On-Wafer Vector Network Analyzer Measurements in the 220-325 GHz Frequency Band

A. K. Fung, D. Dawson, L. Samoska, K. Lee, C. Oleson,[1] G. Boll[2]

Jet Propulsion Laboratory, California Institute of Technology, Pasadena, CA, 91109, USA

[1]Oleson Microwave Labs, 300 Digital Drive, Morgan Hill, CA, 95037, USA

[2]GGB Industries, 4196 Corporate Square, Naples, Florida, 34101, USA

Abstract — **We report on a full two-port on-wafer vector network analyzer test set for the 220-325 GHz (WR3) frequency band. The test set utilizes Oleson Microwave Labs frequency extenders with the Agilent 8510C network analyzer. Two port on-wafer measurements are made with GGB Industries coplanar waveguide (CPW) probes. With this test set we have measured the WR3 band S-parameters of amplifiers on-wafer, and the characteristics of the CPW wafer probes. Results for a three stage InP HEMT amplifier show 10 dB gain at 235 GHz [1], and that of a single stage amplifier, 2.9 dB gain at 231 GHz. The approximate upper limit of loss per CPW probe range from 3.0 to 4.8 dB across the WR3 frequency band.**

Index Terms — **MMIC Amplifiers, Coplanar Transmission Lines, Coplanar Waveguides, Measurement.**

I. INTRODUCTION

To advance electronics to higher frequencies, methods for characterizing components must be available to verify models and designs. The first full two-port on-wafer vector network analyzer (VNA) measurement capability up to 220 GHz was reported in 1999 [2]. Since then further developments have enabled full two-port on-wafer VNA measurements up to 325 GHz. In this document we will report on this test set, which to our knowledge is the first test set capable of full two-port on-wafer VNA measurements covering the WR3 frequency band.

Recent developments in InP high electron mobility transistor (HEMT) and heterojunction bipolar transistor (HBT) technologies have resulted in transistors with extrapolated current gain cutoff (*Ft*) and power gain cutoff (*Fmax*) frequencies well in excess of 220 GHz [3]-[8]. Advances in these devices benefit electronics for communications, millimeter-wave imaging systems and radiometers for earth remote sensing and astrophysics. Components such as InP HEMT amplifiers with more than 10 dB gain at 225 GHz [9] and 10 dB gain at 235 GHz [1] have been demonstrated. To progress MMIC circuits into the submillimeter-wave range (~300 GHz), characterization of *S*-parameters above 220 GHz is essential for new transistor device modeling and verification of MMIC designs.

II. 220-325 GHZ TEST SET

The WR3 test set (see Fig. 1) consists of the 50 GHz VNA *S*-parameter tester, which is composed of the Agilent 85101C display/processor, Agilent 85102B IF/detector, Agilent 8517B *S*-parameter test set, Agilent 83651A synthesized sweeper and Agilent 83620B swept signal generator. To extend the 50 GHz test set to the WR3 frequency band, Oleson Microwave Lab (OML) V03VNA-T/R frequency extension modules are interfaced with the 50 GHz VNA S-parameter test set. One frequency extension module per VNA *S*-parameter port is used, with external amplifiers and attenuators to adjust signal levels between them. To enable on-wafer probing, GGB Industries developed custom-manufactured WR3 waveguide wafer probes. The Model 325 60-µm pitch coplanar waveguide (CPW) probes are used to transition from the output ports of the Oleson frequency extenders to the ground-signal-ground CPW probe pads of the device under test on a wafer. In Fig. 2, we show a photograph of the WR3 on-wafer probe developed at GGB Industries.

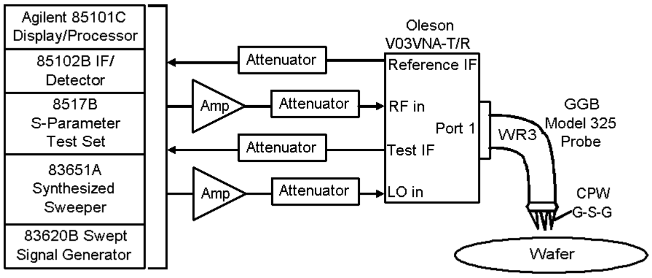

Fig. 1. Schematic diagram of the WR3 on-wafer *S*-parameter VNA test set. Port 2 is implemented in a similar fashion as Port 1 and is not shown in the diagram. Port 2 utilizes a second Oleson (OML) frequency extender, a second GGB probe, additional amplifiers, and attenuators, all interfaced to the same Agilent 50 GHz test set.

Fig. 2. Photograph of the GGB Industries WR3 Model 325 on-wafer probe with integrated bias tee.

III. 220-325 GHz MEASUREMENTS

For the on-wafer WR3 test set, calibration is performed with *line-reflect-line* (LRL) standards from a modified GGB CS-15 alumina calibration substrate. The first and second *line* standards are CPW with lengths 175 µm and 280 µm, and impedences of 50 ohms. The phase difference between the two line standards is 60 and 90 degrees at 220 and 325 GHz, respectively. The *reflect* standard is implemented with both GGB probes lifted off from the substrate and suspended in air. Once calibrated, the reference planes are set at the tip of the GGB CPW probes.

Fig. 3 displays the *S*-parameters of a three-stage 0.07 µm gate length InP HEMT amplifier that is measured with the on-wafer WR3 test set. This design by D. Dawson has a peak gain of 10 dB at 235 GHz; more details can be found in Ref. [1]. Since the Ref. [1] report we have made on-wafer measurements with a different *S*-parameter test set in the 140-220 GHz (WR5) frequency band. This second independent measurement allows for verification of the two test sets at the common 220 GHz band edge. The bias conditions for WR3 measurements are $V_{D1,2,3}$ = 1.299 V (drain voltage of all three stages), $I_{D1,2,3}$ = 36.43 mA (combined drain current of all three stages), V_{G1} = 0.310 V (gate voltage of stage 1), I_{G1} = 70.6 µA (gate current of stage 1), $V_{G2,3}$ = 0.333 V (drain voltage of stage 2 and 3), and $I_{G2,3}$ = 140.3 µA (combined gate current of stage 2 and 3). The bias conditions for the WR5 measurements are $V_{D1,2,3}$ = 1.299 V, $I_{D1,2,3}$ = 36.05 mA, V_{G1} = 0.302 V, I_{G1} = 70.0 µA, $V_{G2,3}$ = 0.325 V, and $I_{G2,3}$ = 140.2 µA. The WR3 and WR5, S_{21} and S_{11}, measurements are approximately continuous at the 220 GHz band edge. Differences in S_{22} may be due to more sensitivity of this parameter to the slight difference of the drain bias condition of the two measurements.

Fig. 4 shows the WR3 *S*-parameters of a single-stage 0.07 µm gate length InP HEMT amplifier. This design also by D. Dawson has peak gain of 2.9 dB at 231 GHz. The bias conditions are V_{D1} = 1.002 V, I_{D1} = 12.08 mA, V_{G1} = 0.358 V, and I_{G1} = 100.3 µA.

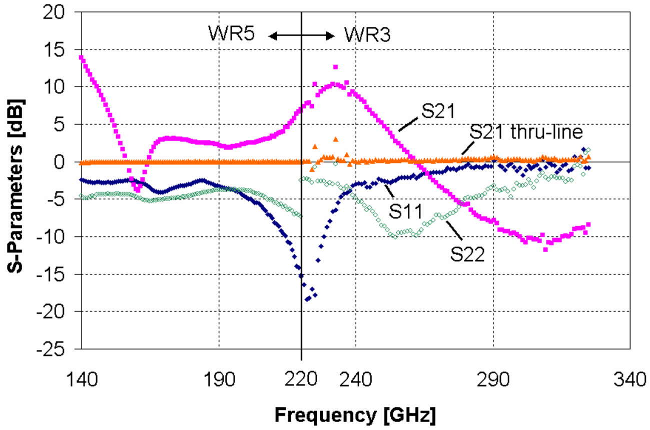

Fig. 3. WR3 and WR5 on-wafer measurements of a three stage InP HEMT amplifier and that of the 175 µm CS-15 thru-line standard. The WR5 calibration is made with the short-open-load-thru (SOLT) standards of a GGB CS-15 alumina calibration substrate.

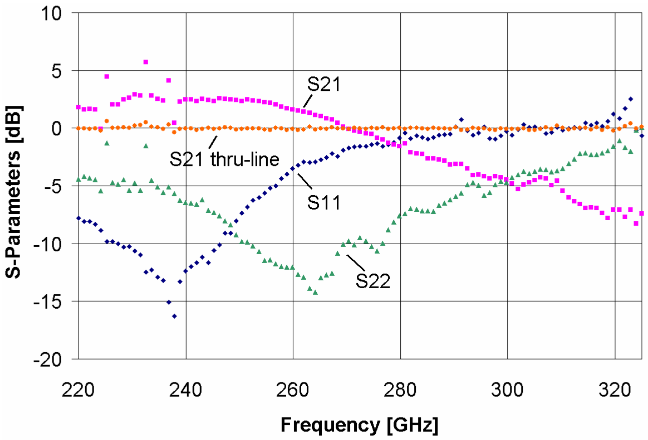

Fig. 4. WR3 on-wafer measurements of a single stage InP HEMT amplifier and that of the 175 µm CS-15 thru-line standard.

IV. PROBE LOSS MEASUREMENTS

The GGB WR3 probe loss is estimated in two ways. We begin by performing a two-port waveguide calibration at port 1 and 2 of the OML WR3 frequency extenders without the GGB probes. A LRL calibration is made with two WR3 shims of length 2.537 mm and 2.911 mm from an OML WR3 waveguide calibration kit. The equivalent phase difference between the two *line* standards is 45 and 170 degrees at 220 and 325 GHz, respectively. The *reflect* standard is implemented with a waveguide flange short and is used to define the reference plane at the port 1 and 2 flange openings of the OML frequency extenders. Fig. 5 shows the transmission response S_{21} of a *thru* (port 1 and 2 flanges are connected directly). From the *thru* data it is apparent that

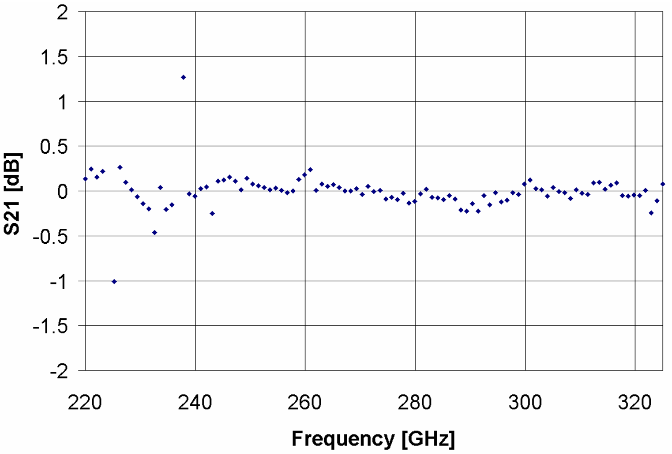

Fig. 5. Transmission measurement (S_{21}) of a waveguide zero-length *thru* after calibration of the Oleson WR3 test set.

waveguide transmission measurements can have an error of approximately ± 0.3 dB, neglecting the two large glitches below 240 GHz. Once calibrated, the GGB WR3 probes are placed back on the port 1 and 2 flanges for loss measurements.

With the GGB probes in place, in the first method to measure the GGB WR3 probe loss, we perform a transmission measurement through the two GGB probes when placed at opposite ends of a 175 µm CPW line of a CS-15 calibration substrate. Fig. 6 shows the transmission data. From the S_{21} measurement an upper limit of probe loss in the WR3 band can be estimated from dividing S_{21} in half and associating the value to loss of each probe. In this way the upper limit of probe loss is estimated to be between 2.8 to 4.8 dB, near the start to end of the frequency band, respectively. Here in setting the upper limit we have neglected loss in the 175 µm CPW line, which is calculated to be 0.060 to 0.074 dB at 220 and 325 GHz, respectively. Additionally, errors from probe placement and contact resistance are also neglected. For confirmation of probe loss we also examine the return loss of each of the two probes when placed on shorts.

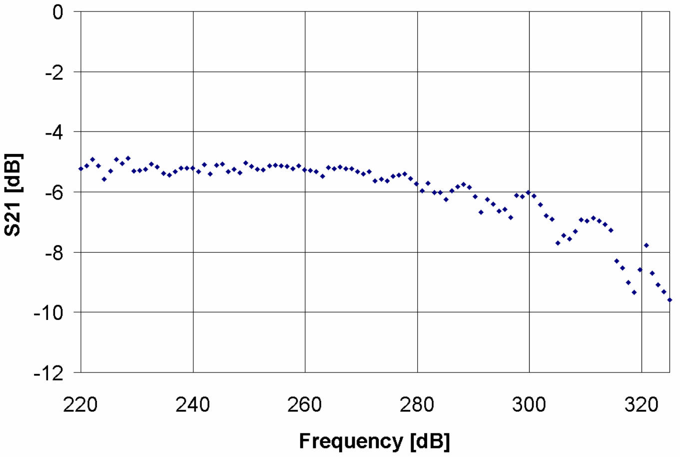

Fig. 6. Insertion loss measurement through two GGB WR3 probes and a 175 µm CPW line from a CS-15 calibration substrate.

Fig. 7 shows S_{11} when one GGB WR3 probe is attached to port 1 of the WR3 frequency extender and the probe tip is placed on a short from a CS-15 calibration substrate. Fig. 6 also shows S_{22} of the second GGB WR3 probe when it is attached to port 2 and terminated with a CS-15 short. From these measurements an upper estimate of probe loss is deduced from dividing S_{11} and S_{22} in half for the forward and return travel of the wave to and from the short. The upper limit of probe loss is estimated to be 3.0 to 4.8 dB, near the beginning and end of the WR3 frequency band, respectively, and is similar to the values obtained from the insertion loss measurement.

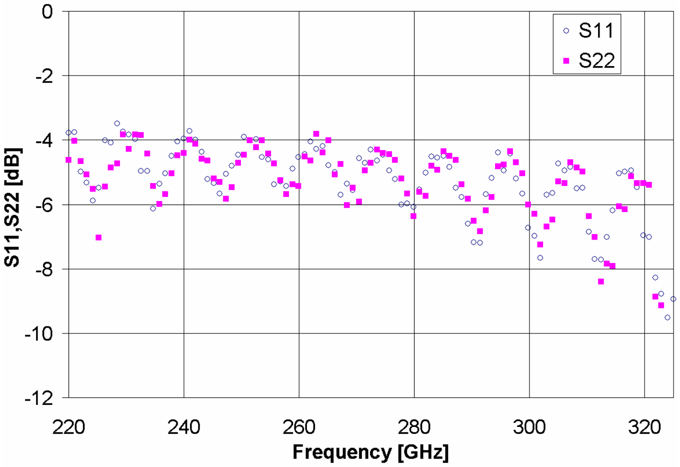

Fig. 7. Return loss measurements of GGB WR3 probes placed on shorts from a CS-15 calibration substrate.

V. CONCLUSION

Full two-port on-wafer VNA measurement capabilities have been extended up to 325 GHz. Methods for calibration in the WR3 band for on-wafer and waveguide measurements have been established. We utilized this new test set to measure the two-port S-parameters of on-wafer amplifiers and to estimate upper limits of loss in the probes used for the WR3 on-wafer measurements. For on-wafer InP HEMT MMIC amplifiers, we have measured for a three-stage amplifier 10 dB gain at 235 GHz, and for a single-stage amplifier 2.9 dB gain at 231 GHz. For GGB WR3 probe loss, we deduce upper limits of loss per probe to be approximately 3.0 to 4.8 dB, near the beginning and end of the WR3 frequency band, respectively.

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