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A 75-110 GHz On Wafer Vector Network Analyzer for Electronic Device Metrology

Final report by:

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Contract No: DAAH04-95-1-0028
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Brief Description of Measurement System and Its Use in W-Band Measurements

This instrumentation grand was used to purchase equipment for the development of a W-band Measurement System. This system was put in place by upgrading existing equipment and purchasing W-band components needed for its operation.. Specifically, most of the funding was used to upgrade an existing 8510 HP network analyzer to a C version. The rest of the funding was used to purchase waveguide components and probes needed for the probe station. The total cost of the equipment including University matching funds reached 160K.

Since the system became fully operational, it has been extensively used for a variety of applications including micromachined W-band filters, W-band mixers and 47 GHz to 94 GHz doublers. The system is located at the facilities of the Radiation Lab and is available to all the faculty of the Electrical Engineering and Computer Science Department who have a need to perform W-band measurements. As an indication of the measurements which have been performed so far on the W-band system, we describe herein some representative results for three of the projects.

- **W-Band Filters [1], [2]**

Millimeter wave integrated circuits require low-loss, low-dispersion, planar transmission line structures. The advantages of using planar components in microwave circuits stem largely from reduced fabrication cost and increased operating bandwidth. Unfortunately, microstrip and coplanar waveguide (CPW) suffer from several problems at millimeter wave frequencies. These include dielectric loss, which increases with frequency, as well as dispersion, substrate moding, and radiation loss, all of which can be directly associated with the air/dielectric discontinuity inherent to substrate supported transmission lines.

To eliminate these parasitic loss mechanisms and improve performance, Si-membrane technology has been utilized by the investigators to develop very low-loss W-band filters. The application of micromachining technology to W-band circuits using the microshield line (see Figure 1) and a new type of micromachined structure - the shielded membrane microstrip (SMM) line (see Figure 2) has led to excellent filter characteristics. A 90 GHz microshield line low-pass filter and several SMM coupled-line band-pass filters centered at 95 GHz have been designed and measured. Theoretical validation of the measurements has been provided by the FDTD analysis technique. This method shows great flexibility and accuracy for W-band circuit analysis, and is used to simulate structures which are supported by both GaAs and membrane. Results of these simulations have allowed for a direct comparison between membrane supported circuits and conventional planar circuits.

Fig. 1: Microshield Line

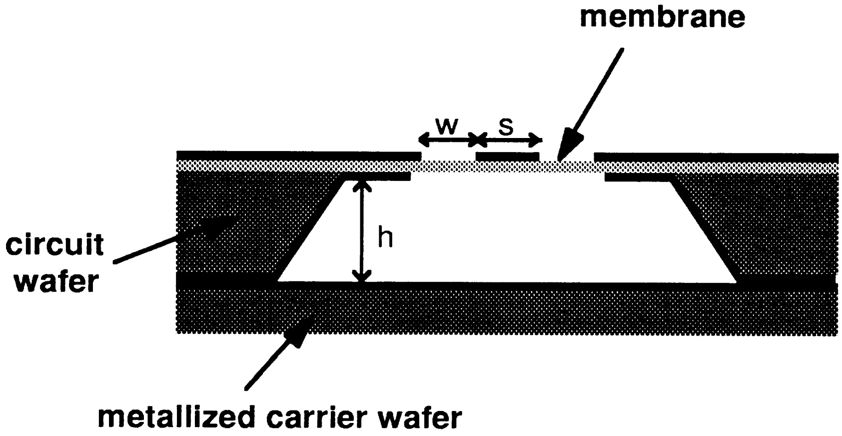
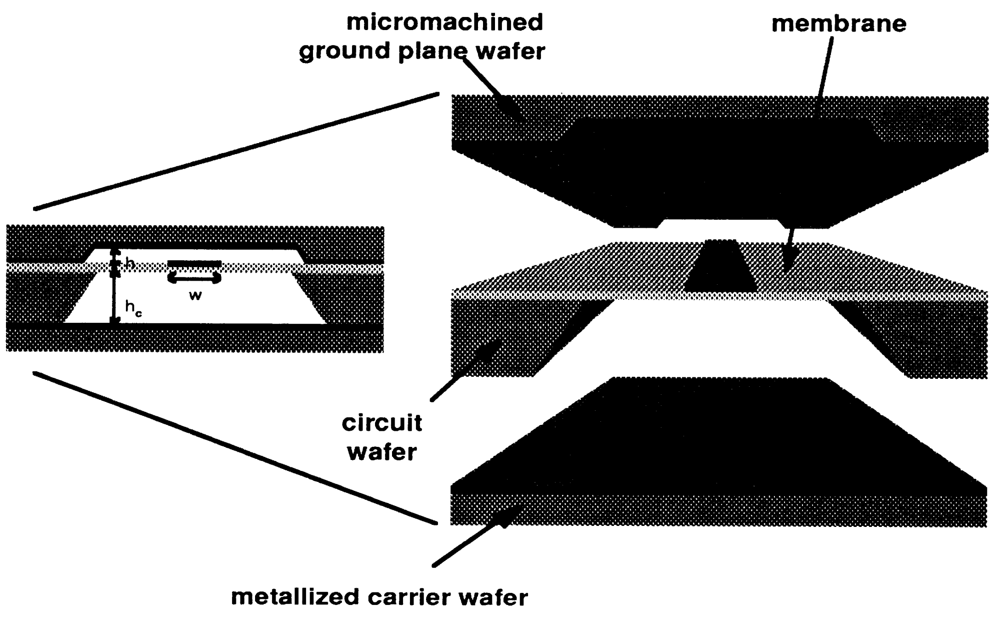


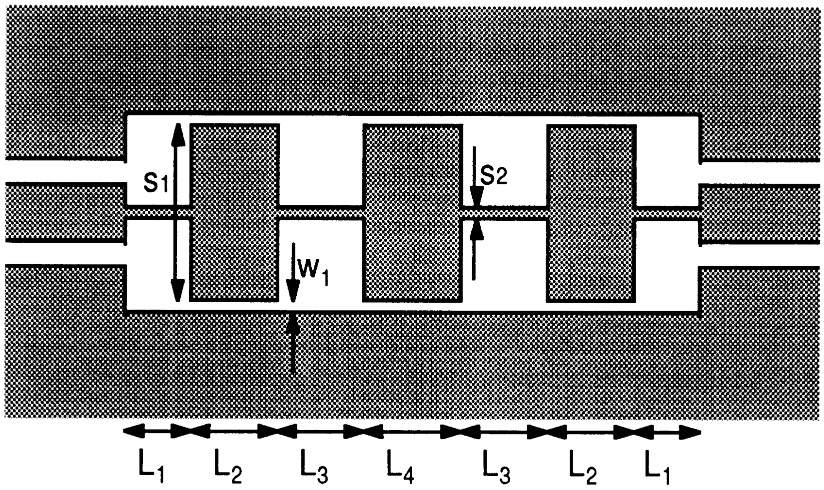
Fig. 2: Membrane Microstrip



A. Low-Pass Filters

A low-pass filter has been designed using a stepped impedance implementation of a 7-section 0.5 dB equal ripple Chebyshev filter prototype is shown in Figure 3. The high and low impedance sections of the filter correspond to 277 Ω and 63 Ω, respectively, while the feed line and filter center impedance are designed to be 92 Ω. The filter section lengths were initially approximated by means of equivalent circuit models for short transmission line sections. Then, quasi-static simulation on *Puff* was used to adjust the stage lengths more accurately. The final step in the design sequence involved full-wave analysis of the filter using the FDTD method. The first FDTD simulation revealed that the filter cutoff frequency was lower than the desired 90 GHz value, so the filter section lengths were scaled appropriately to achieve the correct cutoff frequency.

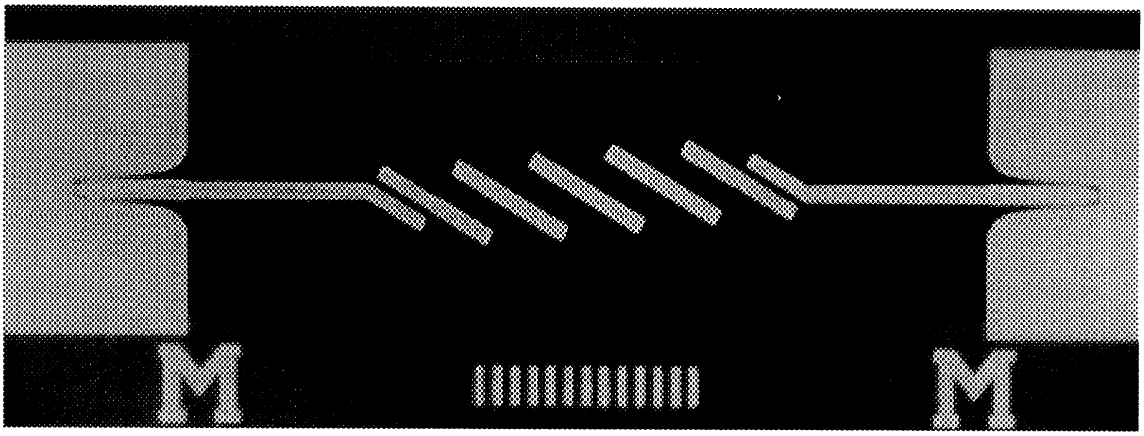
Fig. 3: Low-Pass Filter



B. Band-Pass Filters

The band-pass filters of this work are based on coupled-line resonator designs derived from equal ripple Chebyshev prototypes. Both three- and five-element filters of various bandwidths were designed based on a center impedance of 90 Ω (see Figure 4). A commercially available software package, PARFIL, was used to synthesize the filter geometry, using a ground plane separation and an upper shield separation of 100 μm and 500 μm, respectively. The PARFIL designs were verified by constructing a 2 GHz 47:1 scale model of a 4.3% bandwidth 5-element filter. The dielectric membrane was simulated by a 76 μm thick polyethylene sheet and the filter metallization patterns defined using copper tape. Measurements of the 2 GHz filter revealed that the filter center frequency was not accurately predicted by PARFIL, but the measured bandwidth agreed well with the PARFIL data. The PARFIL design values for line widths and gap spacings were therefore used in the W-band implementation, but the resonator lengths were determined through experimental iteration on the low-frequency model. The desired filter center frequency was achieved when the resonator lengths were scaled to 94.7% of the original design lengths (710 μm instead of 750 μm), and this was confirmed with FDTD simulations at 94 GHz. The effect of the upper shielding cavity was also investigated using the microwave model, and the measured response of the filter changed significantly when the upper shielding surface was removed. Results showed that packaging is very important to these filters.

Fig. 4: Band Pass Filter



C. Measurements and Discussion

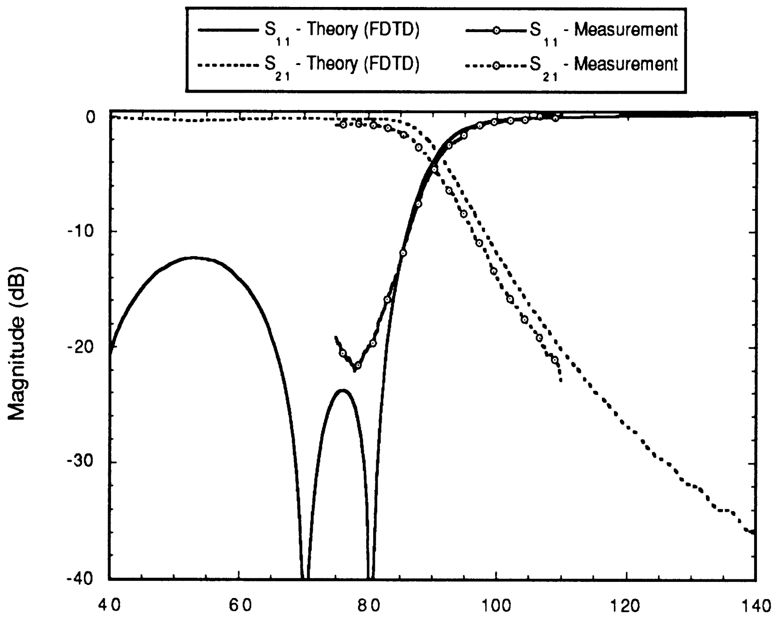
W-band measurements were performed on an HP 8510C Vector Network Analyzer with an HP 85105A Millimeter Wave Controller. On-wafer probing was achieved on a probe station using Model 120 Picoprobes with 150 μm pitch. The DEEMBED calibration program from NIST provided an automated calibration routine based on the Thru-Reflect-Line (TRL) technique . The calibration standards comprised a series of uniform transmission lines (Thru and Line types) and either an open- or short-circuited transmission line to provide the "Reflect." They were fabricated in conjunction with the filter circuits to minimize differences between the standards and the circuits of interest due to processing variations.

Since membranes are not strong enough to withstand the pressure of repeated on-wafer probing, wafer probes must be placed on the silicon support rim of the membrane structure. For W-band measurements, it was found that the best results were achieved when the wafer probes were set as close as possible to the membrane edge. Furthermore, an impedance transformer was used to reduce the matching problems between the high-impedance membrane circuits and the 50 Ω test system impedance. For 92 Ω microshield line, this took the form of a simple quarter-wavelength section of 68 Ω microshield line. For the SMM filters, a developed GCPW-to-SMM transition was employed.

<u>C.1 Low-Pass Filters</u>

The measured response of the low-pass filter from 75-110 GHz is plotted in Figure 5 along with results of the FDTD analysis from 40-140 GHz. The filter achieves a cutoff frequency of approximately 90 GHz, with less than 1 dB passband insertion loss, and the FDTD technique accurately predicts the filter performance. The presence of the membrane does not have a negligible effect on the performance of the circuit, and it is therefore incorporated into the FDTD analysis. It is not exactly modeled as a 1.5 μm thick dielectric sheet, however, since the mesh subsection size in the vertical direction is 44 μm. Instead, a sheet of dielectric with a thickness of 44 μm is placed underneath the conducting lines of the structure. The relative dielectric constant of this "thick membrane" is set to 1.16, so that the effective dielectric constant predicted by the FDTD analysis corresponds to the measured value of 1.08. This method of compensation only provides an approximate model of the membrane effects, however, because the measured $\varepsilon_{r,\,\mathrm{eff}}$ strongly depends on line geometry. Different line geometries will require individually designed "thick membranes" for accurate FDTD simulations.

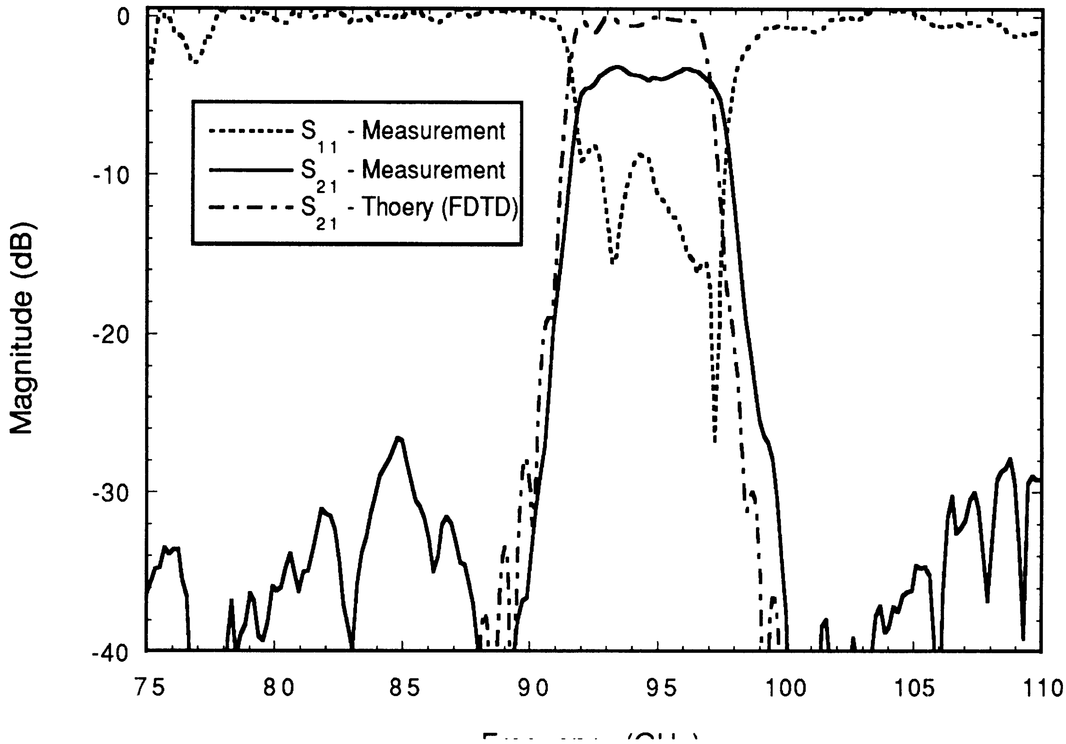
Fig. 5: Theoretical and Experimental Results for the Filter of Figure 3



C.2 Band-Pass Filters

Figure 4 shows a fabricated coupled-line band-pass filter. Three such filters were tested, and the measured results for all of them show low passband insertion loss, sharp roll-off, and high out-of-band attenuation. A filter designed for 4.25% bandwidth achieves a passband insertion loss of 3.6 dB and a bandwidth of 6.1% at a center frequency of 94.7 GHz (see Figure 6). Very good responses were also observed in a 5-element filter which demonstrated insertion loss of 2.2 dB and a 12.5% bandwidth centered at 95 GHz. Measurements of a 3-element have shown a measured insertion loss of 1.4 dB, a center frequency of 94.9 GHz, and a bandwidth of 17.7%.

Fig. 6: Theoretical and Experimental results for the Filter of Figure 4

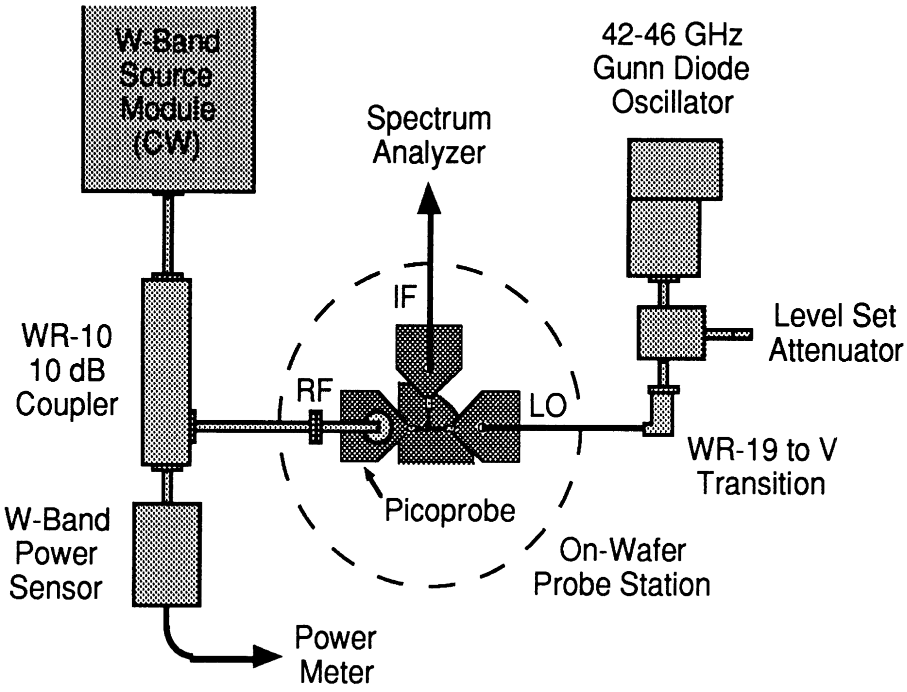


We have also utilized the millimeter-wave network analyzer and probe station for millimeter-wave mixer measurements. With this set-up mixer circuits can be tested using on-wafer probing, which eliminates the need for packaging the mixer in a waveguide mount. The mixer ports are simply fabricated in coplanar waveguide designed to accommodate the appropriate frequency range Picoprobe. Waveguide-to-microstrip or -CPW transitions are not necessary, and true port-to-port mixer characterization can be performed with appropriate on-wafer calibration.

- **W-band x2 Subharmonic Mixer [3],[4]**

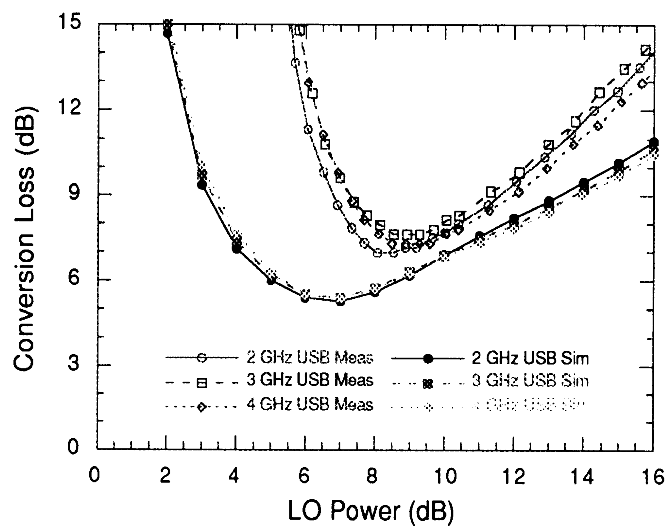
Figure 7 shows a set-up for measuring the conversion loss of a W-band x2 subharmonic mixer. The RF source is an 85104A W-band source module controlled by the 85106C millimeter-wave network analyzer operating in CW mode. The RF power is delivered to the mixer from the coupled port of a WR-10 coupler via a 75-120 GHz Picoprobe. The RF power level is sampled at the direct port of the coupler and measured with a W-band power sensor. The LO source is a U-band Gunn oscillator, and the LO power is delivered to the wafer via 1.85 mm coaxial cable and a DC-67 GHz Picoprobe. A WR-19 level set attenuator is used to control the LO power level. The IF power is extracted by a third probe and measured using a spectrum analyzer.

Fig. 7: W-band subharmonic mixer conversion loss measurement set-up.



The measured port-to-port single-sideband conversion loss of a x2 subharmonic mixer circuit designed to operate at RF frequencies of 92-96 GHz, IF frequencies of 2-4 GHz, and LO frequencies of 45-46 GHz is shown in Figure 8. The minimum SSB conversion loss is 7.0 dB at a 94 GHz RF and an LO power of 8.5 dBm, and represents state-of-the-art performance for a planar W-band subharmonic mixer. The measured results are within 2 dB of harmonic balance simulations; the difference is due to passive circuit losses not accounted for in the simulation.

Fig. 8: Measured mixer SSB conversion loss vs. LO power at RF = 94 GHz for 2, 3, and 4 GHz IF



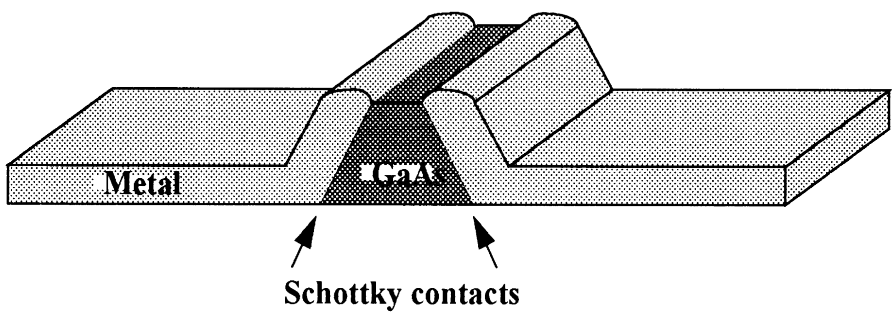
frequencies. Minimum conversion loss is 7.0 dB at 8.5 dBm LO power.

- **47 GHz to 94 GHz Multiplier [5],[6]**

The objective of this effort was to build high power, high frequency, and broad bandwidth planar frequency multiplier circuits that can be readily integrated with other circuits such as mixer diodes in a transceiver application. As part of the study we built multiplier varactor diodes which we then monolithically incorporated in the multiplier design. The transmission line geometry used for this application was a finite ground coplanar waveguide due to its excellent characteristics demonstrated in W band.

The diodes were back-to-back Schottky Diode Varactor (bbSDV) with a structure shown in Figure 9

Fig. 9: Back-to Back Schottky Varactor Diodes.

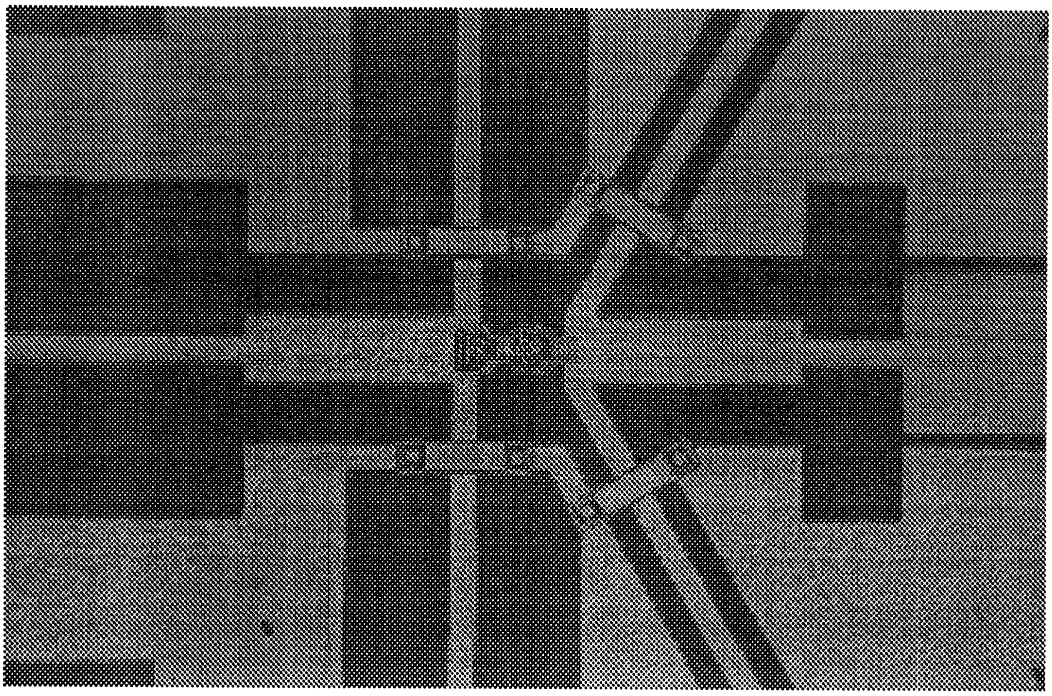


The advantages of these diodes are summarized below:

- Symmetric CV Characteristic, Ideal for a tripler
- Extremely Low Leakage
- Simple to Fabricate, 2 Mask Levels
- Very Good Control of Area
- Low Series Resistance,
- Eliminate Spreading Resistance and
- Shared Depletion region

The diodes and the lines described above were used to design a GaAs doubler from 47 GHz to 94 GHz. A photograph of one of the multiplier circuits is shown in Figure 10. These doublers have been measured recently and give an efficiency of 18% and output power of about 95 mW. This work is still undergoing and will evolve into the design of a 94 GHz receiver.

Fig. 10: 47 GHz to 94 GHz Doubler



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