A Fully Integrated Electromagnetic Energy Harvesting Circuit with an On-Chip Antenna for Biomedical Implants in 180 nm SOI CMOS

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***Abstract*— This paper presents an energy harvesting platform for biomedical implantable sensors based on a far-field electromagnetic radiation. The design is composed of an on-chip dipole antenna and a multi stage Dickson voltage rectifier with threshold compensation order of 4. The operating range is up to 15 cm, including 1 cm of biological tissue with high water content. The optimum frequency for power transmission into the implanted chip through multiple biological tissues is studied as well. The system is fabricated in a 180 nm SOI CMOS technology with a total area of 0.42 mm^2. The chip can provide 1V DC for a 1MΩ resistive load when excited with an 11.2 GHz external transmitter. The maximum efficiency of the wireless link is measured as -51 dB. The voltage rectifier can provide 1V for the 1MΩ load with input power as low as 23 µW (-16.3 dBm).**

Keywords—Wireless Power Transfer; Energy Harvesting; Biomedical Implants; Ultra-low Power Sensors, CMOS, Silicon, On-chip Antenna.

I. INTRODUCTION

The Rising demand for continuous monitoring of human body and health care devices in recent years has resulted in the development of implantable biosensors. Infection risks and mobility concerns constrain the implanted sensors to operate without any transcutaneous wire connection, which gives rise to serious challenges for powering and data telemetry. Although using batteries to power wireless systems is an easy solution, their bulkiness and limited lifetime make them unsuitable for the permanent implantable applications.

A possible solution is to transfer the required power through a wireless link. Most existing wireless power transfer techniques are based on near-field coupling between two coils. The operation distance in this case is determined by the smaller coil size, and in practice, the receiver coil diameter at the implanted side is set to be few centimeters. The size of the coil at the receiver side makes this power transfer mechanism impractical for applications in which it is necessary to implant numerous sensors in the body. Induction based systems utilize MHz waves as carrier frequency [1]. Increasing the carrier frequency leads to size shrinkage of the coils and changes the power transfer mechanism to resonant inductive mode. In this case, the operation range can be increased compared to the coupling mode, but it is still dependent on the smaller coil size.

This problem can be alleviated by using a far-field electromagnetic source for wireless power transmission. It has been shown that the optimum frequency for power transmission into biological tissues is at low GHz frequency ranges [2]. In addition, energy harvesting circuits can be designed with smaller areas and low-profile on-chip antennas leveraging GHz carrier frequencies [3].

In this paper, a fully on-chip CMOS energy harvesting system is presented that can be used for providing the required power to ultra-low power biomedical implants. The challenges of power transmission through biological tissues are addressed, and the energy harvesting system utilizes a multi-stage Dickson voltage rectifier whose sensitivity has been improved with the aid of a self-compensation technique to overcome the threshold voltage of the CMOS transistors. In addition, a simple matching circuit is used to improve the sensitivity of the energy harvesting system.

In section II, the wireless link is studied and the optimum frequency is calculated based on the simulation results. Next, a 10 stage voltage rectifier with threshold compensation technique is described. Finally, measurement results are reported and the performance of the chip is evaluated.

II. WIRELESS LINK ANALYSIS

Available power budget for operation of the system is one of the most important features and is necessary to determine before designing the energy harvesting circuit. The main aims of this work are to increase the operating distance and shrink the size of the chip. In order to fulfill both of these goals, an on-chip dipole antenna is chosen to be used as the receiver. The maximum dimension of the chip is determined by the length of the antenna; therefore, we set the length of the antenna to 1.6 mm.

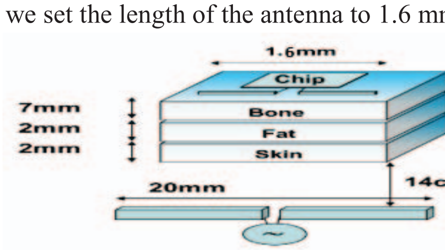

Fig. 1. Configuration of wireless link and composition of intermediating biological tissues and dielectric layers. Bone: 7 mm, Fat: 2 mm, skin: 2 mm

The optimum frequency is a function of the transmitting and receiving antennas in addition to the biological tissues between them. The wireless link depicted in Fig. 1 can be modeled as a two-port network. Considering the frequency-dependent behavior of the biological tissues, we modeled the tissues as dielectric layers with changing permittivity and conductivity with respect to frequency [4]. In order to eliminate the effect of mismatches between the antenna and driving stages, we defined the power transfer efficiency as the ratio of the maximum available received power at the output port of the receiver (P_{avN}) to the input power to the transmitting antenna (P_{in}). Fig. 1 shows the distances between the antennas and the dielectric layers. The power transfer efficiency can be calculated by extracting the S parameters from the simulation results and applying them to (1) - (5).

$$\eta = \frac{P_{avN}}{P_{in}} = \frac{|s_{21}|^2|1 - \Gamma_{in}\Gamma_G|^2}{(1 - |\Gamma_{in}|^2)(1 - |\Gamma_{out}|^2)|1 - s_{11}\Gamma_G|^2} \quad (1)$$

$$\Gamma_{in} = \frac{z_{in} - z_0}{z_{in} + z_0} = s_{11} + \frac{s_{12}s_{21}\Gamma_L}{1 - s_{22}\Gamma_L} \quad (2)$$

$$\Gamma_{out} = \frac{z_{out} - z_0}{z_{out} + z_0} = s_{22} + \frac{s_{12}s_{21}\Gamma_G}{1 - s_{11}\Gamma_G} \quad (3)$$

$$\Gamma_L = \frac{z_L - z_0}{z_L + z_0} \quad (4)$$

$$\Gamma_G = \frac{z_G - z_0}{z_G + z_0} \quad (5)$$

With the configuration of Fig. 1, the power transfer efficiency is plotted in Fig. 2, showing that the maximum η can be achieved by setting the carrier frequency to 11.8 GHz.

The maximum power transfer efficiency is calculated as -48dB. Using an array at the transmitter side can potentially increase the gain of the transmitter, which results in power transfer efficiency boosting. For instance, using a transmitter with a gain of 20 dB improves the power transfer efficiency to – 28 dB, which is almost equal to the efficiency of the near-field coupling mechanism.

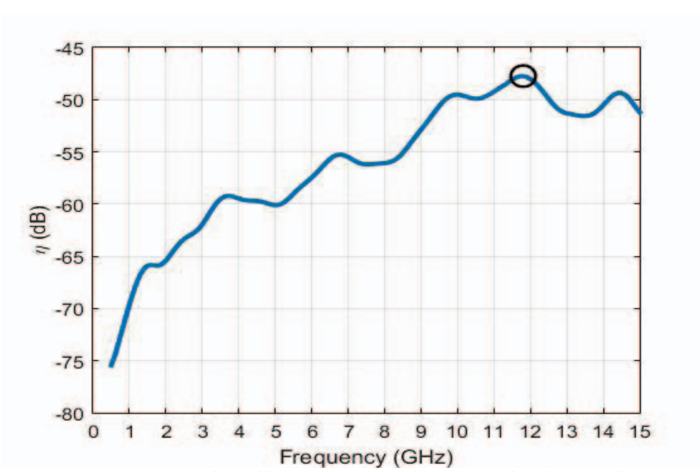

Fig. 2. Power transfer efficiency versus frequency for the configuration depicted in Fig. 1. The maximum efficiency is -48 dB at 11.8 GHz.

III. System Architecture

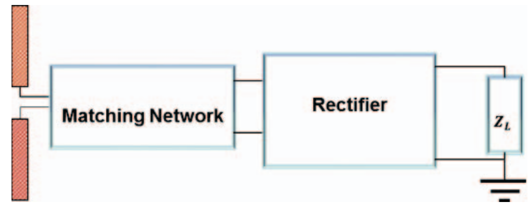

Fig. 3. Block diagram of energy harvesting system with an on-chip dipole antenna.

The energy harvesting system is composed of an on-chip dipole antenna attached to a multi-stage voltage rectifier as shown in Fig. 3. Area limitation dictates that the antenna maximum dimension must be as small as possible. A dipole antenna is selected as the receiver because it has a low profile structure and occupies a small area. It receives incident electromagnetic waves and passes them to the voltage rectifier in order to generate DC voltage at the output node of the rectifier.

Depending on the incident RF signal amplitude, different structures can be used for implementing the voltage rectifier. Usually, structures with higher efficiencies require high voltage amplitudes to be activated and are less sensitive. Considering the SAR limitation, the radiated power cannot be increased arbitrarily. Moreover, because of the wireless link attenuation, the maximum available power at the input port of the rectifier is limited.

The voltage rectifier used in this work is based on a Dickson structure, which uses diode-connected CMOS transistors. The conversion efficiency and sensitivity of these rectifiers are mainly dependent on the threshold voltage of the CMOS transistors. The rectifier nominal load is 1µA at 1V, and a single stage of rectifier unit is not able to provide the required voltage since the RF signal has low amplitude. By cascading multiple stages of rectifier units, the output voltage level can be increased. Decreasing the threshold voltage of the CMOS transistor leads to sensitivity and efficiency improvement. The output voltage of each rectifier stage is greater than the output of previous stages. In a multi-stage rectifier structure, the required voltage for overcoming the threshold voltage of CMOS transistors can be reduced by connecting their gate to the output of the next stages, which is known as threshold compensation technique. Threshold compensation order is defined as number of the transistors in a closed loop that includes the connecting path from the gate of a transistor to the output node of another stage. The order of compensation is dependent on the output voltage requirement and process threshold voltage [5].

We have cascaded multiple rectifier stages with threshold compensation order of 4. Radiating 2W from a horn antenna with a gain of 10 dB provides an AC signal at the rectifier input port, which is increased to 1V after rectification. The multi-stage voltage rectifier with threshold compensation of order 4 is shown in Fig. 4. Mismatch between the dipole antenna and the voltage rectifier is another important source of power loss in energy harvesting systems. It can greatly affect the sensitivity and efficiency of the system; therefore, a shunt inductor is designed in order to resonate with the dipole antenna and voltage rectifier and maximize the amplitude of the RF signal.

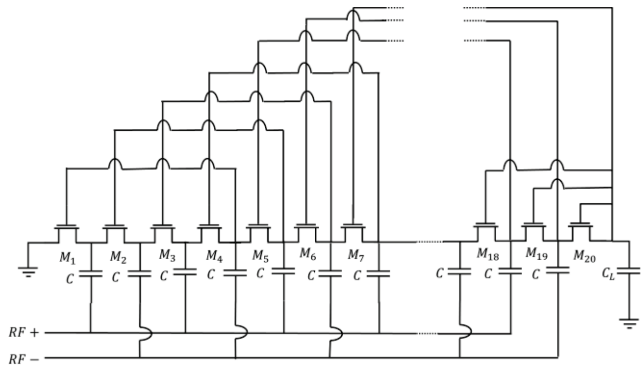

Fig. 4. Multi-stage voltage rectifier. Threshold compensation of order 4.

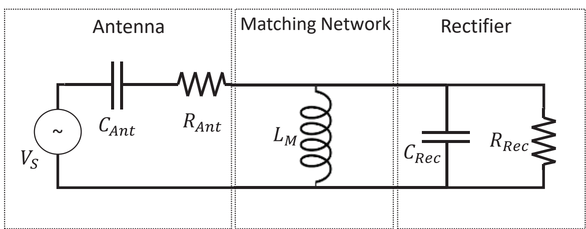

Fig. 5. Simple model of antenna and rectifier impedances and the matching shunt inductor.

The input impedance of the multi-stage rectifier can be modeled as a parallel RC network. On the other hand, the dipole antenna output impedance at the carrier frequency can be calculated based on the simulation results, and it is modeled as a series resistor and capacitor. Knowing the values of these two impedances, a matching circuit is implemented as shown in Fig. 5 to maximize the voltage across rectifiers input ports.

IV. Measurment Results

This design is fabricated in 180 nm SOI CMOS technology, and the chip has been tested to verify the simulation results. The chip micrograph is shown in Fig. 6. The total area of the chip, including a dipole antenna, matching circuit and multi stage rectifier, is 0.42 mm^2.

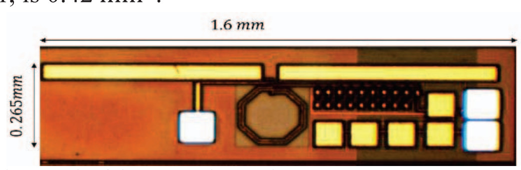

Fig. 6. Micrograph of the energy harvesting system.

We have used a broadband antenna as the transmitting antenna, and placed it 15 cm above the chip. The chip is covered by a layer of chicken breast with the thickness of 1 cm to emulate the configuration in Fig. 1, which was used in simulation. The power transfer efficiency for multiple frequencies has been measured and plotted in Fig.7. The maximum efficiency is achieved at 11.2 GHz. Due to the differences between the biological tissue used in the simulation and measurement, the optimum frequency differs in these two cases.

At the optimum frequency, we have used a horn antenna with a gain of 10 dB in order to compensate the power transfer efficiency and power up the chip with less amount of transmitted power. A capacitor is connected to the output of the voltage rectifier to absorb the voltage fluctuation, and a 1MΩ load, which is the input impedance of the oscilloscope,

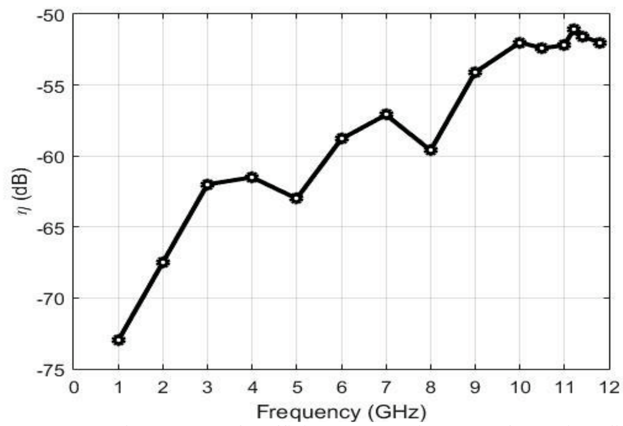

Fig. 7. Measured power transfer efficiency versus frequency form a broadband antenna located 15 cm above the energy harvesting system covered by 1 cm of chicken breast. The maximum efficiency is -51 dB at 11.2 GHz.

is connected to the output node of the rectifier as a nominal load. The minimum required power for achieving 1V with a 1MΩ load is measured as 23 μW (-16.3 dBm). The measured values for the input impedance of the voltage rectifier at 11.2 GHz are Z_{rec} = 3.23- 46.81j, which is equivalent to a parallel 681 Ω resistor and 0.338 pF capacitor. The dipole antenna output impedance at the same frequency is calculated as $Z_{ant} = 5.49 - 89.1j$. Based on these impedances, a 0.577nH inductor is placed between the antenna and rectifier as in Fig.5.

V. Conclusuon

In this work, we presented an energy harvesting system suitable for ultra-low power biomedical implants. All of the components, including the dipole antenna, are implemented on a single silicon chip within 0.42 mm^2.The operating distance of the system is up to 15 cm, which is the highest reported value compared with previous published works. To the best of author's knowledge, this work repots the firs far-field power harvesting system for biomedical implants. In addition, the carrier frequency for power transmission is about 11.2 GHz which is the highest reported carrier frequency for wireless power transfer to implanted biomedical systems. A multi-stage voltage rectifier with threshold compensation of order 4 is used for AC to DC conversion. The minimum required input power to the rectifier for delivering 1V DC voltage to a 1MΩ resistive load is 23 μW, which indicates that this system is useful for powering ultra-low power micro-implants and can be a potential solution for mobile health care devices.

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