FAR INFRARED HETERODYNE SYSTEMS

P. E. Tannenwald
Lincoln Laboratory,* Massachusetts Institute of Technology
Lexington, Massachusetts 02173

ABSTRACT

Three far infrared detectors, the InSb hot electron bolometer, the GaAs Schottky diode and the Josephson point contact junction, have been incorporated as mixers into sensitive heterodyne systems. The performances of existing heterodyne receivers/radiometers using these detectors are described and compared. Other applications of submillimeter heterodyne techniques are discussed.

I. INTRODUCTION

Over the last few years three far infrared detectors (ref. 1) have been developed into useful mixers that are presently being used in a number of applications: InSb, the GaAs Schottky diode, and the Josephson junction. InSb, which acts by way of a hot electron mechanism, has shown itself to be a highly sensitive heterodyne detector between 1 mm and 600 μm. Its very low LO requirement permits a variety of tunable klystron harmonics to be used, and the needed low temperature environment has not been particularly troublesome. InSb's outstanding limitation is its slow relaxation time (10^{-7} sec), leading to a quite narrow IF bandwidth of 1-2 MHz.

The GaAs Schottky diode has proved to be a highly useful room temperature mixer over a wide spectral range with exceedingly broad band IF capability limited to 40 GHz only by IF circuit parameters (ref. 2). In the millimeter region it has been engineered to a high state of perfection in low noise receivers and radiometers, while at submillimeter wavelengths it is just becoming a practical mixer when used in conjunction with quasi-optical techniques. For example, figure 1 shows the design of the Lincoln Laboratory quasi-optical diode mount that covers the range 1 mm to 100 μm with appropriately scaled antenna lengths (see ref. in table I, Fetterman et al.) At the lower frequencies the mixer design problem is relatively much easier inasmuch as waveguide techniques can be employed, and harmonics of tunable klystrons can be used as local oscillators. At far infrared wavelengths, the much more cumbersome optically pumped far infrared lasers are used as LOs, and

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*Supported in part by the U. S. Army Research Office and the Department of the Air Force.

their fixed frequency output makes the wideband IF capability of the Schottky diode imperative.

The superconducting point contact or Josephson junction (JJ) is also just being readied as a mixer in radiometers for field experiments. The planar superconductor-insulator-superconductor (SIS) junction has not yet been operated beyond mm frequencies (ref. 3). JJ receiver systems have excellent sensitivity, but their operational restriction to liquid He temperature and the attendant temperature recycling could be troublesome. One great advantage of JJs is their exceedingly low LO requirement. They have a moderate IF bandwidth of around 100 MHz.

II. FAR IR HETERDOYNE RADIOMETERS/RECEIVERS

Table I lists all the currently operational heterodyne radiometer/ receiver systems from 1.3 mm (230 GHz) to 119 μm (2521 GHz). The dots (•) denote that the detector was cooled. Some estimates and interpolations were made from the information reported in the literature in order to achieve moderate compactness of the data.

The DSB systems noise temperatures from table I are plotted in figure 2 as a function of wavelength. The solid or half-solid points represent low temperature measurements, the open points room temperature operation. The range of currently reported best values of DSB system temperature at 3 mm for both cooled (solid bar) and uncooled (open bar) mixers are also shown for comparison. For room temperature mixers there is a roughly linear trend with unity slope; there is no fundamental basis for this, but it is nevertheless an interesting guide, especially since all the room temperature mixers are GaAs Schottky diodes.

The plot shown in figure 2 makes no allowance for the instantaneous bandwidth available with each detector when estimating signal-to-noise ratios obtainable from observation of sources whose spectral features are moderately broad. To the extent that the observed object exceeds 1 MHz in spectral width, performance of the broad band Schottky diodes increases proportionally as compared with the 1 MHz wide InSb detectors. In other words, in the InSb case a single post-detection channel must be scanned sequentially across the spectral line, while with the Schottky diode the broad band IF can feed a multi-channel filter bank, thus integrating over the whole spectral feature simultaneously. Of course, if the signal intensity is so small as to give only a marginally usable S/N ratio with InSb, then no spectral characteristics would be resolvable with Schottky diodes. This is especially true at the very short wavelengths where optically pumped lasers must be used as LOs, and the system's stability over long integration times has yet to be demonstrated. In the case of superconducting junctions, with their ~100 MHz bandwidth, the situation falls somewhere in between, but closer to the Schottkys.

III. OTHER HETERODYNE APPLICATIONS

Tunable Far Infrared Sources

Low power ($\sim 10^{-7}$ W) tunable sources are now available throughout the submillimeter region by means of tunable sideband generation. In such schemes a tunable millimeter klystron or tunable microwave source is mixed with a fixed frequency optically pumped far infrared laser in a GaAs Schottky diode (refs. 4, 5). The narrow linewidths of these sideband sources make them quite suitable for far infrared spectroscopy. In one particularly sophisticated arrangement, shown in figure 3, the detector in the far IR spectrometer consists of a complete heterodyne receiver that utilizes as LO the same laser with which the source sidebands are generated (ref. 5).

Planar Diode Technology

In the next generation of Schottky diode detectors, discrete whisker contact diodes will be supplanted by a new type of device -- the planar, surface-oriented Schottky diode. This device is fabricated by means of photolithographic techniques in conjunction with ion implantation and proton bombardment (ref. 6). Figure 4 shows a simplified sketch of a whisker contact diode and a planar diode. The surface-oriented character of the planar diode is clearly evident in that both ohmic connecting contacts are brought out in the same surface plane. A photomicrograph of a single diode is shown in figure 5, one of many devices made on a single GaAs chip. Although the sensitivity of planar diodes is presently limited by inefficient coupling of radiation into them, they are used routinely in high-order harmonic mixing and direct heterodyne experiments between 1 mm and 100 μm. They are more rugged and reliable, and ultimately will lend themselves to mass fabrication of integrated antennas, mixer diodes and IF amplifiers on the same chip, and to array configurations for heterodyne imaging in the far infrared.

Frequency Standards

It is generally desirable to measure frequencies of visible lasers in terms of microwave standards. This has been possible with the metal-oxide-metal (MOM) diode, which can mix visible lasers with harmonics of far IR lasers, which in turn are locked to microwave standards (ref. 7). Two improvements over such a scheme would be advantageous: a replacement of the MOM diode by a more reproducible and stable mixing element, and the elimination of the chain of intermediate far IR lasers.

One step in such a direction has been the mixing of a He-Ne laser with a cw dye laser with approximately 80 GHz frequency offset in a reverse-biased GaAs Schottky diode (ref. 8). The beat frequency detector in this case was a sensitive 80 GHz heterodyne receiver. Thus large frequency differences between lasers emitting in the visible can be determined with the high accuracy inherent in heterodyning techniques.

Another step has been the high-order harmonic mixing of a stabilized X-band source with a far IR laser in a planar Schottky diode -- e.g., most recently the 145th harmonic of 12 GHz with a 170 μm formic acid laser (ref. 9). The desirability of extending this to 10 μm or even 1 μm is obvious.

Finally, it has been possible to extend the GaAs diode mixer operation up to 30 THz (ref. 10). Two laser lines in the 10 μm regime from a single stabilized laser cavity, which included two cells filled with CO_2 and isotopic CO_2, respectively, were mixed in both whisker point contact and planar diodes. Figure 6 shows the heterodyne signal produced at 15.6 GHz, with second heterodyning with a microwave LO down to a 50 MHz IF taking place either in the Schottky diode itself or in an external microwave mixer diode. Further experiments are underway to clarify the mixing process at these high frequencies, which could be RC roll-off of thermionic emission or perhaps field emission.

IV. SUMMARY

Three far infrared heterodyne detectors have been developed into useful mixers that are presently being used in radio astronomical experiments and other applications. The lowest system noise temperatures have been obtained with the liquid helium cooled InSb hot electron bolometer. Its principal drawback is the narrow IF bandwidth of 1-2 MHz imposed by the slow electron relaxation time. The superconducting point contact or Josephson junction will probably approach this performance, with somewhat less convenience and perhaps less reliability, but with $\sim$ 100 MHz bandwidth. Both InSb and the JJs require extremely little LO power (microwatts).

The exceedingly impressive performance obtained earlier from GaAs Schottky diodes at 3 mm [room temperature T (system) DSB $\sim 300^\circ$K; cooled T (system) DSB 200°K] is gradually being extended to shorter wavelengths [at 1 mm, T (system) DSB $\sim 2000^\circ$K]. The two principal advantages of GaAs Schottky diode mixers are room temperature operation and, inherently, unlimited IF bandwidth. Further extension of Schottky diode mixers in heterodyne systems to wavelengths as short as 119 μm has also been recently accomplished using quasi-optional techniques, with performance falling off roughly linearly with increasing frequency. In order to fully utilize these advances in detector technology for various radiometric applications, it is now desirable to achieve equal progress in the devlopment of tunabe far infrared LOs, especially solid state sources.

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TABLE I.- OPERATIONAL HETERODYNE SYSTEMS

(dots ● denote receivers that use cooled mixers)

FREQUENCY (GHz)	λ	DETECTOR	NOISE T (DSB)	AUTHORS	LO POWER	IF FREQUENCY	CONV. LOSS	COMMENTS
230	1.3 mm	GaAs S.D.	1250 °K	Erickson*	2 mW	1.3 GHz		2 × klystron
230	1.3 mm	GaAs S.D.	1500	Carlson & Schneider	<10 mW	1.4 GHz	8 dB	subharm. pump
● 230	1.3 mm	InSb	300	Phillips & Jefferts	10^{-4} mW	2 MHz	<10 dB	2 × klystron ●
285	1.05 mm	GaAs S.D.	1450	Erickson	1 mW	1.3 GHz	$T_{IF} = 50°K$	3 × klystron
● 300	1.0 mm	Nb pt. contact	500	Edrich et al.	4 × klystron	1.3 GHz		Cooled FET, $T_N = 45°K$ ●
● 300	1.0 mm	InSb	600	ESA/ESTEC	10^{-3} mW			Carcinotron ●
342	877 µm	GaAs S.D.	2200	Erickson	~10 mW	1.7 GHz	7 dB	Carcinotron
● 346	870 µm	InSb	2000	Phillips et al.		1 MHz		3 × klystron ●
● 452	660 µm	Nb pt. contact	2100	Blaney et al.	10^{-4} mW	100 MHz	11 dB	OP laser, $T_{IF} = 110°K$ ●
● 460	652 µm	InSb	650	ESA/ESTEC	10^{-3} mW			Carcinotron ●
● 492	608 µm	InSb	500	Phillips				5 × klystron ●
● 530	566 µm	InSb		ESA/ESTEC				2 × carcinotron ●
693	433 µm	GaAs S.D.	4200	Lincoln Lab	~10 mW	1.48 GHz		OP laser, $T_{IF} = 100°K$
● 693	433 µm	GaAs S.D.	3800	Lincoln Lab	~10 mW	1.48 GHz	10.5 dB	Diode cooled to 40°K ●
1630	184 µm	GaAs S.D.	19,000	Lincoln Lab	~60 mW	1.48 GHz	12 dB	OP laser LO
2521	119 µm	GaAs S.D.	32,000	Lincoln Lab	~30 mW	1.48 GHz		OP laser LO

*Also personal communication.

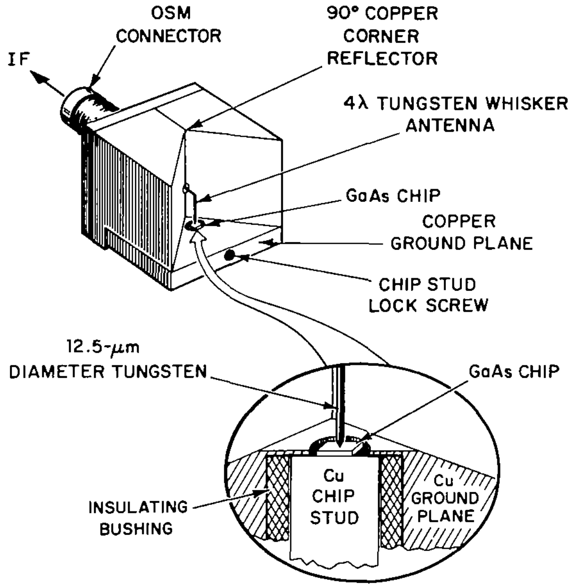


Figure 1.- Quasi-optical 90°-corner reflector diode mount.

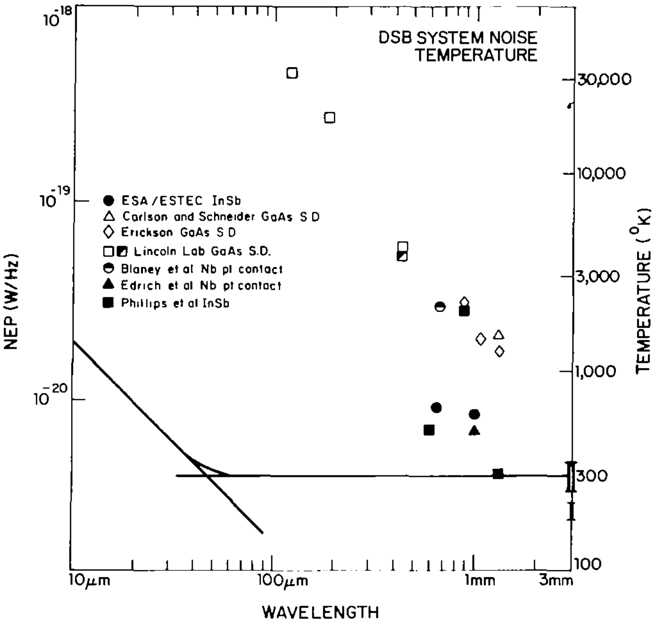


Figure 2.- Performance of operational heterodyne receiver/radiometer systems above 230 GHz. The solid (●) or half-solid (⊖,◪) points represent low temperature results. The ranges of the best 100 GHz room temperature (II) and low temperature receivers (I) are also shown.

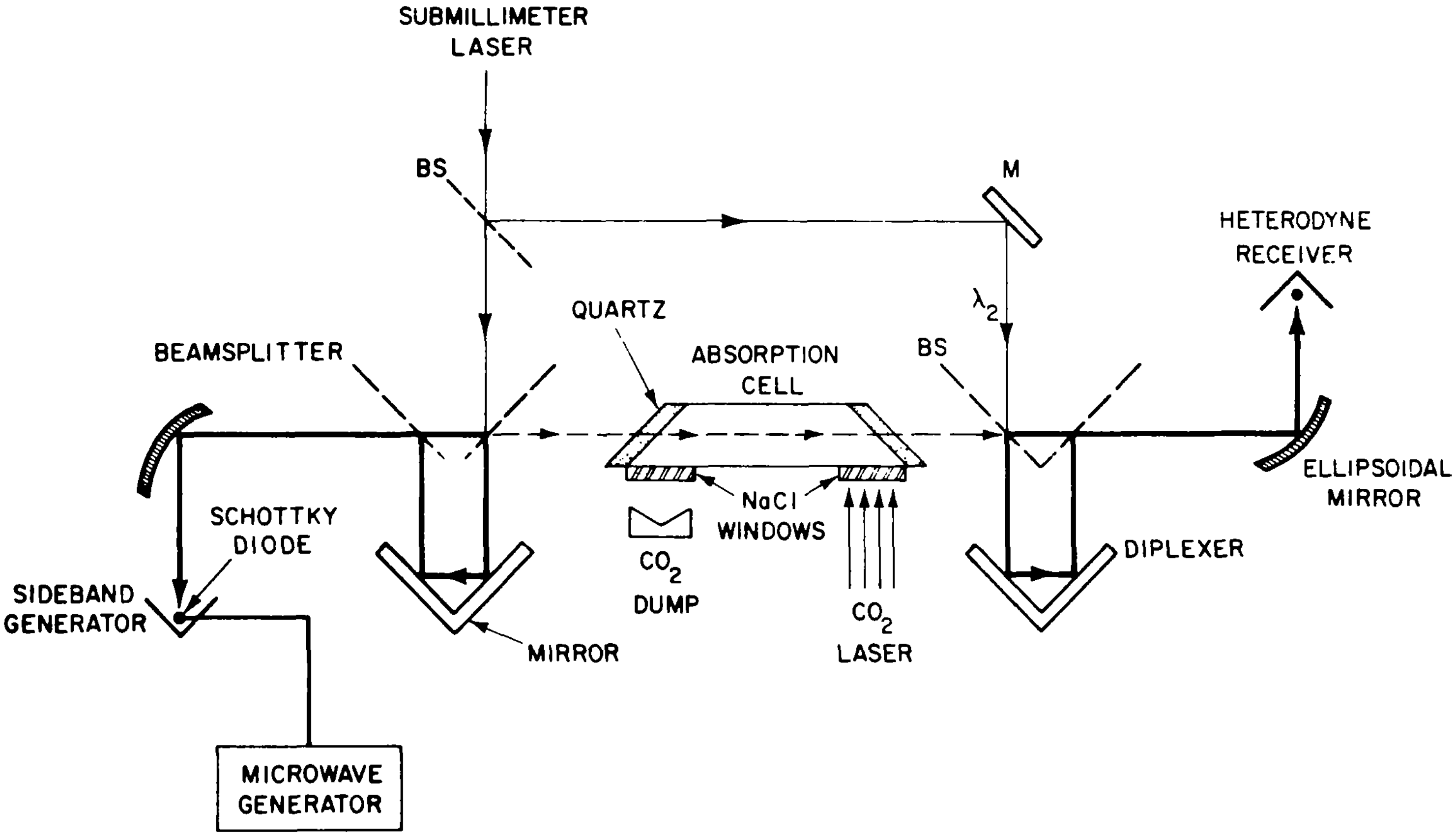


Figure 3.- Sketch of tunable sideband submillimeter spectrometer. Sideband generator and heterodyne receiver each use a Schottky diode mixer. In the particular example shown, CO_2 laser excites molecules under study in absorption cell while tunable submillimeter radiation provides high resolution spectrum of excited state.

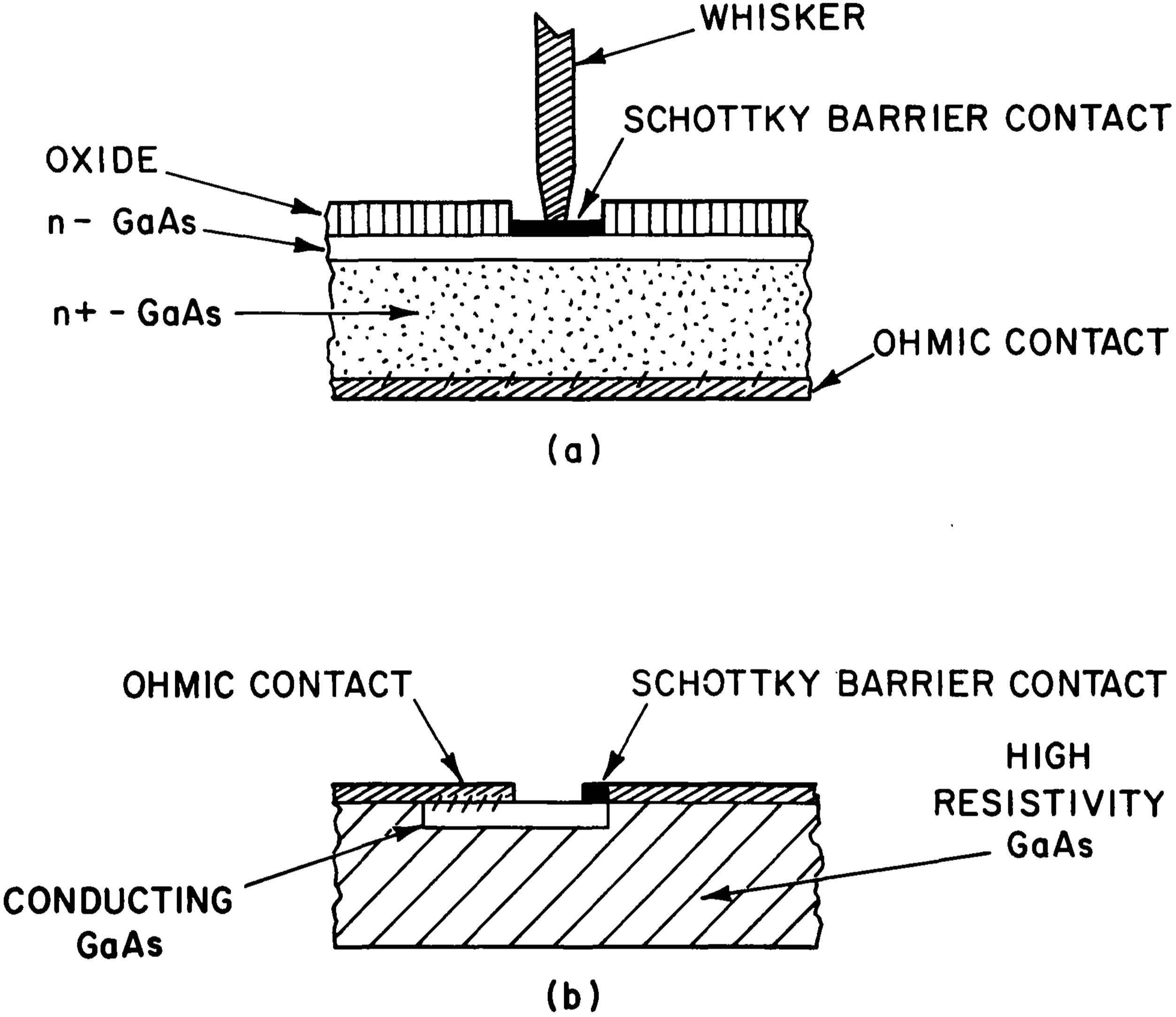


Figure 4.- Sketch of whisker contact diode (a) and planar diode (b). In planar diode both ohmic contacts are brought out in same surface plane.

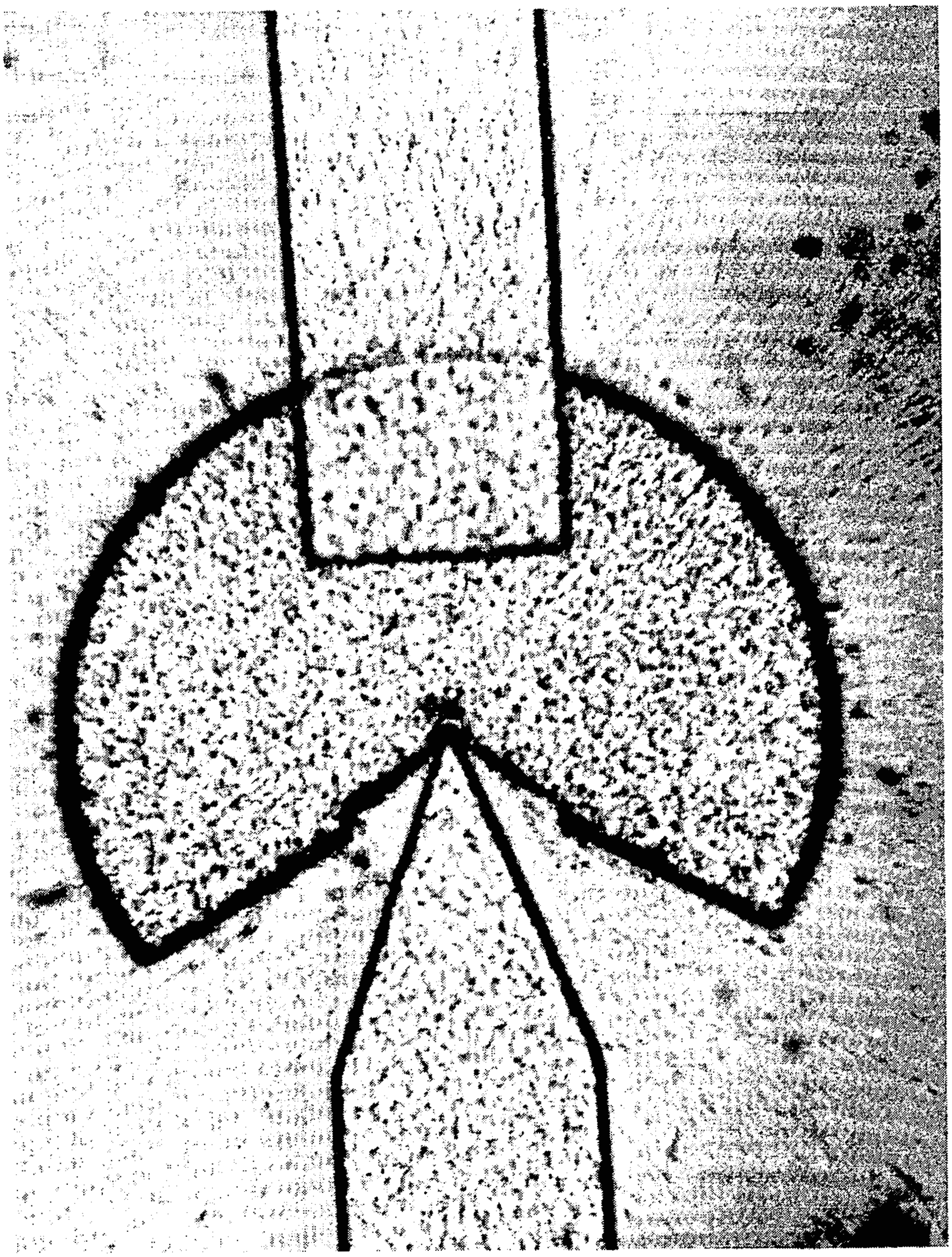
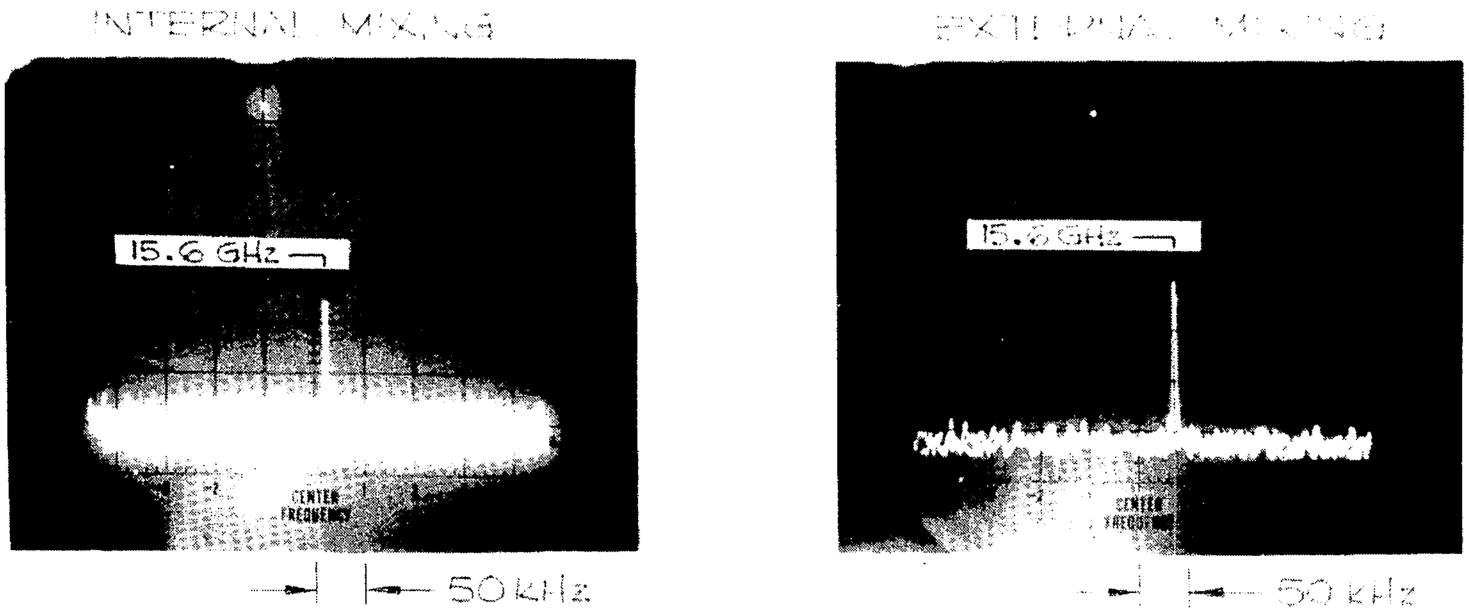


Figure 5.- Photomicrograph of a planar, surface-oriented diode.



SPECTRUM ANALYZER DISPLAYS OF 15.6 GHz BEAT NOTE
HORIZONTAL SCAN: 50 kHz/CM ; I.F. BANDWIDTH : 1 kHz ; VERTICAL SCALE: LINEAR

Figure 6.- Beats between two CO_2 lasers in the 10 μm regime obtained with a GaAs Schottky diode. Second down-conversion to a 50 MHz IF is produced either in the Schottky diode itself or in an external microwave diode.