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ON-WAFER CHARACTERIZATION OF MILLIMETER-WAVE ANTENNAS FOR WIRELESS APPLICATIONS

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ABSTRACT

The paper demonstrates a de-embedding technique and a direct on-substrate measurement technique for fast and inexpensive characterization of miniature antennas for wireless applications at millimeter-wave frequencies. The technique is demonstrated by measurements on a tapered slot antenna (TSA). The measured results at Ka-Band frequencies include input impedance, mutual coupling between two TSAs and absolute gain of TSA.

I. INTRODUCTION:

Several emerging wireless applications, such as, local multipoint distribution services (LMDS) at 28 GHz, fixed wireless broadband local distribution service at 38 GHz and indoor local area network at 60 GHz require low cost printed circuit antennas for communications [1]. These antennas are characterized for their votage standing wave ratio (VSWR) bandwidth and directional gain by measuring the reflection coefficient using a calibrated automatic network analyzer (ANA), and the received power in a calibrated antenna test range, respectively. Some antenna designs may even require a knowledge of the mutual coupling between elements in an array. In order to interface the antenna to the test equipment for measurements a custom built test fixture with a launcher, which at lower millimeter-wave (mm-wave) frequencies is of coaxial type while at higher mm-wave frequencies is of waveguide type, is necessary [2]. In addition these antennas may have a slot line, or a coplanar stripline (CPS), or a coplanar waveguide (CPW) based feed network for simple and efficient feeding [3]. For example, a Vivaldi antenna has a slot line feed. Hence for characterization in addition to the custom test fixture an integral printed transition between the antenna feed line and the coaxial or rectangular waveguide launcher is also required. These transitions and fixtures which are inevitable for measurements impose several limitations. First, the input impedance and the VSWR bandwidth determined at the plane of the test fixture by the ANA is the overall response of the transition, the feed network and the antenna. Therefore these measurements do not present the true antenna characteristics. Second, the uncertainty introduced by the interaction between the test fixture and the antenna is difficult to predict at mm-wave frequencies. Third, the bandwidth of the transitions are typically limited to a few GHz at mm-wave frequencies. Therefore several transitions and fixtures may be required to cover the desired frequency band resulting in high cost. Furthermore, it has been experimentally demonstrated that a coaxial launcher coupled with the CPW feed line can introduce serious moding problems [4].

In this paper we demonstrate a de-embedding technique and a direct on-substrate measurement technique for characterizing mm-wave printed antennas. To the best of our knowledge this demonstration is the first of its kind for printed antennas. The above technique require a pair of ground-signal microwave probes (Picoprobe Model 40A, pitch = 10 mils), a wafer probe station (Cascade Model 42), and an ANA (HP8510C). This characterization technique eliminates the need for custom test fixture and antenna feed network consisting of transitions to microstrip line. Therefore, this technique is extremely accurate, fast and inexpensive when automated for repeated measurements. This technique is also very versatile and is adaptable to most printed antennas; however, for demonstration purpose we have chosen a short tapered slot antennas (TSAs). Short antennas are essential for mobile wireless applications for achieving compactness. The TSA is chosen because of its high gain, wide bandwidth and simple uniplanar construction. The TSAs that are included in this demonstration are the linearly tapered slot antenna (LTSA) and the Vivaldi antenna (VA). The results presented are the input impedance of a LTSA, the mutual coupling between two LTSAs in close proximity and the gain of a VA. The input impedance is determined by the de-embedding technique while the mutual coupling and gain are determined by the direct on-substrate measurement technique.

II. ANTENNA LAYOUT:

Figure 1 illustrates the layout of a typical LTSA with length L, width W, finite width ground planes W_1 on either side, and semi-flare angle θ. The short length of slot line exciting the LTSA has a length L_1 and slot width W_2. The relative permittivity and thickness of the dielectric substrate are indicated as ε_r and D respectively.

III. MEASUREMENT METHODOLOGY:

a.) De-embedding Technique:

In order to isolate the influence of the input slot line feed on the input impedance of the LTSA, the ANA is calibrated using a Thru-Reflect-Line (TRL) calibration technique [5]. This technique relies on standards which are fabricated beside the TSA to be characterized on a single substrate. The inset in Fig. 1 shows a set of slot line TRL on-wafer standards which are used for calibrating the ANA. The standards consists of a slot line thru, a slot line short circuit and a slot line delay line. The thru line length is twice the feed line length. The short circuit line length is the same as the feed line length. The delay line ($2L'_1$) and the thru line ($2L_1$) lengths are related through the following expression [5]:

$$2L'_1 - 2L_1 = 15/[(f_1 + f_2)\sqrt{\varepsilon_{eff}}\,] \text{ cms.} \tag{1}$$

Where f_1 and f_2 are the start and stop frequencies. The calibration of the ANA is done using the National Institute of Standards and Technology (NIST) de-embedding software program [6]-[8]. The software runs on a HP9000 computer and controls the ANA. This program solves a 12-term error model from the thru line two-port measurements, the delay line two-port measurements and the two one-port reflection measurements. The program then establishes an electrical reference plane to which all de-embedded S-parameters are referred. This plane is shown by dashed line in Fig. 1. The reference impedance after error correction is established by the characteristic impedance Z_0 of the delay line. The slot width W_2 of the slot line determines Z_0. Thus, the reflection coefficient of the LTSA is de-embedded from the measured reflection coefficient at the input terminals of the slot line feed.

b.) <u>Direct Measurement Technique</u>:

In this method, the ground-signal microwave probes are calibrated to the tips using an ANA and an open circuit, a short circuit and a matched load as standards. The standards for direct measurements are provided by the probe manufacturer on an impedance standard substrate (ISS). The calibrated probe is then made to contact the input terminals of the slot line and excite the LTSA or the VA. The short length of the slot line between the probe tips and the VA throat minimizes the probe interference.

IV. MEASURED CHARACTERISTICS:

a.) Input Impedance:

The input impedance Z_{in} at the reference plane of the LTSA in Fig. 1 is determined from the de-embedded reflection coefficient (S_{11}) using the well known transmission line equation

$$|S_{11}| \angle\phi = (Z_{in} - Z_0)/(Z_{in} + Z_0). \qquad (2)$$

c.) Mutual Coupling:

The mutual coupling between two LTSAs in close proximity and excited by two calibrated ground-signal microwave probes is determined from the measured direct transmission coefficient ($|S_{21}|$) on the ANA. The two LTSAs can be arranged either in coplanar or stacked configuration. The ground-signal microwave probes are calibrated to the tips as explained in Section III (b) above. Fig. 2 shows the experimental setup and the LTSA parameters.

d.) Absolute Gain:

To measure the absolute gain G, a pair of identical VA excited by two calibrated ground-signal microwave probes are oriented facing each other and polarization matched. The ground-signal microwave probes are calibrated to the tips as in the case of mutual coupling measurements. The distance of separation R between the antennas is such that far-field conditions prevail and is equal to or greater than

$$R = 2D_1^2/\lambda_0. \qquad (3)$$

Where D_1 and λ_0 are the largest aperture dimension of the VA and the free space wavelength at the measurement frequency respectively. The gain is given by Friis transmission formula [9]

$$G_r\, G_t = G^2 = (P_r/P_t)(4\pi R/\lambda_0)^2. \qquad (4)$$

Where G_r is the gain of the receiving antenna and P_r is the power received. Similarly G_t is the gain of the transmitting antenna and P_t is the power transmitted. Since the two VAs are identical $G_r = G_t = G$. The power ratio P_r/P_t is the direct transmission coefficient ($|S_{21}|^2$) taking into consideration the separation between the two antennas and is measured by the ANA. The experimental setup is shown in Fig. 3.

V. MEASURED RESULTS:

To facilitate antenna measurements, the probe station probe arms and the metal stage are mechanically modified and replaced by an expanded foam block respectively. Precaution is also taken to prevent interference from the metal parts of the probe station, partially surrounding and in close proximity to the antenna, by covering them with microwave absorbers.

The real and imaginary part of the de-embedded LTSA input impedance $Re(Z_{in})$ and $Im(Z_{in})$ as a function of the frequency are shown in Fig. 4. The frequency range is chosen as the entire Ka-band to demonstrate the broadband nature of the measurement technique. The figures show a series of resonances which are due to interaction between the reflected waves from the feeding end (throat) and from the open end (termination) of the LTSA. The $Re(Z_{in})$ takes on a value any where from a few tens of ohms to several hundred ohms. The $Im(Z_{in})$ varies between approximately ± 100 ohms over a significant portion of the frequency range.

The measured mutual coupling between two identical coplanar and stacked LTSAs as a function of the horizontal and vertical separation respectively are shown in Fig. 5. The measurements are performed at 29.166 GHz which is the center frequency of the LMDS band. In the two cases that are considered here for identical separations, the coupled power is smaller when the LTSAs are coplanar. This is so because, the centers of the LTSAs are physically further apart to begin with.

The gain for a VA as determined from the measured $|S_{21}|$ as a function of the frequency is shown in Fig. 6. The measurements are performed over the LMDS frequency band. Since the electrical length of the VA increases with frequency, the gain also increases with frequency. The gain for a single element is on the order of 11 dB which is typical for a VA.

VI. CONCLUSIONS AND DISCUSSIONS:

The paper demonstrates for the first time a de-embedding technique and a direct on-substrate measurement technique for characterizing mm-wave printed antennas. The efficacy of the above techniques is demonstrated by first, de-embedding the input impedance of a LTSA; second, by direct on-substrate measurement of the mutual coupling between two LTSAs in close proximity and the gain of a VA. By eliminating the need for custom test fixture and transitions to microstrip line, the above techniques are precise, fast and inexpensive and ideally suited for wireless applications at mm-wave frequencies.

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FIGURE CAPTIONS

Fig.1 Schematic Illustrating the Experimental Set-Up for Measuring the Input Impedance of a LTSA (L = 1.0 inch, W = 0.4474 inch, θ = 12.5° W_1 = 0.125 inch, D = 0.01 inch, ε_r = 10.5).) and the TRL On-Wafer Slot-line Calibration Standards (L_1 = 0.125 inch, W_2 = 0.003 inch, L_1' = 0.1475 inch.

Fig.2 Experimental Set-Up for Measuring the Mutual Coupling Between Two LTSAs (L = 1.5 inch, W = 0.6691 inch, W1 = 0.125 inch, θ = 12.5°, D = 0.01 inch, ε_r = 10.5).

Fig.3 Experimental Set-Up for Measuring the Gain of VA.

Fig.4 De-embedded Real and Imaginary Parts of the Input Impedance of a LTSA as a Function of Frequency.

Fig.5 Measured Mutual Coupling Between Two LTSAs in Coplanar and Stacked Arrangement as a Function of the Separation.

Fig.6 Measured Gain of a VA as a Function of Frequency.

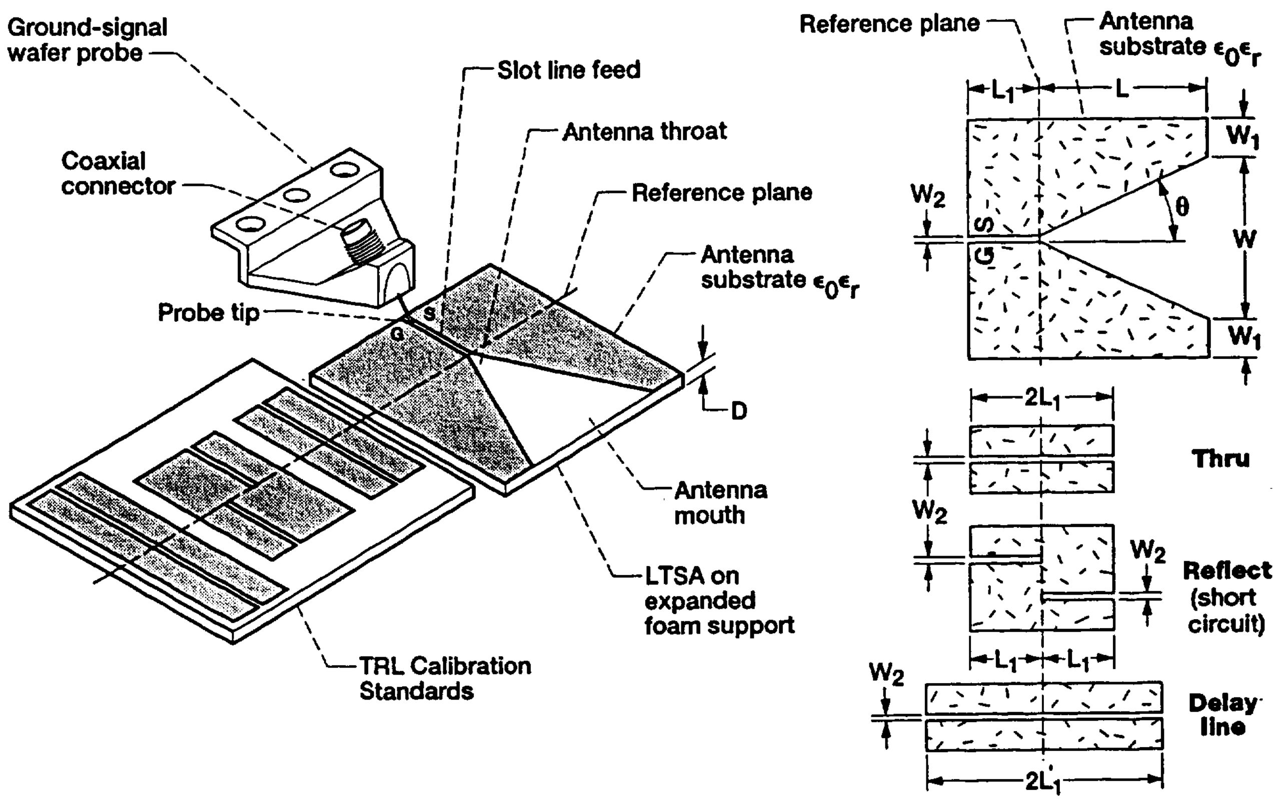


Figure 1.

E-10819 Simons (similar to E-9614) 9pt/100% rjc

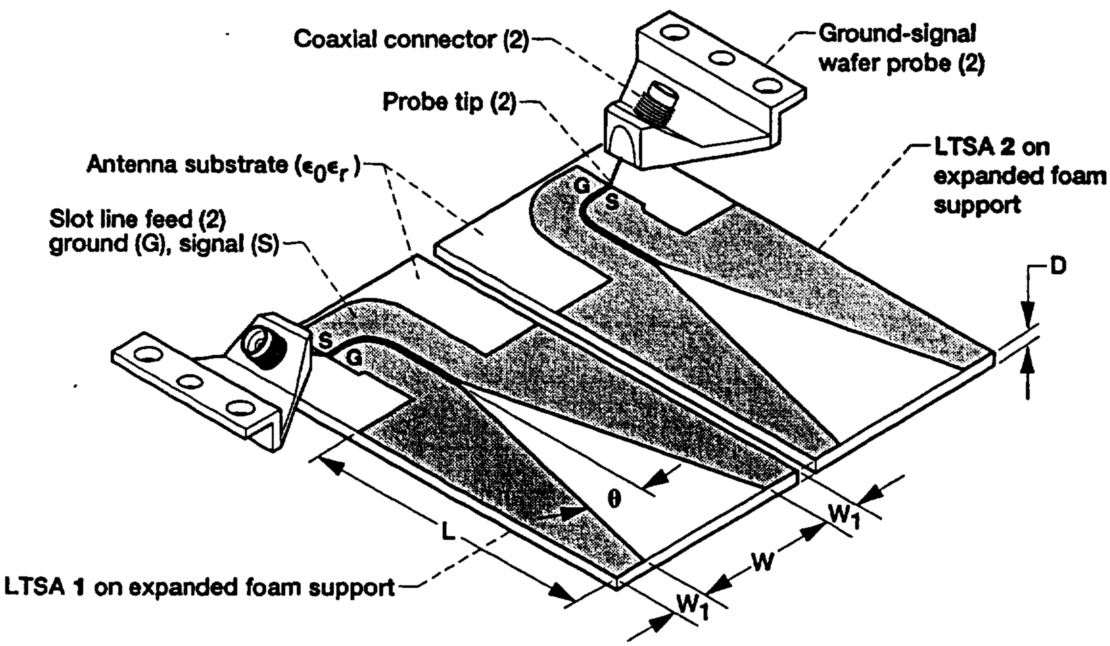


Figure 2.

E-10819 Simons (similar to E-10534) 9pt/100% rjc

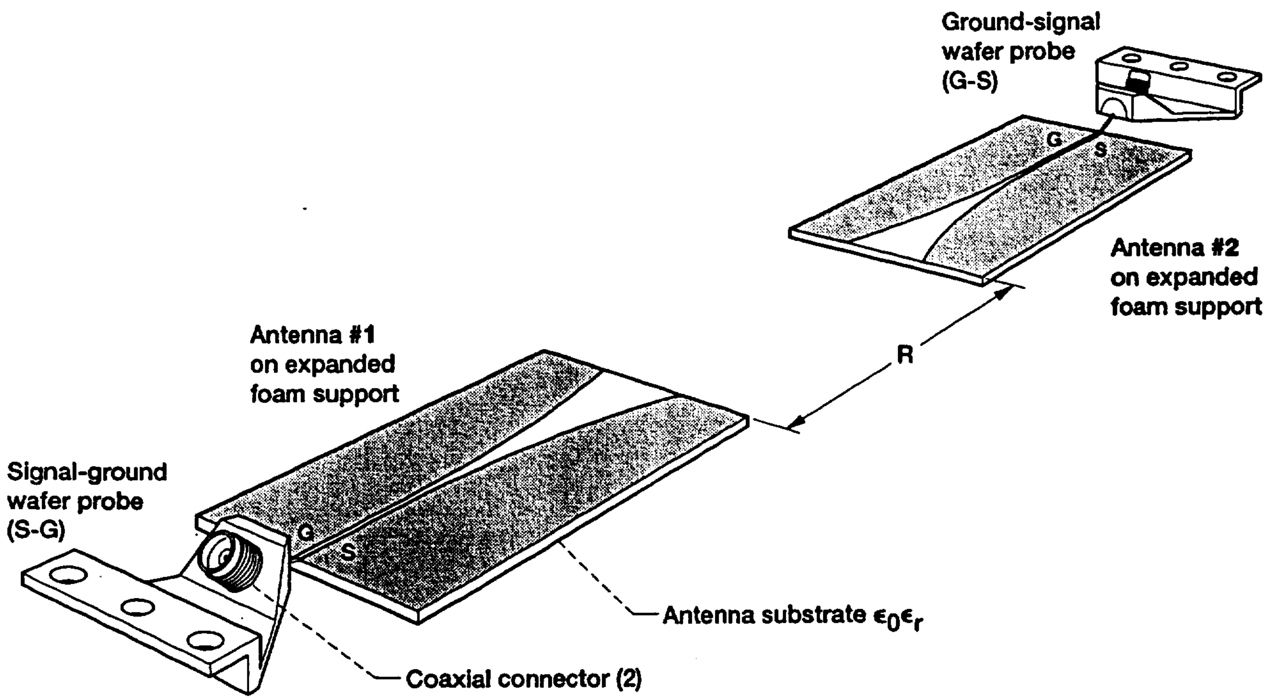


Figure 3.

E-10819 Simons (similar to E-10716) 9pt/100% rjc

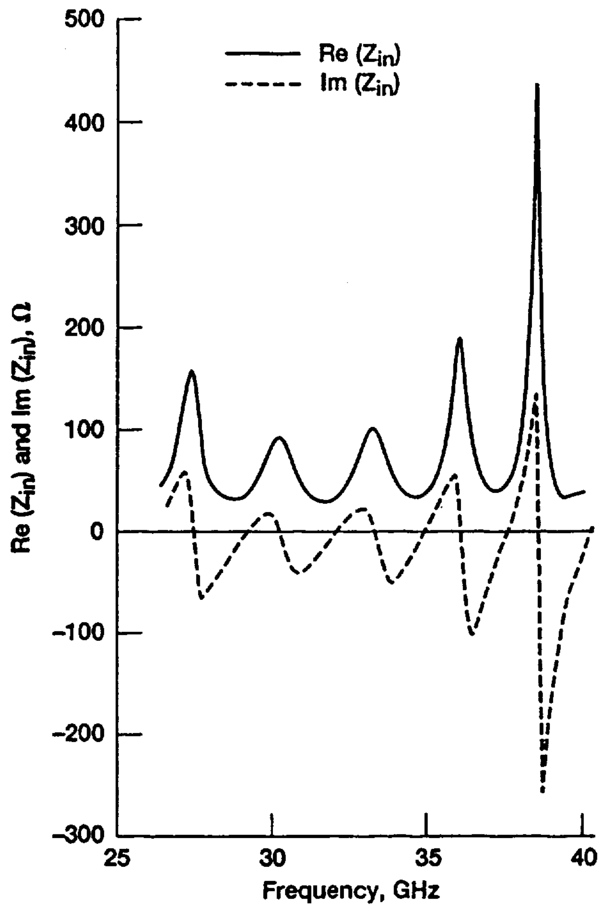
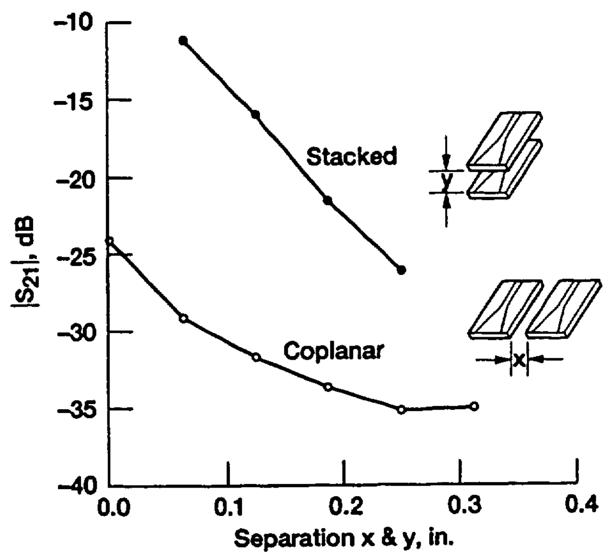


Figure 4

E-10819 Simons 9pt/100% nm From E-10716 old E-10819 fig 6ab



-10
-15
-20
-25
-30
-35
-40
$|S_{21}|$, dB
Stacked
y
Coplanar
x
0.0
0.1
0.2
0.3
0.4
Separation x & y, in.

Figure 5.

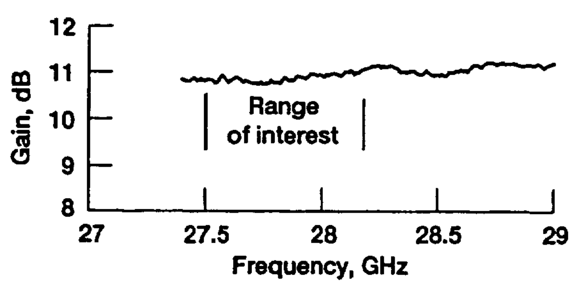

12
11
10
9
8
Gain, dB
27
27.5
28
28.5
29
Frequency, GHz
Range
of interest

Figure 6.