

# Characterization of an Implanted Antenna inside a 3D Printed Multilayer Hip Phantom

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**Abstract**—A Cavity Backed Slot (CBS) antenna is designed to operate inside the human body for the application to smart hip implants at the 2.4 GHz ISM band. A multilayered hip phantom is developed using 3D printed hip and bone models filled with muscle and bone mimicking liquids. A hip stem and a ceramic head by Corail are attached to the femur and the hip bone respectively. The antenna is located at one of the vertices of the metallic stem. The hip phantom is fixed on a turntable and the antenna's performance is measured inside a  $1 \times 1 \times 2 \text{ m}$  portable anechoic chamber. The paper details the measurement set-up and shows that the frequency response and the transmission response of the antenna are within the desired range.

**Index Terms**—implant communications, antenna design, hip replacement surgery, body phantom.

## I. INTRODUCTION

Joint replacement surgeries are one of the top ten surgical procedures that are performed in hospitals in Europe [1]. In 2014, 809206 hip replacements were performed in total in 28 European countries [1]. The rate is increasing especially due to an ageing population (between 2000 and 2010, the rate increased 40% in Denmark; 10% in France). The increasing rate contributes to the growing health expenditure. In 2009, the estimated price of a hip replacement on average in EU was approximately EUR 7300 [1]. 128,777 ( $\sim 16\%$ ) of these replacements required revision surgery, which is more expensive than the primary procedure especially for revisions involving infection [2] in terms of resources and operation time and has higher risks.

At the moment, the only feedback that the surgeon gets post-operation is the pain described by the patient which most of the time is due to irreversible damage. A smart implant which can perform continuous self-monitoring can greatly increase the overall success of an arthroplasty and minimize the trauma that the patient goes through. The reasons for a revision could be aseptic loosening (42%), dislocation (13%), infection (12%), or fracture (6%) [3]. The smart implant can support the detection of a failure by monitoring parameters such as temperature, vibration and pressure as conceptualized in Fig. 1 [4].

Although smart hip implants were investigated in the context of infection detection and in-body sensing in the literature [5], implant communications aspect of it has not been discussed before. In the previous studies, the utilization of the Medical Implant Communication Service was assumed. Since MICS standard operates at 401–406 MHz, resonant antenna design is not considered due to the size restrictions. Here, we are

looking into the implant communication aspect of a smart hip implant and proposing to use the 2.4 GHz ISM band as opposed to the MICS band.

Implant communications is an established area of research with standards in place. However, forming a link between an implanted device and the outside world is not straight forward since the human body is extremely hostile to electromagnetic waves. The antenna design is critical for this objective because forming a reliable link will decrease the transmit power level and hence increase the energy efficiency of the system. The quality of the link depends on the depth of the implant, the surrounding tissue and the near-field losses associated with the antenna design. Hence, an implantable antenna should be tested for its specific application.

Here, an implantable cavity backed slot antenna suitable



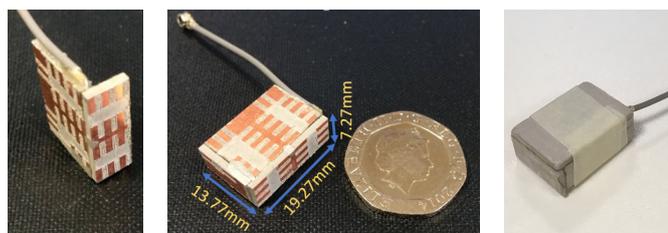
Fig. 1. Conceptual model of smart hip implant, 1: wireless communication, 2: sensing

for smart hip implants is investigated. The antenna is based on (although not identical to) a previous design by one of the authors. In [6], numerical analysis of the implantable antenna was provided. Here, the prototype of that antenna is measured using a dedicated measurement set-up consisting a hip phantom, a collarless metallic femoral stem, a ceramic femoral head, a miniature portable anechoic chamber and a turntable. The antenna is described in Section II briefly to avoid repetition. Section III presents the measurement set-up and Section IV discusses the results.

## II. ANTENNA MODEL

A slot antenna is an antenna that is often preferred for implant communications. Since most of the hip implants are made of titanium, the choice of a cavity backed slot of which cavity is conformal to the titanium surface is a logical choice.

Therefore, an antenna consisting two slots loaded with slits meandered on a shallow cavity is considered here. Both slots are excited simultaneously with a single feed. Although some designs where slots are etched on multiple faces of a cavity were proposed before [7] [8], this antenna differs from the state of the art in two ways. Firstly, it has resonant slots on multiple faces of a single cavity, and secondly the cavity here is a 3D shallow cavity which is formed by uniting 3 perpendicular dielectric blocks. The cavity is a conformal cavity which extends on all the three faces of one of the vertices of the stem as seen in Fig. 2. During prototyping,



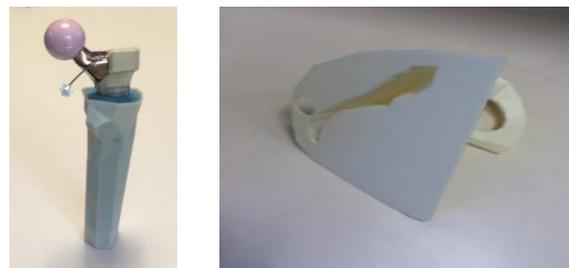
(a) Implant antenna without the superstrate (b) Implant antenna without the superstrate next to a 20 pence coin (c) Implant antenna with the superstrate

Fig. 2. The implant antenna: a slit loaded slot antenna backed with a conformal cavity extending on three planes to be located at one of the vertices of the femoral stem, slit width=1mm, slit length=3mm, first slot length=15.3mm, second slot length=22.3mm

the antenna is printed on 3 pieces of 1.27 mm thick Rogers RT/duroid 6006 with an  $\epsilon_R$  of 6.15. The pieces are glued together and the ground planes are connected using silver ink. The superstrate is then located on the outer faces of the cornered cavity to provide a lossless medium in the strong near-field region. Finally, the antenna is sealed with silicon. This step is essential for the measurements as the antenna will be submerged into tissue mimicking liquids. Although much care was given, the homogeneity of the silicon layer could not be assured. However, the effect of it on the return loss is investigated through simulations. This will be discussed further in Section IV.

### III. MEASUREMENT SET-UP

An approximate hip model is created as a container and 3D printed with Acrylonitrile Butadiene Styrene (ABS). ABS is chosen to be 2 mm thick mimicking the fat layer. It is treated with waterproof spray to avoid leakage. In addition to the hip model, a femur and a hip bone are printed as hollow containers as seen in Figure 3. The containers are filled with muscle and bone mimicking liquids. The liquids were prepared using water, salt, paraffin and emulsifying wax as seen in Figure 4. For the bone tissue, relative permittivity of 16 and conductivity of 0.12 S/m are targeted at the operating frequency. The target was reached using 800 grams of water, 1200 grams of paraffin and 30 grams of wax. For the muscle tissue, relative permittivity of 52 and conductivity of 1 S/m are targeted at the operating frequency. The target was reached



(a) The stem with the implant antenna buried in Femur filled with bone mimicking material (b) Pelvis to be filled with bone mimicking liquid under which the acetabular component of the implant is to be glued



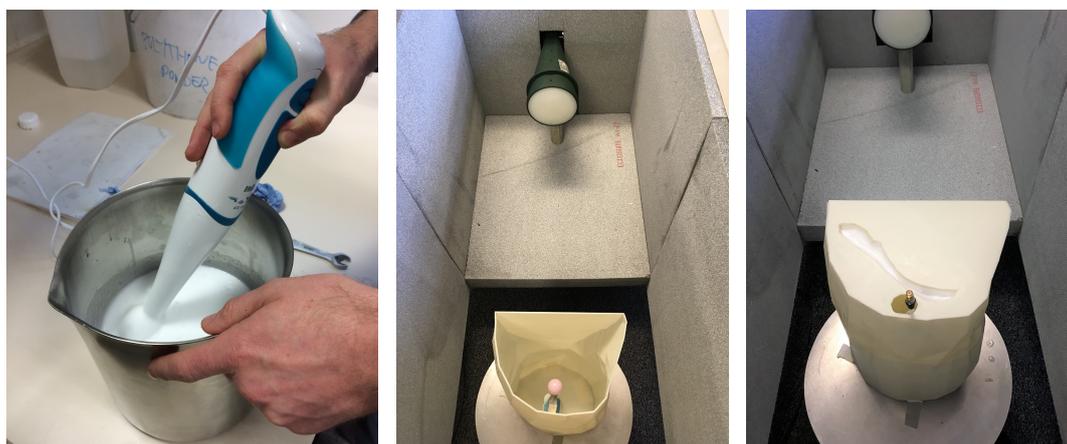
(c) The ABS container to be filled with the muscle mimicking liquid in which the rest of the components are located

Fig. 3. The components of the physical phantom

using 1700 grams of water, 8.5 grams of salt, 300 grams of paraffin and 30 grams of wax. The stem is buried in the femur phantom. The pieces of the phantom are put together and a real size replica of an Ansoft male numerical phantom is obtained as seen in Figure 4. The minimum distance from the implant to the surface is 29.8 mm. The phantom is located on a turntable where the transmission from the implant is measured from 1.20 m distance with a dual polarized horn antenna.

### IV. RESULTS

The implanted antenna has a frequency response as plotted in Figure 5 when located inside the phantom. The antenna operates at the desired frequency band; however, the matching is not as good. The reason behind this worsening is predicted to be the non-homogeneous nature of the silicon layer covering the antenna. In order to validate this prediction, the set-up is simulated with different silicon thicknesses as seen on the same graph. The prototyping process has been complicated due to the 3D nature of the antenna; hence, the prototype could not be further improved. The measurement plan has proceeded with this version of the prototype. Note that the simulated results generated in [6] are different from the ones here due to the fact that the antenna was not covered with silicon and the numerical phantom used was a detailed human phantom (Ansys numerical male phantom [9]) as opposed to the approximate phantom used here. The transmission coefficient between the implant and the horn antenna is measured at 3 different elevations at 2.4, 2.42, 2.44, 2.46, 2.48 and 2.5 GHz as seen in Figure



(a) Phantom development: adding the emulsifying wax (b) Before filled with the bone and muscle mimicking liquids (c) After filled with the bone and muscle mimicking liquids

Fig. 4. Phantom inside the measurement set-up

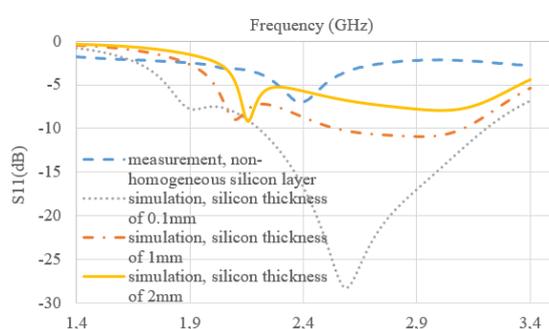


Fig. 5. Measured frequency response of the antenna submerged in muscle mimicking liquid compared to simulated frequency response of the antenna with different silicon thicknesses

6. For each measurement set, the transmission reaches its maximum between  $\phi = 180$  and  $\phi = 240$  and the maximum received power level excluding horn gain is  $-67$  dB. This is an expected result considering the depth of the implant and the directivity of the antenna. On the other hand, we are experiencing a more severe change in elevation. It can be observed that the transmission coefficient changes at the order of 1 dB as the elevation deviates from level position by 2 cm. This demonstrates the importance of using an on-body repeater for deep implant communications [10]. The effect of the accuracy of its position should be further investigated.

## V. CONCLUSION

A conformal cavity backed slot antenna miniaturized using meandering and slit loading is shown to be suitable for smart hip implant applications. It is prototyped and sealed with silicon. A 3D hip phantom is developed using 2 different tissue mimicking liquids. The prototype is measured using the 3D printed hip phantom. It has been shown that 2.4 GHz ISM band is suitable for deep implant communications as proved here for a depth of 3 cm. However, the transmission is sensitive

to receive angle and the usage of an on-body repeater would greatly help the link quality.

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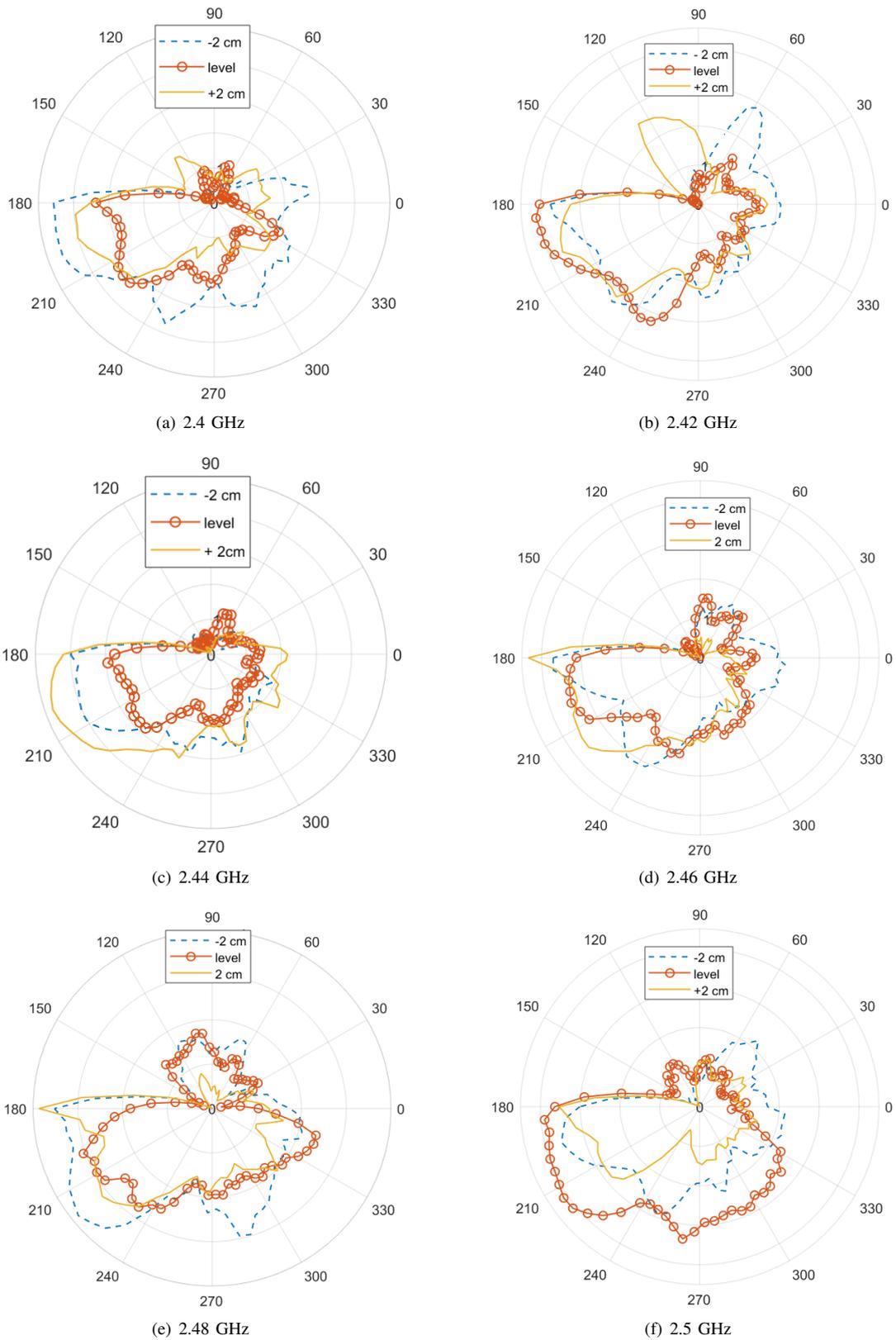


Fig. 6. Normalized transmission coefficient between the implant and the horn antenna (scale: 1dB per division)