New architecture for remote powered wireless transmitter

Mohammad Hossein Sadeghi

Supervisors: Dr. Ir. C.J.M. Verhoeven Dr. Ir. G.L.E. Monna

Delft University of Technology Faculty of Electrical Engineering, Mathematics, and Computer Science Electronics Research Laboratory Systematic Design B.V., Motorenweg 5G, 2623CR, Delft, The Netherlands

Table of Contents:

Acknowledgements	6
Chapter1. Introduction	7
1-1. Overview	7
1-2. Design principle and structure	8
Chapter2. New Architectures of the remote powered win	reless
transmitter system	10
2-1. Introduction	10
2-2. Energy harvesting sources	11
2-3. Overall design structure	13
2-4. Beam energy sources	16
2-4-1. Artificial light source	16
2-4-2. Receiver power unit	18
2-4-2-1. Solar cell	18
2-4-2-2. Test setup, measurements result and decision	19
2-4-2-3. Solar cell model and simulation result	24
2-5. Power requirements	24
2-6. Power management system	25
2-6-1. Inductor base and Switched-capacitor base	25
2-7. Charge control unit	26
2-7-1. Energy storage devices	27
2-7-2. Voltage Sensor	28
2-8. Power consuming devices	28
2-8-1. Sensor	28
2-8-2. Modulator and Wireless transmitter	28
2-9. Artistic impression	30
Chapter3. Charge pump circuit design	31
3-1. Introduction	

3-2. Charge pumps circuits	33
3-2-1. Dickson charge pump	33
3-2-2. Improvement of the charge pump base on Dickson	37
3-2-3. Design and simulation of the proposed charge pump	
3-3. Anti-Phase clock frequency generator	41
3-3-1. Clock generator	41
3-3-2. Design specification and simulation result	44
3-3-3. Buffer circuit design	47
3-3-4. Charge control unit	49
3-5. New criteria of the dynamic gate control charge pump	50
3-5-1. Comparing different types of the charge pumps circuits	53
Chapter4. Conclusion and further work	56
4-1. Summery and further work	56

List of Figures:

Figure 1.Block diagram of the proposed remote powered wireless transmitter.	
Each subsystem is shown separately by dashed lines for clarity	.14
Figure 2.Top schematic of the front view, battom back view of the solar array	.20
Figure 3.The require devices for measurements	.20
Figure 4.I-V characteristics of the measured a-Si:H solar cell	.23
Figure 5.The equivalent circuit model of the solar cell	.24
Figure 6.The conceptual design of the wireless/remote transceiver system	.30
Figure 7.Block diagram of the proposed architecture of the power management	t
system which is connected to the solar cell model and output load capacitor	.32
Figure 8.Schematic of the Dickson charge pump is depicted in 7-a and node	
waveforms is depicted in 7-b	.34
Figure 9.Schematic of the statically gate control charge pump circuit [21]	.38
Figure 10.Dynamically gate control charge pump circuit [21]	.39
Figure 11.Schematic of the three stages ring oscillator	.45
Figure 12.Waveform of the proposed three stages ring oscillator	.46
Figure 13.Basic schematic of the buffer circuit	.47
Figure 14.Output waveform of clock generator	.48
Figure 15.First three stage of the proposed charge pump circuit	52
Figure 16.Output waveform of the adaptive charge pump circuit when the switc	h
is closed after 6 μs	.55

List of the Tables:

Table 1.Approximate amount of the energy of the micro-harvesting energy
sources [1] [9], [11]12
Table 2.Drawbacks of different harvesting technology 13
Table 3.Comparison of the different design structures and functionality in the
micro-solar power system15
Table 4.Compares features of LASER vs. LED [35]17
Table 5.Measured and simulated external parameters of a 300 nm a-Si solar cell
under AM1.5* illumination, in this table "Sim" refers to computer result and "Exp"
is denoted for experimentally result [2]19
Table 6.Measured, external parameters and type of the LED sources22
Table 7.Measured, external parameters, and type of the LASER sources result 22
Table 8.Estimation power of main blocks in remote power wireless transceiver.25
Table 9.Comparisons between inductors base and switched capacitors
converters [4], [11]26
Table 10.Comparisons between batteries and capacitors
Table 11.Comparisons of the different architectures of the transmitter
Table 12.Estimated power consumption of the remote powered wireless
transmitter
Table 13.The specification value for design of the charge pump circuit40
Table 14.Measurements result of the a-Si:H solar cell (300 μm ,DIMES process)
Table 15.Size of the transistors in inverter circuits 46
Table 16.The values of the switching transistors in charge pump circuit51
Table 17.The values of the inverter transistors for gate control of the switching
transistor
Table 18.Comparing test result of the well-known charge pump base on Dickson
Table 19.Summery of the design devices of the remote powered wireless
transceiver

Acknowledgements

I would like to thank my wife for always give me self-confidence and providing the best situation for me.

I would like to thank my parents for always providing me with platform for my work and study. Moreover, they always support me.

I would like to thank my sister and brother for always giving me some suggestion and advice.

I would like to express my appreciation to my supervisors Dr. Ir. C.J.M. Verhoeven and Dr. Ir. G.L.E. Monna for their patient, feedback, technical assistance and wonderful advices.

I would like to thank my friends at TUDelft for their invaluable guidance and support. A special thanks to my dear friends Arash noorozi, Armin Noroozi and Abbas Haddadi for their encouragement and helpful advice during my studies.

Chapter1. Introduction

1-1. Overview

Satellite and space projects and researches are complex and very expensive. Therefore, there are some of the important issues that should be considered in space applications due to the high cost and complexity of the satellite. We can reduce the mass, cost, and complexity of the satellite by transmitting power wirelessly instead of using traditional wire connections.

Using artificial light-solar cell power transmission, it may possible to build wireless sensors in satellite. Artificial light (Light Amplification by Stimulated Emission of Radiation (LASER), Light Emitted Diode (LED), etc) can be considered as a source of energy instead of ambient solar energy due to advantages such as integratability in semiconductor, no power variation and low divergence angle [13], [36]. The average artificial light beam must be significant to generate the power to feed all user-ended devices in the satellite. The reason for using the artificial light as source of power transmission is to avoid the disadvantages of the microwave transmission such as high mass, high fabrication cost, power concentration and their difficult to control in case of failure [32].

Powering devices using the solar cells is one of the important topics in space and satellite applications. The recent developments in micro power energy harvesting especially in micro-solar energy, gives new abilities to designers and scientists like lower area, reduced maintenance cost, etc [3]. However, the power efficiency of the solar cells are still low [2].

Commonly, any micro-solar power system consists of the following components: receiver power unit, power management system, charge control unit and power consumer devices [3], [4], [7].

7

Various sensors (light, temperature, vibration, etc) can be integrated on the satellite depending upon the application and functionality of the system. Theoretically, any sensor can be attached to a wireless transmitter but, as the first step toward developing the system, temperature sensor is targeted, because of its low power consumption and simple structure [23].

Recent technological advances in sensors and electronic devices, energy harvesting sources, energy storage and Micro Electro Mechanical System (MEMS) devices are becoming popular in the industry. They have small size, low cost and low power consumption [1], [4], [12]. However, the power supply system still requires the traditional wire connection. Power consuming electronic devices are increasingly common in electronic devices and applications by increasing the functionality. As a consequence, more wire connections are required in the system which increases the mass, cost, area and complexity of the system.

Wireless power transmission links between artificial light source (LASER or LED) and a distance receiver system. As proof-of-concept the transmission distance is about 10cm and modulated data is transmitted optically to avoid any interference with other electromagnetic signals.

Furthermore, this system can be used in large fridge, cave, etc which is hard to reach. The sensor is placed in different area for measurements. We can receive the data and required information by pointing light to the sensor

1-2. Design principle and structure

This research focuses and discusses the new architecture for a remote powered wireless transmitter. The three following chapters will cover all requirements which are required for this application. Chapter 2 contributions to the advancement of the remote power receiver and wireless transmitter system level design. This system divided into four main subsystems and a light energy source. We will show how each of the four main subsystems can be modeled. These subsystems identify different design choices.

All the subsystem and design consideration are explained separately. The description of the various components, measurements and test results are discussed. At the end, the associated trade-offs in the new architecture to other design and the summery of the required powered in selected designs are included. Finally, we presented the new architecture which is fully integrated in CMOS technology. Based on this system level design, Chapter 3 is dedicated to detail of the power management subsystem which consists of the charge pump with integrated clock frequency generator. Advantages and disadvantages of the charge storage devices are included. The design and simulation results of the clock generator of the charge pump circuit are depicted. Furthermore, the adaptive dynamic gate control charge pump is designed and simulation results are discussed. At the end, the operation and comparisons are included. In chapter 4 the overall properties of the remote powered wireless transmitter are summarized and future work is discussed.

The proposed circuit is based on 0.13 μ m UMC technology and all simulations have been done by Cadence, Spectre, CAD tools.

Chapter2. New Architectures of the remote powered wireless transmitter system

2-1. Introduction

The incident light spectrum from ambient or artificial light is converted to the DC supply voltage in the power receiver unit. This supply voltage is used by all active devices on the remote powered wireless transmitter. The voltage level can be too low to turn on sensor and transmitter devices. Therefore, a power management unit is placed after the power receiver unit. This unit increases the voltage level of the solar cell. All devices can be activated by this voltage level in the power consumer unit.

There are different structures to transmit the output signals such as light and microwave, wires, etc. Light is selected for the proposed structure. Part of incoming light is available for modulating. The modulated data is transmitted by light which is provided by part of the incoming light. The modulated data is transmitted to an optical receiver. Then, outgoing light is received by an optical receiver for further consideration.

Since, power consumption heavily influences various design decisions, we tailor our decision towards the use of very low power devices and use integrated and MEMS devices to reduce the size and power consumption of the system.

LASER and LED were selected to avoid the variation of the solar input energy. Several types of LASER and LED light are measured to find the best power efficiency for the system. The measurement setup, result, and model of the integrated solar cell are provided. Furthermore, power management system and control unit devices are explained. At the end, the new architecture is applied for the power consumer devices such as sensor and transmitter devices. Finally, the trade-offs of different transmitter architectures are summarized briefly and artistic impression is described.

2-2. Energy harvesting sources

Micro-power devices are getting more attention in energy harvesting technology due to improvement in the cost, area and power consumption [3]. Micro-power devices have been designed to consume low power. The power levels of these devices are almost the same level as the power that is provided by the micro-energy harvesting energy. Energy harvesting is defined as transferring the ambient energy into effective electrical energy which is provided to consumer power devices [1], [11].

A number of projects have been done to develop the energy harvesting technology to generate sustainable power. Micro-solar power harvesting gets the most interest due to low cost, simplicity and ease of integration [3]

There are different types of micro-energy harvesting sources such as light, motion/vibration, thermal, Radio Frequency (RF) micro wave, etc. These sources are typically used in sensors, wireless transmitters, displays and Radio-Frequency Identifications (RFID) applications [1], [11], [23].

These sources have different behaviors and characteristics in energy harvesting technology. Some of the energy harvesting devices such as photovoltaic cells, Thermo Electric Generator (TEG), piezoelectric devices and RFID were tested and analyzed for their electrical properties under different conditions [1], [4], [9], [11].

Since the entire energy of the electronic circuit must be provided by micro-energy harvesting, the choice of energy of micro-energy harvesting source is very important. Table 1 shows an approximate amount of energy pointed by each of the micro-energy harvesting sources [1], [4], [9], [11].

Table 1.Approximate amount of the energy of the micro-harvesting energy sources [1], [4], [9], [11].

Micro-energy	Challenge	Energy	Estimated output
harvesting sources		generator	power density
		components	$\mu W/cm^2$
Light	Light intensity	Solar cell	10
		(indoor)	
		Solar cell	15000
		(outdoor)	
Thermal	Temperature	TEG	15-40
	differences		
Vibrations/Motions	Variability of	Piezoelectric	1-330
	vibration	cells	
RF/Micro Wave	RF emission	Transmitter	0.1-100

Solar radiation energy is one of the most abundant sources of energy and provides the highest power density in this technology. Solar cells generate electricity by converting light energy within the *n* and *p* layers of the material. Generated power depends on light intensity, fabrication material, etc. [4], [9], [11]. TEG is base on the "Seebeck" effect and in which a voltage is generated from a temperature difference between two different semiconductors or metals within a p-n junction. These are connected thermally in parallel and electrically in series to generate electricity. Generated power depends on the size of the TEG and requires a large sustained temperature gradient between two surfaces [4], [9], [11].

Vibration/Motion energy is based on piezoelectric, electrostatic or electromagnetic mechanism to generate electricity. For example, electromagnetic generators may use a coil and magnet to generate the electricity. Generated power is sensitive to amplitude and surface frequency of the generators [4], [9], [11].

RF power is based on using the surrounding RF signals and an RF to DC converter that generates a DC voltage. Generated power depends on the

radiated power of the RF signal and the distance between the transmitter and receiver. For example RFID tags use RF energy to power up the electronic circuits.

The drawbacks of other harvesting technology compare to the micro-solar harvesting technologies are shown in Table 2.

Table 2.Drawbacks of different harvesting technology compare to solar harvesting energy

RF Vibration/motion		Thermal	
Cost, area	Sensitive	Hard to generate	

Beam power and microwave are two promising technology for the future of the wireless power transmission. Beam power has advantages compare to the RF such as mass and cost. These reasons make it the modality of choice for use in micro-solar power system. This system is going to be used in space and satellite applications.

2-3. Overall design structure

Several universities and institutes have designed and developed micro-solar power systems for different applications and functionality. These systems have different specifications and requirements such as cost, simplicity, lifetime, flexibility, etc.

There are several considerations in the design of the micro-solar power management subsystem for the energy harvesting supplies. The first task is the trade-off between the output power of the solar cell voltage and current level and power level of the consumer devices. The next consideration is to reduce the dependency of the power management devices on the power supply by regulating the supply voltage. The regulator generates constant voltage or current that is independent of the source or load variation. Furthermore, low threshold voltage transistor and low voltage supply should be considered to reduce power consumption and losses by the power management devices [11]. Commonly, any micro-solar power system consists of the following components: receiver power unit, power management system, charge control unit and power consumer devices [3], [4], [7].

In the new architecture, the solar harvesting energy is provided by artificial lighting (LASER or LED). The light energy is collected by a-Si:H solar cell and converted to electrical energy and that is made available for the remote powered wireless transmitter.

The solar cell voltage is too low to operate all active devices in power consumer unit. As a consequence, power management system generates a higher level supply voltage than input solar supply voltage. Then, all active devices in the power consumer unit will be activated. Transmitter operates continuously when artificial light is available and turns off when there is no lighting.

Block diagram of the proposed remote powered wireless transmitter is shown in Figure 1 and divided to four units by dashed lines.



Figure 1.Block diagram of the proposed remote powered wireless transmitter. Each subsystem is shown separately by dashed lines for clarity

There are different structures to design the micro-solar power system. Different design aspects and flexibility are considered in [7], [8] which are the two leading designs in the micro-solar power system. This circuit is operated by a two level

charge energy storage and software program that controls the charging time of the rechargeable battery. Simple structure and high functionality are considered in [9]. The hardware control used to control the charging a battery and this circuit is operated by a single-level storage. Proof of the ultra low power RF transmission is explained in [4]. They have used the single-level charge storage capacitor and charge control unit to activate the RF circuit. However, these previous circuits have a limitation in performance and efficiency but they work correctly under a certain set of conditions [3].

In our proposed circuit we used a single level charge storing capacitor which is controlled internally by the voltage limiter circuit. The proof of concept and simplicity is considered in this architecture.

Comparison of different design structures and functionalities of the micro-solar power system are shown in Table 3.

Related works	Challenge	Design Structure	Energy
[7],[8]	Flexibility, lifetime,	Two level storage,	Solar
	maintenance	battery	
[9]	Simplicity	One-level storage,	Solar
	maintenance	battery and	
		capacitor	
[4]	lifetime	One-level storage,	Solar and
	Proof of concept	capacitor	Vibration
This work	Simplicity, lifetime,	One-level storage,	LASER and
	flexibility, low cost	capacitor	LED

Table 3. Comparison of the different design structures and functionality in the micro-solar power system

There are some differences between the proposed architecture design and previous works which have been done. We summarize some of the differences as following: First, artificial lighting is used as a source instead of the ambient solar energy. Another is that the charge control unit is only used to monitor the voltage level of the energy storage unit to make sure the voltage level is sufficient to activate the power consumer devices. It means that, there is no control unit circuit to control the charge pump frequency through hardware or software interfaces.

We target applications for which the output voltage of the solar cell will be in the range up to the 560 mV which is achievable by a-Si:H solar cell. This value is large enough to activate the system without any start up circuit or external battery. The unregulated voltage is buffered and then transferred to the charge pump circuit as input supply voltage. The charge pump circuit has high conversion voltage ratio which steps up the voltage to more than 2.7V (the minimum operating voltage for the sensor and transmitter devices is 2.5V). Charge storage device stores the sufficient energy until the voltage level reaches to 3.5V. The charge control unit monitors this voltage level and control the switch which can only close once the system voltage exceeds 3.5V. The sensor, modulator and transmitter devices wait until the voltage passes 3.5V and energy rail to this unit. The output voltage of the charge control unit decreases and stops on 2.7 during the operation because the providing energy is equal to the consuming energy in this time. Then, all active devices start to operate and transmitters transmit the data wirelessly. The sensor and transmitter operating until the light directed onto the cell.

2-4. Beam energy sources

2-4-1. Artificial light source

Recently, ESA, NASA, ENTECH, and some universities have been working on wireless power transmission using LASER radiation to transfer energy to enduser devices [13]. This technology has been used in a solar-rover [31], solar plane [31], distributed wireless sensor network [12], sensors [12], etc. Laser-solar cells remote/wireless power transmission is a technology that uses a laser beam to power solar cells, which then convert the laser power beam into electricity [13]. The advantages of the LASER over sun light are integratability in semiconductor, no power variation and low divergence angle. Furthermore, the angle at which light is incident to the solar cell does not produce the significant losses in transmission. Also, in a few studies, remote power transmitter is using the LED as a source [36].

In this new architecture, LASER and LED both are used to illuminate solar cell to transmit remote power.

Advantages and disadvantages of each light source are summarized in Table 4 for better understanding [35].

source	Advantage	Disadvantage	
LASER	Low Cavity, high power,	Lift time	
	coherent		
LED	Easy to drive	Output power limited,	
		incoherent, High cavity	

Table 4.Compares	features o	of LASER v	s. LED [35]
------------------	------------	------------	-------------

LASER illumination has a degrading effect on the cells and this effect will reduce the efficiency of a solar cell [2]. In our system, this degradation has very small effect to the efficiency of the cell due to the fast transaction between receiver and transmitter. We have to match the output power of LASER or LED with all active devices in the proposed remote powered wireless transmitter. We have done some measurements. The measurement have done base on both light beams due to cost and availability of these lights.

2-4-2. Receiver power unit

In our architecture, receiver is integrated into CMOS technology and consists of an a-Si:H solar cell and a capacitor as buffer. The buffer is placed after the solar cell. This entails converting an unstable limited energy current source into stable limited energy current supply.

Types of the solar cell, light wavelength and the power of the artificial light have great effect on efficient and integrated design. These differences provide different choices in the architecture for transmitter system base on power generated by solar cell.

2-4-2-1. Solar cell

The solar cell can be fabricated from a wide variety of materials such as silicon (Si), Gallium Arsenide (GaAs), etc [2]. These devices are used for power generation in terrestrial, as well as military, commercial, research and space application [2], [14]. Commonly, a-Si solar cell are used in satellite and space mission as power generator, although recently GaAs has also used in satellite and space application because of high efficiency compared to other material. However, this material increases the cost and mass of the system due to larger size and thickness [2]. A-Si:H solar cell good choice for satellite and space application because of the low cost, small mass and are relatively radiation hard [2].

The life time and efficiency of these solar cells have great effect in system design structure in space application [2]. Furthermore, they are well suited for applications that used artificial lighting as a source [4], [33].

We used the a-Si:H solar cell which is fabricated in DIMES (Delft Institute of Microsystems and Nanoelectronics). The measurements result and the characteristic of this cell is shown in Table 5 [2].

18

Table 5.Measured and simulated exterr	nal parameters of a 3	00 nm a-Si solar cell	under AM1.5* illumination,
in this table "Sim" refers to com	puter result and "Exp'	is denoted for expe	rimentally result [2].

Thickness (nm)	300	
Туре	Ехр	Sim
$V_{oc}(V)$	0.85 ± 0.01	0.86
$J_{sc}\left(\frac{A}{m^2}\right)$	140±1	140
FF	0.713 ± 0.01	0 728
Efficiency (%)	8.53 ± 0.02	872
Area (mm ²)	1	6

* AM1.5 (air mass 1.5; illumination with an intensity of 100 $\left| \frac{mW}{cm^2} \right|$)

2-4-2-2. Test setup, measurements result and decision

We have to match the output power from the LASER or LED with all active devices in the proposed remote powered wireless transmitter. For this reason we have done some measurements to find the best criteria for choosing the LASER or LED.

LASER and LED were selected based on cost and availability for demonstration and measurements. Our sources are located at distance of 10cm from the center of the solar cell which is also placed in small satellites. Safety goggles were worn when using the LASER pointer or diodes.

The experimental conditions for all tests were at room temperature in a laboratory in the EWI building in near complete darkness. The set up measurement is placed in a dark box and the ambient light in the room was minimized to reduce any error in measurement and disturbances.

A-Si:H solar cells are fabricated on $300 \,\mu m$ device layer in DIMES technology and have average efficiency of 8.6%. We used a minimum size solar cell for our measurement and covered all the remaining area of the solar cell. The minimum area of the solar cell is 16mm^2 and we prefer to avoid off chip devices in the proposed system. The front view and back view of the cell is shown in Figure 2.



Figure 2. Top schematic of the front view, bottom back view of the solar array

The test setup consists of an array of a-Si cells, ammeter, voltmeter, different light sources such as LED's diode, LASER. The measurement devices and instrument are shown in Figure 3.



Figure 3.The require devices for measurements

We set up the connection between the cell and the ammeter and voltmeter to measure the external parameters of the solar cell.

Up to fourteen voltage and current reading points were taken during the experiment to achieve the highest average output power and current-voltage characteristics (I-V). The measurement results, external parameters and model of the LED and LASER devices are depicted in Table 6 and 7, respectively.

Light	MC053SBLC	LC503FWH1	TLYH190P(F)	MCL053SWC-	TLC5800
Source				YH1	
V _{op.} (v)	3.4	3.2	3.10	3.4	2.7
I _{op.} (mA)	20	20	50	20	50
V _{oc} (V)	0.682	0.720	0.692	0.612	0.677
I _{sc} (μΑ)	550	570	230	550	500
Color	Blue	White	Yellow	White	Red
Intensity	25000	24000	30000	10000	7500
(mcd)					
View	16	15	4	16	4
Angle [°]					

Table 6.Measured, external parameters and type of the LED sources

Table 7.Measured, external parameters, and type of the LASER sources result

Light Source	ADL-	DL-	ADL-	ADL-	Laser
	65055TL	65054TL	65075TR/L	80Y01TL	155
V _{op} (V)	2.5	2.5	2.5	1.9	220
l _{op} (mA)	10	10	10	10	25000
V _{oc} (v)	0.701	0.313	0.542	0.540	0.750
Ι _{sc} (μΑ)	8	3	1	1	100
Color	red	red	red	red	red
Power(mW)	5	5	10	200	50
Wavelength(nm)	650	635	655	808	635

The maximum output current and voltage of the solar cell can be calculated by the following formula [2]:

$$FF = \frac{P_{mp}}{I_{sc} * V_{oc}}$$

$$FF \approx 0.7(\text{constant})[2] \Longrightarrow P_{mp} = 287.28 \mu W$$

$$I_{sc} = 570 \mu A$$

$$V_{oc} = 720 m V$$

$$(1)$$

Where, P_{mp} is maximum power that can be generated by solar cells. I_{sc} is a short circuit current, V_{oc} is open circuit voltage and *FF* (Fill Factor) is the ratio of maximum power over multiplication of I_{sc} and V_{oc} .

Equation (1) shows the maximum output power of the solar cell is $287.28 \,\mu W$ under LED light illumination. This power is able to cover all the required power in our system.

We have found the highest output power by using the *LC503FWH1* LED diode and the I-V characteristics of this cell is shown in Figure 4.



Figure 4.I-V characteristics of the measured a-Si:H solar cell

2-4-2-3. Solar cell model and simulation result

In order to determine the power capability of the solar cell, the circuit model of the solar cell is considered which is shown in Figure 5.



Figure 5.The equivalent circuit model of the solar cell

The model consists of photon current source (I_{photon}), a diode, shunt resistance (R_{Shunt}) which represents the losses due to the diode leakage currents and series resistance (R_{S}) which represents the ohmic contact losses in the front surface of the solar cell [14]. This circuit model is considered for further simulation.

A single capacitor can minimize the ripple between minimum and maximum output voltage of the solar cell. This capacitor acts as temporarily buffer in the new micro-solar power system.

2-5. Power requirements

The power budget of system must be considered in the early stage of the design to have an efficient and practical design. Due to small amount of the output energy available from the power receiver unit, the power consumption of each block must be minimized to arrive at an acceptable efficiency. For this reason we will review the power budget of each block regarding to the previous researches and literatures that is shown in Table 8.

units	Power consumption(μW)
Power management circuit	80
Charge control unit	5
Power consumer devices	27
Total	112

Table 8.Estimation power of main blocks in remote power wireless transceiver

The new architecture was employed to achieve lower power consumption than estimated power consumption and provided very high level of integration.

2-6. Power management system

Power management system is one of the important subsystems in micro-power integrated circuits. There is a large difference between the output voltage level of the power receiver unit and required input voltage supply of all the devices in power consumer unit. Therefore, matching the solar cell voltage with the power consumer devices is very important and the voltage converter performs this function. Typically, converters are based on inductor or switched-capacitor such as a charge pump [11].

2-6-1. Inductor base and Switched-capacitor base

There are different types of converters which are based on inductors such as buck, boost, buck-boost, etc. In this type, the energy is stored in the magnetic field of the inductor. The basic function of the boost voltage converter is to convert the low voltage level on the input to a high voltage level on the output. In many applications, a coupled inductor is also used to step up the voltage of the converter [11]. Usually inductor base converter requires a large inductor to provide sufficient voltage level which increases the cost and area [4], [11]. Charge pump is based on switched-capacitors and collects small amount of energy from the energy sources in a capacitor and pumps these charges into another capacitor toward the load. The frequency of charging and discharging cycle and polarity of the capacitors determine the voltage of the next charging capacitor [11]. In the ideal case the output voltage can increase up to the number of stages multiplied by the input voltage supply. Charge pump has lower efficiency regarding to the leakage current.

Table 9 shows the overall comparison between inductor base and switched capacitor base converter.

Converters type	advantages	Disadvantages
Inductor base	✓ Efficient in arbitrary	> Area
	condition	➢ Cost
		Off-chip
		reliability
Switched-	✓ Ease of integration	Not efficient in some
Capacitor base	✓ Area	condition
	✓ Cost	Leakages
	✓ On-chip	

Table 9. Comparisons between inductors base and switched capacitors converters [4], [11]

Charge pumps have significant advantages over inductor based such as cost, area and ease of integration. A charge pump circuit was used as converter in propose system.

2-7. Charge control unit

2-7-1. Energy storage devices

The energy storage is group of storage elements such as rechargeable batteries (NiMH, NiCd, Lithium (ion / polymer), super capacitors and capacitors. These elements are desirable for the micro-solar power system [4], [7-9]. These devices are used to store the energy coming from power receiver unit and deliver energy power management system and charge control unit.

Different energy storage elements have different charging profile and mechanism. Capacitors have simpler charging profile compared to the batteries and in some application the charging battery also requires a capacitor [3], [4], [7]. We should consider the system requirement such as efficiency, lifetime, capacity, size, maximum current draw and leakage for comparing the rechargeable battery and capacitor. Table 10 shows the differences between batteries and capacitors.

Energy	advantages	disadvantages
storage		
devices		
Battery	✓ high energy density	 limited charge and discharge cycle reliabilities limited lifetime temperature
Super cap or cap	 ✓ unlimited charge and discharge cycle ✓ lifetime ✓ Area 	medium capacity

Table 10. Comparisons between batteries and capacitors

Because our new wireless transmitter devices do not need much energy storage, and because the lifetime of the remote powered wireless transmitter is concern, a capacitor was used. In some applications, the regulator is placed after charge control unit to generate constant-current, constant-voltage to charge the battery or direct connection to the power consumer devices. In this case, power consumption of the regulator has to minimize.

2-7-2. Voltage Sensor

The voltage sensor is used to control the switch between charge control unit and all active devices in power consumer unit. When the capacitor charges reaches a pre-specified level, the switch closes and the input supply connected to the power consumer devices such as sensor, modulator, and transmitter devices.

2-8. Power consuming devices

2-8-1. Sensor

Temperature is one of the parameter in design which has more effect on electronic devices. We chose the temperature sensor because of its large effect in electronic devices. The temperature sensing has been done by using a temperature dependent oscillator. We have chosen a temperature dependent oscillator due to its simplicity and low power consumption as sensing element in propose system [23].

2-8-2. Modulator and Wireless transmitter

There are different types of modulation and transmitter techniques. In proposed system the modulation is done by duty cycle and requires minimum 10 duty cycles for modulating and wireless transmission is considered.

Typical wireless transmitters require many power hungry blocks such as voltage controlled oscillator, phase detector, frequency divider, mixer, etc.

In new architecture employs micro-mirror MEMS, liquid crystal display (LCD) modules and temperature dependent oscillator. These elements were used to reduce the number of elements and power consumption of the transmitter. The LCD turn on and off by the output of the temperature dependent oscillator and acts as an optical switch. The LCD acts as switch if a polarized filter is placed in front of the LCD. In this application, the reflected incoming light is modulated and data will transferred by modulating the incoming light. There are different architectures possible in transmitter design application. The advantages and disadvantages of other architectures compare to the new architecture are shown in Table 11 [11].

Transmitter architecture	advantage	disadvantage
RF	Wireless	High cost, interfering,
		noise
Organic Light Emitted	No interfering,	Medium size, cost
Diode (OLED)		
MEMS mirror	stability, no interfering,	High voltage
	small	(efficiency of solar cell not in
		the expression)
LCD	Low power consumption,	Required polarization
	stability, no interfering,	filter, temperature
	small	(efficiency of solar cell not in
		the expression)

Table 11. Comparisons of the different architectures of the transmitter

Because the new architecture has advantages over others, like simplicity, low power consumption and area efficiency, we will apply our new architecture to the design of the remote powered wireless transmitter.

2-9. Artistic impression

Light illuminates the solar cell to generate electrical power. At the same time, a part of light will be reflected by the MEMS micro mirror which is mounted on the solar cell at a specific angle. The LCD module is turn on and off by output of the temperature dependent oscillator. This module is place on the top of the MEMS micro mirror and acts as optical switch. The outgoing light passes through the polarized filter and LCD, this modulated light is point to the receiver for further calculation and analysis. Figure 6 shows one possible artistic impression diagram of the remote powered wireless transmitter system.



Figure 6.The artistic impression of the remote powered wireless transmitter

This new architecture has many advantages such as, reduced mass, cost and power consumption over other similar systems. Furthermore, this design overcome several problems associated with wire-base electronic devices and has advantage of the wireless transmission without any interference and noise distortion.

Chapter3. Charge pump circuit design

3-1. Introduction

In this chapter, we will discuss the important issues that need to be considered in the design of a power efficient, small and inexpensive charge pump circuit for a micro-solar power system.

One important issue to consider is the power efficiency in micro-power devices. Generally, we are aiming to have maximum power output from the charge pump. Therefore, the power losses must be minimized. Another issue is area efficiency and fabrication cost. The size of the pumping capacitor generally exceeds the area of the charge pump circuit. It should be considered that the larger the chip area the more expensive it will be due to the high fabrication cost. Another issue that we should consider is the ripple of the output voltage of the charge pump circuit. Most applications require low output ripple because large output ripple degrades the performance of these circuits and reduces the efficiency of the system [25].

Generally, the charge pump is a circuit that transfers charges stage by stage by using the capacitors and transistors (NMOS and PMOS) to generate a voltage that is higher than the input supply voltage [21]. Charge pump circuits have been used in various applications in electronic circuits, such as Flash memory and Erasable Programmable Read Only Memory (EPROM) [15], [17], [22]. Also, charge pump circuits have been used in low voltage designs such as RFID application in which the circuits use received RF signal as power source [20], [23]. Another example is micro-solar power system. In this system, solar cell(s) convert light energy into electrical energy [24]. In a micro-solar power system, power is transferred to the sensor and the transmitter devices through a charge pump circuit. The level of input supply voltage is lower than necessary value to

activate the sensor and transmitter devices. Therefore, the charge pump circuit will increase the arriving voltage level from the solar cell.

The power consumption has many effects on the design specification, architecture, loading circuits, energy transfer and so on [29]. For this reason, the power dissipation of the power management system has to be carefully controlled. Table 12 shows the estimated power consumption value of the power management system.

Table 12.Estimated power consumption of the remote powered wireless transmitter

devices	power management system (μW)	
Power consumption	80	

The total power consumption of the power management system is around $80\,\mu\mathrm{W}$.

We will explain separately each unit in the power management subsystem for simplicity and clarity. The block diagram of the power receiver unit is depicted in Figure 7.



Figure 7.Block diagram of the proposed architecture of the power management system which is connected to the solar cell model and output load capacitor

First, in this chapter, we describe the Dickson charge pump which is the bases of many charge pump circuits. Then, we review other charge pump circuits and their improvements such as area efficiency, gain ratio, power dissipation and efficiency. Next, we explain the design of the clock generator and buffer circuit as some of these circuits require clock signal to transfer the charges stage by stage. Furthermore, we discuss the temporary charge storage that is used to store energy and transfer to the power consumer devices. Finally, we will introduce a new adaptive charge pump circuit that further develops techniques to solve the breakdown voltage limitation. At the end, comparisons with other circuits based on the Dickson charge pump are included.

The components were chosen for low voltage threshold and low supply voltage in 0.13 μm UMC technology in this system. The design and simulations have been done using Cadence, Spectre, CAD tools

3-2. Charge pumps circuits

3-2-1. Dickson charge pump

The schematic of a four stage Dickson charge pump is depicted in Figure 8-a. In this circuit NMOS transistors (MD_n-MD_{n+3}) are diode connected (drain-gate connected) and two anti-phase clocks transfer the charge stage by stage through the pumping capacitor (C_{pump}) towards the output. As will be describe later in this section, voltage at stage N+1 (V_{N+1}) has higher voltage value than voltage at N stage (V_n). As result, the output voltage (V_{out}) has the highest voltage value [17], [19], [21], [22].



8-b. Waveform of the four stage Dickson charge pump

Figure 8.Schematic of the Dickson charge pump is depicted in 8-a and node waveforms is depicted in 8-b

Two anti-phase clock signals are represented by V_{ClkB} and V_{Clk} . V_{in} and V_{SS} are the input voltage supply and the voltage at ground connection. Bulks of all transistors are connected to ground and pump capacitors are denoted by C_{pump} .

The operation of Dickson charge pump is shown in Figure 8-b, which shows the voltage waveform in stages N and N+1 in ideal case. It is shown, when CLK goes from zero to V_{Clk} and CLKB goes from V_{Clk} to zero, the voltage at stage N is settled to $V_N + \Delta V$. In this condition, MD_n and MD_{n+2} are reverse biased and MD_{n+1} is forward bias. So, charges will flow from stage N to stage N+1 through MD_{n+1}.

Voltage waveform of each node shows that, the voltages increase by the amount of the fluctuation (Δ V) in the charge pump circuit. This value can be calculated by following formula [19]:

$$\Delta V = V_{Clk} \left(\frac{C_{Pump}}{C_{Pump} + C_{Par}} \right) - \left(\frac{I_{out}}{f_{Clk} (C_{Pump} + C_{Par})} \right)$$
(2)

Where, C_{Pump} and C_{Par} are denoted for pumping capacitance and parasitic capacitance of the transistor (e.g. diffusion capacitance), respectively. If the pumping capacitors are large enough, the C_{Par} can be neglected. I_{out} is the output current, f_{Clk} is the clock frequency.

In ideal case the output voltage is given by the following formula [19]:

$$V_{out} = \sum_{1}^{K} \left(V_{in} - \left| V_{th,K} \right| \right)$$
(3)

K is the number of the stages and $|V_{th}|$ is denoted for voltage threshold of the NMOS or PMOS transistor, depending on which one is considered.

The gain of Dickson charge pump can be defined as the voltage difference between two continuous stages. For example, the voltage gain between stage N and N+1 can be calculated as following [19]:

$$G_V = V_{N+1} - V_N \tag{4}$$

Where, G_v gain voltage between to continuous stage, V_{N+1} and V_N voltage value of the N+1 and N stage, respectively.

In the traditional Dickson charge pump circuit the voltage difference between two stages are the threshold voltage of the transistor between these stages. So, we can rewrite equation (4) as following:

$$G_V = \Delta V - V_{th-N+1} \tag{5}$$

35

Since, the threshold voltage of the transistor V_{th} has a great effect on efficiency and voltage gain of the charge pump circuit, we will write the Mathematical formula of the V_{th} for NMOS transistor for clarity [20]:

$$V_{th,n} = V_{th,n0} - \Delta V_{th,n} \tag{6}$$

Where, $V_{th,n0}$ is the threshold voltage of the NMOS without body effect, and $\Delta V_{th,n}$ is the threshold variation of the NMOS transistors caused by body effect. The threshold variation is explained in equation (7) [20].

$$\Delta V_{th,n} = \gamma \left(\sqrt{2|\phi| + V_{SB}} - \sqrt{2|\phi|} \right)$$
(7)

Where, V_{SB} is source-body voltage, ϕ is the bulk potential, and γ is body effect coefficient [20].

The above formula shows the relation between $\Delta V_{th,n}$ and V_{SB} and shows $\Delta V_{th,n}$ will increase by increasing V_{SB} . As a result, the voltage gain will be reduced due to increase $\Delta V_{th,n}$ and, charge pump circuit reaches to it is maximum output voltage when the threshold voltage and fluctuation voltage have the same value $(\Delta V=|V_{th}|)$.

Generally, the value of V_{Clk} and V_{ClkB} are the same as the input supply voltage (V_{in}) , in this manner, if V_{in} decreases then, ΔV decreases according to (2). Then, G_V of each stage will be decreased according to (5). It is concluded that the Dickson charge pump is not suitable for low voltage input supply and high voltage output due to limited voltage gain and efficiency [17], [21], [22].

These charge pump circuits can be improved in different ways. Several modified circuits have been designed which are reported in [1-8], [25]. In the following section, we summarize the advantages and disadvantages of these modifications.

3-2-2. Improvement of the charge pump base on Dickson

There are different techniques to eliminate the body effect in traditional Dickson charge pump circuits. This problem can be solved by floating-well devices or source-bulk connection. The drawback of this technique is that the charge pump circuit requires very good isolation due to the generated substrate current in floating-well devices. This substrate current may damage other parts of circuits in the same chip. In source- bulk connection, higher parasitic capacitance value affect the charge pumping in each node. This technique requires larger pumping capacitors to have higher boosting ratio in each stage [19]. Larger capacitors require larger areas which increase leakage current, increase power consumption and cost of the fabrication process.

In [28], more than two phase clock frequency (4 or 6 phase) was used to improve the efficiency of the circuits. The drawback of this circuit is that generating the clocks signal consumes more power compared to other circuits [19], [28]. The extra small charge pump circuits designed to control the main charge pump circuit, enhance the efficiency of the circuit, but requires higher power to drive two charge pump circuits and occupies a larger silicon area [15], [16], [19].

Other works have focused on eliminating by the threshold voltage in Dickson charge pump such as statically and dynamically gate control of the transistors. Static gate control of the transistors improves the efficiency and eliminates threshold voltage drop of Dickson charge pump [21], [20]. Schematic of the static gate control circuit is shown in Figure 9 [21].



Figure 9.Schematic of the statically gate control charge pump circuit [21]

The drawback of this circuit is the current leakage in the reverse direction during switching, because the charge transfer switches cannot be on and off completely in each clock cycle [21], [20]. These effects reduce the gain of the charge pump circuit.

Further work has been done to eliminate reverse current (leakage) which happens in static gate control by adding the pass transistors (N and PMOS) [19], [21]. The gate of each switching transistor will be controlled dynamically by the pass transistors. This technique reduces power consumption, eliminates threshold voltage and improves efficiency of the circuit [19], [21]. Commonly this circuit is used in micro-power application and the circuit is shown in Figure 10 [19], [21], [25].



Figure 10.Dynamically gate control charge pump circuit [21]

In this charge pump circuit, switch transistors transfer the charge stage by stage to the output load and these transistors can be completely turned on and off by the two anti-phase clock signals. The drawback of this circuit is the current leakage in substrate.

3-2-3. Design and simulation of the proposed charge pump

Calculation formula for proposed charge pump circuit is quite different from the traditional charge pump circuit which is connected to the voltage source supply. In our system, the solar cell is acting as a current source with limited energy, so the solar cell is modeled as a limited energy current source. The calculation of this type of charge pump will be as following [6]:

$$\left. \begin{array}{l}
I_{avg,O} = f_{clk} * Q_{avg} \\
f_{osc} = f_{clk} \\
Q_{avg} = \frac{1}{N} C_{pump} \left[(N+1) V_{solar} - V_{O} \right] \end{array} \right\} \Rightarrow I_{avg,O} = \frac{1}{N} C_{pump} * f_{clk} * \left[(N+1) V_{solar} - V_{O} \right] \\$$
(8)

Where, $I_{avg,O}$ is average current which is consumed by the sensor and transmitter devices, f_{clk} is the clock frequency of the charge pump which provided by clock generator, Q_{avg} is the average amount of charge being transferred to sensor and transmitter devices and C_{pump} is the stage capacitor.

Our estimation value for the equivalent capacitor of charge pump is 10pF which means each C_{pump} should be around 3.5pF. Table 13 shows the design specifications values of the proposed charge pump that are required.

Specification	Name	Required values
Output voltage	V _{Out}	2.7V
Output current	I _{Out}	10 µ A
Equivalent capacitance of	C_{Eq}	10pF
the charge pump		
Load capacitance	C_{Load}	10pF
Clock frequency	f_{Osc}	≈9MHz

Table 13. The specification value for design of the charge pump circuit

By inserting the values of the Table 13 in equation (9) and solve the equation, we find the required number of stages for proposed charge pump circuit.

$$I_{avg,O} = \frac{1}{N} C_{pump} * f_{clk} * [(N+1)V_{solar} - V_{Out}]$$

$$10*10^{-6} = \frac{1}{N} * 3.5*10^{-12} * 9*10^{6} * [(N+1)0.56 - 2.7]$$

(9)

The above calculation shows that we need a minimum of nine stages to reach the required value. In following, we consider ten stage designs to cover the losses such as leakage current, parasitic capacitances, etc.

3-3. Anti-Phase clock frequency generator

3-3-1. Clock generator

Clock generator for a charge pump can be derived by separate clock system or on chip clock generator. These circuits are designed and implemented for supporting the charge pump operation [29].

There are different topologies for clock generator design in electronic circuit application. We have chosen the ring oscillator because of simplicity, low power consumption and small size of the circuits [26], [29].

Ring oscillators consist of an odd number of inverters which are connected to each other in series in a closed loop. If the gain of the inverter is sufficiently high and total phase shift of the closed loop is 360° the circuit starts to oscillate. The frequency of the oscillation can be calculated by [26]:

$$f_{osc_ring} = \frac{1}{2N\tau}$$
(10)

Where, f_{Osc_ring} is the oscillation frequency N is the number of inverter stages and τ is the propagation delay of each stage.

Hence, the oscillation frequency for the MOS transistor becomes [26]:

$$f_{osc_ring} = \frac{\frac{W}{2L} \mu_{eff} C_{ox} (V_{in} - V_{th})^2}{2NCV_{in}}$$
(11)

Where, μ_{eff} is the effective hole or electron mobility, C_{ox} is the oxide capacitance of the transistor. W and L are width and length of the transistor, respectively.

 V_{in} is the voltage source, V_{th} is the threshold voltage and C is total capacitance seen by inverter stages.

The transistors of the inverters must in the high gain region (i.e. $\frac{V_{in}}{2}$, Where the

 V_{in} is a supply voltage) to reduce the power consumption of the ring oscillator circuit. Another consideration to reduce the power consumption is using low power techniques, such as using sub-threshold operating devices, low input supply, low voltage threshold devices, etc. [26]. We will consider the low voltage supply and low threshold voltage transistor as techniques for design of the propose clock generator.

There are some challenging issues to design clock generators in this application which are mentioned as following: The first issue is the relation between the frequency of the oscillation and equivalent charge pump capacitors regarding the available power source from solar cell. Following calculation will show these limitations:

$$V_{mp} = \frac{1}{C_{Eq}} \int_{0}^{t} i_{mp}(t)t$$
(12)

Where, V_{mp} and i_{mp} are the voltage and current at maximum power point of the solar cell. C_{Eq} is the equivalent capacitance seen by solar cell in this system, which the oscillator should drive. t is the charging time of the equivalent capacitor. Equation 13 shows the relation between C_{Eq} and charging time of the C_{Eq} (i.e. constant value).

The summery of the measurement result of the solar cell are depicted in Table 14.

Specification	Name	Measured values
Maximum input voltage	V _{mp}	560mV
Maximum input current	i _{mp}	500 μ Α
Minimum area	Area	16mm ²

Table 14.Measurements result of the a-Si:H solar cell (300 µm, DIMES process)

$$\left. \begin{array}{l} V_{mp} * C_{Eq.} = i_{mp} * t \\ V_{mp} = 560mV \\ i_{mp}(t) = 500\muA \end{array} \right\} \Rightarrow \frac{C_{Eq.}}{t} = 892 * 10^{-6} \\ \end{array} \tag{13}$$

To find the relation between $C_{Eq.}$ and $f_{osc ring}$ can apply following formula:

$$\tau_{charging} = \tau_{discharging} = \tau$$

$$\tau = 5 * t$$

$$f_{osc_ring} = \frac{1}{2\tau}$$

$$(14)$$

Where, V_{mp} and i_{mp} are the voltage and current at maximum power point of the solar cell. C_{Eq} is the equivalent capacitor of the charge pump. t is the charging time of C_{Eq} and f_{osc_ring} is the oscillation frequency. We considered 5*t is the total charging time of C_{Eq} .

Another issue is that, the area limitation in the design of the whole system. We want to use minimum mass and area because of the high cost of fabrication process.

We want to place all transistors and capacitors in 16 mm² which is the minimum size of the solar cell. Base on the information of the process manual of UMC

 $0.13\,\mu$ m technology, the area of the 1nF capacitor is about 1mm². We should choose the total capacitor value less than 16nF.

In this case, the oscillator must have very low frequency to charge or discharge the capacitor. Therefore, length of NMOS and PMOS transistors of the inverter circuits should be increased. As a consequence, this approach has drawbacks such as higher resistivity, lower amplitude signal, a larger required biasing voltage. So, we should choose optimum value of the charge pump capacitors to improve the efficiency of the power management system.

In this application, we estimated that the ring oscillator must drive a 10pF capacitance due to limited energy from solar cell. The frequency of the oscillator can be calculated by the following formula:

$$C_{Eq.} * f_{osc_Ring} = 89.2 * 10^{-6}$$

$$C_{Eq.} = 10 \, pF$$

$$\Rightarrow f_{osc_Ring} = 8.9 M Hz$$
(15)

The clock oscillation frequency of the charge pump is 8.9MHz if the equivalent capacitance of the charge pumps is 10pF. In further calculation, we consider 9MHz oscillation frequency instead of 8.9MHZ for simplicity.

3-3-2. Design specification and simulation result

In order to have low power consumption a minimum number of the inverter (i.e. three) is proposed to generate the clock signal. We have used the low threshold voltage and low voltage supply (i.e.1.2V) transistors in the proposed clock frequency generator. Figure 11 shows the schematic of the three stage ring oscillator.



Figure 11.Schematic of the three stages ring oscillator

We choose the width of the PMOS transistor 3.46 times larger than NMOS to have almost the same delay time in the 0.13 μ m UMC process [29], [39]. We can see in equation (11) the oscillation frequency depends on $\frac{W}{L}$ ratio of the transistors. As a consequence, increasing the length of the transistor has a great effect to reduce the speed of the transistors and we can reach to require frequency of the ring oscillator, in this way.

The values of the transistors are given in Table 15 which is calculated from equation (11) to have 9MHz oscillation frequency.

Table 15.Size of the transistors in inv	verter circuits
---	-----------------

Transistors (0.13 µm UMC technology)	W (μm)	L(µm)
NMOS	0.16	6.1
PMOS	0.553	6.1

Waveform of the output oscillator is shown in Figure 12. Each period cycle equals to the 109 ns.



Figure 12.Waveform of the proposed three stages ring oscillator

Simulation results demonstrate that the designed ring oscillator operates well and consumes only 545nW during the operation.

3-3-3. Buffer circuit design

The gate capacitance of the $0.13 \,\mu m$ UMC technology devices is in the order of a 2-3 femto Farads. The variation between gate capacitance of these transistors and load capacitor is high. Therefore, we need an output buffer circuit to drive the output load capacitor.

A series of inverters with different width ratios can be used as buffer to drive the output load [27]. The proposed buffer circuit must be able to drive an output load capacitor of 10pF.

In this approach, a series of inverters are connected to each other such that each inverter buffer drives the next larger inverter. The number of the inverters increases until an inverter size is reached to require output value compared to load and have a good response. More explanation to find the width ratio A of the inverters and number of the stages are explained in [27].

We should choose proper values between first and last inverters to reduce the power consumption of the circuit. The first stage of the buffer is minimum width to minimize the loading effect on the oscillator and each inverter will be larger than the previous one by A [27]. The schematic of the buffer circuit is depicted in Figure 13.



Figure 13.Basic schematic of the buffer circuit

In our design, the width ratio is 2.6 and the buffer consists of five stages to drive the equivalent capacitance of the charge pump circuit pumping capacitors of the charge pump circuit. The ring oscillator circuit is connected to the buffer input and a 10pF capacitor to buffer output. For further development we connected ring oscillator to the buffer circuit to drive the equivalent capacitance of the charge pump. The output signal of the clock frequency generator is shown in Figure 14.



Figure 14.Output waveform of clock generator

As it shown Figure 14, the output signals have high rising and falling edge to turn on and off the transistors with oscillation frequency of 9MHz. Also we should mention that the charging time has slop because of the input ripple voltage supply from solar cell. That simulation results and calculation are almost the same. These signals will be used as clock signal in the charge pump circuit. In next section, we will review the charge control unit and the required storage value for propose system.

3-3-4. Charge control unit

In this section, we will calculate the value of the charge storage devices to store a sufficient amount of energy for activating the sensor and transmitter devices. The energy is provided when the solar cell is illuminated by artificial light.

There are different approaches to find the value of a capacitor. The value can be computed for indirectly or directly connection.

In the first case, the energy transferred by the charge pump circuit is not sufficient for driving the sensor and transmitter devices. We should store energy in storage devices such as a capacitor, rechargeable battery or both. The regulator is placed after the charge storage to provide the fixed voltage and current for the sensor and transmitter devices. In the second case, the energy transferred by the charge pump circuit is enough for driving the sensor and transmitter devices.

First, we assume that the energy transferred by the charge pump cannot drive the sensor and transmitter devices directly and we should store charge in a capacitor or rechargeable battery. We selected a capacitor as charge storage device because of their advantages over batteries, which are mentioned in the previous chapter.

We can calculate the required energy to activate the system by the following formula:

$$E_{tran._sensor} = P_{tran._sensor} * T$$

$$T = 40ms$$

$$P_{tran._sensor} = 27 \,\mu W$$

$$\Rightarrow E_{tran._sensor} = 1.08 \,\mu J$$
(16)

Where E_{tran_sensor} the required energy to transmit the signals, P_{tran_sensor} is estimated power required for the transmitter devices signal and T is the total operation time. We estimated the energy required by these devices is around 1.08 µJ during transmission. The sensor and transmitter devices require minimum 2.5V supply voltage for activation. The charge will be accumulating in a capacitor during the operation and the voltage output reach to required value (i.e. 3.5V).

Then, charge control unit monitor the voltage level of the charge capacitor and switch will close between charge pump and regulator. This switch is controlled by voltage limiter circuit and will close when the level of the voltage reaches the required level (i.e.3.5V). Transmitter starts to transmit the signal with small delay due to charging time of the storage capacitor.

If we show the highest voltage level of the charge pump is V_1 and lowest level of the voltage during the transmission by V_2 . The value of the $C_{storage}$ can be calculated as follows:

1

$$E_{tran._sensor} = \frac{1}{2} C_{storage} * (V_1^2 - V_2^2)$$
(17)

$$E_{tran_sensor} = \frac{1}{2} C_{storage} * (V_1^2 - V_2^2) \\ E_{tran_sensor} = 1.08 \mu J \\ V_2 = 3.5V; V_1 = 2.7V \end{cases} \Rightarrow C_{storage} = \frac{2 * E_{tran_sensor}}{(V_2^2 - V_1^2)} = \frac{2 * 1.08 \mu J}{(12.25 - 7.29)V} \approx 435 nF$$
(18)

Where, E_{tran_sensor} is the required energy, $C_{storage}$ is named for the charge storage capacitor. The above calculation shows minimum 435nF capacitor is required to stores 1.08μ J energy.

3-5. New criteria of the dynamic gate control charge pump

After the introduction of basic charge pump concept and all supporting devices of the charge pump circuit, we will present a modification of the dynamic gate control charge pump circuit for our system. The new improvement of the charge pump circuit is done in such a way it is uses PMOS instead of NMOS as switches. It has shown in section 3-2-2, this circuit can solve threshold voltage and body effect problems of the charge pump circuits [18], [20], [21].

There is a possibility for some charges to be injected into the well from gate of the switching transistors. We may be able to solve this problem by good layout and isolation techniques [18], [20], [21].

In the proposed charge pump circuit low V_{th} transistors are used which are suited for micro-power circuit design. We can reach to the maximum level by ten stage charge pump circuit. The voltage level of each stage increase stage by stage. In forth stage the transistor is close to reach the breakdown voltage therefore, we used two different types of transistors in this design for switching to solve the breakdown voltage limitation. We should replace the 1.2V supply voltage transistors with 3.3V supply voltage transistors due to break down voltage limitation after forth stage. This technique is applied to prevent drain-source voltage of each transistor reaches its breakdown voltage due to pumping. The following values have been calculated in order to have highest charge transfer in each stage. Sizes of these transistors are presented in Table 16.

Switching transistor	W _s (µm)	L _s (µm)
PMOS (1-4)	2	0.12
PMOS (4-10)	5.6	0.340

Table 16.The values of the switching transistors in charge pump circuit

To have fast switching and have less power consumption by inverters we used the small size transistors. The design values of the inverters are presented in Table 17.

Value	$W_n(\mu m)$	$L_n(\mu m)$
NMOS (1.2V)	0.16	0.12
PMOS (1.2V)	0.553	0.12
NMOS (3V)	0.453	0.34
PMOS (3V)	1.56	0.34

Table 17. The values of the inverter transistors for gate control of the switching transistor

The schematic of the three first stage of the adaptive charge pump is depicted in Figure 15 and each stage has pumping capacitor of 3.5pF and the storage capacitor is 10pF.



Figure 15. First three stage of the proposed charge pump circuit

We show the first three stages of the proposed charge pump for clarity in Figure 15. The operation of the propose circuit comes in to following:

Let's consider the gate control for M_{S3} .

When $V_{Clk} = V_{in}$ and $V_{ClkB} = 0$, V_3 is changed to $V_3 + \Delta V$ charging of C_3 . If $V_3 + \Delta V - V_2 \le V_{th,p}$ and $V_{Gs3} \le V_3 + \Delta V$ then M_{p3} is turned on (closed) and causes M_{s3} to turn off (Open). Also, M_{n3} is open in this condition which requires $V_2 - (V_1 + \Delta V) \le V_{tn}$.

On the other hand, When $V_{Clk} = 0$ and $V_{ClkB} = V_{in}$, V_2 is change to $V_2 + \Delta V$ by couple effect of C_2 . M_{S3} should be turned on (closed) by turning on M_{n3} . Hence it requires $V_2 - (V_1 + \Delta V) \ge V_{in}$ and $V_{Gs2} \ge V_3 + \Delta V$. Also, we should hold the off state for M_{p3} which requires $V_3 + \Delta V - V_2 \ge V_{ip}$.

In addition, this charge pump circuit does not require the start up circuit due to very low threshold voltage. Therefore, proposed charge pump circuit is suitable for micro-solar power system.

3-5-1. Comparing different types of the charge pumps circuits

Ideally, the output voltage of the new proposed ten stage charge pump circuit with input supply of 0.56V should be as high as 5.6V. This value is lower than ideal case because of the leakage in N-Well substrate due to transition. This result shows the proposed charge pump has high power efficiency as compared to others. This circuit has power efficiency of 91%. To show the effectiveness of the proposed charge pump, comparing to others base on Dickson charge pump, is considered. The simulation and test results of different charge pump circuits are given in Table 18.

Table 18.Comparing test result of the well-known charge pump base on Dickson

	Ref [17]	Ref [18]	Ref [21]	This work
source	Ideal voltage	Ideal voltage	Ideal voltage	Limited
				power, current
				source
Technology	0.25μ <i>m</i>	0.35 µ m	0.8µm	0.13µm
Voltage	0.9	1	2	0.56
supply(V)				
Stages	10	10	10	10
V_{out} (V) when	≈7	≺8 *	NA	5.1
I _{Load} =0				
Average	≈16	≈36	≈37	≈ 17.5
output power				
(µW)				
C _{Pump} (pF)	10	15	15	3.5
f _{Clk} (MHz)	50	10	5	9

*- limited duo to Junction breakdown voltage

The novelty of this circuit is that it is designed to operate with a limited energy current source supply. All compared charge pumps use ideal unlimited power voltage source except in our design. This circuit just requires 0.56V supply to reach 5.1V and there is no start up circuit to activate the charge pump. This circuit consumes only 68μ W during operation. Moreover, simulation shows that our charge pump circuit can operate even with a source input voltage as low as 0.45V and still offer good pumping performance.

We consider 250K Ω resistor as equivalent impedance of the sensor and transmitter devices for finding the output value of the charge pump circuit. The graph in Figure 16 shows a charging phase of the device, charge pump to 3.5V in 6 µs with 9MHz clock signal. When charge pump reach to 3.5V, then switch will close and connect to 250K Ω resistor.



Figure 16.Output waveform of the adaptive charge pump circuit when the switch is closed after $6 \,\mu s$

As we can see in Figure 16, output waveform of the charge pump has lower pumping ratio between 0.5 and $1.2 \,\mu$ s during the operation, because the circuit has two different types of transistors (i.e. threshold voltage, input supply voltage, etc). Also, Figure 16 shows that this circuit can connect to the transmitter directly and switch can close in 2.7V. The voltage level reaches to the 2.7V which makes it possible for continuous operation after $4 \,\mu$ s.

As we have mentioned before, these techniques were applied to avoid the break down voltage after the first four stages.

Chapter4. Conclusion and further work

4-1. Summery and further work

We have presented the new architecture of the remote powered wireless transmitter. The new architecture presented in this thesis has certainly brought us one step closer on the route to realizing the great potential of the remote power wireless sensing. Whereas, others attempts have focused on wireless communication and sensing elements.

This research is concerned with micro-power applications such as solar, vibration/motion, thermal, and RF energy harvesting.

In this system, power will transmitted optically by LASER or LED to provide power to the system. We show that LASER or LED lights are suitable and stable power source for micro power transmission technology.

We presented a system model that consists of four units: power receiver, power management system, charge control and power consumer devices such as sensor, LCD, etc. Circuit functionality like the charge pump, sensors, modulator, and transmitter devices has been kept simple and complexity has been minimized. In the new architecture we also minimize the power consumption of the system by using an LCD and MEMS micro mirror. The summery of the overall properties of the new remote powered wireless transmitter are given in Table 19.

Units	Design selection	
Light source	LED, LASER	
Power receiver unit	A-si:H solar cell, capacitor	
Converter	Charge pump circuit	
Charge control unit	Capacitor	
Power consumer devices	Temperature dependent oscillator, LCD	

Table 19.Summery of the design devices of the remote powered wireless transceiver

The different topologies of the charge pump based on Dickson have been discussed. The dynamic gate control charge pump circuit was selected for high efficiency and good performance. The effect of the parasitic capacitor was minimized in the proposed charge pump circuit. The performance of the charge pump circuit was verified through the calculation, simulation and comparisons. This circuit has efficiency of 91% and increases output voltage up to 9 times higher than input supply voltage during the operation. The voltage breakdown limitation was solved by using two different voltage supply transistors. The drawback and advantages of this design are explained.

The proposed charge pump uses ten pumping capacitor in each stage with 3.5pF capacitor. The power management unit also includes three stage ring oscillator with five stage buffer circuit. They consume a $68 \mu W$ during operation.

The proposed charge pump is optimized for clock frequency of nine MHz due to limited energy source. The charging time is set by voltage sensor in charge control unit, in this case determined by the voltage level of the charge storage capacitor. This voltage level is adequate for the power consumer devices. Most of the chip area is devoted to the charge pumping and storage capacitor.

The power consumer devices requires minimum 2.5V for activation, so the solar cell current and voltage fed the charge pump that generates minimum 2.5V from the LASER or LED light.

With the current integrated circuit and MEMS in fabrication, we are going to build remote powered wireless transceiver with communication range of 10cm and power consumption of $27 \,\mu\text{W}$. Another advantage of this power management subsystem is that, the system is self-powered and a start up circuit is not necessary.

We also have solved the interfering problem by modulating the outgoing light which is happen in RF wireless communications and efficiency of solar cell is not in the expression for transmitting data. This circuit is implemented in UMC 0.13 μ m technology and simulation results show the theoretical approaches were successful.

57

We would like ask to support the further consideration of this research which is design a complete remote powered wireless temperature sensor.

References:

- [1].Murugavel Raju, "Energy harvesting, a game –charging combination for design engineers". MCU strategic Marketing, Texas instruments. Nov 2008.
- [2]. Arjen Klaver, "Irradiation-induces degradation of the amorphous silicon solar cells in space". PHD thesis, TUDelft, 2007.
- [3]. Jaein Jeong, Xiaofan Fred Jiang, David E. Culler,"Design and Analysis of Micro-Solar Power Systems for Wireless Sensor Networks Culler". *EECS*, 2007.
- [4]. Shad Roundy, Brian P. Otis, et al., "A 1.9GHz RF Transmit Beacon using environmentally Scavenged Energy", IEEE Int. Symposium on Low Power Elec. and Devices, 2003.
- [5].Farhan Simjee and Pai H. Chou, "Everlast: Long-life, super capacitoroperated Wireless Sensor Node". *ISLPED*, October 4-6, 2006. Tegemsee, Germany.
- [6]. Hui S., Chi-Ying T. and Wing-Hung K., "A micro power management system and maximum output power control for solar energy harvesting application". *ISLEPD*, August 2007,
- [7]. Xiaofan Jiang, Joseph Polastre, and David Culler, "Perpetual Environmentally Powered Sensor Networks". Information Processing in Sensor Networks, P. 463-468, April 2005.
- [8]. Prabal Dutta, Jonathan Hui, Jaein Jeong, Sukun Kim, "Trio: Enabling Sustainable and Scalable Outdoor Wireless Sensor Network Deployments". *IPSN*, April 19–21, 2006, Nashville, Tennessee, USA.
- [9]. Vijay Raghunathan, Aman Kansal, et al., "Design Considerations for Solar Energy Harvesting Wireless Embedded Systems". IEEE, No 64, 2005, Los Angeles California, USA.

- [10]. Pavan Sikka Peter Corke, Philip Valencia, "Wireless adhoc sensor and actuator networks on the farm". *IPSN*, April 19–21, 2006, Nashville, Tennessee, USA.
- [11]. Peter Spies, Markus Pollak, Gunter Rohmer, "Power Management for energy harvesting application" www.iis.fraunhofer.de/.../power_management_for_energy_harvesting_app lications_tcm278-91133.pdf
- [12]. Brett A. Warneke, Michael D. Scott, et al., "An autonomous 16mm³ Solar-Powered Node for Distributed Wireless Sensor Networks. *IEEE Sensors*, Vol. 1, 2002, Orlando, Florida, USA.
- [13]. Joe T. Howell, Mark J.O'Neill, Richard L. Fork, "Advance receiver/converter experiments for laser wireless power transmission". SPS, June 30- July2, 2004, Granada, Spain.
- [14]. "Measuring photovoltaic Cell I-V Characteristics with the Model 2420 Source Meter Instrument". Keithley application Note series, Num. 1953.
- [15]. Hongchin Lin, Kai-Hsun Chang and Shyh-Chyi Wong, "Novel high positive and negative pumping circuits for low supply voltage", *IEEE*, 1999.
- [16]. Sheng-Yeh Lai and Jinn-Shyan WangHsing, Ming-Hsiung, Chia-Yi.,"A high-efficiency CMOS charge pumps circuit.", *IEEE*, 2001
- [17]. Kuo-Hsing Cheng, Chung-Yu Chang, et al., "CMOS charge pump for sub-2.0V operation", *IEEE*, 2003.
- [18]. Mohammad Mahdi Ahmadi and Graham Jullien, "A new CMOS charge pump for low voltage applications", *IEEE*, 2005.
- [19]. Ming-Dou Ker, Shih-Lun Chen, Chia-Shen Tsai," Design of charge pump circuit with consideration of gate-oxide reliability in low-voltage

CMOS processes", *IEEE Journal of solid –state circuits*, Vol. 41, No. 5, May 2006.

- [20]. Davor Vinko, Tomislav Svedek, Tomislav Matic, "Modification of the Cockcroft-Walton charge pump by using switched capacitors technique for improved performance under capacitive loads", WSEAS Transactions on Circuits and Systems, Issue1, Vol. 8, January 2009.
- [21]. Jieh-Tsorng Wu, and Kuen-Long Chang, "MOS charge Pumps for Low-Voltage Operation", *IEEE Journal of solid-state circuits*, Vol. 33, No. 4, April 1998.
- [22]. Jong shin Shin, In-Young Chung, et al., "A new Charge Pump without Degradation in Threshold Voltage Due to Body Effect", IEEE Journal of solid-state circuits, Vol. 35, No. 8, August 2000.
- [23]. Fatih Kocer, and Michael P. Flynn." An RF-powered, Wireless CMOS temperature Sensor", *IEEE Sensors journal*, Vol. 6, No. 3, June 2006.
- [24]. Hui Shao, Chi-Ying Tsui and Wing-Hung Ki," An Inductor-less Micro Solar Power Management System Design for Energy Harvesting Applications", *IEEE*, 2007.
- [25]. Ryan Perigny, "Area Efficiency Improvement of CMOS Charge Pump Circuits". A Master of the science thesis submitted to Oregon State University.****
- [26]. Mina Danesh and John R. Long, "Ultra-low power transmitter UWB-FM sensor networks". *STW*, The Netherlands, 2007
- [27]. Srinivasa R. Vemuru and Edwyn D. Smith, "Variable taper CMOS buffer design" *IEEE Journal of solid-state -circuits*, Vol. 26, No. 9, Sep.1991.

- [28]. Gyu-Ho LIM, Sung-Young SONG, et. al.," Charge pump design for TFT-LCD driver using stack –MIM capacitor". *IEICE Trans. Electron*, Vol.E91-C, No.6, June 2008.
- [29]. Feng Pan , Tapan Smaddar, "Charge Pump Circuit design ",PP.93-99, 2006
- [30]. Arash Noroozi, C. J. M. Verhoeven, G. L. E. Monna, E. K. A. Gill, "A Reconfigurable multi-band GNSS receiver front-end for space application, *NAVITEC 2008.*
- [31]. Beamed Laser Power for UAVs. http://www.nasa.gov/centers/dryden/news/FactSheets/FS-087-DFRC.html
- [32]. F. steinsiek, K. H. Weber, et al., "Wireless power transmission experiment using an airship as relay system and movable rover as ground target for later planetary exploration missions", ESA work shop, ESTEC, Nov. 2-4, 2004, Noordwijk, The Netherlands.
- [33]. Geoffrey A. Landis, "Space power by Ground-Based Laser illumination", *IEEE*, Vol. 6, P.3-7 Nov 1997.
- [34]. Jane A. Yater, Roland A. Lowe, et al., "Pulsed Laser illumination of photovoltaic cells. NASA Technical Memorandum 106820.
- [35]. Carter Moursund, "Led's vs. Laser Diodes for wireless communication", ClearMesh Networks, Dec 2006.
- [36]. Shogo K., Kosuke K., "A fundamental experiment for discretewavelength LED solar simulator", *Science Direct*, Solar Energy Materials & solar cells 903364-3370, 2006.
- [37]. Toshihiko Ishiyama, Yasuyuki kanai, Junichi Ohwaki and Masato Mino. "Impact of a wireless power transmission system using an ultrasonic air transducer for low-power mobile application". *IEEE ultrasonic symposium*, 2003.

62

- [38]. UMC 0.13 μm Mixed Mode 1.2V Twin Well Metal-Metal capacitor Enhancement Process High speed Low V_t Device SPICE Model (BSCIM#V3.2.4 Global Model) Document, version 0.3 Phase 1, date:5/11/2005
- [39]. UMC 0.13 μm MM/RF CMOS FSG foundry Design Kit user Manual,
 2006