# MILLIMETER WAVE TESTS AND INSTRUMENTATION

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**Abstract**

The recent growth in millimeter wave applications has created a corresponding demand for millimeter wave tests and instrumentation. Network analyzers, signal analyzers, signal generators, power meters and noise figure analyzers will be discussed in this article. Optimum choice of instrumentation for specific applications will also be presented.

## 1. Introduction

Millimeter wave frequencies are between 30 and 300 GHz (wavelengths from 10 to 1 mm). Millimeter waves are attenuated by atmospheric constituents and gases at different rates for different frequencies [1]. Frequencies where gaseous absorptions are at minimum are called atmospheric windows. Regions of maximum absorption are called absorption bands. The main millimeter wave atmospheric windows are centered around 35, 94, 140 and 220 GHz, and the main absorption bands are around 60, 120 and 182 GHz. Figure 1 shows these windows and bands.

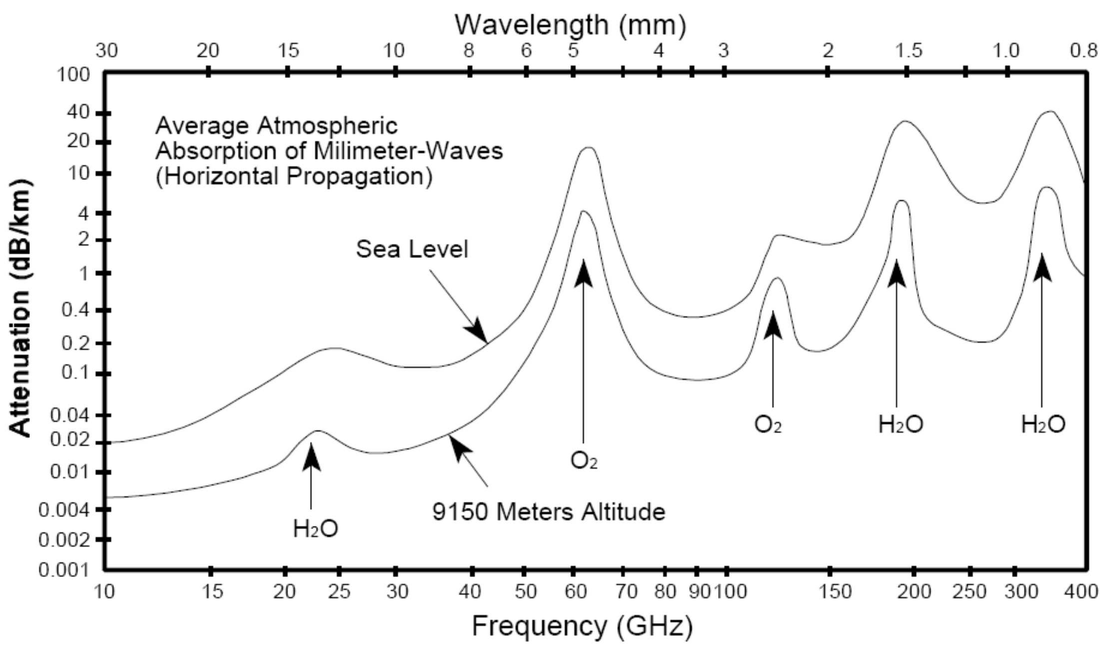


**Figure 1**. Atmospheric Absorption of Millimeter Waves

The main applications for millimeter wave systems are in communications, homeland security, imaging, radar and spectroscopic observation. Most millimeter wave applications employ millimeter wave measurement systems to verify device specifications. These measurement systems utilize microwave instrumentation and external up/down converters to perform the required tests. This paper will present an overview of millimeter wave tests and instrumentation across the range of 30 to 325 GHz.

## 2. Millimeter Wave Applications

Typical millimeter wave applications are around atmospheric windows or absorption bands. Some of these applications are: 1). Satellite Communications at 60, 94, and 140 GHz, 2). Scientific research at 220 and 240 GHz, 3). Imaging and homeland security at 94 GHz, and 4). Automotive radar at 77, 94, and 140 GHz.

Connections between millimeter wave applications and measurement systems can be one of four methods: coaxial, waveguide, probe on wafer or antenna. Table A shows coaxial millimeter wave connectors [2].

**TABLE A: COAXIAL MILLIMTER WAVE CONNECTORS**

| Type | Other Name | Maximum Frequency In GHz | Usable Frequency In GHz |
|---|---|---|---|
| **3.5 mm** | APC-3.5 | 34 | 36 |
| **2.92 mm** | K, OS-2.9 | 40 | 46 |
| | | | |
| **2.4 mm** | OS-2.4 | 50 | 52 |
| **1.85 mm** | V | 65 | 70 |
| **1.0 mm** | W | 110 | 118 |

Millimeter wave waveguide bands are shown in Table B. Current designation, band frequency range and waveguide inside dimensions in mils are also shown in Table B. Since waveguides are designed to work in the $TE_{01}$ mode, each band has a cut off frequency as shown in Table B. Below this cut off frequency, millimeter waves cannot propagate into the waveguide. Waveguide bandwidths are typically around 50%. It is strongly recommended to work below the $TE_{20}$ or twice the cut off frequency of waveguide bands.

**TABLE B: WAVEGUIDE BANDS AND CHARACTERISTICS**

| WG Band | Current Designation | Frequency in GHz | Cutoff Frequency in GHz | Dimension in Mils |
|---|---|---|---|---|
| **WR-22** | Q | 33-50 | 26.34 | 224 x 112 |
| **WR-19** | U | 40-60 | 31.36 | 188 x 94 |
| **WR-15** | V | 50-75 | 39.87 | 148 x 74 |
| **WR-12** | E | 60-90 | 49.35 | 122 x 61 |
| **WR-10** | W | 75-110 | 59.01 | 100 x 50 |
| **WR-08** | F | 90-140 | 73.77 | 80 x 40 |
| **WR-06** | D | 110-170 | 90.84 | 65 x 32.5 |
| **WR-05** | G | 140-220 | 115.75 | 51 x 25.5 |
| **WR-04** | Y | 170-260 | 137.52 | 43 x 21.5 |
| **WR-03** | H | 220-325 | 176.71 | 34 x 17 |

Probes are designed to be attached to connectors from one side and wafers on the other side. Table C shows the popular coaxial probe frequency ranges [3].

**TABLE C: PROBE FREQUENCY RANGES**

| Probe Number | Connector Type | Frequency Range |
|---|---|---|
| **1** | 2.92 mm | 40 GHz |
| **2** | 2.40 mm | 50 GHz |
| **3** | V | 65 GHz |
| **4** | 1.85 mm | 67 GHz |
| **5** | 1.00 mm | 110 GHz |

The connection between the wafer probe to the test system could be coaxial or waveguide. Wafer probes that connect to waveguides cover only the waveguide bandwidth (e.g. 75-110 GHz). At the present time probes are available commercially up to 220 GHz [4]. Antennas, receiving or transmitting, cover the application's bandwidth, e.g. 76-77 GHz, 60-61 GHz, or 94-95 GHz. Most applications consist of transmitters and receivers, only transmitters, or only receivers.

Information to be transmitted and/or received is usually contained in modulation techniques. Some of these techniques are AM, FM, Pulsed, Phase or FMCW. Measurement systems need to verify the output power, the modulation purity of the information, and the sensitivity of the receiver.

## 3. Millimeter Wave Test Parameters and Specifications

Test parameters and specifications are strong functions of the specific application. However, the following are basic specifications for most applications:

1. Frequency: Transmit and/or Receive
2. Bandwidth: Transmit and/or Receive
3. Modulation
4. Power Transmit (min/max), Receive (min/max)
5. Distance/Resolution
6. Antenna or Beam Width
7. Update Rate
8. Mechanical dimension and weight
9. Power Supply (voltage, current, and DC power consumption)
10. Interface
11. Cost
12. Technology Used.

Millimeter wave ranges can be divided into three regions. The first is 30-50 GHz which usually uses coaxial connectors and cables, and is considered by some users as a microwave region. The second region is 50-110 GHz, and is crowded with commercial and non-commercial applications. Activities in this region can be as high as 50% of the entire millimeter wave spectrum. The third region is 110-325 GHz, constitutes 20% of all activities, and is growing rapidly over time.

Most millimeter wave applications have a very small bandwidth of < 1 GHz. The modulation bandwidth is much smaller than the application bandwidth, usually 10-100 MHz.

Millimeter wave applications can be used in one of four modes: 1). CW mode, 2). Modulated CW mode, 3). Pulsed RF mode, and 4). Pulsed RF and pulsed bias modes. The number of ports could vary from two ports to multiports (4, 5, 6…) and could be single ended or differential.

Signals transmitted and/or received can be modulated in scalar or vector techniques. Millimeter wave measurements can be divided into three ranges: 1). In band, 2). Out of band, and 3). In band harmonic. Table D shows a summary of millimeter wave application parameters.

**TABLE D: MILLIMETER WAVE APPLICATION PARAMETERS**

| **Frequency** | RF | MW | MMW |
|---|---|---|---|
| **MMW (GHz)** | 30-50 | 50-110 | 110-325 |
| **Application BW** | Narrow Band | Wide Band | Ultra Wide Band |
| **Modulation BW** | Narrow Band | Wide Band | |
| **Power** | Low | Normal | High |
| **Connections** | Coaxial | WG | Probe |
| **Type of Measurement** | In band | Out of band | Harmonic |
| **DUT** | 2PSE | 2PD | MPD |
| | | | |
| **Signal Mode** | CWRF | Pulsed RF | PRF/PB |
| **Signal Source** | Scalar (AM, FM, P, P) | Vector | |

## 4. Millimeter Wave Instrumentation

Measurement systems are determined by types of millimeter wave applications and specifications. However, most systems consist of four instruments: signal generators (scalar or vector), signal analyzers (scalar or vector), network analyzers (scalar or vector) and power meters. For specific applications, noise figure analyzers and/or phase noise systems are required.

### 4.1 Signal Generators

Millimeter wave signal generators with full waveguide coverage are key factors in millimeter wave applications. Most millimeter wave users already own microwave signal generators and want to extend present microwave measurement capabilities up to 325 GHz [5].

Two ways to generate millimeter wave signals are up converting or multiplying. For scalar modulation and measurements, multiplying the output of microwave signal generators will be optimum. For example, multiplying by 6 using the range of 10-20 GHz will deliver the frequency range of 75-110 GHz in the WR-10 waveguide band. However, an up converter is required for vector modulation to keep the relative phase in control at millimeter wave frequencies. Typical output powers are: +13 dBm for 33-50 GHz, +10 dBm for 50-75 GHz, +7 dBm for 75-110 GHz, zero dBm for 110-170 GHz, -10 dBm for 140-220 GHz, and -20 dBm for 220-325 GHz. New techniques are in progress to generate millimeter wave signals from photo mixing. However, the output power is much lower than multiplying or up converting. Figure 2 shows a typical millimeter wave signal generator. Research is in progress at the present time to generate sub-millimeter wave signals at 330-500 GHz in the WR-2.2 waveguide band, and 500-750 GHz in the WR-1.5 waveguide band.

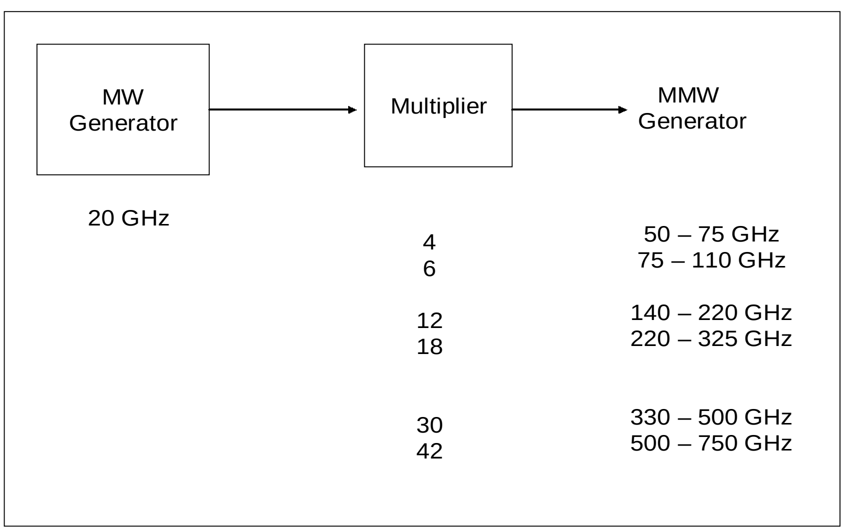


**Figure 2: Typical Millimeter Wave Signal Generator**

### 4.2 Signal Analyzers

For scalar analysis measurements, harmonic mixers are used to down convert the millimeter wave signal into the IF of microwave signal analyzers. Table E shows the IF and LO frequencies of signal analyzer manufacturers A – G [6]. The signal analyzer's firmware determines the harmonic number and displays the correct spectrum. Figure 3 shows a typical millimeter wave signal analyzer. For vector modulation, a digital wide bandwidth IF section (30-80 MHz) is used [7, 8] to analyze the millimeter wave signal.

**TABLE E: EXTERNAL MIXER PARAMETERS**

| Manufacturer | **IF in MHz** | **LO in GHz** |
|---|---|---|
| A | 310.7<br>321.4 | 3.0-6.8<br>2.3-6.8 |
| B | 410.7 | 3.0-12.0 |
| C | 421.4 | 3.4-7.9 |
| D | 421.99 | 3.5-7.9 |
| E | 521.4<br>689.3 | 3.0-6.0<br>3.5-7.0 |
| F | 741.4<br>221.4 | 7.5-15.2<br>5.2l-13.1 |
| G | 2000<br>525/3525 | 2.0-6.0<br>8.1-17.9 |

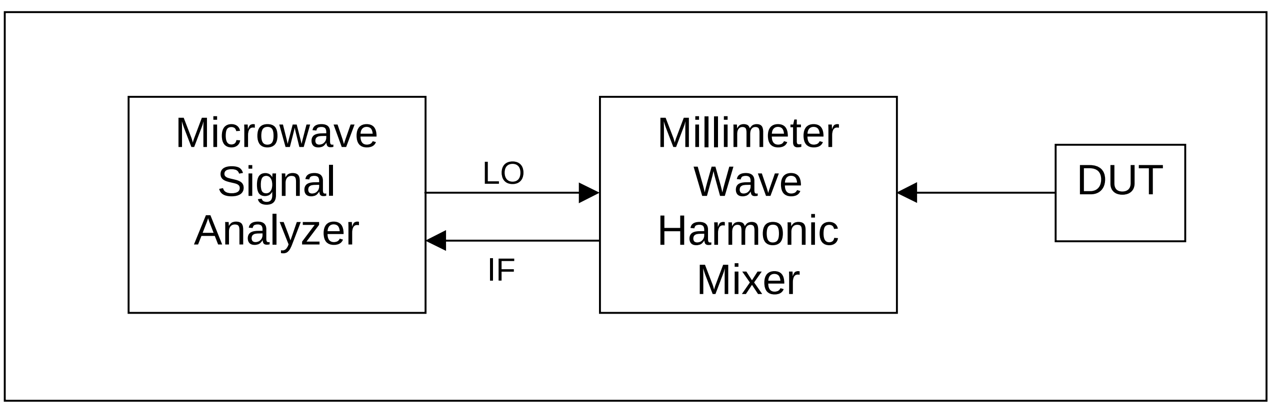


**Figure 3: Typical Millimeter Wave Signal Analyzer**

### 4.3 Network Analyzers

For scalar network analyzers, detectors are used to capture the magnitude of millimeter wave signals. Once the DC voltage is delivered to the network analyzer the display is shown using the same signal processing as in RF or microwave frequencies. Thus, the appropriate detector must be found to establish a complete scalar network analyzer to cover the appropriate waveguide band.

The vector network analyzer is different because the signal phase needs to be determined and calibrated at the DUT's millimeter wave frequencies. Multiplying the microwave signal from below 20 GHz to the millimeter wave band is the first step. The incident and reflected waves are down converted using a dual directional coupler and two harmonic mixers. These signals are connected to the vector network analyzer's IF input. Calibration is done at the millimeter wave band using standard TRL, OSLT, LRM or any other calibration technique. For each waveguide band there exists a unique calibration hardware kit. At the present time, there are commercial vector network analyzers that measure up to 325 GHz [7, 8]. Figure 4 shows a typical millimeter wave vector network analyzer.

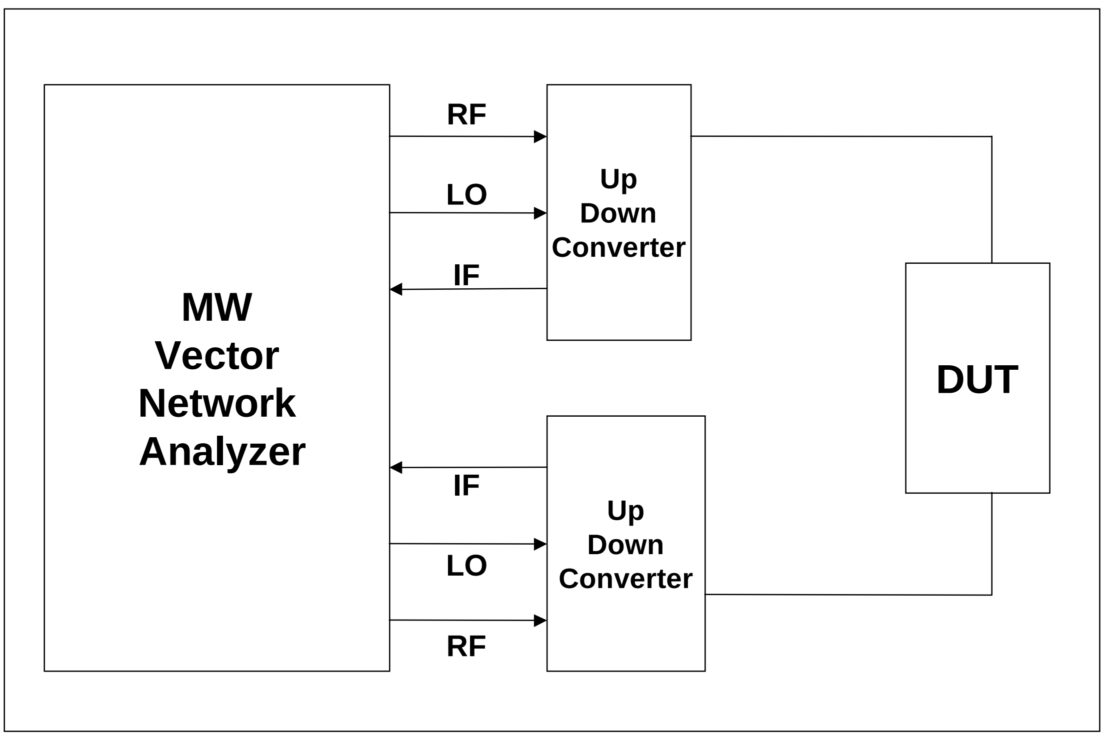


**Figure 4: Typical Millimeter Wave Vector Network Analyzer**

Two types of millimeter wave vector network analyzers are CW and pulsed. Depending on the pulse width and repetition rate, one specific type of analyzer is more suitable than others. The pulsed bias technique is used to test high power DUTs at the wafer level to avoid device self heating [9, 10].

### 4.4 Power Meters

Microwave power is measured using power meters with power sensors. At millimeter wave frequencies a sensor is required to be connected and calibrated to a power meter to display the millimeter wave power. There are commercial power meters and sensors up to 110 GHz with traceability and verification paths [7, 8]. Above 110 GHz, there is some progress in measuring power using sensors in these millimeter wave bands. More progress is needed in this area to measure millimeter wave power up to 325 GHz with a traceability path.

### 4.5 Noise Figure Analyzers

To measure the noise figure of DUTs at microwave frequencies, the Y-factor technique is used with a noise source. Noise figure and gain can be displayed up to 26.5 GHz. Noise sources are available up to 50 GHz. Figure 5 shows a typical millimeter wave noise figure analyzer. More progress is needed in this area to measure millimeter wave noise figure up to 325 GHz with a traceability path.

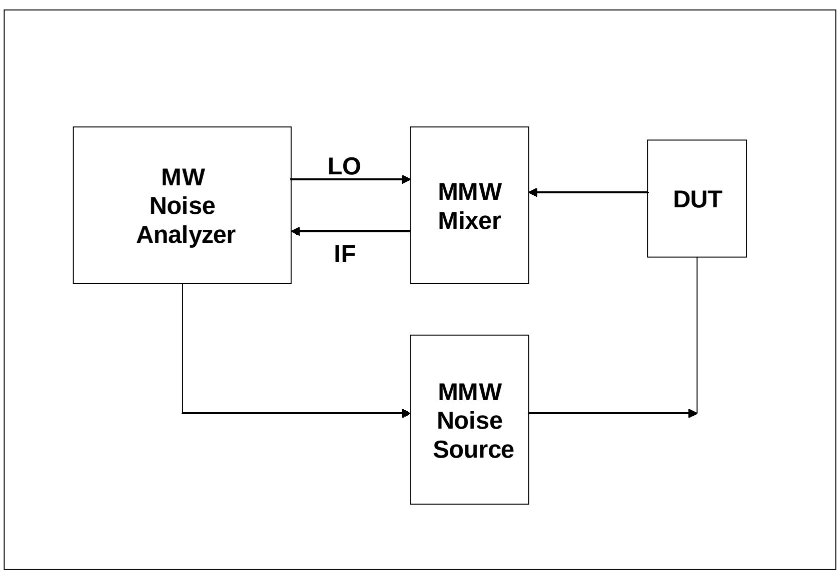


**Figure 5: Typical Millimeter Wave Noise Figure Analyzer**

### 4.6 Phase Noise Systems

Similar to microwave phase noise measurements, a mixer is needed to down convert the millimeter wave signal to DC and then measure the phase noise. There are a few systems available at the present time that can be used with ease.

### 4.7 General

Millimeter wave measurements could be displayed in three different domains: time, frequency or modulation. Most millimeter wave measurement systems use the frequency domain, and then convert to time domain, if needed. The environment of the application and/or measurement systems usually start out as research which turns into development and ends up in a production environment. Each of these environments has their own requirements and constraints. For example, research needs to prove the concept on only a few units. However, production needs to repeat the same process and produce the required product over and over. Depending on actual quantity, measurement time will be optimized to reduce test time. Table F outlines the above mentioned items.

**TABLE F: MEASUREMENT ENVIRONMENTS**

| **Domain** | Time | Frequency | Modulation |
|---|---|---|---|
| **Analyzer** | Signal | Network | Noise/Power |
| **Phase** | Research | Development | Production |
| **Quantity** | Small | Medium | Large |
| **Measurement Time** | Low | Medium | High |

## 5. Millimeter Wave Test Trade Offs

Calibration is required for vector network analyzers, vector signal generators, and vector signal analyzers. At millimeter wave frequencies, the calibration is critical to accomplish highly accurate measurements. Slower sweep or larger numbers of points are also important for accurate measurements.

The noise floor of the test instrumentation needs to be at least 10-15 dB better than the DUT noise floor. Similarly, the maximum input power (or output power from the DUT) should not generate any harmonic distortion of the test instrumentation.

Overall, the measurement dynamic range of the measurement instrumentation should be 20 dB higher than the DUT dynamic range. Measurement uncertainty should also be calculated for any measurement system. Usually better measurement uncertainty requires more averaging or lower IF resolution bandwidth. This leads to longer measurement time.

## 6. Conclusion

Extending the frequency range of microwave instrumentation to the millimeter wave range was described in this paper. Signal generators, network analyzers, and signal analyzers, both scalar and vector, were presented. Trade offs for millimeter wave application testing were discussed.

## References


[1] Mohamed M. Sayed and Giovonnae F. Anderson, *50-to-110-GHz High-Performance Millimeter Wave Source Modules*, Hewlett-Packard Journal, Vol. 42, No. 2, April 1991, pp.50-64.

[2] WA1MBA, *RF Connectors for Upper Frequencies,* www.wa1mba.org.

[3] Cascade Microtech, Inc. www.cascademicrotech.com.

[4] Picoprobe by GGB Industries, Inc., www.ggb.com.

[5] OML, Inc., Morgan Hill, CA. *Frequency Extension Source Modules to Extend Signal Generator Capability from 50-325 GHz.* Microwave Journal, March 2004.

[6] OML, Inc., Morgan Hill, CA. *Millimeter Wave Spectrum Analysis Harmonic Mixer Application Notes,* www.oml-mmw.com.

[7] Anritsu Co., Richardson, TX, www.us.anritsu.com.

[8] Agilent Technologies, Inc., Palo Alto, CA, www.agilent.com

[9] Anthony Parker, Jonathan Scott, James Rathmell and Mohamed Sayed, *Determining Timing for Isothermal Pulsed-bias S-parameter Measurements,* IEEE MTT-S International Symposium Digest, San Francisco, June 1996.

[10] Huei Wang and Mohamed Sayed, *W-Band MMIC Characterization in an Isothermal Environment,* IEEE Microwave and Guided Wave Letters, Vol. 5, No. 12, December 1995, pp.429-431.