Switched version of the Cockcroft-Walton charge pump for driving capacitive loads

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Abstract: - This paper presents a switched Cockcroft-Walton (SCW) charge pump designed for driving capacitive or low current resistive loads. The proposed charge shows great improvement in output voltage levels that it achieves, and in number of capacitors needed for reaching a certain voltage level. Also, it requires no additional clocking scheme besides the present single phase AC signal. The proposed SCW charge pump was simulated and compared with the CW charge pump.

Key-Words: - Charge pump, Driving capacitive loads, High-voltage generation, Voltage multiplier

1 [1]Introduction

Charge pumps are on-chip circuits used for generating voltage levels higher than voltage available from power supply [1]. One of the areas where they are commonly used, are the RFID circuits. More specific, the passive RFID circuits, which do not have power supply of their own, but they use the RF signal generated from the reader as power source. The power transmitted to the RFID tag in that manner, depending on the certain conditions such as reader-tag distance, sometimes is not sufficient to be used for powering of the circuit. This is the main reason for usage of *indirectly* powered circuits. The idea is that the tag „waits“, while the charge pump is charging [2]. When the voltage stored in pumps capacitors reaches predefined value, the control circuit discharges the capacitors allowing the tag to perform its function, usually sending the serial number. When used in *indirectly* powered circuits the charge pump sees only capacitive load which consists of output capacitor and capacitors in each stage of the charge pump. This opens a necessity to design charge pumps which are suitable to operate under capacitive load.

Another important aspect of the passive circuits and on-chip integrated circuits in general, is that they are to occupy the smallest area possible. Since the capacitors, with respect to the transistors, occupy the majority of the chip surface, their number is significant factor in scaling down the circuit size.

Fig.1 shows the circuit schematics of the 4-stage Cockcroft-Walton (CW) charge pump. The circuit consists of diode connected MOSFETs and pumping capacitors. The body of each MOSFET is connected to the ground (not shown in Fig.1). This is very simple design since it doesn't requires any additional clock signals or DC voltage levels. Drawback of this charge pump is the gain loss due to threshold voltage drop and by the body effects of the stage MOSFETs, as in (1).

$$V_{out} = \sum_{i=1}^{k} \left(V_{AC} - V_{tni}\right) + \left(V_{AC} - V_{tnout}\right) \qquad ,(1)$$

, where V_{tni} is a threshold voltage of i^{th} and V_{tnout} of the output MOSFET and k is the number of identical pre-output stages.

A more recent approach to charge pump development is usage of the switched capacitors circuits and heap charge pumps [3]-[5]. Both approaches are rather similar, and are based on charge pump design incorporating only capacitors and switches instead of diodes or diode connected MOSFETs. Those designs require up to four non-interleaving clock signals in order to operate switches, which must be able to completely

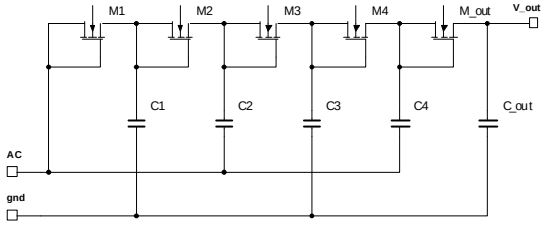

Fig.1 A 4-stage Cockcroft-Walton (CW) charge pump

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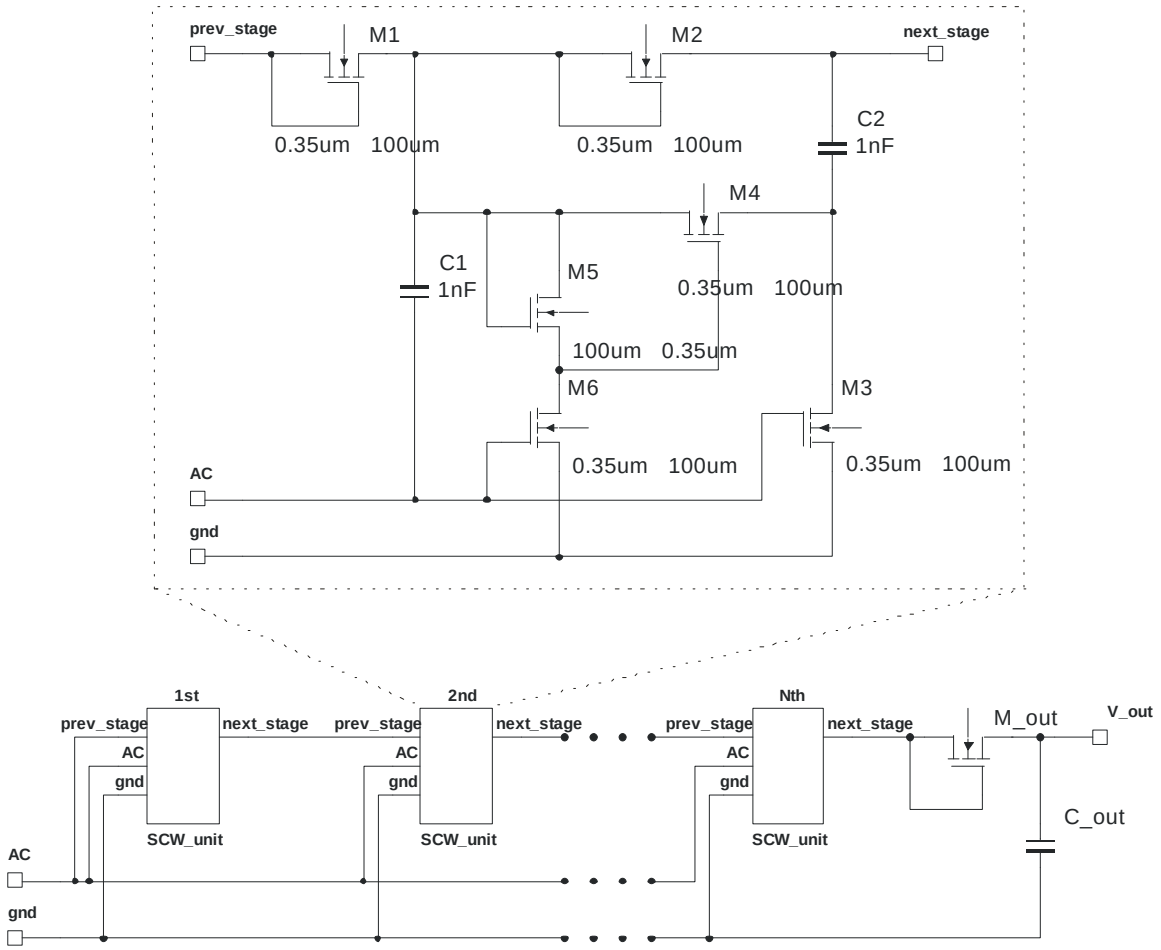

Fig.3 Switched CW charge pump unit

turn off and on in order to ensure the proper charge pump operation [6], [7].

In this paper we propose a version of switched Cockcroft-Walton (SCW) charge pump for driving capacitive loads. The design is fairly simple. The charge pump requires only the AC signal , with U_m greater than U_{tn}, which can be sine or square wave, as opposed to majority of reported charge pumps which require DC voltage and/or special clocking schemes [8]-[14]. No DC voltage is needed for this charge pump, what makes this charge pump suitable for usage in RFID tags, where only the RF signal is available for DC voltage generation.

2 Switched CW Charge Pump

In the switched CW charge pump two regular pumping stages are merged into one major pumping unit which, when modeled with diodes and switches, consists of 2 capacitors, 2 diodes and 2 switches, as shown on Fig.2. There are two operational states for this charge pump. In first, while switch S1 is closed and S2 opened, the charge pump charges as ordinary CW charge pump. In second state, when switch S1 is opened and S2 closed, the charge unit capacitors C1 and C2 are through switch S2 connected serially and the voltage passed to the next pumping unit is significantly higher.

The full charge pumping unit schematics is shown in Fig.3. Due to better clarity of the schematics, the connections between ground and the body of each MOSFET are not shown. M1 and M2 are diode connected MOSFETs which with capacitors C1 and C2 form a regular CW charge pump. MOSFETs M3 and M4 are used as switches S1 and S2, respectively. Two additional MOSFETs M5 and M6, are added to ensure that M4 (switch S2) can be completely turned on and off. In fact, M5 and M6 form an inverter driving stage for MOSFET M4, where the active load resistor M5 is made of a long MOSFET, keeping the power consumption minimal.

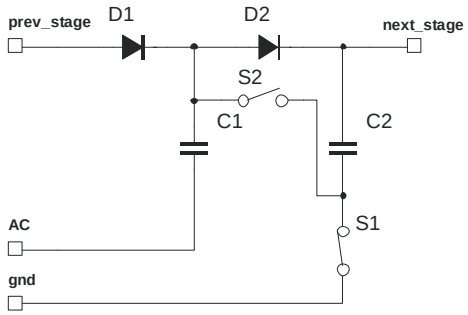

Fig.2 Switched CW charge pump unit modeled with diodes and switches

When M6 is turned on, the gate of the M4 is connected to the ground, thus M4 is turned off. When M6 is turned off, the voltage level of capacitor C1 is through M5 brought to the gate of the M4, hence turning it on.

This way, when AC signal is positive, the M3 and M6 are turned on, and the M4 is turned off. This is first operational state in which the charge pump charges as regular CW charge pump. When AC drops to its negative value, the MOSFETs M3 and M6 are turned off, M4 is turned on, and charge pump is in the second operational state where the heaped voltage (serially connected) from capacitors C1 and C2 is passed on the output of the pumping unit.

By cascading the SCW charge pump units a SCW charge pump with any even number of stages can be made, as shown in Fig.3.

3 Simulation

Simulation of the switched CW charge pump is done with Multisim 2001® software, using 0.35μm n-well CMOS level 49 SPICE models [15].

In the comparison between CW and SCW charge pump, the number of pumping stages is one of the parameters. Basically, the number of stages is equal to the number of capacitors in the charge pump, without the output stage. The SCW charge pump consists of charge pump units which are two pumping stages merged together. This is the reason why only the charge pumps with even number of stages were simulated.

By increasing the number of pumping stages, the voltage increases accordingly. For exclusively capacitive load, with no parallel resistive load applied to the output capacitor, comparison between output voltages of the SCW and CW charge pump, for a different number of pumping stages, and different values of the pumping capacitors, is given in Fig.4. The typical capacitance values for pumping capacitors in related papers [1]-[14] vary from 1pF up to 30 nF.

For SCW with 10 pF pumping capacitors can be seen the output voltage drop for 8-stage charge pump caused by power consumption of the additional MOSFETs added to the charge pump units.

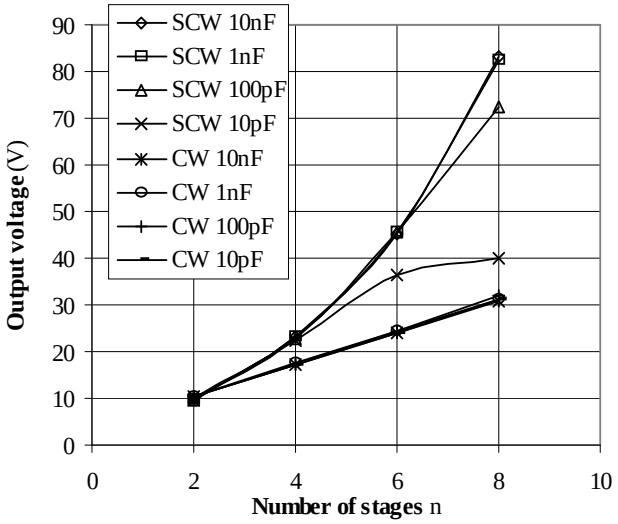

Fig.4 Output voltage comparison for SCW and CW charge pump for a different number of pumping stages, and different values of the pumping capacitors, V_{AC}=3.5V.

3.1 Output characteristics

The output characteristics V_{out} vs. I_{out} of the SCW and CW charge pump are compared. The both charge pumps are 8-stage charge pumps with 10 pF, 100 pF, 1 nF, and 10 nF capacitors, and the frequency of the AC supply is set to the 1 MHz sine wave. Amplitude of the AC supply voltage is set to 3.5 V. Results of the comparison are given in Fig.5.

The SCW charge pump is designed to work under capacitive or low current load. For that reason the output currents in Fig.5 are given in logarithmic scale, which gives better overview of the low current region.

3.1 Charging time

The significant factor in charge pumps which are used in indirectly powered circuits is the charging time. The charging times of the SCW charge pump presented in this paper and CW charge pump are compared, and the result are given in Table 1. Note that the charging time values in Table 1 are time values needed for a certain charge pump to reach the 90% of it's maximal output voltage which is much higher for SCW charge pump.

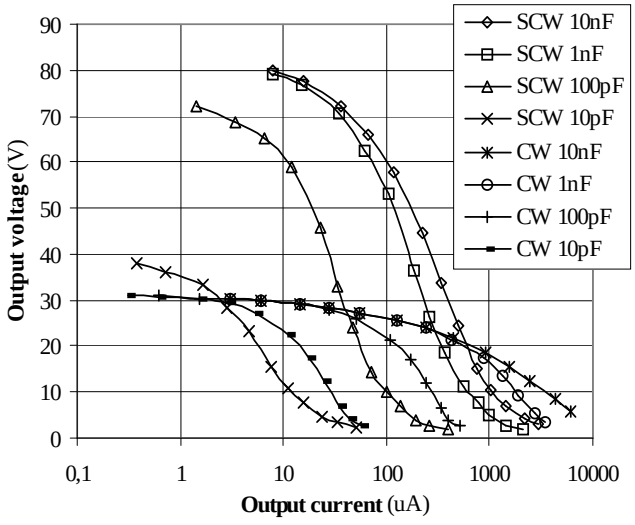

Fig.5 Output voltages of the 8-stage SCW and CW charge pump under different output currents, logarithmic scale, V_{AC}=3.5V

TABLE 1
CHARGING TIME FOR 90% OF MAXIMAL OUTPUT VOLTAGE [μS]

Number of stages *n*	10pF		100pF		1nF		10nF	
	CW	SCW	CW	SCW	CW	SCW	CW	SCW
2	7.2	11	9.3	19	31	82	320	1200
4	19	36	27	55	98	268	840	2400
6	42	90	52	150	177	465	1300	3500
8	72	138	99	408	260	1000	2000	7500

TABLE 2
OUTPUT VOLTAGES FOR SCW AND CW CHARGE PUMP FOR CHARGING TIME IN WHICH CW REACHES 90% OF ITS MAXIMAL OUTPUT VOLTAGE VALUE, V_{AC}=3.5V

Number of stages *n*	10pF		100pF		1nF		10nF	
	CW	SCW	CW	SCW	CW	SCW	CW	SCW
2	9.4	7.7	9.7	7.4	9.3	7.5	9.4	8.1
4	15.5	16.3	15.7	16.8	15.8	18.7	15.7	18.8
6	21.8	24.7	22	25.9	22	33.6	21.6	34
8	28.3	30	28.9	35.7	28	46	27.8	52

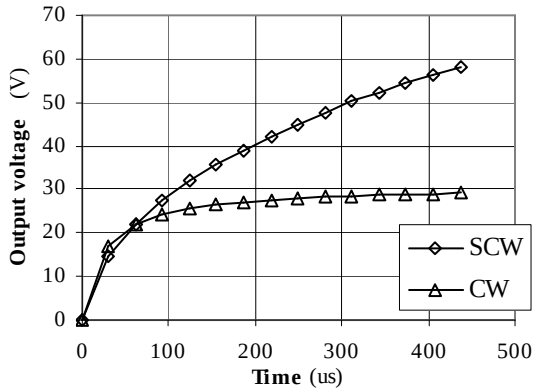

Fig.6 Output voltages in the charging process for 8-stage SCW and CW charge pump with 1nF pumping capacitors, V_{AC}=3.5V.

For better comparison between charge pumps Table 2 shows output voltage values for SCW and CW charge pump for charging time in which CW reaches 90% of its maximal output voltage value. The results in Table 2 show us that the SCW charge pump has improved performance also when the charging time is taken into consideration.

The charging processes for 8-stage SCW and CW charge pumps with 1nF pumping capacitors are given by Fig.6. Both charge pumps have approximately the same charging time (CW slightly better) until the CW reaches 70% of its maximal output voltage. After that the CW pump slows down charging toward its lower output voltage, and SCW continues charging much quicker.

4 Conclusion

The design we showed offers great save in number of capacitors needed for desired output voltage. To match the 8-stage SCW charge pump characteristics the CW charge pump would have to be at least 24-stage pump. This means that 2/3 of CW pumping capacitors can now be removed without decreasing the output voltage, what offers great chip area saving. Drawback of the SCW is that it cannot cope with CW when higher currents are needed. The best results of SCW are expected in driving low current, preferably capacitive loads, and indirectly powered circuits.

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