A 5.1-μW UHF RFID Tag Chip integrated with Sensors for Wireless Environmental Monitoring

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Abstract:

A RF-powered transponder with temperature and photo sensors is designed and fabricated for environmental monitoring. The transponder gathers power from external ISM (860 – 960MHz) band RF signal and senses ambient temperature and light It contains a supply volage generator, a temperature-compensated ring oscillator, an oversampling synchronizer, a PTAT temperature sensor and an abrupt transition buffered photo sensor. Its internal clock frequency has variation less than 7% for 1.5-V supply voltage and 90^{o}C temperature change. The transponder occupies 0.4mm^2 with 0.25-μm CMOS process and dissipates only 5.14-μW during active state.

1. Introduction

Recently, the radio-frequency identification (RFID) is widely used in a number of applications including supply chain management, access control and public transportation[1]. When the RFID is combined with sensory systems such as temperature, humidity and pressure sensing, its application area can be extended even to environmental monitoring. Its batteryless and wireless characteristics and the ID number assigned to each sensor can support maintenance and field-deployment of multiple sensor units.

In this paper, we propose a new type of ISM band transponder with temperature sensor and photo sensor while reducing its power consumption and die area efficiently.

Fig. 1 shows the architecture of the proposed transponder. The incident RF signal from the base station is converted to dc supply voltage internally and stored in a large internal capacitor. The stored energy provides power to all active blocks on the transponder chip. In most of conventional RFID, the system clock is extracted from or locked to incident RF signal [2, 3]. But when signal frequency is much higher, these methods are inefficient because of their high power consumption. In addition, recent preference for UHF band with wide operation range and small size antenna brings up power problem to the conventional RF-powered system.

In our transponder, the fully integrated clock generator independent to external RF signal is proposed to reduce power consumption. The proposed clock generator is composed of a temperature-compensated ring oscillator and an oversampling synchronizer. The ring oscillator provides reference current and clock needed in the temperature sensor to reduce power consumption and area due to the sensor.

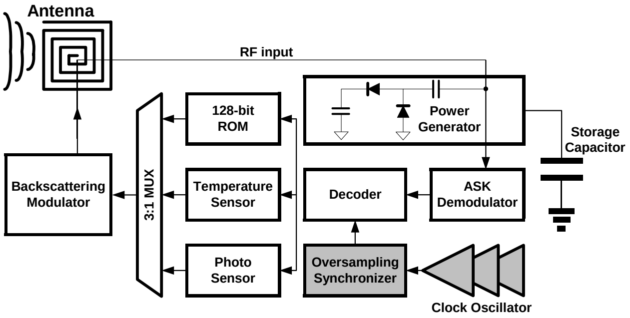

Figure 1. Proposed Architecture

The ROM block and the two sensor blocks are enabled exclusively by the command from base-station for efficient power management. The RF interface between the transponder and the reader is based on EPC RFID generation2 protocol [4].

2. System Overview

If the transponder is to be enabled, the base station provides RF power in ISM band (860 - 960MHz) to the transponder. Sufficiently high dc supply voltage above 2V is generated from weak incident RF signal under 500mV amplitude by multistage charge pump. Schottky diodes are used for efficient charge pumping [1].

The transponder operates in three states – ready, interrogating and active states. The operation sequence is described in Fig. 2. When the transponder receives an energizing RF field, it enters the ready state in which only the internal clock generator is activated. A request from the base station makes the transponder enter interrogating state. In this state, demodulator and decoder are activated to enable ROM block or one of the two sensor blocks. Command data are transmitted with 30% ASK modulation depth. ASK modulation makes input power weak during the interrogating state. For safe operation, commands are always followed by preamble sequence to stop possible activated blocks. The preamble is also the key sequence to synchronize internal clock to input data. In the active state, the selected functional block is activated and the requested data are transmitted

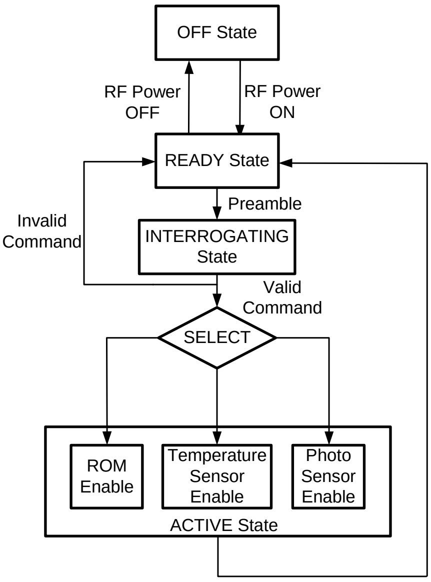

Figure 2. State diagram of the transponder

to the base station through backscattering modulation. After the active state, transponder returns to the ready state automatically.

3. Design of Building Blocks

3.1 ASK Demodulator

To obtain full swing bit sequence from ASK modulated RF signal, the envelope of the input signal is compared to average level and then amplified. Typically, average signal is obtained by sending the envelope signal to RC network with large time constant [5]. But this method needs resistor and capacitor of large value resulting in the increase of the chip area. In this study, the demodulator of Fig. 3 employs diode-connected NMOS pair to obtain the average signal.

When the envelop signals are between Vhigh and Vlow, the NMOS pair limits the voltage on node X to the range from Vhigh – Vth to Vlow + Vth. If the difference between Vhigh and Vlow is less than 2Vth, the NMOS in its subthreshold condition acts as a large resistor. We can effectively make average signal while saving much area by removing the large passive units.

3.2 Integrated Clock Generator

Current starved ring oscillator is often used for clock generation in low power-oriented systems [6]. Most of them focus on robustness against supply voltage variation.

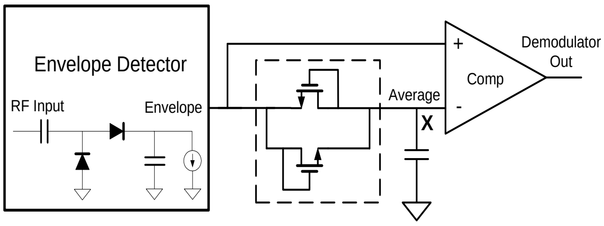

Figure 3. ASK Demodulator using NMOS pair

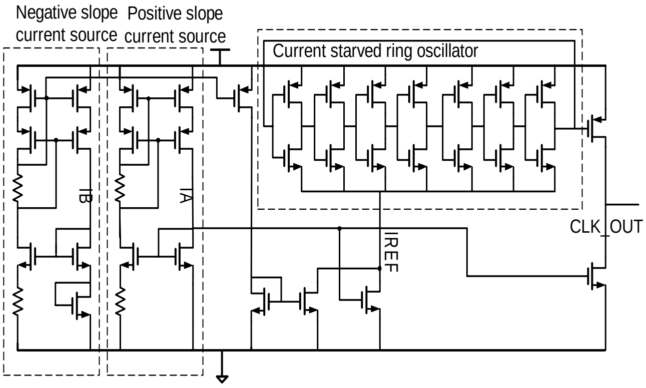

Figure 4. Temperature Compensated Ring Oscillator

However, in the proposed transponder, independence of the reference clock to both of the supply voltage and temperature is mandatory to transmit accurate temperature information to the base-station. A schematic diagram of the temperature compensated ring oscillator is presented in Fig. 4. The amount of bias current is the key parameter to determine the frequency of the current starved ring oscillator. Two MOS-based biasing circuits generate complementary reference currents. One (IA) has a positive slope to temperature variation and the other (IB) has a negative slope. By matching the magnitude of the slopes and summing two currents, temperature-independent bias current (IREF) can be obtained to drive the current starved ring oscillator. To reduce the effect of supply voltage variation and lower minimum operation voltage, low voltage cascode current mirrors are adopted. The frequency variation of the oscillator is measured less than 7% of the average 330-kHz at 1.5-V supply voltage and 90^{o}C temperature change.

Although the oscillator's output is stabilized, it is not enough to sample demodulated bit stream accurately due to its frequency error and synchronization problem. To remedy these problems, an oversampling synchronizer is utilized. The proposed synchronizer is shown in Fig. 5. The demodulated data is encoded in Manchester code and all commands are followed by preamble. The preamble is selected as the same sequence as specified in EPC RFID protocol for generation2 identity tag [4].

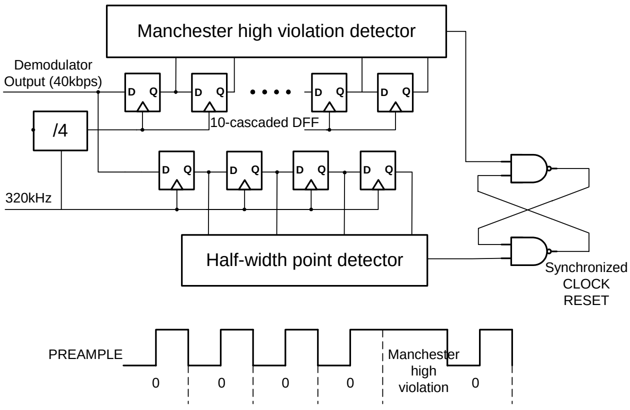

Figure 5. Oversampling Synchronizer

The Manchester high violation (01110) in the preamble is used for synchronization. The synchronizer aligns the positive edge of the system clock to the incoming bit's half width point which is the most resistive point against frequency variation and noise.

3.3 Temperature Sensor

Fig. 6 shows the integrated temperature sensor. The temperature sensor is composed of two blocks, absolute temperature (PTAT) current source and the comparator. In this circuit, temperature can be measured by capacitor charging time. When the sensor is enabled, the reference current starts charging an internal large capacitor(Cp). The reference current generated insensitive to temperature variation in the oscillator, it is shared with the sensor circuits. The voltage developed on the capacitor is compared to Vbe signal which is decreasing in proportion with temperature. Consequently, the charging time is also linear to temperature. The continuous value of time is digitized to number of pulses by single-slope ADC and sent to the base-station. For accurate AD conversion, the reference clock stable under various conditions should be generated, which is already made in the oscillator.

3.4 Photo Sensor

Fig. 7 shows the schematic circuit diagram of the integrated photo sensor. The photocurrent proportional to incident light intensity discharges the node capacitor to the threshold level. The duration of the output pulses is same as the discharging time or light intensity. When the photo sensor is enabled, the average amount of the photocurrent is around 1pA. This current makes the output signal of the comparator drive the output buffer with the transition time in the order of milliseconds. To reduce the short circuit power due to the long transition time of the input signal, the abrupt transition buffer is adopted instead of the normal inverter buffer. This buffer doubles the effective threshold voltage. The overall transconductance reduced by the source degeneration and body effect is compensated by the boosted output resistance and there is no gain loss. This buffer has the narrow transition region and suppresses its short circuit power efficiently.

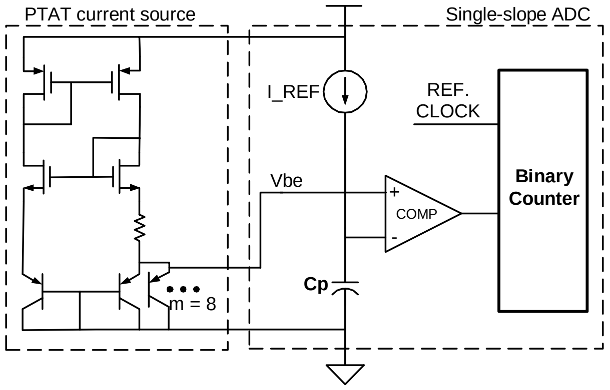

Figure 6. Temperature Sensor

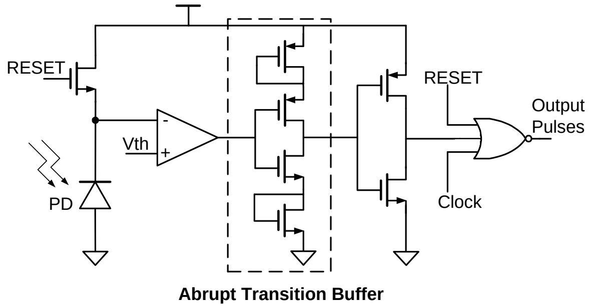

Figure 7. Photo Sensor

4. Measurement Results

Fig.8 is the chip micro photograph of the RFID sensor IC. It is fabricated by 0.25-μm CMOS process and its area is 0.6 x 0.7 = 0.42-mm^2. The MOS capacitor filled in the empty area acts as not only decoupling capacitor but also energy-storage one.

During active state, it dissipates 5.1-μW at 1.5-V internal voltage. The clock generator consumes 1.2-μA and the temperature sensor block consumes only 0.8-μA at 1.5-V supply voltage.

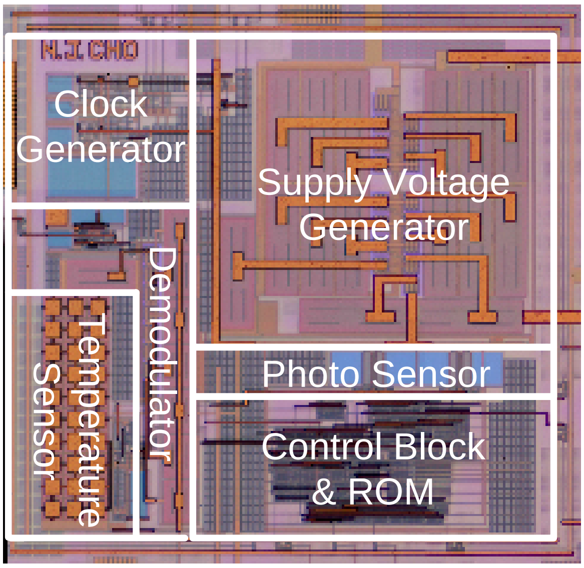

Figure 8. Chip micro photograph (0.6mm x 0.7mm)

Fig 9. shows the measured frequency fluctuation of the proposed ring oscillator with variation of the temperature and supply voltage. The range of the frequency variation is within 7% of the average clock frequency, 330-kHz. Its stable clock frequency guarantees the exact sampling of the demodulated bit stream. In addition, the accuracy of the ADC in the sensor block is enhanced by the stable clock frequency

Fig. 10 shows the measured waveforms for the synchronization of clock to data. When the Manchester high violation is detected, reset pulse is enabled and system clock is set to low. At the next '1' bit signal's half point, the system clock is regenerated and starts to sample command bits correctly. The output pulse counts

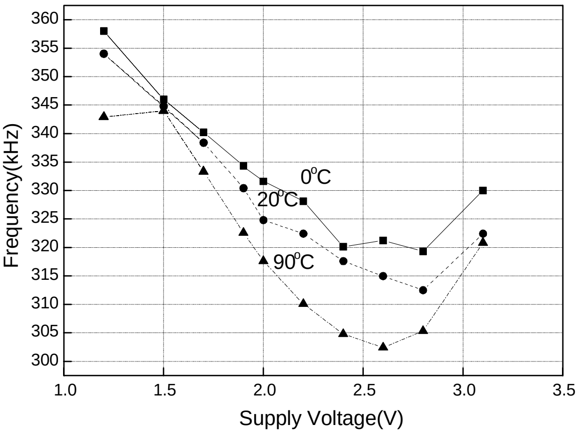

Figure 9. Frequency variation of the oscillator

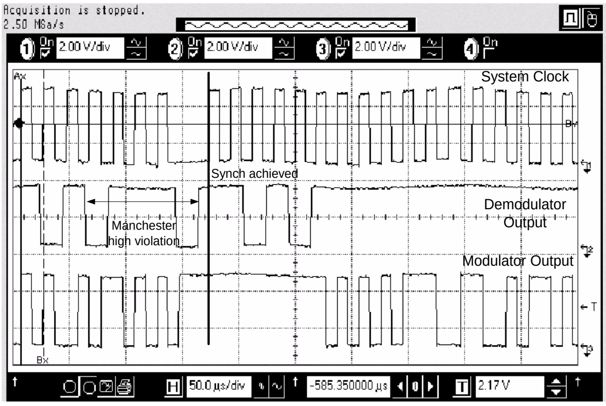

Figure 10. Measured waveforms for clock synchronization with data

of the temperature sensor are measured and given in Fig. 11 with the temperature varied from 0°C to 80°C.

The 10-bit binary counter is integrated on the sensor's output port for counting of the number of pulses. The measured value of the counter output reflects exactly the variation of the temperature. Fig. 12 shows the measured output pulse duration of the photo sensor as a function of the light intensity. The photo diode is a simple PN diode – nonsalicided NMOS source junction. We expect more linearity can be obtained if the photo diode process is optimized.

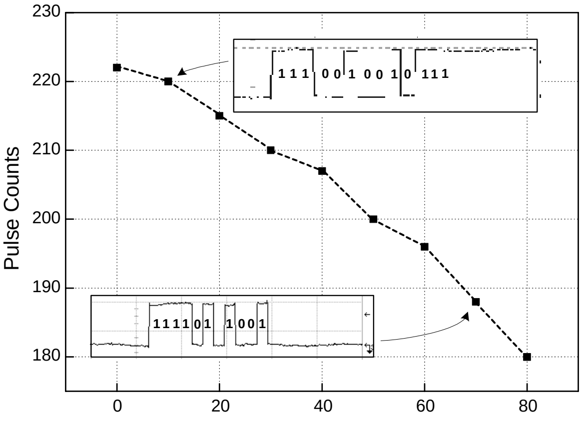

Figure 11. The measured characteristics of the temperature sensor

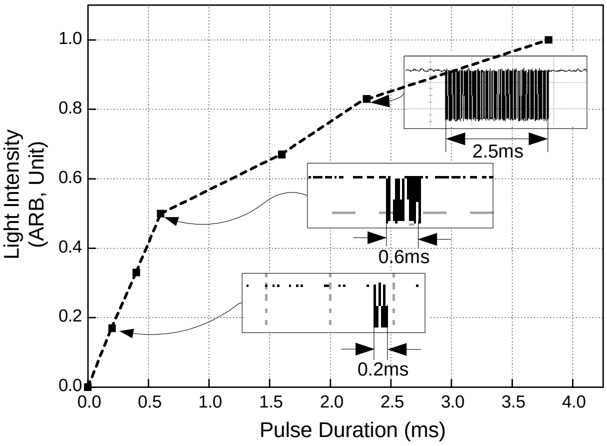

Figure 12. The measured characteristics of the photo sensor

5. Conclusions

We present a RF powered transponder with temperature sensor and photo sensor for environmental monitoring. The temperature compensated ring oscillator and oversampling synchronizer solved the problem caused by high radio frequency field and integration of sensor blocks. The generated clock signal has maximum 7% variation under 1.5-V supply voltage sweep and 90°C temperature change. The chip size is minimized by sharing common blocks and substituting large passive elements with active devices.

The transponder is fabricated in 0.25-µm CMOS process. The chip area is 0.6mm x 0.7mm excluding pads. Total power consumption is 5.14µW during active state.

References:

[1] Karthaus, U., Fischer, M., "Fully integrated passive UHF RFID transponder IC with 16.7uW minimum RF input power.", IEEE. J. Solid-State Circuits,Vol. 38, Oct. 2003, pp. 1602-1608

[2] Kocer, F., Walsh, P.M., Flynn, M.P., "Wireless, remotely powered telemetry in 0.25um CMOS", *Radio Frequency Integrated Circuits (RFIC) symposium*, June. 2004, pp. 339 – 342.

[3] Masui, S, Ishii, E, Iwawaki, T, Sugawara, Y., Sawada, K., "A 13.56 MHz CMOS RF identification transponder integrated circuit with a dedicated CPU", in *IEEE Int. Solid-State Circuits Conf. Dig. Tech. Papers*, Feb. 1999, pp. 162 – 163.

[4] Robert F. Zwillinger. How to write exhaustive references. In Ben H. Jackson, editor, IEEE conference on article relevance, pages 57-58, IEEE, June 2003.

[5] Yu, H., Najafi, K., "Low-power interface circuits for bio-implantable microsystems", in *IEEE Int, Solid-State Circuits Conf. Dig. Tech. Papers,* Feb. 2003, pp. 194 – 487.

[6] Warneke, B.A., Pister, K.S.J., "An Ultra-Low Energy Microcontroller for Smart Dust Wireless Sensor Networks", in *IEEE Int. Solid-State Circuits Conf. Dig. Tech. Papers,* Feb. 2004, pp. 316 – 323.