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<http://dx.doi.org/10.1109/LAPC.2009.5352555>

PUBLISHER

Loughborough University (© IEEE)

VERSION

AM (Accepted Manuscript)

LICENCE

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Bendable Plaster Antenna for 2.45 GHz Applications

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Abstract— A plaster antenna for a 2.45 GHz applications is presented. Measurement results for different use cases are given, and bending effects are examined. The proposed structure exhibits a 6 dBi on-body gain, and covers the 2.4–2.5 GHz ISM band in all use cases. The effect of bending the antenna on the SAR has been investigated by simulations. The antenna is suitable for medical applications.

I. INTRODUCTION

Bodyworn antennas, and especially disposable plaster antennas can prove useful in patient monitoring in e.g. hospitals or home nursing, or in monitoring athletes' recovery after training.

Current technology requires the transmitter to be a belt-carried box, but in the future we may see disposable transmitters printed on plasters, harvesting their transmit power from ambient radio waves. Plaster antennas are also feasible for passive RFID applications such as locating a patient.

In this paper we present a patch antenna with the substrate made of commercially available plaster material. The patch is designed flexible. The feed uses snap-on buttons to connect the antenna to a coaxial cable.

Some problems have been encountered with the previous plaster antennas [1]. The resonance frequencies were seen to shift when the antennas were bent. Also the peak SAR values were high. All this was seen to be due to the slits cut in the antennas. In this paper we focus on how these problems can be fixed.

The antenna structure with dimensions is introduced in Section II. In Section III, the measured antenna properties are presented, and the effects of bending and humidity are examined. The simulated SAR values are presented in Section IV, and Section V concludes the work.

II. ANTENNA STRUCTURE

The proposed antenna structure is a conventional rectangular patch, fed with a short microstrip line. Eight layers of commercial Mefix plaster (self-adhesive polyacrylate [2]) form the substrate. Only a part of the ground plane is covered with the substrate plaster; this results in reduced losses compared with a substrate the size of the ground plane. Small slits are cut in the ground plane, to make it more flexible.

Figure 1 presents the antenna shape, and the dimensions are listed in Table I. The important dimensions are marked with an asterisk, and the rest may be allowed to vary. During tests, the manufacturing tolerance was at least ± 0.5 mm.

Fig. 1 The antenna structure. Grey: metal; pink: edges of the plaster substrate. The eight slits (white) cut in the ground plane are identical, 0.5 to 1 mm wide. The structure lies upon a 10-cm plaster square, which is then attached to the skin. Middle: perspective view of the structure, substrate thickness exaggerated. Bottom: a closeup of the feed point.

Commercial snap-on buttons are used to feed the antenna. One male button is punched through the ground plane and another one through the short microstrip line feeding the patch. A coaxial cable with female buttons is used for measurements. The patch and the substrate are not placed at the centre of the ground plane, to allow some space around the button. The

TABLE I
ANTENNA DIMENSIONS IN MILLIMETRES. IMPORTANT DIMENSIONS ARE
MARKED WITH AN ASTERISK.

patch length *	L_p	50	patch width *	w_p	60
ground length	L_g	80	ground width	w_g	90
	L_1	20	metal strip width	w_s	4...5
	L_2	10	slit width		0.5...1
feed line width		5.5	feed inset *	p	1
substrate length		60	substrate width		70
substrate thickness *	h	1.36	substr. dielectric constant	ϵ_r	1.38
button diameter		7	substr. loss tangent	$\tan \delta$	0.02
button place 1	b_1	10	button place 2	b_2	2...3

spacing between the buttons is due to the button size (diameter 7 mm). The snap-on button feed is described in detail in [3].

The metallic parts of the tested prototypes were cut out of copper foil tape. In the future and in mass production, the antennas could be e.g. inkjet printed.

As shown in previous research [1], slits can be cut in patch antennas. One must make sure there is a continuous path for the current in both the patch element and the ground plane. Here the slits are vertical, as is the radiating current mode. Cutting slits in the patch increases the input impedance and the Q value. Slits in the ground plane decrease the Q value because the tissue losses increase, and consequently the SAR increases as well. Cutting the antenna makes it more sensitive to bending, i.e. bending a cut antenna changes its resonance frequency more than of a solid antenna.

Compared to the previous patch antennas [1], this antenna is designed to have a stable resonance frequency even when slightly bent. [With no slits under the patch feed point, the SAR value is reduced. [check with the simulations pls]]

III. MEASUREMENT IMPEDANCE AND RADIATION

Seven prototype antennas were constructed and tested. The input impedances were measured using a vector network analyser. In all the measurements the antennas were fed using a 7-cm coaxial cable with snap-on buttons. The placement of the buttons introduces an uncertainty of 5 to 10 ohms in resonant resistance and 10 MHz in resonance frequency.

A Satimo Starlab system with about a 1 dB accuracy [4] was used in all the free-space radiation pattern measurements. The on-body radiation patterns were measured in an anechoic chamber. The set-up allowed only the horizontal pattern measurement. The expected accuracy of the on-body measurements is about 2 dB in the main lobe.

A. Input Impedance On-Body

Plaster antennas are designed to be attached directly to the skin, and thus the free-space performance is of no practical importance. However, it is easy to design, model, and measure

Fig. 2 The measured input impedance. a) Return loss on the dB scale; b) an enlarged view of the Smith chart. On arm, we see that the bending causes the impedance to lower. The resonance frequency detunes slightly, due to bending in the xy as well as the xz plane, and also due to the inaccuracy associated with the button feed. Because the manufacturing tolerances, the centre frequency is not exactly 2.45 GHz.

antenna prototypes in free space, and apply the predicted body influence to the design process.

Compared to free-space measurements, the body lowers the input impedance by about 5 ohms. There is virtually no detuning effect. The increased losses are seen in the lowered Q value: from about 28 in free space to about 25 on-body. This means that the bandwidth grows by 10 MHz.

It is difficult to isolate the effects of the dielectric body and bending, because the body cannot be made fully flat. Attaching the antenna to the arm, the input impedance is lowered by few ohms compared to on-torso, as further described in section III C.

Figure 2 shows the S_{11} curve of the antenna placed on various places on the body. On arm, the antenna is curved in the yz plane, but bending also in the xz plane is unavoidable. Some detuning is observed, mostly due to the snap-on button feed arrangement, but also because of bending in the xz plane. Nevertheless, the usable bandwidth is more than 100 MHz, enough to cover the 2.45 GHz ISM band.

The input impedance does not vary from person to person. Variation in the measurement results is mainly caused by the snap-on buttons in the feed (see [3]) and by the deformation of the antenna.

TABLE II
RESULTS OF THE HORIZONTAL PATTERN MEASUREMENT

	torso	arm	air
max. gain (dBi)	5...7	6...7	7
Front-to-back ratio (dB)	10...15	20	15

B. Radiation Patterns On-Body

In free space, the gain was measured to be 7 dBi and the radiation efficiency 73% (−1.4 dB). The peak on-body gains in the horizontal plane are slightly lower than in free space, as listed in Table II. With a small user, a distinct back lobe is seen when the antenna is placed on the torso; with large users the front-to-back ratio is larger. On the arm, the body shadows the backwards direction by 20 dB, regardless of the user size. Fig. 3 illustrates the effect of different users on the radiation pattern, and free-space and on-body patterns are compared in Fig. 4.

The measurements were repeated using three test subjects, and the results were seen to agree within the measurement inaccuracy, except for the back lobe. Results are also consistent with the earlier experiments on plaster antennas [1].

C. Bending

The effects of bending were examined by attaching the antennas on styrofoam cylinders. The bending radii were 47 mm, 68 mm, and 115 mm, corresponding to arm, thigh, and side of the thorax. Here the yz bending refers to ‘bending around a cylinder directed along the x axis.’ The bent antenna always has the patch on the upwards side, i.e. the antenna is always convex.

If the antenna is bent in the yz plane, the input impedance reduces, and as a result the bandwidth narrows. This effect is more pronounced in air than on body: when the antenna is moved from torso to arm, the impedance changes less than due to a similar bending in air. The change in resonance frequency is seemingly random.

Bending the antenna in the xz plane alters the current flow paths, and thus the resonance frequency increases. In air, the 68 mm bending radius was seen to increase the resonance frequency by 50 MHz, or half the bandwidth to be covered. The 47 mm radius resulted in 70 MHz detuning. Again, if the antenna is bent on the body, we observe detuning of 5 to 20 MHz, much less than in air. Bending in the xz plane does not change the input resistance at resonance.

Table III summarises the measured changes in input impedances and resonance frequencies due to bending.

The radiation patterns were measured with the antennas bent on styrofoam. Bending causes the main lobe to widen, and thus the gain drops by 0.5 dB. The radiation efficiency does not change due to bending.

In use the antennas are simultaneously bent in both planes. The xz bending should be minimised when the antennas are

Fig. 3 The measured horizontal plane (yz plane) patterns on two test subjects: 1—a 68-kg female, 2—a 88-kg male. There is a strong shadowing effect by the body. The patterns were measured at 2440 MHz (arm) and 2480 MHz (torso). Radial scale in dBi.

Fig. 4 The measured horizontal plane (yz plane) patterns in free space and on body. The test subject is the male in Fig. 3. The patterns were measured at 2440 MHz (arm and free space) and 2480 MHz (torso). Radial scale in dBi.

TABLE III
MEASURED CHANGES IN INPUT IMPEDANCE AND RESONANCE DUE TO BENDING. POSITIVE VALUE: BENDING INCREASES THIS.

	air 47 mm	arm 47 mm	air 68 mm	thigh 68 mm
ΔZ_{in} (yz bending, ohms)	−10	−5	−10	−6
Δf_{res} (xz bending, MHz)	+70	+5	+50	+20

attached to the body. The limbs and thorax are the most feasible body parts considering this.

To make the bent antennas more comfortable, they could also be constructed bent. The eight plaster layers and the associated glue make the substrate quite rigid, which results in the antenna being easily wrinkled. If the layers were attached to each other on a cylinder, the antenna would be easier to bend on the arm. Otherwise there would be no need to change the structure, except perhaps to move the inset feed point.

D. Humidity

Attaching plaster antennas to the body makes them subject to a humid environment. To simulate the effect of humidity,

two sample antennas were tested in a climate chamber. The test was a 24-hour run in 37 °C, with a relative humidity of 90%. This corresponds to very heavy use, excluding showering. After the treatment, the copper foil had changed colour, but the antenna did not seem moist.

The resonance frequency was seen to shift upwards by 10 to 20 MHz, and the 6-dB bandwidth to grow by 10 MHz, indicating increased losses. No significant change was observed in the resonant resistance or radiation parameters. Hence the antenna material seems very stable in the predicted using environment.

Tests with previous plaster antennas have shown that a sweating user does not affect the antenna parameters [1]. The main problem associated to sweating is that sweaty antennas easily come off the skin. Showering is certain to short-circuit the antenna, unless it is somehow protected—and such protection would make the antenna feeding clumsy.

IV. SPECIFIC ABSORPTION RATE (SAR)

In this section, the SAR from the antenna will be considered when the antenna is bent around a cylinder. In this work Empire commercial FDTD software has been used (www.empire.de).

The SAR was calculated at 2.45GHz. The phantoms were homogeneous with the following properties: relative permittivity, $\epsilon_r = 37.97$, conductivity, $\sigma = 1.88\text{S/m}$, mass density = 1000kg/m^3 . All results in this section are normalized to 1W input power. It was assumed that the largest bend radius would have the largest effect, therefore, three geometries were considered: 1) the flat antenna on a 94mm thick rectangular phantom, 2) the flat phantom on a cylindrical phantom (radius =47mm) and 3) the antenna bent around a 47mm cylindrical phantom (see Figure 5). The results are shown in Table IV.

Fig. 5 The patch antenna bent around a cylindrical phantom with a 47mm radius.

TABLE IV
SIMULATED SAR NORMALISED TO 1W.

Antenna	Phantom	1g SAR (W/kg)	Power absorbed (W)
Flat	Flat	0.87	0.023
Flat	Cylinder: 47mm radius	0.62	0.024
47mm bend radius	Cylinder: 47mm radius	0.87	0.019

Table IV shows that the effect on SAR of bending the antenna around a cylinder is relatively small. Only 2% of the power is absorbed in the phantom, this shows that the metallic ground plane is effective at shielding the body. In fact the maximum SAR occurs between the strips in the ground plane. With 1W input power, the IEEE SAR limits are not breached. The 10g SAR values are always smaller than the 1g SAR values and will not break the ICNIRP limits in Europe [1]. The SAR from the antenna in this paper is lower than the previous design [1].

V. CONCLUSION

A patch antenna structure with a plaster substrate has been proposed. The antenna covers the band from 2.4 to 2.5 GHz in all the use cases. The measured on-body gain is 6 dBi, but the backwards radiation is shadowed by 15 dB. The simulated SAR has been considered when the antenna is bent around a cylinder. Bending changes the antenna properties, but the structure is usable on curved body parts if properly placed.

Compared to the previous plaster antennas [1], the proposed structure is much less sensitive to bending. The SAR values were also not substantially affected by bending the antenna. This antenna produces a lower SAR than in [1] and the ground plane means that relatively little energy will be absorbed in the body.

The proposed plaster antenna is applicable for all kinds of patient monitoring systems, or it can be modified for RFID use.

ACKNOWLEDGMENT

Sincere thanks to Mr. Joel Salmi and B.Sc.(Econ.) Timo Kellomäki who lent their bodies for the measurements, and to M.Sc. Janne Kiilunen and M.Sc. Kirsi Saarinen who helped with the climate chamber measurements. Tiiti Kellomäki's work was funded by the Graduate School in Electronics, Telecommunication and Automation (GETA).

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