A Design of a High-Speed and High-Efficiency Capsule Endoscopy System

Kihyun Kim*, Sumin Yun, Sungho Lee, *Student Member, IEEE*, Sangwook Nam, *Member, IEEE*, Young Joong Yoon, *Senior Member, IEEE*, and Changyul Cheon, *Member, IEEE*

***Abstract*—This paper presents a high-speed and high-efficiency capsule endoscopy system. Both a transmitter and a receiver were optimized for its application through an analysis of the human body channel. ON–OFF keying modulation is utilized to achieve low power consumption of the in-body transmitter. A low drop output regulator is adopted to prevent performance degradation in the event of a voltage drop in the battery. The receiver adopts superheterodyne structure to obtain high sensitivity, considering the link budget from the previous analysis. The receiver and transmitter were fabricated using the CMOS 0.13-μm process. The output power of the transmitter is -1.6 dB·m and its efficiency is 27.7%. The minimum sensitivity of the receiver is -80 dB·m at a bit error ratio (BER) of 3×10^{-6}. An outer wall loop antenna is adopted for the capsule system to ensure a small size. The integrated system is evaluated using a liquid human phantom and a living pig, resulting in clean captured images.**

***Index Terms*—Automatic gain controller (AGC), CMOS radio frequency (RF) integrated circuit, ON–OFF Keying (OOK) modulator/demodulator, wireless body area network.**

I. Introduction

An endoscope is an essential device in medical applications for its ability to examine the digestive tract accurately. However, it is inconvenient to use in a conventional wired endoscopy system because wired endoscopy causes considerable discomfort to patients. Also, the conventional instrument is limited in terms of its test coverage due to its finite length. Moreover, in the long and twisted small intestine, it is cannot easily access all of the digestive organs. These issues are directly related to the quality of the diagnosis. Therefore, many novel endoscopy examination methods, such as ultrasound detection and wireless telemetry, have been developed [1], [2].

Among them, the wireless capsule system that Iddan was the first to describe is suitable for a substitution device of conventional endoscopy [3]. It could be small enough to be swallowed by patients without causing any discomfort. And, the capsule system has the advantage of offering a means of direct examination of the entire digestive tract with no anesthesia or insufflations [4], [5]. Therefore, many systems for radio frequency (RF) capsule endoscopy have been developed in the 433/868/915 bands [6] or 2.4 GHz bands [7].

In a capsule endoscopy system, the system bandwidth is an important issue related to the accuracy of the diagnosis. As the digital communication data rate is proportional to the capsule system bandwidth [8], the bandwidth should be wide enough to handle the transmission of high-resolution image data in real time. In real environments, as the movement of the locomotive capsule is affected by the speed of peristalsis, high-quality image data are advantageous for accurate diagnoses [9], [10].

The existing system has a data rate of about 1–2 Mb/s [11], [12] and it is difficult to render a smooth real-time image, as its frame rate is generally about 5 f/s or less. In the biomedical industry, Zarlink and Toumaz technologies have developed the devices for biomedical sensor that also have low data rate [13], [14].

Recently, a high-speed system capable of 10 Mb/s at 3–5 GHz was introduced [15]. However, this system did not have an adequate frame rate and its capsule size was too large for patients to shallow it. Another solution for a high frame rate was introduced as a compression technique, but this technique increases complexity of the modem and consumes a considerable amount of power [16]. Generally, the data rate is inversely proportional to the efficiency. Therefore, implementation of a high frame rate and a high-efficiency system is not straightforward.

This paper presents the high-speed and high-efficiency capsule endoscopy system by optimizing the system at 500 MHz. Its frequency to minimize propagation loss and the link budget were calculated from an analysis of the human body channel in Section II. The issue about the optimum frequency bands for wireless telemetry in human body was already discussed about the aspect of electromagnetic filed in [17]. However, these results cannot directly suggest the link budget for a system design. Using the previous our study discussed in [18], more detailed analyses and explanations are presented for a system design. A transmitter and receiver were implemented in the 0.13-μm

Manuscript received July 21, 2011; revised October 10, 2011; accepted December 3, 2011. Date of publication December 28, 2011; date of current version March 21, 2012. This work was supported by the Korea Ministry of Knowledge Economy through the Intelligent Microsystem Center (IMC). *Asterisk indicates corresponding author.*

*K. Kim is with the Applied Electromagnetics Laboratory, School of Electrical Engineering and the Institute of New Media and Communications, Seoul National University, Seoul 151-742, Korea (e-mail: kihyun@ael.snu.ac.kr).

S. Yun is with the Applied Electromagnetics Laboratory, School of Electrical Engineering and the Institute of New Media and Communications, Seoul National University, Seoul 151-742, Korea (e-mail: snam@snu.ac.kr).

S. Lee is with the Korea Electronics Technology Institute (KETI), Gyeonggi 463-816, Korea (e-mail: 2sungho@gmail.com).

S. Nam is with the School of Electrical Engineering and Institute of New Media and Communications, Seoul National University, Seoul 151-742, Korea (e-mail: snam@snu.ac.kr).

Y. J. Yoon is with the Microwave and Antenna Laboratory, School of Electrical and Electronic Engineering, Yonsei University, Seoul 120-749, Korea (e-mail: yjyoon@yonsei.ac.kr).

C. Cheon is with the Department of Electrical and Computer Engineering, University of Seoul, Seoul 130-743, Korea (e-mail: changyul@uos.ac.kr).

Color versions of one or more of the figures in this paper are available online at http://ieeexplore.ieee.org.

Digital Object Identifier 10.1109/TBME.2011.2182050

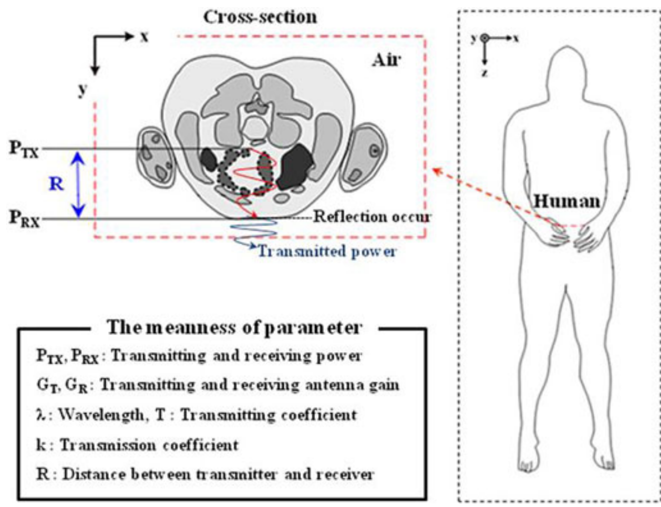


Fig. 1. Conceptual figure in propagation loss calculation.

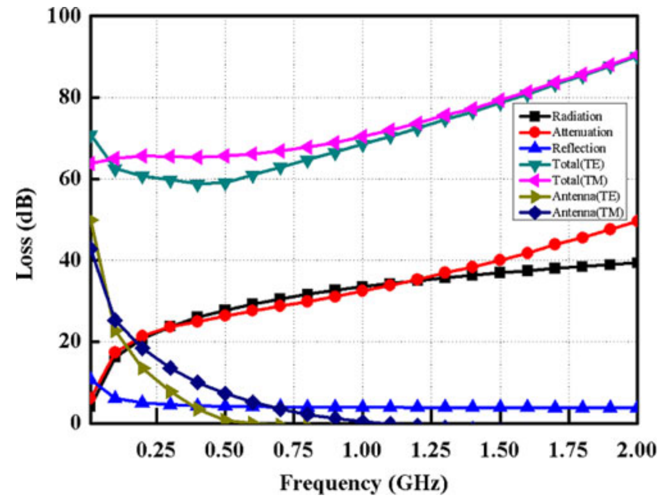


Fig. 2. Total transmitting loss in the human body model.

CMOS process, and each system performance was verified in Section III. Simultaneously, considering the space limitation for transmitting antenna at 500 MHz, the system adopts an outer wall loop antenna that reduces the capsule size and offers better performance than a helical antenna or a planar spiral antenna that have been studied for a capsule systems [19]–[21]. Finally, through an image recovery experiment in a liquid human phantom and in the digestive organs of a live pig, the designed system was tested in Section IV.

II. Finding the Optimum Frequency and System Specification

A. Propagation Loss in the Human Body

The propagation loss analysis is essential for optimizing system specifications for a capsule endoscopy application. It helps to find the optimum frequency to minimize propagation loss. The propagation loss analysis is performed through an established model [22], which operates on the premise that a body consists of a homogeneous material, as described by the Federal Communication Commission.

Given this information, the propagation loss can be calculated through the Friis formula [23], considering the transmission loss in a body, as shown in (1). However, the formula should be used only if R is larger than λ, which could be validated in human body at hundreds of MHz due to its high permittivity. The Fig. 1 is shown as conceptual figure in propagation loss calculation and the meanness of all parameters as follows:

$$\frac{P_{RX}}{P_{TX}} = G_T G_R T^2 \left(\frac{\lambda}{4\pi \cdot R}\right)^2 e^{-2|\mathrm{Im}[k]|R}. \qquad (1)$$

The equation shows the total loss that consists of the antenna gains, the radiation loss as well as the attenuation and reflection. In this analysis, G_R is assumed as unity gain since the physical dimensions of receiving antenna are not strictly limited at outside body. However, G_T should be obtained from the following equation based on an antenna theory [24]

$$G_T = E \cdot D \qquad (2)$$

where E is efficiency and D is the directivity of transmit antenna. In general, the transmitting antenna for capsule endoscope size is smaller than the wavelength of operating frequency. Therefore, it is assumed that the directivity of the small antenna is defined 1.5 [19].

The efficiency of transmitting antenna could be obtained from the spherical modes analysis. The spherical modes are divided into two parts, which consist of transverse magnetic (TM) mode and transverse electric (TE) mode. The modes are related to dipole and loop antenna, respectively.

If the antenna is considered as small antenna, its efficiency is determined by each lowest order mode as the (3.17) in [25]. However, the antenna's bandwidth effect is not considered in that equation and it should be included in the analysis. The gain of antenna including its bandwidth is as in (8) in [26]. Therefore, TM and TE mode antenna gain could be obtained. Moreover, T^2, λ, k can be obtained from electromagnetic theory in a lossy medium [27].

Finally, the total transmitted losses are shown Fig. 2 on the condition of antenna's dimension = 10 mm and minimum antenna's bandwidth = 100 MHz, R = 15 cm. The graph includes the losses of the transmitting antenna's gain, the radiation, the attenuation and the reflection. Its propagation loss is validated only if R is larger than λ.

In the results, the minimum total losses in the human body are shown to be approximately 59 dB at a frequency of 400–600 MHz when a loop antenna is used. And, the losses are 66 dB at same frequency bands when a dipole type is used.

B. Link Budget Calculation

Although the loop types are more efficient than the dipole types in the conductive material such as the human body, the loop types have realization issue [25]. Therefore, the TM total loss was chosen for link-budget calculation.

TABLE I
LINK BUDGET OF OOK SYSTEM FOR A WIRELESS CAPSULE ENDOSCOPE

Frequency band 490MHz~510MHz (OOK, 20Mbps)	Power	
Power of transmitter	- 3 dBm	- 72 dBm
Antenna gain	- 7 - 3 dB	
Propagation + Radiation + Reflection	- 59 dBm	
Link margin	10 dB	
Noise figure of rceiver	5 dB	- 82 dBm
SNR(Env. Detection, BER 10^{-5})	14 dB	- 87 dBm
Thermal noise power	- 101 dBm	- 101 dBm

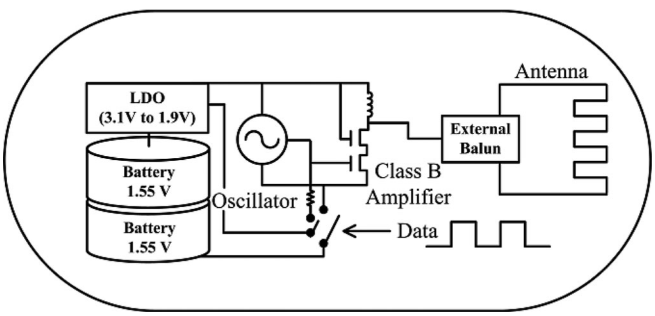


Fig. 3. OOK transmitter for a calusle endoscopy.

From the previously calculated propagation loss analysis, the optimum frequency to minimize the propagation loss is determined to be 500 MHz. The system bandwidth is set to 20 MHz to support a data rate of 20 Mb/s. The output power of the transmitter was set to -3 dB·m, which is the average power. The transmitting antenna gain is set to -10 dB with a 3 dB margin. Table I shows the link budget configuration. The sum of the total loss in the body is -69dB. Therefore, the expected receiving power is -72 dB considering the transmitting power.

On the other hand, the thermal noise power is calculated as -101 dB·m at 300 K when the data rate is 20 Mb/s. From the noise power, if the envelope detector has a signal-to-noise ratio (SNR) of 14 dB at 10^{-5} bit error ratio (BER) theoretically, the receiver's SNR is -82 dB including the receiver's noise figure (5 dB). This result has an expected receiving power margin of 10 dB. The margin is important in the analysis, as the homogeneous human body model is not quite valid and because personal variations exist. This can make antenna matching or propagation loss problems.

III. IMPLEMENT

A. Transmitter Design

A simple structure should be implemented in the capsule system for high-speed and low power. Therefore, ON–OFF keying (OOK) modulation is utilized. The structure of the transmitter is shown in Fig. 3. For a high efficiency, all components should be switched ON/OFF by baseband data with a falling and rising time less than 10 ns to guarantee a 20-Mb/s data rate [18].

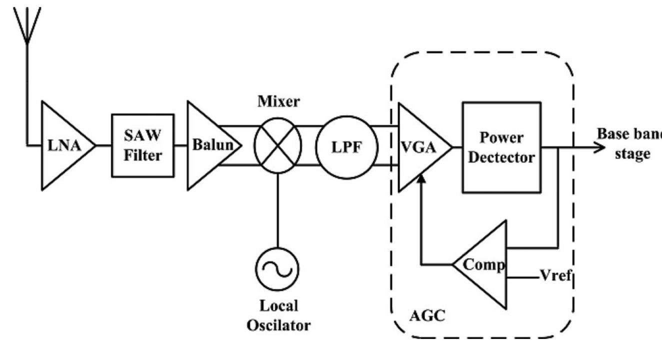


Fig. 4. Gain-saparted receiver for a capsule endoscopy.

The transmitter uses Renata 394 (1.55 [V]) type batteries (two in series), which may cause to critical problems such as variations in the output power and the center frequency in the transmitter during operation. Therefore, the low drop output (LDO) regulator, a dc linear voltage regulator, is adopted to stabilize the supply at 1.9 [V] independent of the battery voltage.

A ring oscillator has faster startup time than an *LC* oscillator [28]. And, the operation frequency can be controlled without an external passive inductor. Moreover, a ring type has good stability in the human body maintaining a constant temperature. Therefore, a ring-type oscillator was adopted for high-speed system.

For achieving a good efficiency and output power, a class B amplifier was chosen for our system. The class B amplifier has an ON/OFF characteristic depending on input data. Also, the gate bias 500 mV is switched by input data, which could save a leakage power.

B. Receiver Design

The receiver could compensate the large attenuation signal through the human body by using a superheterodyne architecture, as shown in Fig. 4. The structure could divide a receiver's gain into RF and intermediate frequency (IF) gains, which reduce the unwanted interaction between the RF and IF stages. Therefore, it can produce a good stability of the receiver despite its high gain.

Using a proposed structure, the RF and local frequency are set to 500 and 400 MHz, respectively. An automatic gain controller was utilized at the IF stage to cover changes in the received signal power according to the location of the capsule endoscopy [29]. Also, the differential signal processing was used for reducing unwanted common mode noise bounds. It was established by adopting a active balun for integration. Every circuits are implemented as conventional structure such like cascode low noise amplifier (LNA), Gilbert-type mixer, Chebyshev-type active low-pass filter. However, a surface acoustic wave (SAW) filter (SA500AP) provided from SAWNICS (http://www.sawnics.com) was externally used to remove out-of-band interference signals. Its steep skirt performance could reject unwanted signal and a SAW is generally used in mobile communication.

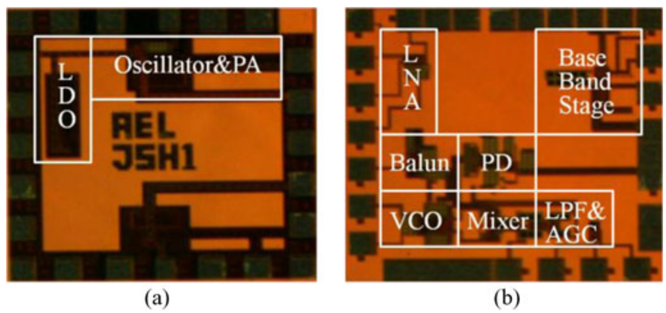


Fig. 5. Microphotograph of designed system: (a) inner transmitter and (b) outer receiver.

TABLE II
FEATURE OF DESIGNED TRANSMITTER FOR A WIRELESS CAPSULE ENDOSCOPE

Data rate	**20 Mbps**
Average power / Output power of transmitter	**0.7 mw / -1.6 dBm**
The efficiency of transmitter at 3.1 [V] battery	**27.7%**
Technology (CMOS)	**0.13 um**
Carrier frequency	**500MHz**
Chip Area	**1mm^2**

C. Performance Measurement Results

The transmitter and receiver were fabricated using 0.13-μm CMOS process with each die area of 1 mm $\times$ 1 mm as shown in Fig. 5.

The Fig. 6(a) shows the output spectrum in the frequency domain when a data from CMOS camera is delivered to designed transmitter. The result shows the center frequency and its peak power shown 500 MHz and -3.72 dB·m, respectively. When the transmitter is in an ON/OFF state, the modulation makes the power spread in a certain frequency range. Therefore, the channel power is measured with the 20-MHz channel bandwidth, as shown in Fig. 6(b).

From the measurements, the overall efficiency of the transmitter including the LDO is 27.7% with an output power of -1.6 dB·m at a 3.1 [V] supply. However, the efficiency, a ratio of the output power to the total dissipated power, is 41% at a 2.1 [V] supply when the battery is discharged. Finally, Table II shows features of the transmitter capsule. Its performance satisfies the requirements of the link budget in Section II.

Since every circuit is integrated in single chip at the designed receiver, only a BER test and LNA measurements are performed. The LNA with SAW filter was measured with vector network analyzer as shown in Fig. 7. It presents a good skirt performance and a gain of 18 dB including the SAW filter's insertion loss.

To measure the sensitivity of designed receiver, a BER test was performed with a PN23 random OOK signal. The receiver showed sensitivity of -80 dB·m with a BER value of 3×10^{-6} at a data rate of 20 Mb/s. The dissipated dc power of the receiver is 22.8 mW at this test condition. Fig. 8 shows the results of the BER test using the E4438C signal generator (Agilent). The sensitivity of the receiver satisfies the link budget calculated in

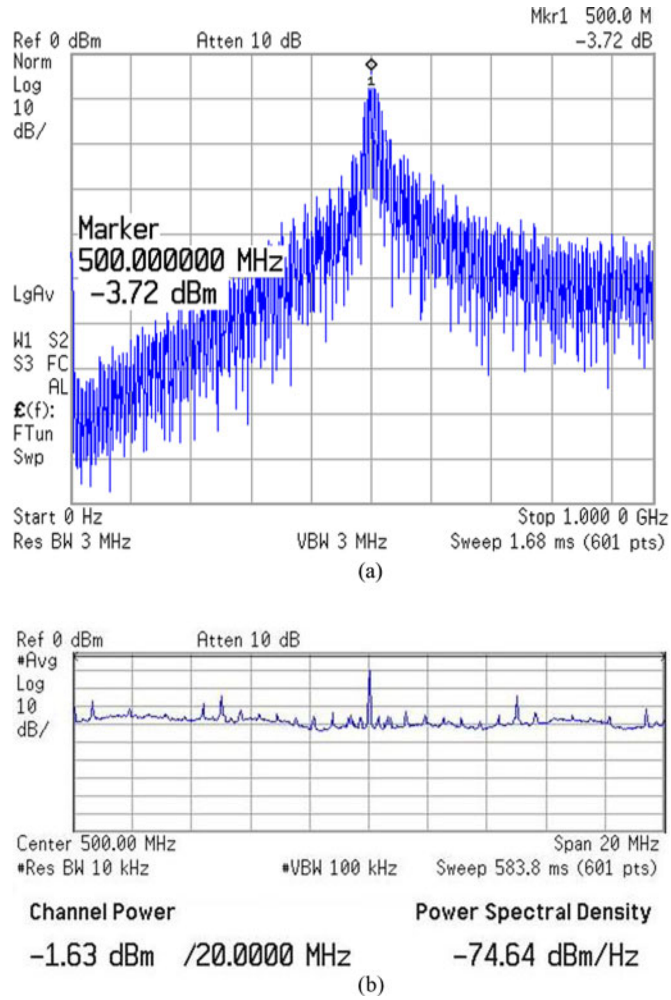


Fig. 6. Transmitter measurement results: (a) Output spectrum. (b) Average channel power in 20 MHz.

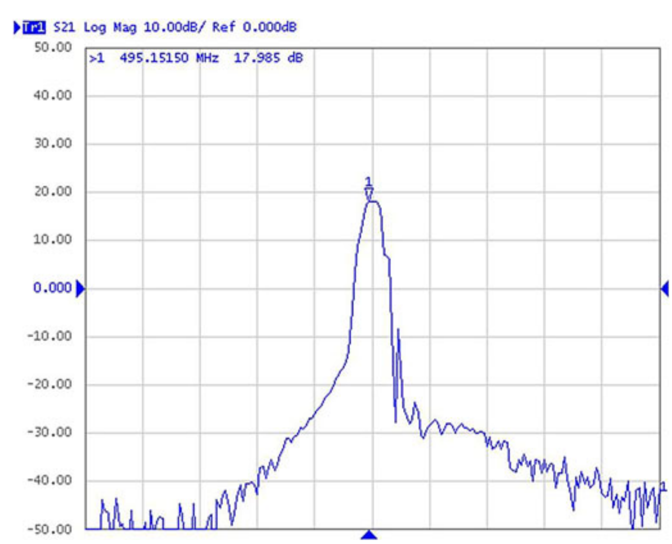


Fig. 7. Small signal gain of LNA with SAW filter at vectror network analyzer.

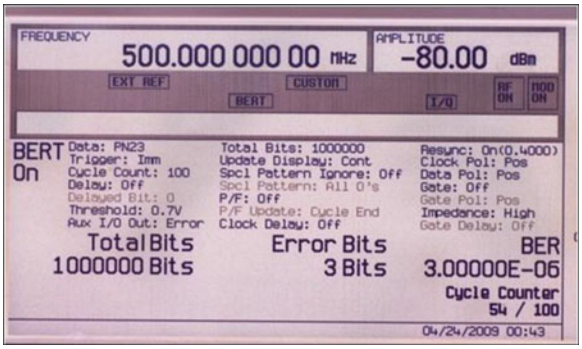


Fig. 8. Bit-Error-Rate test results at Agilent E4438C.

TABLE III
FEATURE OF DESIGNED RECEIVER OF A WIRELESS CAPSULE ENDOSCOPE

Data rate/BER	**20 Mbps / < 10^{-5}**
Average DC power	**22.8 mw**
Sensitivity	**-80dBm**
Radio frequency/Intermidiate frequency	**500/100 MHz**
Input dynamic range	**-50 to -80dBm**
Supply voltage	**1.2[V]**
Technology (CMOS)	**0.13 um**
Chip Area	**1mm^2**

previous section. Table III shows the features of the designed receiver for a capsule endoscopy system.

IV. Image Recovery Experiment

A. Capsule Integration

The integrated capsule consists of several parts. It includes a CMOS camera and a transmitter, the antenna, and the batteries. Fig. 9 shows the integrated capsule transmitter and the components. All of the components are covered with a plastic capsule shell with a diameter of 12.5 mm and a length of 30 mm. The CMOS camera is provided by a company from I3SYSTEM (http://www.i3system.com). An outer wall loop antenna that is dipole type is adopted to reduce the capsule size and to ensure a high gain. A conventional balun (B0322J5050A00) provided from Anaren (http://www.anaren.com/) is used for the connection between the antenna and the transmitter as shown Fig. 3, because the differential type of antenna used here. To connect the balun to the antenna, two holes were made with a drill on the shell, and both devices were soldered with two thin metal wires through each hole as shown Fig. 10.

B. In the Liquid Human Phantom

A liquid human phantom presents an environment similar to that of a human or a pig. It is a mixture of several materials, and its electrical properties are same as the average values of characteristics of human organs such as the conductivity or permittivity. Therefore, an experiment using a liquid human phantom presents a good reference for the animal test.

Fig. 9. Photo of the integrated capsule endoscopy with outer antenna.

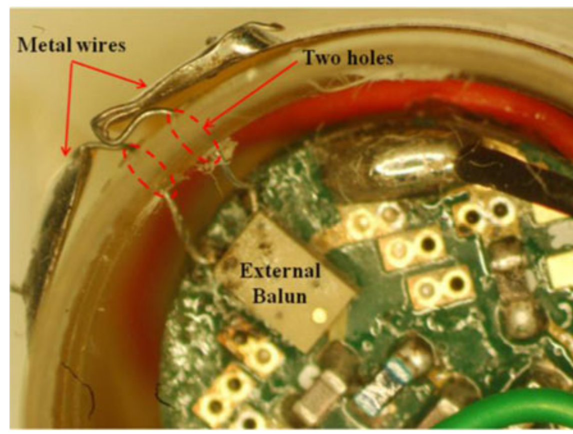


Fig. 10. Connection between balun and antenna.

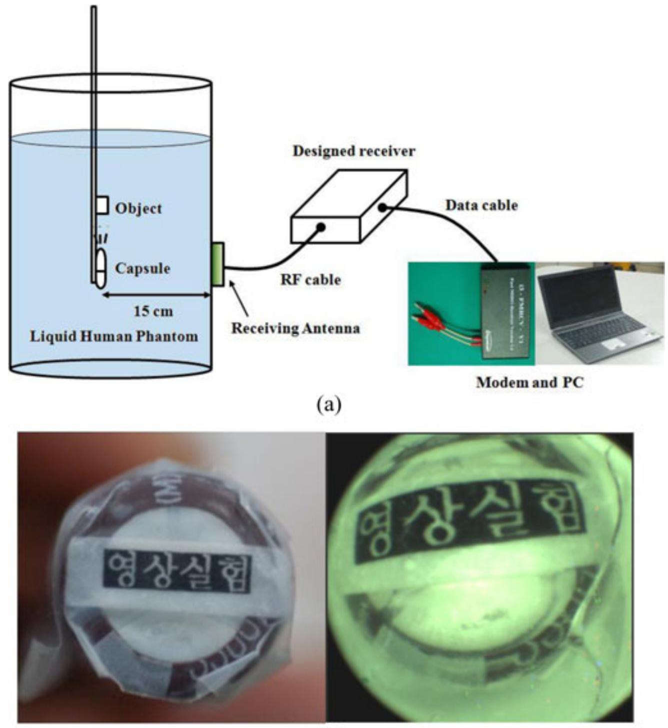
To verify the system operation, image tests were performed in the liquid human phantom [8]. Fig. 11(a) shows the measurement setup applied during the image recover test. The receiving antenna adopted a buffer layered type for low reflection loss [30]. I3SYSTEM company provides the modem and the PC software to decode the transmitted data. Fig. 11(b) shows the actual object (left) and image captured (right), respectively.

The recovered image suggests that an each system described in Section III could operate well together in the environment that is similar to the human body.

C. In a Pig's Stomach and Large Intestine

The image recovery was also performed by using alive pig to verify the system operation in more practical case. The measurement setup is almost same in [8]. The capsule camera transmits images having a 340 $\times$ 340 pixel resolution at 10.5 f/s without using a compression technique. Fig. 12 shows the resulting images in the pig's stomach and large intestine.

In the pig's stomach and large intestine, the high frame images were recovered through the designed system. This result can ensure the validation of our system for wireless capsule endoscopy with high data rate and low power consumption.



(a)

(b)

Fig. 11. Image recovery test in the liquid human phantom: (a) Measurement setup. (b) Actual object (left) and captured image (right).

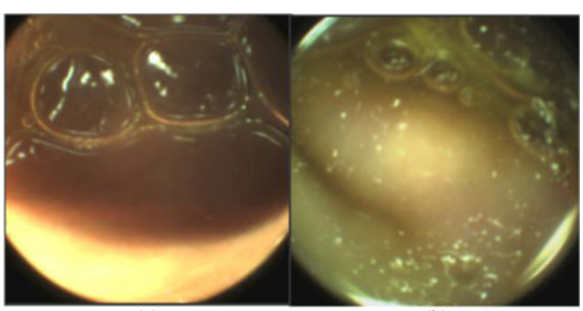

(a) (b)

Fig. 12. Recovered images in the living pig: (a) Stomach wall. (b) Large intestine wall.

V. Conclusion

An optimized system for a capsule endoscope is presented through the human body channel analysis and link budget calculation in this paper. The system is implemented in a 0.13-μm CMOS process and verified through measurement. Also, an outer loop antenna was used for the small capsule design. The designed system has been successfully operated in liquid human phantom and in alive pig. Therefore, the designed low power system is well suited for high-speed capsule endoscope system.

References

[1] B. Chi, J. Yao, S. Han *et al*., "A 2.4GHz low power wireless transceiver analog front-end for endoscopy capsule system," in *Proc. IEEE Int. Symp. Circuits Syst.*, May 2006, pp. 4907–4910.

[2] Y. Gao, Y. Zheng, S. Diao *et al*., "Low-power ultra wideband wireless telemetry transceiver for medical sensor applications," *IEEE Trans. Biomed. Eng.*, vol. 58, no. 3, pp. 768–772, Mar. 2011.

[3] G. Iddan, G. Meron, A. Glukhovsky *et al*., "Wireless capsule endoscopy," *Nature*, vol. 405, pp. 417–418, May 2000.

[4] A. Glukhovsky, "Wireless capsule endoscopy," *Sensor Rev.*, vol. 23, no. 2, pp. 128–133, 2003.

[5] L. Wang, T. D. Drysdale, and D. R. S. Cumming, "*In situ* characterization of two wireless transmission schemes for ingestible capsules," *IEEE Trans. Biomed. Eng.*, vol. 54, no. 11, pp. 2020–2027, Nov. 2007.

[6] P. Quinlan *et al*., "A multimode 0.3-200-kb/s transceiver for the 433/868/915-MHz bands in 0.25-/spl mu/m CMOS," *IEEE J. Solid-State-Circuits*, vol. 39, no. 12, pp. 2297–2310, Dec. 2004.

[7] A. Fakher, M. J. Deen, and H. deBruin, "Low-voltage, low-power and low phase noise 2.4GHz VCO for medical wireless telemetry," in *Proc. Can. Conf. Electr. Comput. Eng.*, May 2004, vol. 3, pp. 1321–1324.

[8] S. Lee, J. Lee, Y. Yoon, and S. Park, "A wideband spiral antenna for ingestible capsule endoscope systems: Experimental results in a human phantom and a pig," *Trans. Biomed. Eng.*, vol. 58, no. 6, pp. 1734–1741, Jun. 2011.

[9] F. Carpi, S. Galbiati, and A. Carpi, "Controlled navigation of endoscopic capsules: Concept and preliminary experimental investigations," *IEEE Trans. Biomed. Eng.*, vol. 54, no. 11, pp. 2028–2036, Nov. 2007.

[10] H. M. Kim, S. Yang, J. Kim, S. Park, J. H. Cho, J. Y. Park, T. S. Kim, E.-S. Yoon, S. Y. Song, and S. Bang, "Active locomotion of a paddling-based capsule endoscope in an *in vitro* and *in vivo* experiment (with videos)," *Gastrointestinal Endosc.*, vol. 72, no. 2, pp. 381–387, 2010.

[11] B. Chi, J. Yao, S. Han, X. Xie, G. Li, and Z. Wang, "Low-power transceiver analog front-end circuits for bidirectional high data rate wireless telemetry in medical endoscopy applications," *IEEE Trans. Biomed. Eng.*, vol. 54, no. 7, pp. 1291–1299, Jul. 2007.

[12] S. Itoh, S. Kawahito, and S. Terakawa, "A 2.6 mW 2fps QVGA CMOS one-chip wireless camera with digital image transmission function for capsule endoscopes," in *Proc. IEEE Int. Symp. Circuits Syst.*, May 2006, pp. 3353–3356.

[13] B. Peter. (2006, Jul.). RF integrated circuits for medical implants: Meeting the challenge of ultra low power communication [Online]. Available: http://www.cmoset.com/uploads/Peter_Bradley.pdf

[14] Toumaz UK Ltd. Sensium Life Platform Product Brief TZ2050 [Online]. Available: http://www.toumaz.com/uploadsv3/wysiwyg_editor/files/TZ205000-MPB%20Product%20brief%20Sensium%20Life%20Platform%20V1_2.pdf

[15] Y. Gao, Y. Zheng, S. Diao, W. Toh, C. Ang, M. Je, and C. Heng, "Low power ultra-wideband wireless telemetry transceiver for medical sensor applications," *IEEE Trans. Biomed. Eng.*, vol. 58, no. 3, pp. 1291–1299, Mar. 2011.

[16] J. Thoné, S. Radiom, D. Turgis, R. Carta, G. Gielen, and R. Puers, "Design of a 2 Mbps FSK near-field transmitter for wireless capsule endoscopy," *Sens. Actuators, A: Phys.*, vol. 156, no. 1, pp. 43–48, Nov. 2009.

[17] L. C. Chirwa, P. A. Hammond, S. Roy, and D. R. S. Cumming, "Electromagnetic radiation from ingested sources in the human intestine between 150 MHz and 1.2 GHz," *IEEE Trans. Biomed. Eng.*, vol. 50, no. 4, pp. 484–492, Apr. 2003.

[18] K. Kim, S. Lee, E. Cho, J. Choi, and S. Nam, "Design of OOK system for wireless capsule endoscopy," in *Proc. IEEE Int. Symp. Circuits Syst.*, May 2010, pp. 1205–1208.

[19] S. Yun, K. Kim, and S. Nam, "Outer wall loop antenna for ultra wideband capsule endoscope system," *IEEE Antennas Wireless Propag. Lett.*, vol. 9, pp. 1135–1138, Dec. 2010.

[20] S. I. Kwak, K. Chang, and Y. J. Yoon, "The helical antenna for the capsule endoscope system," in *Proc. IEEE Antennas Propag. Symp.*, Jul. 2005, vol. 2B, pp. 804–807.

[21] 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, Nov. 2006.

[22] D. L. Means, K. W. Chan. (2001 Jun.). Evaluating compliance with FCC guidelines for human exposure to radio frequency electromagnetic fields [Online]. Available: http://www.fcc.gov/Bureaus/Engineering_Technology/Documents/bulletins/oet65/oet65 c.pdf

[23] H. T. Friss, "A note on a simple transmission formula," *IEEE Trans. Proc. IRE.*, vol. 34, no. 5, pp. 254–256, May 1964.

[24] C. Balanis, *Antenna Theory*, 3rd ed. Hoboken, NJ: Wiley, 2005.

[25] A. Karlsson, "Physical limitations of antennas in a lossy medium," *IEEE Trans. Antennas Propag.*, vol. 52, no. 8, pp. 2027–2033, Aug. 2004.

[26] 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.
[27] D. K. Cheng, *Field and Wave Electromagnetics*, 2nd ed. Boston, MA: Addsion-Wesley, 1989.
[28] T. Miyazaki, M. Hashimoto, and H. Onodera, "A performance comparison of PLLs for clock generation using ring oscillator VCO and LC oscillator in a digital CMOS process," in *Proc. IEEE Asia South Pacific Design Automation*, 2004, pp. 545–546.
[29] H. Park, S. Lee, and S. Nam, "An inductorless CMOS 0.1-1GHz automatic gain control circuit," in *Proc. Eur. Microw, Conf.*, Oct. 2008, pp. 456–459.

Kihyun Kim received the B.S. degree in electrical engineering from Korea Aerospace University, Gyeonggi, Korea, in 2008, and the M.S. degree from Seoul National University, Seoul, Korea, in 2010, where he is currently working toward the Ph.D. degree in electrical engineering.

His research interests include in CMOS implementation of wireless communication transceivers in biomedical.

Sumin Yun received the B.S. degree in electrical engineering, from the Seoul National University, Seoul, Korea, in 2008, where he is currently working toward the Ph.D. degree.

His main research interests include on-body antenna and its theoretical analysis for BAN applications.

Sungho Lee (S'08) received the B.S. and M.S. degrees in electrical engineering from Sogang University, Seoul, Korea, in 1998 and 2000, and the Ph.D. degree from Seoul National University, Seoul, Korea, in 2011, respectively.

From 2000 to 2009, he was a Senior Design Engineer with the GCT semiconductor, San Jose, CA., where he was involved in various RF transceiver developments for wireless communication applications, including WCDMA, PHS, GSM, and S/T DMB. Since 2010, he has been a Senior Researcher with Korea Electronics Technology Institute (KETI), Gyeonggi, Korea.

Sangwook Nam (S'87–M'88) received the B.S. degree from Seoul National University, Seoul, Korea, in 1981, the M.S. degree from the Korea Advanced Institute of Science and Technology (KAIST), Seoul, Korea, in 1983, and the Ph.D. degree from the University of Texas at Austin, Austin, in 1989, all in electrical engineering.

From 1983 to 1986, he was a Researcher with the Gold Star Central Research Laboratory, Seoul, Korea. Since 1990, he has been a Professor with the School of Electrical Engineering and Computer Science, Seoul National University. His research interests include analysis/design of electromagnetic (EM) structures, antennas and microwave active/passive circuits.

Young Joong Yoon (S'88–M'93–SM'10) received the B.S. and M.S. degrees in electronic engineering from Yonsei University, Seoul, Korea, in 1981 and 1986, respectively, and the Ph.D. degree in electrical engineering from the Georgia Institute of Technology, Atlanta, in 1991.

From 1992 to 1993, he was a Senior Researcher at the Electronics and Telecommunications Research Institute, Daejeon, Korea. In 1993, he joined Yonsei University as Faculty Member, where he is currently a Professor at the School of Electrical and Electronic Engineering. He is also the Vice-President of the Korean Institute of Electromagnetic Engineering and Science. His research interests include antennas, RF devices, and radio propagations.

Dr. Yoon received the President's Award for his contribution to the improvement of science and technology in 2006.

Changyul Cheon (S'87–M'90) was born in Seoul, Korea, on April 5, 1960. He received the B.S. and M.S. degrees in electrical engineering from the Seoul National University, Seoul, Korea, in 1983 and 1985, respectively, and the Ph.D. degree in electrical engineering from the University of Michigan, Ann Arbor, in 1992.

From 1992 to 1995, he was with the Department of Electrical Engineering, Kangwon National University, Chuncheon, Korea, as an Assistant Professor. He is currently a Professor of electrical engineering at the University of Seoul (UoS), Seoul, Korea. His group at UoS is currently involved with the design and analysis of microwave and millimeter-wave passive device using FEM, FDTD, and MoM techniques as well as analysis of scattering problem. His research interest includes microwave application for biological applications.