Design and Implementation of the RF Systems for Bi-directional Wireless Capsule Endoscopes

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ABSTRACT

This paper explains that the RF systems for bi-directional wireless capsule endoscopes were designed and implemented. The designed RF systems for a capsule endoscope can transmit the images of intestines from the inside to the outside of a body and the behavior of the capsules can be controlled by an external controller simultaneously. The bi-directional wireless capsule endoscope consists of a CMOS image sensor, FPGA, LED, battery, DC to DC Converter, transmitter, receiver, and antennas. The transmitter and receiver which were used in the bi-directional capsule endoscope, were designed and fabricated with 10mm(diameter) x 3.2mm (thickness) dimensions taking into the MPE, power consumption, system size, signal to noise ratio and modulation method. The RF systems designed and implemented for the bi-directional wireless capsule endoscopes system were verified by in-vivo experiments. As a result, the RF systems for the bi-directional wireless capsule endoscopes satisfied the design specifications.

Keywords: Bi-directional wireless capsule endoscope, CMOS image sensor, Transmitter, Receiver, Small-loop antenna, MPE(Maximum Permissible Exposure), In-vivo experiment.

1. INTRODUCTION

Recently, there have been many attempts to reduce the pains and increase the accuracy of diagnoses in medicine. In particular, new techniques and devices are being developed for the observation of the digestive organs[1,2].

The electric endoscope is used to observe the digestive organs. It has a slender insertion tube and a CCD(Charge Coupled Device) image sensor for obtaining images in the distal end. Also, the inside of an insertion tube is empty, therefore the surgical

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treatments that are a sampling of tissue and medication, can be performed through it. The electric endoscope, however, has defects. It has a limited observation range and there are drawbacks when drilling the gastrointestinal tract. Spurred by these needs, the capsule endoscope was developed [3-5].

At the beginning of biomedical telemetry, Beenken and Dunn developed a technique for the short distance radio telemetry of physical information[6]. Further research on biomedical telemetry was performed by R.S. Mackay, including several discrete electronic devices and short-wavelength EM wave techniques[7]. Meanwhile, modern wireless telemetry, as introduced by Uchiyama and Saito, used a wireless telemetry capsule to monitor the gastric pH based on an iridium oxide electrode mounted on a telemetry capsule[8]. In particular, in relation to monitoring gastrointestinal diseases, a new type of video-telemetry capsule has been developed that can be swallowed. It tracks down the gastrointestinal tract while transmitting images[9]. As such, the capsule, 11mm in diameter and 30mm in length, (i.e. about the size of a pill), provides a kind of inside view at a rate of two frames per second. Its video images are transmitted using UHF-band telemetry to aerials taped to the body.

While being moved by peristalsis, the capsule can only transmit images one-way from the inside to the outside of the human body. Consequently, it is impossible to control camera behavior, including the ON/OFF power functions and effective illumination inside the intestines.

The capsule endoscope can visualize the entire small intestines, without pain and radiation. Also, there is no danger of drilling in the gastrointestinal tract because the locomotion principle of the endoscope capsule and food are identical. The current capsule endoscope cannot be controlled by the user outside of the body. In the case where a capsule can acquire and transmit images from the intestines, the size of the module and the power consumption are limited. In order to solve this problem, bi-directional wireless communication technology is necessary to control capsule power by an external switch[10]. The bi-directional communication method for capsule endoscopes was suggested by Park etc.. However, the suggested capsule endoscope used analog camera and a commercial decoder chip. So, it consumes high power and takes long settling time of image sensor, and frequent image degradation is caused by the communication noise. Therefore, integration of various internal circuit in the capsule was very hard, thus, the size of the capsule become big. Moreover, the suggested capsule used the 315MHz AM modulation method for the transmitting the obtained image. It introduces potential dangers such as mixture noise because the 315 MHz band is included in the broadcast band.

Also, bi-directional wireless communication is essential in terms of being synchronized with movement mechanisms in the future. Therefore, the capsule must be small, able to be swallowed and controllable.

In this paper, we designed and fabricated the RF systems for a bi-directional wireless capsule endoscope which must be small, able to be swallowed and controllable. The RF systems consist of the 1.2 GHz PSK transmitter which transmits video images, the 433 MHz OOK(On Off Keying) receiver which receives controlled signals, and the transmitting and receiving small multi-loop antennas. We manufactured a prototype of a capsule endoscope using the designed RF systems, with a diameter of 11mm and a length of 32mm. We conducted an in-vivo experiment using the manufactured system. We confirmed the performance of the RF systems for a bi-directional wireless capsule endoscope.

2. CONSTRUCTION AND SPECIFICATIONS OF THE RF SYSTEMS

The proposed bi-directional wireless capsule
endoscope consists of a CMOS image sensor, lighting LED, transmitter, receiver, two antennas and battery, as shown in Figure 1.

We considered the MPE(Maximum Permissible Exposure), the human body's attenuations, permissible output—transmitting and input—receiving powers, the power consumption, and the antennas' gains in order to design the RF systems for the bi-directional wireless capsule endoscope.

2.1 Maximum permissible exposure for human safety

A few years ago, many commissions including the FCC(Federal Communications Commission), IEEE (International of Electrical and Electronics Engineers), ICNIRP(International Commission on Non-Ionizing Radiation Protection), provided guidance and recommendations on the protection from NIR(Non-Ionizing Radiation) for the purpose of advancing NIR protection for the benefit of people and the environment. We have applied the recommendations of the commissions to the design of the capsule endoscope. Figure 2 shows the limits of the MPE to the radio frequency electromagnetic fields, 3kHz to 300GHz, under controlled exposure conditions[11-15].

The permissible power is a minimum 1mW/cm² and a maximum 10mW/cm² in the 10MHz ~ 1500 MHz range, as shown in Figure 2. Up until now, however guidance and recommendations regarding the inner human body have not been provided. In this paper, we applied the limits of the MPE to decide the specifications of the RF systems, in consideration of the attenuation caused by the human body.

2.2 Selection of the transmitting and receiving frequencies

We selected the transmitting frequency, 1.2GHz range and the receiving frequency, 400MHz range taking into consideration the limits of the MPE, attenuations of the human body, interference effects and the bulk of the RF systems for the capsule endoscope.

2.3 Decision of the transmitting and receiving power in the RF systems

When we decided the output power of a transmitter and the sensitivity of a receiver in the capsule endoscope, the influence on the human body, transmitting and receiving antennas and the position of the RF systems were considered. Then, the transmitter that was used to send video images in the capsule endoscope, was designed with an output power of 0dBm for the 1.2GHz range transmitter. This output power of the 1.2GHz
transmitter satisfies the limits of the MPE and is appropriate for receiving video images in the outer receiver. As before, the sensitivity of the 400MHz range receiver is \(-75\text{dBm}\) which sufficiently satisfies the specifications for the receiving of controlling signals from the control unit.

2.4 Modulation

Though digital communication systems required more wide frequency bands than the analog communication systems, signal processing is easy. There is immunity to noises that are generated in the transmission channels and the fading. We chose the FSK(Frequency Shift Keying) method so as to be able to realize the constant envelope, to be able to process signals easily. We selected a simple structure in the 1.2GHz range transmitter, and an OOK method that is suitable for a rate data transmission for the 400MHz range receiver\[16, 17\].

2.5 Transmitting and receiving antennas

The biirectional wireless capsule endoscope must be small enough to swallow. There are restrictions in bi-directional communication when using one antenna, but we can’t use a duplexer because of the dimensions in the capsule endoscope. Therefore, we designed two antennas, a transmitting antenna and a receiving antenna, which are of the small multi-loop type. They are small in terms of electricity needed and 9mm in diameter. These antennas have suitable characteristics of omni-direction radiation in the bi-directional wireless capsule endoscope.

3. DESIGN AND FABRICATION OF THE RF SYSTEMS

We designed and fabricated a 1.2GHz transmitter, a 400MHz receiver, transmitting and receiving antennas by applying the RF systems’ specifications.

3.1 FSK(Frequency shift keying) transmitter in the capsule

The transmitter used in the capsule endoscope, as shown in Figure 3, consists of a voltage-controlled oscillator (VCO), a buffer amplifier, a transmitting antenna, and it is a simple structure.

The oscillator can be divided into a negative resistance part and a resonator part. In this study, we have designed the Colpitts oscillator by using the microstrip line in a resonator part. The microstrip line resonator offers superior phase noise and frequency stability characteristics to the LC-resonators and it is also small and compact which is suitable for the capsule endoscope. The VCO consists of an oscillator with a tuning varactor diode attached. The voltage(VIDEO data voltage: 5V (high), 0V (low)) applied to the tuning varactor diode tunes the frequency of the oscillator. The measurement results of the fabricated VCO are \(-108.83\text{dBc/Hz} (@100kHz offset)\) phase noise, and \(-6\text{dBm} \) output power, \(-11\text{dBc} \) harmonic suppression in the 1.2GHz range. The buffer amplifier plays an important role in the transmitter, stabilizing the VCO by isolating it from the antenna and the increasing gains. The measurement results of the fabricated buffer amplifier are 12.65 dB in gain and 27.75dB in isolation.

The transmitter, including the VCO and buffer amplifier, was fabricated on one surface, (10mm in diameter and 1.6mmn in thickness), as illustrated in Figure 4.

Fig. 3. Block diagram of the transmitter.
Fig. 4. Fabricated transmitter has a diameter of 10mm; the dashed line is the Colpitts oscillator, the solid line shows the buffer amplifier and the ellipse is the microstrip line (width = 0.6mm, length = 3.5mm, relative dielectric constant = 3.38, Quality factor = 184) used in a resonator part.

On the condition of being supplied with only 3V of DC power, and without the video data signals, the measured output power of the fabricated transmitter is -0.67 dBm, as illustrated in Figure 5. In general, the transmitter’s phase noise output may set the system’s limits for dynamic range and reception sensitivity. The fabricated transmitter’s phase noise is -106 dBc/Hz(@100kHz), as shown in Figure 6, and the result of the measurement is appropriate for this wireless capsule endoscope system. Figure 7 represents the harmonic suppression characteristic of the transmitter. In most cases, the first harmonic is suppressed by about 20 dB, but the fabricated transmitter shows a better harmonic suppression characteristic at -28.83 dBc.

The characteristics of the fabricated transmitter are illustrated in Table 1.

Table 1. Characteristics of the fabricated 1.2GHz transmitter

<table>
<thead>
<tr>
<th>Contents</th>
<th>Measurements</th>
</tr>
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<tbody>
<tr>
<td><strong>VCO</strong></td>
<td></td>
</tr>
<tr>
<td>Frequency Range</td>
<td>1202 – 1245 [MHz]</td>
</tr>
<tr>
<td>Output Power</td>
<td>-6 [dBm]</td>
</tr>
<tr>
<td>Phase noise (@100 kHz offset)</td>
<td>-108.83 [dBc/Hz]</td>
</tr>
<tr>
<td><strong>Buffer Amp</strong></td>
<td></td>
</tr>
<tr>
<td>Gain</td>
<td>12.65 [dB]</td>
</tr>
<tr>
<td>Isolation</td>
<td>27.75 [dB]</td>
</tr>
<tr>
<td>Bias</td>
<td>3 [V] / 5 [mA]</td>
</tr>
<tr>
<td><strong>FSK Tx</strong></td>
<td></td>
</tr>
<tr>
<td>Modulation Frequency</td>
<td>1204 – 1225 [MHz]</td>
</tr>
<tr>
<td>Output Power</td>
<td>-0.67 [dBm]</td>
</tr>
<tr>
<td>Phase noise (@100 kHz offset)</td>
<td>-106 [dBc/Hz]</td>
</tr>
<tr>
<td>1st Harmonic</td>
<td>-28.83 [dBc]</td>
</tr>
</tbody>
</table>
The modulated video signal for transmitting digital data, 2Mbps in the data rate acquired by the image sensor, is illustrated in Figure 8. Figure 9 shows the transmitting and receiving video signals in the oscilloscope.

3.2 OOK(On off keying) receiver in the capsule

The 400MHz range receiver structure, using a commercialized chip which is applied with the superheterodyne method, is illustrated in Figure 10.

The fabricated receiver, (10mm in diameter and 1.6mm in thickness), is illustrated in Figure 11.

The sensitivity of the receiver is represented -75dBm in 100bps data rate.

![Fig. 8. Spectrum shape of the modulated video signal.](image)

![Fig. 9. The video signal transmitted from the capsule endoscope(ch1) and received in the external receiver(ch2).](image)

![Fig. 10. Block diagram of the receiver.](image)

![Fig. 11. Fabricated receiver (10mm in diameter).](image)

The proposed bi-directional wireless capsule endoscope is able to demodulate external signals so as to control the behavior of the CMOS image sensor, the four LEDs during the transmission of video images and to switch the transmitter on/off during the sending of unnecessary video images. Since the proposed capsule endoscope can simultaneously transmit a video signal and receive a control signal determining the behavior of the capsule itself, the total power consumption of the capsule endoscope can be reduced by turning off the camera power during off time, and separately controlling the LEDs for appropriate illumination within the human body.

The control signal has the form of a bit stream that is considered to be the 5bit address, 4bit data(4bit, $2^4=16$) and dead time. To avoid any interruption or communication from transmission noise in wireless communication, each control signal is expressed by a repetitive form, each bit is repeated twice.

Figure 12 shows the transmitting and receiving
control signals in the case of a LEDs ON state.

In this proposed control system, we can make 16 different control signals (4bit, 2^4 = 16). Therefore, the wireless capsule endoscope could be granted a variety of the functions.

### 3.3 Transmitting and receiving antennas

The antennas, which are needed in the bi-directional wireless capsule endoscope, must be small in size, have the omni-directional radiation and the suitable gain for the good transmission.

Figure 13 shows the structure of the proposed small multi-loop antenna.

On the condition of fixing the antenna’s outside diameter at 9mm, we decided two parameters, the wires’ diameter and turn number for the bi-directional wireless capsule endoscope. As a result, we determined the physical characteristics which guarantee a good performance for the 1.2GHz range transmitter and the 433MHz range receiver respectively, as shown in Table 2.

Figure 14 shows the fabricated small multi-loop antennas that are used in the bi-directional wireless capsule endoscope.

The antennas must maintain the characteristics of omni-directional radiation which are to be used the bi-directional wireless capsule endoscope in the human body. The radiation pattern, as shown in Figure 15, has all of the omni-directional characteristics.

The proposed antennas, electrically small, have low gains in comparison with standard antennas. The measured antenna gains were -15.98dBi in the 1.2GHz range and -12.41dBi in the 400MHz range. Although the fabricated antennas have lower gains than other kinds of antennas, they are small in size, which is a requirement in the bi-directional wireless capsule endoscope, and they can handle the communication with the external systems.

<table>
<thead>
<tr>
<th>Table 2. Physical characteristics of the fabricated antennas</th>
</tr>
</thead>
<tbody>
<tr>
<td>Frequency Range</td>
</tr>
<tr>
<td>Wire Diameter</td>
</tr>
<tr>
<td>Turn Number</td>
</tr>
<tr>
<td>Total Length</td>
</tr>
<tr>
<td>Outside Diameter</td>
</tr>
</tbody>
</table>

![Fig. 12. Transmitted(ch1) and received(ch2) LED lighting control signals: 4bit data = 0111(LEDs on state).](image)

![Fig. 13. The structure of the small multi-loop antenna.](image)

(a) Transmitting antenna (b) Receiving antenna

Fig. 14. Fabricated antennas: connected to the 3.5mm connector for the measurements.
4. IN-VIVO EXPERIMENT AND RESULTS

The bi-directional wireless capsule endoscope, which consists of a CMOS image sensor (PP710DC, 1/7 inch CIF, Pixelplus Co., Ltd., Korea), FPGA (XCR3064CF56, Xilinx, USA), receiver, transmitter, antennas, LEDs (IWS-16T-WXWF, 1.6mm * 0.8mm * 0.4t, ITSWELL Co., Ltd., Korea) and battery (CRI/3N, Sanyo Co., Ltd., Japan) was designed and implemented. Table 3 shows the electrical and physical characteristics of the components used in the capsule endoscope.

To confirm the operation of the RF systems, the in-vivo experiments were performed on the intestines of a dog and a pig. For the in-vivo experiments, the capsule endoscopy system was implemented. The bi-directional wireless capsule, including the fabricated RF systems, is 12mm in diameter and 32mm in length. The external receiver for the video signal and the external transmitter for the control signal are illustrated in Figure 16.

We conducted the in-vivo experiment at Yonsei Medical Center in Korea under an anesthetic

<table>
<thead>
<tr>
<th>Components</th>
<th>Physical Characteristic(mm)</th>
<th>Electrical characteristic</th>
</tr>
</thead>
<tbody>
<tr>
<td>CMOS</td>
<td>Diameter: 11, Length: 2</td>
<td>24mA(3V)</td>
</tr>
<tr>
<td>FPGA</td>
<td>Diameter: 11, Length: 1.5</td>
<td>5mA(3V)</td>
</tr>
<tr>
<td>Transmitter</td>
<td>Diameter: 10, Length: 1.6</td>
<td>4mA(3V)</td>
</tr>
<tr>
<td>Receiver</td>
<td>Diameter: 10, Length: 1.6</td>
<td>10mA(3V)</td>
</tr>
<tr>
<td>LED</td>
<td>1.6mm<em>0.8mm</em>0.4t</td>
<td>43mA(3V)</td>
</tr>
<tr>
<td>Total power consumption</td>
<td>160mA(3V)</td>
<td></td>
</tr>
</tbody>
</table>

Table 3. The electrical and physical characteristics of the components used in the capsule endoscope: full operating time (3.7 hours), Dome size (4.4mm)

Fig. 16. Photographs of the bi-directional wireless capsule endoscopy system: (a) endoscope capsule (12mm in diameter, 32mm in length), (b) external transmitter (with the monopole antenna), (c) external receiver (with the loop antenna).
condition. The experiment sets, the external receiving system for acquiring images and the transmitting system for controlling the capsule endoscope, are located 1 meter from the pig. We obtained the satisfactory results, which are the acquisition of clear images and the control of the capsule’s LEDs On/Off. To confirm this systems’ transmission distance, we measured the fabricated systems within a permissible range, a distance of 5 meters. From these results, we verified that the control system operated well within a 5 meter distance. In the image receiving systems case, however, noises occurred in the received images at a distance of more than 1 meter.

The fabricated capsule can operate continuously for about 3.7 hours (Battery capacity: 160mA/hour, power consumption: 43mA). As a result, if we can control the voltage supplied in the bi-directional wireless capsule endoscope, the capsule should be able to work for more than full operating times (3.7 hours) so as to guarantee its ability to operate throughout the whole small and large intestine.

The acquired image from the pig’s intestines, using the fabricated wireless capsule endoscope, as shown in Figure 17, is distinct. From this experiment, it can be verified that the designed RF systems for the capsule endoscope satisfied the required specifications.

5. CONCLUSION

In this study, the RF systems for a bi-directional wireless capsule endoscope were designed and implemented. The RF systems can transmit the images of intestines outside of the body and the behavior of the capsules can be controlled by an external controller simultaneously. The bi-directional wireless capsule endoscope consists of a CMOS image sensor, FPGA, LEDs, battery, converter, transmitter, receiver, and antennas. We performed an in-vivo experiment. It can be verified that the RF systems could satisfy the required specifications. The proposed techniques promote a greater efficiency in medical technology and help improve a patent’s quality of life.

Thus, if the designed transmitter and receiver of the capsule endoscope are integrated and fabricated to a single chip, the bi-directional wireless capsule endoscope can be widely used in medical diagnosis. Furthermore, it can be recognized as the only medical device that can simultaneously perform observations, control the capsule’s movements and acquire several biomedical signals (pH, temperature and pressure).

6. REFERENCES


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