PROGRESS IN SUBMILLIMETER WAVELENGTH INTEGRATED MIXER TECHNOLOGY

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Abstract

Higher levels of device and circuit integration lead to vast improvements in millimeter and submillimeter wave Schottky mixer performance. Monolithic technologies exhibit wider operating bandwidth, reduced noise temperature, and lower LO power consumption than flip-chip methods. In addition integrated technologies offer a simplified design process, easier assembly, and drastically improved repeatability. These characteristics make planar integrated Schottky mixers the most promising technology for radiometers when cryogenic cooling is not acceptable.

This discussion focuses on the development of 585 GHz and 1 THz integrated mixers. The devices are fabricated using the MASTER wafer bonding technique on a hybrid GaAs/quartz substrate. At 585 GHz the integrated mixer's DSB performance has been measured to be T_{sys}=1608 K, T_{mix}=1184 K, L_{mix}=6.5 dB at P_{LO}=1.6 mW. If the LO power is reduced to P_{LO}=300 μW, DSB T_{sys} is only 1890 K. This is the best room temperature mixer ever reported above 500 GHz for either planar or whisker-contacted technologies.

I. Introduction

Detection of submillimeter-wave radiation is of great interest to scientists studying interstellar chemistry, star formation, and galactic structure. Research has also been driven by the need to observe radiation emitted from a number of molecules in the Earth's atmosphere such as O_3, ClO, and OH at 206 GHz, 640 GHz, and 2.5 THz, respectively. The military is also interested in analyzing submillimeter wavelength radiation. For example, compact range radar uses heterodyne detectors to measure the radar signatures of objects in a laboratory environment.

These applications require mixers with sufficient spectral sensitivity, bandwidth, and minimal LO power consumption. Although SIS junctions and hot electron bolometers now offer the best sensitivity in the THz frequency range, for many applications cryogenic cooling is not acceptable. Also, this level of sensitivity is often not required. In these instances, GaAs Schottky diodes are the preferred mixer technology. State-of-the-art receivers in the THz regime have used quarter-micron diameter whisker-contacted Schottky diodes [1]. These mixers have achieved record sensitivity [2][3], but they are difficult to space qualify due to the fragility of the whisker contact.

Several groups have developed planar Schottky diode technologies with an integrated finger replacing the whisker [4][5][6]. The UVA surface channel diode is depicted in Figure 1. This device is more easily space-qualified due to the integrated contact between finger and anode. Several research groups have successfully used discrete planar diodes in millimeter and submillimeter wave applications in both waveguide and quasi-optical implementations [7][8][9].

Jeffrey Hesler's work at UVA on a 585 GHz fundamental, fixed-tuned waveguide mixer deserves a special note. This mixer was completely designed using Hewlett Packard's HFSS and MDS and demonstrated one of the best-reported receiver and mixer noise temperatures at 585 and 690 GHz [10]. Hesler used a traditional flip-chip soldering technique to mount a discrete planar mixer diode onto his quartz circuit. Although this scheme was successful around 585 GHz, the mixer was challenging to assemble and would be difficult to scale to the THz regime.

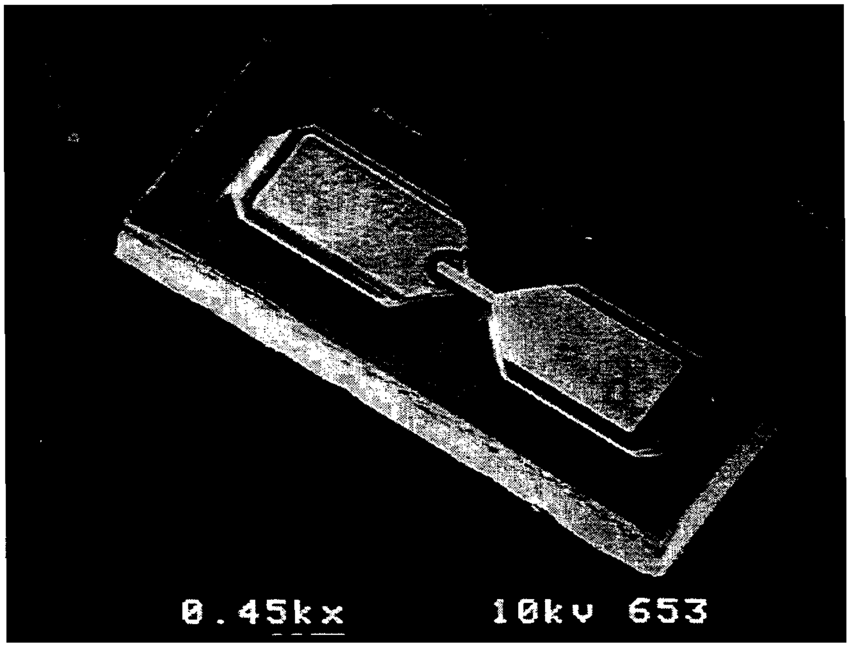

Fig. 1: UVA surface channel planar diode

II. Integrated Planar Mixers on Quartz

As operating frequencies are pushed higher, there are several issues which limit discrete planar mixer performance. The bulky, high dielectric GaAs substrate increases pad to pad capacitance, dielectrically loads the waveguide, adds extra losses to the mixer circuitry, and makes fitting discrete diodes into higher frequency blocks difficult or impossible. In addition, the imprecise alignment of the diode to the surrounding circuitry and the non-repeatable nature of the flip-chip mounting process negatively impacts RF performance, test repeatability, and computer simulation predictability.

One method of eliminating these problems is to integrate the GaAs diode with a low dielectric substrate. Removing the GaAs substrate and replacing it with quartz, for example, significantly reduces the pad to pad capacitance by leaving only a small, thin GaAs active area around the device anodes. UVA successfully has fabricated discrete planar diodes on quartz [11] and RF results at 215 GHz indicate improved performance over GaAs substrate devices [12]. Figure 2 shows a mixer diode with a quartz substrate [11]. Further integration is possible by incorporating the mixer circuitry. This achieves perfect alignment between the diode and filters without soldering or handling a discrete diode chip. The potential benefits of this configuration include better noise performance, wider bandwidth, better LO coupling, higher maximum operating frequency, better modeling predictability, and easier, more repeatable mixer assembly [13].

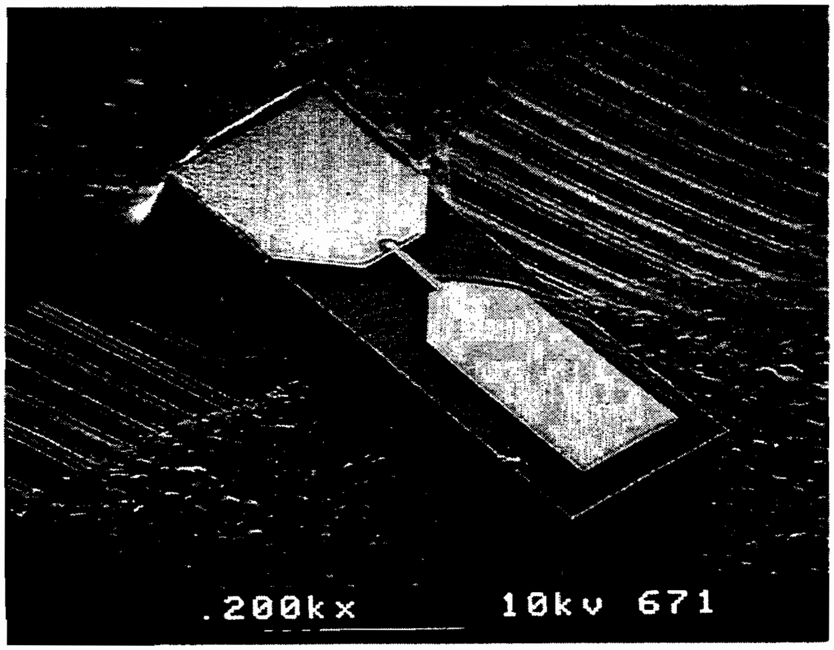

Fig. 2: Planar mixer diode with quartz substrate

In 1993 NASA's Jet Propulsion Laboratory (JPL) developed an integrated mixer on quartz using a heat-cured epoxy to hold the mixer diode and filters down to the substrate [14]. This device structure, named QUID, was an excellent first step. At first the epoxy that filled in the surface channel was causing problems with coupling radiation into the diode. An epoxy etch technique developed at UVA helped improve the mixer performance by 20-30% [15][16]. QUID devices exhibit good subharmonic performance at 640 GHz with DSB T_{mix}=2500 K and $L_{mix}\approx 9$ dB [17]. The DSB T_{mix} remains less than 3500 K over a 1.5 to 14 GHz IF band. However, the presence of the epoxy is worrisome. Even after etching it from the surface channel area, this lossy material still sits beneath the diode pads and filters. This impacts RF performance and also has reliability issues in terms of out-gassing and long-term robustness.

III. MASTER Integrated Mixer Technology

To avoid the concerns associated with epoxy bonding, an integrated mixer technology has been developed at UVA. The Method of Adhesion by Spin-on-dielectric Temperature Enhanced Reflow (MASTER) uses a patent pending semiconductor to substrate bonding process to attach the thin GaAs active areas of the mixer diode to a quartz substrate in a rightside-up orientation [13][18]. In addition, the filter circuitry is fabricated in perfect alignment with the diode using a raised diode mesa structure. Using this technique, 585 GHz and 1 THz integrated, fundamental mixers have been fabricated.

The fabrication process begins by forming the anode and ohmic contacts on a full thickness GaAs wafer covered with an SiO_2 passivation layer. The wafer is mounted face-down to a carrier, and wet etchants are used to remove the bulk GaAs substrate and AlGaAs etch stop layer. The remaining 4-5 μm of GaAs are the active layers of the mixer diode and are bonded rightside-up to a quartz wafer using the MASTER technique. A mesa etch then removes the GaAs from outside the device areas, and the spin-on-dielectric (SOD) bonding material is plasma etched in those regions to reveal the surface of the quartz substrate. A layer of Ti/Au is e-beam deposited over the entire wafer to form the Schottky anode contact. This seed layer is also used to electroplate the diode finger contacts and microstrip filter circuitry. After plating the seed layer is removed with a RIE process. Figure 3 shows an array of MASTER devices after this step. Note the microstrip filters are formed directly on quartz outside of the device mesa. The surface channel etch step is performed next to form a low parasitic air bridge underneath the finger contact. The SOD is then plasma etched to remove it from the surface channel area. In the final devices, the SOD only remains underneath the small device pads. Figures 4 and 5 show MASTER devices after the surface channel air bridge is formed. The device wafer is then mounted face down to a carrier and the quartz substrate is thinned to the proper thickness. For the 585 GHz and 1 THz mixers fabricated for this work, the quartz substrate thicknesses were 37.6±0.9 μm and 25.0±0.7μm, respectively. Dicing is performed to separate the wafer into individual circuits. The overall dimensions

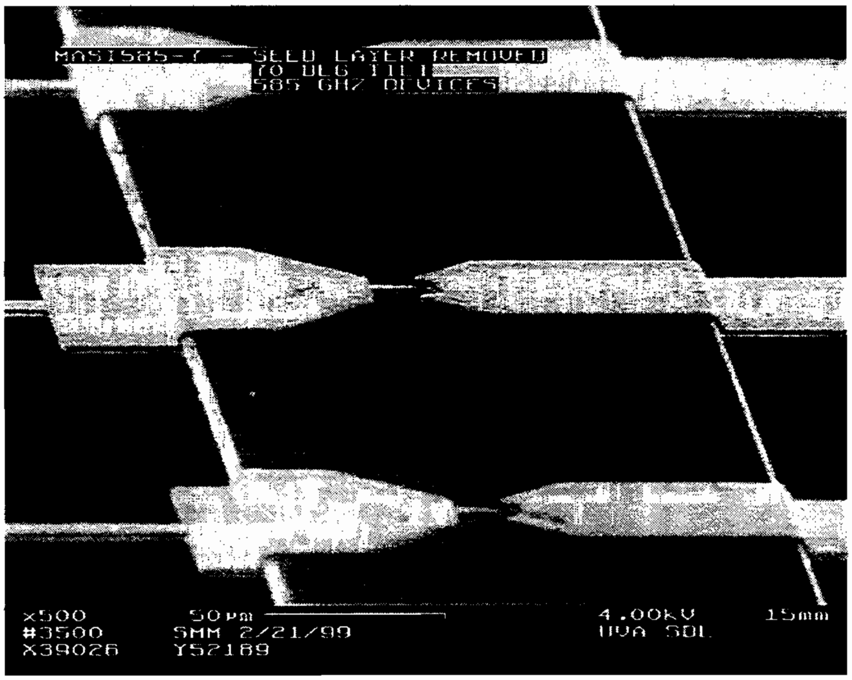

Fig. 3: MASTER devices after seed layer removal step

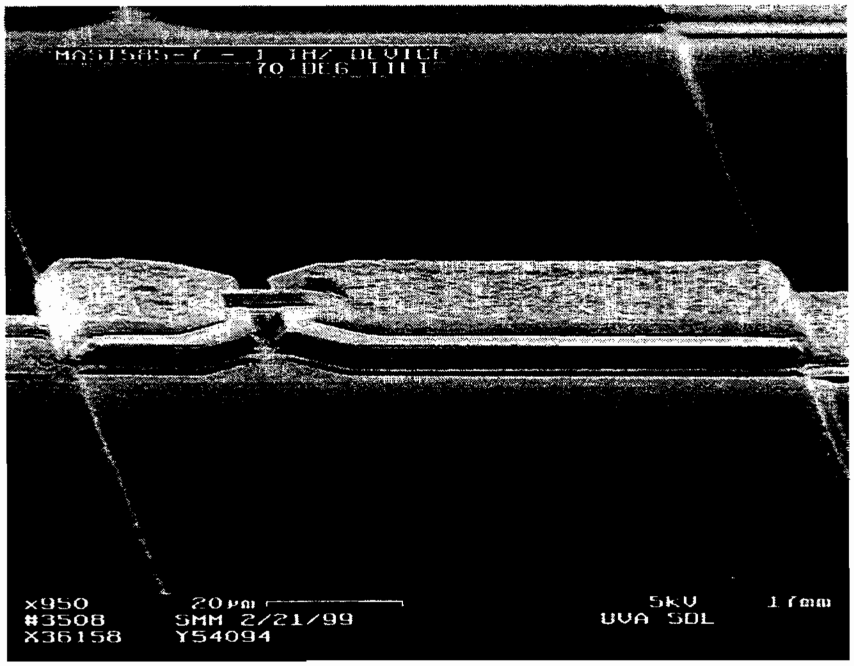

Fig. 4: MASTER device after surface channel etch

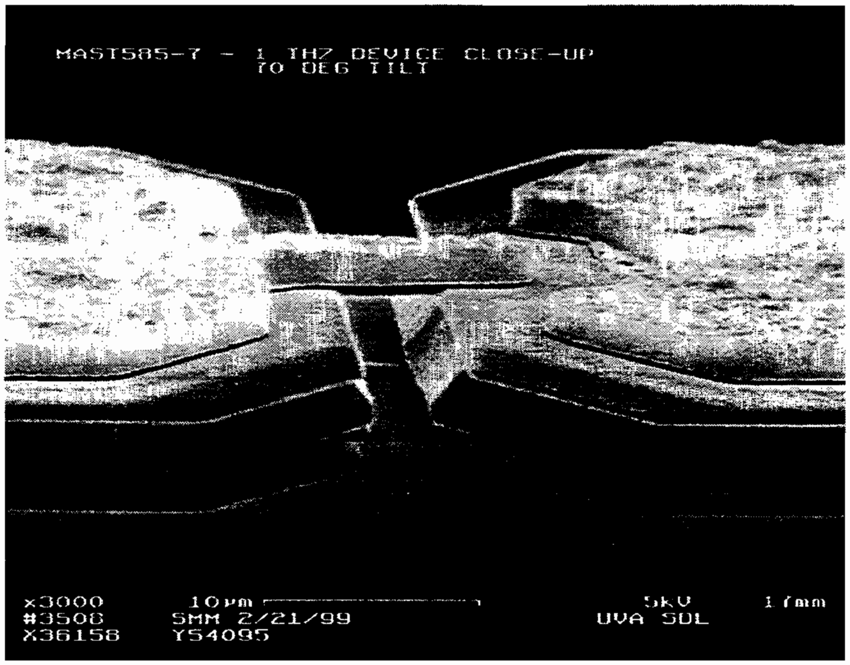

Fig. 5: Close-up of MASTER device after surface channel etch

for 585 GHz and 1 THz mixers were 1850 x 92 μm and 1065 x 59 μm. At this point, the diode's I-V characteristics are measured. Table 1 summarizes typical DC I-V and capacitance parameters for these devices. The uniformity from chip to chip was excellent.

IV. RF Design and Test Results for MASTER Mixers

The designs for the 585 GHz and 1 THz integrated mixers were based upon Hesler's previous 585 and 690 GHz fundamental fixed-tuned waveguide mixers [19]. The computer modeling was done in Sonnet and Hewlett Packard's HFSS and MDS. Figures 6 and 7 show the 585 GHz and 1 THz designs that were fabricated in each wafer batch.

RF testing of the 585 GHz MASTER mixers was performed in UVA's FIR lab. The waveguide block, mounting techniques, and RF test setup are explained in Hesler's dissertation [19]. However, with integrated devices the mounting now only requires placing the mixer in the block, butting the LO waveguide probe up against the input waveguide, and attaching two bond wires. Figure 8 shows a MASTER mixer mounted in a metal 585 GHz waveguide block. The LO source was a CO_2 pumped FIR laser. Only preliminary RF data has been taken thus far. The best performance at 585 GHz is DSB T_{sys}=1608 K, T_{mix}=1184 K, L_{mix}=6.5 dB consuming P_{LO}=1.6 mW. T_{sys} increases only 18% when the LO power is reduced to 0.3 mW. Table 2 summarizes these results and includes

<table>
<tr><th colspan="2">Diode Parameter</th><th colspan="2">Measured Value</th></tr>
<tr><td colspan="2">N_d</td><td colspan="2">$4x10^{17}$ cm^{-3} n-type</td></tr>
<tr><td colspan="2">d_{anode}</td><td colspan="2">0.9 μm nominal</td></tr>
<tr><td colspan="2">R_s</td><td colspan="2">10-12 Ω</td></tr>
<tr><td colspan="2">V_{knee} (I=1μA)</td><td colspan="2">490-510 mV</td></tr>
<tr><td>ΔV (I=10-100 μA)</td><td>η</td><td>77-78 mV</td><td>1.31-1.33</td></tr>
<tr><td colspan="2">C_{j0} @ f=1 MHz</td><td colspan="2">1.5 fF (calculated)</td></tr>
<tr><td colspan="2">C_{total} @ f=1 MHz</td><td colspan="2">5-7 fF</td></tr>
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Table 1: I-V parameters for 585 GHz and 1 THz MASTER mixers

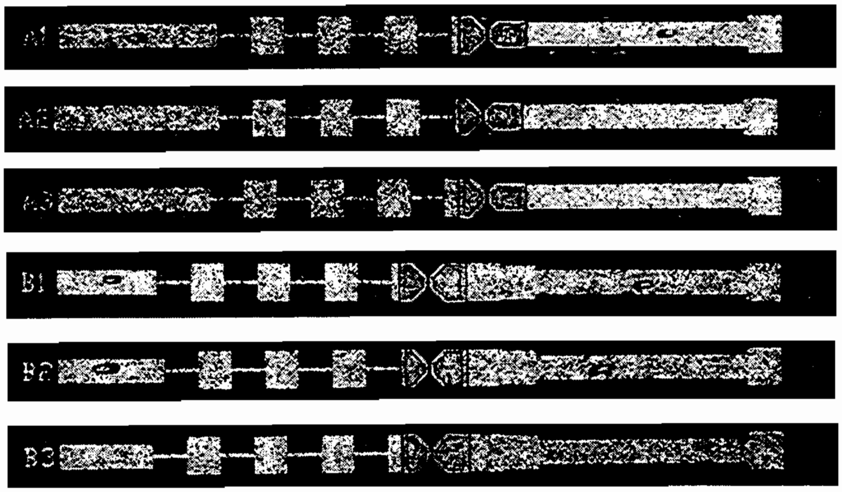

Fig. 6: 585 GHz MASTER mixer circuit variations

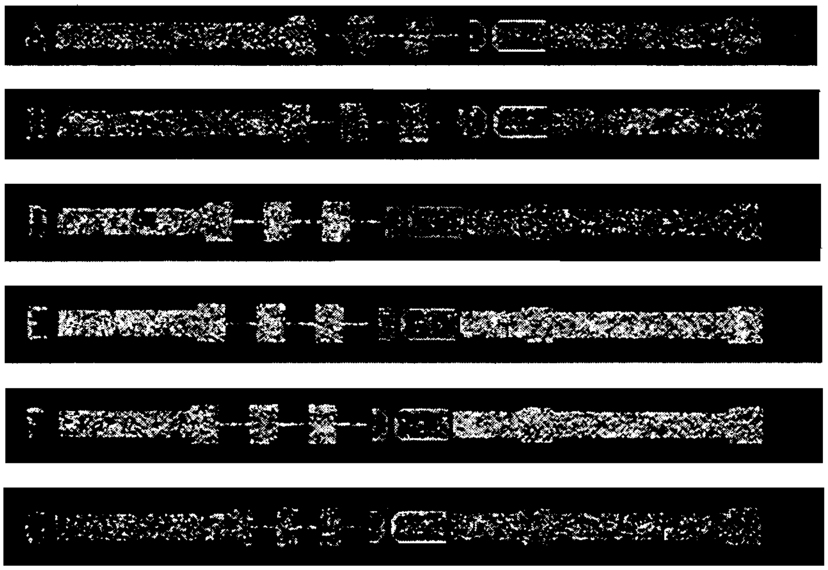

Fig. 7: 1 THz MASTER mixer circuit variations

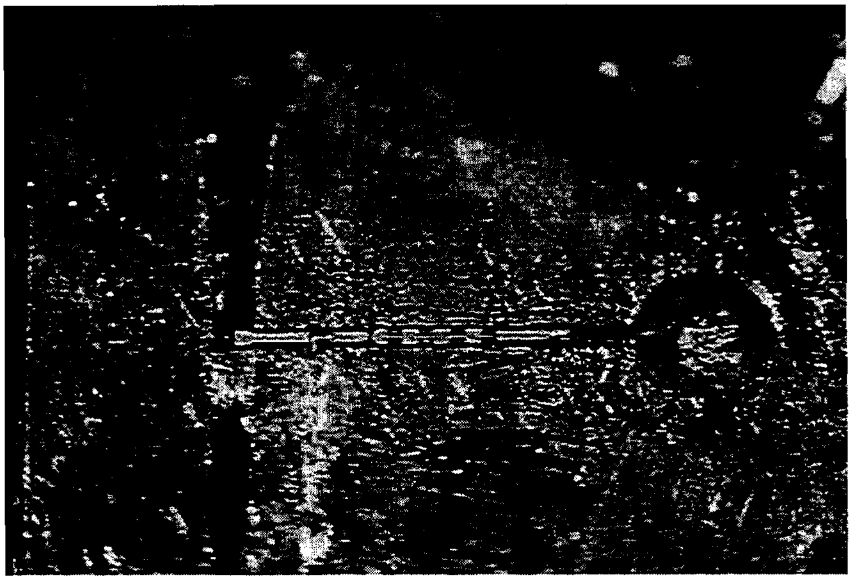

Fig. 8: 585 GHz MASTER mixer mounted in block RAL

Freq. (GHz)	Device Technology Description	T_{sys} (K)	T_{mix} (K)	L_{mix} (dB)	P_{LO} (mW)	Refer.
557	Whisker-contacted, waveguide, mech. tuners, metal block	1600	1200	8.0	not known	[21]
585	**MASTER A1 integ. planar, fixed-tuned, RAL block**	**1608**	**1184**	**6.5**	**1.60**	**this work**
585	**MASTER A1 integ. planar, fixed-tuned, RAL block**	**1890**	—	—	**0.30**	**this work**
585	SC1T5-S10 discrete planar, fixed-tuned, RAL block	2380	1800	7.6	1.16	[10]
640	QUID integ. fund. planar, mech. tuners, Metal block	2720	1636	7.93	0.35	[20]
640	QUID integ. subharm. planar, mech. tuners, Metal Block	—	2500	9.0	3.5-3.8	[17]
640	MASTER integ. subharm. planar, mech. tuners Metal Block	—	2396	10.98	4.7	[13]
690	SC1T5-S5 discrete planar, fixed-tuned, RAL Block	2970	2240	8.8	1.04	[10]

Table 2: Summary of Schottky Mixer Performance in the 500-700 GHz range

current state-of-the-art RF measurements from the literature as a comparison [20][21]. All data quoted is room temperature. From this table it is deduced that this research has produced the best room temperature mixer results above 500 GHz. This is the first time a planar Schottky mixer has achieved better performance than the best whisker-contacted mixers [21] in this frequency range.

Currently, the 1 THz MASTER mixers have been designed, fabricated, and fully characterized at DC. They are awaiting a waveguide block before RF testing is begun. The small dimensions of the waveguides at terahertz frequencies are a major difficulty for fabricating high quality blocks.

V. Summary

Waveguide mixers based on planar Schottky diodes have promised to match the performance of whisker-contacted mixers while producing more repeatable and predictable behavior. However, the increased parasitics associated with the planar structure and the imprecision of mounting discrete diodes into surrounding mixer circuitry have kept the planar mixer from achieving this goal. The QUID technology developed at JPL was a good first step. The integration of the diode and filter circuitry improved planar mixer performance, but the presence of the epoxy adhesive limited its ability to supercede whisker-contacted devices. The MASTER device technology has overcome these shortcomings through the conception and full development of a novel integrated Schottky mixer. By forming the mixer diode rightside up and the microstrip filters directly on the quartz substrate, parasitic capacitance and dielectric losses have been minimized. These mixers have demonstrated the lowest room temperature noise temperature above 500 GHz, outdoing even the best whisker-contacted mixers. They also maintain good performance at significantly reduced LO power levels. This has been accomplished without any mechanical tuning in an easy to assemble package which requires no soldering or diode alignment. The mixers are easy to design and model, and their performance is predictable from device to device.

This work has extended the usability of monolithic device technologies far into the submillimeter wavelength regime. MASTER integrated devices have set new levels of achievement for Schottky mixers in terms of noise performance, LO power consumption, and conversion efficiency in a robust, space-qualifiable structure. This technology is readily extended to other devices such as varactors and amplifiers. With the use of a low parasitic hybrid device technology such as MASTER, the possibility of submillimeter wavelength MMIC chips integrating not only passive but active devices has become a reality.

VI. Acknowledgments

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