A CMOS AC/DC charge pump for a wireless sensor network

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Abstract: An AC/DC charge pump implemented with MOS FETs has been presented for wireless sensor network applications. The proposed AC/DC charge pump can generate a stable output with low power dissipation and high pumping efficiency, which has been implemented in 0.13 μm CMOS technology. The proposed charge pump employs MOSFET diodes with low thresholds, and improves the conversion efficiency. The analytical model of the voltage multiplier, the simulation results, and the chip testing results are presented.

Key words: AC/DC; charge pump; wireless sensor network; CMOS
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1. Introduction

With the development of automatic identification and the enlargement of its application scope, it is requested that whole circuit blocks or a whole system is integrated into single chip as a system on chip (SOC) to increase chip function and reduce the overall cost of a whole system. The design for wireless sensor networks has become an important research subject in recent years. The energy supply problems for wireless sensor has a new method, that is around the use of UHF ultra high frequency electromagnetic waves get their energy to work in your environment.

A charge pump, also called a voltage multiplier, converts received AC or DC input voltage to a stable DC output voltage. Depending on the type of input, the charge pump can be classified as an AC/DC type or DC/DC type. Due to their simple structure and good conversion performance, charge pump circuits have been widely used in EEPROM, flash memories, Radio Frequency Identification (RFID), wireless sensor network and many other applications. In a transponder, a charge pump converts radio frequency energy to DC voltage as AC/DC type.

A typical AC/DC charge pump circuit is comprised of a capacitor–diode network[1]. The circuit pumps charge from the power supply to the output terminal stage by stage to increase the output voltage[2]. In order to increase the output voltage and conversion efficiency, Schottky diodes are generally used for their low conduction resistance and low junction capacitance. However, the particularity of the manufacturing processes for Schottky diodes and the inconsistency in quality between different product batches often makes the integration of the Schottky charge pump incompatible with standard CMOS circuits and thus limits its applications.

This paper presents a novel AC/DC charge pump for wireless sensor network applications. Instead of using expensive Schottky diodes, the proposed charge pump employs MOSFET diodes with low thresholds ($V_{\rm th}$) that are compatible with standard CMOS technologies. With a low-power output regulator, the proposed charge pump converts input radio frequency (RF) signal power into DC voltage with a high conversion efficiency and input-independence.

2. Analytical model of the AC/DC charge pump

The presented charge pump mainly consists of two blocks, a basic MOS charge pump and a low power regulator, which are connected in series. The former is to realize the AC/DC energy conversion with high efficiency and the latter is to stabilize the output DC voltage with low power dissipation.

2.1. Basic MOS charge pump

Figure 1 shows an AC/DC charge pump which utilizes NMOS FETs connected as diodes. Analyzing the initial unit voltage multiplying cell (UVMC) shown in Fig. 2, multiplying capacitor C_{n-1} and C_n can look like a pair of DC voltage sources. $C_{\rm A}$ is a coupling capacitor that combines input voltage $V_{\rm i}$ and V_{n-1}, with the voltage drop on C_{n-1}, to provide a recharging voltage for the next multiplier. Suppose Vd$_{n-1}$ is the voltage drop on NMOS FET M$n-1$, Vd$_n$ for Mn and $V_{\rm A}$ is the DC voltage at point A, under steady-state conditions, we have

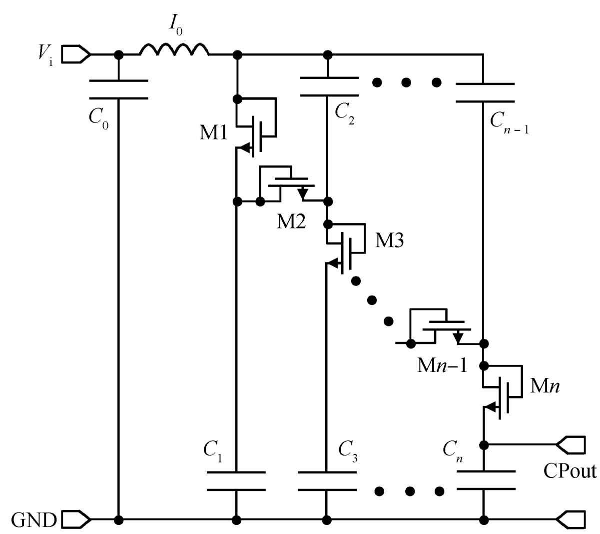

Fig. 1. Schematic of a basic MOS charge pump.

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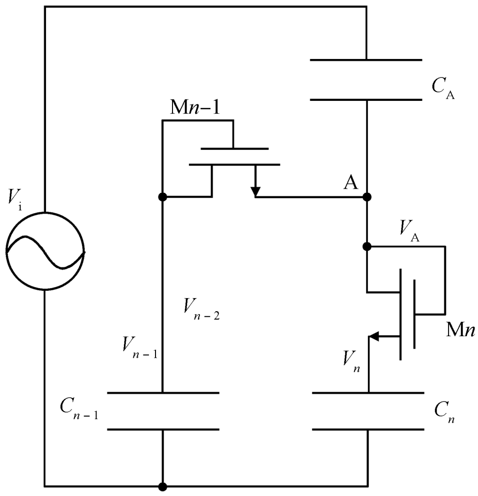

Fig. 2. Initial unit voltage multiplying cell.

$$V_A = V_{n-1} - \mathrm{Vd}_{n-1}, \quad V_A = V_n + \mathrm{Vd}_n. \tag{1}$$

If W/L of two MOS FETs is identical (both equal to I_{ds}), we have

$$\mathrm{Vd}_n = \mathrm{Vd}_{n-1} \quad \Rightarrow \quad V_A = \frac{V_n + V_{n-1}}{2}. \tag{2}$$

The actual input signal for M_n is $V_A + V_i$. Assume ΔV is the unit voltage increment, namely,

$$\Delta V = V_i - \mathrm{Vd}, \quad \frac{V_n + V_{n-1}}{2} + \Delta V = V_n,$$
$$\Rightarrow \quad V_n = V_{n-1} + 2\Delta V. \tag{3}$$

If re-defining a pair of MOS FET and capacitor as new UVMC, the stage number in Fig. 1 becomes two, namely,

$$\therefore V_n = V_{n-2} + 2\Delta V, \tag{4}$$

where $n = 2k+1$, k is the ordinal number of initial UVMCs and equal to 1, 2, 3…. With the same aspect ratio for all the MOSFETs in the charge pump, every ΔV would be identical. Iterate the above formula, and we have

$$V_n = V_{n-4} + 4\Delta V = V_{n-6} + 6\Delta V, \tag{5}$$

and finally, $\therefore V_n = n\Delta V$, which results in

$$V_n = n\Delta V = n\left(V_i - \mathrm{Vd}\right), \tag{6}$$

where n is the number of NMOS FETs and the circuit stage number. Equation (6) gives a mathematical expression for the charge pump output voltage. In RFID applications, due to the lack of input power, the output voltage and conversion efficiency of the AC/DC charge pump are hence the two primary performance parameters. One has to pay extra attention to tradeoffs affecting these parameters.

2.1.1. Output voltage

According to Eq. (6), with constant input signal power, augmenting stage number n and minimizing Vd are the easiest ways to increase output voltage. However, because the increase of the stage number is subject to degradation of power

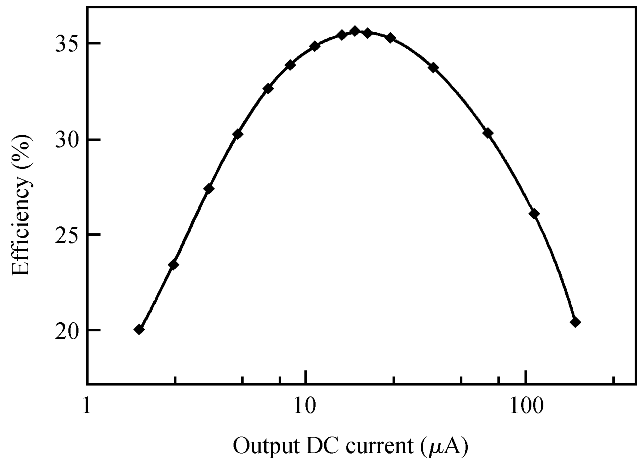

Fig. 3. Efficiency versus output DC current.

dissipation and conversion efficiency, the only feasible way is to lower the voltage drop Vd on every NMOS FET.

Due to a short connection between gate and drain, all NMOS FETs work in the saturation region, namely,

$$\mathrm{Vd} = V_{ds} = \sqrt{2I_{ds}/\beta} + V_{th}, \tag{7}$$

where $\beta = \mu n C_{ox} W/L$[3]. Obviously in a fixed output current I_{ds}, the bigger W/L and the smaller V_{th} are, the lower Vd is. As a result, in order to obtain a bigger output, a lower V_{th} MOS FET and a larger aspect ratio should be adopted. In the practical design, transistors with a low threshold voltage are used to obtain improved performance.

2.1.2. Conversion efficiency

The charge pump conversion efficiency is defined as

$$\eta = P_o/P_i = 1 - P_{loss}/P_i, \tag{8}$$

where P_i, P_o and P_{loss} is the input power, output power and circuit power loss, respectively. Because of RF, all multiplying and coupling capacitors are actually shorted, and every NMOS FET can be roughly modeled as a channel resistance R_c and a parallel capacitance C_p. In the course of multiplying, a NMOS FET is recharged in a positive half period and discharged in another. Therefore, a single transistor power loss consists of both recharging and discharging portions.

$$\begin{aligned} P_{loss} &= I_{re}^2 R_c + I_{dis}^2 R_c \\ &= \frac{1}{2}\left(\frac{V_i}{R_c}\right)^2 R_c + \frac{1}{2}\left(\frac{V_i}{|Z_{cp}|}\right)^2 R_c \\ &= \frac{1}{2}V_i^2\left(\frac{1}{R_c} + R_c\omega^2 C_p^2\right). \end{aligned} \tag{9}$$

It is evident that P_{loss} is smallest and η is largest when

$$R_c = \frac{1}{\omega C_p}. \tag{10}$$

In the saturation region,

$$R_c = \frac{1}{g_m} = \frac{V_{gs} - V_{th}}{2I_o}. \tag{11}$$

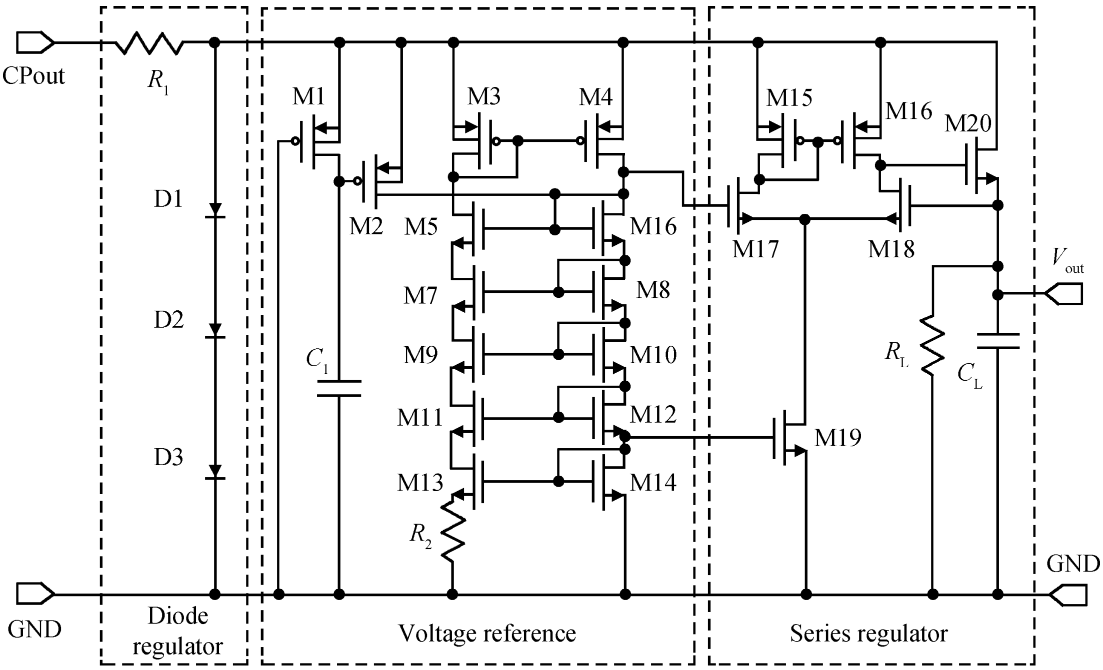

Fig. 4. Schematic of the low-power regulator.

Therefore, as shown in Fig. 3, there is a given output current I_o that corresponds to the largest conversion efficiency.

2.2. Low-power regulator for charge pump

Due to the variance between V_i, RF input signals with different power levels, modulation indexes and modes will generate quite different and even unstable output voltages through the charge pump[4], which is not desired for a steady DC supply in a wireless sensor network. For stabilizing the output voltage, Figure 4 presents a proposed low power regulator that includes a diode regulator, a voltage reference and a series regulator.

The diode regulator simply utilizes three series diodes to provide an elementary regulating strategy, which only confines a large output swing to a comparatively low but still apparent and unfavorable degree. For the two following portions, such pre-regulation is necessary and makes them work properly in an appropriate and acceptable supply swing range to produce a more precise and stable output.

To reduce power dissipation, the required high reference voltage, for example 1.6 V, is directly generated through a β self-biasing voltage reference instead of the conventional way to accurately amplify a pre-generated low reference voltage. As shown in Fig. 4, M5–M14 build up a five times cascade connection to increase output resistance and all operate in the subthreshold region for reduced power consumption. In the subthreshold region, the drain–source current[5] is approximately:

$$I_{sds} = I_{do}\frac{W}{L}e^{q(V_{gs}-V_{th})(nkT)}, \tag{12}$$

where

$$I_{do} = \mu_n C_{ox}\left(\frac{kT}{q}\right)^2 e^{1.8}. \tag{13}$$

If the W/L of M13 is made Q times larger than that of M14 and both have the same L, V_{gs} of M13 and M14 can be rewritten in terms of the current I_{sds} as

$$V_{gs13} = n\frac{kT}{q}\ln\frac{I_{sds}L}{I_{do}QW} + V_{th}, \tag{14}$$

and

$$V_{gs14} = n\frac{kT}{q}\ln\frac{I_{sds}L}{I_{do}W} + V_{th}. \tag{15}$$

In addition, we have

$$V_{gs14} = V_{gs13} + IR_2. \tag{16}$$

Solving for the subthreshold current I_{sds} using Eqs. (12), (14) and (15), we have

$$I_{sds} = \frac{nkT}{qR_2}\ln Q, \tag{17}$$

which is independent of the DC supply source and is much smaller, only in the order of magnitude of several dozen nA, than the current operating in a typical saturation region. With such a constant and small current, the voltage on the drain of M6 can be also stable and independent of the power supply. Moreover, for minimizing the RF input power, since such reference is expected to work under a power supply as low as possible, the current mirror load M3–M4 utilizes the low V_{th} PMOS FETs to reduce the requisite V_{ds} voltage drops as well.

A series regulator simply utilizes a differential amplifier and a negative feedback NMOS FET to make the output fixed on the given reference voltage. In order to achieve low-dropout regulation and ensure that M20 operates in the saturation region, a native transistor the same as the one in a basic charge pump and greatly large W/L are employed.

By far, through the multiplying of the basic charge pump and the regulating of a low-power regulator, input RF signals are converted into a stable and input-independent output, which can be used as the power supply for a wireless sensor network with good efficiency.

Table 1. Comparison between different reported CPs.

Parameter	Ref. [2]	Ref. [4]	Ref. [6]	This work (Basic CP)
Technology	0.18 μm CMOS	0.35 μm CMOS	0.18 μm CMOS	0.13 μm CMOS
Size (μm^2)	154 × 105	—	600 × 600	161 × 128
Clock frequency (MHz)	0.78	0.9	13.56	900
Input voltage (V)	2.0	—	0.7–1.3	0.08–0.4
Output voltage (V)	9.8	—	2.0–5.1	2.33–8.07
Loading resistance (MΩ)	54	1	0.1	0.1

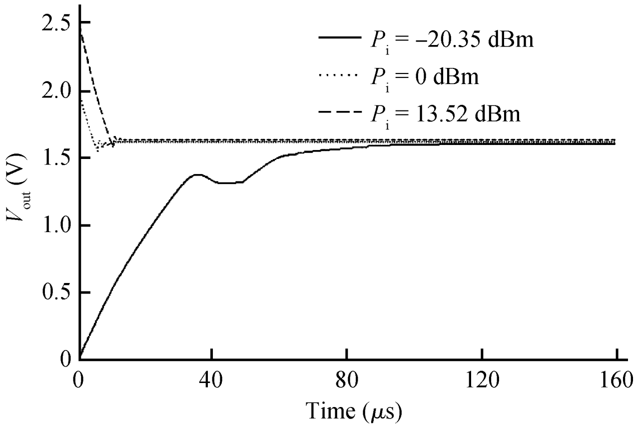

Fig. 5. Simulation results of the MOS AC/DC charge pump.

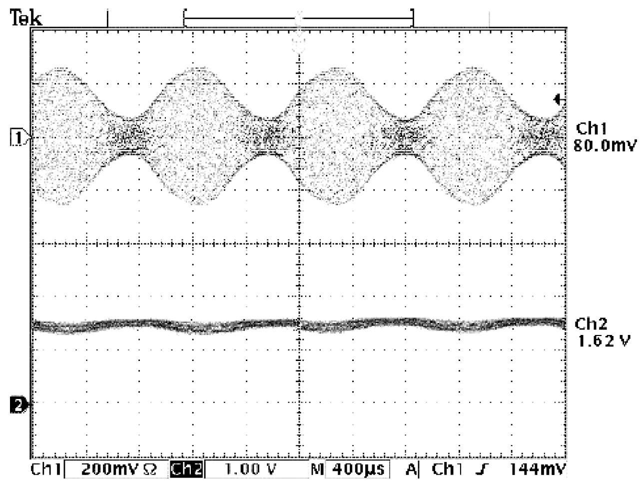

Fig. 7. Testing results of the AC/DC charge pump output voltage.

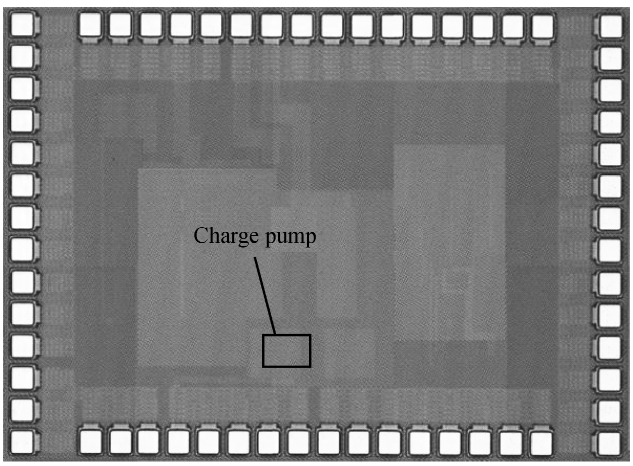

Fig. 6. Photograph of the presented circuits.

3. Simulation results

Figure 5 shows the simulation result of the output voltage of the proposed charge pump with different input signals. Based on the practical design demands, the output needs to reach 1.62 V with a 100 kΩ load resistor. Our simulation shows that with an input of 900 MHz RF, power changes from –20.35 to 13.52 dBm, the deviation of the output V_{out} from 1.62 V is less than 0.05 V. These simulation results have indicated that the presented novel AC/DC charge pump is capable of providing an efficient, stable and input-independent power supply for a wireless sensor network.

4. Fabrication and measurements

We have implemented the proposed circuits in a 0.13 μm CMOS. The chip photograph is shown in Fig. 6, which can be easily fitted into wireless sensor network chips. Meanwhile, it also provides good compatibility with various CMOS digital or analog integrated circuits. Figure 7 shows the testing result of the AC/DC charge pump output voltage. As Table 1 summarized, this work has a low input voltage, minimum loading resistance and the highest frequency; when the amplitude of the 900 MHz RF input signal is –20.35 dBm, the output voltage is stable at 1.62 V, and the obtainable largest conversion efficiency is still 22.42%, which is higher than the reported result in Ref. [4]. This agrees with the post-simulation results very well. These testing results have indicated that the presented novel circuit is capable of providing an efficient, stable and input independent power supply for a wireless sensor network.

5. Conclusion

This paper presents a novel power supply section of a wireless sensor network. Theoretical analyses and circuit simulations used for the design optimization have been presented. Proved by the chip testing, the circuit demonstrates the capability of generating stable and input-independent DC voltages as the power supply for a wireless sensor network. Using more stable and compatible MOS FET'S, these new circuits eliminate the process defects existing in the conventional Schottky diode based charge pump. The proposed circuits are hence more compatible with other CMOS circuits and can be used in a wireless sensor network.

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