2.4 GHz Plaster Antennas for Health Monitoring

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***Abstract*— Commercial plaster material (polyacrylate) is used as an antenna substrate. Two 2.45 GHz patch antennas are introduced, both designed to be attached directly to the skin. Measured efficiencies are 70 % in free space and 60 % on-body. Measured on-body gains of each antenna are 6.2 and 1.4 dBi. Simulated 1 g specific absorption rates (SAR) of the two antennas are 2.3 W/kg and 1.6 W/kg using 1 W input power. 10 g SAR values are 0.6 W/kg and 1.2 W/kg. Antenna feeding using snap-on buttons is investigated and has been found useful.**

***Index Terms*— Antennas, medical services, microstrip antennas.**

I. INTRODUCTION

Many medical applications require gathering data of the patient's condition. Examples include heart rate, breath rate, and blood oxygen level. Usually these data are transmitted via a cable, which limits the patient's movements.

Freedom of movement is especially important in home nursing and in monitoring athletes' recovery after training. As an alternative to cables, the patients could carry a belt-worn device which records data and transmits the results wirelessly to the system whenever possible. Plaster-based sensors have been developed in the recent years [1]. As printed electronics evolves, the whole system including the measurement electronics, data gathering, radio transceiver, and antenna could be integrated on a single, disposable plaster.

In this paper, we examine the feasibility of plaster material as an antenna substrate, and present two antenna structures. The antennas are to be attached directly to the skin, like regular wound-care plasters. To minimise the effect of the body on the antennas, a ground plane is used. Slits are cut in the antennas to increase flexibility and breathability.

The antenna structures as well as the electrical properties of the plaster are described in Section II. Section III contains measured results for the regular antenna parameters. Simulated SAR values are presented in Section IV. We describe an alternative feeding method using snap-on buttons and examine the effect of the user sweating on antenna parameters in Section V. Section VI concludes the work.

II. ANTENNA STRUCTURES

The goal of the design process was to design antennas on a plaster substrate that cover the frequency band from 2.4 to 2.5 GHz. Linear polarisation was desired, because circular polarisation characteristics would depend too much on antenna bending, as shown by our ongoing research. The antennas were designed to be flexible and breathable.

TABLE I
PATCH ANTENNA DIMENSIONS (IN MILLIMETRES)

ground and substrate		patch and feed		slits and strips	
w_g	81	w_p	47	w_c	3
l_g	80	l_p	48	w_b	4
w_s	57	w_f	4.5	w_a	1
l_s	58	l_{in}	15	p	1
h	1.36	g	1	l_1	10
				l_a	5

Commercially available Mölnlycke Mefix [2] plaster material (self-adhesive polyacrylate) was chosen as the substrate. Its dielectric properties were measured at 2.45 GHz. The dielectric constant is about 1.38 and loss tangent 0.02. Compared to a PCB material the dielectric constant is very low but losses are about the same as of a poor PCB.

The conducting material of the antennas was copper tape. In the future, the antennas could e. g. be printed on the plaster. Research is going on to find a suitable conducting material for wearable antennas.

We must use a ground plane, because the antennas operate less than one millimetre from the body. The reactive near-field is then trapped between the radiating element and the ground plane. This reduces the effect of the user on input impedance (resonance frequency) and radiation, and lowers SAR.

Two antennas were designed, one a half-wave patch and the other a quarter-wave antenna short-circuited to the ground. The substrate for both is an 8-layer plaster, which is 1.36 mm thick. The dimensions of the antennas are given in Figs. 1, 2, 3, and 4, and in Tables I and II.

To increase flexibility and breathability, slits were cut both in the antenna elements and ground planes. The x-directional slits do not affect the current flow of the radiating mode, however extra horizontal strips had to be added at the feed point level to allow for y-directional current at the feed. The antenna dimensions are a trade-off between antenna efficiency and breathability.

III. MEASURED RESULTS

Regular antenna parameters, the input impedance and radiation pattern, were measured both in free space and on-body.

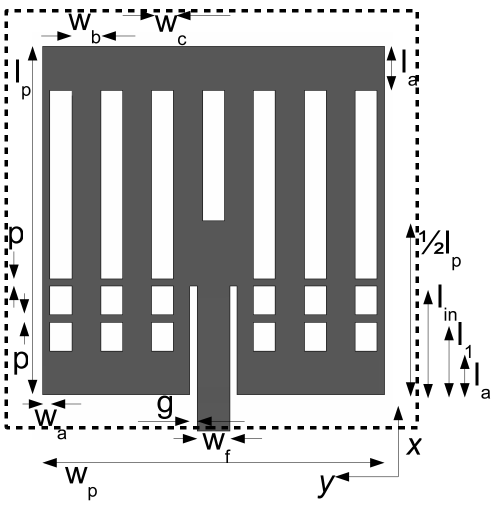

Fig. 1. Dimensions of the patch antenna–the part above substrate. The substrate is shown dashed.

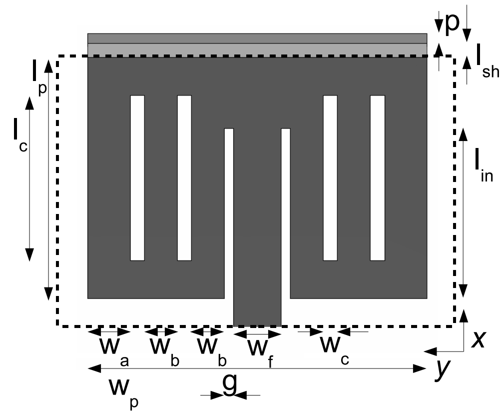

Fig. 3. Dimensions of the quarter-wave antenna–the part above substrate. The light gray part (length l_{sh}) is bent from above the substrate to the ground plane level, so that the uppermost part (length p) is actually a part of the ground plane. The patch is thus short-circuited to the ground. The substrate is shown dashed.

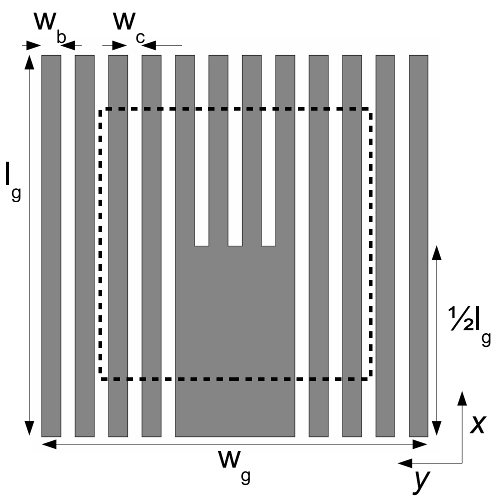

Fig. 2. Dimensions of the patch antenna ground plane. A substrate (shown dashed) of width w_s, length l_s, and height h is placed at the centre of the ground plane. Note that the substrate does not cover all of the ground plane. The whole structure lies on two layers of plaster (thickness about 0.3 mm). The slits in the ground plane and the patch coincide.

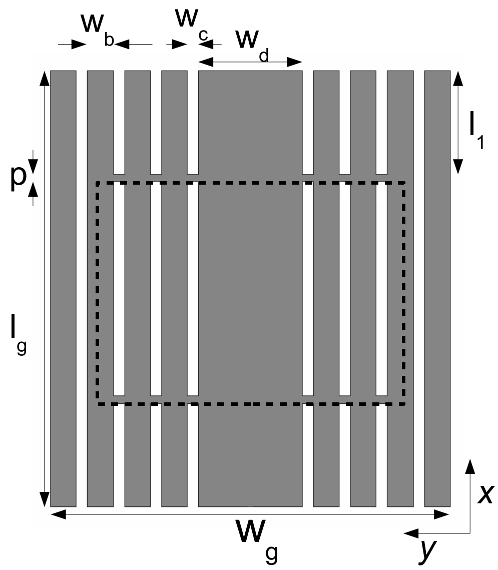

Fig. 4. Dimensions of the quarter-wave antenna ground plane. The parts of width p here (upper one) and in Fig. 3 coincide. A substrate (shown dashed) of width w_s, length l_s, and height h is placed on the ground plane centred in the y direction. The whole structure lies on two layers of plaster (thickness about 0.3 mm). The slits in the ground plane and the patch coincide.

TABLE II

QUARTER-WAVE ANTENNA DIMENSIONS (IN MILLIMETRES)

ground and substrate		patch and feed		slits and strips	
w_g	54	w_p	36	w_a	4.5
l_g	59	l_p	25.5	w_b	3.5
l_1	14	w_f	5	w_c	1.5
l_s	28.5	l_{in}	18	w_d	14
w_s	42	l_{sh}	2	l_c	17.5
h	1.36	g	1	p	1

A. Input Matching

The 2.45 GHz ISM band (Industrial–Scientific–Medical) extends from 2.4 to 2.5 GHz, a bandwidth of 4.1 %. This can be covered by the 6-dB band of an antenna with a Q value of less than 28.

We measured the antenna input impedances using a vector network analyser. For on-body measurements the antennas were attached to the abdomen in order to avoid bending which would possibly interfere with the measurement.

The human body lowers the resonance frequencies of both antennas. At the same time the input resistance at resonance frequency is lowered. The Q value decreases when the antenna is placed on the body, indicating losses in the body. Figures 5 and 6 illustrate the change. The values in free space and on-body are listed in Table III.

TABLE III

INPUT IMPEDANCE MEASUREMENT RESULTS

	patch	quarter-wave
input resistance, free space	54 Ω	58 Ω
input resistance, on-body	42 Ω	51 Ω
Q, free space	27	23
Q, on-body	23	19
resonance frequency change between free space and on-body	$<$ 20 MHz	$<$ 5 MHz

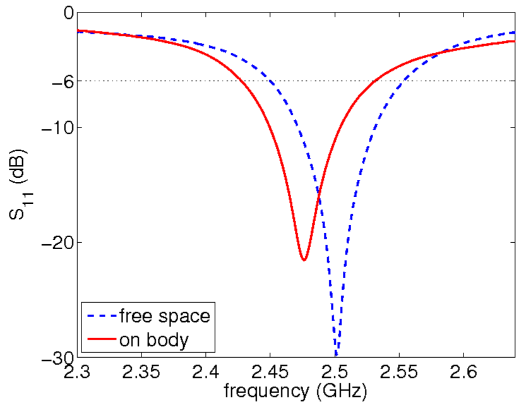

Fig. 5. The S_{11} of the patch antenna. User affects the resonance frequency but the change Q value (bandwidth) is small. Some of the observed frequency change may be due to antenna bending on-body.

Although the antennas are designed to be flexible especially regarding bending about the x axis, they are both sensitive to strong bending. Wrapping the antennas about a styrofoam cylinder of diameter 94 mm caused the resonance frequency to drop by 40 MHz. The prototypes described here may be used only on flat parts of the body, such as on the chest or back. If the antennas are placed on arms or other such places to imply antenna curvature, it is necessary to redesign the element length to attain the desired resonance frequency.

B. On-Body Radiation Patterns

The on-body radiation patterns were measured in an anechoic chamber. The antennas were attached to the abdomen. We only measured the radiation patterns in the yz plane. The inaccuracy associated with the on-body results is about ± 2 dB. The antennas were also measured in free space, using a Satimo StarLab system [3]. From the free-space measurements we get the radiation efficiency, and from the change in Q value between free-space and on-body we can estimate the bodyworn efficiency.

Table IV summarises the measured free-space and on-body results. Example radiation patterns are presented in Figs. 7 and 8, which show the horizontal plane when the antenna feed cable points downwards.

Measurements show that both antennas perform well on-body. The radiation efficiency in free space (about 70 %) is quite large considering that the antennas were made on a plaster substrate. Even a non-uniform ground plane prevents

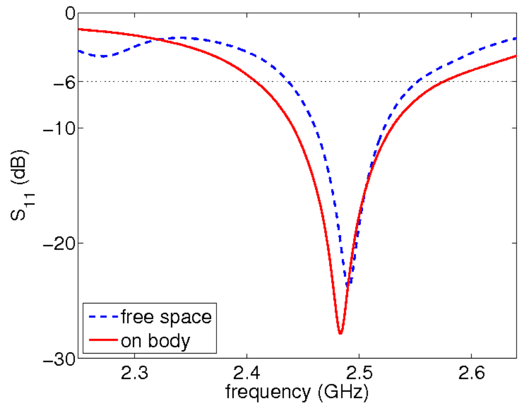

Fig. 6. The S_{11} of the quarter-wave antenna. The resonance frequency does not change significantly but the bandwidth grows.

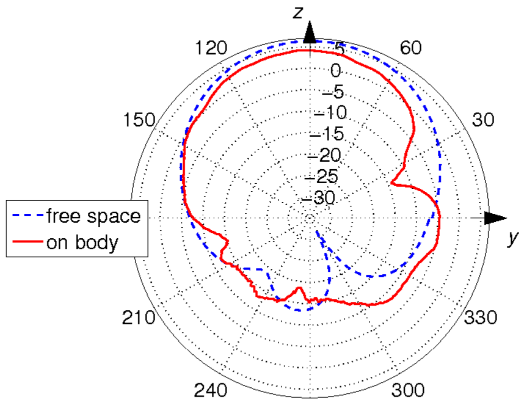

Fig. 7. Patch antenna radiation patterns at 2.5 GHz, in the yz plane, x-directionally polarised. Radial scale is in dBi.

TABLE IV

RADIATION PATTERN MEASUREMENT RESULTS.

	patch	quarter-wave
radiation efficiency in free space	70 %	72 %
maximum gain in free space	6.7 dBi	4.2 dBi
maximum gain when worn	6.2 dBi	1.4 dBi
radiation efficiency on-body (estimate)	60 %	60 %
bodyworn eff. (estimated from Q)	85 %	83 %

the radiation efficiency from dropping too much on the body. The bodyworn efficiency can be calculated from

$$\text{bodyworn efficiency} = \eta_{\text{rad}}^{\text{on-body}} / \eta_{\text{rad}}^{\text{free space}} = Q^{\text{free space}} / Q^{\text{on-body}}$$

where the η_{rad} is the radiation efficiency and Q is the Q value [4]. The right side of the equation assumes that only one mode is present both in free space and on-body and that only the loss Q changes.

IV. SIMULATED SPECIFIC ABSORPTION RATE

This section considers the specific absorption rate (SAR) at 2.4 GHz from the two plaster antennas. SAR is the standard criteria for measuring the amount of electromagnetic energy

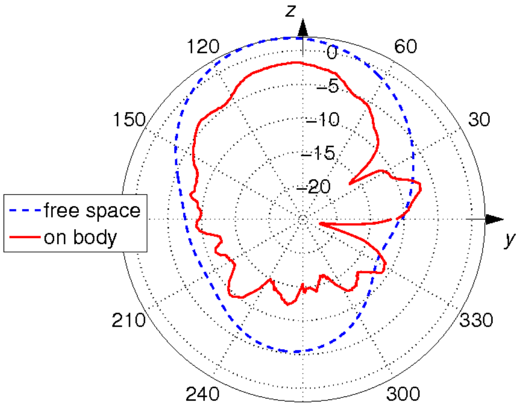

Fig. 8. Quarter-wave antenna radiation patterns at 2.5 GHz, in the yz plane, x-directionally polarised. Radial scale is in dBi.

absorbed in the body and is calculated as

$$\text{SAR} = \frac{\sigma |E|^2}{\rho}$$

where $|E|$ is the rms magnitude of the electric field strength vector, ρ is the mass density of the material in kg/m^3 and σ is the electrical conductivity in S/m. [5]

Note that the maximum 1 g SAR, defined by international ANSI/IEEE standards (used by the FCC in the USA) is 1.6 W/kg [6]. The 10 g SAR is comparable to the European ICNIRP safety standards of 2.0 W/kg [7].

The SAR values in this paper were simulated in CST [8] by placing the antenna next to a digital human body model. The model is from The Visible Human Project [9]. To reduce the memory constraints and improve the computation speed, the body was truncated to leave a section of the torso and also by using one homogenous tissue, see Fig. 9. Homogeneous phantoms are often used for SAR studies as they are well known to give conservative SAR values [5], [10]. SAR measurements and simulations generally agree to within 10 % [5].

The electrical properties of the body simulating tissue were σ = 1.88 S/m, ϵ_r = 37.97, and ρ = 1000 kg/m^3. The Visible Human model was imaged with the subject lying on a flat metallic bench and consequently the phantom has a flat back. The antenna designs in this paper are planar and therefore the centre of the lower back was a convenient place to locate the antenna. In future work, we will bend the antenna so that it can be added to the arm or leg. All results in this section have been calculated with 1 W input power.

To make the SAR simulation easier, the simulated patch antenna model was slightly different from the measured one. The centre slit of the simulated model is 7 mm longer and the metal strips adjacent to it are 1 mm narrower than in the measured one. The effect of this difference on SAR is negligible. The measured and simulated quarter-wave antennas are identical.

The 1 g SAR of the patch antenna was 2.27 W/kg and the 10 g SAR was 0.59 W/kg. Therefore, with a 1 W input power the antenna would be below the limits in Europe but not in the USA. If this antenna were to be used in the USA, the input power would have to be limited to 0.7 W. Fig. 10 shows that the largest 1 g SAR volume is located near the feed of the antenna and this is much larger than other 1 g volumes. Fig. 11 shows that the 10 g SAR distribution is more uniform.

The quarter-wave antenna has a smaller 1 g SAR of 1.58 W/kg, see Fig. 12. This means that this antenna would not breach the IEEE safety standards. However the 10 g SAR of 1.21 W/kg, see Fig. 13, was twice as large as with the patch antenna. The 1 g and 10 g SAR plots of the quarter-wave antenna have a similar pattern to each other.

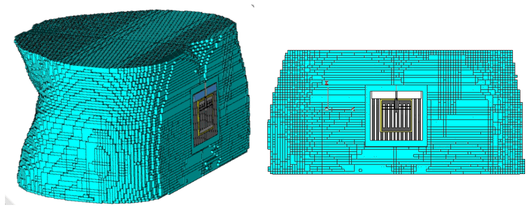

Fig. 9. Patch antenna on the back of the torso model. Feed line points upwards.

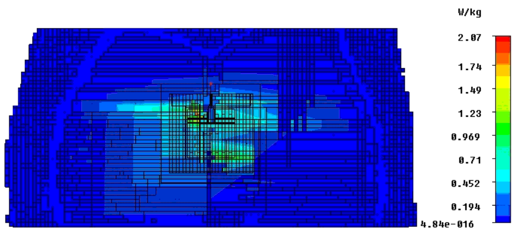

Fig. 10. The 1 g SAR of the patch antenna. Feed line points upwards.

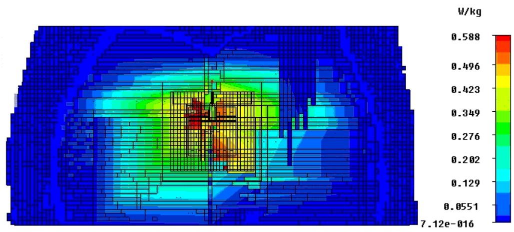

Fig. 11. The 10 g SAR of the patch antenna. Feed line points upwards.

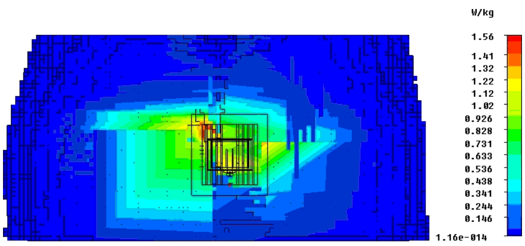

Fig. 12. The 1 g SAR of the quarter-wave antenna. Feed line points downwards.

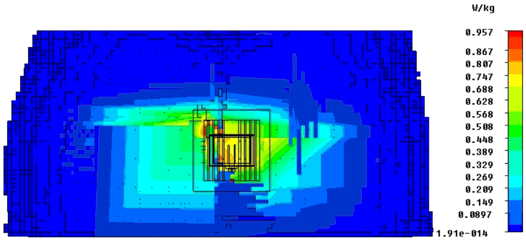

Fig. 13. The 10 g SAR of the quarter-wave antenna. Feed line points downwards.

V. Antennas in Use

Finally, the antennas were tested in real operating conditions. To make the RF connection cheaper, we investigated the usability of snap-on buttons. The antennas were also subjected to a harsh environment, namely a sweating user.

A. Snap-On Buttons in Feed

RF connectors are expensive and thus not suitable for disposable single-use antennas. Instead, we experimented using snap-on buttons, a technique proposed in [11]. In [11], the antennas were fed using a pin through the ground plane. The exact feeding position was found difficult to control.

The antennas proposed in this paper employ an inset microstrip feed line. The snap-on buttons are connected to the microstrip instead of the patch. This gives us more control of the feed impedance, and additionally it is easier to connect the coaxial cable to the edge of the antenna rather than through it. Problems arising from our approach include a very long transition from the coaxial cable to the microstrip, which adds inductance in the feed, and the fact that the coaxial cable may move in use.

We measured the time domain response of a button-fed 50-ohm microstrip line. The reflection from the button was better than −14 dB up to 3 GHz. This indicates that snap-on buttons are suitable for use in cheap commercial devices.

B. Sweating Effects

The product sheet of the plaster material describes the plaster as nonabsorbent, but states that air and water vapour would pass through [2]. Thus it was expected that sweating would not alter the antenna parameters significantly.

We attached the antennas to the back of a male who then jogged for 45 minutes, sweating heavily. No cables were attached to the antennas during the exercise. The radiation patterns and input impedances were measured afterwards. The antennas were not wet to touch after they had been shaken dry. The glue had however partially failed. The user's shirt was dry at the places where the antennas had been.

The radiation patterns were measured right after sweating, and the input impedances about one hour after it.

Sweating reduced the antenna efficiencies by between 2 and 8 %. The radiation patterns were unaffected. The measured resonance frequencies were not changed by sweating. The input impedance decreased by about 8 ohms (patch) or 6 ohms (quarter-wave). The Q value of the quarter-wave antenna reduced from 28 to 24, whereas for the patch antenna the change was smaller than measurement uncertainty.

VI. Conclusion

Antennas made on a plaster substrate have been described. The antennas employ a ground plane between the radiating element and the user to reduce losses. Slits cut in both the elements and the ground planes add flexibility and breathability.

The bandwidth of the plaster antennas covers the 2.4 GHz ISM band. The input impedance is not significantly affected by the body presence. The gain of the half-wave patch antenna is 6.2 dBi and the quarter-wave patch 1.4 dBi, both measured with the antenna attached to the abdomen. Estimated body-worn efficiencies (radiation efficiency on-body compared to the free-space value) of the antennas are 85 %.

The SAR values of the antennas were quite high. Particularly the patch antenna would break the U.S. SAR limits if more than 0.7 W is fed into the antenna. The SAR could be reduced by adding more metal to the antennas, especially in the areas of high current density near the feed point.

Of the two antennas described here, the larger one (patch) was seen to be better, especially in terms of the on-body gain. However, if smaller antennas are desired, the quarter-wave antenna has proven useful as well.

Acknowledgment

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