Implementation of a 2.45GHz Passive RFID Transponder Chip in 0.18μm CMOS*

MENG-LIEH SHEU, YU-SHENG TIAO, HANG-YU FAN AND JI-JIN HUANG

Department of Electrical Engineering
National Chi-Nan University
Puli, Nantou Hsien, 545 Taiwan

In this paper, a passive 2.45GHz band RFID transponder chip for high data rate communication and with low power consumption has been presented. The passive transponder chip contains five parts: a voltage multiplier converts received RF signal to the DC power supply, a mode selector decides the operating status, a low power dissipation LC-tank voltage control oscillator, a 32-bit read only memory, and a modulator. The RF-to-DC circuit can generate the required power supply and bias voltages from received 2.45GHz RF signal with 250mV amplitude. The data stored in 32-bit ROM can modulate the 2.45GHz carrier generated by VCO at up to 153Mbps for backscattering the data. The chip was designed and implemented by using TSMC 0.18μm 1P6M CMOS process. The chip area is 905μm × 652μm with simulated power consumption less than 4mW. The measurement and simulation results are well matched.

Keywords: RFID, passive, transponder, ASK, LC-tank VCO

1. INTRODUCTION

In recent years Radio Frequency Identification (RFID) systems have become very popular in a great number of applications, such as anti-theft system in mall, management of logistics, tracking of animal and patient, and pre-paid cards of public transports etc. [1]. Comparing with the omnipresent barcode systems, RFID systems can work very well without restrictions on the place and direction to the reader. For example, the dirt or damp on the surface of tags, which may make barcode unreadable, has little influence on RFID systems. Besides, advanced RFID transponders can incorporate microprocessor with a large quantity of memory in a tiny chip to perform complicated functions, such as data protection and cryptography, which are not possible in barcode systems.

A typical RFID system, as shown in Fig. 1, consists of application system, reader and transponder. When a transponder appears in the operation range of reader, it starts receiving both energy and data from the reader. The rectify circuit in the transponder collects and stores the energy for powering the other circuits in the transponder [2-4]. After collecting enough energy the transponder can operate and send back pre-stored data to reader, like electronic article code or tag ID code. The reader then passed the received response data to a server for system application, such as the request of price and manufacture information of commodities, or user authentication.

The transponders (or the tags) in RFID systems can be classified into passive and
active according to the power provision to the transponders. Passive transponders do not have their own power supply, and therefore draw all power required from the reader by electrical or magnetic field coupling. Conversely, active transponders incorporate a battery which supplies all or part of the power for the operation.

RFID systems are operated at widely different frequencies, ranging from 125kHz long wave to 5.8GHz in the microwave range. According to the operating frequency of the reader, RFID systems can be classified into: low frequency band (125kHz-135kHz), high frequency band (13.56MHz), UHF band (860MHz-930MHz), and microwave band (2.45GHz and 5.8GHz). RFID systems operating at frequencies between approximately 100 kHz and 30 MHz use inductively coupling. Lower frequency systems are primarily used due to the better penetration ability. By contrast, microwave systems are coupled using electromagnetic fields. Microwave systems have a significantly longer operating range and shorter antenna size than inductive systems.

In this paper, the design of a passive transponder operating at 2.45GHz microwave band is presented. The transponder chip is implemented using TSMC 0.18\(\mu\)m CMOS process. The chip can generate the required power supply from received 2.45GHz RF signal with 250mV amplitude. The 32-bit data stored in on-chip ROM is backscattering at a rate up to 153Mbps. The chip area is 905\(\mu\)m \(\times\) 652\(\mu\)m with simulated power consumption less than 4mW. In section 2, the data transmission of RFID is briefly described. The design and simulation of 1.5V passive RFID transponder is presented in section 3. Section 4 shows the implementation and measurement of the designed chip. At final conclusion is made.

2. DATA TRANSMISSION OF RFID

The typical transmission methods of energy and data between the reader and transponder in RFID systems are inductively coupling and backscatter coupling [1]. The inductively coupling transponders are usually operated passively as shown in Fig. 2 (a). The antennas of reader and transponder can be regarded as a transformer to couple energy from reader to transponder. By modulating the loading of the transformer data can be transmitted between reader and transponder reciprocally.

The backscatter coupling, as shown in Fig. 2 (b), is usually used in microwave band RFID system. Power \(P_{in}\) is emitted from the reader’s antenna. A small proportion of \(P_{in}\) is received by the transponder’s antenna and is rectified to charge the storing capacitor for serving as a power supply. After gathering enough energy, the transponder starts working.
A proportion of the incoming power is reflected by the transponder’s antenna and returned as power $P_{\text{return}}$. The reflection characteristics can be influenced by altering the load connected to the antenna. In order to transmit data from the transponder to the reader, a load resistor $R_L$ is switched on and off in time with the transmitted data stream. The magnitude of the reflected power $P_{\text{return}}$ can thus be modulated and picked up by the reader’s antenna.

Amplitude shift keying (ASK) modulation is suggested in RFID system for its simplicity. In ASK modulation the amplitude of the carrier is switched between two states controlled by the binary transmitting code sequence. Fig. 3 shows an ASK with 100% modulation factor which is also called ON-Off Keying (OOK modulation).

### 3. DESIGN AND SIMULATION OF 1.5V PASSIVE RFID TRANSPONDER

The proposed RFID transponder, as shown in Fig. 4, consists of an RF to DC circuit, an operation mode selector, a voltage controlled oscillator, a digital control circuit with memory and a modulator. The description of each circuit block is as follows.
Fig. 4. Circuit block diagram of proposed RFID transponder.

![Circuit block diagram](image)

3.1 RF to DC Circuit

The passive transponder gathers energy from the RF signal received at its antenna. For a 2.45GHz reader with 500mW EIRP, as the transponder has a distance of 1 meter from the reader, the received power at transponder will be around −10dBm [1]. In order to convert the attenuated RF signal into a sufficient high DC voltage for the power supply of passive transponder, an on-chip RF-to-DC rectifier circuit is required. The RF-to-DC circuit is composed of \(N\) stages of voltage-doubling circuit [5], as shown in Fig. 5. The voltage-doubling circuit can derive an output with double of the \(RF_{IN}\) voltage level. However, the diode-connected MOS has a turn-on voltage equals to the threshold voltage \(V_T\) of MOS. For receiving RF signal with amplitude less than 0.5V, native NMOS with low threshold voltage (74mV) provided by TSMC 0.18\(\mu\)m process is employed here to construct the RF to DC converter. The \(M1\) and \(M2\) are native NMOS connected as a Schottky diode. \(C1\) and \(C2\) are coupling capacitors constructed by MIM, \(Cs\) is para-
sitic capacitance, and $V_{IN}$ is a DC reference voltage for which can be set to GND in this case.

To derive the $V_{out}$ of $N$-stage circuit, referring to Fig. 5 (b) and assuming $C1 = C2 = C$, the voltage difference between nodes $n$ and $n + 1$ can be derived as: [6]

$$V_{n+1} - V_n = \frac{C}{C+Cs}V_P - V_T,$$  \hspace{1cm} (1)

where $V_T$ is the turn-on voltage of MOS, and $V_P$ is the peak to peak voltage of RF input signal. After cascading $N$ stages, the voltage at node $N$ with respect to $V_{IN}$ can be written as:

$$V_N - V_{IN} = N\left[\frac{C}{C+Cs}V_P - 2V_T\right].$$  \hspace{1cm} (2)

In practical case, an additional diode is used to isolate the output terminal from load, so the output voltage $V_{out}$ can be written as:

$$V_{out} = V_{IN} + N\left[\frac{C}{C+Cs}V_P - 2V_T\right] - V_T.$$  \hspace{1cm} (3)

Rearrange Eq. (3) and set $V_{IN}$ to be ground, we can get the equation as:

$$V_{out} = N\left(\frac{C}{C+Cs}\right)V_P - (2N + 1)V_T.$$  \hspace{1cm} (4)

The calculated output voltage of single-stage is about 158mV for the 2.45GHz RF signal with a peak-to-peak voltage $V_{PP}$ of 0.5V, $V_{IN} = 0$, $C = 30fF$, $V_T = 74$ mV, and $Cs = 10fF$. The required stages for RF to DC circuits to generate a set of voltages for $Vb$ (0.5V), $V+$ (1.6V), and $VDD$ (1.8V), are $N = 3$, 9 and 16, respectively. Fig. 6 shows the simulated waveforms of the different $N$-stage RF-to-DC converters for the required voltages. Fig. 7 shows the ideal and simulated output voltages versus number of stages. A decrease of 0.302V, about 8.48% error, occurs at the 16-stage circuit. The deviation comes mainly from the body effects neglected in Eq. (4).

![Fig. 6. Simulation of RF-to-DC circuits with different $N$ stages.](image_url)
Fig. 7. The output voltage of $N$-stage voltage-doubling circuits vs. number of stages $V_{out}$ is calculated from Eq. (4), and $V_{sim}$ is simulated value.

Fig. 8. Circuit of mode selector.

3.2 Mode Selector

For efficiently using the limit energy in transponder, the mode selector can switch the transponder to operate either in charging mode or in enable mode. The mode selector employs comparators with low power consumption [7], as shown in Fig. 8, where $M5$, $M6$ and $M7$ are small current sources. Due to the small current the comparator output can not have a full swing, so a common-source amplifier ($M8$ and $M9$) is employed to increase the output swing. $C_C$ is an off-chip large capacitor for energy storing. When the stored energy in $C_C$ is enough, $M10$ will turn ON to provide power for the subsequent circuits in the transponder. The voltages $V_b$, $V_+$, and $V_{DD}$ of the comparator are generated from three RF to DC circuits individually, as described in section 3.1. Fig. 9 is the simulation result of the mode selector. When $V_+$ is 1.6V and the $C_C$ voltage achieves 1.65V, the mode selector will turn on $M10$ and source power. When the power voltage drops to 1.58V, $M10$ will turn off and force the transponder entering into charging mode again. The voltage supplies to RL will keep at 1.5V in the enable mode. The simulated power consumption of mode selector is less than 600μW.
2.45GHz PASSIVE RFID TRANSPONDER

Fig. 9. Simulation result of mode selector.

FIG. 10. CIRCUIT OF LC-VCO.

3.3 Voltage-Controlled Oscillator (VCO)

Voltage-controlled oscillator (VCO) can generate a reference clock for the data carrier signal and the digital control circuit. LC-tank VCO (LC-VCO) [8] is employed for the consideration of power consumption. In Fig. 10, M18, M19 and the LC-tank form a cross-coupled oscillator; M11-M16 is for Vbias generation. The long channel MOS is adopted here to reduce the influence of the process variation. To decrease the effect of temperature on Vbias, two-stage temperature compensation [9] is used to design the bias circuit. Besides, the gate of M15 is connected to VDD, so it can switch on the bias circuit and dispense with the additional start up circuit. The inductors and MOS-Varactors are provided by TSMC 0.18μm CMOS process. The control voltage Vc changes the capacitance of MOS-Varactors resulting the changes of oscillating frequency proportionally.

Fig. 11 shows the simulation result of LC-VCO with Vc = 0.9V. The oscillation frequency is 2.45GHz with an output swing of 639mV. The oscillation frequency is from 2.94GHz to 2.35GHz when the control voltage is varying from 0V to 1.3V. The power consumption and phase noise of VCO are less than 1.1mW and −101.592dBc/Hz @1MHz,
Fig. 11. Simulated waveform of LC-VCO.

Fig. 12. The oscillation frequency versus $VDD$.

Fig. 13. The digital control circuit.
respectively. Fig. 12 shows the output frequencies versus \( VDD \). When \( VDD \) is ranging from 1.4V to 1.65V, the output frequency of VCO is varying from 2.388GHz to 2.521GHz, an error less than 3%.

### 3.4 Digital Control Circuit

The digital control circuit is composed of a divided-by-16 circuit, 3-bit and 2-bit counters, a 3 to 8 decoder, and an 8 to 1 multiplexer, as shown in Fig. 13. The divided-by-16 circuit receives 2.45GHz signal and generates 153.125MHz clock out. The 3-bit counter controls the 8-to-1 multiplexer to convert the selected ROM data byte to a serial bit sequence feeding the modulator. The 2-bit counter with the 3-to-8 decoder addresses the 4 bytes of ROM to output 8-bit data. Therefore a sequence of 32-bit data is generated. The ROM is realized in NOR-type with pre-set data of 01010101, 10101010, 00001111 and 11110000.

### 3.5 Modulation Circuit

ASK modulation is carried out by employing a 2-to-1 multiplexer as shown in Fig. 14. The serial data from ROM control the transmission gate to modulate the 2.45GHz carrier signal from VCO. Hence the modulation out is either the oscillator frequency or null as shown in Fig. 15. The power consumption is less than 1mW. Fig. 16 shows the simulation result of 128-bit pseudo random binary sequence.

### 4. THE IMPLEMENTATION AND MEASUREMENT OF RFID CHIP

A 2.45GHz passive RFID transponder chip is implemented using TSMC 0.18\( \mu \)m 1P6M CMOS process. It employs RF MOS transistors, native NMOS transistors with low \( V_T \), MOS-Varactors, spiral inductors and MIM capacitors. Fig. 17 is the chip photograph of the fabricated transponder with a chip area of 905\( \mu \)m \( \times \) 652\( \mu \)m.
The transponder chip is mounted on an FR4 printed circuit board (PCB) for measurement as shown in Fig. 18. The measured signal is picked up by a low-loading probe (Picoprobe Model 34A with −3dB bandwidth at 3GHz) and a high speed oscilloscope (Agilent infinium 54853A) as shown in Fig. 18. The measured RF-to-DC with charging up to 1.8V and discharging down to 1.2V is shown in Fig. 19. Fig. 20 shows the measured VCO output frequency. The control voltage is $V_c = 1V$ and the output frequency is 2.45GHz. Fig. 21 shows the measured $jitter_{p-p} = 35.82ps$. The measured and simulated
VCO tuning range is shown in Fig. 22. The measured tuning range is 520MHz (2.89GHz-2.37GHz). Fig. 23 shows that the measured phase noise of VCO is $-77.31 \text{dBc/Hz}$@1MHz. Due to the power supply of VCO is directly connected to VDD without regulation, which varies with the charging and discharging voltage at $C_c$ of mode selector shown in Fig. 8, the measured phase noise has a difference of 24dB from the simulation value. Fig. 24 shows the measured output waveform of the digital control circuit. Fig. 25 shows the
Fig. 25. Measured output waveform of modulation.

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<th>Table 1. Comparison with other RFID transponders.</th>
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measured output of the ASK modulation. The modulation factor is 0.62 and a little different from the simulation result of 0.72. The reason is that the probe we used has a −3dB bandwidth at 3GHz and results an attenuation of −1.41dB (about 0.85) at 2.45GHz. Hence the measured power factor can be calibrated to be 0.620/0.85 = 0.73, which is very close to the simulation result. Table 1 lists the comparison with other works. A very high data rate with adequately low power consumption is achieved at our work.

5. CONCLUSION

In this paper, a passive 2.45GHz microwave band RFID transponder chip is presented for high data rate communication and low power consumption. The passive transponder chip can generate the required power supply from a received 2.45GHz RF signal with 250mV amplitude. The data are backscattering at up to 153Mbps using ASK modulation. The chip was designed and implemented by using TSMC 0.18μm 1P6M CMOS process. The chip area is 905μm × 652μm with simulated power consumption less than 4mW. The measurement and simulation results are closely matched.
REFERENCES


Meng-Lieh Sheu (許孟烈) received his B.S. and M.S. degrees in Electronics Engineering from National Chiao Tung University, Hsinchu, Taiwan, in 1984 and 1986, respectively. From 1986 to 1989, he served as an instructor at the Electronics Engineering Department of Chung-Hwa Junior College, Taipei, Taiwan. In 1995, he earned a Ph.D. degree in Electrical Engineering and Computer Science from National Chiao Tung University. From 1995 to 2000, he worked as an associate researcher at the Chip Implementation Center (CIC) and became a deputy manager.
of the MPC Service division in 1999. In August 2000, the next year after the catastrophic earthquake, he joined the faculty of the Electrical Engineering Department, National Chi Nan University, Puli, Taiwan. His current area of interest includes VLSI design and test, system on chip/silicon IP design, sensor readout, and mixed-signal IC design.

Yu-Sheng Tiao (刁宥升) received his B.S. degree in Electronic Engineering from Kun Shan University, Tainan, Taiwan, in 2000, and received his M.S. degree in Electrical Engineering from National Chi Nan University in 2002. He is currently studying towards a Ph.D. degree in Electrical Engineering at National Chi Nan University. His current areas of interest includes VLSI design, analog circuits design and sensor readout.

Hang-Yu Fan (范航宇) received his B.S. degree in Electronic Engineering from National United University, Miaoli, Taiwan, in 2001; and received his M.S. degree in Electrical Engineering from National Chi Nan University in 2006. He is now an IC design engineer at ADDtek Corp., Hsinchu.

Ji-Jin Huang (黃繼進) received his B.S. degree in Electrical Engineering from National Chi Nan University in 2008. He is currently studying toward his M.S. degree in Electrical Engineering at National Tsing Hua University, Hsinchu.