A DUAL-FUNCTION HELIX ANTENNA WITH WIRELESS COMMUNICATION AND POWER TRANSMISSION CAPABILITIES FOR CAPSULE ENDOSCOPE

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Abstract: Wireless endoscope has attracted a great number of research efforts for its non-invasive diagnosis procedure and the ability to provide comprehensive images of the gastrointestinal (GI) tract of patients. However, significant design challenges still exist in wireless endoscope design. One of them is the design of an antenna with good antenna efficiency and omni-directional radiation pattern while satisfying all related regulations in the human body environment. Another comes from the power supply, e.g. only the limited number of batteries can be accommodated due to the small volume of the capsule. In this work, a dual-functional helix antenna is presented, which addresses both aforementioned demands. The antenna is designed on a flat flexible liquid crystalline polymer (LCP) substrate and rolled up into a cylindrical shape, resulting in a three-dimensional helix structure. The helix operates as a far-field antenna at 400 MHz for wireless communication while it serves as an inductive element for near-field wireless power transmission at 150 kHz. With a helix outmost diameter of 6 mm and a height of 7.6 mm, the antenna demonstrates an omni-directional radiation pattern at 400 MHz. With a CMOS based voltage regulator circuit integrated with the antenna, a stable DC output voltage of 2.6 V with respect to a wide range of input AC voltage values has been demonstrated.

Keywords: capsule endoscope, wireless charging, helix antenna, flexible electronics, dual-functional antenna

INTRODUCTION

An endoscopic approach is utilized in gastrointestinal (GI) tract related diseases diagnosis and management. However, traditional endoscopes are limited in its depth of insertion, and trauma related with this kind of diagnosis has been reported [1]. Recently, a great deal of research efforts has been exerted in wireless endoscopes, especially for the antenna and power solutions [2-4]. Due to the dispersive nature of human body, antenna efficiency is one of major concerns. And antenna design in the human body environment requires an accurate but economic human body model which could reflect key parameters such as the relative permittivity and conductivity of the body organs. Since the electrical length of a passive RF device is sensitive to both parameters, antennas designed in free space are usually not optimized to be used in the human body environment. An antenna for wireless endoscopes has been reported in [2], however, it was designed in free space and human body effects were not taken into consideration. Lee et al. [4] demonstrated an antenna works in a swine body, however, the antenna took significant capsule area and the integration of the antenna into the wireless transceiver circuitry could be difficult to implement since the antenna and the transceiver are on different circuit boards. This kind of multiple layer design could be expensive for mass production since it requires complicated electrical interconnection design as well as mechanical and thermal design procedure.

With the advanced CMOS technology, it is relatively easy to implement necessary electronic components for an endoscope such as a microcontroller, a wireless transceiver, sensor interfacing circuits and so forth. However, battery capacity is not quite scalable for a wireless endoscope system. To address the power supply issue, an inductive link for wireless endoscope online charging has been reported [3]. However, the wireless charging system takes large foot print and system volume, and the coils in [3] are designed only for charging purposes. An additional antenna for wireless communication is needed and the interaction between the wireless communication antenna and the charging coils has not been studied.

In this work, we present a helix antenna which has both a wireless communication function and a wireless charging capability in one single device. This antenna is designed on a flexible liquid crystalline polymer (LCP) substrate and is simply rolled up into a cylindrical shape to implement such an antenna. All necessary electronics can be placed on the same LCP plane with the antenna and, therefore, no lossy and complicated inter-layer communication via would be needed. Both the far field radiation functionality and the near field power transmission functionality are detailed.

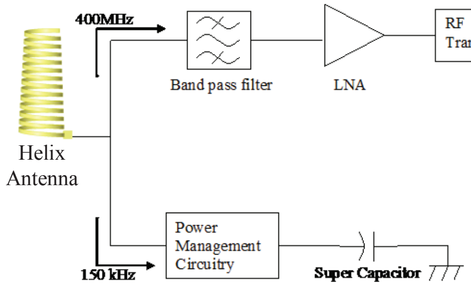


Fig.1 Principle of operation

DUAL FUNCTIONAL OPERATION

Fig. 1 shows a circuit schematic to delineate the dual functional antenna operation. The helix antenna is linked to two path ways: one is to the high frequency transceiver through a band pass filter (BPF) and a low noise amplifier (LNA) (the upper branch in Fig. 1), and the other is to the energy storage device through the power management circuit (the lower branch in Fig. 1).

Since the antenna is designed to have an input impedance matched in a radio frequency (RF) of 400 MHz, when an RF signal comes in, it preferably goes to the RF link while it won't go through the low frequency link because of impedance mismatch. Meantime, a low frequency signal such as one at 150 kHz will not go through the RF signal path because it is blocked by the band pass filter while it can go to the low frequency path through the power management circuit.

HELIX ANTENNA DESIGN

This section details the antenna design procedure. Since we are targeting a kind of antenna operating in the human body, we first look at the electromagnetic characteristics of the human body, and then the antenna design and fabrication procedure are following.

Human Body Model

The human body forms a complicated propagation channel for electromagnetic waves. It is dispersive and the constitutive parameters including relative permittivity and conductivity vary significantly as a function of frequency. The human body is lossy since a large portion of radiated energy from the antenna will be dissipated by the human body which results in a very low antenna power efficiency. This absorbed RF energy may cause negative effects on the body such as hyperthermia. Therefore, medical devices dealing with electromagnetic signals are subject to institutional regulation. In the United States, the specific absorption rate (SAR) is used to evaluate the amount of RF energy absorbed by the human body. SAR is defined as Eq. (1):

$$SAR(W/kg) = \int \frac{\sigma(r)|E|^2}{\rho(r)} dr \qquad (1)$$

where **σ** is the conductivity in S/m, **ρ** is the mass density in g/cm^3, E is the electric field strength in V/m. SAR indicates electromagnetic energy absorbed by unit weight, where either 1g or 10g sample is used for such a measurement. Federal Communication Commission (FCC) regulates that the maximum SAR measured in the human body should not exceed 1.6 W/kg [5].

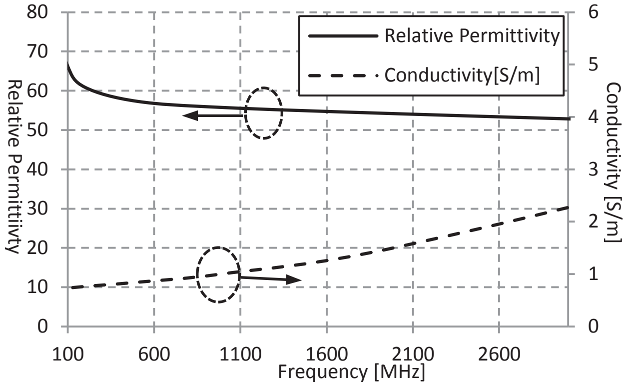


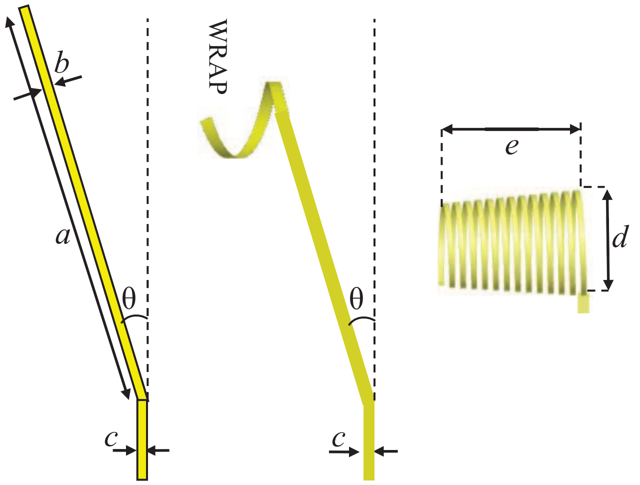
Fig.2 Human body frequency response

Due to the complex nature of the human body, we adopt the commercially available human body model from the high frequency structure simulator (HFSS, Ansys Inc.). This model offers the human body outline as well as frequency dependent permittivity and conductivity information for major human tissues and organs.

The human body parameters are extracted as shown in Fig. 2. The relative permittivity rolls off exponentially toward higher frequency while the conductivity increases as a function of frequency. Therefore, according to Eq. (1), a higher frequency band is expected to show a high SAR value for the same E field strength.

Antenna Design

Now that we have the human body model parameters available, the antenna can be properly designed for the operation of the inside human body. The antenna is designed based on a commercially available LCP substrate, (Ultralam 3850, Rogers, Inc.), which has a thickness of 4 mil (0.1 mm), a dielectric constant of 2.9, and a loss tangent of 0.0012.



(a) (b) (c)

Fig. 3 Schematic of the proposed helix antenna: (a) Metal trace on a flat substrate; (b) Wrapping of the metal trace; (c) Fully wrapped helix antenna: a = 220 mm, b = 0.3 mm, c = 0.65 mm, d = 6 mm, e = 7.6 mm, θ = 1.9°

The antenna design begins with a piece of tilted copper trace as shown in Fig. 3(a), where the tilting angle is exaggerated for clarity. In this work, a tilting angle of θ = 1.9° is used. The antenna is formed by wrapping the flexible substrate into a cylindrical shape as shown in Fig. 3(b). The final antenna schematic is shown in Fig. 3(c) where a helix with a varying diameter for each turn is implemented. Comparing to the normal turn-by-turn winding approach, the wrapping up method enables the easy and convenient implementation of a helix antenna.

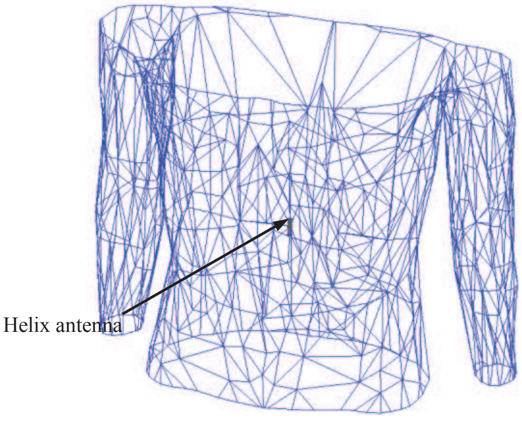
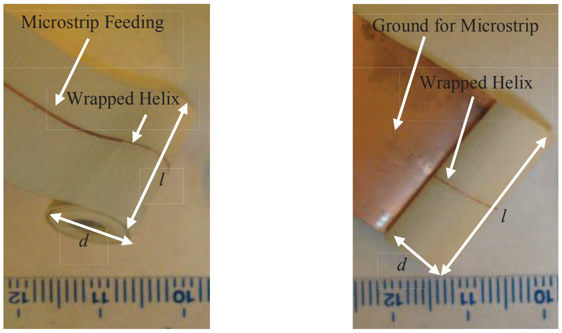


Fig. 4 Antenna simulation in the HFSS human body model

Antenna design and optimization is performed using the high frequency structure simulator (HFSS, Ansys, Inc.), a 3-D full wave microwave simulator using the finite element method (FEM). The antenna is placed in the HFSS human body model for analysis as shown in Fig. 4.

The antenna is carefully optimized and is fabricated on the flexible substrate using a milling machine (S100, LPKF Inc.). The fabricated antenna is shown in Fig. 5.



(a) (b)

Fig. 5 Fabricated antenna: (a) Front view; (b) Rear view, l = 22 mm, d = 6 mm

The fabricated helix antenna shows dual functions in two different frequencies, i.e. a radiation antenna at 400 MHz for wireless communication and an inductive coil at 150 kHz for wireless power transmission. Device characterization is provided below.

ANTENNA FAR FIELD PERFORMANCE

A phantom for the human body is prepared for antenna performance tests. In this work, a solution recommended by FCC is used [6]. The chemical compositions used for the phantom are summarized in Table. 1.

TABLE 1. Composition of the human body phantom

Components	Percentage by weight (%)
Sugar	46.78
NaCl	1.49
Bactericide	0.05
Hydroxyethyl Cellulose	0.52
Water	51.16

The human body phantom solution is kept at room temperature. The relative permittivity at 400 MHz is 58.0 and the conductivity is 0.83 S/m. These values are very close to those of the human body model obtained in Fig. 2, where the HFSS human body model shows a relative permittivity of 58.3 and a conductivity of 0.81 S/m. The antenna return loss is measured using an Agilent E5071C network analyzer after a standard one port calibration procedure. The measured antenna return loss is shown in Fig. 6.

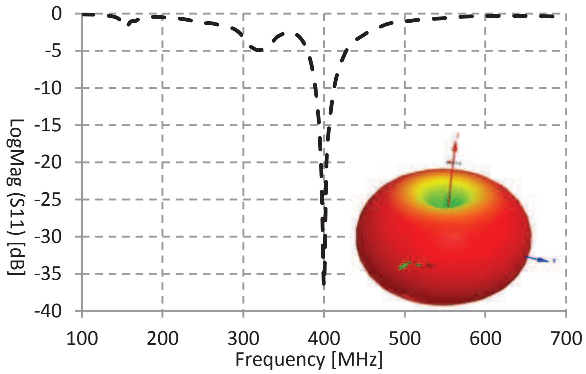


Fig. 6 Measured RF return loss of the helix antenna. Inset: simulated omni-directional radiation pattern

We can see a good return loss performance at 400MHz. The antenna has an antenna gain of -10 dBi and an efficiency of 98 % in free space. However, in the human body, the gain drops to -38 dBi and the efficiency is only -63 dB which is mainly due to the body absorption of electromagnetic waves. Fig. 6 inset shows the simulated omni-directional radiation pattern.

ANTENNA NEAR FIELD PERFORMANCE

The wireless power transmission uses inductive coupling between the external coil and the helix. The input voltage level can be varied depending on the capsule position and orientation. Therefore, a wireless power management IC has been designed using the ONSemi 3M2P 0.5 μm CMOS process. It is composed of a high efficiency rectifier, a precision voltage reference, and a voltage regulator as shown in Fig. 7.

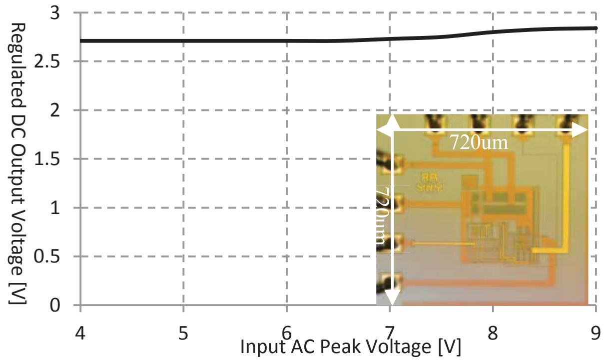


Fig. 7 Measured DC output as a function of input AC voltage. Inset shows an optical photomicrograph of the power management IC die

Voltage regulation performance with the swept input AC voltage over a wide range of 4 V and 9 V has been characterized using an Agilent waveform generator 33120A at 150 kHz as shown in Fig. 7. It shows a very stable output voltage of 2.6 V in the test.

CONCLUSION

In this paper, a dual functional helix antenna for both wireless RF communication and wireless near field power delivery is demonstrated. The antenna is implemented based on a flexible substrate, and is fabricated by patterning a piece of copper trace and wrapping the trace on the substrate into the desired cylindrical shape for the endoscope application. The helix antenna shows an excellent omni-directional radiation pattern as well as wireless charging capability. As future work, SAR and localized temperature due to the antenna will be studied.

ACKNOWLEDGEMENT

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