Dedicated Antenna Less Power Efficient OOK Transmitter for mm-Cubic IoT Nodes

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***Abstract*—This paper proposes a compact VHF-band OOK transmitter that uses coils for radiation as well as oscillation, eliminating the need for an external antenna. This feature contributes to fewer number of components, smaller volume and and lower cost. We prototyped the transmitter with 2.8 mm × 2.8 mm × 4.2 mm volume. For shortening the startup time and enabling high-speed communication, we devise a scheme that provides a weak current for quick start of LC oscillation. Measurement results show that the start time of LC oscillation is reduced from 400 ns to 40 ns, and 1m communication at 3Mbps is possible. The minimum energy consumption per bit of the proposed transmitter is 205 pJ/b.**

I. Introduction

Aggressive scaling of VLSI technology has made it possible to perform signal processing in a small volume like cubic-millimeter [1], [2]. To make use of such a small volume computing in the era of "Internet of Things (IoT)", the small volume nodes should be equipped with wireless communication function. Once the small volume node becomes able to transmit signals wirelessly, the information obtained and processed by the node can be collected for cyber physical system, industry 4.0, smart city, etc. Small volume nodes can be attached to everything around us, and hence millimeter-cubic class nodes have a potential to change our life significantly.

On the other hand, in many cases, integrating a high-performance transmitter is difficult since the size of nodes is extremely small. Fortunately, high communication speed is not demanded in most of IoT applications, especially for small volume sensor nodes. Device cost is rather more important than performance. Another key requirement is low power operation since each node is expected to operate for a long time with a compact and small capacity battery. Even when the power is wirelessly provided and the transmitter operates intermittently, the amount of energy stored in such a small volume is highly limited, and low energy operation is indispensable. From the above, we conclude that the following features are required for small wireless nodes for IoT.

- Small volume
- Low cost
- Low energy per bit
- Low standby power

This paper proposes a simple VHF band transmitter that uses two inductors both for oscillation and radiation. The proposed transmitter does not use a dedicated 50Ω antenna and hence the impedance matching is unnecessary. These features are helpful for reducing the number of components and consequently the volume and cost. As for the power, we develop a scheme that minimizes the dead-time of on-off keying (OOK) for improving the communication speed and reducing energy per bit. For achieving low standby power, the proposed transmitter can be completely turned off in the sleep mode. To demonstrate the performance, we made a 2.8 × 2.8 × 4.2 mm^3 prototype of the proposed transmitter using discrete devices. Experimental results show that the transmitter achieved 1 Mbps communication for 1m distance at 1.0V supply voltage. In this case, the energy consumption per bit is 205 pJ / bit.

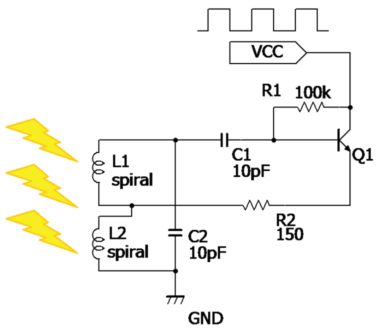

Fig. 1. Proposed transmitter.

II. Proposed Transmitter Structure and Its Implementation

Fig. 1 shows the schematic of the proposed transmitter. The transmitter is based on a collector-grounded type Hartley oscillator circuit that includes two coils for LC oscillation. In the proposed transmitter radiates electromagnetic waves from these two coils instead of an external dedicated antenna. Let us explain the basic operation of the Hartley oscillator. Q1 in the schematic is a VHF/UHF band transistor and is used as a current amplifier. When a signal is applied to the base of Q1, a current-amplified same-phase signal arises at the emitter. By injecting the current-amplified signal into the tap of the coil, a positive feedback circuit is composed and starts to oscillate. Also, the signals other than the resonance frequency are attenuated by the tuning circuit consisting of

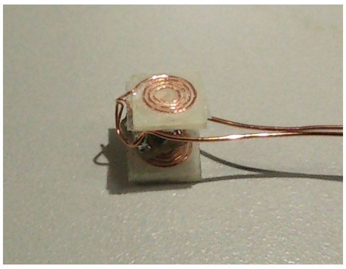

Fig. 2. Prototype of proposed transmitter.

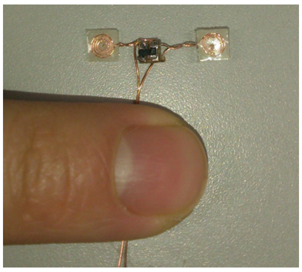

Fig. 3. Expanded view of prototype.

L1, L2, and C2, and then the this circuit outputs a sine wave at the resonance frequency.

OOK modulation is accomplished by powering on or turning off the oscillator as depicted in Fig. 1. A short time later after the power-on, After the power-on, the oscillation, i.e. “1” radiation starts a short time later. This duration between the power-on and the oscillation start is a wasteful time for OOK and this dead-time limits the maximum communication throughput since the symbol time cannot be smaller than the dead-time. To improve the throughput, this dead-time should be minimized. In addition, the dead-time minimization is helpful to reduce the energy since the signal transmission finishes in a shorter time. Besides, the prototype evaluation, which will be shown in the next section, shows that the dead-time is 400 ns, which means the maximum throughput is limited to 2.5 Mbps.

This dead-time originates from the coil inductance. When the transmitter is powered on, the inductor generates counter electromotive force and then the coil cannot conduct current immediately after the power-on. From another point of view, in the case that non-zero current is flowing in the coil beforehand, the generated counter electromotive force can be mitigated. Consequently, the current necessary for oscillation begins to flow earlier and the dead-time becomes shorter. This non-zero current is provided by giving voltage V_{mid} as VCC during “0” transmission. Note that the oscillator is not oscillating at V_{mid}. This V_{mid} should be determined taking into account the trade-off between the dead-time reduction and power consumption during “0” transmission.

Figs. 2 and 3 show the prototype of the proposed transmitter. 1.6 mm $\times$ 0.8 mm chip resistors and capacitors are used for the prototype. The size of the transistor Q1 is 1.6 mm $\times$ 1.6 mm. Fig. 4 shows a 3.6 mm-diameter four-turn spiral coil (for L1, L2), in which polyurethane copper wires of 0.15 mm are wound on both sides of a glass epoxy(FR-4) substrate. The inductor value estimated by network analyzer (Agilent Technologies, E5071C) is 100.13 nH.

Let us discuss the advantage and disadvantage of the proposed transmitter. The most significant advantage is that the proposed transmitter does not have a dedicated 50-Ω antenna and consequently the impedance matching circuitry is unnecessary. As a result, the transmitter can be composed of only five components except the coils, which is highly desirable for small volume implementation. In addition, the

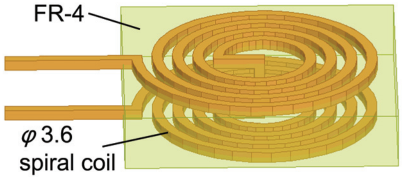

Fig. 4. Spiral coil for tuning circuit.

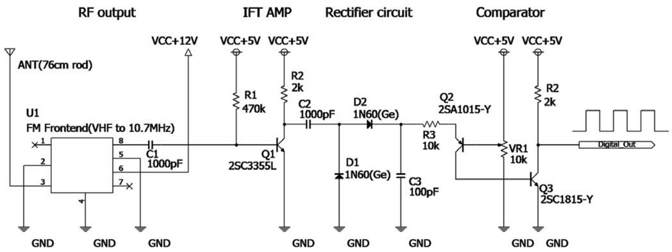

Fig. 5. Schematic of receiver.

loss originating from impedance mismatch can be eliminated. On the other hand, there is a disadvantage of poor frequency stability. Due to the poor frequency stability, each node needs wider frequency band for communication. This disadvantage, however, is not a big issue in applications that many transmitter nodes share a single receiver that receives a wide range of frequency.

III. Evaluation

To confirm the effectiveness of the proposed transmitter, we evaluate the performance of transmitter.

A. Receiver Structure

The transmission power of the transmitter is small and then we need to perform sufficient amplification on the receiving side. To facilitate the receiver design by minimizing the portion of the high frequency circuit, we adopted a super heterodyne circuit as a receiver. An intermediate frequency of 10.7 MHz is generated by frequency conversion, and this intermediate frequency is amplified and processed. Here, to save the design time, a commercial FM frontend manufactured by Mitsumi is used for frequency conversion. The intermediate frequency is 10.7 MHz and hence the maximum communication speed with this receiver is limited to several Mbps. Fig. 5 shows the schematic of the implemented receiver, and Fig. 6 shows a photo of the receiver. For the antenna of the receiver, a 76 cm rod antenna was used.

B. Power Consumption

Fig. 7 shows the signal observed at the emitter of transistor Q1 with an oscilloscope when VCC is 3V. The proposed transmitter oscillated at 108MHz with 3.34 V magnitude, as we expected.

Fig. 8 shows the current consumption of the transmitter when the power supply voltage is varied from 0.6 V to 3 V. The red vertical line in the figure corresponds to 0.66 V,

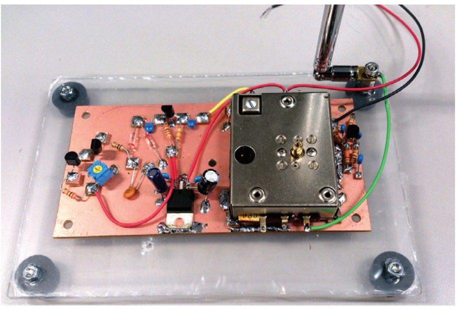

Fig. 6. Photo of receiver.

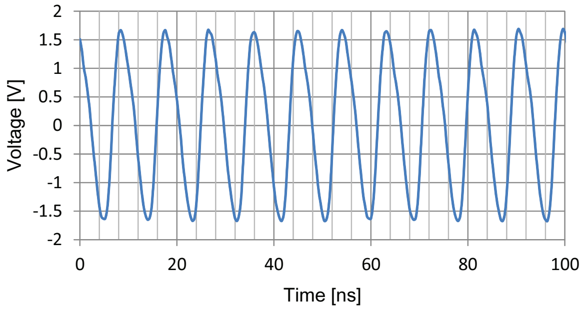

Fig. 7. The signal measured at the emitter.

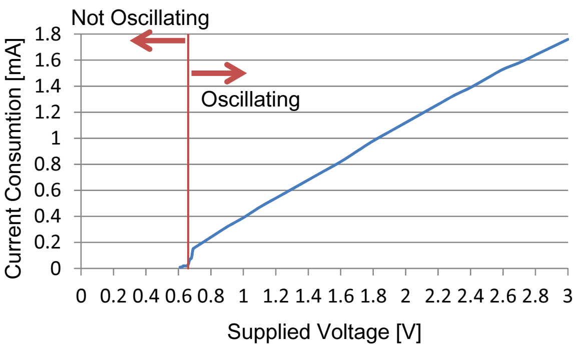

Fig. 8. Current consumption versus supply voltage.

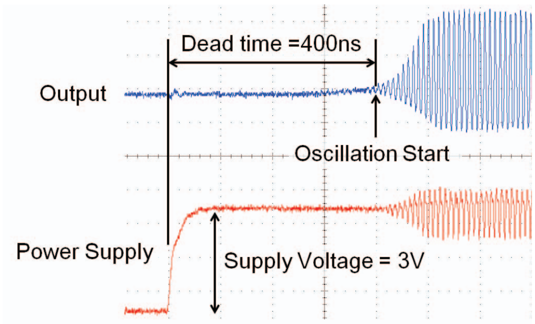

Fig. 9. Dead-time at the start of oscillation.

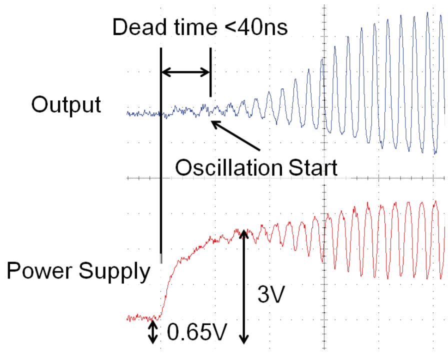

Fig. 10. Shortened dead-time.

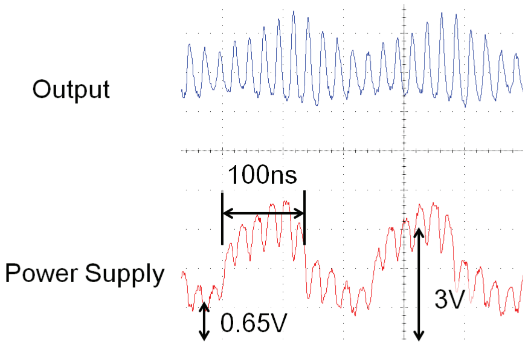

Fig. 11. Transmitter output for 3 V, 20 Mbps communication.

which is the minimum voltage required to start oscillation. The proposed transmitter can operate at a wide range of supply voltage. Fig. 8 also shows that the current rapidly increases when the power supply voltage exceeds 0.65 V, where 0.65 V is the base-emitter saturation voltage of Q1. Beyond 0.7V, the current is proportional to the power supply voltage, which is due to the following reason. Transistor Q1 operates in forward active mode. In this case, the collector current is kept constant even with the collector potential variation as long as the base current is constant. On the other hand, the circuit in Fig. 1 is a fixed bias type circuit. The base current is proportional to the collector potential and the collector current is proportional to the base current. Consequently, the collector current becomes proportional to the collector potential, i.e. VCC.

C. Baud Rate

Fig. 9 shows the power supply voltage (red line) and the signal waveform at the emitter of Q1 (blue line) when the power supply voltage VCC is changed from 0 V to 3 V. When powering on the transmitter, the oscillation starts after a certain amount of dead-time. In this case, 400 ns dead-time is necessary. As discussed in Section II, this dead-time limits the throughput and hence we introduced V_{mid} for reducing the dead-time. According to Fig. 8, V_{mid} is set to 0.65 V, where it is the maximum voltage that cannot start the oscillation. The current at 0.65 V is 0.02 mA and it is negligible compared to the current during “1”.

Fig. 10 shows the signal at the emitter when the power supply voltage is raised from V_{mid} = 0.65 V to 3 V. The dead-time is reduced to 40 ns, which is 1 / 10 or less compared to 0 V to 3 V transition. This shorter dead-time can contribute to the throughput improvement. Fig. 11 shows that 20 Mbps transmission is feasible at 3 V operation thanks to the shortened dead-time.

Finally, the communication speed including both the trans-

TABLE I
TRANSMISSION RANGE VS COMMUNICATION SPEED.

	Communication speed[Mbps] (Energy per bit)		
Range [m]	1V	2V	3V
1	1.0 (205pJ/b)	3.0 (380pJ/b)	3.0 (890pJ/b)
5	0.8 (256pJ/b)	1.4 (814pJ/b)	1.4 (1910pJ/b)

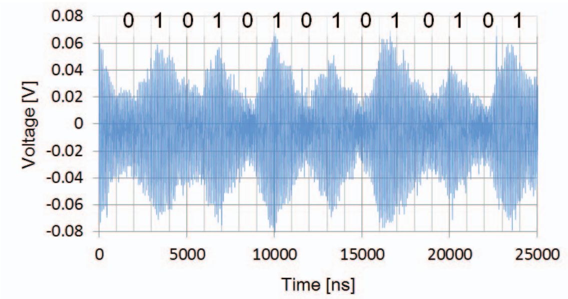

Fig. 12. Received signal from transmitter, 5 m away from receiver.

mitter and receiver was evaluated by observing the output of the FM front end circuit in Fig. 5 with an oscilloscope. A rectangular wave with 50% duty ratio was given from a function generator to the proposed transmitter as VCC and the maximum frequency at which the waveform could be reproduced on the oscilloscope was evaluated. Three supply voltages of 1, 2 and 3V and two distances of 1 m and 5m between the transmitter and receiver were tested. Results are listed in Table I. This table also includes energy per bit under each condition. For 5 m communication, the supply voltages of 2 and 3V achieved 1.4 Mbps throughputs. The output waveform of the FM front end in the receiver is shown in Fig. 12. We can see the transmitted waveform of 600 kbps is well reproduced. As for 1 m, the supply voltages of 1 V achieved 1.0Mbps, and of 2, and 3V achieved 3.0 Mbps throughputs. The lowest energy per bit of 205 pJ/bit was attained at 1 V. Fig. 13 shows the waveform at the receiver when a 500 kHz, i.e, 1 Mbps, signal was transmitted by the transmitter operating at 1 V with 1 m distance. We can see the intermediate frequency of 10 MHz is amplitude-modulated at 500kHz. In this case, the power consumption per bit is 205 pJ / bit. It should be noted that the throughput in each condition depends on the receiver performance and, with a more sophisticated receiver, the energy per bit could be further reduced, which is one of our future works.

The measurement results of the proposed structure are summarized in Table II. Table II also shows comparisons with related studies on small transmitters. We can see that the proposed transmitter achieved better throughput and energy per bit than [3] and comparable performance to [4] [5] without any dedicated external antenna. This clarifies that the coils used for LC oscillation can be also utilized for electromagnetic wave radiation. The proposed transmitter needs no impedance matching and hence it is suitable for smaller volume implementation.

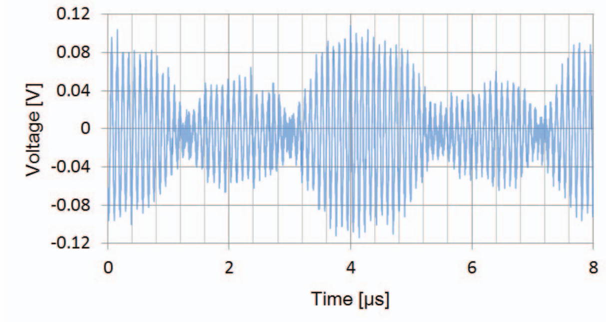

Fig. 13. Waveform at receiver in case of 1Mbps communication.

TABLE II
COMPARISON WITH RELATED WORKS.

	[3]	[4]	[5]	This Work (1V)	This Work (2V)
Implementation	CMOS 130nm	CMOS 180nm	CMOS 130nm	discrete components	
Antenna	ext	ext	ext	int	
VDD [V]	1.5	0.7	1.2	1.0	2.0
Power (mW)	2.7	0.7	1.68	0.39	2.24
Modulation	2FSK	2FSK	2FSK	OOK	
Data rate	48kbps	5Mbps	4Mbps	1Mbps	3Mbps
Energy/bit(nJ/b)	56.25	0.14	0.42	0.205	0.38

IV. CONCLUSION

In this paper, we proposed a VHF-band OOK transmitter that used coils for radiation as well as oscillation, eliminating the need for an external antenna. This feature makes it possible to reduce the number of components, resulting in volume and cost reduction. As for the power, by developing a scheme that minimizes the dead-time of OOK, we shortened the dead time from 400 ns to 40 ns or less and achieved a communication speed of 1 Mbps at a communication distance of 1 m. In this case, the energy per bit was 205 pJ/bit. Tuning the implementation of the transmitter and receiver for higher throughput is one of our future works.

ACKNOWLEDGEMENTS

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