On-Wafer Testing of Circuits Through 220 GHz

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Abstract: We have jointly developed the capability to perform on-wafer s-parameter and noise figure measurements through 220 GHz. S-parameter test sets have been developed covering full waveguide bands of 90-140 GHz (WR-08) and 140-220 GHz (WR-05). The test sets have been integrated with coplanar probes to allow accurate measurements on-wafer. We present the design and performance of the test sets and wafer probes. We also present calibration data as well as measurements of active circuits at frequencies as high as 215 GHz.

Introduction

Applications for frequencies higher than 100 GHz have been limited to radio-astronomy and earth remote sensing. Improvements in semiconductor technologies have pushed active circuits to frequencies higher than 100 GHz. Potential applications for these high frequencies include communications, radar, passive imaging and high speed digital networks. In order to realize the potential commercial applications for these circuits, test equipment must be developed which can characterize these circuits in a rapid cost-effective manner. Network analyzers are currently available spanning the continuous frequency range 0.1-110 GHz. We present the results of three separate development efforts which, when combined, allow for on-wafer characterization at frequencies up to 220 GHz.

Network Analyzer Frequency Extension

Network analyzers are commercially available with frequency coverage up to 110 GHz. Coverage at frequencies higher than 50 GHz has typically been accomplished with frequency extenders employing multipliers and harmonic mixers (Figure 1). This basic

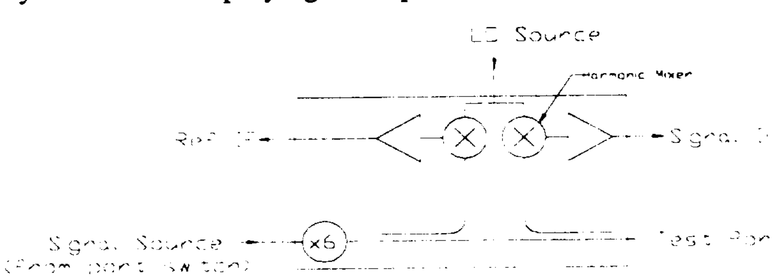

Figure 1. Network analyzer frequency extender. A full T/R module is shown. A simple T module has only a Signal harmonic mixer.

concept is readily extendable to frequencies as high as 220 GHz, and possibly as high as 325 GHz. Millimeter-wave test sets can be readily adapted for use with network analysis equipment from Hewlett-Packard (HP) and Anritsu, taking advantage of the familiar interfaces used industry-wide.

Such millimeter-wave test sets, or frequency extension modules, must be useable with readily available vector network analysis equipment. The following design criteria were established. 1) The configuration of the frequency extension modules must follow accepted industry practice and be able to yield S11 and S21 information in a minimal test system and all four "S" parameters in a complete system. 2) The IF frequency to be utilized must be compatible with the most common open-architecture analyzers from HP and Anritsu. 3) The signal radio frequency (RF) and local oscillator (LO) drive requirements must chosen with cost acknowledged as a major design restraint.

To accomplish meaningful S-parameter measurements a combination of two "T/R" modules or one "T/R" module and a "T" module are required. The "T/R" module is capable of generating a coherent test signal and developing two down converted measurement signals. The down converted signals include a reference signal (A1) which is a simile of the stimulus signal, and a response signal (B1) which contains information describing the device under test (DUT). This module can be used to measure Transmission (T) S21 characteristics or Reflection (R) S11 characteristics of the DUT. A "T" module consists of a single down converter for receiving the "T/R" module test signal as modified by the DUT (B2) to measure the Transmission (T) S21 characteristics of the DUT. The use of two "T/R" modules allows the simultaneous measurement of S11 and S21 in the forward direction and S12 and S22 in the reverse direction.

The down converter IF frequency range is 10 MHz to 300 MHz. The exact frequency is determined by the analyzer. The LO drive frequency range is normally limited to 20 GHz to limit that synthesizer's cost. The RF drive frequency range used is as high as possible and is limited only by the available frequency range of other components in the "T/R" module. The test signal is produced by a two-stage multiplier chain, with each stage driven into saturation to produce the flattest and most stable signal. The test signal is applied to a directional coupler through an isolator to provide a good source match for the measurement.

The RF drive is fed to only one "T/R" module at a time in the case of a two "T/R" module system. By virtue of the signal path chosen, forward or reverse, the test converters develop either S11 and S21 or S22 and S12. The test converter in the module containing the "active" signal source produces the reflection signal and the test converter in the inactive module produces the transmission signal. The LO drive is "split" and provided to all of the modules in any given test set configuration. In the "T/R" module, the LO signal is "split" again and fed to both down converters. The LO is then coherent at any converter with respect to any other converter. The total system becomes coherent through comparison of any of the test converter signal to the "active" reference converter signal enabling phase and amplitude information to be obtained. These downconverters are made up of balanced harmonic mixers and low noise I.F. amplifiers. The LO harmonic used for the conversion process is always the highest useable for the band of interest within the 20 GHz LO limitation.

The dynamic range of these modules varies with the desired waveguide band of operation. The dynamic range achieved for the 90 to 140 GHz band is typically better than 80 dB. The corrected source match is typically 35 to 40 dB and the corrected directivity is typically 45 to 50 dB enabling reflection measurements to better than 60 dB (Figure 2). A 150-220 GHz test set using "T/R" and "T" modules exhibits greater than

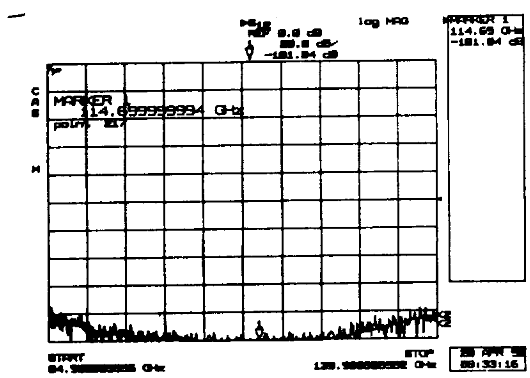

Figure 2a. Calibrated dynamic range of through measurement, 85-140 GHz.

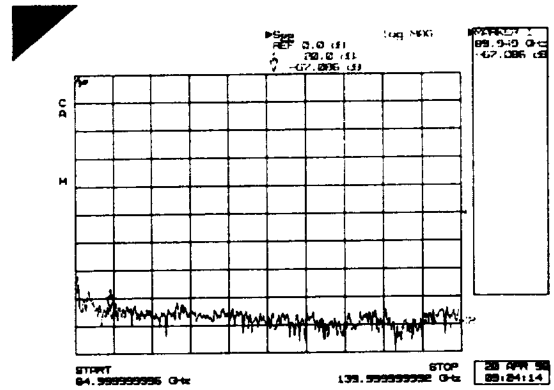

Figure 2b. Calibrated dynamic range for reflection measurements, 85-140 GHz.

50 dB (Figure 3) dynamic range for through measurements and a minimum of 25 dB for reflection measurements, although full calibration will yield even greater dynamic range.

The test signal power ranges from –10 to +3 dBm, which may exceed the input

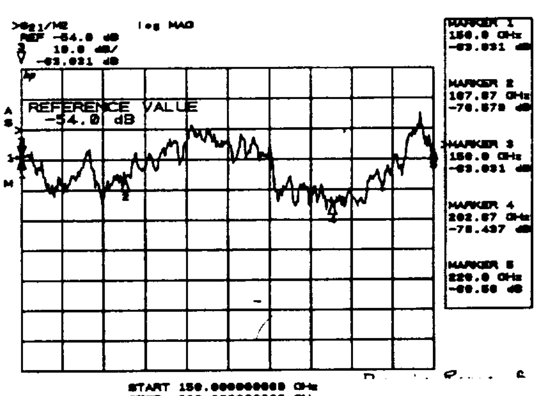

Figure 3a. Dynamic range of through measurement, uncalibrated, 150-220 GHz.

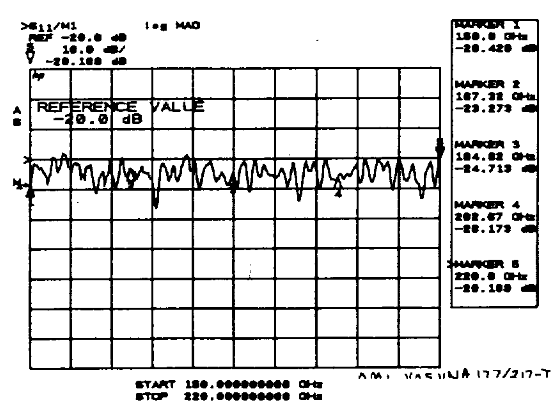

Figure 3b. Uncalibrated one-port response of waveguide termination, short reference, 150-220 GHz.

level handling capability the DUT being tested. When this problem is foreseen, provision can be made for attenuating the test signal power. The IF output level of the downconverters may exceed the calibrated input power capability of the analyzer. In that case the particular IF causing the overload can be attenuated to an acceptable level. The design of these modules allows operation for prolonged periods of time in a laboratory environment. Several systems of WR-08 have been delivered and multiple WR-05 systems will be in operation shortly. A WR-06 design has been completed and design efforts are underway for WR-04 and WR-03. The lack of commercially available waveguide components currently limits these efforts to WR-03, i.e., 325 GHz

Millimeter-wave Wafer Probes

Circuit measurements at frequencies above 100 GHz have required packaging of circuits into waveguide blocks. This technique is slow and cumbersome, and often does not yield true circuit performance. Commercialization of high frequency circuits requires high volume low-cost characterization of circuits.

A line of co-planar probes for on-wafer testing of sub-millimeter circuits has been developed by GGB Industries, Inc., and sold under the Picoprobe trademark. The 220 GHz probe shown in Figure 4, has a short coaxial probe body coupled to a WR-5 waveguide section for connection to test instruments. In common with all Picoprobe microwave probes, the probe tips are individually spring-loaded Beryllium-Copper for making reliable connection even to non-planar structures. The design is readily extendable to 300 GHz and above. A bias T is included to provide current (up to 1.5A) to the circuit under test and includes loss elements to absorb signals below the WR-5 cutoff frequency (115 GHz) where the waveguide becomes highly reflective. A special miniaturized co-planar calibration substrate (CS-15) has been developed for SOLT, LRL, and LRM calibrations which is based on 25 micron wide signal lines and 25 x 25 micron probe pads.

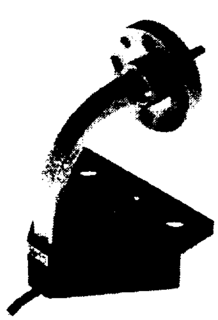

Figure 4. Photo of 220 GHz wafer probe

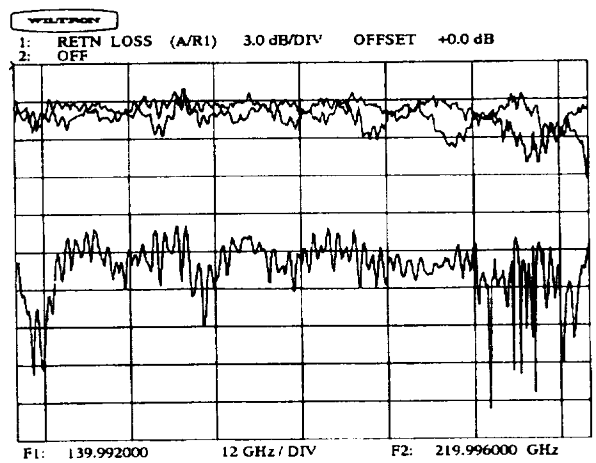

Figure 5. One-port performance of 220 GHz probe. The two top traces show open and short, while the bottom shows a load.

The one-port performance of the 220 GHz probe, Figure 5, shows the reflection from a short and an open (top two traces) and that from a 50 Ohm load (bottom trace). The approximately 4dB two-way loss for the short and open indicates a one-way loss of about 2dB. The raggedness results from the limited dynamic range of the custom built scalar network analyzer assembled at GGB Industries, Inc., for use in the development of this probe.

90-140 GHz S-Parameter Measurements

Waveguide calibrations on the 90-140 GHz test set are performed using a mechanical calibration kit. The kit comprises accurate waveguide shims, loads and shorts. A software calibration kit for the HP8510, based upon existing WR-10 waveguide kit, was customized for the WR-08 components. Full two-port calibrations are performed using HP's algorithm for SOLT (or Offset Short) or TRL. Both methods result in accurate calibrations with a measured dynamic range of 80 dB for through measurements and 60 dB for reflections (Figure 2). Calibrations are performed with IF averaging of 64 for reduced measurement noise, with no significant reduction in sweep time.

For measurements of amplifiers, care must be taken to avoid saturation of the amplifier with the input signal. Attenuation is required to reduce the signal level well below saturation of any amplifier stage. For the test sets described in section 2 this typically required 20 dB attenuation for most 4-stage amplifiers measured. This reduced the dynamic range for reflections by approximately 20 dB.

Wafer-probe calibrations simply use the GGB, CS-5 calibration kit. The preferred calibration method is SOLT due to the simplicity and absence of relative probe motions. At high frequencies, inaccuracy of probe placement at micron scales results in calibration errors. The probe-station employed in the 90-140 GHz measurements has a computer controlled stage with 1 μm repeatability. Calibration data for the wafer probes are shown in Figure 6.

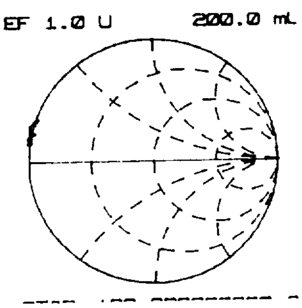

Figure 6a. Short standard from 80-140 GHz

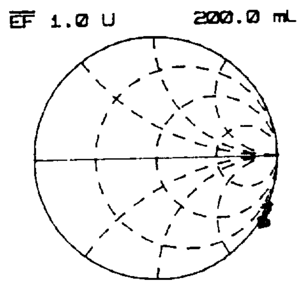

Figure 6b. Open standard from 80-140 GHz

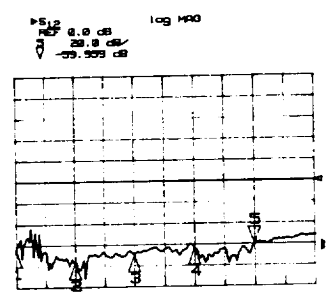

Figure 6c. Probes up and separated, demonstrating functional dynamic range from 80-140 GHz

Measurements of several multi-stage amplifiers were performed using the 90-140 GHz test sets and wafer probes. Amplifiers were designed and fabricated by TRW for use in Earth remote sensing (1). The gain of a 3-stage amplifier is shown in Figure 7.

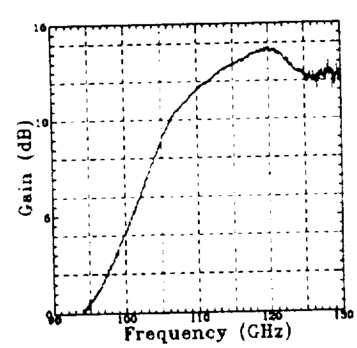

Figure 7. Gain data from a 3-stage single ended InP amplifier from TRW.

A receiver was fabricated using a second-harmonic mixer, 400 MHz IF amplifier and a power meter. Measurements were limited to a single frequency due to the limited bandwidth of the available mixer. The receiver was calibrated using hot/cold loads in front of a feed horn attached to a wafer probe. The receiver was attached to the output probe. The loss in the probes was calibrated with the network analyzer test set. The loss of two probes on a short through line was divided by two to approximate the loss of a single probe.

Making measurements on active wafers proved cumbersome using hot/cold loads, so a transfer standard was employed. A 150-190 GHz amplifier was packaged into a waveguide block. With the input terminated, and the output attenuated to provide a stable output impedance, the amplifier proved to be an ideal semiconductor noise source with an ENR of 10 dB. The estimated error in the noise figure measurement is less than 1 dB.

A second advantage of the amplifier noise source, was that it enabled the use of an HP8970 noise figure meter as an IF processor. This allowed for bias optimization of measured circuits, a task which was tedious and inaccurate with the hot/cold loads.

Several amplifiers were measured at 170 GHz. A TRW two-stage balanced amplifier was measured to have 5 dB gain and 6 dB noise figure with the gain in excellent agreement with the CW gain measurements described above. A second 2-stage balanced design was measured with 6 dB gain and 7 dB noise figure. Finally, the 6-stage CPW amplifier was measured to have 20 dB gain and 8 dB noise figure.

Conclusion

We have developed a variety of test equipment suitable for wafer probe measurements at frequencies as high as 220 GHz. These test sets extend the range of fully calibrated wafer probe measurements through 140 GHz and demonstrate the feasibility through 220 GHz. We have also developed the capability of performing accurate on-wafer noise measurements at 170 GHz extendable to 220 GHz. In the process we have developed a novel semiconductor noise source using an amplifier. This development effort has demonstrated the feasibility of on-wafer measurements on semiconductor devices at frequencies as high as 220 GHz.

Acknowledgments

We would like to thank Richard Lai, Matt Nishimoto and Mike Sholley of TRW. Portions of the research described in this paper were carried out by the Jet PropulsionLaboratory, California Institute of Technology, under a contract with the National Aeronautics and Space Administration.

References

1. "High Performance D-Band (118 GHz) Monolithic Low Noise Amplifier" M. Nishimoto et al, IEEE-MTT, International Microwave Symposium, Anaheim, CA , 1999
2. "An InP MMIC HEMT MMIC LNA with 7.2 dB Gain at 190 GHz", R. Lai, et al IEEE Microwave and *Guided Wave Letters*, November 1998
3. "High Gain 150-215 GHz MMIC Amplifier With Integral Waveguide Transitions", S. Weinreb et al, IEEE Microwave and Guided Wave Letters, vol. 9, no. 7, July, 1999

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JPL

Introduction

Semiconductor technology has progressed to the point where amplifiers operating at frequencies above 200 GHz are practical.

Applications: Earth remote sensing (NASA), astrophysics, communications radar systems, passive imaging and high-speed switching (logic or optical de/modulation).

Practical application of these circuits requires fast, inexpensive characterization.

⟹ **Wafer Probing**

Requires high frequency network analysis and wafer probes

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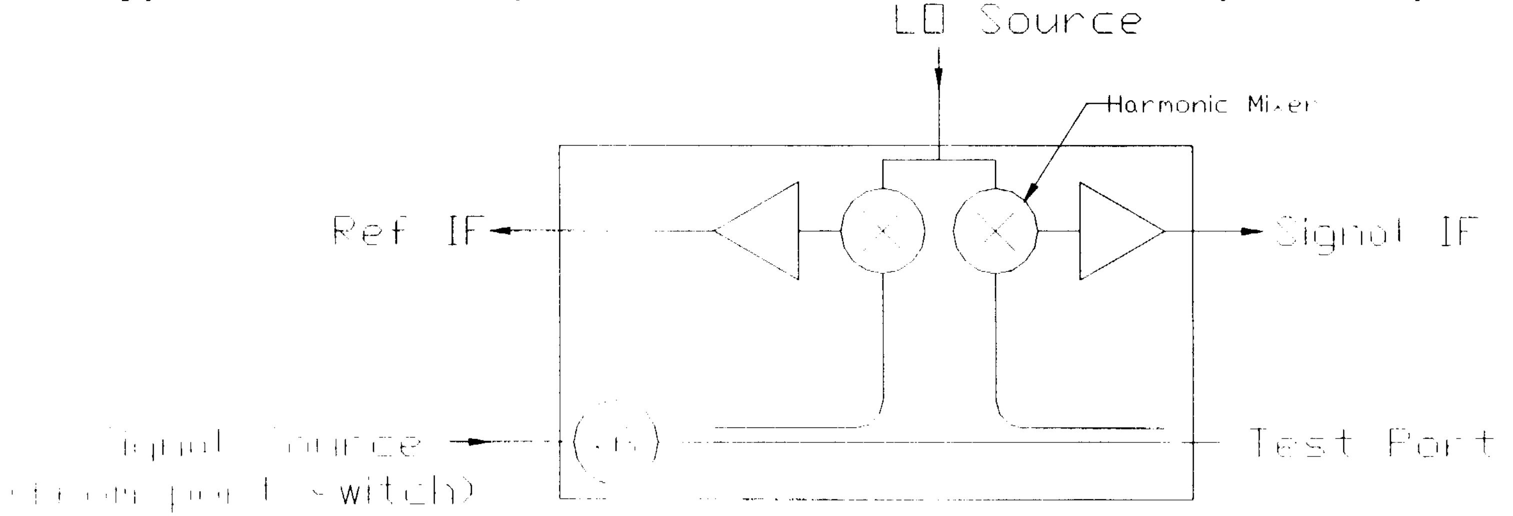
Millimeter-wave Network Analysis

Standard vector network analyzers from HP and Anritsu can be readily adapted to high frequencies with external extenders.

The typical extender requires stimulus, reference and response capability



Extenders can be fabricated in waveguide bands through 220 GHz.

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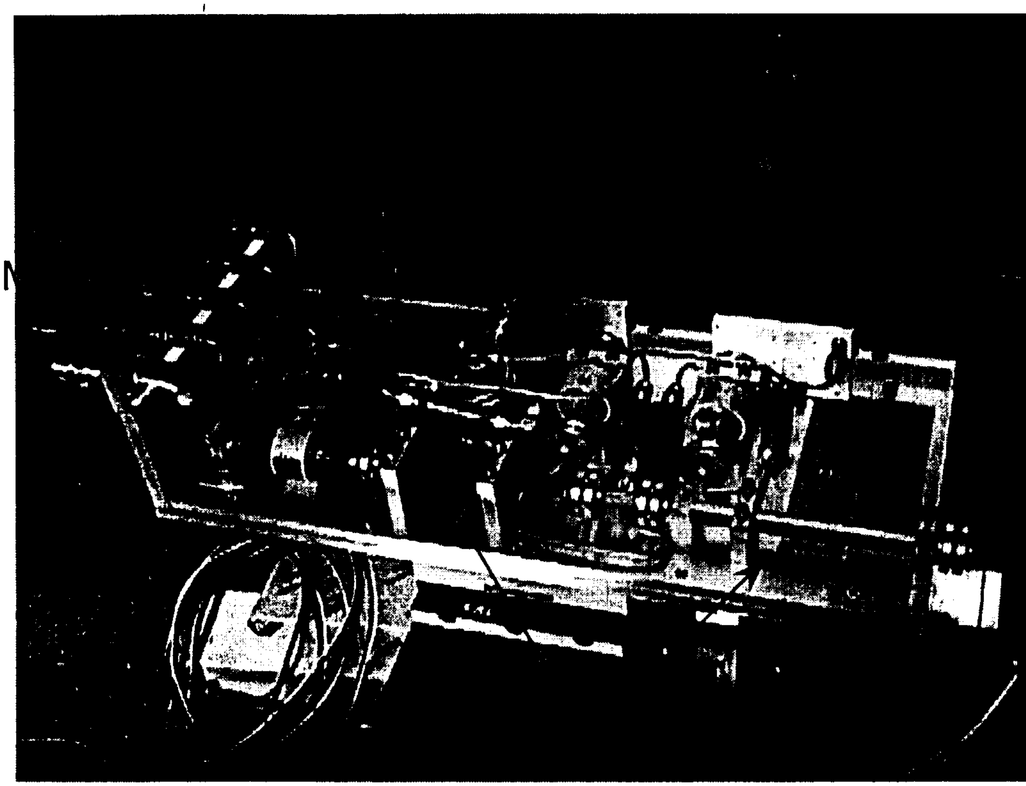
90-140 GHz VNA Extender (OML)



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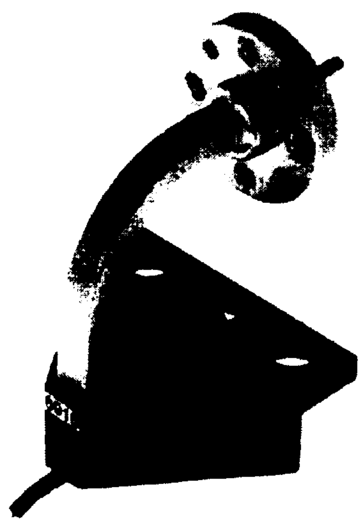
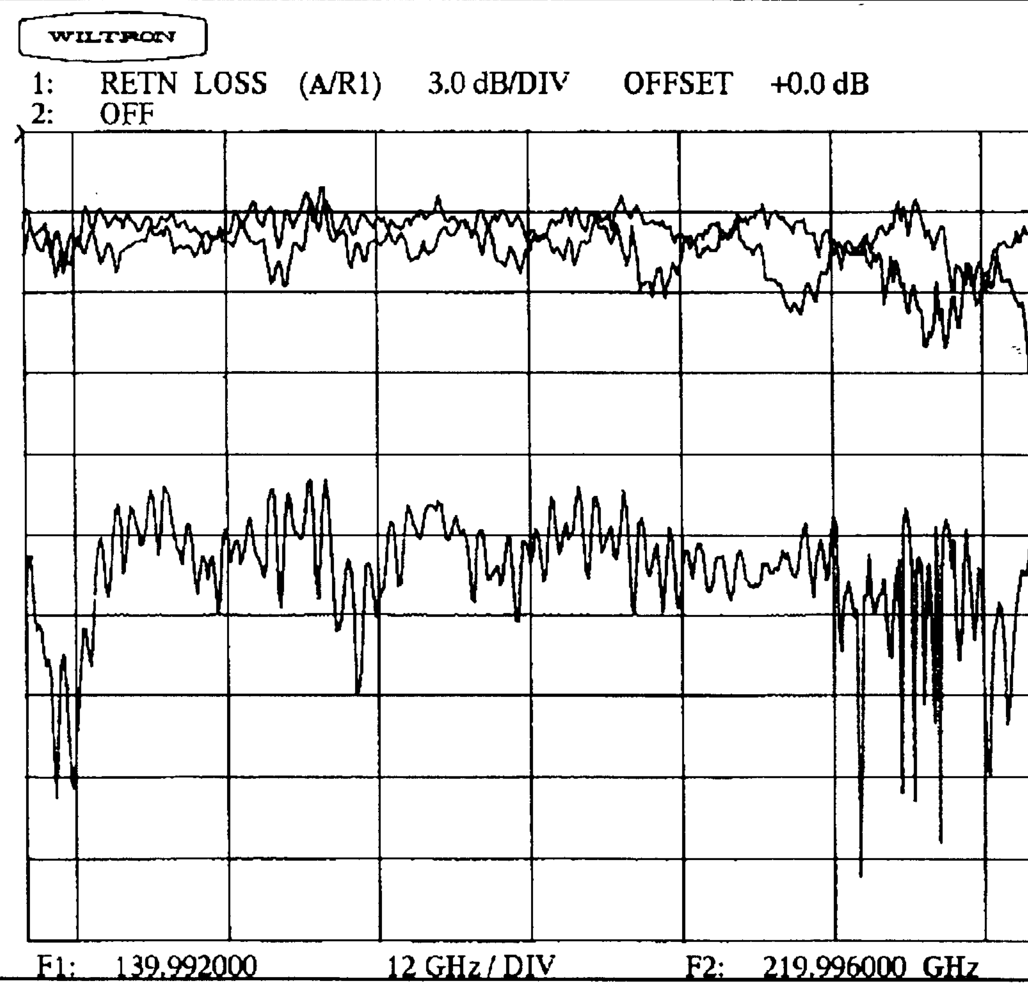
140 & 220 GHz Wafer Probes (GGB Industries)

- Air-CPW design
- low loss
- good VSWR
- bias tee





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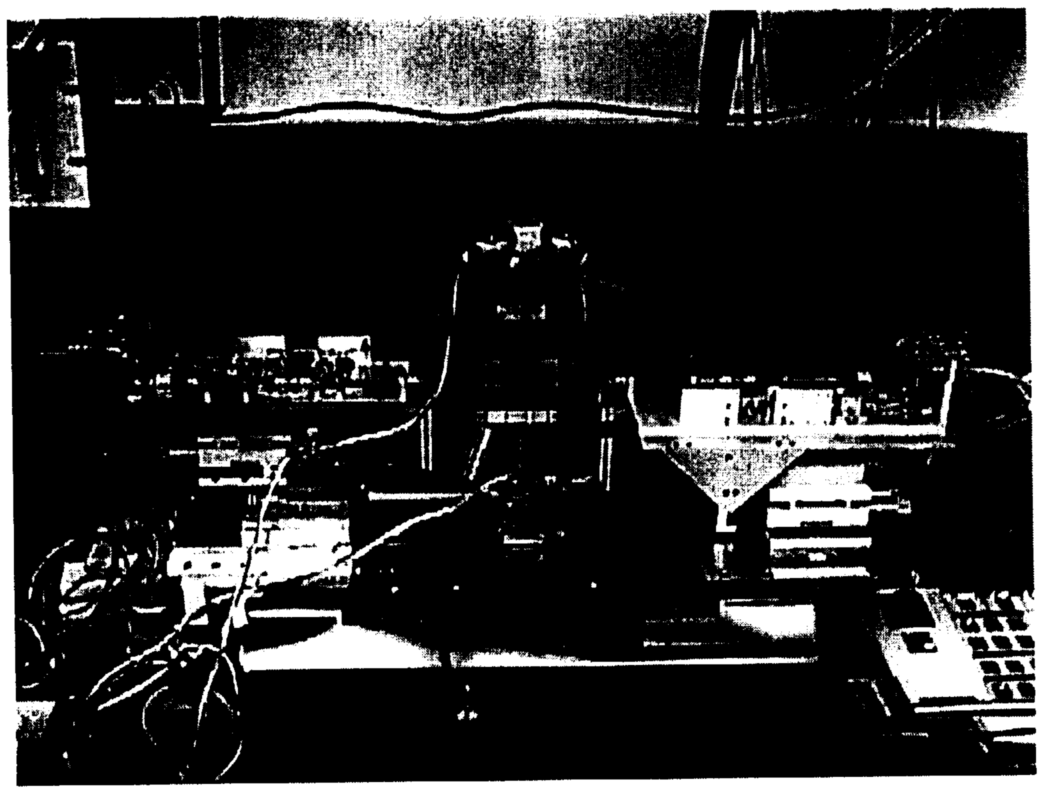
90 (80?)-140 GHz Wafer Probe Test Set

- **Full 2- port capability.**
- **Large dynamic range**



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140-220 GHz Pseudo-Scalar Wafer Probe Test Set

WR-5 Frequency extender integrated at JPL (in a hurry!)
2-Port 1-path capability (ie S21 or S11 only)

No reference coupler or mixer was available. Measurements were pseudo-scalar (phase-locking not implemented). Calibration were simple response cals.

Source Multiplier: 12X, ~100 μW output, 140-220 GHz
Mixers: 12X, ~ 35 dB CL
Isolators: 3dB IL, 20 dB IRL
Directional Coupler: 11 dB coupling, directivity ?
Calibrated Rotary Vane Attenuator: ~3 dB IL

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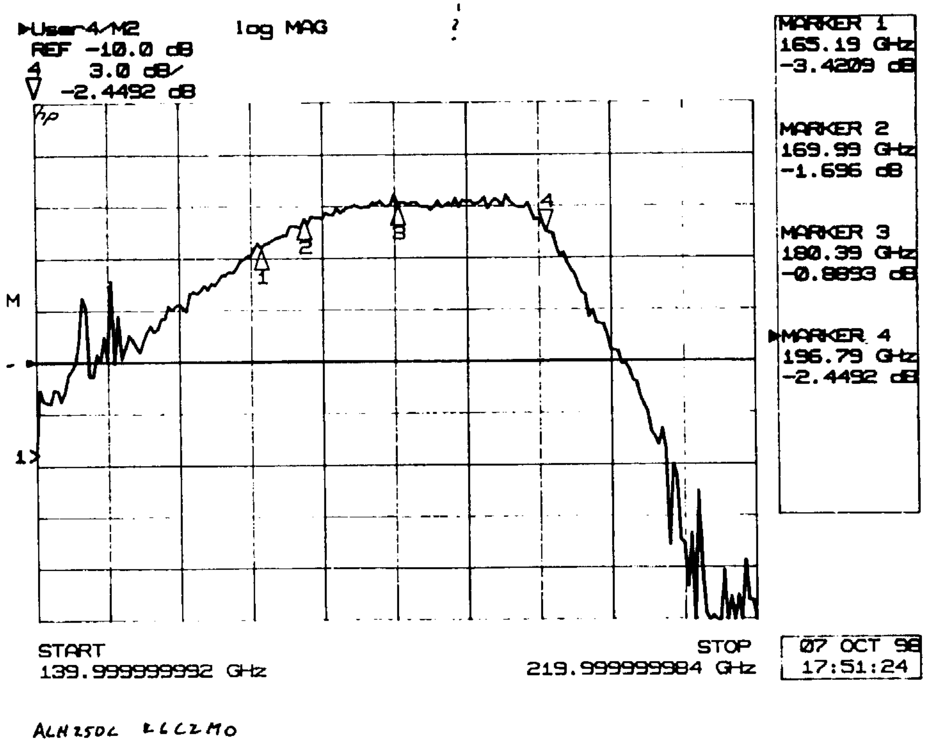
TRW 183 GHz LNA Development

160-196 GHz LNA:

- 2-Stage balanced design
- 80 nm gate length device
- g_m >1200 mS/mm
- 7 dB noise figure at 170 GHz measured on-wafer (different wafer)
- 10 dB gain



Gain measured on-wafer at JPL

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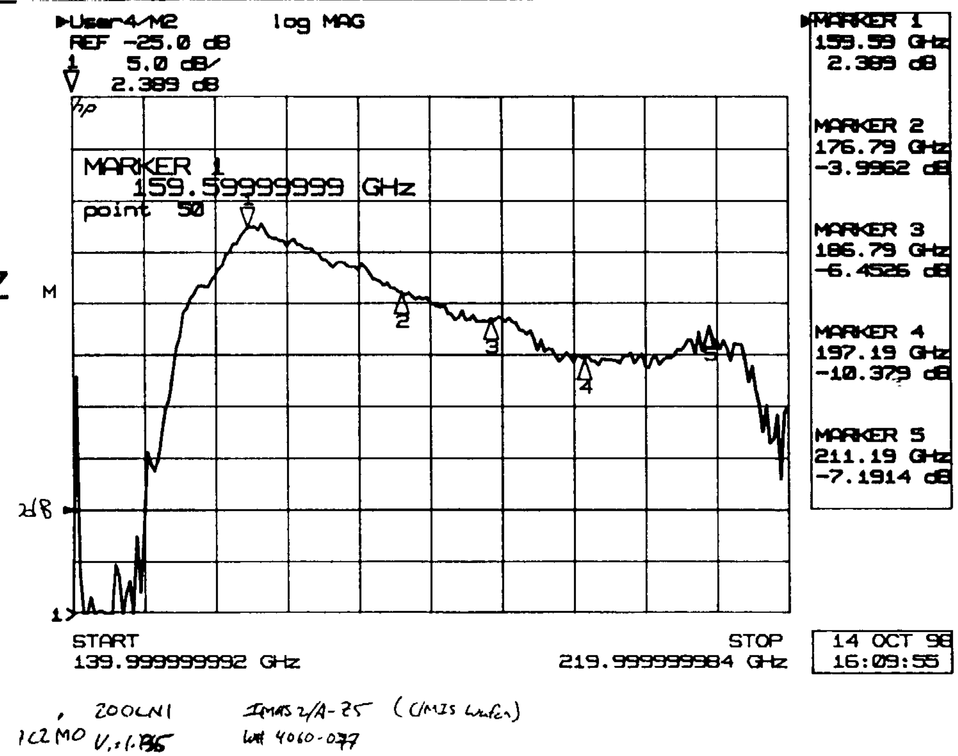
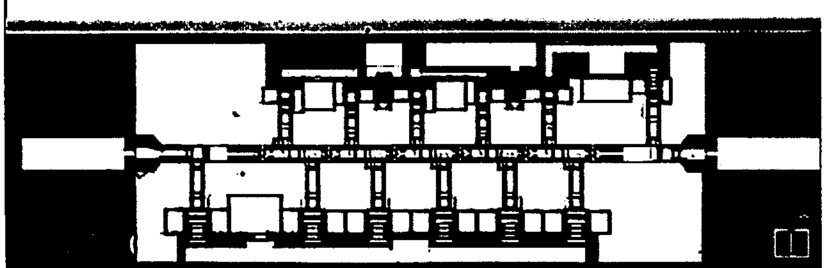
TRW IMAS 183 GHz LNA Development

150-215 GHz LNA:

- 6-Stage CPW design from S. Weinreb
- >15 dB gain at 215 GHz
- 8 dB noise figure at 170 GHz with 14 dB gain measured on-wafer (different chip)





Gain measured on-wafer at JPL

WR-5 GHz On-Wafer Noise Testing

System Requirements:

Noise source standard- calibration originates from hot/cold loads
Low noise receiver- conversion loss < 12 dB (amplifier helps)
Low-loss probes