SiGe Process Integrated On-Chip Dipole Antenna on Finite Size Ground Plane

Mehdi Seyyed-Esfahlan, Mehmet Kaynak, Benjamin Göttel and Ibrahim Tekin, *Senior Member, IEEE*

***Abstract*— This paper investigates the effect of a finite size ground plane on the radiation pattern and reflection coefficient of an SiGe process integrated on-chip antenna. A flat 77 GHz on-chip strip dipole antenna integrated with a lumped LC balun circuit is designed and implemented. For increased directivity, the etched silicon substrate is placed on a metal ground plate. The on-chip antenna with the LC balun circuit is connected to GSG pads for measurement purposes. The antenna is well matched at the original resonance frequency band with 7-12 GHz impedance bandwidth and 4 dBi measured gain at 85 GHz.**

***Index Terms*—Millimeter wave radar, 77 GHz on-chip antenna, GSG pad, antenna on finite ground plane.**

I. Introduction

THERE is extensive research on on-chip antennas above the 60 GHz band for unbalanced fed antennas (such as slot or microstrip patch type of antennas) and balun circuits feeding balanced antennas like dipoles. Multiband on-chip T-type antenna applications with 30% efficiency have been demonstrated in [1], where dielectric resonators are used as parasitic resonators to excite the antenna in multiple frequencies. Their dimensions, location on the chip and the geometrical shapes of the antennas (dipole, 2-elements Yagi, rhombic and loop antennas) show significant effects on maximum gain (rhombic antenna with a gain of -0.2 dBi) on the 60 GHz band [2]. A wide band balun is presented with -6.5 dB reflection coefficient to feed a Yagi antenna which radiates up to 0.5 dBi at 77 GHz in [3].

Previous studies on various types of on-chip antennas on upper 60 GHz band [4] show very low or negative gain unless they are incorporated with another method such as using reflectors or silicon lenses [5]. The small size of the manufactured device and the substrate loss are basic challenges that drive the interest in the methods of feeding, measuring, design and fabrication of these types of antennas. In this paper, we propose dipole type antennas that occupy small areas on chips that can obtain a few dB gain for antennas with proper antenna geometry and balun design, and use IHP LBE module to decrease substrate loss and place a finite size ground plane for increased directivity.

This work was supported in part by The Scientific and Technological Research Council of Turkey (TUBITAK) under Grant 111E061.

M. S. Esfahlan and I. Tekin are with the Electronics Engineering, Sabanci University, IST 34956, Turkey (e-mails: msesfahlan@sabanciuniv.edu; tekin@sabanciuniv.edu). M. Kaynak, is with Technology/Process Integration IHP GmbH, Frankfurt 15236, Germany (e-mail: kaynak@ihp-microelectronics.com). B. Göttel is with Karlsruhe Institute of Technology, Karlsruhe, Germany.

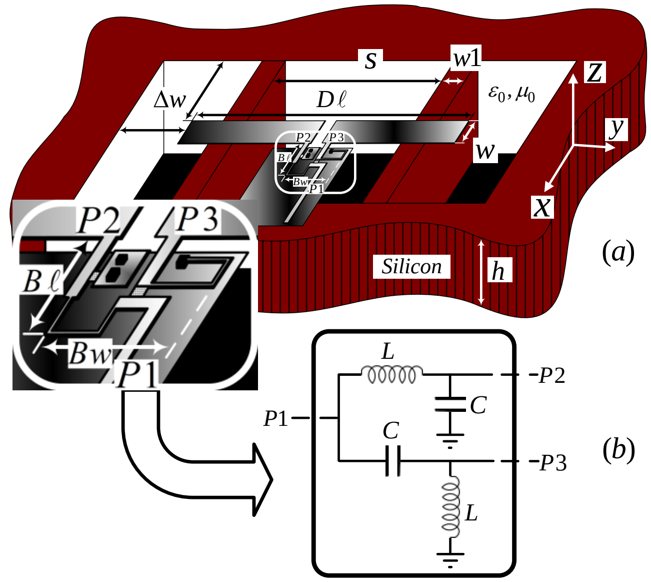

Fig. 1. 3-D schematic of the designed 77 GHz flat dipole antenna and its equivalent lumped circuit for the feeding LC balun.

An earlier design of an on-chip strip dipole antenna with an integrated lumped balun structure [6-7] is measured only for input impedance on an undiced full wafer and simulated with the GSG port only for very small ground plane size. However, size of the ground plane can both affect the input impedance and the drastic effect on the radiation pattern [8].

A standard BiCMOS process with an additional LBE module is used to realize the antennas. The silicon substrate below the antenna is etched away to eliminate the substrate loss and a ground plane is placed below the etched silicon substrate for increased directivity. Note that this antenna is integrated to the SiGe process and will not bring any other integration loss with the rest of active circuit.

The rest of the paper is organized as follows: In section II, detailed analysis about the balun structure and dipole will be presented. In section III, simulation and measurement results will be presented for the antenna, and finally the paper will be concluded in section IV.

II. Balun and On-Chip Strip Antenna

In this section, technology of the LBE process and the circuits for balun and antennas will be explained in detail. The designed antenna will be connected to a differential LNA based receiver for higher linearity and less substrate coupling noise. To measure an isolated differential antenna with a single ended GSG probe, an additional LC balun with lumped C and transmission line based inductors is designed and manufactured together with the dipole antenna. A sketch of the on-chip dipole antenna integrated with the LC balun circuit is shown in Fig. 1. The antenna is optimized for 77 GHz operation with a small ground plane size similar to antenna size and without an RF GSG port. Antennas and the feeding balun circuit are embedded in a thin layer of back-end-off-line (BEOL) SiO_2, and the silicon substrate (ε_r = 11.9, thickness of 700 μm) under the antenna is etched away using IHP LBE module. To increase the stability of the remaining silicon oxide layer, two silicon bars are left between the etching windows (Fig. 1). The cross section of the process is also shown in Fig. 2. The Metal1 line is used as the ground for the balun circuit and the antenna part while the Metal5 line is used for the signal of the balun circuit and the antenna structure. These metal lines are embedded in a SiO_2 layer (ε_r = 4.1) which has a total thickness of 11.4 μm.

A. *Balun Circuit*

To decrease the total occupied chip area, an on-chip strip dipole antenna is integrated with the lumped LC balun as shown in Fig. 1. The LC balun converts the single ended signal from P1 to differential signals with passive LC components at ports P2 and P3 (Fig. 1). The inductors are formed by thin-film microstrip lines while the metal-insulator-metal (MIM) capacitors available in technology library are used. S-parameters simulations are performed using 3D electromagnetic software HFSS® version 13.0 between 50 and 100 GHz. An inductor value of L = 140 *p*H and a capacitor value of C = 37 *f* F are obtained for the balun structure at the desired frequency [6]. The simulation results for the designed balun are shown in Figs. 3 and 4 for S-parameters and phase difference between ports, respectively. The input port is well matched at the desired frequency and 3.75 dB insertion loss for input and each of the output ports (P2 and P3) are obtained at 77 GHz. Left side scaling in Fig. 4 shows phase difference (in degree) between input port and each of the output ports (Φ_{12} and Φ_{13}). Right side scaling belongs to phase difference between output port and equals to $\Phi_{23} = \Phi_{13} - \Phi_{12}$. Φ_{23} is -181 degrees at the desired frequency. The balun structure occupies an area of 210 μm × 212 μm. For measurement purposes, an additional 500 μm long microstrip line is connected to decrease the effect of the RF measurement probe on the antenna radiation pattern.

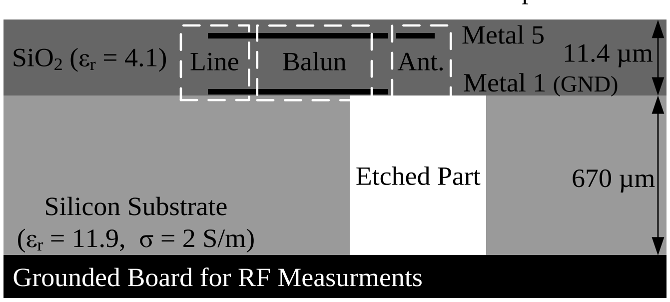

Fig. 2. Cross section view of the etched substrate and different layers illustration.

B. *Strip Dipole Antenna*

The dimensions of the strip type dipole antenna and the parameters of the balun circuit are optimized for both the impedance matching in a 50 Ω measurement system and the maximum gain of the antenna. Simulations are performed in order to optimize the design parameters of dipole length (D*l*), width of the silicon bars (*w*1), and etching window size (Δ*w*).

C. *GSG Pad*

Designed antenna needs to be measured to compare with the results of simulations. To measure the antenna parameters including reflection coefficient with a Network analyzer, additional GSG pads are drawn in layout of the antenna. Ground pads are connected to the Metal 1 ground plane through vias. Signal pad is connected to the antenna with a 50 Ω microstrip line length of 500 μm.

III. Simulation and Measurement Results

In this section, simulation and measurement results will be given for the antenna with GSG port integrated with the balun circuit on a very large size ground plane.

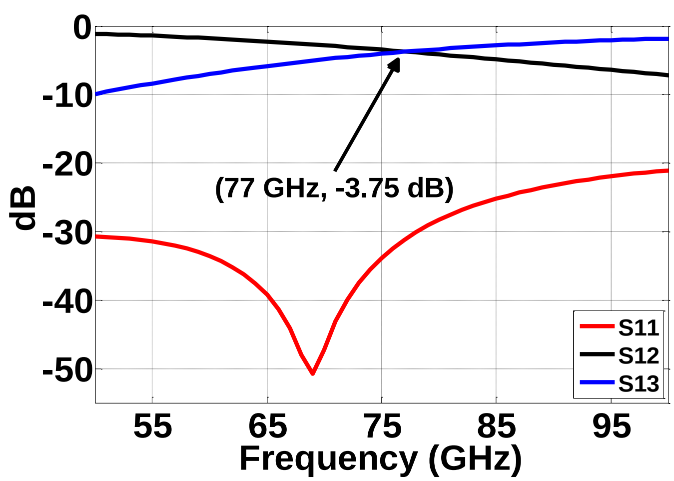

Fig. 3. Simulated reflection coefficient at P1 (S11) and scattering parameters between P1-P2 (S12) and P1-P3 (S13) ports.

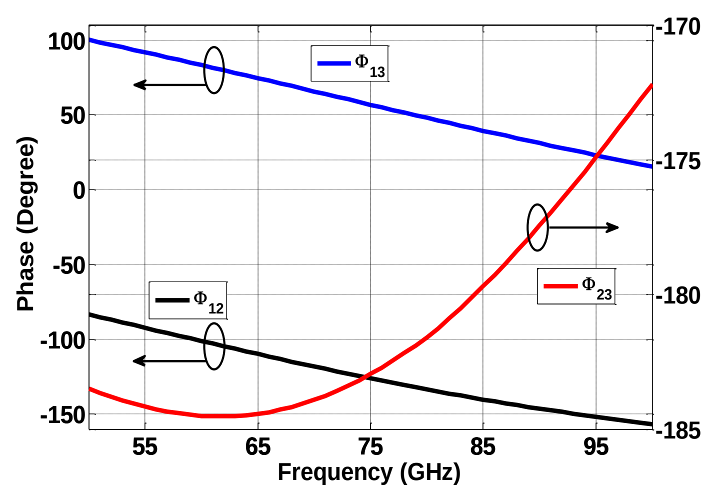

Fig. 4. Left-side scaling for simulated phase difference between P1-P2 (Φ_{12}), P1-P3 (Φ_{13}) and right-side scaling for P2-P3 (Φ_{23}) ports.

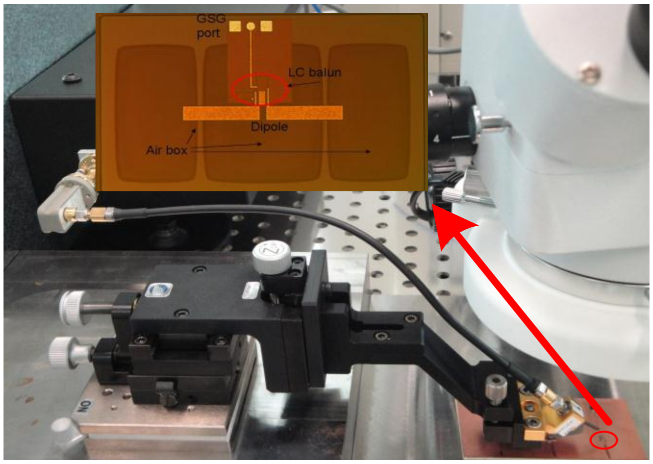

Fig. 5. Manufactured antenna and measurement setup.

Measurements are performed for reflection coefficient, radiation pattern and gain of the antenna. Reflection coefficient is measured at Sabanci University (SU), using PNA-X 5245A network analyzer with ACP-110 110 GHz probes, KIT and IHP. The experimental setup for measuring reflection coefficient at SU is illustrated in Fig. 5. Manufactured antenna chips are further mounted on a piece of PCB board using epoxy (glued with very tiny epoxy bullet by the side of chips) and cured for measurement.

Fig. 6 shows reflection coefficient of the simulated and measured antenna. The results of simulated antenna with GSG pads include both a small (red curve) and a large ground plane (blue curve) to show the effect of ground plane size. For the antenna with small ground plane, the minimum of the reflection coefficient is simulated as 14 dB at 82 GHz; with achieving 12 GHz 10 dB bandwidth. The addition of GSG pads shifted the resonance frequency to 82 GHz. As the ground plane size is increased as shown with solid blue curve, the simulated antenna on a large ground plane has 10 GHz, 10 dB impedance bandwidth around resonating frequency of 85GHz with -13.5dB reflection coefficient. Increased size of the ground plane shifts the resonance frequency further. Both IHP and KIT have measured antenna with 8 GHz 10 dB-

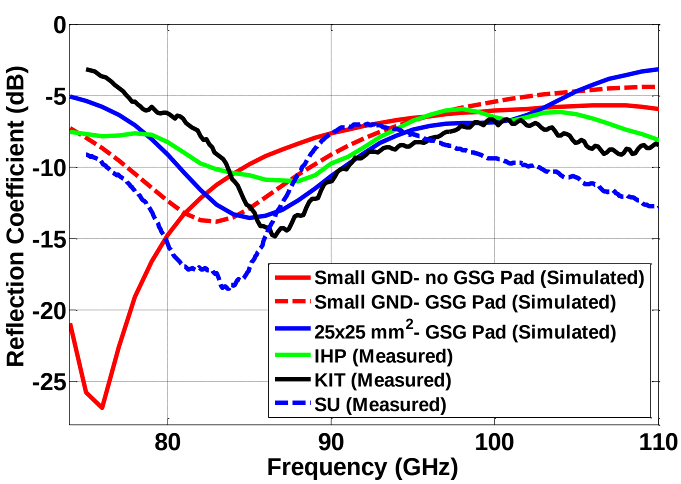

Fig. 6. Reflection coefficient of the antenna on small and large ground plane for simulation and measured on large ground plane by IHP and KIT.

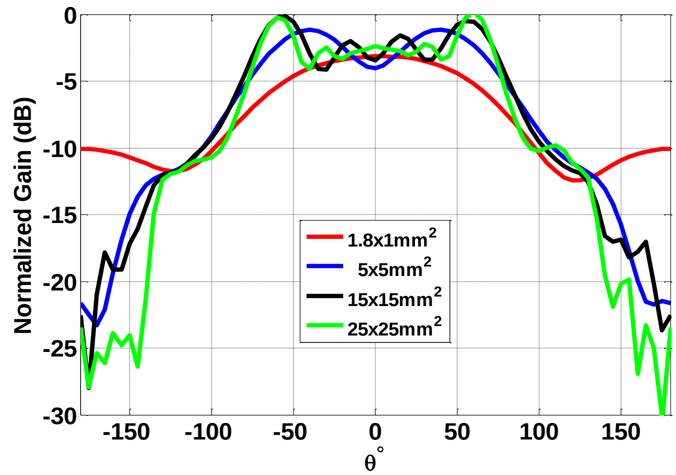

Fig. 7. E-plane gain of the simulated antenna on small/large ground planes.

bandwidth around 86.5 GHz with -11dB and -15 dB reflection coefficients, respectively. Measured reflection coefficient at SU (dashed blue curve) has 12 GHz bandwidth around 83.5 GHz with -19 dB reflection coefficient. Depending on the size of the ground plane, the resonance frequency of the antenna is shifted to upper frequencies. The discrepancy between simulated and measured result may also be caused by the value of dielectric constant assumed in simulations (At higher frequencies, dielectric constant of silicon may change). Return loss/ reflection coefficient measurements are very sensitive to the placement of GSG probe. In a manual setup, at the antenna resonance, changing depth of GSG probe and also the location on the GSG probe can easily change the measured value of return loss/ reflection coefficient. A 10 dB return loss value can easily be varied ±5 dB with the probe location. In Fig. 6, antenna resonances are correctly measured with some frequency shifts in 80-100 GHz range. These shifts can easily be induced by the measurement setup and GSG probes. Measurement setups at different institutes have produced very close measurement results as shown in Fig. 6.

The effect of ground plane size on the E-plane (yz plane in Fig. 1) radiation pattern is shown in Fig. 7 for ground plane sizes including planes the same as the antenna size (1.8mm × 1mm), $(1.28\lambda_o)^2$, $(3.85\lambda_o)^2$ and $(6.4\lambda_o)^2$ to show their effect on antenna radiation pattern shape and gain. For a small ground plane, the maximum gain -3.14dBi is simulated at θ=0º, and for a larger ground plane $(1.28\lambda_o)^2$, a maximum gain of -1.16 dBi at θ=±40º is obtained. As the ground plane size is increased, two additional lobes appears at θ=±60º with 0 dBi gain 2 dB larger than the gain at θ=0º due to surface waves. For finite grounded thick substrates, surface waves can propagate and diffract/reflect from the ground plane and distort the radiation pattern. The source of these lobes is the TM0 surface wave from left silicon substrate.

In Fig. 8, measured and simulated E and H-plane (xz plane in Fig. 1) radiation patterns which are normalized to their maximum values are shown for 77 GHz. E-plane radiation patterns (red and black curves) are wider than the H-plane radiation patterns (green and blue curves). For the E-plane, there are two side lobes due to the effect of the surface wave at

60 degrees. Gain at these side lobes is 3 dB larger than the gain at θ=0º. The H-plane radiation pattern is more directive than the E-Plane pattern. For wide angle range around 0º, the measured E-plane radiation pattern is well matched with the simulated result. Measured and simulated gain at θ=0º versus frequency for the band of 75 to 110 GHz is displayed in Fig. 9. Around the operation frequency, the measured and simulated results are in good agreement. Since the antenna is matched better in the band 85 GHz to 90 GHz (measured S11 by KIT in Fig. 6) higher gain is obtained at θ=0º in this band (85-90 GHz). Maximum gain (at θ=0º) of 4.1 dBi at frequencies 84.8 GHz and 88 GHz is achieved. Measured antenna gain at $\theta = 0º$ for frequencies 77 GHz and 85 GHz are -1.9 dBi and 4 dBi, respectively. Note that a free space dipole has 2.2 dBi gain, and when placed above a ground plane; one can target a gain of 5.2 dBi from the on-chip strip dipole antenna assuming lossless feeding circuit and good impedance matching.

IV. Conclusion

For 77 GHz automotive radar applications, an on-chip dipole antenna with integrated LC balun circuit is presented. To increase the gain of the antenna while matching the impedance to 50 Ω, the substrate is etched using IHP LBE module. Both the simulation and experimental results are in good agreement and provides -19 dB reflection coefficient and 4.1 dBi gain at desired frequency band. GSG pads add capacitance to the input impedance and shift the resonance frequency higher. To tune the antenna with the GSG pads at 77 GHz, the antenna can be redesigned by decreasing the length of antenna arms and adjusting the LC balun parameters. From our measurements, we can suggest that larger than $(4\lambda_o)^2$ size is enough for a large ground plane. However, problem of surface wave excitation due to thick substrate should be handled to remove the distortion in radiation patterns.

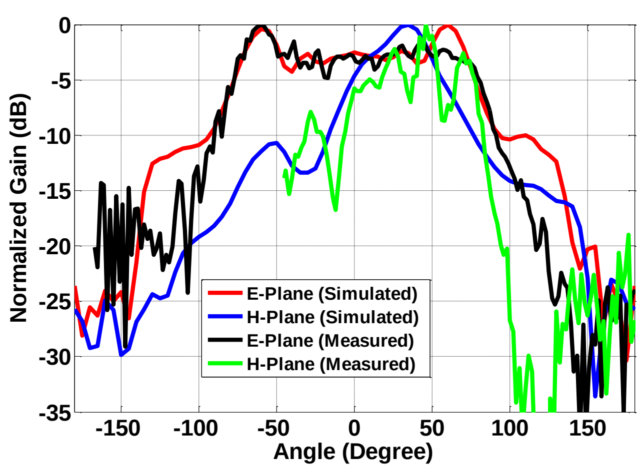

Fig. 8. Simulated and measured radiation pattern for E and H-plane at 77 GHz.

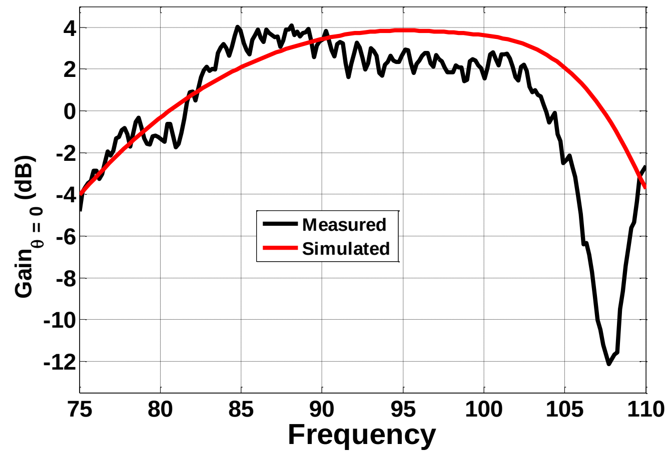

Fig. 9. Measured and simulated antenna gain versus frequency.

References

[1] M. R. N. Ahmadi, and S. Safavi-Naeini, "On-chip Antennas for 24, 60, and 77GHz Single Package Transceivers on Low Resistivity Silicon," *IEEE International Symposium on Antennas and Propagation*, pp. 5059–5062, June 2007.

[2] F. Gutierrez, S. Agarwal, K. Parrish, and T. S. Rappaport, "On-Chip Integrated Antenna Structures in CMOS for 60 GHz WPAN Systems," *IEEE Journal on Selected Areas in Communications*, vol. 27, no. 8, pp. 1367–1378, Oct. 2009.

[3] Y.-H. Chuang, H.-L. Yue, C.-Y. Hsu, H.-R. Chuang, "A 77-GHz Integrated On-Chip Yagi Antenna with Unbalanced-to-Balanced Bandpass Filter Using IPD Technology," *Proceedings of the Asia-Pacific Microwave Conference (APMC)*, pp. 449–452, Dec. 2011.

[4] Y. P. Zhang, M. Sun, and L. H. Guo, "On-Chip Antennas for 60-GHz Radios in Silicon Technology," *IEEE Transactions on Electron Devices*, vol. 52, no. 7, pp. 1664–1668, July 2005.

[5] S. Beer, G. Adamiuk, and T. Zwick, "Novel Antenna Concept for Compact Millimeter-Wave Automotive Radar Sensors," *IEEE Antennas and Wireless Propagation Letters*, vol. 8, pp. 771–774, 2009.

[6] M. Seyyed-Esfahlan, M. Kaynak, and I. Tekin, "A 77 GHz On-Chip Dipole Antenna with Etched Silicon Substrate," *13th International Symposium on RF MEMS and RF Microsystems*, pp. *–*, July 2012.

[7] I. Tekin and M. Kaynak, "A 77 GHz On-Chip Dipole Antenna Integrated with Balun Circuits for Automotive Radar," *IEEE International Symposium on Antennas and Propagation and USNC-URSI National Radio Science Meeting, USA*, pp. 1-2, July 2012.

[8] A. K. Bhattacharyya, "Effect of Finite Ground Plane on the Radiation Characteristics of a Circular Patch Antenna," *IEEE Transactions on Antenna and Propagation*, vol. 38, no. 2, pp. 152–159, Feb. 1990.