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Design and Probe Based Measurement of 77 GHz Antennas for Antenna in Package Applications

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***Abstract*— The development and the measurement of two planar antenna structures is presented. These antennas are prospective candidates for the integration into compact millimeter-wave packages for 77 GHz automotive Radar applications. The antennas were manufactured using only one metal layer on top of a 127 µm Alumina substrate. Gain, radiation pattern and Return Loss of the antennas are characterised using a novel probe based measurement setup.**

***Index Terms*— Slot antennas, Millimeter wave antennas, Antenna measurements, Millimeter wave measurements, Millimeter wave radar**

I. Introduction

The increasing capabilities and cost reductions of SiGe HBT technology [1] and Si CMOS [2] technology have made millimeter wave (mm-wave) frequencies attractive for low cost applications. One promising application are automotive radar systems in the allocated frequency bands at 76-77 GHz and 77-81 GHz [3]. The goal is to realize radar systems with compact dimensions, high performance and low cost. The small wavelength at mm-wave frequencies offers a way to reduce the size of the passive components, but also demands high-precision machining and increases the requirement regarding packaging interconnects. One possibility to further decrease the size of a complete radio frequency (RF) system and to relax the requirements for the interconnects is to integrate the antenna into the RF package. This way, only baseband signals need to be conducted from and to the package. However, integrating an antenna into a package is not an easy task.

The main requirements, beside low-cost and compact dimensions, are sufficient bandwidth, high efficiency, suitable pattern, and the prevention of substrate waves. Different packaging approaches can be found among literature [4-7]. Monolithic integration [4] offers the possibility of realizing all active and passive devices including the antenna on a single semiconductor die. However, Silicon is generally a poor antenna substrate. High permittivity and low resistance drastically reduce the antenna efficiency. Special techniques have to be used to either enhance the resistivity [8] or to selectively remove the substrate below the antenna [9]. Yet this enlarges the costs in the production cycle. Realizing multi-layer substrates [6-7] offers the highest integration capability because several substrate layers can be used to realize passive components and base band circuitry. The high costs have however prevented LTCC of becoming a candidate for mass market consumer equipment [10]. Using a ceramic substrate for the antenna and integrating this substrate into the package [5] offers the highest degrees of freedom. The antenna substrate can be chosen for optimum performance and the package itself can be used for beam shaping. The drawback is a more complex packaging process.

In this work, we intend to generally examine the performance of 77 GHz antennas on a ceramic substrate for their suitability regarding the integration into Radar packages. The antennas are realized using only one metal layer on top of an Alumina substrate, which is very cost efficient. In Section II the antenna structures are presented. Section III shows the measurement setup which was used to characterize the antennas while Section IV and Section V give results and conclusions, respectively.

II. Antenna Structures

All antennas were manufactured on a 127 µm thick, 4" x 4" large Alumina substrate ($\varepsilon_r = 9.9 \pm 0.2$; $\tan\delta = 0.001$). The structures were etched in a single gold layer. The substrate was then sawed into the smaller antenna substrates (3 x 7 mm^2), which contain the antennas, the feeding lines, and the RF probe pads, as shown in Fig. 1.

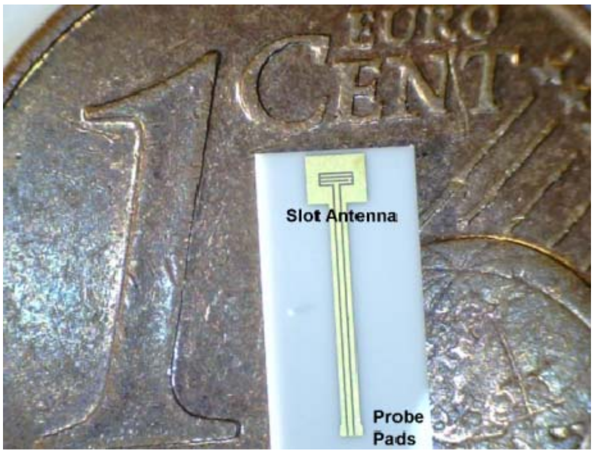


Fig. 1. Slot antenna, feeding lines and probe pads

The difficulty in designing antennas on Alumina is the large permittivity that causes most of the energy to be radiated into the substrate. The main task therefore is to place the antenna on a position on the substrate where it does not cause substrate waves but still radiates most of the energy. Substrate waves would either cause the efficiency to shrink because of the losses in the substrate or would strongly influence the radiation pattern because the energy in the substrate waves is radiated from the edge of the substrate. The thickness of the substrate was chosen to the smallest thickness available (127 µm), which is about one ninth of the wavelength in Alumina at 80 GHz.

The antennas are planar structures that use only one metal layer. This enables them to be interconnected via solder balls to an Integrated Circuit (IC) in a flip-chip attachment. To allow measurement with a coplanar microwave probe all antennas are fed with a 50 Ω coplanar waveguide (CPW) transmission line that ends with the probe pads. The width of the inner conductor of the CPW line is 95 µm, the outer conductors have a width of 90 µm while the distance of the conductors is 40 µm. The probe pads are designed for a GSG probe with a pitch of 150 µm.

Antenna 1 is a folded slot antenna, as shown in Fig. 2. This antenna is the dual antenna to the folded dipole. It is attractive because it offers an easy way to influence its impedance. By introducing multiple parasitic slots the high input impedance of a single slot antenna Z_s can be decreased by

$$Z_{s,N} = \frac{Z_s}{N^2} , \qquad (1)$$

where N is the total number of slots and $Z_{s,N}$ is the impedance of the folded slot antenna with N slots [11]. This relation however only holds while the currents and fields are equal in all slots. This assumption is only true for a small number of slots.

In our case, an antenna with two slots shows an impedance of about 150 Ω. Using (4) an antenna with four slots would have an impedance of 37.5 Ω. Yet the simulations show an impedance of about 55 Ω. This verifies the trend of (1), but also shows that the impedance decreases by a smaller factor than $1/N^2$.

The antenna's resonance frequency is specified by the slot length which is 0.8125 mm in our case. The width and the distance of the different slots are 40 µm. The ground plane around the slots was designed with finite dimensions. The simulations showed that the size of this ground plane has a large influence on the radiation pattern. In the final layout the ground plane has a size of 1.3 x 0.8 mm^2.

Antenna 2 is a dual bow-tie antenna, as shown in Fig. 2. It is also a slot antenna that can be fed by a CPW transmission line. In that case the slots are becoming wider in direction of the sides. Similar to a biconical dipole this leads to an enhanced bandwidth. The dual bow-tie antenna is known to yield wide bandwidth and high efficiency [12] while offering an easy way to influence the impedance for a given resonance frequency by changing the dimensions w_1 and w_2. The resonance frequency is again given by the slot length l, which is 1.6 mm in our case. An optimized bandwidth was found for the slot widths $w_1 = 0.32$ mm, $w_2 = 1.5$ mm. In the case of the dual bow-tie antenna the size of the ground plane did not affect the radiation diagrams but rather the impedance and bandwidth. In the final layout it has a size of 2 x 1.5 mm^2.

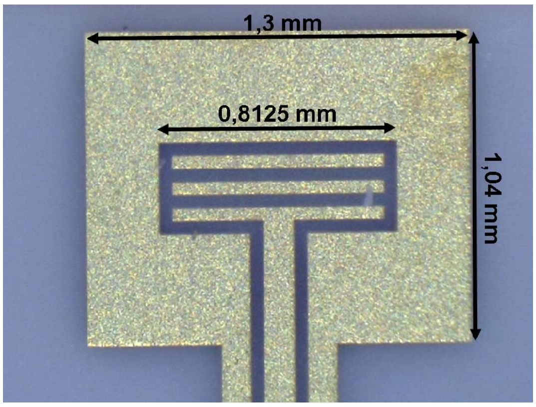


Fig. 2. Folded slot antenna

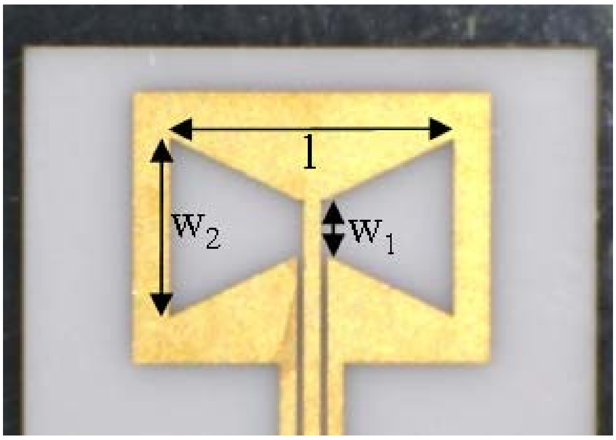


Fig. 3. Dual bow-tie antenna

III. MEASUREMENT SETUP

The antennas are measured with a new setup in which a coplanar micro-wave probe is used to contact the antenna [13]. This technique eliminates the need of a coaxial connector which would be extremely challenging to mount to the small antenna substrate [14] and which is not required in the final packaging solution. Hence, the antenna is measured exactly where it will be connected to the IC later. This however makes it impossible to measure the antenna in an ordinary anechoic chamber where the Antenna Under Test (AUT) is positioned on a tower that rotates around its axis. The movement of the tower would lead to vibrations that could affect the probe alignment or even damage probe and AUT. Therefore a setup has to be used in which the AUT and the probe do not move and in which a reference horn is moving on a sphere around the AUT to measure the radiation pattern. Additionally, the AUT may not be placed on a probe station like in [15], because the metallic parts would drastically impact the antenna performance.

In our setup, as shown in Fig. 4, the AUT is positioned in the middle of the setup. The AUT itself is placed in air while the antenna substrate is attached to a sample holder at its end. The sample holder is made of Rohacell® foam which resembles air, as shown in Fig. 5. The AUT is contacted by a coplanar microwave-probe and is used as the transmit antenna during the measurement.

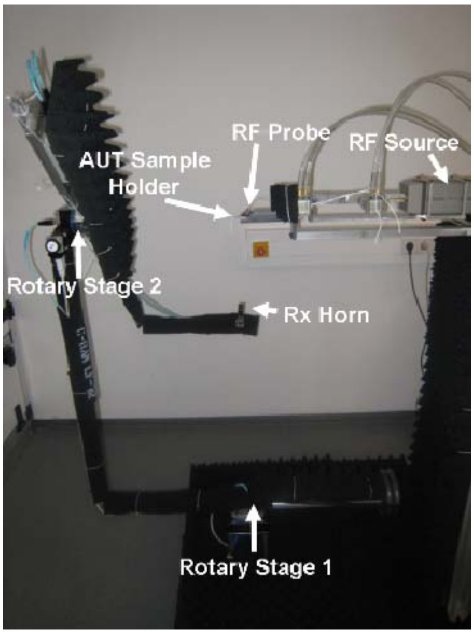


Fig.4. Antenna measurement setup

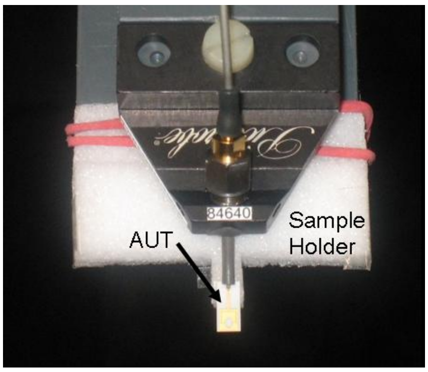


Fig. 5. AUT sample holder and RF probe

Using two rotational stages and two arms a receive horn can be moved on nearly the full sphere around the AUT in a distance of 60 cm. This far field distance allows the characterization of apertures as large as 11 cm^2 at 80 GHz. Hence it is even possible to measure arrays or complete packages together with a lens or a reflector. The orientation of the receive horn can be twisted around 90 degrees so that both polarizations can be measured. With the setup nearly the complete 3D radiation pattern of the AUT can be measured, as well as the complex antenna impedance at the point where the antenna is connected to the MMIC later.

To de-embed the influence of the probe an OSL calibration is accomplished before the measurement of the AUT using a custom made wafer chuck that can be attached to the measurement setup instead of the AUT sample holder. To calibrate the gain a reference horn with well known gain is connected to the RF source instead of the AUT. Using a custom bended waveguide it is guaranteed that the horn is positioned at the same spot as the AUT would be.

IV. Measurement and Simulation Results

The E- and H-Plane of both antennas are identical. The H-Plane is perpendicular to the feeding lines and can be measured completely. The E-Plane is parallel to the feeding lines and can be measured in a range of 255˚, while the rest of the plane is blocked by the table. In both planes 0˚ is the direction upwards and ±180˚ is the direction downwards through the antenna substrate.

Fig. 6 shows the measured and simulated return loss of the folded slot antenna. It can be observed that the matching deteriorated in the targeted range around 80 GHz. This can be explained by the inaccuracy of the substrate permittivity and the line width tolerances of the thin film process that caused the effective slot length to slightly decrease. Nevertheless a matching of nearly better than 10 dB can be observed from 75 to 92 GHz. The measured radiation patterns at 80 GHz (Fig.7) show good agreement with the simulation results. It can be observed that the gain decreases in the direction 0˚, but the antenna still offers a good omni-directional pattern and an average gain of about 0 dBi.

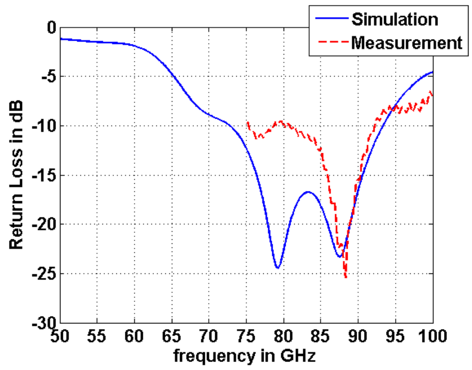
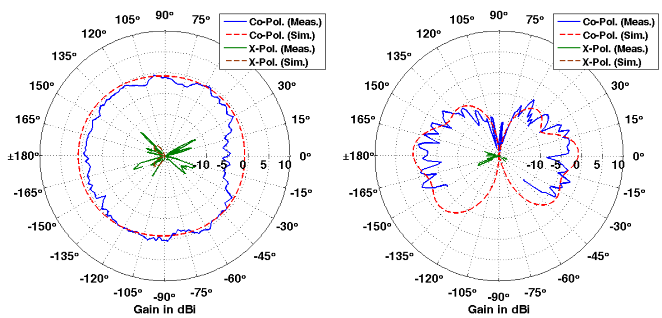


Fig. 6. Return Loss of the folded slot antenna



(a) (b)

Fig. 7. Gain of the folded slot antenna: (a) H-Plane. (b) E-Plane.

The dual bow-tie antenna has a return loss of better 10 dB from 75 to 87 GHz (Fig.8) and by that a slightly smaller bandwidth compared to the folded slot antenna. The measured and simulated input return loss show good agreement. This antenna seems to be less susceptible regarding slight changes of the permittivity and the lengths. The measured radiation patterns at 80 GHz also confirm the simulation results and verify the omni-directional behaviour. A slighly smaller decrease in gain in the direction 0˚ compared to the folded slot antenna can be observed. A disadvantage is the stronger radiation in cross-polarization, especially in the H-plane. The reason is probably the antenna's geometry that causes an electric field vector parallel and perpendicular to the feeding lines.

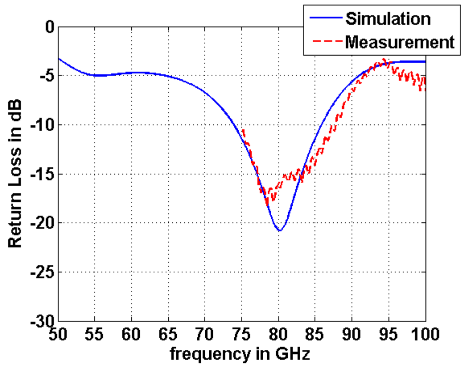
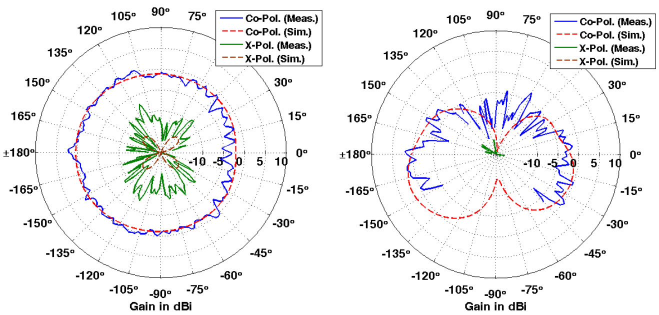


Fig. 8. Return Loss of the dual bow-tie antenna



(a) (b)

Fig. 9. Gain of the dual bow-tie antenna: (a) H-Plane. (b) E-Plane.

V. Conclusions

Two planar omni-directional slot antennas in the 77 GHz band were presented and compared. The antennas were manufactured in a single gold layer on a 127 µm thick Alumina substrate. They were measured with a novel setup in which a coplanar microwave probe is used to contact the antennas. Therefore the antennas are characterized exactly at the point where they could be connected to the IC later. Both antenna structures show an excellent omni-directional pattern and an average gain of around 0 dBi. The folded slot antenna has a larger bandwidth and consumes a smaller substrate area. The impedance of the bow-tie antenna can be tuned continuously while the impedance of the folded slot antenna can be tuned in steps. The dual bow-tie antenna seems to be less sensitive to changes in permittivity and length but causes a stronger cross-polarization due to its geometry. In further work the dependency of the antenna performance on the substrate size will be examined and a packaging concept for 77 GHz radar systems using the presented antennas will be surveyed.

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References

[1] W. Perndl, H. Knapp, M Wurzer, K. Aufinger, T.F. Meister, T.F. Bock, W. Simburger, A.L. Scholtz, "A low-noise, and high-gain double-balanced mixer for 77 GHz automotive radar front-ends in SiGe bipolar technology," *Radio Frequency Integrated Circuits (RFIC) Symposium, 2004. Digest of Papers. 2004 IEEE* , pp. 47-50

[2] Heydari, B. and Bohsali, M. and Adabi, E. and Niknejad, A.M., " A 60 GHz Power Amplifier in 90nm CMOS Technology," *Custom Integrated Circuits Conference, 2007. CICC '07. IEEE*, pp. 769-772,

[3] M. Schneider, "Automotive Radar – Status and Trends," *Proc. German Microwave Conference GeMiC, Ulm, Germany,* pp. 144-147

[4] Ojefors, E.. and Sonmez, E.. and Chartier, S. and Lindberg, P.. and Schick, C.. and Rydberg, A.. and Schumacher, H., "Monolithic Integration of a Folded Dipole Antenna With a 24-GHz Receiver in SiGe HBT Technology," *Microwave Theory and Techniques, IEEE Transactions on,* vol. 55, pp. 1467-1475, 2007

[5] Zwick, T. and Liu, D. and Gaucher, B.P., "Broadband Planar Superstrate Antenna for Integrated Millimeterwave Transceivers," *Antennas and Propagation, IEEE Transactions on*, vol. 54, pp. 2790-2796, 2006

[6] Zhang, Y.P. and Sun, M. and Lin, W., "Novel Antenna-in-Package Design in LTCC for Single-Chip RF Transceivers," *Antennas and Propagation, IEEE Transactions on,* vol. 56, pp. 2079-2088, 2008

[7] Bairavasubramanian, R. and Papapolymerou, J., "Development of V-band Integrated Front-Ends on Liquid Crystal Polymer (LCP) Technology," *Antennas and Wireless Propagation Letters, IEEE,* vol. 7, pp. 134-137, 2008

[8] Chan, K.T. and Chin, A. and Lin, Y.D. and Chang, C.Y. and Zhu, C.X. and Li, M.F. and Kwong, D.L. and McAlister, S. and Duh, D.S. and Lin, W.J., "Integrated antennas on Si with over 100 GHz performance, fabricated using an optimized proton implantation process," *Microwave and Wireless Components Letters, IEEE, vol.* 13, pp. 487-489, 2003

[9] Neculoiu, D. and Muller, A. and Pons, P. and Bary, L. and Saadaoui, M. and Buiculescu, C. and Andrei, O. and Enachescu, R. and Dubuc, D. and Grenier, K. and Vasilache, D. and Petrini, I. and Plana, R., "The design of membrane-supported millimeter-wave antennas," *International Semiconductor Conference, 2003. CAS 2003.,* vol.1, 2003

[10] Yoshida, S. and Tsubouchi, K. and Tosaki, A. and Oguma, H. and Kameda, S. and Nakase, H. and Takagi, T., "Radiation characteristics of ultra-small wireless communication modules for 60GHz band WPAN," *Antennas and Propagation Society International Symposium, 2008. AP-S 2008. IEEE*

[11] Tsai, H.S. and York, R.A., "Multi-slot 50-Ω antennas for quasi-optical circuits," *Microwave and Guided Wave Letters, IEEE,* vol. 5, pp. 180-182, 1995

[12] Eldek, A.A. and Elsherbeni, A.Z. and Smith, C.E. and Kai-Fong Lee, "Wideband slot antennas for radar applications," *Radar Conference, 2003. Proceedings of the 2003 IEEE,* pp. 79-84, 2003

[13] T. Zwick, C. Baks, U.R. Pfeiffer, Duixian Liu, and B.P. Gaucher. "Probe based mmw antenna measurement setup". *Antennas and Propagation Society International Symposium*, 2004. IEEE, 1:747–750 Vol.1, June 2004

[14] S. Ranvier, M. Kyrö, C. Icheln, C. Luxey, R. Staraj, and Vainikainen P. "Compact 3-d on-wafer radiation pattern measurement system for 60 ghz antennas". *European Cooperation in the Field of Scientific and Technical Research*, 2008

[15] R. Simons, "Novel On-Wafer Radiation Pattern Measurement Technique for MEMS Actuator Based Reconfigurable Patch Antennas," *Antenna Measurement Techniques Association Meeting and Symposium,* 2002