A 356-μW, 433-MHz, Rail-to-Rail Voltage Amplifier with Carrier Sensing Function for Wireless Sensor Networks

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Abstract **— We describe a low-power voltage amplifier that is suitable for RF (radio frequency) receivers in a WSN (wireless sensor network). Since a sensor node has a strict energy budget in a WSN, it often enters itself into a standby mode when no communication is required, and hence a standby power have to be suppressed as well as an active power in order to maximize a lifetime of a WSN. For this sake, it is effective to reduce an RF block's power in a sensor node because it is the major power-consuming block. We propose a simple rail-to-rail voltage amplifier with low-standby-power and low-active-power capabilities that is suitable to a subsequent digital interface. The target frequency is set to 433 MHz, and the voltage gain achieves 26 dB. The standby and active powers are 24 nW and 356 μW, which are lower than the conventional inverter-type voltage amplifier by 86% and 46%, respectively. The proposed amplifier features a carrier sensing function in addition to the low-power operation since it has a minimum input amplitude to be amplified. By using this function, we can set a carrier sensing level as a threshold level, which is important to avoid collisions and interferences in a WSN that cause needless communications.**

Index Terms **— Wireless sensor network, voltage amplifier, carrier sense, on-off keying.**

I. INTRODUCTION

A. Conventional Voltage Amplifiers

Recent advances in microsensors, integrated circuits, and wireless communication technologies enable WSNs (wireless sensor networks) comprised of a number of small nodes to be emerging [1]. One of the most important issues on the WSNs is to extend an available period, say, network lifetime as long as possible under the condition that each sensor node has only a strict energy budget. For this sake, it is effective to reduce a power of an RF (radio frequency) block in a sensor node since it is the major power-consuming block in the whole.

In the conventional researches, low-power RF receivers for WSNs have been proposed [2]-[3]. They adopt OOK (on-off keying) where data are modulated by existence of a signal (e.g. "1" for signal, and "0" for no signal). OOK is a simple modulation, and thus can be implemented with simple and low-power hardware. In [3], an LVA (low-voltage amplifier) is adopted as the first-stage amplifier in a receiver, after which there are inverter-type voltage amplifiers connected in series without any inductors. This circuit adopts an incoherent architecture, but is "digitally" analog. It works at a frequency of 433 MHz rail-to-rail. Figure 1 shows the inverter-type voltage amplifier. This amplifier does not require a bias adjustment because it has a feedback loop made of a resistor, and can automatically set a bias voltage to a half of a supply voltage. This type of amplifier has a high voltage gain, and is well utilized in a piezoelectric oscillator, but always draws short currents. Thereby, large power consumes even if no signal is input, and the chain of the inverter-type voltage amplifiers reaches 94% of the total power in the receiver [3].

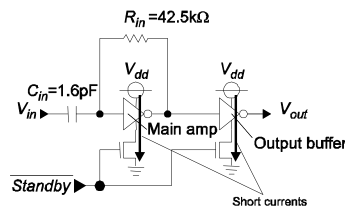

Figure 1. Schematic of inverter-type voltage amplifier.

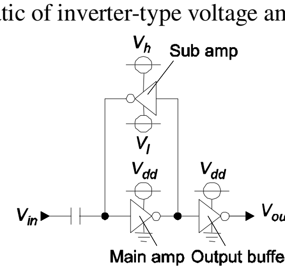

Figure 2. Schematic of latch-type voltage amplifier.

Instead of the inverter-type voltage amplifier, a latch-type voltage amplifier in Fig. 2 has been proposed to suppress the short current [4]. It has bistability thanks to the latch property, and the two bias points are fixed to V_h and V_l, at which a less short current flows through the main amplifier. This is because V_h and V_l are slightly shifted from the middle of a supply voltage, but they have to be supplied externally in [4]. When a signal is input, the main amplifier amplifies it, and at the same time drives the sub amplifier. The sub amplifier helps the amplification of the main amplifier by its feedback. However, this conventional latch-type voltage amplifier only accepts a square wave. When a sine wave is input, the two bias voltages fluctuate due to a phase error between the input and feedback signals. Therefore, we cannot use this latch-type voltage amplifier in an RF application.

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B. Standby Power

In WSNs, sensor nodes are intermittently activated since a data rate is low. The activation ratio is just 10^{-3} [5], and sensor nodes enters a standby mode in the rest period. Hence, a low standby power is important, and must be less than 10^{-4} of an active power. Otherwise, the standby power becomes dominant, and a lifetime of WSNs turns out short.

C.Carrier Sense

We should avoid data collisions and interferences in WSNs so as not to waste a power budget. While one node is transmitting data, it is desirable that other nodes around it do not communicate. One method to solve the problem is a carrier-sensing approach, which is widely utilized in many MACs (media access controls). All nodes make a carrier sense before they transmit data. If they detect a carrier, they defer packet transmission. A typical carrier-sensing scheme is to measure an RSSI (received signal strength indicator). A channel is regarded as busy if detected energy in the channel is above a threshold; otherwise it is regarded as idle. The RSSI carrier sense requires an additional A/D converter to detect the energy, which consumes not negligible power. Thus, this kind of carrier sense is unsuitable for a low-power wireless sensor node. We will describe another approach in the next section.

II. PROPOSED VOLTAGE AMPLIFIER (BSAMP)

We propose a low-power voltage amplifier with carrier sensing capability for OOK, named a BSAMP (bistability amplifier). The schematic is illustrated in Fig. 3 (a). C_{fb} and R_{fb} are added to Fig. 2 in order to stabilize the bias points and to accept a sine wave. The intermediate voltages (V_h and V_l) are supplied by a voltage generator described later on. The sub amplifier has a small dynamic range restricted by V_h and V_l, however, it can boost amplifying operation with its feedback. The main amplifier amplifies an input voltage (V_{in}), and drives an output buffer. Figure 3 (b) is a layout in an OKI 0.15-μm SOI process technology. We take all parasitic elements and parasitic effects into account in simulations carried out with Agilent Technologies ADS. In this paper, we compare the proposed BSAMP with the conventional voltage amplifier in Fig. 1 by means of the circuit simulations.

A. DC Characteristics

Figure 4 (a) explains the operating points of the BSAMP working at a supply voltage of 1 V. The operation curves of the main and sub amplifiers intersect at two points. Every time an amplitude of V_i goes over V_a (=(V_h–V_l)/2), the bias points of the main amplifier alternate. The voltage gain at the bias point is almost the same as the conventional one because V_a is a small value (=25 mV) and the bias points are near to the maximum slope at V_m.

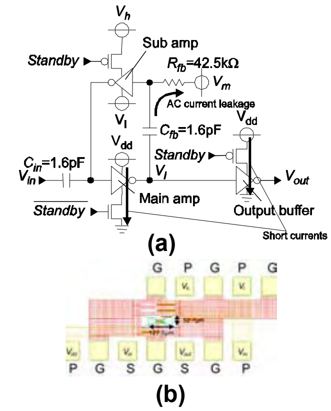

Figure 3. (a) Schematic, and (b) layout of BSAMP. Layout size is 128 x 53 μm^2.

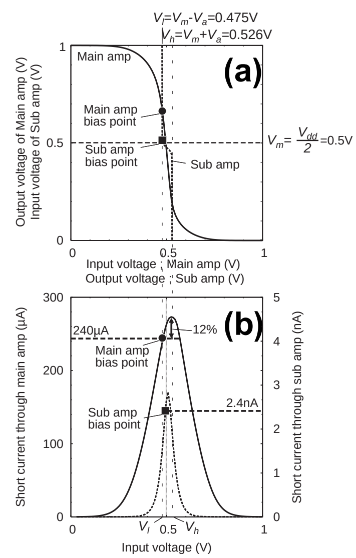

Figure 4. DC characteristics of BSAMP. (a) Bias voltage, and (b) bias current.

Figure 4 (b) illustrates the bias currents flowing through the main and sub amplifiers. The bias current through the main amplifier is reduced to 240 μA (12% down from the maximum) thanks to the shifted bias voltage, which also lowers a short current flowing through the output buffer. The bias voltage of the sub amplifier is fixed to V_m (=0.5 V), but the bias current through it is very small in nature because the supply voltage is just 50 mV (=V_h–V_l). In the proposed BSAMP, the zigzag cut-off scheme can be accommodated that minimizes a standby current [6] while in the conventional one, it would not and two nMOS are inserted as power gating (see Fig. 1). The bias voltages would turn out to fluctuate in the multistage inverters of the conventional amplifier if the zigzag scheme was applied, which would result in low voltage gain. In contrast in the proposed BSAMP, the zigzag cut-off scheme is quite effective since the bias voltage of the sub amplifier is moved to a lower value by the cut-off PMOS in the standby mode. The power consumed by the bias current and the standby power are 278 µW and 24 nW, which demonstrates that we save 59% and 86%, respectively.

B. Operation in Active Mode

In the BSAMP, when V_{in} is input to the main amplifier and an amplitude of V_i is less than V_a, the sub amplifier tries to convergence V_{in} to its bias voltage using the feedback because the bias point is a stable point. Figure 5 is the voltage gain characteristics at an operating frequency of 433 MHz, and exhibits the threshold function. When the input amplitude ($|V_{in}|$) is equal to 0.04 V, the amplitude of V_i gets equal to 0.05 V, whose point is the threshold. We can exploit this salient feature as a carrier sense described in the following subsection. As an input amplitude increases, the voltage gain is degraded due to output saturation since the proposed amplifier is rail-to-rail. We can obtain the maximum voltage gain of 26 dB when an input amplitude is 0.04 V. Note that we suppose there is an LVA just before the BSAMP, since the value of 0.04 V is large if the BSAMP is used as a first-stage amplifier.

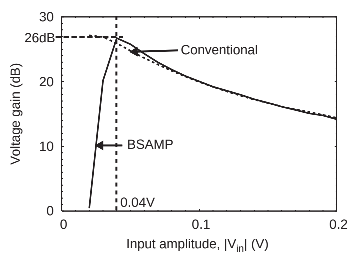

Figure 5. Voltage gain characteristics.

Figure 6 shows the frequency characteristic in terms of voltage gain in the conventional and proposed amplifiers. In the figure, the input amplitudes are set to 0.1 V in both. Since a $C_{in}R_{in}$ time constant in Fig. 1 dominates the cut-off frequency in the conventional amplifier, we set the highest value (42.5 kΩ) to R_{in} that we can design with the given technology. As well as in the proposed BSAMP, we also set R_{fb} to 42.5 kΩ in order not to flow an AC leakage through R_{fb}. Beyond 1 GHz, the BSAMP's characteristic is degraded since a voltage gain of the sub amplifier is lowered at a high frequency, which suppresses the input amplitude. This, in turn, degrades a voltage gain of the main amplifier like a negative feedback.

Figure 7 illustrates the power characteristics when an input amplitude ($|V_{in}|$) is changed. The active power is 31% lower than the conventional amplifier at an input amplitude of 0.04 V. Note that it indicates the saving factor when a signal is "1" (case that a signal has a 0.04-V amplitude). If there is no signal (signal "0") in an active mode and $|V_{in}|$ is zero, the active power at the signal "0" is the same as the short power mentioned in the previous subsection. Because the saving factor is larger at the signal "0", we can save an active power more as a duty ratio of a signal becomes smaller.

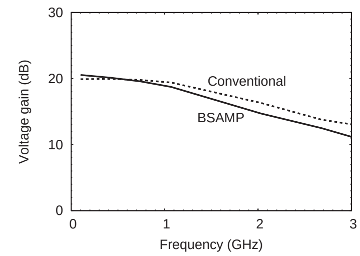

Figure 6. Frequency characteristics.

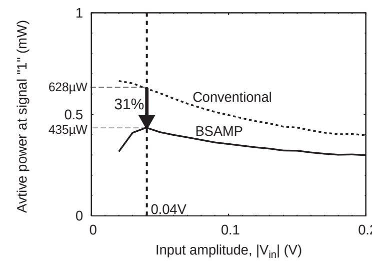

Figure 7. Power characteristics.

C. Voltage Generator and Carrier Sense

Figure 8 shows the circuit diagram of the voltage generator for the sub amplifier that can generate the three kinds of voltages (V_h, V_l, and V_m). Because $V_a=(V_h-V_l)/2$, we can change V_a programmatically with a combination of *Selv*[*i*] by controlling the impedance between V_h and V_l nodes. The power of this programmable voltage generator is 4.5 µW even in an active mode thanks to the low-power characteristic of the sub amplifier. In the standby mode, the leakage power can be suppressed to 8 nW with *Standby*, */Standby*, and *Selv*[*i*] signals.

We assume that transmitted binary data are represented by Manchester encoding, and then modulated by OOK as an RF signal. This makes it easy to distinguish busy and idle carrier. In Manchester coding, for example, "0" and "1" are encoded as "01" and "10", respectively. Each encoded symbol involves "1", which is modulated into a certain amplitude in an OOK RF signal. Thus, a receiver may detect it during one Manchester encoded symbol as a busy carrier, while it does not at all in case of an idle carrier. Most packets are lost if a BER (bit error rate) exceeds a certain value, say 10^{-3}, since one bit error destroys a packet. No matter how larger a BER is, it is still useful for the carrier sense. For example, even if a BER is 10^{-1}, the carrier sense succeeds, in other words, detects the carrier amplitude within one Manchester symbol with 90% probability. It does not matter that most of packets can not be received correctly. Our carrier sense utilizes this fact.

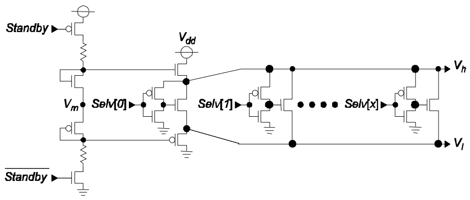

Figure 8. Schematic of voltage generator.

Figure 9 shows a concept of our carrier sense. In this figure, Node A transmits packets to Node B, and Node C is one of the interference nodes existing out of the carrier sense range of Node A. A received power is degraded as a distance increases. A threshold of signal intensity (P_{amp}) is fixed so that a certain BER is achieved. If a received data (P_{data}) from Node B is larger than P_{amp}, it means that Node B can correctly receive packets from Node A. In contrast, we set another threshold of carrier intensity (P_c) only to sense a carrier, and thus a quality BER is not guaranteed due to the weak received power. A carrier sensing range is determined by P_c. Note that P_c is smaller than P_{amp}. The BSAMP has a blind voltage range that is below a minimum input amplitude. In the BSAMP, we can adjust the value of the minimum input amplitude for P_{amp} and P_c. When a node senses a carrier, a threshold for P_{amp} is set in the BSAMP, while a threshold for P_c is set when a node is receiving packets. To lessen collisions at a receiver node, the carrier sensing range (r_c) should be larger than the transmission range (r_t). A smaller threshold for P_c enables a sender node to detect transmissions from other nodes existing around receiver node. This may prevent collisions considerably. On the other hand, a larger threshold for P_{amp} needs larger blind voltage range, which enables to detect only a large amplitude and suppresses small interference signals. Even if Node A cannot detect Node C's transmission, Node B can suppress the interference signal from Node C because its amplitude is smaller than P_{amp}.

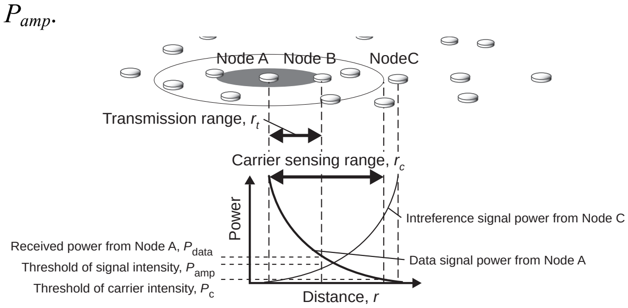

Figure 9. Carrier sense.

.D. Total Power Reduction

The power savings are summarized in Table 1. The standby power is less than 10^{-4} of the active one. To calculate the total power, we assume an activation ratio is 10^{-3}. We can achieve 54% saving in total when we utilize the proposed BSAMP in a sensor node

TABLE I

TOTAL POWER COMSUMPTION.

	Standby	Active			Total
		Sig. "0"	Sig. "1"	Average	
Conv.	167 nW	680 µW	628 µW	654 µW	821 nW
BSAMP	24 nW	278 µW	435 µW	356 µW	380 nW
Saving	86%	59%	31%	46%	54%

III. CONCLUSION

We have proposed the BSAMP (bistability amplifier) that is suitable for RF receivers in a WSN. The voltage gain is 26 dB. The standby and active powers are lower than the conventional inverter-type voltage amplifier by 86% and 31%, respectively. The operating power achieves 380 nW when an activation ratio is 10^{-3}. The proposed amplifier has a carrier sensing function without adding other circuits since it inherently has a minimum input amplitude to be amplified. This function is important to avoid collisions and interferences that cause needless communications.

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