Design and Analysis of a 6 GHz Chip Antenna on Glass Substrates for Integration with RF/Wireless Microsystems

P. M. Mendes*, M. Bartek(1), J. N. Burghartz(1), J. H. Correia,
Dept. of Industrial Electronics, University of Minho, Portugal
(1)Lab. of ECTM/DIMES, Delft University of Technology

Abstract: We report on design and characterization of chip-size antennas for operation at 6 GHz and use in wireless microsystems. Use of a glass substrate and application of wafer-level chip-scale packaging (WLCSP) techniques like adhesive wafer bonding and through-wafer electrical via formation, combined with the selected antenna type allows on-chip integration and is the main issue of our work. A short-range wireless link between two systems both equipped with a 11.7x12.4 mm^2 patch antenna (measured characteristics: 6 GHz central frequency, 100 MHz bandwidth @ -10 dB, 3 dB gain, 51% efficiency) realized on a Corning Pyrex #7740 glass substrate is demonstrated.

I. INTRODUCTION

Distributed systems equipped with short-range wireless communication capabilities will highly be facilitated if cheap and easy-to-use 'on-chip' or 'in-package' solutions would be available. The antenna is the key element in order to fully integrate a wireless microsystem in a single chip. The integration requires a small antenna on a low-loss substrate material compatible with integrated circuits fabrication. Standards for wireless communications operating at higher frequencies, e.g. HIPERLAN and IEEE802.11a, are making chip size antennas to become a topic of interest [1]. Moreover, due to the frequency increase, the provided bandwidth becomes also acceptable both for data communications and sensor applications. If the frequency is sufficiently high we can even think in the development of MEMS antennas. Those antennas may have the ability to tune the operating polarization [2] or to shape its radiating beam in a preferable direction [3].

Different solutions have been suggested to achieve antenna integration within a single chip [4, 5, 6]. Since silicon high losses are prohibitive for antenna integration, most of the proposed solutions rely on high resistivity silicon (HRS) or micromachined substrates. The HRS solution uses a substrate with the same electrical characteristics but lower losses. Micromachined substrates are obtained by means of a ratio between air and silicon. According to this ratio, we must extract the electrical properties for each substrate. Wafer-level chip-scale packaging (WLCSP) techniques, like adhesive wafer bonding and through-wafer electrical via formation, allows the use of different substrates together with silicon [7]. Our approach uses the Corning Pyrex #7740 glass wafers as substrate for antenna integration on-chip.

MEMS technology and WLCSP techniques when applied to packaging of RF silicon ICs represent truly added value as at a limited cost 3D passive structures can be realized. The use of glass wafers allows the reduction of the losses at the expense of a size increase of the integrated antenna. Glass substrate allows also the antenna direct coupling on a chip with RF electronics, which offers potential of low cost, low profile and simplified assembly [1].

II. ANTENNA DESIGN

The antenna prototype is displayed in Figure 1 and was designed to be totally compatible with integrated circuit fabrication. The design of the antenna is outlined below.

A. Technological Aspects

The integrated antenna requires silicon-compatible substrate suitable for radiation. The use of a glass for on chip integration is currently under development [7]. To be a good radiator, the antenna

0-7803-7846-6/03/$17.00 ©2003 IEEE

should be built on a substrate with low-dielectric constant and low losses. The substrate thickness should not be thick to avoid surface wave excitation, but should not be thin to keep the bandwidth within acceptable values. Also the metal patch should not contribute to the overall losses.

We have used the Corning #7740 Pyrex glass. This substrate has a dielectric constant of 4.8, and a loss tangent of 0.005%. The wafer thickness is 500 ± 25 µm. The metalization layers were done using a 2 µm layer of aluminium. Instead, copper can be used to decrease metal losses. Figure 2 summarizes the antenna integration concept.

B. Antenna Modeling

The patch antenna was first designed based on the equations from the transmission line model (TLM) approximation [6]. That approximation states that the operating frequency of a patch antenna is given by:

$$f_r = \frac{1}{2(L+\Delta L)\sqrt{\varepsilon_{reff}}\sqrt{\mu_0\varepsilon_0}} \qquad (1)$$

where L is the length of the antenna, ε_0 and μ_0 are the free space dielectric permitivity and permeability, ε_{reff} is the effective dielectric permitivity:

$$\varepsilon_{reff} = \frac{\varepsilon_r+1}{2} + \frac{\varepsilon_r-1}{2}\left[1+12\frac{h}{W}\right]^{-1/2} \qquad (2)$$

where ε_r and h are the relative dielectric permitivity and thickness of the substrate, and W is the width of the patch. Because of fringing effects, the antenna looks larger than its physical dimensions. ΔL takes this effect in account and can be computed from:

$$\Delta L = 0.412h\frac{(\varepsilon_{reff}+0.3).(W/h+0.264)}{(\varepsilon_{reff}-0.258).(W/h+0.8)} \qquad (3)$$

The input impedance of the antenna must be matched to the feed line by choosing the correct position for the feeding point [6]. Because the antenna must be fed with the microstrip, the connection to a point inside the metal patch requires the use of an inset. Using the values given by TLM approximation, a model for the antenna was built in HFSS as shown in Figure 3. The model was used to trim the antenna dimensions for the desired frequency, to find the dimensions of the inset that provides impedance matching between it and the feed line, and to analyze the influence of glass parameters on antenna performance.

The prototype was fabricated at Delft Institute of Microelectronics and Submicron Technology, TU Delft. The antenna was totally fabricated with the process steps used in IC fabrication.

III. MEASUREMENTS AND ANALYSIS

The operating frequency and bandwidth were obtained from reflection measurements. The return loss was measured with an 8510C vector network analyzer. The measured values for the antenna using the glass substrate are plotted against the simulated data in Figure 4. We can see that the simulated and measured data agrees quite well. The obtained operating frequency was 5.995 GHZ and the -10 dB return loss bandwidth ~100 MHz. The efficiency was measured using the Wheeler cap method [8]. The results are plotted in Figure 4. From the measurements we obtained an efficiency of 51%, which is close to the HFSS computed value of 52%. This value is higher than the values that can be obtained with HRS [9]. The effect of wafer thickness tolerances was analyzed and the results are shown in Figure 5. It was observed that varying the substrate thickness from 475 µm to 525 µm the operating frequency remains almost the same but the antenna efficiency changes from 49% to 54%. To check the influence of the metal patch losses on the overall efficiency, the aluminium thickness was changed from 2 µm to 10 µm. The antenna efficiency didn't change significantly, which means the standard metalization thickness can be used for antenna fabrication. Nevertheless, new designs are now being done using copper to check its influence on metal losses.

Far-field gain patterns measurements were done using the DUCAT anechoic chamber facility at IRCTR-TU Delft and compared with results from simulations. The measured gain was ~3 dB. The obtained values are plotted in Figure 6, were we can observe that measured values are again in good agreement with simulated ones. As it was expected, the antenna exhibits a linear polarization characteristic and the power is mainly radiated to the topside of the antenna. Nevertheless, it would be desirable a smaller power level at the back of the antenna. This drawback results from the small size of the ground plane. A wireless link between two prototypes was established and a power of – 43 dBm was received when they were placed one meter apart and the transmitting antenna was fed with 0 dBm.

IV. CONCLUSIONS

Glass substrate was analyzed as a candidate for chip antenna integration. The antenna fabrication was based on standard integrated circuits fabrication. The combination of glass substrate with WLCSP allows the possibility of antenna integration with RF/Microwave circuitry. The microstrip patch antenna was fabricated on a Pyrex wafer, operating at 5.995 GHz with approximately 100 MHz of bandwidth and a gain of ~3 dB. These characteristics fulfill the requirements for short-range communications in the 5-6 GHz ISM band. The antennas fabricated on Pyrex substrate have better performance (efficiency up to 52%) when compared to antennas on HRS substrate (efficiency around 20 %).

We are now using shorting pins together with a folded structure to reduce the antenna size by four. This work demonstrates that patch antennas on glass operating at 5-6 GHz are feasible for integration on a RFIC chip for wireless sensor networks.

ACKNOWLEDGEMENTS

The authors would like to thanks the Portuguese Foundation for Science and Technology for funding this project (SFRH/BD/4717/2001 and POCTI / ESE / 38468 / 2001), M. Hajian and J. Zijderveld, from IRCTR-TUDelft, for their helpful support in far field pattern measurements.

REFERENCES

[1] Jun Zhao; S Raman, “An Integrated Chip-Scale Active Antenna for 5-6 GHz Wireless Microsystems”, RAWCON 2002, pp. 149–152, 2002.

[2] R.N Simons, Donghoon Chun; L.P.B Katehi, “Polarization Reconfigurable Patch Antenna Using Microelectromechanical Systems (MEMS) actuators”, IEEE APS Int. Symp., Vol. 2, pp. 6-9, 2002.

[3] R.N Simons, Donghoon Chun; L.P.B Katehi, “Reconfigurable Array Antenna Using Microelectromechanical Systems (MEMS) Actuators”, IEEE APS Int. Symp, Vol. 3, pp. 674-677, 2001.

[4] Chris R. Trent, Tom M. Weller, “Design and Tolerance Analysis of a 21 GHz CPW-fed, Slot-Coupled, Microstrip Antenna on Etched Silicon”, IEEE APS Int. Symp., Vol. 1, pp. 402-405, 2002.

[5] Zhang, Y.P., “Integration of Microstrip Patch Antenna on Ceramic Ball Grid Array Package”, Electron. Lett. , Vol. 38 Nº 5, pp. 207 –208, February 2002.

[6] Garg, R., Bhartia, P., Bahl, I., Ittipiboon, A., Microstrip Antenna Design Handbook, Artech House, 2001.

[7] A. Polyakov, P. M. Mendes, et al., “Processability and Electrical Characteristics of Various Glass Substrates for RF Wafer-Level Chip-Scale Packages”, Proc. 53rd Electronic Components and Technology Conference, New Orleans, Louisiana, USA, May 2003.

[8] Edward H. Newman, Peter Bohley, C.H. Walter, “Two Methods for the Measurement of Antenna Efficiency”, IEEE Trans. Antennas Propagat., vol 23, Nº 4, pp. 457-461, July 1975.

[9] P. M. Mendes, J.H. Correia, M. Bartek, J.N. Burghartz, “Analysis of Chip-Size Antennas on Lossy Substrates for Short-Range Wireless Microsystems”, Proc. SAFE 2002, Veldhoven, The Netherlands, pp. 51-54, November 2002.

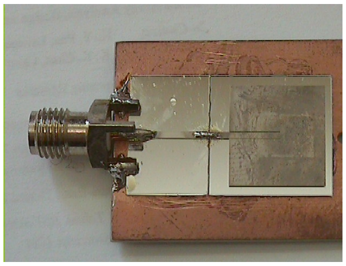

Figure 1 – Patch antenna prototype on a glass substrate.

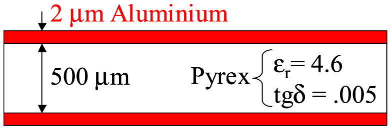

Figure 2 – Cross-section showing the materials.

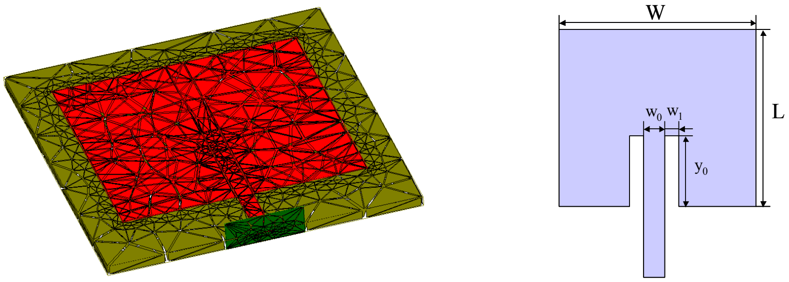

Figure 3 – Meshed model of the HFSS patch antenna and layout with dimensions in mm. L = 11.7, W = 12.4, y_0 = 4.7, w_0 = 0.8, w_1 = 0.05.

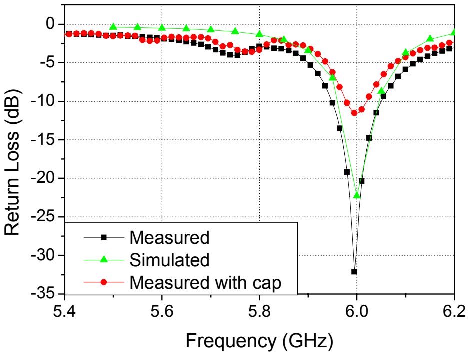

Figure 4 – Measured and simulated return loss. Used to obtain the antenna efficiency.

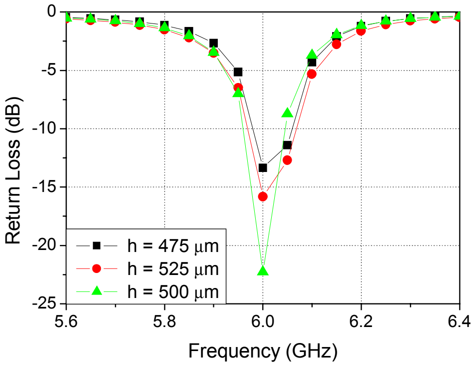

Figure 5 - Return loss of the antenna as a function of wafer thickness, h.

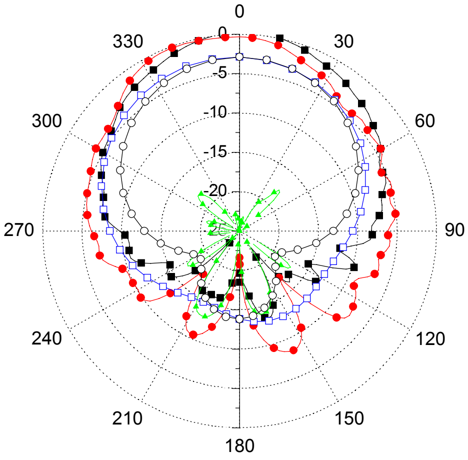

Figure 6 – Measured and simulated gain patterns at 5.995 GHz.

Measured copolar E-plane
Measured copolar H-plane
Measured crosspolar E-plane
Simulated copolar E-plane
Simulated copolar H-plane