Efficiency Measurement of Millimeter Wave On-chip Antennas

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***Abstract*—This paper describes a simple and accurate method to measure the radiation efficiency of millimeter-wave on-chip antennas. Based on the Wheeler method a cap is designed which is compatible with the coplanar waveguide feed of the antenna. This method is applied to a 35 GHz on-chip antennas. the measured efficiency is compared with the simulated radiation e**

Keywords- Antenna efficiency, millimeter wave, on-chip antenna, Wheeler method.

I. Introduction

Radiation efficiency is one of the important characteristics of an antenna, which represents the portion of the input power delivered to the outer space by a transmitter antenna, or the amount of the received power by antenna aperture delivered to the receiver system. Any improvement in the antenna efficiency results in a larger transmission range for a fixed input power, or less power consumption (longer battery life) for a fixed transmission range, which is a significant advantage for portable wireless systems. The reported values for efficiency of many millimeter-wave antennas in the literature are based on 3D EM simulations. Usually CAD tools overestimate the antenna efficiency due to the following reasons:

1- Underestimating the substrate loss at mm-wave frequencies

2- Underestimating the fabrication errors especially at the antenna feed network

3- Reducing the model size (and antenna feed length) for faster speed

4- Numerical and modeling errors

At the millimeter-wave frequency range (30-300 GHz), where wavelength is in the order of silicon chip, implementation of on-chip antenna is more feasible than microwave frequencies. However, the antenna measurement is still a challenge at this frequency range.

This paper describes a simple but accurate method to measure the efficiency of on-chip antennas and obtain more reliable and realistic values.

II. Antenna Efficiency

Radiation efficiency of an antenna, η, is defined as [1]

$$\eta = \frac{P_{rad}}{P_{in}} \quad (1)$$

where, P_{rad} and P_{in} denote the radiated power and the input power to the antenna, respectively. This section proposes a configuration to increase the efficiency of the on-chip antenna and reduce the crosstalk to other circuits on the same substrate.

Another definition for efficiency, which is used by CAD tools, is the ratio of maximum antenna gain to the maximum antenna directivity:

$$\eta = \frac{G_{Max}}{D_{Max}} \quad (2)$$

III. On-chip Antenna Efficiency Measurement

The measurement method used in this work is based on the Wheeler method [1], which is applied to a 35 GHz on-chip antenna. The antenna design has been described in [2]. The antenna under test (AUT), shown in Fig. 1, consists of a rectangular dielectric resonator ($\varepsilon_r \approx 36$) excited by an H-slot antenna fabricated in IBM SiGe5AM process. The total silicon area for the implementation of antenna is 2 mm×1.5 mm. The H-slot is excited by a coplanar waveguide (CPW). The DR used in this work has a size of a=1.6mm, b=1.15mm, and h= 0.5 mm. In [2] it is shown that the antenna pattern covers the upper half plane. The maximum gain of the antenna structure is 1 dBi. Furthermore, the half-power beamwidth of the on-chip antenna exceeds 120 degrees.

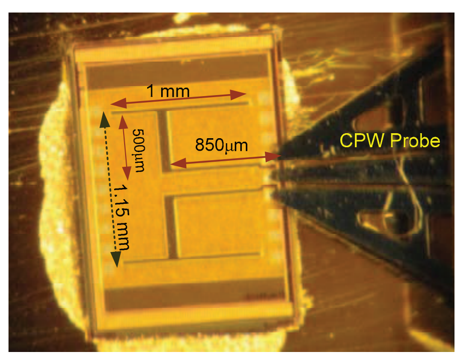

Fig. 1. The antenna under test excited by a CPW probe. The dielectric resonator is not shown.

Wheeler method is a fairly accurate way to measure the efficiency of the electrically small antennas. Usually, the antenna under test is probed from the bottom while it radiates in the upper hemisphere, but in this work, we have modified the Wheeler cap to be used for CPW-fed antennas. The Wheeler cap comprised of a cylindrical cavity, with 10 mm diameter and 8 mm depth, grooved in an Aluminum cube as shown in Fig. 2. A small opening (around 3 mm) was made for the CPW probe The ground lines of the CPW probe are in contact with the body of the cap during measurements.

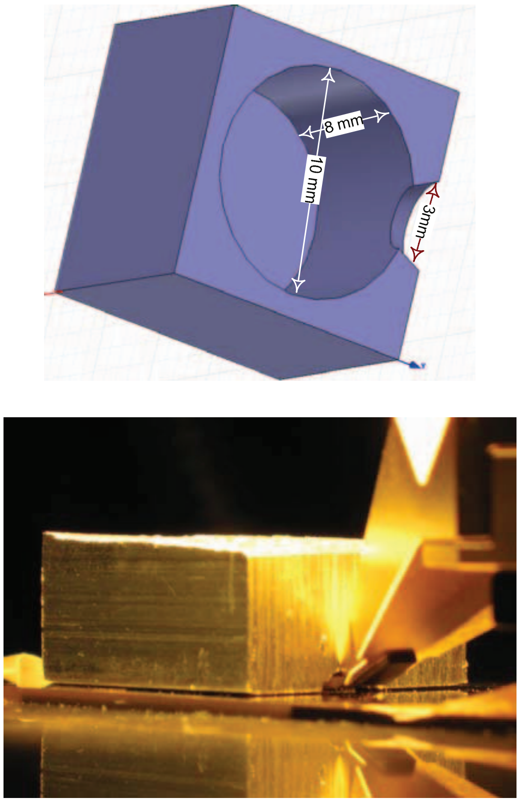

Fig. 2. Top: the Wheeler cap design for the efficiency measurement. Bottom: Wheeler cap placed on the antenna.

To apply Wheeler method for antenna efficiency measurement, the reflection coefficient (S_{11}) of the on-chip antenna system is measured twice: once with the Wheeler cap and once without it. Then 10 dB fractional bandwidth of the antenna (BW) was calculated in each case, and then the Q factor was found from the following relation [3]

$$Q_{\cdot} = \frac{v-1}{\sqrt{v}BW} \qquad (3)$$

where v is the Voltage Standing Wave Ratio (VSWR), which is related to the return loss (RL) by:

$$v = VSWR = \frac{\sqrt{RL}+1}{\sqrt{RL}-1} \qquad (4)$$

For RL =10 dB, v is equal to 1.925 (~2). Let Q_W and Q_0 denote the Q factors of the DR antenna with and without Wheeler cap. Then the efficiency at the resonance frequency is [4]

$$\eta = 1 - \frac{Q_0}{Q_W} \qquad (5)$$

Fig. 3 shows the results of the efficiency measurement test for the AUT. The 10 dB fractional bandwidth of the radiating AUT is 11.2 %. With Wheeler cap the bandwidth reduces to 5.8%. From (3), the values of Q_0 and Q_W are calculated as 5.9 and 11.5. Thus, from (5) the radiation efficiency is more than 48%. It is interesting to calculate the theoretical minimum quality factor, or Chu's limit for this antenna structure, given by [5]:

$$Q_{Chu} = \frac{1}{(kL)} + \frac{1}{(kL)^3} \qquad (4)$$

where L is the (largest) antenna size. For L =1.15 mm and k= $2\pi/\lambda_0$ at 34.5 GHz, the Chu's limit is 2.9. Replacing L by 1.6 mm which is the largest DR size, gives Q_{Chu}=1.6. So, It is seen that the measured Q factors are above the Chu's limit.

To find the efficiency of the proposed on-chip antenna at other frequencies, a 3D EM simulator (HFSS) is used. The efficiency is calculated by integrating the received power on a closed surface. Fig. 4 shows the simulated efficiency of the AUT. It is seen that the maximum simulated efficiency is 59%, which happens at 34.9 GHz. In this simulation some measured results were used to modify the antenna modeling. However, there is the simulated efficiency is 10% more than the simulated one. At most one fifth of this error is due to the opening in the Wheeler cap for probing the AUT. The rest is caused by some or all of the four reasons mentioned in the introduction of this paper.

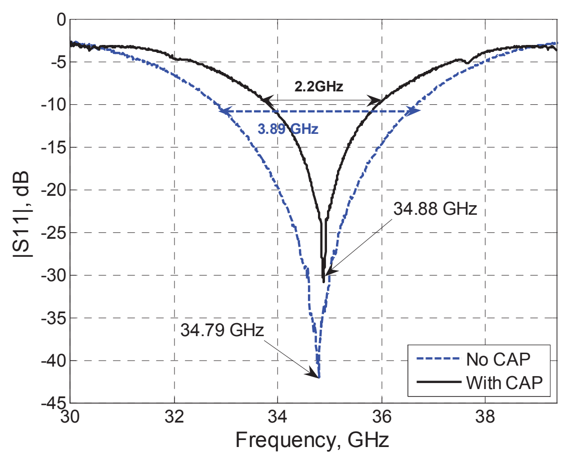

Fig. 3. Wheeler test results for the on-chip antenna. The reflection coefficient of the antenna is measured with and without the Wheeler cap. A slight shift in the resonant frequency is observed after placing the cap.

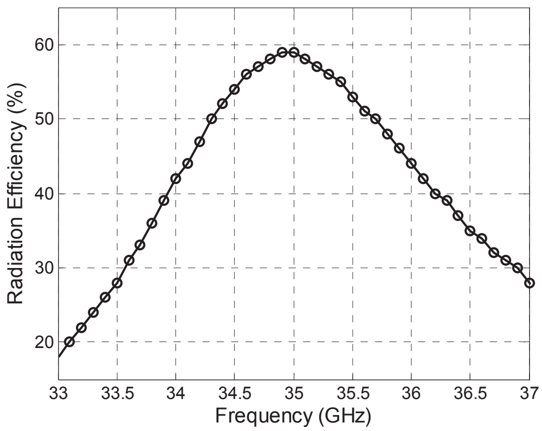

Fig. 4. Simulated radiation efficiency of the entire structure which shows a maximum of 59% at the resonance frequency.

Acknowledgment

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