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A 400-mV Bluetooth Low-Energy Transmitter Using a Capacitor Switch across a Transformer for achieving a Wide Tuning Range Voltage-Controlled Oscillator

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Abstract

In this study, a 2.1-mW, 2.4-GHz transmitter operating on a 400-mV DC power supply was developed using a simple direct-modulation closed-loop configuration. Connecting a capacitor bank switch via a transformer in the voltage-controlled oscillator (VCO) to the frequency-divider circuit can expand the frequency-tuning range without reducing VCO performance. A modulation-output spectrum satisfying the Bluetooth low-energy transmitter mask specifications is achieved, together with a VCO phase noise of −101 dBc/Hz @1 MHz.

1. Introduction

The Internet of Things sensor network is used for data collection from factory equipment, home appliances, the environment, and human vitals using wireless connection. This development has created a demand for sensor networks that use ultra-low supply-voltage sources such as solar batteries or energy-harvesting technology. Figure 1 shows the block diagram of a sensor network using an energy harvester instead of battery power to perform long-term operations. A small energy harvest voltage which is around 400mV is boosting to the 1.8 V power supply for LSI. However, the boot converter suffers a power loss because of its efficiency being around 70%. In this study, a Bluetooth low-energy (LE) radio frequency (RF) block directly operates a energy-harvesting power source to reduce the total power consumption.

This paper focuses on developing a transmitter system for the Bluetooth LE system, which is a widely-used sensor network system operating under a supply voltage of 400 mV.

2. Bluetooth Low-Energy Transmitter system

A direct open-loop modulation Bluetooth system with a small number of RF components was reported in [1]. However, one of the issues of this system is that VCO is operated without a phase-lock loop (PLL) after the channel are selected, and frequency accuracy become to worse. To solve this problem, a new direct closed-loop modulation system is proposed, which is shown in Fig. 2.

The input digital frequency-shift keying (FSK)-modulated signal is band-limited using a Gaussian filter with a gain-control amplifier (GCA) that determines the modulation bandwidth on the basis of the external terminal voltage. The FSK signal is modulated using a RF VCO variable-capacitor, which modulates the accurate frequency using the primary PLL circuit. The PLL bandwidth is set within the FSK modulation bit rate of 1 MHz. Furthermore, since there is a trade-off between the PLL lock-up time and frequency-tracking speed, the bandwidth-to-frequency ratio of the FSK is set to minimize the lock-up time and it does not necessarily follow the 1-MHz bandwidth. The FSK modulation signal of the Bluetooth LE is then output from the VCO.

3. VCO and High-frequency Divider Circuits

A conventional VCO and a divide-by-2 high-frequency divider circuit for the PLL system are shown in Fig. 3. The high-frequency divider circuits comprise two MOSFET transistors stacked with load resistance (RL). This topology does not operate under the 400 mV power supply.

The VCO has two different types of block capacitors. One is a varactor diode, which continuously changes its capacitance in order to change the frequency channel, and the other is a capacitor bank (shown in Fig. 4), which changes the two-bit step for a wide tuning range.

When the capacitance bank circuit is on the VCO side (Fig. 3), the source voltage of the switching MOSFET transistor takes on the value of the central potential of the VCO power source (around 200 mV). Even if 400 mV is applied to the switch, the MOSFET transistor of gate-source voltage is only 200 mV; thus, the switch cannot enter the fully ‘ON’ state and the frequency range cannot be expanded in the conventional circuit.

To address this issue, we propose a new system topology (shown in Fig. 4 (b)) and a new circuit (shown in Fig. 5). The input-stage transistors of the divider were replaced by the transformer; this enabled operation at an ultra-low supply voltage of 400 mV. By directly connecting the inductor of the divider to the VCO inductor with a transformer, we reduced the power consumption and the size of the buffer-amplifier circuit between the VCO and the divider while maintaining the same chip area.

In addition, the capacitor bank circuit that we propose includes a transformer with a grounded center tap on the divider side; this enables the switching MOSFET transistor to be fully ON at 400 mV (Fig. 5). A comparison between the simulation results of the VCO tuning range and the transformer Q factor for the conventional and proposed topologies is shown in Fig. 6. The VCO tuning range of the proposed topology is twice as wide at a 400-mV supply voltage.

4. Measurement Results

A prototype of the ultra-low voltage supply Bluetooth LE transmitter is fabricated using the 65-nm standard CMOS technology. The die micrograph is shown in Fig. 2.

Figure 7 shows the VCO performance of the transmitter chip. The VCO oscillates at 2.4 GHz under a 400-mV power supply. A phase-noise performance of −101 dBc/Hz is achieved for a 1-MHz offset. The total frequency band achieved is 450 MHz. These results are sufficient to meet the Bluetooth LE frequency range specification of 82.5 MHz in the 2.4-GHz band.

Figure 8 shows a divide-by-2 high-frequency divider output signal at 2.4 GHz and the power-amplifier buffer-output terminal signal spectrum of the Bluetooth LE transmitter. As shown in Fig. 8(b), the output level is −6 dBm, which corresponds to an external 10-dB power gain of the PA component.

The output spectrum meets the Bluetooth LE spectrum mask at 1.5 MHz. The current consumption of the transmitter system is 2.1 mW for a 400-mV supply voltage.

5. Conclusions

This paper presents a novel Bluetooth LE transmitter for energy-harvesting wireless sensor applications that has low power consumption and is functional at ultra-low supply voltages.

Table 1 shows a comparison between the Bluetooth LE transmitter performances of the proposed design and state -of -the -art designs. This prototype Bluetooth LE transmitter chip achieves a minimum supply voltage operation of 400 mV.

6. References

[1] H. Ishikuro *et al.*, IEEE *ISSCC Dig.* (2003) 94.
[2] Y. Liu, *et al.*, IEEE *ISSCC Dig.* (2003) 446.
[3] A. Wong, *et al.*,IEEE *ISSCC Dig*. (2012) 300.

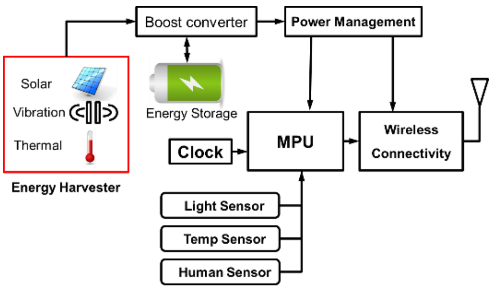

Fig. 1 System block diagram of a sensor network using energy harvesting.

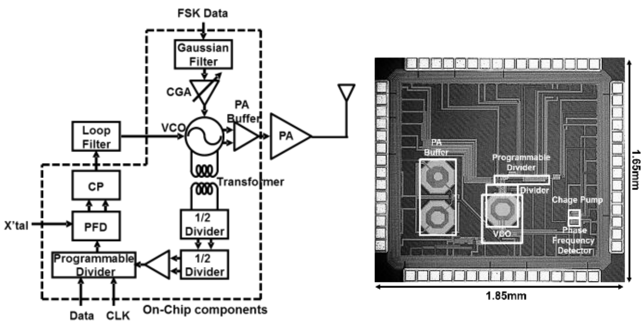

Fig. 2 Architecture of the proposed Bluetooth LE transmitter and die photo.

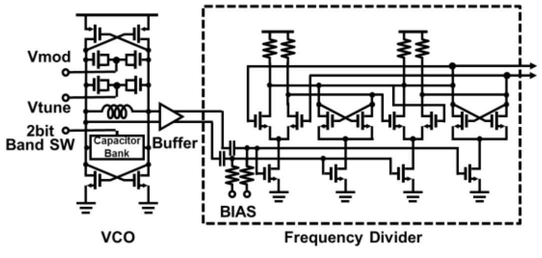

Fig. 3 Conventional VCO and the frequency divider circuits.

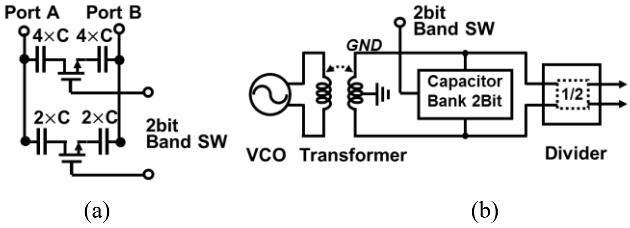

Fig. 4 (a) Two-bit capacitor bank circuit. (b) Proposed VCO and divider system.

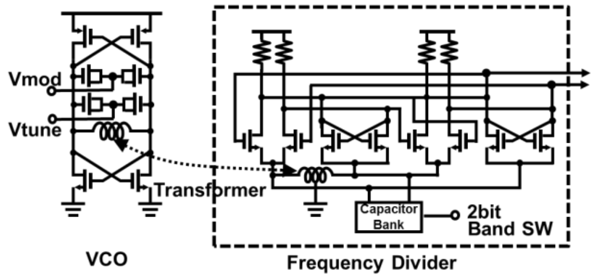

Fig. 5 Proposed VCO and frequency divider circuits.

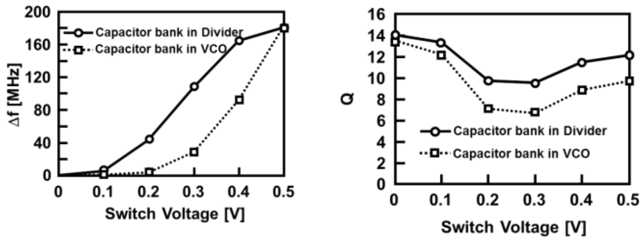

Fig.6 VCO tuning range and transformer Q factor.

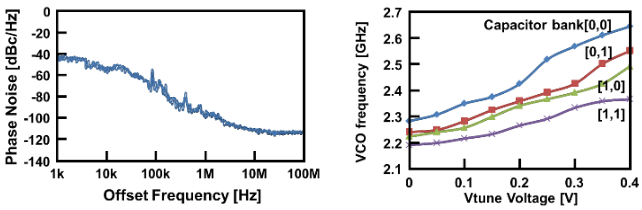

Fig. 7 VCO phase-noise and tuning range characteristic.

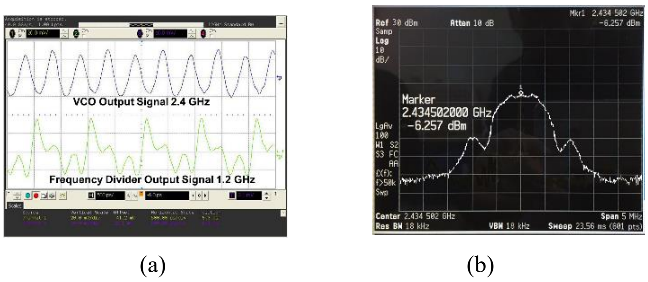

Fig. 8 (a) Divider output signal. (b) Output signal spectrum.

Table 1 Performance comparison of Bluetooth LE RF chips.

	This work	[189]	[3019]
Technology	65nm	90nm	130nm
Supply Voltage	0.4 [V]	1.2 [V]	1 [V]
Power consumption	5.2 [mW]	5.4 [mW]	8.9 [mW]
Output Power	−6 [dBm]	0 [dBm]	0 [dBm]
Wireless System	Buletooth LE	Buletooth LE	Buletooth LE