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An Implantable and Conformal Antenna for Wireless Capsule Endoscopy

Jingchen Wang, Mark Leach, Eng Gee Lim, Zhao Wang, Rui Pei and Yi Huang

***Abstract*—This paper proposes an implantable antenna with ultra-wide bandwidth operating in the Medical Device Radio communications Service band (MedRadio) (401-406 MHz) for wireless capsule endoscopy (WCE). Simulation and experimental results show the proposed antenna has good performance in terms of the return loss and hence bandwidth from 284 MHz to 825 MHz. The maximum realized gain of this antenna is -31.5 dBi at 403 MHz. The maximum simulated input power is <1.7 mW in order to satisfy the SAR regulations in the IEEE standard. The tolerance of the antenna owing to bendability and different WCE shell thicknesses is investigated. These indicate that the proposed antenna is a good candidate for WCE.**

***Index Terms*—wireless capsule endoscopy, implantable antennas, ultrawideband antennas**

I. Introduction

THE wireless sensor or wireless capsule endoscope, is an ingestible capsule that can take and send pictures, in real-time, of the digestive tract including stomach, large bowel or colon and part of the small bowel after being swallowed, allowing disease characteristics to be observed. The WCE communication system requires a transmitter which must have a compact size, consume ultra-low power, and offer a wide bandwidth, which should be optimized for signal transmission through the human body. Some implantable antennas have been designed in [1-3], however they cannot be used for WCE applications due to limitations on the size of the antenna for WCE. Outer wall loop antennas have been proposed in [4-5] for capsule systems, saving space inside the capsule whilst offering better performance than an antenna within the capsule.

Bandwidth is another essential requirement for the antenna, as this directly determines the communication data rate. For WCE systems to be able to complete transmission of high resolution images in real time, then a high data rate and hence wide bandwidth is necessary. In addition, the bandwidth should not be sensitive to fabrication requirements i.e. radius of capsule ensuring its suitability for various WCE products.

In this paper, a flexible surface mountable planar antenna with ultra-wide bandwidth is proposed. The design and performance of the implantable antenna are presented in Section II. Section III investigates the performance of the antenna as well as the influence of capsule radius and shell thickness on its performance. Measurement setup and measured results are illustrated in Section IV. Conclusions are provided in Section V.

Manuscript received February 15, 2018, revised March 18, 2018; accepted May 7, 2018. This work was partially supported by the XJTLU Research Development Fund (PGRS-13-03-16, RDF-14-03-24 and RDF-14-02-48) and XJTLU Key Programme Special Fund (KSF-P-02).

Jingchen. Wang, Mark Leach, Eng Gee Lim, Zhao Wang and Rui Pei are with the Department of Electrical and Electronics Engineering, Xi'an-jiaotong Liverpool University, Suzhou 215123, P. R. China. (e-mail: jingchen.wang@xjtlu.edu.cn; mark.leach@xjtlu.edu.cn; enggee.lim@xjtlu.edu.cn; zhao.wang@xjtlu.edu.cn; rui.pei@xjtlu.edu.cn)

Yi. Huang is with the Department of Electrical Engineering and Electronics, The University of Liverpool, Liverpool L69 3BX, U.K (e-mail: Yi.Huang@liv.ac.uk).

II. Antenna Designs and Performance

A WCE (as shown in Fig. 1) is typically around 11 mm×26 mm in size and weighs around 4 grams. Besides the miniature color video camera, the capsule contains a light source, batteries, sensors, a transmitter and an antenna [6]. A WCE antenna must be designed to work within the environment of the human body, however, body tissues are lossy dielectric materials and so absorb electromagnetic waves, decreasing the power available externally for reception and limiting the system link budget. Furthermore, the antenna should be designed to have an omni-directional radiation pattern, enabling the receiver to detect the transmitted signal regardless of the orientation or location of the capsule.

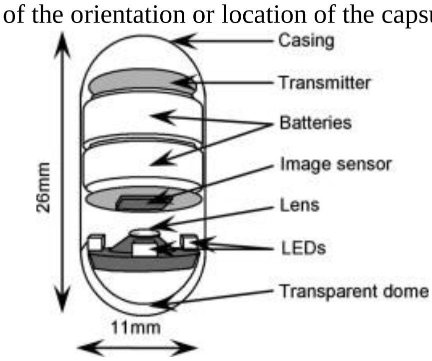

Fig. 1 The components and dimensions of a typical WCE

A. Antenna Designs

An implantable and conformal antenna with an ultra-wide bandwidth is proposed in this work using the meander line technique. This small antenna is suitable for the WCE's cylindrical capsule structure for a minimum radius and total length of 3 mm and 21 mm respectively. Fig. 2(a) shows the physical layout of the designed antenna and details of the dimensions are provided in TABLE I.

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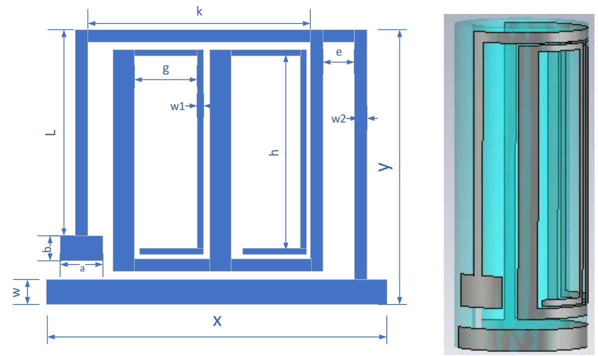

(a) (b)

Fig. 2. (a) Geometric design of proposed antenna; (b) Physical layout model of designed antenna on surface of capsule.

TABLE I: Detailed Dimensions of The Proposed Antenna (Units: mm)

Parameter	Value	Parameter	Value
x	15	w1	0.3
y	15.2	w2	0.5
a	2.5	w	1
b	1.5	h	11.6
L	11.5	g	2.25
k	9.5	e	1.5

The proposed flexible implantable antenna has dimensions of 15 mm×15 mm×0.79 mm. To save space inside the capsule and to satisfy biocompatibility with other components inside the capsule, the antenna is designed to be conformal to the exterior of the capsule with a cylindrical shape (radius=3 mm) using Roger's 5870 substrate (ε_r=2.55). The cylinder is modelled as air filled and is shown in Fig. 2(b).

B. S-parameter

The human body includes muscle, bone, blood and fat, each of which has different dielectric and conductivity characteristics. This leads to a very complex electromagnetic structure to simulate or construct and also leads to a large computational burden, hence costing more in simulation time. Therefore, an equivalent homogeneous human body phantom with a dielectric constant of ε_r=56 and conductivity of σ=0.8 S/m [7] is used in this paper. A simplified large body model has been constructed in CST Microwave Studio as an elliptical cylinder with length 360 mm, width 240 mm and height 100 mm, which is comparable to the typical dimensions of a human adult abdomen [8]. Due to the large simulation time for this model, a smaller model has been constructed with length 120 mm, width 80 mm and height 100 mm. Comparison of the reflection coefficient (S_{11}) results obtained from each model is shown in Fig. 3. The similarity of these results validates the use of the smaller model allowing a reduction in simulation time. It can be seen that the proposed antenna has an ultra-wide bandwidth of at least 541 MHz (284-825 MHz) for S_{11}<-10 dB, which covers the MedRadio band and the 433-434 MHz ISM (Industrial Scientific Medical) band, which is therefore sufficiently wide to communicate well.

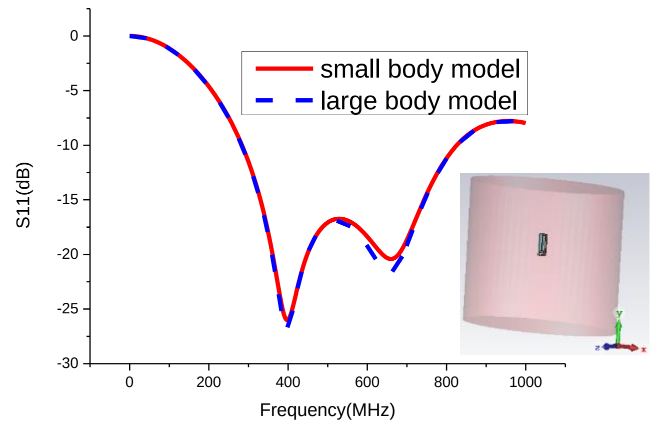

Fig. 3. Simulated S_{11} of proposed antennas in small and large human body phantoms.

The antenna is conformal to the outer wall of the capsule and has an ultrawide bandwidth, thus it can overcome detuning effects, which may happen when the capsule passes different tissues and parts within the digestive tract, whilst still supporting high data rate transmission.

C. SAR Calculations

A human model called Gustave 176 cm tall and with a weight of 69 kg from the CST Voxel family was used to evaluate the SAR generated by the antenna and is shown in Fig. 4.

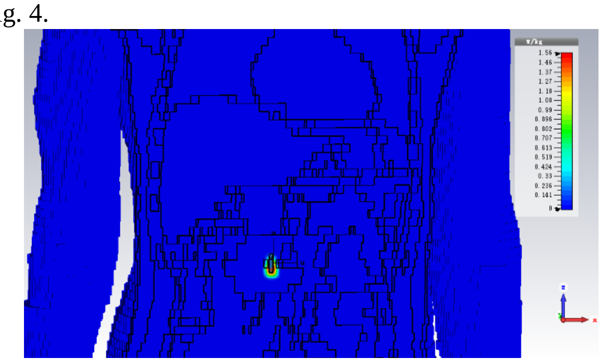

Fig. 4. Evaluated SAR of implantable antenna in human body model.

When the input power of the antenna is assumed 1 W, the simulated maximum 1-g average SAR value for this implantable antenna is 913 W/kg according to IEEE standards. To satisfy the IEEE SAR regulations (1.6 W/kg) [9], the power delivered to the antenna should be below 1.7 mW at 403 MHz.

III. The Effect of Capsule Dimensions and Internal Components

A. The effect of capsule dimensions

To investigate the tolerance of the antenna owing to bending and different capsule shell thicknesses, the radius of the capsule model and shell thicknesses are varied in the CST simulation.

Firstly, the effect of capsule cylinder radius, and hence the amount of bending of the antenna around the capsule, on antenna performance is considered. The proposed antenna is bent on to capsules of varying radii in both simulation and

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practical settings. The reflection coefficient, S_{11}, of the proposed antenna is investigated by curving the planar antenna around cylindrical structures with varying radii. The radii used for simulation are 2.5 mm, 3 mm, 5 mm, 10 mm and 15 mm. The simulated results of S_{11} for each radius are shown in Fig. 5. It can be seen that there is little impact on the bandwidth of antenna covering MedRadio band due to the radius of the cylinder. This means that the same antenna can be used for various WCE designs of different sizes.

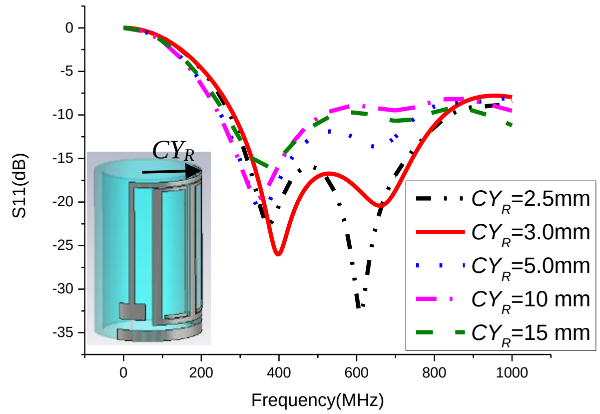


Fig. 5. Simulated antenna S_{11} for varying cylinder radii.

Secondly, the effect of capsule shell thickness is investigated. The proposed antenna is bent and located on the surface of a dielectric layer illustrating the capsule shell. In this case, the radius of capsule is fixed at 3 mm. The thickness of the shell is then varied as: 0.79 mm, 1.5 mm and solid. Fig. 6 illustrates the performance of antenna with these different shell thicknesses. The thickness of the capsule shell is seen to have little influence on the performance of this antenna.

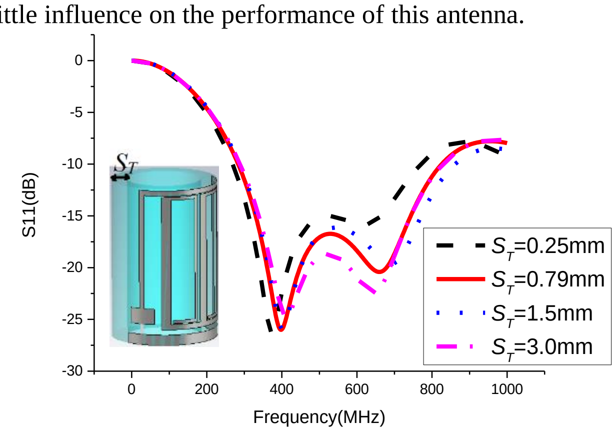


Fig. 6. Simulated antenna S_{11} for different shell thicknesses.

The characteristics of the conformal antenna are not affected significantly by either the cylinder radius or the shell thickness. The designed antenna has sufficient bandwidth to transmit high resolution images at a reasonable data rate. Therefore, the tolerance of this antenna to fabrication requirements is high, potentially leading to lower fabrication costs.

B. *The effect of internal components*

Capsule endoscopes contain many internal components, including camera, sensors and batteries which may affect the antenna performance. Batteries, as the largest components in capsule endoscopes, may have the most significant effect on antenna performance [4,11]. Therefore, it is necessary to conduct simulations for this case and investigate the performance of the antenna with a battery inside the model surface. The battery is modeled as a PEC cylinder which is coaxial to the capsule shell. The battery has been placed inside the capsule at its bottom as shown in Fig. 7 and the battery length is set as 5 mm and 10 mm. The simulated S_{11} of the proposed antenna for the two different battery lengths are shown in Fig. 7.

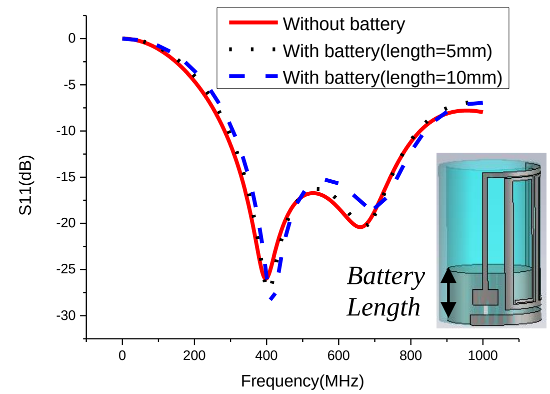
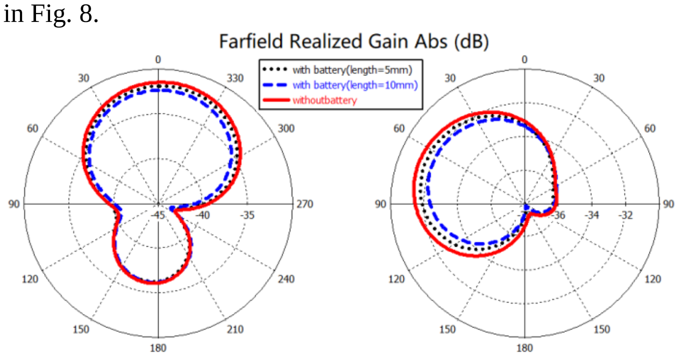


Fig. 7. Simulated S_{11} of proposed antenna with internal battery in different length.

It can be seen from Fig. 7 that the resonant frequencies have been shifted upwards to 410 MHz and 415 MHz for the battery lengths of 5 mm and 10 mm, respectively. However, the bandwidth of the proposed antenna is almost the same covering over 500 MHz, which is comparable to the simulation without the battery. The radiation efficiency of the proposed antenna without the battery is -35.79 dB, and with batteries of lengths 5 mm and 10 mm this decreases to -36 dB and -36.51 dB, respectively. In addition, the simulated 2-D radiation patterns of the proposed antenna with and without the battery are shown in Fig. 8.



(a) (b)

Fig. 8. Simulated radiation patterns of proposed antenna in (a) xy-cut plane; (b) yz-cut plane (403 MHz).

It can be seen from Fig. 8 that the patterns in all cases display a similar shape, except for a slight decrease in realized gain. The maximum realized gain is seen to be -31.5 dB when there is no battery inside the capsule. Comparisons of this design with other works are shown in TABLE II.

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TABLE II: COMPARISONS OF THIS ANTENNA WITH OTHER WORK

Ref.	Types	f_0 (MHz)	Capsule Size (mm)	FBW $\lvert S_{11}\rvert < -10dB$	Realized Gain (dBi)
[4]	Outer wall surface	403	17×ϕ7	50% (327 MHz-530 MHz)	-28.4
[10]	Outer wall surface	434	17×ϕ7	4% (425 MHz-456 MHz)	-22.4
[11]	Inner wall surface	2450	27×ϕ11	113.6% (1640 MHz-5950 MHz)	-26.1
[12]	Inside	2400	26×ϕ11	4.92% (2380 MHz-2500 MHz)	-27.2
This work	Outer wall Surface	433	21×ϕ6	134.2% (284 MHz- 825 MHz)	-31.5

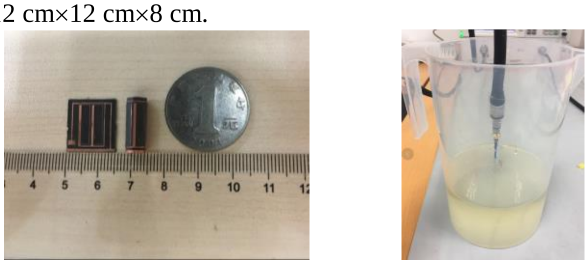
IV. MEASUREMENT SETUP AND RESULTS

A "Tissue-simulating liquid" is needed to provide a human body phantom environment to allow practical measurement of the antenna. The tissue-simulating liquid is a mixture of sugar, NaCl, De-ionized water, Hydroxyethyl Cellulose, Diacetin and Glycol [13]. To form a dielectric constant of 56 and conductivity of 0.8 S/m at 403 MHz, the recipe for the tissue-simulating liquid is summarized in TABLE III.

TABLE III: RECIPE FOR THE TISSUE-SIMULATING LIQUID

Sugar	Nacl	De-ionized water	Hydroxyethyl cellulose (HEC)	Diacetin and Glycol
45.17%	2.98%	51.3%	0.5%	0.05%

The fabricated antenna was bent to fit a capsule shape as shown in Fig. 9(a). The antenna was soldered directly to an 8 cm length of 50 Ω RF cable and connected to a calibrated Vector Network Analyzer (VNA) port. The 50 Ω length of cable was de-embedded from the measurement by shifting the reference plane on the VNA. The measurement process is shown in Fig. 9(b); where the antenna is placed at the center of a plastic container filled with the tissue-simulating liquid. The volume of tissue-simulating liquid in the container is 12 cm×12 cm×8 cm.



(a) (b)

Fig. 9. (a) Fabricated implantable antenna; (b) Measurement of proposed antenna in tissue-simulating liquid.

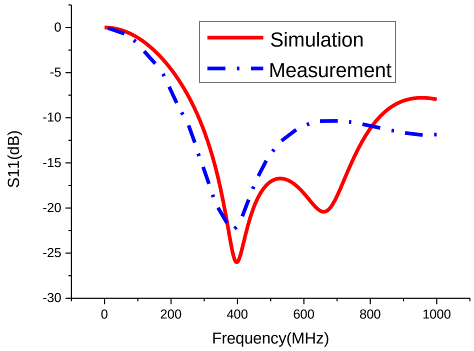


Fig. 10. Simulated and measured S_{11} of proposed antenna in the human body/tissue-simulating liquid.

In Fig. 10, a frequency shift is seen to exist between the simulation and measurement results. The bandwidth of the proposed implantable antenna is very wide, covering the MedRadio band and the 433-434 MHz ISM band. The value of S_{11} drops below -10 dB over a larger frequency range in comparison to that in the simulation results. Overall, the measured results show good agreement with the simulated results over the valid tissue-simulating liquid range.

V. CONCLUSION

In this paper, an implantable, conformal and ultra-wideband antenna is designed and proposed for use in a WCE. To make good use of the capsule surface, the antenna can be stuck firmly to surface of the capsule. Simulation results illustrate that this antenna offers good performance with a large return loss and wide bandwidth of 541 MHz. The maximum realized gain is -31.5 dBi at 403 MHz. The tolerance of the antenna owing to bending, different shell thicknesses and various sized batteries placed inside the capsule has also been investigated. Since the radius of the capsule, the shell thickness and internal battery have only a small influence on the performance of the proposed antenna, then the fabrication tolerance can be greatly relaxed. This proposed antenna is, therefore a good candidate for application in wireless capsules.

ACKNOWLEDGMENT

The authors would like to express their sincere gratitude to CST AG for providing the CST STUDIO SUITE® electromagnetic simulation software package under the China Key University Promotion Program, and their comprehensive support.

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