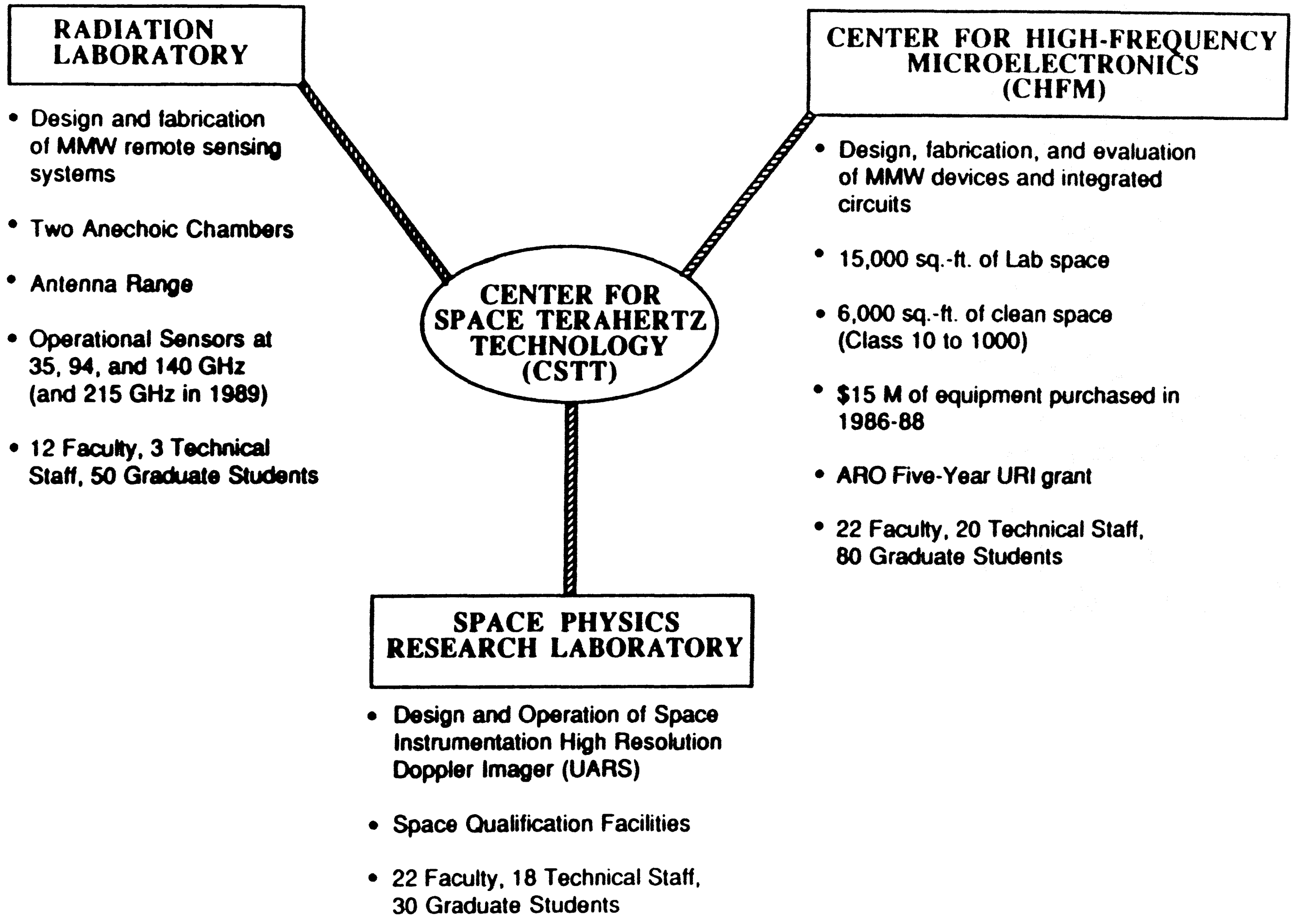
3.2 Organization Structure

The NASA/Center for Space Terahertz Technology draws its technical support from three research facilities: (1) the Center for High Frequency Microelectronics (CHFM), (2) the Radiation Laboratory, and (3) the Space Physics Research Laboratory. Brief descriptions of these facilities are given in Figure 13. A total of 13 research projects are currently being funded by NASA/CSTT, involving 14 research and teaching faculty and 30 graduate students. The projects, which were selected in accordance with a four-year "road map" developed by the Center's Executive Committee and approved by a NASA-appointed oversight committee, cover a wide range of activities extending from growing novel semiconductor materials for heterostructure solid-state devices, to fabricating monolithic imaging arrays and examining the THz emission spectra of planetary atmospheres. In several cases, the projects are conducted in collaboration with other institutions, such as the Jet Propulsion Laboratory (JPL) and the University of Virginia.

3.3 "Road Map"

The flow diagram shown in Figure 14 represents a road map for the progress of research activities from the component or subsystem level towards the overall receiver-integration level, and Figures 15 and 16 provide more detailed listings of the activities being pursued by the Solid-State and the Antenna and Quasi-Optics groups. No attempt will be made in here to discuss all of these projects in detail; instead, we will use examples to highlight the approach and development process associated with some specific elements of heterodyne-receiver design and fabrication.

a. *Local oscillator power.* Generation of low-noise oscillator power at THz frequencies is probably the single most crucial factor with regard to the development of THz heterodyne receivers today. As was mentioned earlier, Gunn oscillators have served as the primary source of power at frequencies up to about 120 GHz. To operate at higher frequencies has necessitated the use of multipliers or subharmonic mixers. The NASA/CSTT program is investigating four approaches for generating local oscillator power in the 0.1 to 1 THz region: (1) Resonant Tunneling Diodes, (2) Tunnel Transit-Time (TUNNETT) devices, (3) operating a Gunn diode in a second-fundamental mode, and (4) quantum well devices using thermionic emission. The investigations include theoretical-model analyses, fabrication of the devices using novel semiconductor materials and heterostructures, DC analysis of their i-v characteristics, and RF testing. Following a performance evaluation of these four techniques over the next two years, we will then focus our development activity on the most promising candidate in



RADIATION LABORATORY

- Design and fabrication of MMW remote sensing systems
- Two Anechoic Chambers
- Antenna Range
- Operational Sensors at 35, 94, and 140 GHz (and 215 GHz in 1989)
- 12 Faculty, 3 Technical Staff, 50 Graduate Students

CENTER FOR HIGH-FREQUENCY MICROELECTRONICS (CHFM)

- Design, fabrication, and evaluation of MMW devices and integrated circuits
- 15,000 sq.-ft. of Lab space
- 6,000 sq.-ft. of clean space (Class 10 to 1000)
- $15 M of equipment purchased in 1986-88
- ARO Five-Year URI grant
- 22 Faculty, 20 Technical Staff, 80 Graduate Students

CENTER FOR SPACE TERAHERTZ TECHNOLOGY (CSTT)

SPACE PHYSICS RESEARCH LABORATORY

- Design and Operation of Space Instrumentation High Resolution Doppler Imager (UARS)
- Space Qualification Facilities
- 22 Faculty, 18 Technical Staff, 30 Graduate Students

Figure 13. NASA/CSTT couples to three research units.

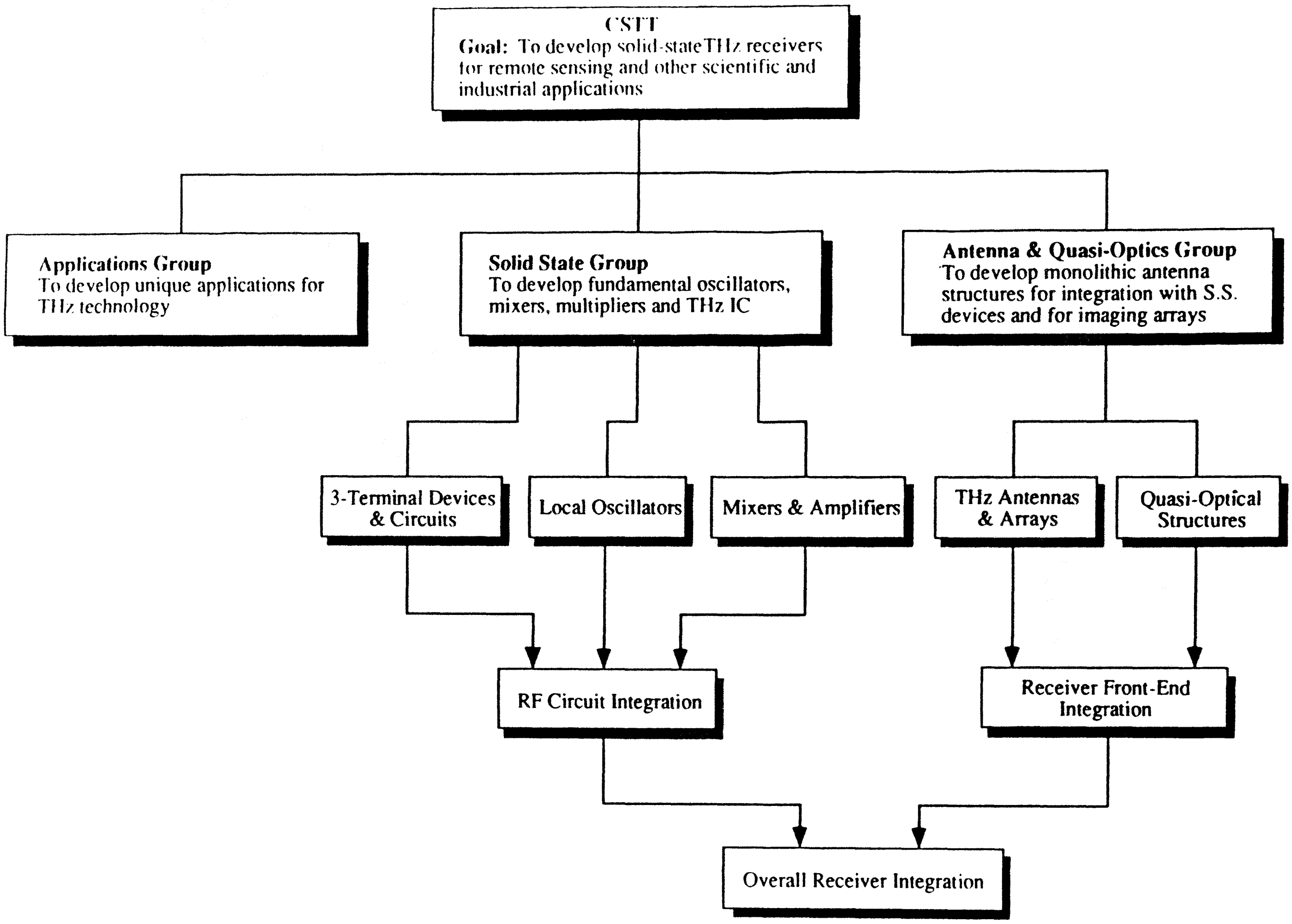


Figure 14. Organizational structure and research plan.

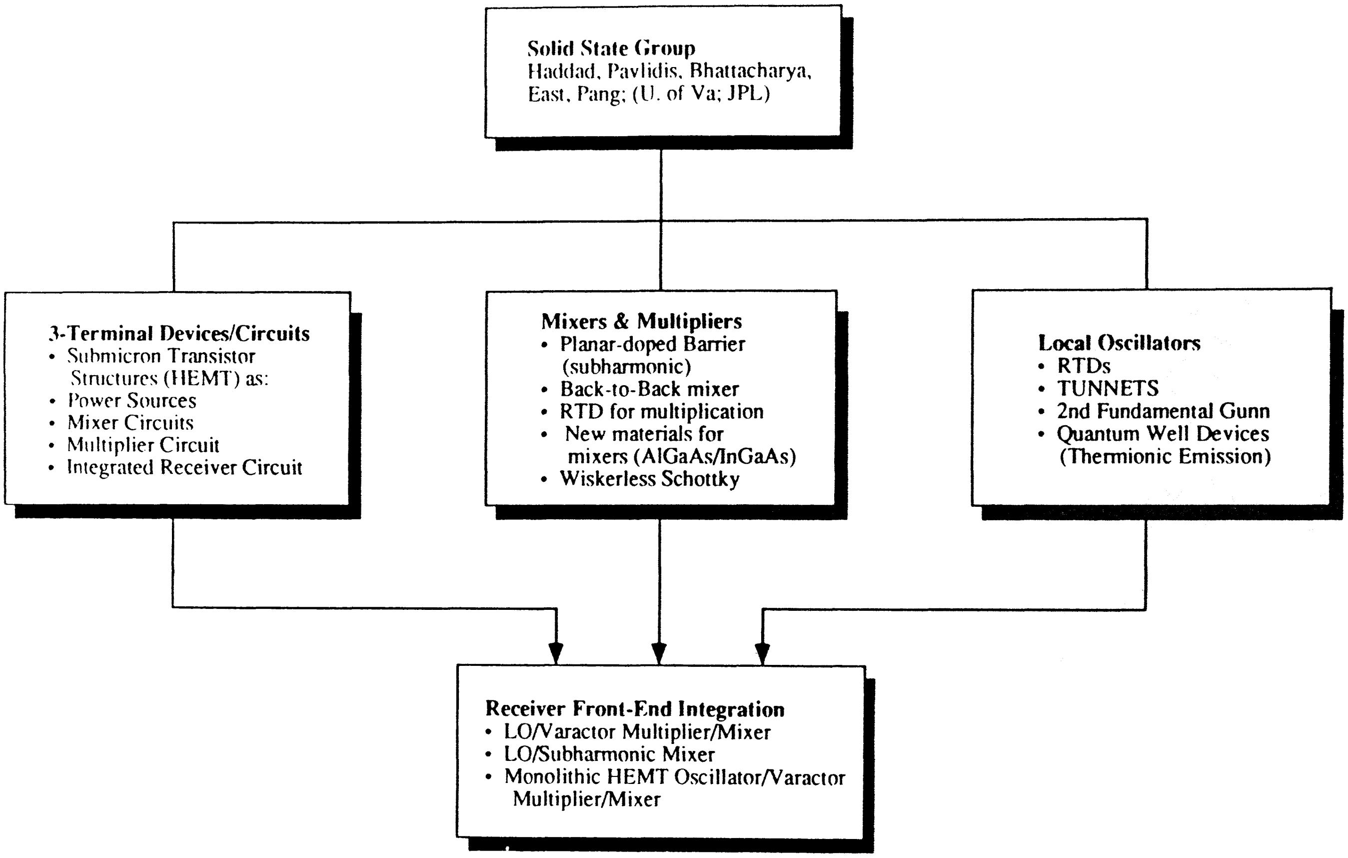


Figure 15. Research activities of the Solid-State Group.

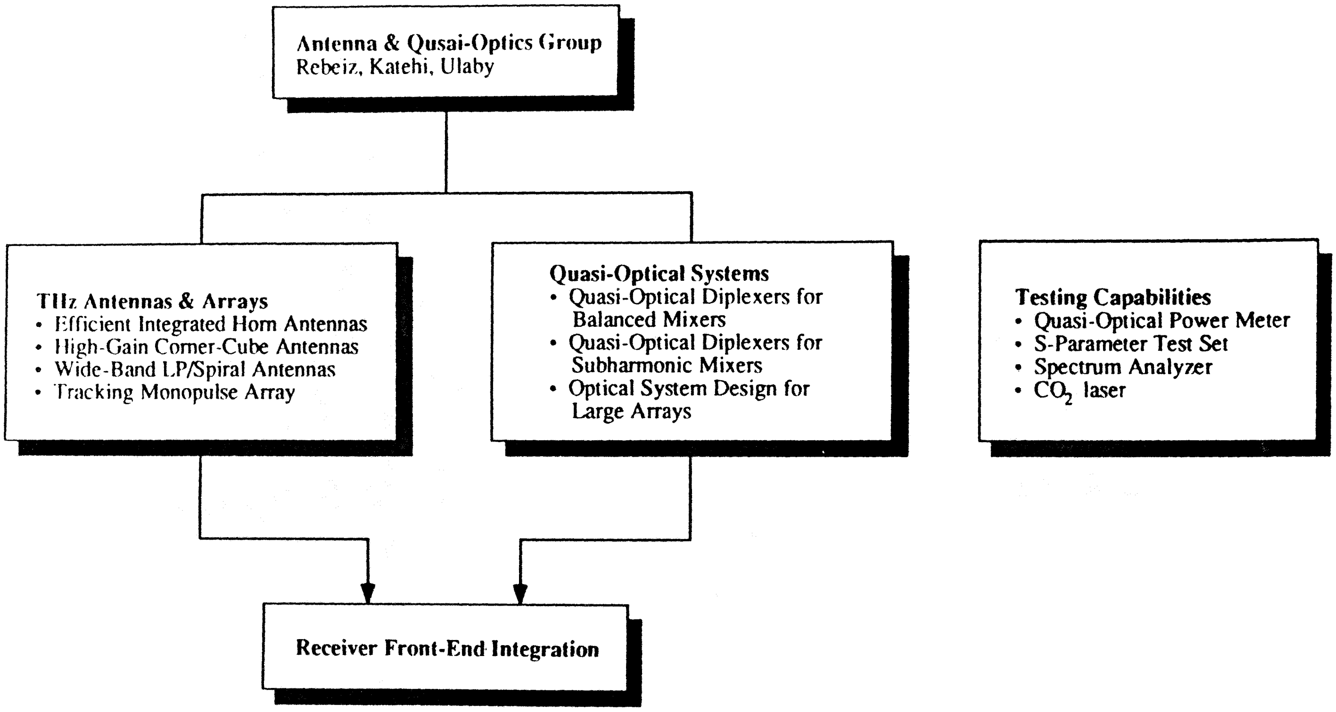


Figure 16. Research activities of the Antennas and Quasi-Optics Group.

subsequent years. Our goal is to develop devices capable of providing 1 mW of power at 1 THz by 1993.

b. *Subharmonic-mixer receiver.* The "traditional" approach used at millimeter and submillimeter wavelengths for designing the front end of a heterodyne receiver is based on single-ended mixers--specifically Schottky diodes and SIS devices--which requires quasi-optical combining of the LO and input RF signals prior to focusing the beam onto the mixer element (Figure 12). A modified version of this approach is shown schematically in Figure 17. Two orthogonally

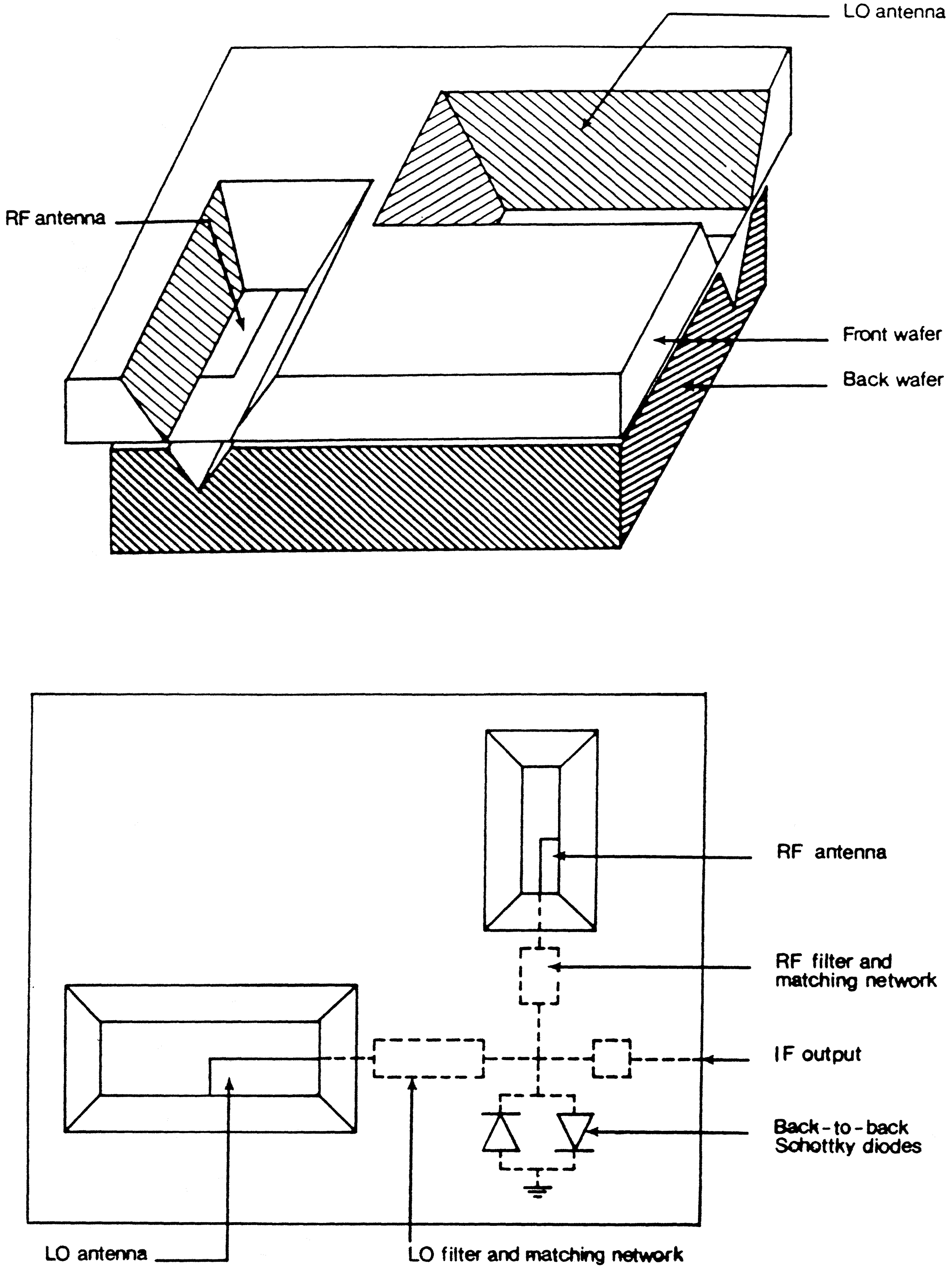


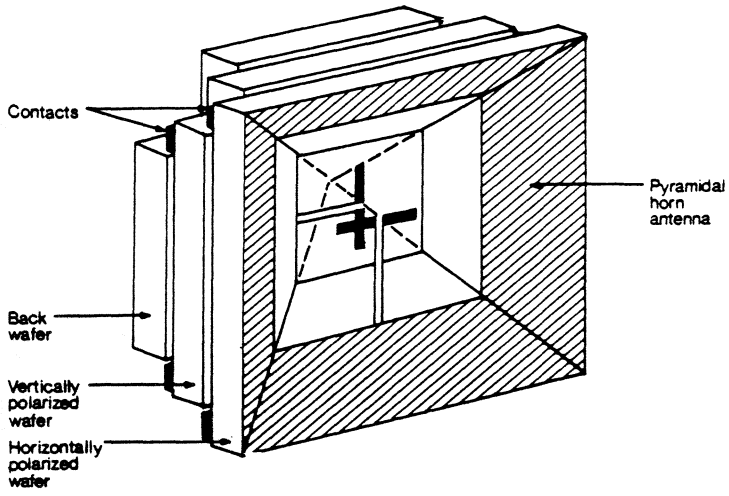
Figure 17. Subharmonic receiver configuration. The RF signal at ω_S and the LO signal at $\omega_{S/2} \pm \omega_{IF}$ are received by orthogonally polarized corner-cube antennas.

polarized corner-reflector antennas are used to couple the RF signal at ω_S and the LO signal at $\omega_{S/2} \pm \omega_{IF}$ to a pair of back-to-back Schottky diodes located on a wafer on the back side of the antennas. A 183 GHz model has been designed and is currently being fabricated and should be ready for performance evaluation soon. This design approach avoids the need for a quasi-optical diplexer as well as the construction difficulties associated with placing the mixer diodes in a reduced-height waveguide structure.

The corner-reflector antennas are particularly suitable for coupling to f/2 reflector systems. To couple the f/1 reflector systems, the pyramidal horn is a preferable choice, in which case orthogonal dipoles can be integrated on a thin membrane located inside the horn cavity (Figure 18), together with a balanced-mixer placed at their terminals.

c. *Monolithic integrated-circuit receiver.* The schematic shown in Figure 19 represents a design for a 180 GHz monolithic integrated-circuit receiver using sub-micron HEMT technology. The local oscillator, doubler, and mixer will all be fabricated as a single circuit. At present, the investigation is examining the performance of each of these three circuit elements individually, as well as modeling the matching networks and examining techniques for coupling the input RF signal to the mixer.

d. *Large-area bolometer for absolute power measurement.* The measurement of power at millimeter-wave frequencies is conventionally made using waveguide power meters. A power meter uses a thermistor or a diode detector suspended in a waveguide, and its frequency coverage is limited to the waveguide band associated with the guide dimensions. At frequencies above 100 GHz, the calibration accuracy is at best ±1 dB, and no power meters are currently available at frequencies above 300 GHz. To remedy this situation, a novel monolithic power meter was developed for THz applications using a 4 x 4 mm



Balanced-Mixers Using Double-Polarized Horns

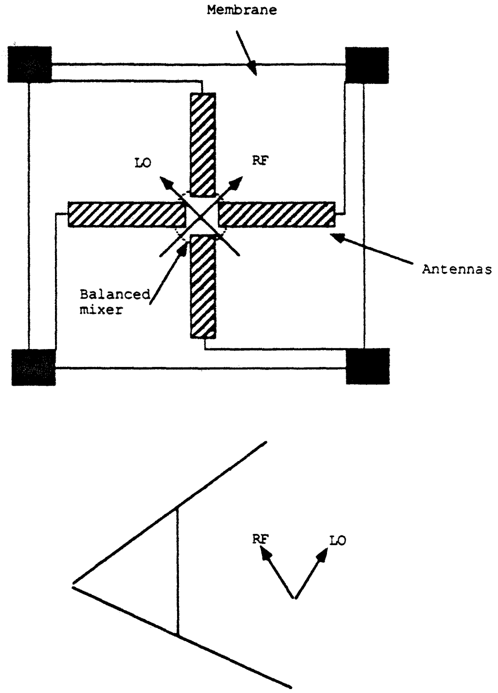


Figure 18. The top figure shows two dipole antennas placed at different locations inside the horn cavity. In the lower design, the two antennas are placed on the same membrane with a balanced mixer between them.

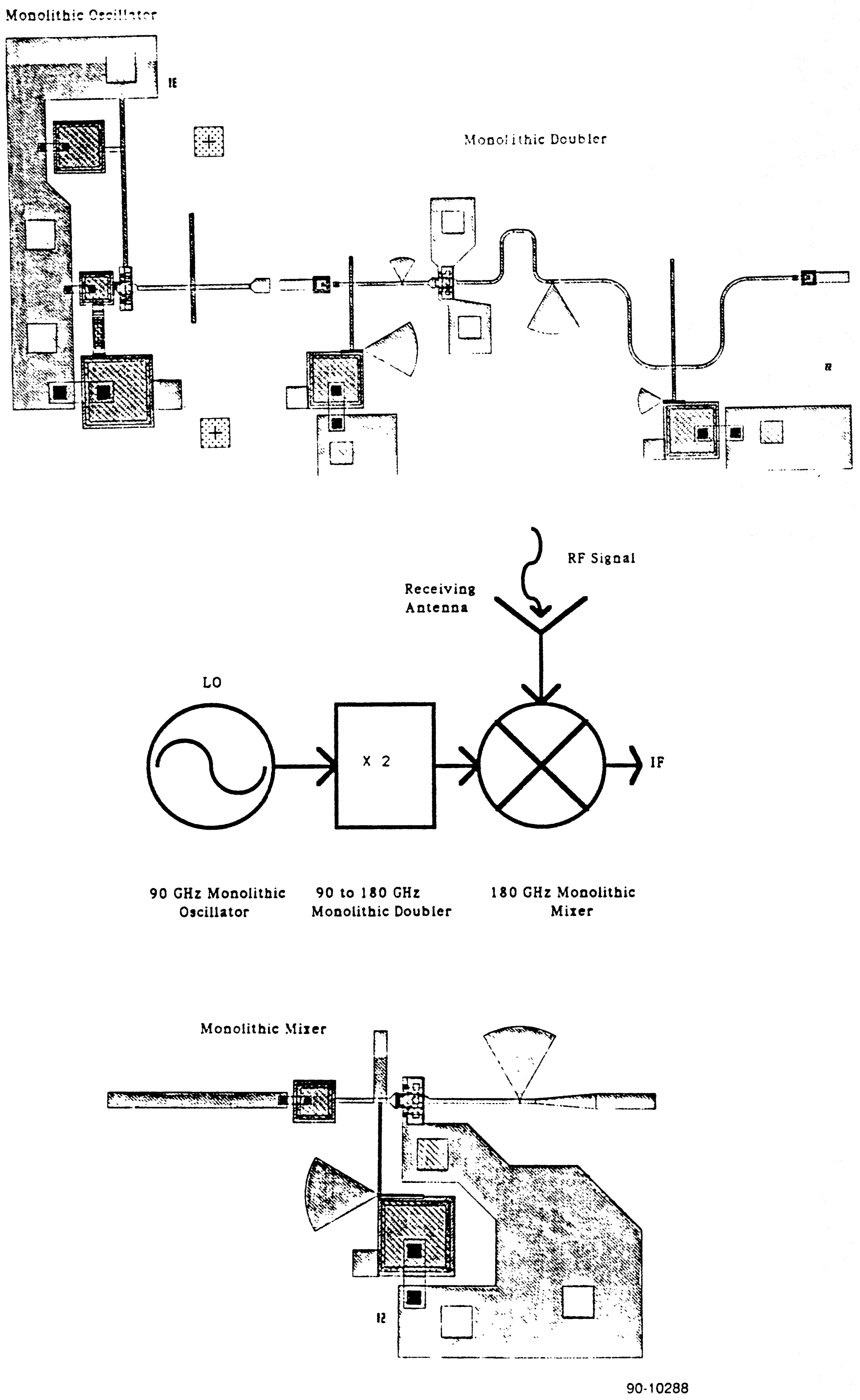


Figure 19. Schematic for a 180 GHz monolithic integrated-circuit receiver.

Bismuth bolometer integrated on a 1.2 mm-thick dielectric membrane (Figure 20). The bolometer is expected to have a wide frequency response extending well into the several THz region. The NEP of the detector was measured to be 3 nW $Hz^{-1/2}$ at a video modulation frequency of 300 Hz. This is the highest sensitivity of a THz-frequency room-temperature power meter reported to date.

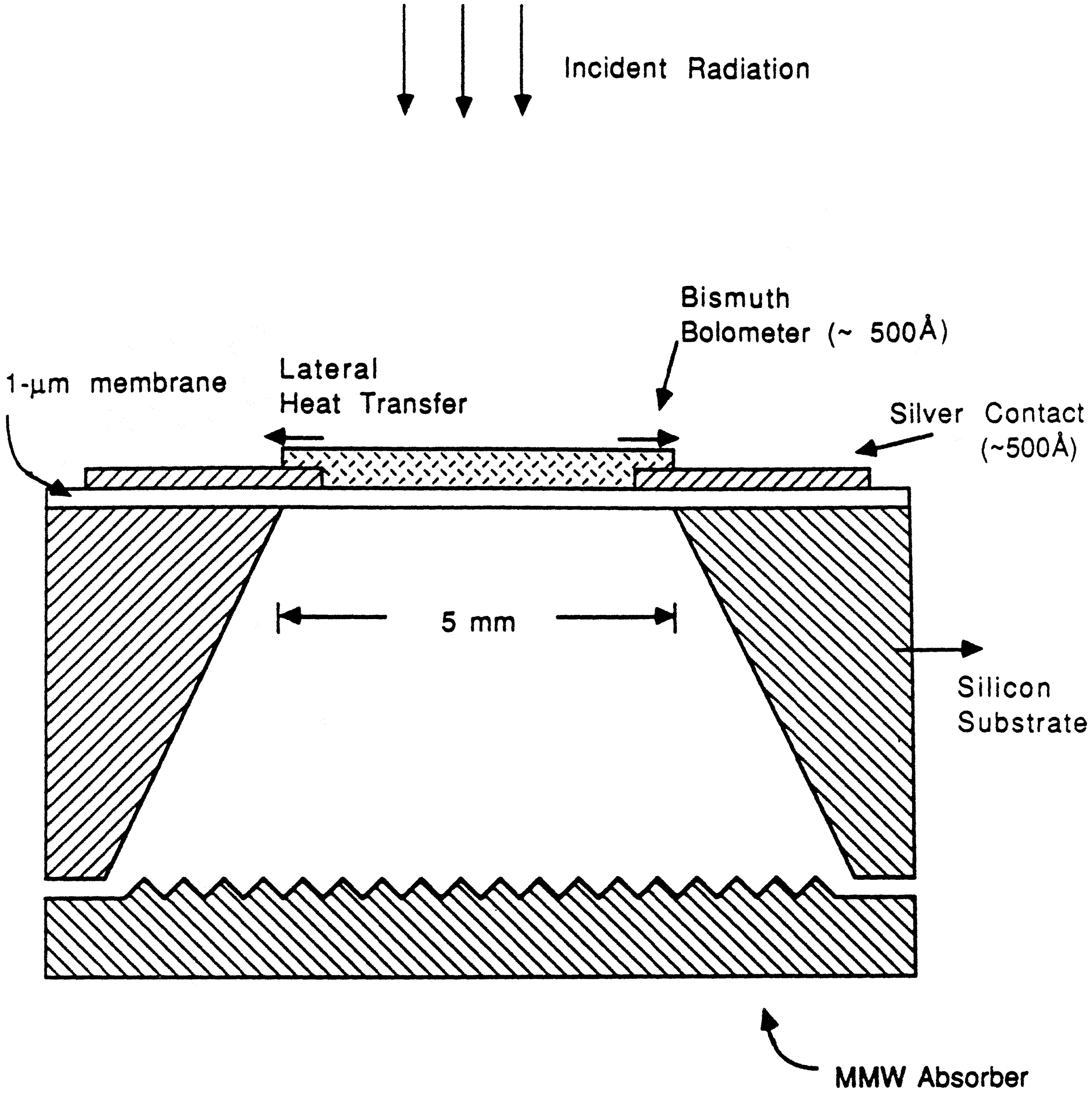


Figure 20. Wideband high responsivity THz power meter.

The preceding examples represent a subset of the research projects being conducted under the Space Terahertz Technology program at The University of Michigan, some of which are treated in more detail in other papers contained in the *Proceedings* of this Symposium.

4. CONCLUDING REMARKS

Within its brief 18-month history, the NASA/CSTT has developed an ambitious plan for developing solid-state technology for the construction of THz heterodyne receivers and their use in support of spectral line observations. The goal of the program is to develop at The University of Michigan a major U.S. facility for research in this field and to establish cooperative relations with NASA, industry, and other academic institutions involved in space THz technology. Holding the First International Space Terahertz Technology Symposium at The University of Michigan is only the first step toward that goal.

REFERENCES

[1] Payne, J. M., "Millimeter and Submillimeter Wavelength Radio Astronomy," *IEEE Proceedings*, Vol. 77, 1989, pp. 993-1017.

[2] Jewell, P. R., J.M. Hollis, F. J. Lovas, and L. E. Snyder, "Millimeter- and Submillimeter-wave Surveys of Orion A Emission Lines in the Ranges 200.7-202.3 GHz, 203.7-205.3 GHz, and 330-360 GHz," *Astrophys. J. Suppl.*, Aug. 1989.

[3] Waters, J. W., "Microwave Limb-Sounding of Earth's Upper Atmosphere," *Atmospheric Research*, 23, 1989, pp. 391-410.

[4] Phillips, T. G., "Techniques of Submillimeter Astronomy," in *Millimeter and Submillimeter Astronomy*, R. D. Wolstencroft and W. B. Burton (editors), Kluwer Academic Publications, Norwell, MA, 1988, pp. 1-24.

[5] Archer, J. W., "Low-Noise Heterodyne Receivers for Near-Millimeter-Wave Radio Astronomy," *IEEE Proceedings*, Vol 73, 1985, pp.109-130.

[6] Fetterman, H. R., G.A. Koepf, P. F. Goldsmith, B. J. Clifton, D. Buhl, N. R. Erickson, D. D. Peck, N. McAvery, and P. E. Tannenwald, "Submillimeter Heterodyne Detection of Interstellar Carbon Monoxide at 434 Micrometers," *Science*, Vol. 211, 1981, p. 580.

[7] Rebeiz, G. M., *et al.*, "Monolithic Millimeter-Wave Two-Dimensional Horn Imaging Arrays," Accepted for publication in *IEEE Transactions on Antennas and Propagation.*

[8] White, G. J., "Receiver Technology", in *Millimeter and Submillimeter Astronomy*, R. D. Wolstencroft and W. B. Burton (editors), Kluwer Academic Publications, Norwell, MA, 1988, pp. 27-93.

[9] Goldsmith, P. F., "Quasi-Optical Techniques at Millimeter and Submillimeter Wavelengths", *Infrared and Millimeter Waves*, Vol. 6, 1982, pp. 277-343.

[10] Tucker, J. R., and M. J. Feldman, "Quantum Detection at Millimeter Wavelengths", *Rev. Mod. Phys.*, Vol. 57, 1985, pp. 1055-1113.

[11] Phillips, T. G., and K. B. Jefferts, "A Low Temperature Bolometer Heterodyne Receiver for Millimeter Wave Astronomy", *Rev. Sci. Instrum.*, Vol. 44, 1973, pp. 1009-1014.

[12] Archer, J. W., "Millimeter Wavelength Frequency Multipliers", *IEEE Transactions on Microwave Theory and Techniques*, Vol. MTT-29, 1981, pp. 552-557.

[13] Rebeiz, G. M., W. G. Regehr, D. B. Rutledge, R. L. Savage, and N. C. Luhmann, Jr., "Submillimeter-Wave Antennas on Thin Membranes", *Infrared and Millimeter Waves*, Vol. 8, 1987, pp. 1249-1255.

[14] Feldman, M. J., "Theoretical Considerations for THz SIS Mixers", *Infrared and Millimeter Waves*, Vol. 8, 1987, pp. 1287-1292.

[15] Tolmunen, T. J., and A. V. Räisänen, "An Efficient Schottky-Varactor Frequency Multiplier at Millimeter Waves. Part I: Doubler", *Infrared and Millimeter Waves*, Vol. 8, 1987, pp. 1313-1336.

[16] Tolmunen, T. J., and A. V. Räisänen, "An Efficient Schottky-Varactor Frequency Multiplier at Millimeter Waves. Part II: Doubler", *Infrared and Millimeter Waves*, Vol. 8, 1987, pp. 1337-1353.

[17] Mattauch, R. J., and T. W. Crowe, "GaAs Schottky Devices for Submillimeter Wavelengths", *Infrared and Millimeter Waves*, Vol. 8, 1987, pp. 1235-1241.