Super-Regenerative Receiver for Capsule Endoscopy Application Using Digital Counter

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***Abstract* — This paper presents a low-power and high-speed Super Regenerative Receiver (SRR) for wireless capsule endoscopy at 500 MHz. The operating frequency was selected for its minimum propagation loss in the human body. To achieve low power consumption, the self-quench method was used through a digital count. Using 0.13μ m CMOS technology, the receiver was designed and verified by simulation. A data rate of 10Mbps was achieved for detecting -85dBm signals with a DC power consumption of 0.96mW at 1.2[V].**

***Index Terms* —capsule endoscopy, digital counter, OOK modulation, self quench, super regenerative**

I. INTRODUCTION

Endoscopy is important to diagnose internal diseases for patients. It can visually examine the digestive tract and help the doctor make an accurate medical examination. However, conventional endoscopy causes pain in patients. Therefore, many examination methods have been developed [1]. Among these, the capsule endoscopy system has been researched for a long time. Direct examination without any anesthesia or insufflations is an advantage of capsule endoscopy. In addition, the capsule can inject a medicine into the human body for treatment. It is efficient in that the diseased area inside the body can be directly treated by injecting the drug. However, the receiver in the human body should be integrated with a transmitter to control the capsule. However, a transmitter brings about the limitation of power consumption for the capsule endoscopy system.

The super-regeneration technique can be a solution for this limitation. The technique was first suggested by Edwin Armstrong in 1922 [2]. It is good as a low power application due to a small number of active devices, and a high gain.

In this design, we analyzed the propagation loss between the inside and outside of the human body to find the optimum frequency for the capsule endoscopy application. The link-budget was calculated from the analysis. In addition, the required sensitivity of the receiver with a safety margin was selected. The digital counter was adopted for self-quench and low power consumption. Receiver implement was utilized with 0.13μ m CMOS technology.

II. SYSTEM DESCRIPTION

Fig. 1 shows the overall architecture of the proposed super-regenerative receiver. It consisted of three parts: Isolation Amplifier (IA), oscillator, and digital controller for self-quench including a delay line. Generally, an envelope detector is used for super-regeneration. In our design, a digital controller was adopted instead of an envelope detector due to its low-power consumption and high-speed. The isolation amplifier between the antenna and oscillator was used to inject the Radio Frequency (RF) power into the oscillator tank and reduce the leakage of the oscillation signal back to the antenna. In addition, it could amplify the signal from the antenna. The oscillator functions as a clock in the self-quench structure. It can make a quench signal with the controller and delay line.

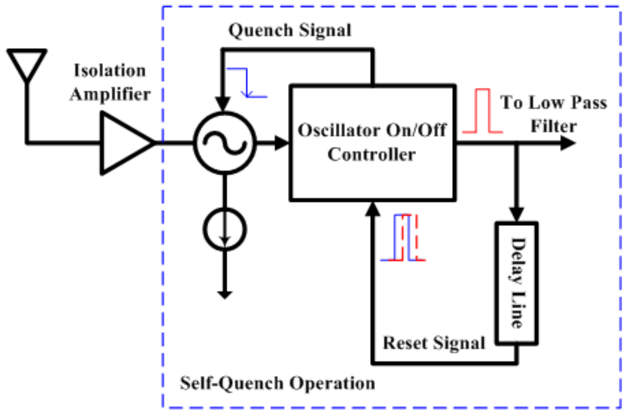

Fig. 1. Block diagram of the proposed receiver front-end

The proposed technique was based on the detection of variation in the start-up time of the tuned oscillator for discrete intervals of time. If the RF signal comes into the oscillator or not, the oscillator periodically starts up and shuts off by a periodic quenching signal. When the oscillator starts up, the controller senses the signal from the oscillator and counts the number of oscillations. If the number equals some fixed number, the controller shuts off the oscillator. After a time delay, the controller can be reset without an external clock through the delay line by itself, which makes the oscillator start-up again. When the RF input is injected into the oscillator, the start-up time of the oscillator is reduced. Therefore, the period of the quench signal is reduced by injecting the signal proportionally, which can be used for detecting the data through the Low Pass Filter (LPF). Fig.2 shows the algorithm of the proposed system when a 2-bit counter is adopted in the controller.

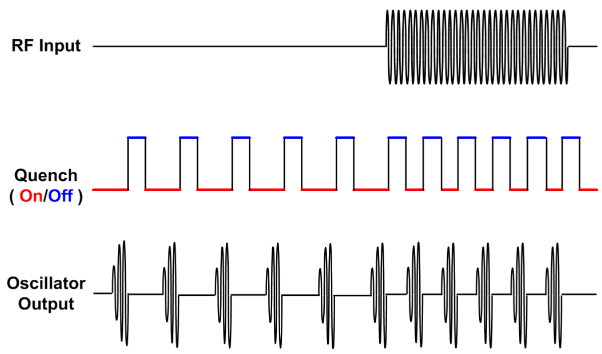

Fig. 2. The proposed system operation at time-domain

III. Searching Frequency and Required Sensitivity For Capsule Endoscopy Application

A. The Human Body Analysis

To design the proposed capsule endoscopy application, the optimum frequency to minimize loss inside the body should be found. The overall analysis was based on previous works [3]. The model was established for the analysis of the propagation loss in the human body [4]. It made some important assumptions such as that a body consists of homogeneous material whose characteristics is average muscle as presented by the Federal Communication Commission (FCC) [5]. The distance between the transmitting antenna and the receiver antenna was fixed at 15 cm. The receiving power from the antenna was calculated through the Friis's formular, which considered the transmitting loss in a body as describe in (1)

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

P_{TX} is the transmitting power and P_{RX} is receiving power. G_T and G_R are the antenna's gains for transmitting and receiving respectively. R is the distance between the receiving and transmitting antennas. λ is the wavelength and k is the propagation constant of the material. T is the transmission coefficient between the body and air interface. The equation shows the total loss is consists of the transmitting antenna's gain and loss of propagation, the attenuation, and the reflection. We assumed that receiving antenna has unity gain. The maximum gain of the transmitting antenna was assumed as -5 dB at a half power bandwidth (HPBW) of 100 MHz. The calculation results apply to the human body model [6]-[7]. Therefore, the total transmitted losses are shown in Fig.3. As a result, the transmitter antenna's directivity was set 1.5 when its radius was 5 mm whose sphere could include the entire structure of the single antenna. Fig.3 presents the minimum total losses in the human body which was -67 dB at 500 MHz.

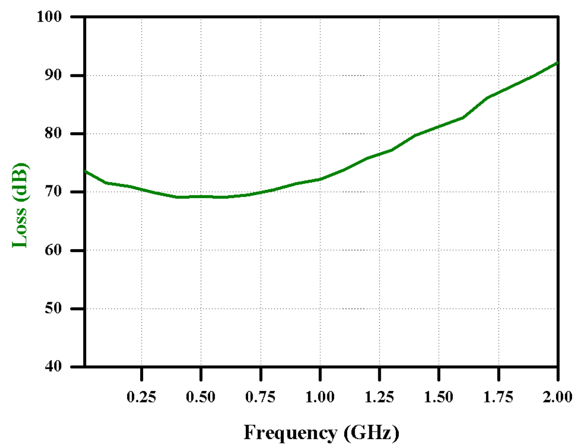

Fig. 3. The propagation loss in human body.

TABLE Ⅰ . The summary of the link budget

Frequency 495MHz~505MHz (OOK, 10Mbps)	Power (dBm)
Transmitting power = -3 dBm	-3
Antenna gain = -10 dB	-13
Propagation Loss = -57 dB	-70
Expected receiving power = -70 dBm	
Link margin = 15 dB	
Noise figure of receiver = 5 dB	-85
SNR(Env. Detection, BER=10^{-5}) = 14 dB	-90
Thermal noise power = -174 + 70 = -104 dBm	-104

B. The Required Sensitivity

The optimum frequency for a wireless capsule endoscopy was selected as 500 MHz. For the link budget configuration, the several conditions were assumed. The transmitted power was set -3 dBm which is an average power. The noise figure of the receiver was fixed as 5 dB. In addition, thermal noise was considered to calculate the link budget.

Table. Ⅰ presents the results of the link budget for the receiver. The expected receiving power including the antenna gain with -5 dB margin was -70 dBm. The thermal noise power becomes -103 dBm at 300 K for a 10Mbps data rate. If the theoretical envelope detector had 14 dB Signal-to-Noise Ratio (SNR) at 10^{-5} Bit-Error-Rate (BER), the received power was -85 dB including the assumed noise figure of the receiver. The results show a 15 dB link margin and the value is enough to design the receiver.

IV. Circuit Design

A. Isolation Amplifier

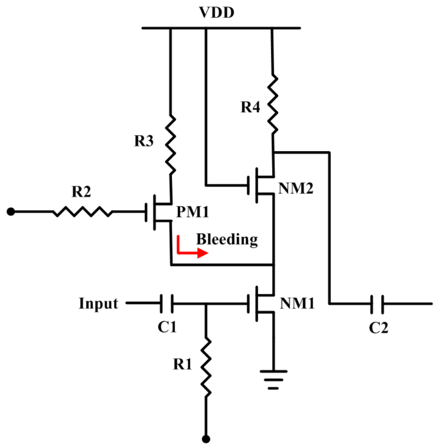

Fig. 4. Isolation amplifier circuit

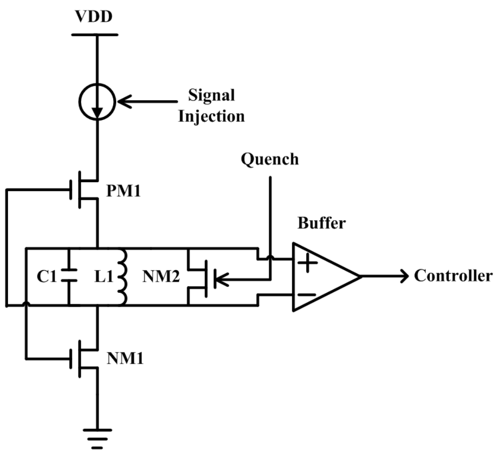

Fig. 5. LC-Oscillator circuit with buffer

Fig. 4 shows the designed isolation amplifier structure. To satisfy the sensitivity of -85dBm at 10Mbps, the amplifier was designed with 3-stages. In front of the first stage, a matching circuit externally exists to match the antenna impedance. The current bleeding technique was adopted to increase the gain of the amplifier. A p-type transistor (PM1) was used to prevent signal leakage into the bleeding circuit. Since the impedance toward PM1 drain was high enough. The resistor R3 was adopted to decrease the sensitivity of the bleeding circuit by bias voltage. The R3 was operated as a negative feed-back resister in the bleeding circuit.

B. LC-Oscillator with Buffer

Fig. 5 shows the oscillator with buffer to connect with the digital controller for the system. It has an inherently high-speed and low-power consumption [8]. Therefore, it is suitable for capsule endoscopy application.

The RF signal is injected into the current source of the oscillator and it changes the start-up time. The L1 (47nH) and C1 (2.2pF) consist of LC-tanks for the oscillation frequency that should equal the injected signal frequency for high sensitivity. The NM2 is a switch for quenching the oscillator

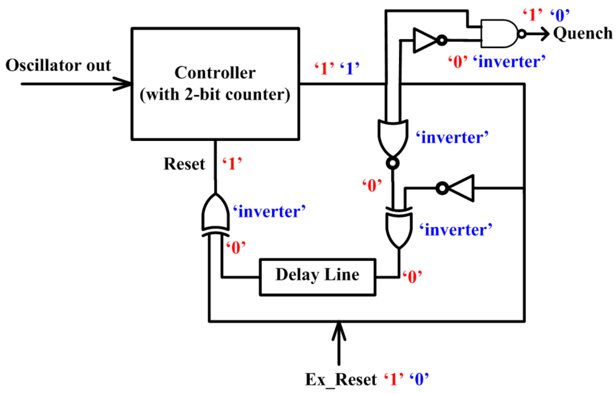

Fig. 6. The digital block for self-quench.

by controlling the quality factor of the LC-tanks. A differential buffer was adopted to deliver the signal to the controller. Generally, the differential buffer has a robustness of supply or else ground noise occurs from the bonding wires. It is good for the stable quenching operation.

B. Controller with Delay Line

For a self-quench without a clock signal, a digital controller was adopted with a delay line. Fig. 6 shows the digital block of the system. An external reset port was used to reset the digital block initially. When the controller is externally reset to '1', the quench port expresses '1' to shut-off the oscillator. After an external reset '0', all gates are operated as inverters and the oscillator starts up. The controller output is kept as '1' and the quench port changes to '0', until the count number reaches '10' at the 2-bit counter in the controller. When the number becomes '11', the controller output transfers to '0' and the quench port changes to '1', which turns off the oscillator. After the time delay, the controller is reset again through the delay line, which consists of the inverter array. These operations repeat periodically until the module is initiated by the external reset.

The total quenching times related to the data rate are the sum of the reset time, oscillator start-up time, and counting time. To decrease the counting time, a 2-bit counter was used, which reduces the power consumption of oscillator.

V. Simulation Results

The proposed super regenerative receiver was designed for 0.13 μ m CMOS technology. A 1.2 [V] DC is supplied to the overall receiver. ADS was used to design an isolation amplifier and oscillator. The digital blocks were designed with hspice. Moreover, the overall system was simulated with hspice including the boding wires at 0.4 nH at each supply and ground. The simulation results of the gain, noise figure, and input reflection characteristics of the IA stage are shown in Fig. 7. The simulation results of the IA stage were presented with a gain of 38 dB, and the NF was under 3dB at 500MHz.

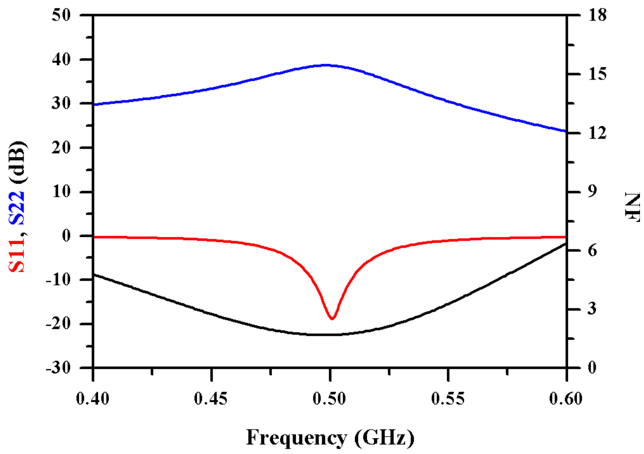

Fig. 7. The simulation result of IA stage.

For the overall system, the transient simulation is shown in Fig. 8. The RF power with random data was driven into the designed receiver. The injected signal had a 10Mbps data rate and -85 dBm power level. An input voltage wave was observed at the node of the next matching network. The proposed receiver operating power consumption was 0.96 mW.

VI. Conclusion

In this work, a super regenerative receiver for capsule endoscopy application was designed using 0.13μ m CMOS technology. The receiver operating frequency was 500 MHz based on the analysis of the human body. For high-speed and low power consumption, a self-quench and counter was adopted for the super regeneration receiver. Fig. 9 shows the receiver layout and chip size at 950x 730 μ m^2, which includes the pads. The results of the simulation show that total DC power consumption was 0.96mW at 1.2 [V] and the sensitivity was -85dBm at 10Mbps.

Acknowledgement

The research was supported by the Intelligent Micro system Center (IMC; http://www.microsystem.re.kr), which carries out one of the 21st century's Frontier R & D Projects

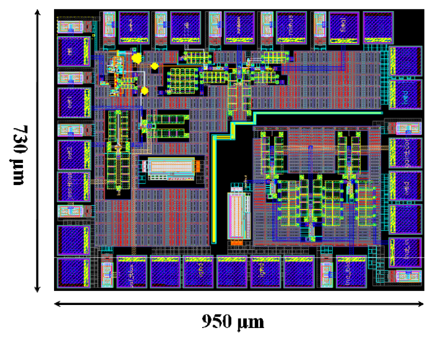

Fig. 8. The designed receiver chip layout

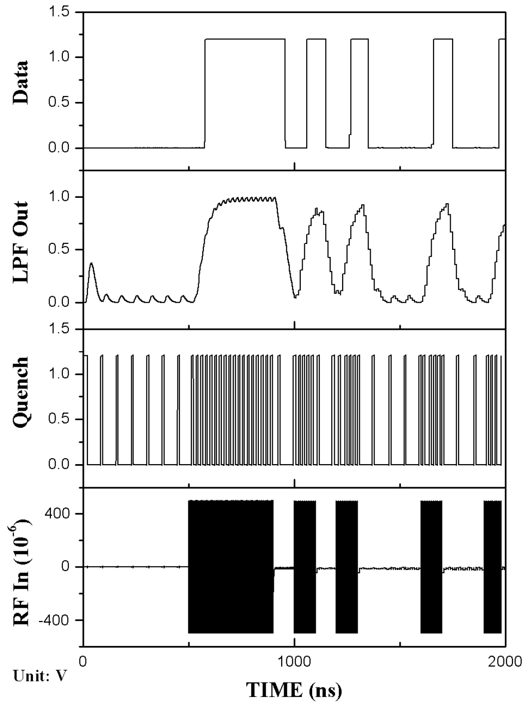

Fig. 9. The transient simulation of proposed receiver.

sponsored by the Korea Ministry Of Commerce, Industry, and Energy

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