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# A High-Efficiency Low-Cost Wire-Bond Loop Antenna for CMOS Wafers

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## I. INTRODUCTION

The high-level integration of radio transceivers for WLAN applications has become an increasing interest, because it can provide the benefits of cost reduction and system reliability. These highly-integrated radio systems are also designed with differential architectures, which is a great advantage in current silicon technology because it permits higher linearity and better immunity to common-mode noise caused by power supply variations and substrate coupling. Furthermore, the design of differential-feed antennas is essential to alleviate the adverse effects of bulky and lossy baluns. The fully integrated differential radio system from a circuit to an antenna will not only reduce the assembly cost and PCB area of a discrete antenna, but also improve the transmitter power efficiency and the receiver noise performance [1]. The antenna-on-chip solution on a silicon substrate, however, has a poor radiation efficiency of about 5 % due to the low resistivity and high permittivity of silicon [2]. To reduce silicon substrate loss, a multi-layered differential patch antenna was presented in [1]. The patch could obtain a radiation efficiency of 84 % at 5.4 GHz. In addition, a Yagi differential antenna implemented in a thin cavity-down ceramic material was also reported for highly integrated 60-GHz radios which had a peak gain of 6 dBi and 93 % radiation efficiency at 62 GHz [3]. Both antennas, however, require LTCC processing steps. In this paper, a simple low-cost vertical-type loop antenna that can be easily integrated with differential-feed circuits on low-resistivity silicon is proposed. The antenna consists of two asymmetrical wire bonds that are manufactured by a conventional wire-bond technique. A CPW-to-slot line transition is utilized for the on-wafer antenna characterization. The input impedance and gain patterns are measured and compared with full-wave simulation data.

## II. A VERTICAL-TYPE WIRE-BOND LOOP ANTENNA DESIGN

The proposed vertical-type loop antenna consists of two wire bonds of different sizes. Both wire bonds start from the ends of a differential line and terminate at a shorted-metal pattern. It is important to note that no ground plane is needed. A slot line for a differential feed was printed on 525- $\mu\text{m}$  thick silicon of resistivity 8  $\Omega\cdot\text{cm}$ . The width of the slot was 10  $\mu\text{m}$  and the widths of both metal lines were 100  $\mu\text{m}$ . Each end of the differential-feed line was also connected to the 50- $\Omega$  CPW line, which had a 100- $\mu\text{m}$  wide signal line and 60- $\mu\text{m}$  gaps between the signal and the ground. The performance of the CPW-to-slot line transition on the low-resistivity silicon was investigated in ADS Momentum, which calculated an insertion loss of less than 3.5 dB/mm and a mismatch loss of less than 30 dB from 45 to 55 GHz.

Each wire for the vertical-type loop antenna is a 25- $\mu\text{m}$  thick round-aluminum wire which was bent into a semicircle. The total length of the wires corresponds to  $1-\lambda$  at the antenna's resonant frequency. In order to investigate the relationship between the wire-bond height and the radiation efficiency, the small wire-bond height was fixed to  $0.01 \lambda_0$ , and the large wire-bond height was varied from 0 to  $0.3 \lambda_0$  at 50 GHz in HFSS. As the wire-bond height ( $h$ ) for the large loop was varied, the distance ( $d$ ) between the ends of

the large loop was adjusted to keep the same resonant frequency, maintaining the total circumference of the loop which was one wavelength at 50 GHz. When the large-loop height was increased from 0 to  $0.18 \lambda_0$ , the radiation efficiency also increased from 8 to 47.8 % at 50 GHz in the simulation.

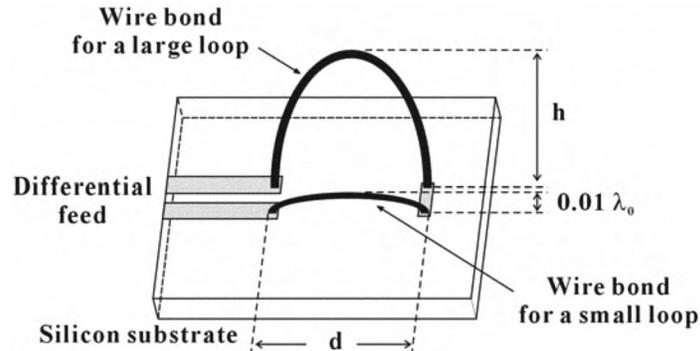


Figure 1. Sketch of the vertical-type wire-bond loop antenna with a differential feed.

### III. MEASUREMENT PROCEDURE

A 1500-Å-thick layer of silicon nitride followed by a  $\sim 1.2\text{-}\mu\text{m}$ -thick gold layer was deposited onto a low-resistivity silicon wafer. The two layers were etched to create the CPW-to-slot line transitions. The feed line was made to have 3-mm length to locate the probe in the far-field region. The wires for large loops were bonded individually to make different heights; such as  $0.08$ ,  $0.16$  and  $0.2 \lambda_0$ . The two-antenna method using a standard gain-horn antenna was applied to perform the antenna gain measurement [4]. A test fixture, as shown in Figure 2, consisted of a center stage to support the sample antenna and a semicircular hoop made of polyethylene to mount the standard gain horn. Two ends of the hoop were connected to the two stepper motors for the E- and H-plane pattern measurements. To reduce the multi-path reflections and scattering from nearby metallic objects, an absorbing material with  $-20$  dB absorption rate was used. A two-port SOLT was performed to calibrate out the cable loss and a second tier one-port SOLT was also executed to calibrate out the loss in the probe connected to the sample antenna. The far-field radiation patterns were measured at 26.9-cm away from the wire-bond antenna. The receiving horn was moved in small increments of  $1.8^\circ$  around the antenna and the  $S_{21}$  data was recorded at each point. The radiation patterns were measured in the E-plane which is an elevation plane and the H-plane which is azimuth.

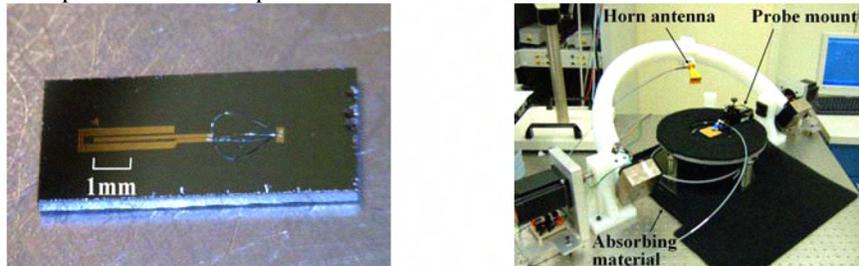
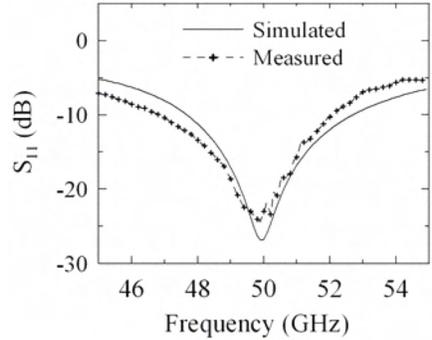


Figure 2. Photos of a fabricated antenna and a test fixture used for gain measurements [4].

### IV. MEASUREMENT RESULTS

The performances of four loop antennas of different heights were measured. Due to limitations of the wire bonding machine, the heights for the large loops were slightly smaller than the design and the heights for the small loops were slightly larger than the design. This variation did not have a significant effect on the antenna resonant frequency.

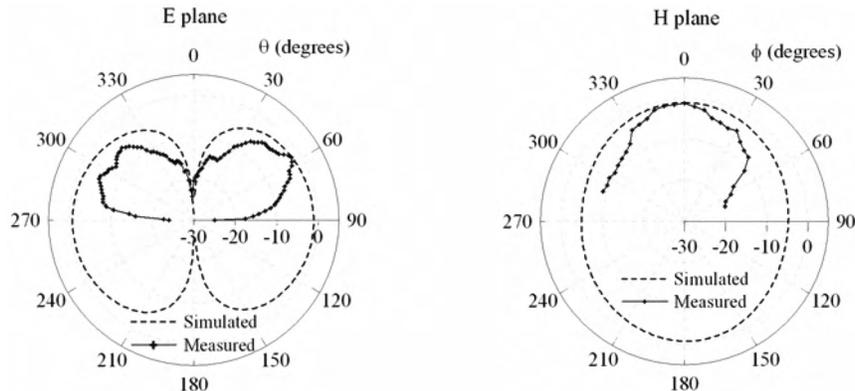
Figure 3 shows one of the measured antenna input mismatch losses, compared with the simulation result. The resonant frequency was almost same as the simulation of 50 GHz.



**Figure 3. Measured sample antenna mismatch loss compared to simulation data.**

In order to get a gain pattern, the Friis formula was applied to the measured  $S_{21}$  data between the standard gain horn and each sample antenna. Before the gain was calculated, the loss of a 6-mm back-to-back CPW-slot transition was measured and found to be about 25 dB at 50 GHz. Therefore, half of this loss (12.5 dB) was added to the measured gain to account for the feed line loss. The measured gain patterns for the  $0.16 \lambda_0$ -height wire-bond antenna are plotted in Figure 4. The E-plane pattern is in agreement with the simulation pattern. The maximum gain is -2 dBi at 57.6 degrees compared to -0.8 dBi at 90 degrees from the simulation. The gain value at 90 degrees shows a sharp drop, because the horn antenna dropped below the surface of the stage and was not in the line-of-sight of the sample antenna. The H-plane pattern shows a peak gain of -1.3 dBi at 0 degrees compared to -1 dBi at 0 degrees from the simulation. At  $60^\circ < \phi < 90^\circ$ , the horn was not in the line-of-sight of the sample antenna, which is the reason for the drop in gain.

Since the radiation efficiency could not be measured directly with the test fixture, the approximate values for the efficiencies were calculated by comparing the measured peak gain with the simulated directivity. As shown in Figure 5, the radiation efficiencies were 5.3 %, 8.5 %, 33.4 %, and 40.2 % for 0,  $0.08 \lambda_0$ ,  $0.16 \lambda_0$ , and  $0.2 \lambda_0$  height large loops, respectively. The efficiencies were a little lower than the simulation results. The reduced large-loop height and increased small-loop height made the loop area smaller than intended, which could explain the efficiency drop in the measurement. The silicon resistivity used in the simulation was  $8 \Omega \cdot \text{cm}$ , but the actual manufacturer's tolerance on the resistivity was 5~10  $\Omega \cdot \text{cm}$ , meaning that the real resistivity may not have been  $8 \Omega \cdot \text{cm}$ . When the loop height becomes much higher than  $0.2 \lambda_0$ , the loop area for radiation decreases. Therefore, an optimal loop height for the maximum radiation efficiency exists.



**Figure 4. Measured gain patterns in E- and H-plane compared to simulations.**

In addition, to confirm the necessity of a small-height loop instead of a printed metal line, the radiation efficiency was also measured when the printed metal line was used. The efficiency decreased from 33.4 % to only 24 %, which was due to loss from the low-resistivity silicon substrate.

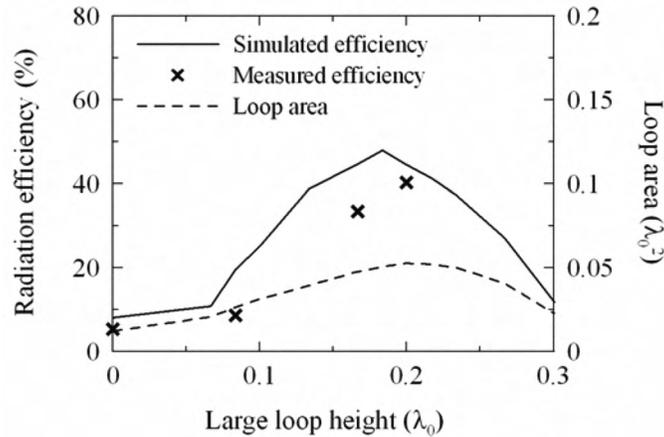


Figure 5. Estimated radiation efficiency from the measured gain, and the loop area for radiation were plotted against large loop height.

## V. CONCLUSION

The performance of a vertical-type loop antenna made by two asymmetrical wire bonds on a low-resistivity silicon substrate was investigated. The large-loop height was increased from 0 to  $0.3 \lambda_0$ , and the peak gain and radiation efficiency were observed after numerically removing the feed-line loss of 4 dB/mm at 50 GHz. When the loop height was increased from 0 to  $0.2 \lambda_0$ , the radiation efficiency showed a big improvement from 5.3 % to 40.2 % on a silicon substrate of  $\sim 8 \Omega\text{-cm}$  resistivity. Wire bonding is not only a cost-effective but also repeatable process, and this antenna can be easily connected to the front-end circuit with a differential-feed network. Therefore, the proposed vertical-type wire-bond antenna is a promising technique for high-efficiency on-chip radio antennas.

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