Wireless hydrotherapy smart suit for monitoring handicapped people

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ABSTRACT

This paper presents a smart suit, water impermeable, containing sensors and electronics for monitoring handicapped people at hydrotherapy sessions in swimming-pools. For integration into textiles, electronic components should be designed in a functional, robust and inexpensive way. Therefore, small-size electronics microsystems are a promising approach. The smart suit allows the monitoring of individual biometric data, such as heart rate, temperature and movement of the body. Two solutions for transmitting the data wirelessly are presented: through a low-voltage (3.0 V), low-power, CMOS RF IC (1.6 mm x 1.5 mm size dimensions) operating at 433 MHz, with ASK modulation and 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. 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^2, providing a 90 MHz bandwidth and ~0.3 dBi of gain. On a glass substrate, the antenna uses 12 mm^2, provides 100 MHz bandwidth and ~3 dBi of gain.

Keywords: Chip-size antenna, smart textiles, e-textiles, RF CMOS transceiver

1. INTRODUCTION

Today, the link between textiles and electronics is more realistic than ever. An emerging new field of research that combines the strengths and capabilities of electronics and textiles into one: electronic textiles, or e-textiles is opening new opportunities. E-textiles, also called smart fabrics, have not only wearable capabilities like any other garment, but also have local monitoring and computation, as well as wireless communication capabilities. Sensors and simple computational elements are embedded in e-textiles, as well as built into yarns, with the goal of gathering sensitive information, monitoring vital statistics, and sending them remotely (possibly over a wireless channel) for further processing [1].

For integration into everyday clothing, electronic components should be designed in a functional, unobtrusive, robust, small, and inexpensive way. Therefore, small single-chip microelectronic systems rather than large-scale computer boxes are a promising approach. This proposal presents a wireless electronic shirt that monitors the cardio-respiratory function and it is able to recognize qualitatively and quantitatively the presence of respiratory disorders, both during wake and sleep-time in free-living patients with chronic heart failure, providing clinical and prognostic significance data. With the ongoing progress of miniaturization, many complex and large electronics systems will soon be replaced by tiny silicon microchips measuring just a few square millimeters. Your shirt, coat or sweater, is the device. Conductive fibers woven into the fabric using standard textile techniques carry power sensors, actuators, and microcontrollers embedded in the cloth. Software controls the communications inside the on-fabric network and can send radios signals using Bluetooth or any flavour of the IEEE 802.11 wireless standard to PCs and PDAs, and over Internet. Manufacturers can mix and match sensors, processors, and communications devices that plug into knitted or woven garments made from cotton, polyester, or blends. These devices have the look and feel of typical garments and, after the attachments are unplugged, can be tossed into the washing machine. Applications are astoundingly diverse and following examples will demonstrate the implementation of microelectronics components into clothes and textiles structures in a reliable and manufacturing way.Researchers at Tampere University of Technology, Finland, developed a machine-washable jacket, vest, trousers, and two-piece underwear set for snowmobilers. The jacket is embedded with a GSM chip, sensors monitoring position, motion, and temperature.

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If a crash occurs, the jacket automatically detects it and sends a distress message to emergency medical officials via SMS. Infineon Technologies, Germany, unveiled a carpet that can detect motion – of unwanted intruders, for example – and also light the way to exits in the event of a fire [2]. The carpet is woven with conductive fibers and studded with pressure, temperature, or vibration sensors chips, microcontrollers and light-emitting-diodes (LEDs).

The concept of the wireless hydrotherapy smart suit for monitoring handicapped people in terms of individual biometric data, such as heart rate, temperature and movement of the body will be presented.

2. DESIGN

Wet suits are used when diving in water temperatures over 20 degrees Celsius. This wetsuit is mostly made from thin neoprene, which provides limited thermal protection, and lined with a nylon fabric to make it easy to put on and take off. The neoprene itself insulates the warm layer against the cold of the surrounding water. A close fit is essential to ensure the suit efficiently works, as too loose a fit will simply allow the warm layer to flush away and be replaced by cold water. Wetsuits are cheap and simple. They lose buoyancy and thermal protection as they compress at depth. Wetsuits are also commonly worn for water sport activities other than diving, such as wind surfing. Fig. 1 shows an artist impression of the smart suit with a cap.

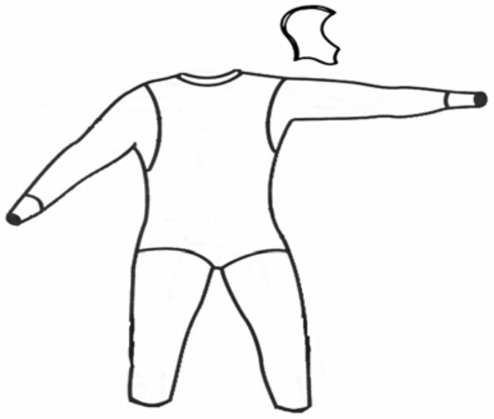

Fig.1. An artist impression of the neoprene smart suit.

The wireless smart suit will be lightweight, machine washable, comfortable, easy-to-use shirt with embedded sensors. To measure respiratory and cardiac functions, sensors are plugged into the shirt around patient’s chest and abdomen. A single channel ECG measures heart rate and an accelerometers network records patient posture and activity level, and inductive copper filaments will be used for monitoring the respiratory function. The electronics interface sensors and a RF transceiver will be fabricated in CMOS technology in order to send radio signals to PCs or PDAs. Also, an on-chip bulk-micromachined antenna at 5.7 GHz was implemented with each sensor; this approach will lead a wireless sensor network avoiding data wires. These microsystems will have the look and feel of typical garments and, after the attachments are unplugged, can be tossed into the washing machine.

The monitoring electrodes are sewed in the textile material achieving a good skin contact. A 2-axis accelerometer senses patient posture and activity level. A network of CMOS temperature sensors distributed in the suit determines the body temperature. Also, 2 power-supply lines are available in all electronic regions of the suit. A 3 V battery is the supply voltage. We want demonstrate the implementation of microelectronic components into clothes and textile structures in a reliable and manufacturable way. Damage of the components by washing processes and daily use must be avoided. This solution so far requires removal of the electronics before starting the cleaning process [1]. Additional analysis in the future may include respiration rate, blood oxygen saturation and a complete electrocardiogram (ECG) diagnostic.

2.1. Transceiver at 433 MHz

The first solution for transmitting the biometric data was wirelessly through a low-voltage (3.0 V), low-power, CMOS RF IC (1.6 mm x 1.5 mm size dimensions) operating at 433 MHz, with ASK modulation. A regular antenna on the cap of the suit was implemented. A 3 V battery is the supply voltage. Fig. 2 shows the microchip fabricated in CMOS technology 0.7 μm, 2 metals, 1 polysilicon layer.

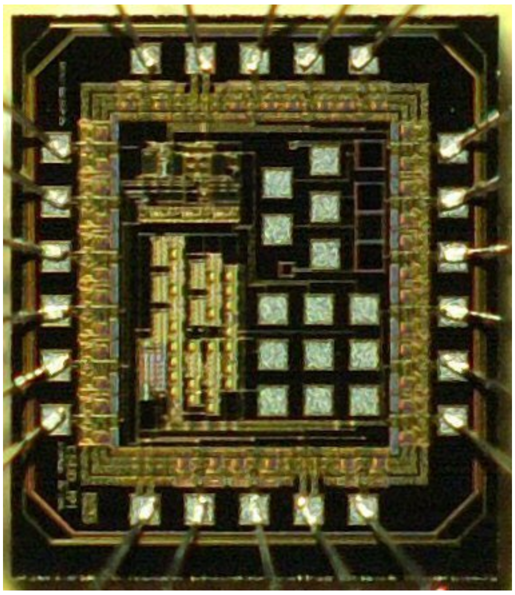

Fig. 2. RF CMOS transceiver at 433 MHz (1.6 mmx 1.5 mm size dimensions).

2.2. Chip-size antenna

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 [3-6]. 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 [7] 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 permitivity, dielectric losses, metal conductivity and thickness, should be evaluated to understand its influence on overall antenna performance.

This section 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.

3. ANTENNA

3.1. 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 permitivity, $\varepsilon_r = 11.7$ and a conductivity $\sigma = 0.02$ S/m – 0.05 S/m. For Pyrex wafer it was considered $\varepsilon_r = 4.6$, and a loss tangent of 0.5% (values known @ 1 MHz). The wafers thicknesses were 525 μm ± 25 μm for HRS and 500 μm for glass. To decrease the substrate losses when using HRS, a 300-nm layer of thermal silicon dioxide was used. This layer has an $\varepsilon_r = 3.9$ and is assumed as an insulator. Finally, the metalization layers were realized using a 2 μm layer of aluminium. Another possibility considered is to use copper to decrease metal losses. All these parameters are summarized on the following figure.

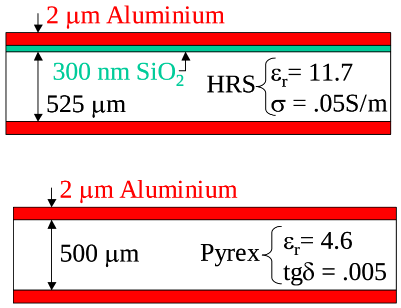

Fig. 3. Cross-section showing the materials used for antenna fabrication.

3.2. 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 [8]. In this way we have for the dominant TM mode the resonant frequency:

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

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.

In order to facilitate its characterization, the antenna was designed to have a 50 Ω input impedance. The input impedance of the antenna can be adapted by choosing the right position for the feeding point [8]. Its value is maximum at the patch border and decreases as we move inside according to:

$$Z_{in} = Z_{\max} \cos^2(y\frac{\pi}{L}) \qquad (3)$$

where Z_{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 Ω 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 [9] 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. 4.

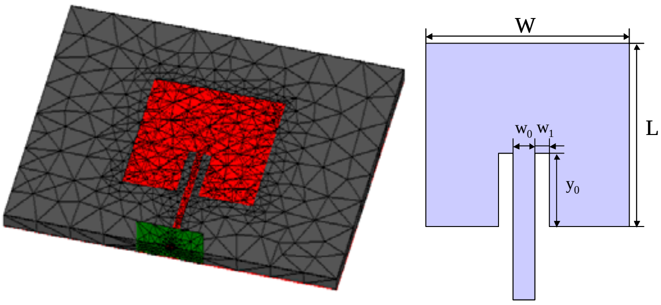

Fig. 4. Meshed model of the HFSS patch antenna and layout with dimensions.

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.

4. MEASUREMENT 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.

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. 6. 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.

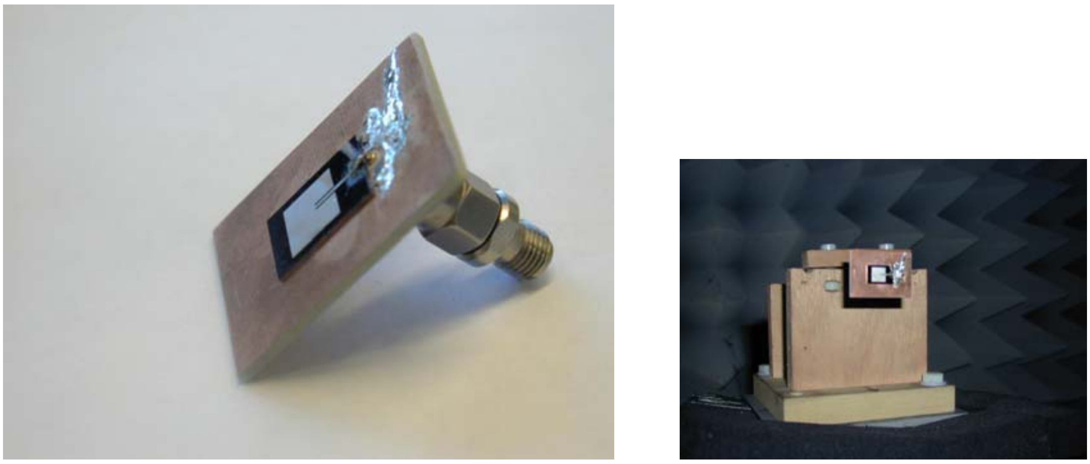

Fig. 5. Carrier with patch antenna and setup used to measure the gain pattern.

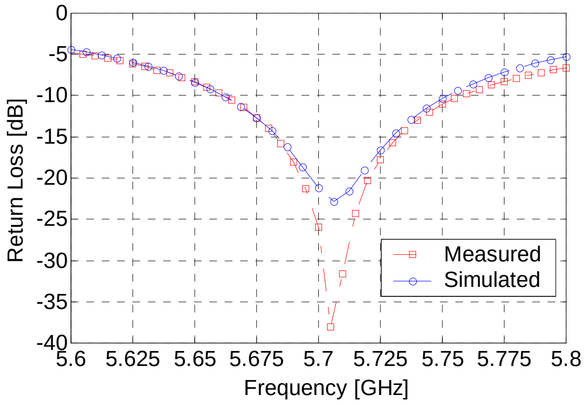

Fig. 6. Measured and simulated return loss for the antenna using HRS as substrate.

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. 7.

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 [10]. 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. 8. 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 %.

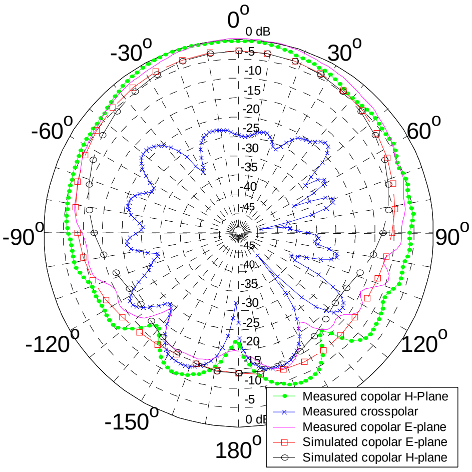

Fig. 7. Measured gain patterns at 5.705 GHz for the antenna on HRS substrate.

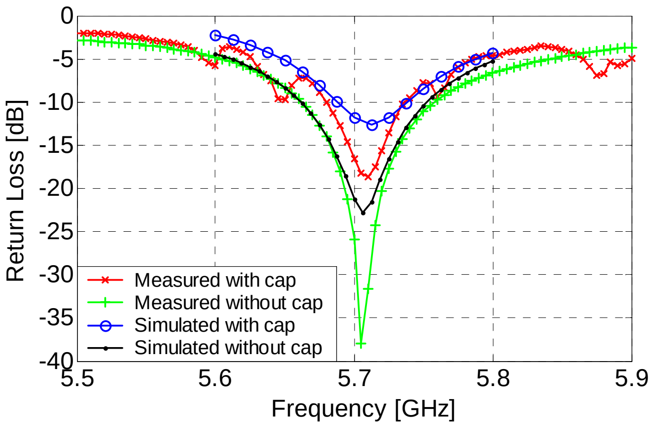

Fig. 8. Measured and simulated return loss, with and without cap, for patch antenna on HRS substrate.

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 transmition 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 where 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:

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

where l is the propagation distance and λ 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 μm to 550 μm and oxide thickness from 1 μm to 10 μm the operating frequency changed from around 5.7 GHz to 5.85 GHz. Changing the substrate conductivity from $\sigma = 0.02$ S/m – 0.05 S/m we found that efficiency changes from 19.6 % to 30.1 %.

5. 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 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 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.

The wireless smart suit can be a powerful tool, helping health professionals with rapid, accurate and sophisticated diagnostic concerning cardiopulmonary disease in order to evaluate the presence of breathing disorders in free-living patients when are doing hydrotherapy in swimming-pools.

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.

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