A5P-X **Circuits for Biomedical Systems III** (Poster)
Time: Monday, May 31, 2010, 9:30 - 11:00
Place: Times Square 8
Chair(s): Ralph Etienne-Cummings, *Johns Hopkins University*
Franco Maloberti, *University of Pavia*

A6P-Q **Specialty Amplifiers** (Poster)
Time: Monday, May 31, 2010, 11:20 - 12:50
Place: Times Square 1
Chair(s): Igor Filanovsky, *University of Alberta*

Design of OOK System for Wireless Capsule Endoscopy

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Abstract—**This paper presents the design and realization of wireless capsule endoscopy. For this system, the optimum frequency band is investigated to maximize the overall efficiency. To achieve low power consumption, a simple On-Off Keying (OOK) transmitter is utilized. To detect the transmitted signal from within the body, an external receiver adopted a super-heterodyne structure and exhibited a sensitivity of -80dBm at BER 10^{-5}. The system operates at up to 20Mbps. The OOK system is demonstrated in internally in a pig's body, showing clear internal body photos.**

I. INTRODUCTION

In the medical field, an endoscopy is an instrument to visually examine the digestive tract. Conventional endoscopy examination is very painful for patients. Therefore, until now, many novel endoscopy examination methods have been developed using ultrasound detection, and the wireless telemetry [1]. Among these methods, the capsule endoscopy system has a merit of a direct examination of the entire digestive tract without any anesthesia or insufflations. This noninvasive characteristic reduces the patients' pain and lowers the risks associated with conventional endoscopy systems.

To stably operate the system regardless of the personal variations (ex. Thickness of the abdomen), either the transmitter output-power or the receiver sensitivity should be increased. However, the output power of the endoscopy is limited to prevent harmful effects to the human body. Therefore, increasing the sensitivity of the receiver is crucial to improve the performance of the system. Moreover, the receiving signal power is dependent on the location of the capsule endoscopy. Therefore, the receiver should have a wide dynamic range.

In this design, we analyzed the propagation loss in the human body at some distance. The study provides information about the link budget minimized loss in this system. The transmitter for the capsule endoscopy utilized a simple controlled LC oscillator for OOK modulation [2]. The receiver block adopted a super-heterodyne structure, based on the link budget of the analyzed propagation loss.

II. ANALYSIS OF HUMAN BODY

A. The propagation loss in the human body

The propagation model is established to calculate the propagation loss in the human body [3]. It is assumed that a body consists of homogeneous material which has the characteristics of average muscle describe in FCC (Federal Communication Commission) [4]. The distance between the transmitter and the receiver is set as 15 cm. In this case, the detected power from the transmitter at the receiving antenna can be calculated from the Friis's formular, considering the transmitting loss in a body as shown in (1).

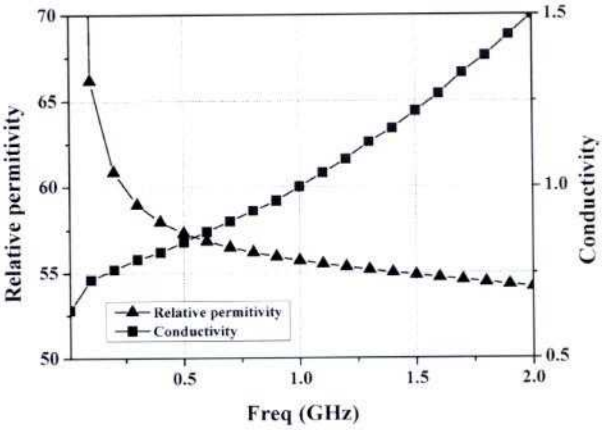

Fig. 1. The homogeneous human body model

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

P_{TX} is the transmitted power and P_{RX} is the received power. G_T and G_R are the transmitting and receiving antenna's gains respectively. R is the distance between the transmitter and the receiver. λ is the wavelength and k is the propagation constant of the material. T is the transmission coefficient between body and air interface, which can be reduced by using proper matching layer. The equation shows, the total loss consists of the transmitting antenna's gain and the loss of the propagation, as well as the attenuation and the reflection. The maximum gain of the transmitting antenna is -5dB at a half power bandwidth (HPBW) of 100 MHz. This value results from calculations applied to the human body model, as shown in Fig.1 [5]-[6]. Finally, the total transmitted losses are shown Fig.2, it is assumed that antenna's directivity is 1.5. The graph includes the losses from the antenna's gain, the radiation, the attenuation and the reflection when the condition of Tx antenna's radius = 5mm whose sphere can include the entire structure of the single antenna and bandwidth = 100 MHz and distance = 15 cm. Following Fig.2, the minimum total losses

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in the human body can be addressed about -67 dB at a frequency of 400~600 MHz.

B. The link budget

The required specifications of a wireless capsule transmitter are shown in the Table 1. From previous propagation loss analyses, the optimum frequency for a wireless capsule endoscopy communication can be determined to be 500 MHz and the overall system bandwidth is set to 20 MHz to support a data rate of 20 Mbps. The output power of the transmitter is set to 0dBm and the antenna gain (which is considering the practical antenna bandwidth) is -10 dB, with a -5 dB margin. For a low power system, an On-Off Keying(OOK) system is chosen and the rise(fall) time should be 10 ns which is a fifth of 50 ns for a 20 Mbps data rate.

Table 2 shows the link budget configuration. The transmitted power(0dBm) is an average power. The transmitting antenna gain is -10 dB, and the sum of the total loss in the body is -57 dB. Therefore, the expected receiving power is -67 dB.

after a while, the thermal noise power become -101 dBm at 300 K, when the data rate is 20 Mbps. The theoretical envelope detector has 14 dB Signal-to-Noise Ratio (SNR) at 10^{-5} Bit-Error-Rate (BER). Therefore, including the receiver's noise figure(5 dB), the receiver's SNR is -82 dB. It has a margin of 15 dB in expected receiving power. The margin is so important to the application, since in reality the homogeneous human body model is not valid and the personal variations exist. These things variations create antenna matching or propagation loss problem.

III. IMPLEMENTATION

A. Transmitter

The structure of the transmitter is shown in Fig. 3. In order to design a highly efficient OOK transmitter, all the components should be switched on/off with baseband data. The falling and rinsing time of 5 ns can guarantee a 20 Mbps data rate [2]. Since the supply voltage is provided from a battery, the transmitter adopts an OOK modulation and the limited output power is 0 dBm. Fig.4 shows the schematics of the LC oscillator and the output buffer. The LC oscillator utilizes current reused-type and has the advantage of low power. To use the application, the external L0 is adjusted to 500 MHz. Also, the L1 for inter-stage matching and the inductor for output matching can be externally controlled to adjust the output power.

B. Receiver

The architecture of the receiver is shown in the Fig.5. To acquire the performance of -80dBm sensitivity at BER 10^{-5}, the overall gain of the receiver should be high. Only the amplification method at the RF stage can lead to oscillation because a positive-feedback path can be made by wire bonding or a parasitic component in the layout. Therefore, Super-Heterodyne architecture is chosen and the overall gain is divided into RF and IF gains. The divided gain can reduce the interaction between RF and IF stages. Generally, this super-heterodyne conversion is more stable than other structures. The LO frequency is set to 400MHz, considering existing image signals and IF filter chracteristics.

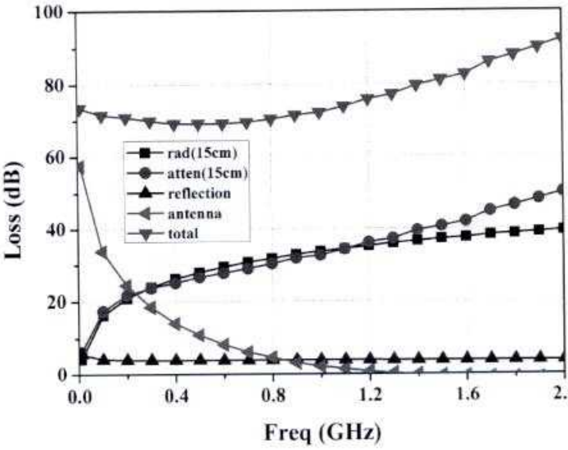

Fig. 2. The total transmitting loss in the human body

TABLE I.

THE SPECIFICATION FOR T_x OF A WIRELESS CAPSULE ENDOSCOPE

Data rate/BER	**20 Mbps/ 10^{-5}**
Average power of transmitter / Output power	**1 mw / 0dBm**
Response tiem of transmitter(t_r, t_f)	**10 ns**
HPBW(Half Power BandWdith)	**100 MHz**
The diameter of antenna for T_x / Gain	**10 mm / -10dB**
The gain of antenna for R_x	**0 dB**
The noise figure of R_x	**5 dB**

TABLE II.

THE LINK BUDGET OF OOK SYSTEM FOR A WIRELESS CAPSULE ENDOSCOPE

Frequency band 490MHz~510MHz (OOK, 20Mbps)	**Power (dBm)**
Power of Tx = 0dBm	**0**
Antenna gain = -10dB	**-10**
Propagation + Radiation + Reflection = -57dB	**-67**
Expected receiving power = -67dBm	
Link margin = 15dB	
Noise figure of R_x = 5dB	**-82**
SNR(Env. Detection, BER=10^{-5}) = 14dB	**-87**
Thermal noise power = -174 + 73 = -101 dBm	**-101**

Also, to cover changes in the receiver signal power according to the location of capsule endoscopy, an automatic gain control amplifier (AGC) is utilized at the IF stage. The AGC has a 30 dB dynamic, therefore detects receiving powers ranging from -50 dB to -80 dB.

The front-end LNA adopts a cascade structure to achieve low noise figure, high voltage gain, and strong isolation. Fig.6 (a) shows the LNA schematic. To utilize the external band pass filter, a source follower is used as an output buffer for output impedance matching. The LC load (C2 and L1) of the LNA is tuned to resonate at 500MHz and additional resistor (R0) makes extended bandwidth of 50MHz to support a 20 Mbps data rate.

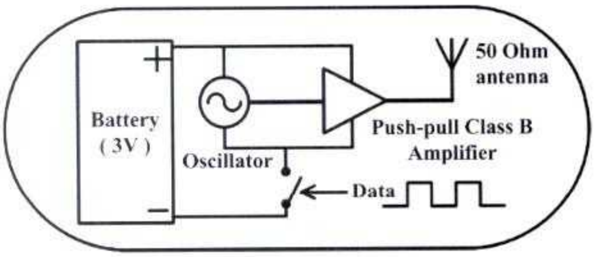

Fig. 3. The structure of transmitter.

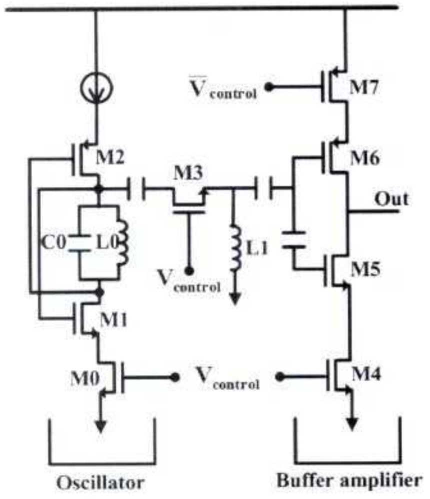

Fig. 4. The circuit of transmitter.

Since differential signal processing is insensitive to unwanted noise bounds, a balun is required. For the balun, we adopted an active balun as shown in Fig. 6 (b). This balun increased the RF gain and reduced the external area through integration. A common source amplifier and a common gate amplifier are utilized to generate a differential signal. Also, to create the same gain, the bias level is carefully chosen. In addition, a common gate structure is useful for input matching with wideband matching. The input impedance of common gate amplifier is $1/g_m$, which can be controlled by the current of M0.

In case of a mixer, a double balanced structure is more efficient than a single balanced mixer in terms of the linearity, noise figure, and the isolation between local frequency and the radio frequency. In this design, the widely-used Gilbert-type mixer with RC-load is used. Typically, OOK system is easily affected by interference signal, which induces BER degradation. Therefore, after LNA, an external surface acoustic wave filter was used to remove out-of-band interference signals. The local oscillator frequency is 400MHz and it can easily be implemented using a cross coupled LC oscillator with a digitally controlled capacitor array for frequency tuning.

The IF stage consist of a low pass filter (LPF)and an automatic gain controlled amplifier (AGC). The AGC is also consists of a power detector (PD), a logarithmic variable gain amplifier (VGA) and a comparator. The LPF adopted a Chebyshev type with 150 MHz f_{3dB} frequency to remove out-of-band interferers. The AGC block [7] is utilized to achieve the wide bandwidth characteristic. The power detector makes the output voltage logarithmically proportional to the power input. Finally, a differential amplifier compares PD output signal with an 1st RC filtered average output signal with a very large resistor and capacitor.

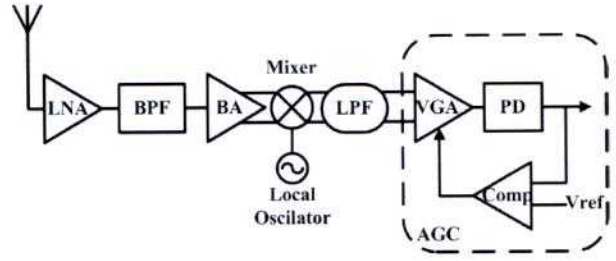

Fig. 5. The structure of receiver

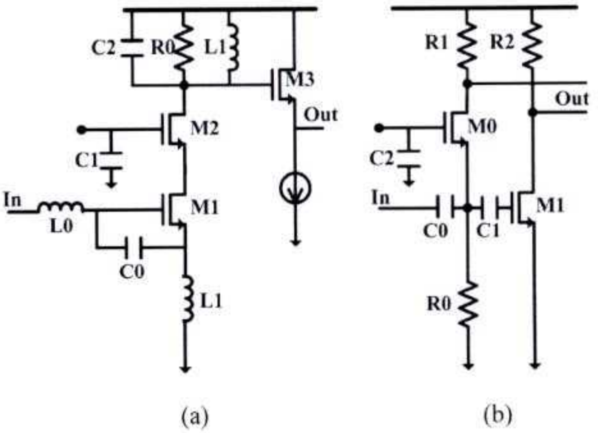

Fig. 6. The circuit of (a) LNA and (b) balun amplifier.

IV. MEASUREMENT RESULT

The transmitter and receiver are fabricated in a standard 0.13um CMOS process. The chip photographs are shown in Fig. 8. The die sizes are 745 μm × 745 μm and 1000 μm × 1000 μm, respectively. The OOK transmitter was measured with a random digital signal with 50% average duty ratio. When the output power was 0 dBm, the overall transmitter efficiency was 26%. To measure the sensitivity of the receiver, an Agilent E4438C is used for BER test. PN23 signal was used as a test random signal with 20 Mbps data rate. The test results are shown in Fig. 7. The measured sensitivity was -80 dBm at 10^{-5} BER and showed no error bit for stronger signal. The DC power dissipation of receiver is about 20 mW under 1.2 V. Finally, the transmitter with the camera covered capsule was inserted into a pig's body, the receiver was externally located from the transmitter as a distance of 15cm and tested with a modem connected with computer program. The antennas of [8]-[9] is used. Through the experiment, high quality images were acquired. The two images are shown in the Fig.9. Clear internal body photos could be seen with this capsule endoscopy.

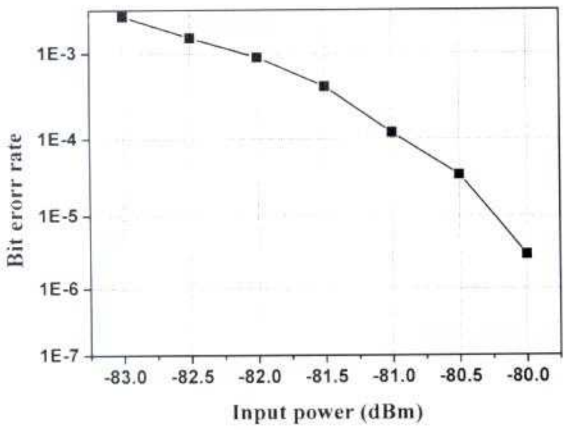

Fig. 7 The BER test result of receiver

V. CONCLUSION

To design a wireless capsule endoscope system in the body, the major transmitter requirements are low power (<3mW) and an output power that is 0 dBm. The performance of the receiver is restricted within the low power limits of transmitter. Therefore, using the human body model, we calculated the propagation loss in the body and it resulted in -67dB of the minimum power. Applying the above result, we calculated the link budget of the OOK system and a link margin of 15dB. The calculated minimum sensitivity of the receiver is -82 dBm. Finally, On a BER test, the sensitivity of designed receiver is -80 dBm at BER 10^{-5} of 20 Mbps. This specification is reasonable for stable communication from within a human body to a distance of 15 cm as shown by the calculations. Finally, the validation of the system was verified through the animal experiment.

ACKNOWLEDGMENT

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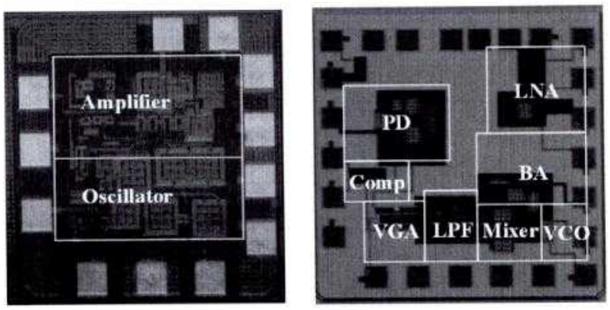
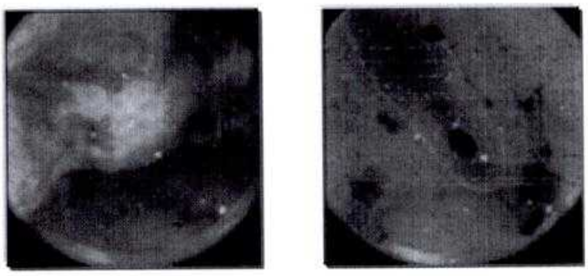


(a) (b)

Fig. 8. The chip photograph of transmitter (a) and receiver (b)



(a) (b)

Fig. 9. (a) the stomach and (b)the colon of animal experiment images.

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