

# Analysis of Chip-Size Antennas on Lossy Substrates for Short-Range Wireless Micro Systems

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**Abstract**—This paper presents the design and characterization of a patch antenna built on lossy substrates compatible with integrated circuits fabrication. Two different substrates were used for antenna implementation: high-resistivity silicon (HRS) and Corning Pyrex #7740 glass. The antenna prototypes were built to operate close to the 5 GHz ISM band where applications like HIPERLAN and IEEE802.11a are standardized. They operate at a center frequency of 5.705 GHz (HRS) and 5.995 GHz (Pyrex). The studied parameters were: substrate thickness, substrate losses, oxide thickness, metal conductivity and thickness. The antenna on HRS uses an area of 8 mm<sup>2</sup>, providing a 90 MHz bandwidth and ~0.3 dBi of gain. On a glass substrate, the antenna uses 12 mm<sup>2</sup>, provides 100 MHz bandwidth and ~3 dBi of gain.

**Keywords**—Patch antennas, chip-size antennas, antenna integration.

## I. INTRODUCTION

Nowadays, realization of fully integrated wireless RF transceivers is a challenge pursued by many researchers. The demand for short-range wireless networks interconnecting all the working devices in one room is pushing the companies to find a cheap and easy way of having its products equipped with such functionality. Furthermore, systems based on sensor and actuator arrays are becoming available. Excepting a few situations, the wireless connection is the preferable way of achieving communication between those devices.

One of the key elements to achieve a fully integrated wireless micro system on a single chip is the antenna. Usually this component is placed outside the main chip due to well known constraints. First and most important of all, the antenna tends to consume a lot of chip area. If placed quite close to the circuitry there is a possibility of interference. It is also a device that circuit designers are not familiarized with.

Different types of antennas have been suggested as candidates to be integrated within a single chip [1,2,3,4]. A patch antenna was developed because of its inherent advantages: low profile, light weight, low volume, low

fabrication cost, possibility of linear and circular polarizations with simple feed, possibility for dual-frequency and dual-polarization, easiness to be integrated with microwave integrated circuits, feed lines and matching networks can be fabricated simultaneously with the antenna structure. Notwithstanding these advantages, usually they provide small bandwidth, low efficiency, and for standard design, relatively large area consumption. However, with the new standards for wireless communications operating at higher frequencies, chip size antennas become a topic of interest due to its size reduction. If the frequency is sufficiently high we can even think in some MEMS antenna. Those kinds of antennas may have the ability to tune the operating polarization [5] or to shape is radiating beam in a preferable direction [6]. Besides the size reduction due to the frequency increase, the provided bandwidth becomes also acceptable both for data communications and sensor applications. Due to the small range operation, the usually low gain provided by these antennas is supposed to be enough.

Since the antennas should be suited to be integrated/embedded, the fabrication steps must include only materials and techniques compatible with the standard foundry processes. The standard processing steps found in a foundry fit quite well the need to fabricate a standard patch antenna. The main challenge is the material to be used as substrate. Parameters like substrate thickness, dielectric permittivity, dielectric losses, metal conductivity and thickness, should be evaluated to understand its influence on overall antenna performance.

This paper describes the steps used to validate the model used for studying the behavior of a patch antenna fabricated on lossy substrates usually found in standard IC fabrication foundries. Two different substrates were used: high-resistivity silicon (HRS) and Corning Pyrex #7740. Parameters like wafer thickness and resistivity tolerances, substrate losses, oxide thickness, metal conductivity, antenna gain and efficiency, were analyzed.

## II. ANTENNA DESIGN

### A. Technology Constraints

To be a good radiator, the antenna should be built on a substrate with low dielectric constant and losses. Also the metal patch should not contribute to the overall 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.

The two types of substrate we have investigated for antenna design were the high resistivity silicon and Corning #7740 Pyrex glass. For simulations we have considered HRS with a dielectric permittivity,  $\epsilon_r = 11.7$  and a conductivity  $\sigma = 0.02 \text{ S/m} - 0.05 \text{ S/m}$ . For Pyrex wafer it was considered  $\epsilon_r = 4.6$ , and a loss tangent of 0.5% (values known @ 1 MHz). The wafers thicknesses were  $525 \mu\text{m} \pm 25 \mu\text{m}$  for HRS and  $500 \mu\text{m}$  for glass. To decrease the substrate losses when using HRS, a 300-nm layer of thermal silicon dioxide was used. This layer has an  $\epsilon_r = 3.9$  and is assumed as an insulator. Finally, the metalization layers were realized using a  $2 \mu\text{m}$  layer of aluminium. Another possibility considered is to use copper to decrease metal losses. All these parameters are summarized on the following figure.

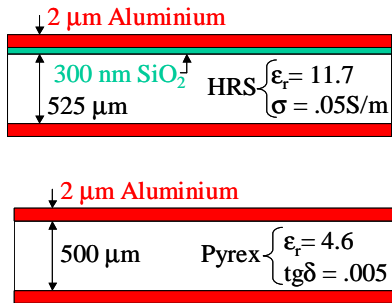


Figure 1– Cross-section showing the materials used for antenna fabrication.

### B. Antenna Modeling

With the technological constraints in mind, the first step was to find the shape dimensions of our patch antenna.

A close value for the antenna length,  $L$ , is known to be half wavelength in the substrate. A first better value can be found using the equations from the transmission line model (TLM) approximation [4]. In this way we have for the dominant TM mode the resonant frequency:

$$f_r = \frac{1}{2(L + \Delta L) \sqrt{\epsilon_{\text{reff}}} \sqrt{\mu_0 \epsilon_0}} \quad (1)$$

where  $L$  is the length of the antenna,  $\epsilon_0$  and  $\mu_0$  are the

free space dielectric permittivity and permeability,  $\epsilon_{\text{reff}}$  is the effective dielectric permittivity:

$$\epsilon_{\text{reff}} = \frac{\epsilon_r + 1}{2} + \frac{\epsilon_r - 1}{2} \left[ 1 + 12 \frac{h}{W} \right]^{-1/2} \quad (2)$$

where  $\epsilon_r$  and  $h$  are the relative dielectric permittivity 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.  $\Delta L$  takes this effect in account.

In order to facilitate its characterization, the antenna was designed to have a  $50 \Omega$  input impedance. The input impedance of the antenna can be adapted by choosing the right position for the feeding point [4]. Its value is maximum at the patch border and decreases as we move inside according to:

$$Z_{\text{in}} = Z_{\text{max}} \cos^2 \left( y \frac{\pi}{L} \right) \quad (3)$$

where  $Z_{\text{max}}$  is the impedance at  $y = 0$ . Because the antenna was to be feed with a microstrip, the connection to a point inside the metal patch requires the use of wire bonding or an inset. The model was first built in Momentum ADS taking the values given by TLM approximation. The first step was to find the dimensions of the inset that provides the match to a  $50 \Omega$  microstrip line. Despite ADS Momentum simulator (a 2.5D simulator) ability to account for multilayer geometries it assumes the dielectric layers as being infinite. However, the finite size of the ground plane and substrate affect the antenna behavior [7] and the 3D High Frequency Structure Simulator (HFSS) was used to include those effects.

Picking the dimensions obtained with ADS Momentum we built a 3 dimensional model of the patch antenna as shown in fig. 2.

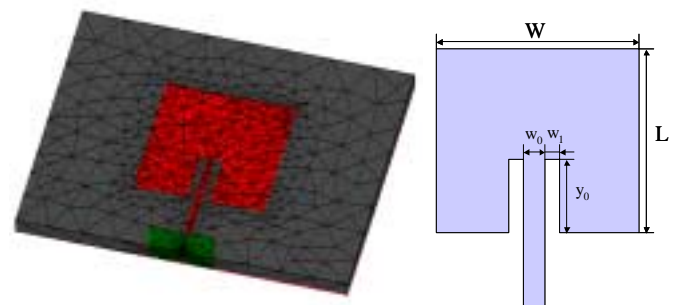


Figure 2 – Meshed model of the HFSS patch antenna and layout with dimensions.

The next table shows the dimensions of the antenna for

both kinds of used substrates.

	HRS	Pyrex
L	7.7 mm	11.7 mm
W	7.6 mm	12.4 mm
$y_0$	3.1 mm	4.7 mm
$w_0$	0.36 mm	.8 mm
$w_1$	0.32 mm	.05 mm

Table 1 – Dimensions of the patch antenna.

The prototype was fabricated at Delft Institute of Microelectronics and Submicron Technology, TU Delft.

### III. MEASUREMENTS AND ANALYSIS

The antenna characterization requires the placement of a SMA connector on the back of the microstrip antenna, as shown on fig. 3. The surface of the aluminum metal patch was activated by means of electroless Ni deposition to allow soldering with the SMA connector.



Figure 3– Carrier with patch antenna and setup used to measure the gain pattern.

The 8510C vector network analyzer was used to measure the return loss. The measured values for the antenna using HRS substrate are plotted against the simulated data on fig. 4. We can see that the simulated data agrees quite well with the measured. The obtained operating frequency was near to 5.705 GHz and the -10 dB return loss bandwidth was 90 MHz.

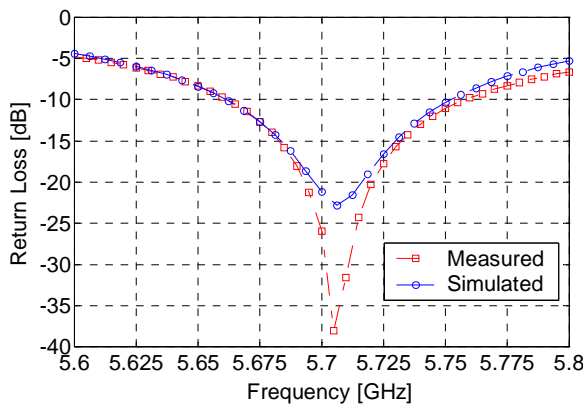


Figure 4– Measured and simulated return loss for the antenna using HRS as substrate.

The return loss of the antenna on glass was also measured. For that antenna the measured operating frequency is 5.995 GHz and the -10 dB return loss bandwidth is 100 MHz.

The DUCAT anechoic chamber facility at IRCTR-TU Delft was used to measure the far field gain patterns. The results are plotted on fig. 5.

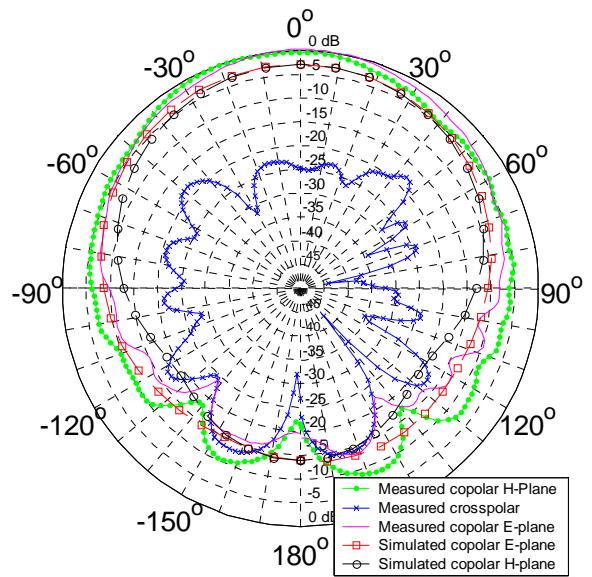


Figure 5– Measured gain patterns at 5.705 GHz for the antenna on HRS substrate.

We can see 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. The maximum gain obtained was around 0.3 dBi. This small gain is essentially due to low efficiency, since the substrate is highly lossy. The gain for the antenna on glass was ~3 dBi. The gain increase is mainly due to a higher efficiency of the antenna.

The antenna efficiency can be computed from simulations. To measure it we can use using different methods [8]. In this work the Wheeler cap method was adopted. This method is based on the comparison between return loss measurements with the antenna radiating into free space and not radiating. The last condition is usually obtained by placing a metallic cover around the antenna under test. From those measurements the efficiency can be computed. We did it experimentally and theoretically with the help of HFSS.

The obtained results of using the Wheeler cap method are plotted on fig. 6. The figure shows agreement in the behavior when it is radiating and it is not, both for simulations and measurements. Using the data from measurements we obtain an efficiency of 18.6 %, which is quite in agreement with the value computed by HFSS,

that was 19.6 %.

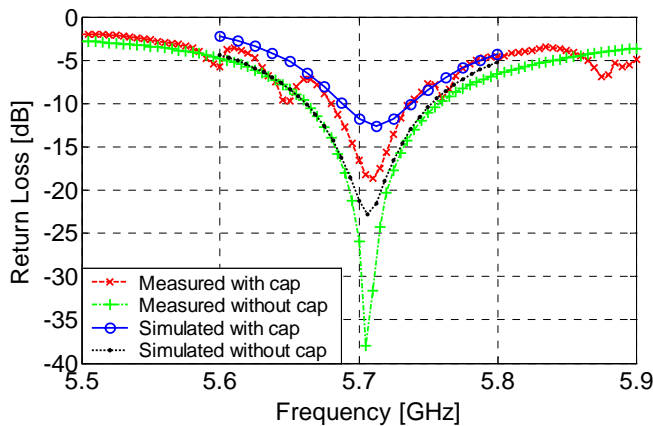


Figure 6 – Measured and simulated return loss, with and without cap, for patch antenna on HRS substrate.

Using the same method, the efficiency of the antenna on Pyrex was also measured. For this substrate, the measured efficiency rises to values around 40%. It's a better value but still quite low. It is necessary a better material to increase this value. This value agrees again with the one computed by HFSS.

The final experiment was the signal transmission and reception using two of the fabricated antennas on HRS. The radiating antenna was connected to a signal generator and the receptor antenna to the spectrum analyzer. They were placed around 1 meter apart and the output power set to 0 dBm. A signal power of -50 dBm was received. This result is in agreement with all the other measured characteristics. The free space attenuation of a microwave signal can be described by:

$$A = \left( \frac{4\pi l}{\lambda} \right)^2 \quad (4)$$

where  $l$  is the propagation distance and  $\lambda$  is the wavelength. If we use the last equation with all the previously measured we can easily conclude that they all agree. To check the material tolerances we performed some simulations to check the influence of the substrate thickness and resistivity tolerance, and we changed also the oxide thickness. It can be seen that varying the substrate thickness from 500  $\mu\text{m}$  to 550  $\mu\text{m}$  and oxide thickness from 1  $\mu\text{m}$  to 10  $\mu\text{m}$  the operating frequency changed from around 5.7 GHz to 5.85 GHz. Changing the substrate conductivity from  $\sigma = 0.02 \text{ S/m} - 0.05 \text{ S/m}$  we found that efficiency changes from 19.6 % to 30.1 %.

#### IV. CONCLUSIONS

Antenna fabrication using the available standard

fabrication processes used in IC fabrication was verified. This shows possibility of antenna integration with circuitry. A 3D model was built and used to accurately predict the antenna input and output characteristics. Two different materials were tested for antenna substrate.

The microstrip patch antenna fabricated on HRS has area of 8  $\text{mm}^2$  and operates at 5.705 GHz with approximately 90 MHz of bandwidth and a gain of 0.3 dBi. The microstrip patch antenna fabricated on Pyrex has area of 12  $\text{mm}^2$  and operates at 5.995 GHz with approximately 100 MHz of bandwidth and a gain of 3 dBi. These characteristics fulfill the requirements for short-range communications for using the 5 GHz ISM band. The antennas fabricated on Pyrex substrate have, despite their larger size, better performance (efficiency up to 40%) when compared to antennas on HRS substrate.

Currently, we are designing a new type of antennas based on a more complex geometry. Their significantly smaller size will allow better integration within micro-systems.

#### V. ACKNOWLEDGEMENTS

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#### REFERENCES

- [1] B.A. Floyd, Hung Chih-Ming; K.K O, "Intra-chip wireless interconnect for clock distribution implemented with integrated antennas, receivers, and transmitters", IEEE J. of Solid-State Circuits, Vol. 37, N° 5, pp. 543–552, May 2002.
- [2] Zhang, Y.P., "Integration of microstrip patch antenna on ceramic ball grid array package", Electronics Letters, Vol. 38 N° 5, pp. 207–208, February 2002.
- [3] Jun Zhao; S Raman, "An integrated chip-scale active antenna for 5-6 GHz wireless Microsystems", RAWCON 2002, pp. 149–152, 2002.
- [4] Garg, R., Bhartia, P., Bahl, I., Ittipiboon, A., Microstrip Antenna Design Handbook, Artech House, 2001.
- [5] 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.
- [6] 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.
- [7] S.A Bokhari, J.R Mosig; F.E Gardiol, "Radiation Pattern Computation of Microstrip Antennas on Finite Size Ground Planes", IEE Proc. Microwaves, Antennas and Propagation, Vol. 139, N° 3, pp. 278-286, June 1992.
- [8] David M. Pozar, Barry Kaufman, "Comparison of Three Methods for the Measurement of Printed Antenna Efficiency", IEEE Trans. Antennas Propagat., vol 36, N° 1, January 1988.