Outer-Wall Loop Antenna for Ultrawideband Capsule Endoscope System

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***Abstract*—The capsule endoscopy system has been used to obtain an image from the inside of the human digestive tract. To acquire high-resolution images, a loop antenna with ultrawide bandwidth is proposed. It is part of the outer wall of the capsule, thus decreasing volume and increasing performance, and uses a meandered line for resonance in an electrically small area. The proposed antenna makes maximal use of the capsule's outer surface, enabling the antenna to be larger than inner antennas. The measured result shows that the gain of the proposed antenna is higher than that of inner antennas. Return loss and radiation pattern are investigated through simulation and measurement, showing that the proposed antenna has an ultrawide bandwidth of 260 MHz (from 370 to 630 MHz) for $\mathrm{VSWR} < 2$ and an omnidirectional radiation pattern. Using identical antenna pairs in the equivalent body phantom fluid, antenna efficiency is measured to 43.7% (−3.6 dB).**

***Index Terms*—Capsule antenna, endoscopy system, loop antenna, meander, small antenna, wideband.**

I. Introduction

THE CAPSULE endoscopy system uses a wireless transceiver system to obtain medical images of the inside of the human body [1]. This wireless inspection has changed the way subjects are examined. A subject just takes the endoscopy capsule and lives a normal life. The swallowed capsule travels through the digestive tract, gathering images from the camera module and transferring them to the external receiver, where they are saved. Medical diagnosis can be made after inspection of these images. This wireless alternative also creates less discomfort when compared to conventionally intrusive methods.

Transmit power in a capsule endoscope system is limited by the safety guide for human body to electromagnetic (EM) field and by the battery capacity. Also, the data rate is limited by the bandwidth of the system. An ultrawideband (UWB) capsule endoscope system using chirp spread spectrum modulation was proposed to obtain a higher data rate than 10 Mb/s with low power consumption [2].

As the capsule moves through the digestive tract, properties of the body tissue surrounding it change. Therefore, a narrowband antenna can be detuned due to the various material properties. A UWB antenna, however, could maintain its operation because of its ultrawideband characteristic. UWB also enables monitoring through high-resolution images. However, designing a UWB antenna into the capsule is fundamentally difficult due to the fact that the capsule size is electrically small.

For wideband operation, monopole antennas enclosed by a capsule were presented [3], [4] with wide bandwidth around 500 MHz. Their cylindrical volume, however, occupies space inside the capsule, which increases the size of the capsule and makes it uncomfortable to swallow.

To decrease the minimum size of the capsule, a dipole antenna with meandered line was fabricated on the outer wall of the capsule [5]. It had a higher center frequency (1.4 GHz) than monopole antennas [3], [4]. Lines of dipole are meandered in the way current is aligned for the extension of effective length of the antenna. It enveloped only the top dome of the capsule and achieved polarization diversity by a meandered dipole line. However, its bandwidth was less than 200 MHz, not wide enough for a UWB system at 1.4 GHz.

In this letter, we propose a UWB antenna fabricated on the outer wall of the capsule. In small antenna theory, as the radius of sphere including the full antenna structure increases, the limitation of radiation efficiency increases [6]. Since the proposed antenna uses the whole capsule surface, it is expected to show better radiation efficiency than antennas inside the capsule. The proposed antenna therefore not only saves capsule volume, but also increases radiation efficiency.

II. Antenna Design

A. Operation Frequency

During the entire endoscopy procedure, the capsule is surrounded by lossy body tissues that significantly reduce the signal strength and affect the radiation of the antenna. Therefore, it is essential to investigate propagation in a lossy medium.

To investigate these effects, the human body is considered as an averaged homogeneous medium as described by the Federal Communications Commission (FCC) [7].

The homogeneous human body model is shown in Fig. 1. The permittivity and conductivity of the body change with the change in operating frequency.

On the basis of Friis's formula, the total loss between transmitter and receiver was calculated with the distance between the transmitting and the receiving antennas set to 15 cm. It was calculated that the minimum total loss is achieved when operation frequency is between 400∼600 MHz [8]. Thus, the operation frequency of the proposed antenna is determined around 500 MHz.

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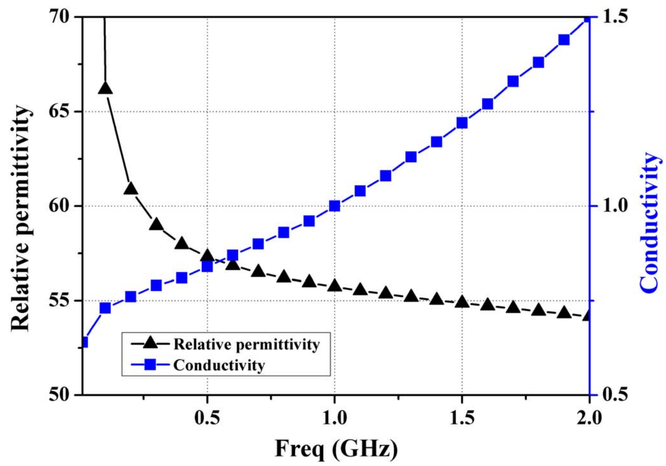

Fig. 1. Homogeneous human body model [8].

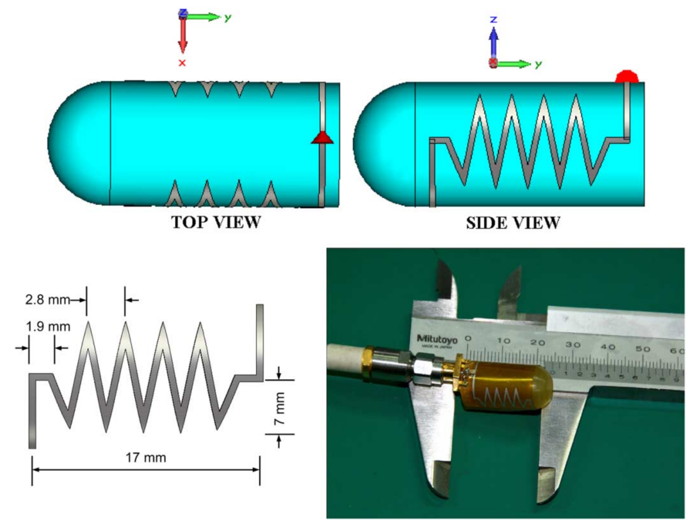

Fig. 2. Proposed outer-wall loop antenna.

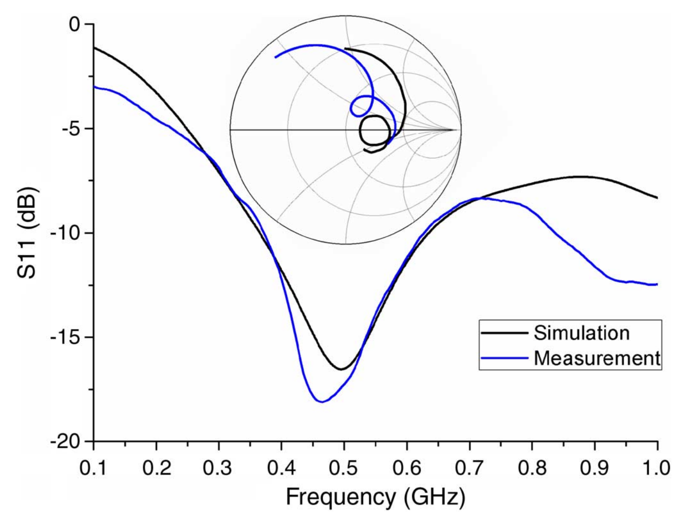

Fig. 3. Comparison between simulated return loss and measured return loss.

B. Meandered Loop Antenna

As the size of the antenna is limited by the properties of the capsule, the dimensions and material properties of the capsule should be described first. The capsule is made of the dielectric material ultem (relative permittivity 3.15), which is very stable against variation of temperature, humidity, and frequency. The outer and the inner radius of the capsule are 5.5 and 5 mm, respectively. Its length is 24 mm. The top dome lies over the camera, so it is excluded from the design area, as antennas there could affect image quality. The conductor used for antenna structure is copper. Gold or other stable materials can also be used for safe operation.

The fundamental design issue in designing the capsule antenna is the antenna miniaturization, as at 500 MHz, the free-space wavelength (60 cm) is much larger than the capsule length. Fortunately, the homogeneous body material surrounding the capsule has high permittivity, giving a dielectric loading effect [9] that significantly reduces the effective wavelength. Thus, it is relatively easy to design a small antenna in the human body than in air.

The proposed antenna is placed on the outer wall of the capsule, as illustrated in Fig. 2. It is a full-wavelength loop antenna with symmetric pattern with respect to center of the capsule. The resonance frequency depends on the length of the loop. For resonance in the electrically small design area, the loop length needs to be extended. A meander technique is suitable for this purpose. By meandering sides of the loop antenna, total length can be increased enough to resonate at 500 MHz. The height of the meander line and the gap between meander patterns can be used as tuning parameters. After adjusting the dimension of the meander and number of meander patterns, the optimum values of these parameters are obtained. The height of the meander line and gap between meander patterns are set to 7 and 2.8 mm, respectively. The opposite side of the loop line is meandered in the same way. The feeding point of the proposed antenna is indicated by a triangle in Fig. 2.

III. Simulation and Measurement

In simulation, the external medium of the capsule is set to homogeneous body-equal material (relative permittivity 56.4, conductivity $\sigma = 0.82$ S/m at 500 MHz) referring to the FCC [7]. The antenna is placed at the center of body-equal material. The simulation is performed using CST Microwave Studio.

The proposed antenna is fabricated on a flexible printed circuit board (PCB) with a polymide of thickness 25.4 μm and a copper line of thickness 18 μm. The fabricated antenna is attached to the outer wall of the capsule as illustrated in Fig. 2. For differential feeding, a balun (Analen B0322J5050A00) is used at the feeding point of the antenna, with an SMA connector connected to the unbalanced line of the balun. For measurement, the capsule is inserted in the plastic container filled with a human-equivalent phantom with the same electrical characteristics as an averaged homogeneous body at 500 MHz.

The simulated return loss and the measured return loss in the human-equivalent phantom are presented in Fig. 3. The measured result shows that the proposed antenna has an ultrawide bandwidth ranging from 370 to 630 MHz for $\mathrm{VSWR} < 2$. The measured result agrees well with the simulated result. With 50% fractional bandwidth, proposed antenna can be used in a UWB system.

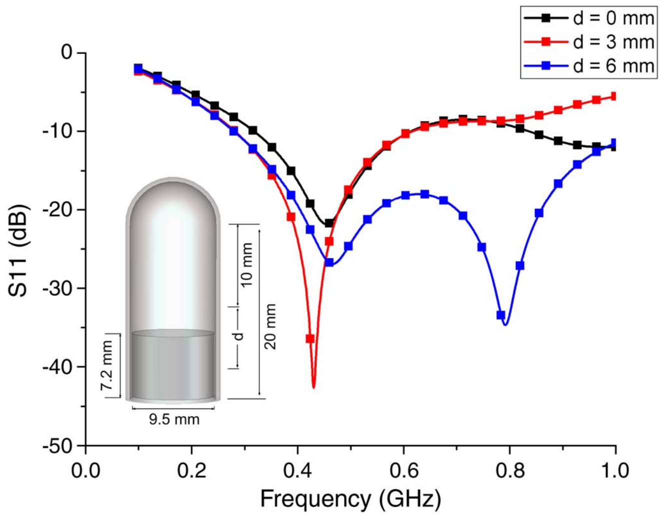

Fig. 4. Simulated return loss with battery in various positions. (d: distance from the center of cylindrical capsule face to the center of the battery).

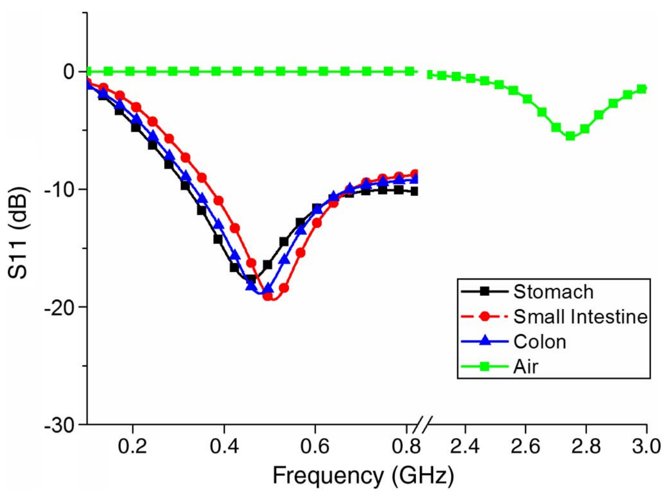

Fig. 5. Simulated return loss in various tissues.

The endoscopy capsule should contain many electrical components, i.e., camera, battery, PCB. However, electrical components near the antenna can affect its operation of the outer-wall loop antenna. Because of their size, batteries are expected to have the most significant effect. Batteries are simply represented as a PEC cylinder with diameter 9.5 mm and height 7.2 mm as shown in Fig. 4. By adjusting distance from the center, effects of batteries in various positions are simulated.

The simulated return losses are shown in Fig. 4. Although there are decreases in resonance frequency, return losses lower than −10 dB are maintained around 500 MHz.

Once a capsule is swallowed, it passes the stomach ($\varepsilon_r = 66.706$, $\sigma = 1.035$ S/m), small intestine ($\varepsilon_r = 63.876$, $\sigma = 1.958$ S/m), colon ($\varepsilon_r = 66.706$, $\sigma = 1.035$ S/m, all at 500 MHz), and other small digestive organs. Fig. 5 shows the simulated return loss of the proposed antenna in various tissues and air. Because of its UWB characteristic, it can maintain S11 lower than −10 dB for a range of ±100 MHz about the center frequency. In air, first resonance of the proposed antenna occurs

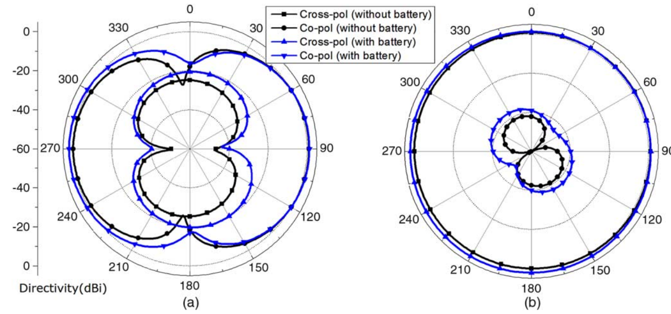

Fig. 6. Simulated radiation patterns of proposed antenna in (a) xy-cut plane and (b) yz-cut plane.

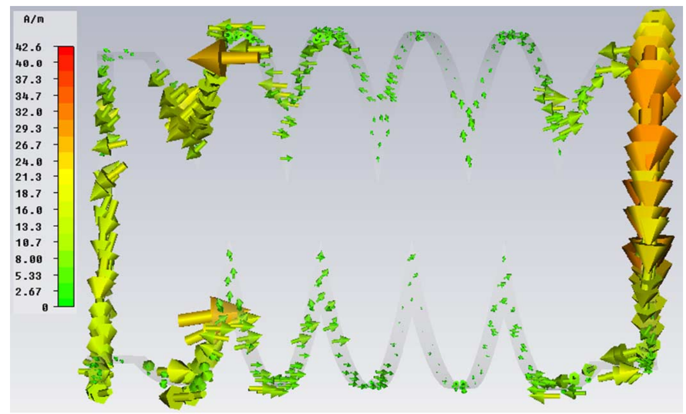

Fig. 7. Current distribution.

at 2.75 GHz, and the radiation efficiency at first resonance is simulated to −0.025 dB.

The radiation pattern of the proposed antenna is shown in Fig. 6. It indicates that the proposed antenna pattern is omnidirectional like a conventional dipole antenna. The radiation pattern considering battery is also simulated with the battery placed at $d = 6$ mm. It has a similar pattern as that of the battery-free case, except for a slight increase in the directivity.

To illustrate its operation, current distribution is presented in Fig. 7. The current is oriented downward at the feeding point, which is placed at one end of the loop. It flows to the opposite end of the loop. Since the current changes its direction at the center of the meander pattern, maximum current flows in the same direction at each end of the antenna, as presented in Fig. 7.

Two aligned currents make radiation pattern similar to the dipole pattern. At the center of the meander pattern, radiations from meander pattern are out of phase to each other because the current is reversed at the center of the meander pattern. As currents in the meander line cancel out, they contribute little to radiation.

Compared to antennas inside the capsule, outer-wall antennas use the given design space maximally. In small antenna theory, as antenna size increases, limitation of maximum gain increases. Therefore, it is expected that an outer-wall antenna would have a higher gain than an inner antenna. We compared the gain of the proposed antenna to those of inner antennas in the same capsule at 500 MHz. Fat monopole spiral antenna [3] and monopole spiral antenna [4] are used as reference inner antennas. Dimensions of each antenna are shown in Table I. They

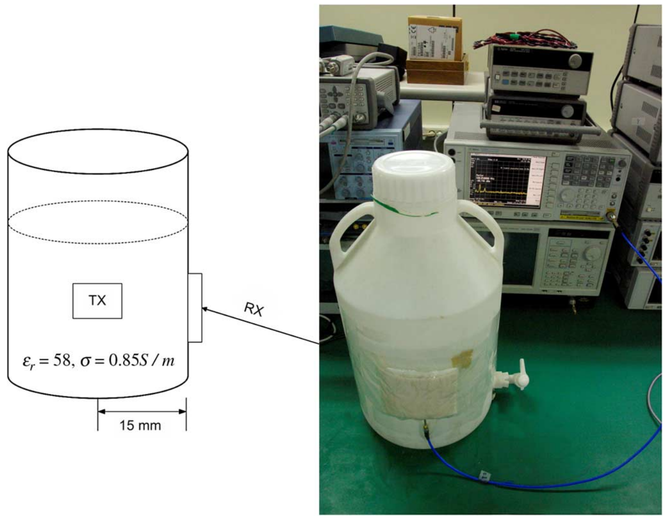

Fig. 8. Simulation setup.

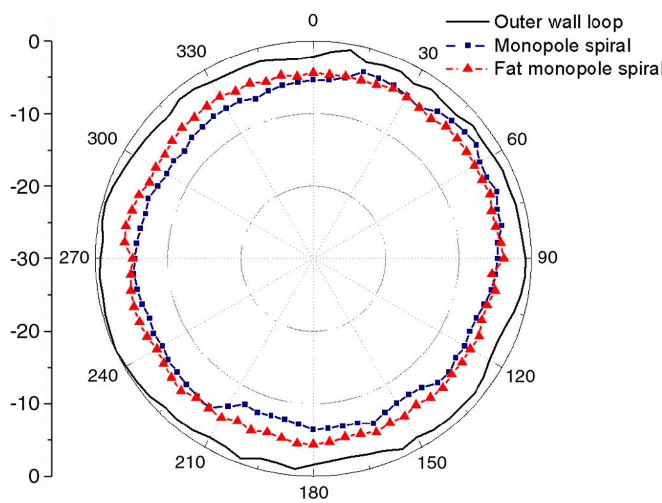

Fig. 9. Normalized measured power of receiving antenna.

TABLE I
AVERAGED MEASURED POWER

Antenna	Normalized power (dB)	Dimension (mm)
Outer Wall Loop	-1.37	11 x 11 x 17
Monopole Spiral	-5.62	10.1 x 10.1 x 3
Fat Monopole Spiral	-4.71	10 x 10 x 4

have wide VSWR < 2 bandwidth at either side of 500 MHz. Inner monopole antennas and the proposed antenna have omnidirectional radiation patterns at 500 MHz. We compared gain in the H-plane, using the measurement setup illustrated in Fig. 8. The antenna to be measured is placed at the center of a plastic container filled with human-equivalent phantom. Each antenna is integrated with the same transmitter, of which output power is 1 mW [10]. The receiving antenna is placed outside of the container, 15 cm from the transmitter. Received power is measured using a power spectrum and normalized to the maximum value of the received power when the transmitter is integrated with the outer-wall loop antenna. The result is shown in Fig. 9 and Table I.

The result shows that, in overall angle in H-plane, the outer-wall antenna has higher gain than inner antennas. As we expected, the receiving antenna on the surface of the container could receive more power when power is transmitted by the outer-wall loop antenna.

Using an identical outer-wall loop antenna in the human-equivalent phantom, antenna efficiency is calculated. One antenna is set to transmitter, and the other to receiver, with the H-planes of each antenna in the same plane. Then, we can measure receiving power from a transmitter with 1 mW. The distance between two antennas set to 15 cm. Because the effect wavelength in the human-equivalent phantom at 500 MHz is 7.633 cm, 15 cm is enough for satisfying the far-field conditions.

From the received power, antenna efficiency can be calculated from Friis's formula. Attenuation loss in the human-equivalent phantom and insertion loss of balun is also considered in the calculation. The simulated directivity of 1.9 is used in calculation as illustrated in Fig. 6.

In measurement, received power is -57.8 dBm. Using Frii's formula, antenna efficiency of the proposed antenna is calculated to be 43.7% (-3.6 dB).

IV. CONCLUSION

A loop antenna with meander pattern is proposed for a UWB endoscope system. It is fabricated on the outer surface of the capsule, thus reducing the size of the capsule by the volume previously occupied by the inner antenna. Although capsule size is reduced, the radius of sphere enclosing the entire structure of the antenna is increased, giving higher gain than an inner antenna. The proposed antenna has omnidirectional radiation patterns, favorable in endoscopy communication.

The proposed antenna has VSWR < 2, a bandwidth of 260 MHz (from 370 to 630 MHz), and radiation efficiency of 43.7%. With its UWB characteristics and high radiation efficiency, it can be used in UWB endoscope systems.

REFERENCES

[1] G. Iddan, G. Meron, A. Glukhovsky, and P. Swain, "Wireless capsule endoscopy," *Nature*, vol. 405, no. 6785, p. 417, May 2000.
[2] K. Kim, M. Jeon, K. Kim, J. Lee, and S. Nam, "Human body communication using chirp spread spectrum modulation," *J. Korean Inst. Commun. Sci.*, vol. 35, no. 5, pp. 440–446, May 2010.
[3] S. I. Kwak, K. Chang, and Y. J. Yoon, "Small spiral antenna for wideband capsule endoscope system," *Electron. Lett.*, vol. 42, no. 23, pp. 1328–1329, 2006.
[4] S. H. Lee and Y. J. Yoon, "Fat arm spiral antenna for wideband capsule endoscope systems," in *Proc. RWS*, 2010, pp. 579–582.
[5] P. M. Izdebski, H. Rajagopalan, and Y. Rahmat-Samii, "Conformal ingestible capsule antenna: A novel chandelier meandered design," *IEEE Trans. Antennas Propag.*, vol. 57, no. 4, pp. 900–909, Apr. 2009.
[6] L. J. Chu, "Physical limitations of omni-directional antenna," *J. Appl. Phys.*, vol. 19, pp. 1163–1175, Dec. 1948.
[7] Federal Communications Commission, "Dielectric properties of body tissues at RF and microwave frequencies," Washington, DC, 2008 [Online]. Available: http://www.fcc.gov/cgi-bin/dielec.sh
[8] J. Lee and S. Nam, "Q evaluation of small insulated antennas in a lossy medium and practical radiation efficiency estimation," in *Proc. Korea–Jpn. Microw. Conf.*, Nov. 2007, pp. 65–68.
[9] S. R. Best, "A discussion on electrically small antennas surrounded by lossy dispersive materials," in *Proc. EuCAP*, 2006, pp. 1–7.
[10] K. Kim, S. Lee, E. Cho, J. Choi, and S. Nam, "Design of OOK system for wireless capsule endoscopy," in *Proc. IEEE ISCAS*, 2010, pp. 1205–1208.