A Wireless Power Management Microsystem for Endoscopic Capsule Robot
Ding-kun Peng, Shun Yao, Jin-yong Zhang, Lei Wang

ABSTRACT This paper presents a customized wireless power management microsystem for endoscopic capsule robot. The microsystem is composed of a rectifier, a regulator, a battery charger and a low dropout (LDO) regulator. The electromagnetic energy signal received from a self-resonant coil is rectified and then regulated to generate a stable DC voltage for charging the Li-ion battery. Stable DC voltage is provided for driving the capsule robot using the LDO regulator. The microsystem was fabricated in 0.18-μm CMOS high voltage process with a die size of 2.4mm*1mm. The microsystem was evaluated in details, and the test results suggest that the microsystem works as intended. The rectifier achieves the peak voltage conversion efficiency of 79.3% with a 3MHz input of 4.48V amplitude. The charger circuit can charge the battery with a constant current of 10mA, and auto-control the switching of charge and discharge state. The regulator and LDO provide relatively constant output voltage in spite of the variations of input voltage and load current.

KEYWORDS Endoscopic Capsule Robot rectifier; LDO; Charger

1 Introduction

Conventional endoscope examination is discomfort and cannot inspect the entire gastrointestinal (GI) tract, therefore endoscopic capsule has received extensive research interests and there are already several commercial products in the market [1]. Most of these endoscopic capsules travel in vivo by the peristalsis of the GI tract and the doctors could only inspect the area of interests with limited degree of freedoms. Undoubtedly a capsule robot that moves autonomously within the GI tract could revolutionize the current endoscopic capsule examinations [5-9].

One challenge of endoscopic capsule robot is the power supply system due to the limitation of the battery capacity. This has motivated the recent development of wireless power transmission system for endoscopic capsule robot using inductive coupling [5-6]. But their efficiency is quite low when the distance between two coils is long. The wireless power transfer via the strongly coupled magnetic resonances has been reported in 2007 [7], which is able to transfer 60 watts with 40% efficiency over distances in excess of 2 meters in their report. In this work, we adopt this theory to transfer the power because of its high efficiency.

However the inductive receiver voltage is unstable and sinusoidal voltage, and cannot supply sufficient power for the capsule system. So a rechargeable battery for storing power and supply a stable DC voltage to the capsule system is required. Consequently the design of AC to stable DC conversion, charger and regulator circuits becomes very important.

In this paper, we proposed a novel energy supply method for the endoscopic capsule robot to solve the problem of energy shortage and limited working hours for endoscopic capsule robot. The system includes the high-efficiency rectifier, regulator, charger circuit, LDO, and rechargeable Li-ion button battery. The microsystem is designed using a 0.18-μm CMOS high voltage process.

2 Microsystem Architecture

The block diagram of the capsule endoscopic robot power management and control system is described in Fig.1. The power is transferred to the capsule endoscopic robot implanted in human body via strongly coupled magnetic resonances at the frequency of 3MHz. Then the power is supplied to charger circuit to charge the Li-ion battery, the output voltage of Li-ion battery is regulated by the LDO2 which provides sufficient power for three electromagnetic drivers.

A customized rechargeable Li-ion button battery is installed in the internal capsule robot, with the volume of 12 mm by 10 mm and the capacity of 30 mAH. The maximum discharge current and the normal operating voltage range of this battery are 100mA and 3V-4.2V,
respectively. By controlling the different working state of LDO, the rechargeable Li-ion button battery can fully meet the requirements of endoscopic capsule robot. In the charging process, the drive system stops working. After the battery voltage reaches 4.2V, control circuit turns on the LDO, the battery started to supply power for LDO and drive system to promote the movement of endoscopic capsule robot.

3 Circuit Implementation

A. Rectifier

A rectifier is required to convert the received sinusoidal voltage to an unregulated DC voltage $V_{\text{out}}$. Fig. 2 illustrates the symmetrical circuit of the proposed voltage full-wave bridge rectifier consisting of two comparators, storage capacitor (CL) and eight MOSFETs [8].

![Fig.2 Voltage rectifier](image)

MN1-MN2 and MP1-MP2 operate as switches to reduce the voltage drop between $V_{\text{in}}$ of the receive coil and $V_{\text{out}}$, and get a higher efficiency. If the voltage $V_{\text{in}}$ is higher than $V_{\text{out}}$, the output of Comp1 is 0 and MP1 is on. So MP1 is pushed into deep triode region where it is on and produces a much smaller dropout along the main current path to $V_{\text{out}}$. Operation of MP2 is identical to that of MP1.

Because the comparator is not ideal, there exists feedback-current problem causing power waste and efficiency degeneration. The sizes of transistors MN1-MN2 and MP1-MP2 are very large to allow the rectifier sourcing a large output current and minimize the conduction resistance. Auxiliary PMOS transistors S1-S4 have been implemented and bulk voltages of MP1-MP2 are dynamically controlled by using auxiliary PMOS, making the bulks of PMOS transistors always be connected to the highest potential to avoid body-effect, leakage currents and latch-up.

B. Regulators

The voltage from a rectifier is usually unstable because the voltage amplitude of the received coil changes when the capsule moves in human body and the rectifier also generates ripples. A regulator is required to make the supply voltage stable and clear, while having a very low voltage dropout and getting a higher efficiency. As shown in Fig.3, the designed LDO regulator comprises an error amplifier (MN1-MN4, MP1-MP4 and $R_4$), a high-gain second stage(MN7-MN8 and MP9-MP10), a PMOS pass device and feedback resistors ($R_3$-$R_5$), a transconductance-boosting circuit (MN5-MN6) [9], a compensation capacitance $C_c$ and an off-chip loading capacitance $C_L$. $V_{\text{ref}}$ and biasing stage are generated by a high PSRR bandgap reference source which is integrated in the regulator.

![Fig.3 Schematic circuit of LDO regulator](image)

C. Battery Charger Circuit

We design a Li-ion battery charger circuit for the special battery fixed inside the endoscopic capsule robot, as shown in Fig.4.

![Fig.4 Schematic circuit of charger](image)

The charger circuit consists of a current reference [10], a voltage reference, a start-up circuit and charge core circuit. The reference current is mirrored to the power device MP5 to supply accurate charger current. The capsule endoscopic robot should be control the switch between charge and discharge state automatically for it is implanted in human body. We use the hysteresis comparator to controlled switch. By monitor the voltage...
of the battery, the charger circuit can automatically control the switching between the charge and discharge state. Hysteresis comparator is biased by the reference current to make the hysteresis voltage be immobility with supply voltage and temperature variation.

D. LDO

The output voltage of battery usually changes with the storing energy variation. We apply an LDO to provide power supply for the control and drive system. Fig.5 gives the block diagram of LDO, which consists of a power device, feedback resistors, a bandgap voltage reference, an error amplifier, a soft-start circuit, an Over-Temperature Protection circuit (OTP) and an Over-Current Protection circuit (OCP) [11].

The bandgap reference provides the reference voltage \( V_{ref} \) for the error amplifier. The output feedback voltage \( V_{fb} \) and \( V_{cf} \) are compared by the error amplifier, the difference is then amplified to control the state of power device, ensuring a stable output \( V_{out} \).

![Fig.5 Block diagram of LD](image)

The soft-start circuit can realize a smooth launch of the entire circuit to prevent the inrush current phenomenon which causes permanent damage for the LDO.

OCP and OTP are important components of LDO. The entire circuit will be turned off by OTP when the temperature rises to a set value, and the circuit goes back to work when the temperature drops to a certain value. The OCP circuit will turn off the chip quickly when the load current exceed limit current to avoid large power dissipation.

4 Experimental Results

The proposed wireless powering supply microsystem is implemented in SMIC 1P6M 0.18 μm CMOS technology. The chip micrograph is shown in Fig.6, where the die size of the complete chip is 2.4 mm by 1.0 mm.

![Fig.6 Chip micrograph of the proposed wireless charging microsystem](image)

The rectifier receives power from a signal generator at 3 Hz and provides voltage greater than 4.48 V for a loading resister of 394Ω with a 0.55 μF storage capacitor. Fig.7 shows the rectifier waveform of the rectifier. The conversion efficiency of voltage is 79.3%.

![Fig.7 Waveforms showing the obtained DC levels of the rectifier](image)

The input voltage range of the regulator is designed from 4.5V to 6V for charger applications using rectifier output voltage. The regulator can operate down to 4.48 V with preset output voltage of 4.4 V, and the output voltage variety about 1.64mV when the input voltage changes from 4.48 V to 6V.

The line transient response of the regulator is illustrated in Fig.8. The line transient response measurement for an input that varies from 4.5 to 6V shows a maximum variation at the output of 58mV. The figure indicates a maximum voltage variation of 1.32% during a full line transient responses. As shown in Fig.9, the regulator achieves 34 dB PSRR at 3MHz, using a 50nF off-chip capacitor. The total quiescent current of the proposed LDO1 structure is 85.1 μA(include protect circuit and voltage reference) under input voltage 6V.

![Fig.8 Measured line transient response for an input step from 4.5 to 6V and a load current 12mA.](image)

Fig.10 shows the waveform of the battery voltage
variation with charge time at 10mA current. The control circuit turns on the charge circuit when the battery voltage is less than 3.175 V, and then charges the battery, when the voltage of the battery achieves 4.275 V, the output of the hysteresis comparator turn on the switch which stops the charge state and powers the LDO.

The output voltage of the LDO is 3V, the DC line and load regulation performance of the LDO is 3.55mV/V and 0.31mV/mA, respectively. The start-up time of the proposed LDO for load current of 100mA is about 360μs. Fig.11 and Fig.12 show the line and load transient response of the proposed LDO when the input voltage and the output current is changed between 3.2 to 4.2V and 0 to 100mA, respectively. The maximum voltage variation is less 55 mV and 24mV, respectively. TABLE I summarizes the test performance of the proposed wireless power supply microsystem.

### Table 1. Test Performance Summary

<table>
<thead>
<tr>
<th>Block</th>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rectifier</td>
<td>VCE</td>
<td>79.3% (R&lt;sub&gt;L&lt;/sub&gt;=394Ω, f=3MHz, C&lt;sub&gt;L&lt;/sub&gt;=0.55μF)</td>
</tr>
<tr>
<td></td>
<td>dropout voltage</td>
<td>0.08V</td>
</tr>
<tr>
<td></td>
<td>line regulation</td>
<td>1.09mV/V</td>
</tr>
<tr>
<td></td>
<td>load regulation</td>
<td>1.035 mV/mA</td>
</tr>
<tr>
<td></td>
<td>maximum undershoot</td>
<td>&lt;80 mV</td>
</tr>
<tr>
<td></td>
<td>PSRR@3MHz</td>
<td>34dB</td>
</tr>
<tr>
<td></td>
<td>Power supply</td>
<td>4.4V</td>
</tr>
<tr>
<td>Charge circuit</td>
<td>V&lt;sub&gt;OUT&lt;/sub&gt;</td>
<td>4.273V</td>
</tr>
<tr>
<td></td>
<td>V&lt;sub&gt;IN&lt;/sub&gt;</td>
<td>3.174V</td>
</tr>
<tr>
<td></td>
<td>Charger current</td>
<td>10mA</td>
</tr>
<tr>
<td>LDO2</td>
<td>output voltage</td>
<td>3V</td>
</tr>
<tr>
<td></td>
<td>full load current</td>
<td>100 mA</td>
</tr>
<tr>
<td></td>
<td>quiescent current</td>
<td>165.8μA</td>
</tr>
<tr>
<td></td>
<td>dropout voltage</td>
<td>0.04 V</td>
</tr>
<tr>
<td></td>
<td>line regulation</td>
<td>3.55mV/V</td>
</tr>
<tr>
<td></td>
<td>load regulation</td>
<td>0.31mV/mA</td>
</tr>
<tr>
<td></td>
<td>maximum undershoot</td>
<td>55mV</td>
</tr>
<tr>
<td></td>
<td>PSRR@1MHz</td>
<td>14.3dB</td>
</tr>
</tbody>
</table>

5 Conclusion

A n integrated wireless power supply microsystem has been realized for endoscopic capsule robot application using a 0.18 μm CMOS high voltage technology. The die size of this microsystem is 2.40 mm². Compared with the traditional power supply system composed discrete devices, it effectively reduces the system power dissipation and volume. Experimental results show that a stable and clear DC voltage source can be generated by rectifier and regulator, and the charger circuit can use the output voltage safely. When the battery energy changes, the control and drive system could obtain stable voltage from the LDO. The system measures showed that results meet the design requirements.

References


Author

Dingkun Peng : studying at Shenzhen Institutes of Advanced Technology, Chinese Academy of Sciences. His research interests include analog and mixed-signal integrated circuit design.