200 GHz WAVEGUIDE BASED SUBHARMONICALLY-PUMPED MIXERS WITH PLANAR SCHOTTKY DIODES

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ABSTRACT

Extremely sensitive subharmonically pumped mixers (SHPMs) have been developed that utilize planar Schottky diodes fully integrated with the appropriate circuitry on a quartz substrate. The successful demonstration of these low noise mixers relied on several new technologies such as the development of the QUID (Quartz substrate Up-side-down Integrated Device) process and the successful use of T-gate like structures for low parasitic Schottky contacts. Based on these technologies, 200 GHz SHPMs measured in our lab have achieved better performance than any previously reported whisker contacted or planar Schottky diode SHPM at comparable frequency. In fact, the achieved noise sensitivity is only about 1.5 times worse than the best ever whisker contacted fundamental mixers at this frequency.

INTRODUCTION

Present day millimeter and submillimeter-wave space-borne radiometers usually employ whisker contacted Schottky diodes as the basic nonlinear element. For a number of years now, a concerted effort has been made at various laboratories to develop and demonstrate that the whisker contacted diodes can be replaced with planar diodes without sacrifice in performance. Recent results have indicated that the appropriate planar structure can perform as well as whisker contacted diodes at least up to 350 GHz [1-3]. The use of planar technology also allows researchers to deploy circuits that were very difficult or impossible to fabricate with whiskered diodes. This is especially true for multiple diode circuits such as series or balanced varactors, balanced and subharmonically pumped mixers etc. where not only is the circuit geometry a limitation with whiskered devices, but good circuit performance depends critically upon having diodes with identical electrical and physical characteristics. In 1993 it was demonstrated

[3] that planar discrete diodes can work quite well as SHPM's, outperforming their whisker contacted counterparts. By using a planar diode chip instead of a whiskered anode, the difficulty of contacting and mounting very small devices was alleviated but not completely removed. One still had to mount the discrete devices by hand, and it was clear that as the frequency of operation increased, the device package size would rapidly become a limiting factor. The present paper will discuss the technology that we have developed and demonstrated for monolithically integrating the diode chip with quartz based filter circuitry in order to overcome the discrete device mounting problem. Moreover, a new style planar diode, with very low parasitic resistance and capacitance, has been developed and deployed in place of the traditional circular-anode diode. The most recent results obtained at 200 GHz with these new devices and circuits are presented.

DEVICE FABRICATION TECHNOLOGY

We have developed two major modifications to current submicron device fabrication technology that enable us to produce very high frequency planar-Schottky-diode waveguide mixers. First, we have monolithically mated the GaAs diodes with the lower-dielectric-constant lower-loss quartz-based microwave/millimeter-wave circuitry used to couple power in and out of the mixer block. This has been accomplished using a process we refer to as the QUID (Quartz substrate Up-side-down Integrated Device) process. In this process, the fully integrated GaAs device and surrounding circuitry are mounted up-side-down on a quartz carrier with a thermally cured epoxy. The GaAs substrate is then completely etched away everywhere except for a small region around the active devices. A final backside dry mesa etch ensures that all of the unnecessary GaAs is removed. After the backside process, individual circuits are diced and glued into their supplied microstrip housing in the waveguide block. Two wire bonds to the circuit metallization provide a DC return on one side of the diodes and an IF output line to a standard K-connector bead on the other. The 200 GHz circuits are fabricated on 2 cm diameter, 150 μm thick crystal quartz. By integrating the 200 GHz devices with the mixer circuitry i.e. the LO pass and the IF pass filters, the mounting package grows to 300 μm by 9000 μm and is extremely easy to handle. Also, the QUID process allows for the total removal of all of the unnecessary GaAs, thus leaving a low-profile, less-lossy structure in the waveguide channel. Details of this process have been described in [4,5].

The thermally cured epoxy presently being used (EPO-TEK 301-2) has a dielectric constant of 3.1 at 1 MHz and seems to be more robust than the UV cured epoxy used in earlier implementations of the QUID process. SEM's of the diode chip, diced through the anode fingers, indicates that the glue thickness averages about 12 microns. With the use of pressure during the epoxy cure cycle we have been able to reliably reduce the glue thickness to under 8 microns. For 200 GHz applications this thickness does not seem to introduce any excess loss, however at 600 GHz, we are pretty sure the epoxy adds significantly to the LO coupling loss in our mixer blocks. Currently, we are exploring a new glue-less process which we believe will eliminate this potential problem and further enhance the usefulness of the QUID process.

The second modification we have introduced to the traditional planar Schottky diode fabrication process is the use of "T-gate" like structures in place of the usual SiO_2 rimmed circular anodes. Traditionally, circular anodes patterned in a dielectric layer have been used to form the Schottky contacts. As the frequency of operation is increased, the device area must be scaled accordingly and the inevitable parasitics reduced to as low a level as possible. However, as the anode area is scaled down to micron dimensions it becomes increasingly harder to obtain uniform Schottky contacts since it involves the etching of the passivating dielectric. Moreover, for submicron dimensions, optical lithiography becomes extremely difficult and non-reproducible. We have now incorporated an anode process that uses a structure similar to the "T-gates" of high frequency transistors. These anode structures were initially developed for Schottky collector resonant tunneling devices as reported in [6].

The "T-anode" Schottky diode utilizes an e-beam direct write procedure and can be scaled to frequencies as high as 2.5 THz [7]. Currently, we are not using any passivating dielectric with the T-anode devices, however, we are exploring this additional step now in case it is required to improve reliability. The passivation step can easily be incorporated in our present process by a PECVD deposition of nitride or oxide after the anodes have been formed. Besides the anode formation process, other fabrication steps follow closely the surface channel etch technology introduced in 1989 [8].

Figure 1 shows the T-anode devices in detail. Fig. 1(a) shows the top front view. Fig. 1 (b) and (c) show the side view with the air-bridge and surface channel respectively. The finger starts out being 4 μm wide, then reduces to 2 μm right before the edge of the channel etch, and finally further reduces to a width of 0.4 μm before contacting the 0.2 μm wide T-anode footprint. For 200 GHz the nominal anode area has been selected to be 1 μm^2 resulting in a footprint of 0.2 μm by 5 μm. The T-anode process uses a trilevel PMMA procedure that enables one to fabricate mini air-bridges along with the actual anode structure. This capability is utilized to further reduce the parasitic capacitance. After the anodes have been written and developed, a final SEM inspection is done to verify that the anode footprint area has been opened. Once this is confirmed, Ti/Pt/Au are evaporated to form the Schottky contact.

The use of a thin long anode strip with surrounding parallel ohmic stripes on each side, rather than a circular anode, reduces the series resistance associated with the diode. Applying the simple model of the diode series resistance as indicated in [6], consistent with our device structure, shows that a factor 2 reduction in series resistance can be obtained by using a 0.2 μm by 5 μm anode as compared to a 1 μm by 1 μm anode.

MEASURED RESULTS AND DISCUSSION

Tests of the "T-anode" diodes and QUID circuitry were performed in our 200 GHz subharmonically-pumped mixer block described elsewhere [3]. The best results obtained to date are shown in Fig. 2 along with the diode DC characterization. The total capacitance of the diodes, including the hammerhead filters, is measured to be about 17 fF. Each anode is calculated to have a depletion layer capacitance of about 3 fF and from independent measurements, we know that the pad-to-pad capacitance is about 5-6 fF and that the filter structure adds another 3 fF of parasitic capacitance. Thus, the pad-to-finger capacitance is about 2 fF. We believe this capacitance can be reduced further with the removal of the epoxy layer which currently surrounds the anode fingers.

The best noise temperature is obtained at 200 GHz, namely about 600 K double-side-band with a corresponding conversion loss of 4.7 dB. The LO power vs. frequency plot shows that the filters/block have a resonance at around 95 GHz, hence the large LO power requirement for proper device pumping near this frequency. This problem has been corrected with a simple modification of our existing filter structure and results from the new design will be shown later. The mixer performance as a function of intermediate frequency is shown in Fig. 3. In the top curve the block tuning was optimized for best noise performance at 1.5 GHz IF, while in the bottom plot the tuning was optimized at an IF of 8 GHz. These results indicate that with optimization at 8 GHz a noise temperature of 1500 DSB can be obtained over the 1-10 GHz IF bandwidth. Greater IF bandwidth is possible by reducing the distance of the IF/DC return bond wire from the RF signal waveguide, where the diodes reside.

When the spectral coverage of our flight program changed from line measurements at 215 GHz to a revised complement of molecular species centered at 240 GHz a new block was fabricated and initial performance results from this block are given in Fig. 4 along with DC characterization of the diode. The lowest noise temperature we have measured with this new block is about 900 K DSB at 112.5 GHz with a corresponding conversion loss of about 6.2 dB. The LO power vs. frequency plot however shows that we have been able to correct for the filter resonance of the old block and indeed excellent LO coupling is obtained from about 105 to 130 GHz. At the optimum point, only about 1.5 mW of LO is required to pump both diodes with no external bias applied.

In order to put these results in the proper perspective it is important to see how they compare with theoretical predictions and performance of previously published mixer data at similar frequencies. The results of a computer simulation using the device characteristics presented in Fig. 2 appears as Fig. 5. The model for this simulation has been discussed in detail in [9]. In the simulation it is assumed that both diodes are identical and that the first and second harmonics are terminated with 50 Ω loads while all other harmonics are shorted. The mixer performance is plotted as a function of finger inductance with the solid line indicating results when there is no parasitic capacitance and the long dashed line indicating results for a device with 6 fF of pad-to-pad capacitance and 2 fF of finger-to-pad capacitance (corresponding to our measured parasitic capacitances). The short dashed line indicates the best measured performance from our mixer and since we still do not know what the finger inductance of our device is, we cannot precisely locate the measured points on the abscissa. The plots show that our measured results lie within a factor of 2 of the theoretically derived performance under ideal embedding conditions. This is encouraging, however there still remains room for improvement.

Finally, Fig. 6 shows the performance of various published mixer results at similar frequencies. The figure shows that our results are only a factor 1.5 worse than the best results reported for fundamental whisker contacted diodes at the same frequency.

CONCLUSIONS

SHPM's with T-anode Schottky diodes monolithically integrated with the appropriate circuitry on quartz have been developed and tested at 200 GHz. A waveguide mount incorporating these technologies has yielded a robust, extremely sensitive, subharmonically pumped mixer which is expected to fly on NASA's Earth Observing System Microwave Limb Sounder. The measured performance is currently 1.5 times worse than the best reported whisker contacted Schottky diode mixer and there is still room for some improvement with the removal of the glue layer in the QUID process. The devices are easily scaled and we continue to work on improving the mixer performance as we move this technology towards higher frequencies.

ACKNOWLEDGMENTS

We wish to acknowledge P. Maker and R. Muller for the e-beam work, M. Mazed and R. Wilson for technical discussions and all those members of the JPL Submillimeter Wave Advanced Technology team who contributed to this effort. This work was performed under the Center for Space Microelectronics Technology at the Jet Propulsion Laboratory under contract with NASA OACT.

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(a)

(b)

(c)

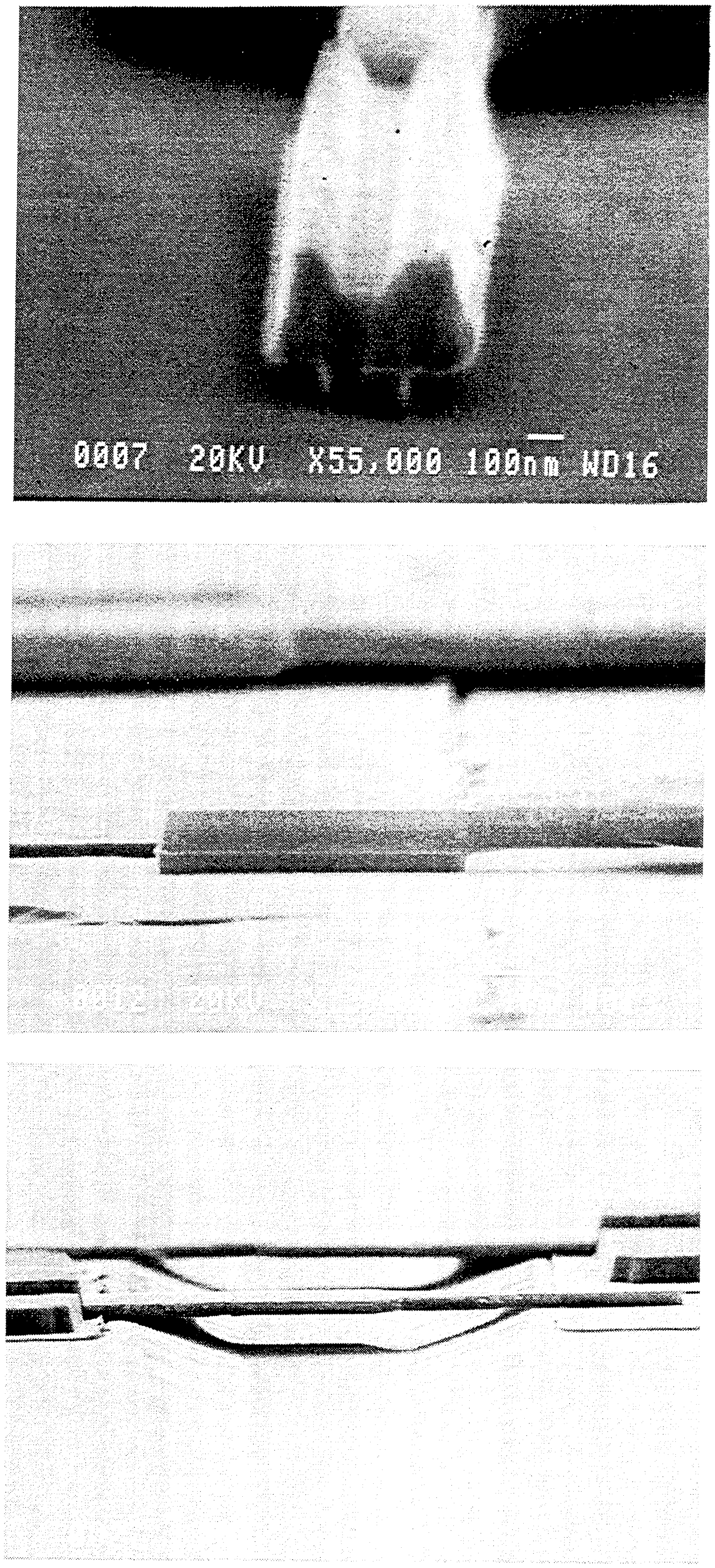


Figure 1: Various views of the T-anode diodes.

MIXER TEST

Block 200B4 Diode T041795-L1

	eta	Is (A)	Rs (ohm)	Co (fF)	Ctot
Anode 1	1.2	1.90E-15	8.7	3	17 fF
Anode 2	1.16	6.80E-16	9.7	3	

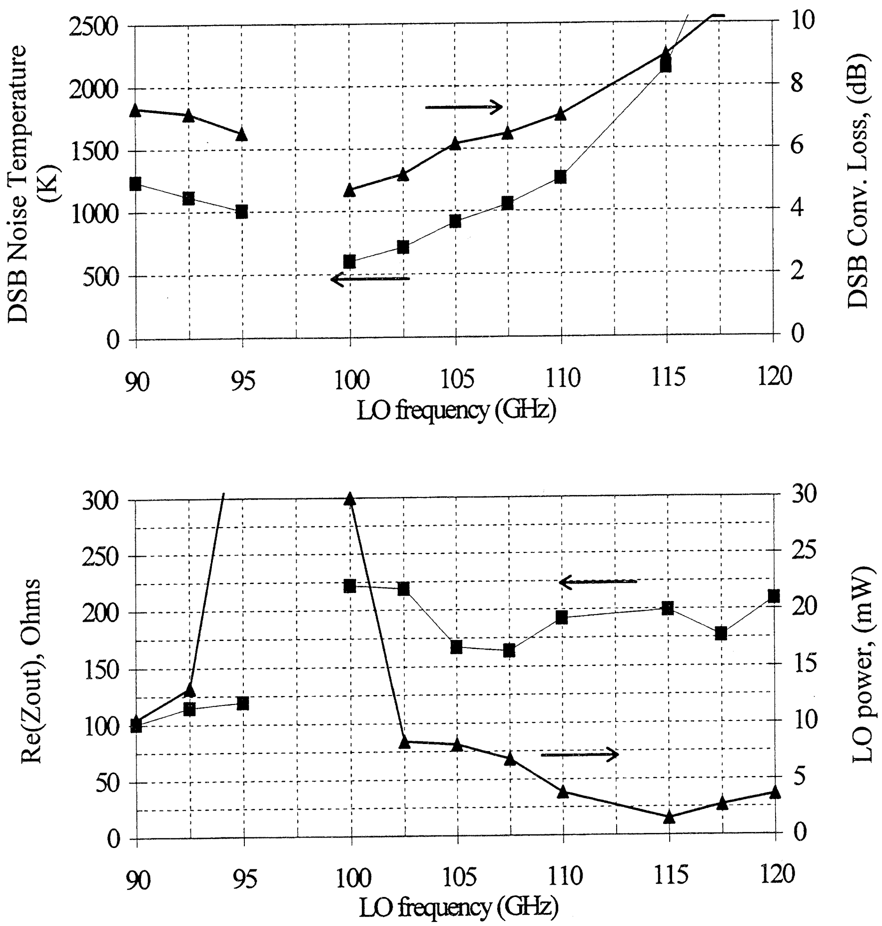


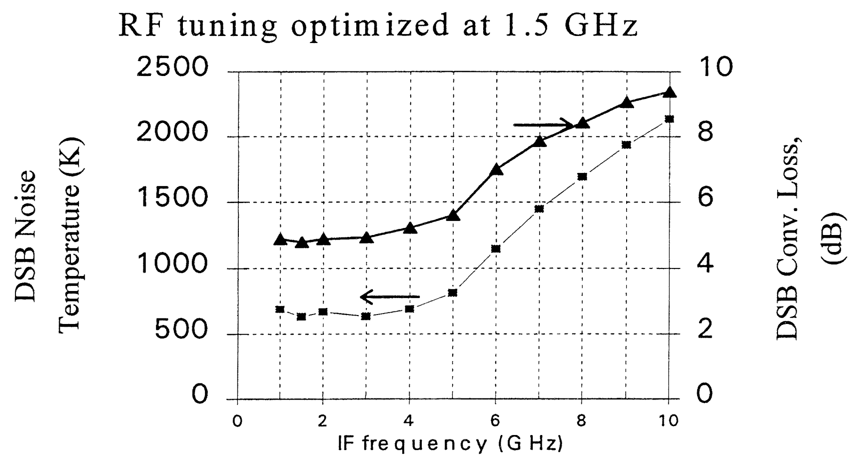
Figure 2: Schottky diode subharmonically pumped mixer performance in the 215 GHz block.

MIXER TEST (IF SWEEP)

Block 200B4 Diode T041795-L1

	η	Is (A)	Rs (Ω)	Co (fF)	Ctot
Anode 1	1.2	1.90E-15	8.7	3	17 fF
Anode 2	1.16	6.80E-16	9.7	3	

LO : 100 GHz, constant power



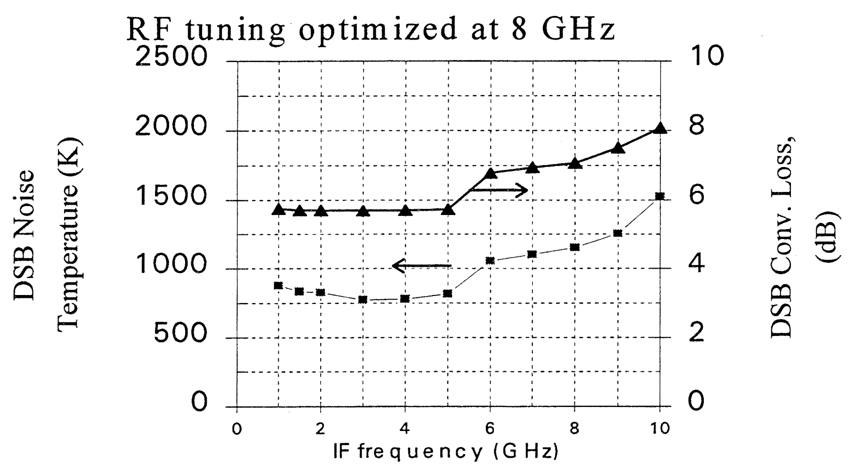


Figure 3: IF sweep of the mixer in the 215 GHz block.

MIXER TEST

Block 240A1 Diode T041795-D4

	η	Is (A)	Rs (ohms)	Co (fF)	C_{tot}
Anode 1	1.19	6.70E-16	13	3	17 fF
Anode 2	1.16	8.10E-16	10	3	

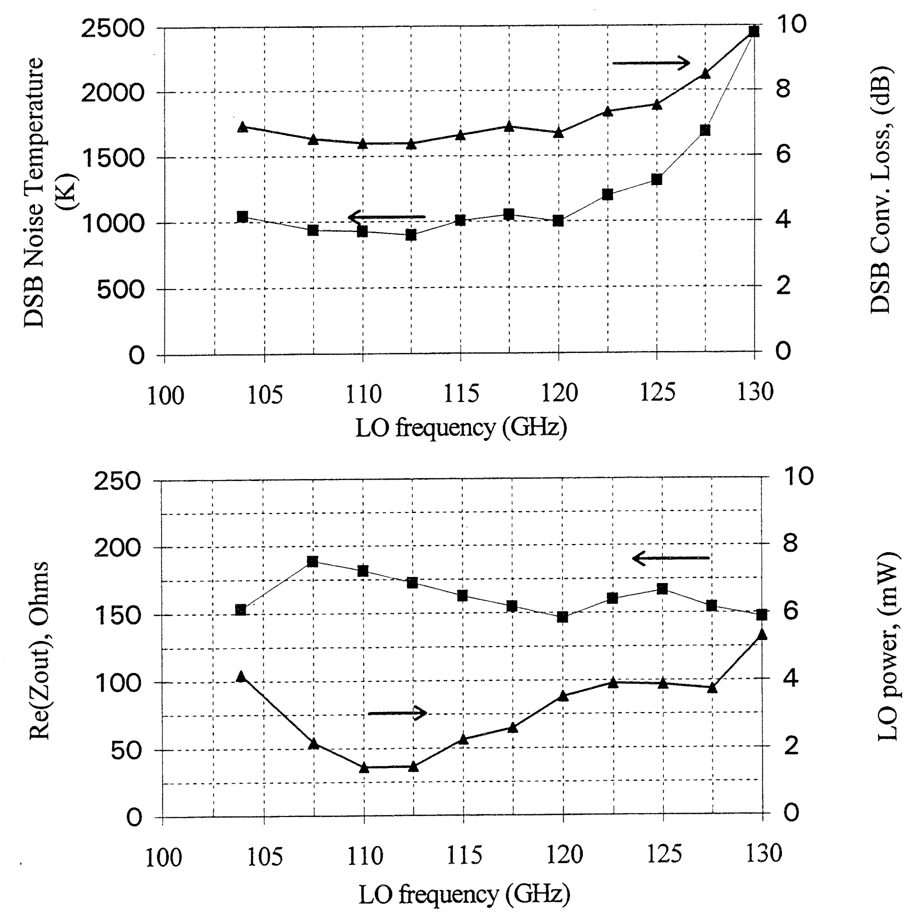


Figure 4: Performance of subharmonically pumped Schottky diode mixers in the 240 GHz block.

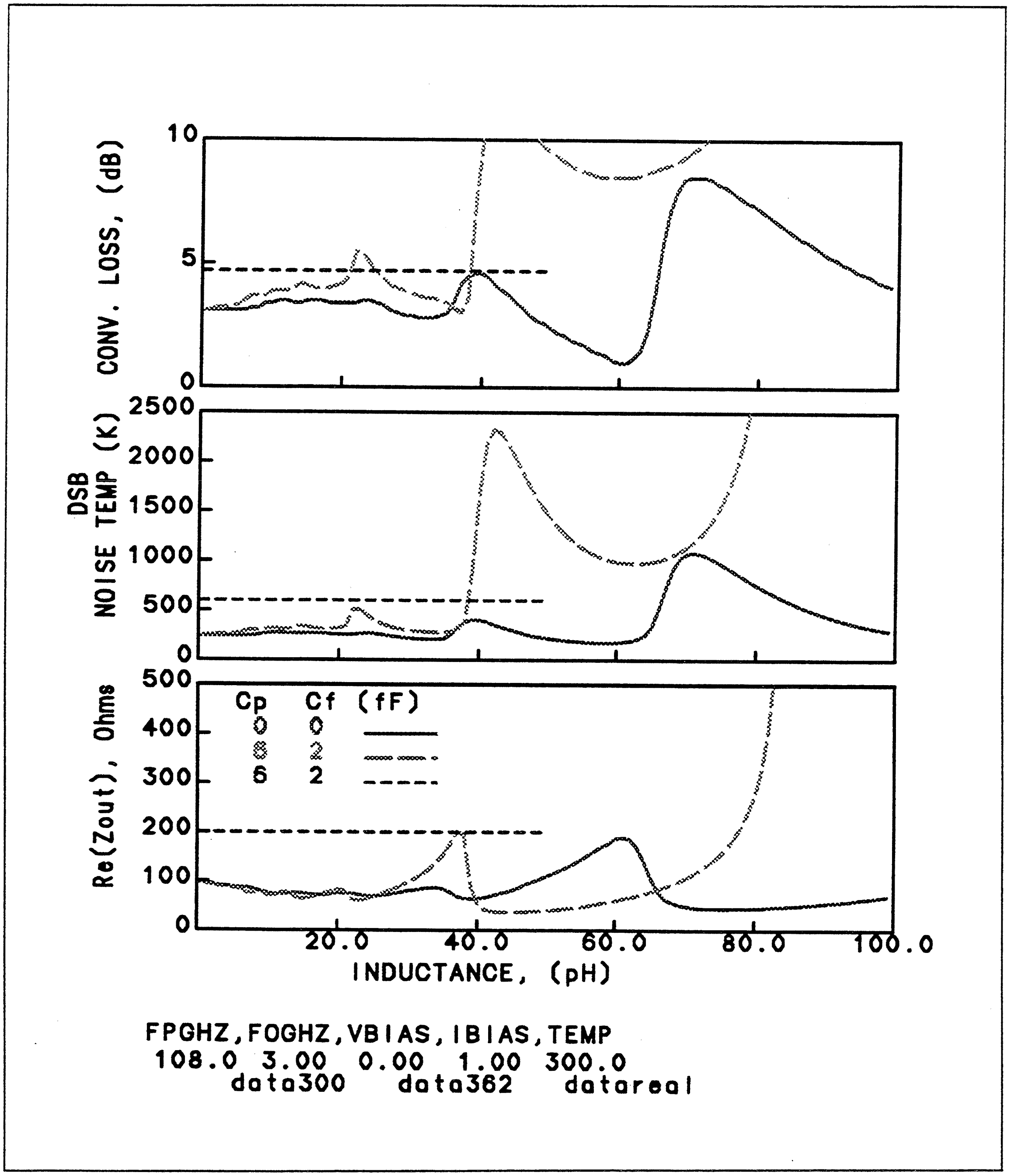


Figure 5: Computer simulation of the mixer performance at 200 GHz as a function of finger inductance. The solid line assumes no parasitic capacitance while the long dashed line assumes parasitic capacitance present in our devices. The short dashed line shows the measured performance. Since it is not certain what the finger inducatance is in our devices, the best result has been plotted as a constant.

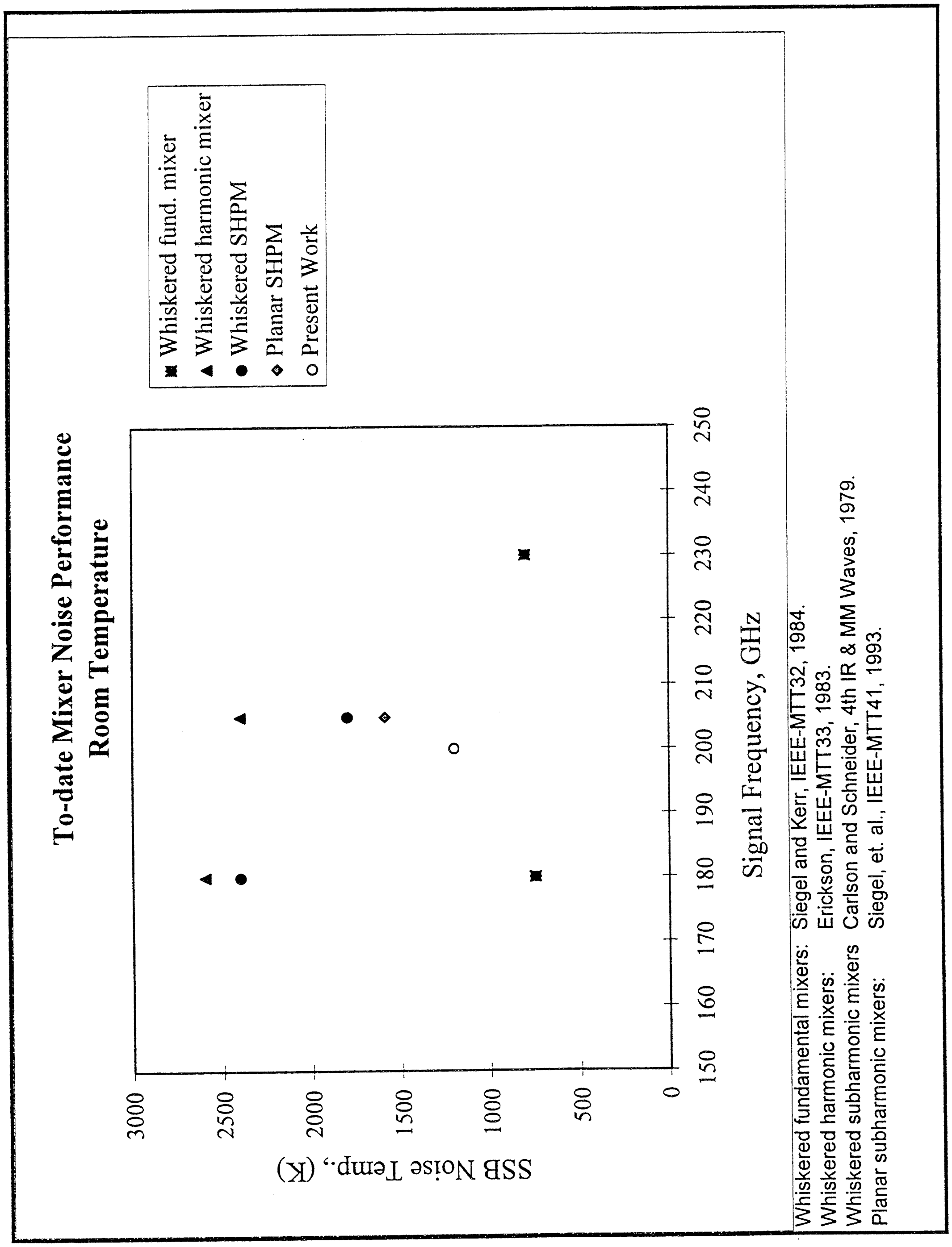


Figure 6: Comparison of various mixers operating around 200 GHz.