Miniaturized Antenna and Integrated Rectifier Design for Remote Powering of Wireless Sensor Systems

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***Abstract*— The design methodology of a miniaturized tag antenna and an integrated rectifier for remote powering of wireless sensor systems operating at 2.45 GHz ISM band is presented. To maximize the power transfer the antenna input impedance is matched to the conjugate of the rectifier impedance. The overall efficiency of the rectenna is evaluated through the combination of the simulations and experimental results with the antenna-rectifier chain (rectenna) and the radiating source antenna (transmitter) respectively. A 16x8mm^2 tag antenna placed 12 cm apart from a transmitter having $2W$ of P_{EIRP} provides maximum output power of 560 μW. The efficiency of rectenna is analyzed considering CMOS process variations affecting the rectifier.**

***Index Terms*— Wireless remote powering, miniaturized antenna design, wireless sensor systems.**

I. Introduction

Wireless implantable sensor systems for continuous monitoring of subjects require a few hundreds of micro-watts of power consumption [1]. Wireless remote powering of such sensor systems can be performed with near-field inductive coupling or far-field electromagnetic coupling. The choice of the operation frequency of the wireless remote powering link for the sensor is a function of power consumption, implant size, read range or proximity, transmission medium and data rate. For high data rate and high read range high frequency communication is preferred whereas higher power delivery makes near-field remote powering more suitable.

This paper describes the combined design approach of a 2.45 GHz tag antenna along with an integrated rectifier for remote powering of passive wireless sensor systems. This method enables the design and evaluation procedure of miniaturized rectennas for remote powering of passive sensor nodes in small animals [2]. The designed antenna achieves small area thanks to its high frequency of operation and meandered geometry. In the case of implantable antenna, losses due to absorption of tissues should be taken into account. This work focuses on the design and measurements with free-space model. This method is accurate enough and simplifies the design and measurement of the rectenna.

II. Far-Field Remote Powering and Impedance Matching for Maximum Power Transfer

Friis transmission equation allows to evaluate the output power of a rectifier connected to a tag antenna in free space as follows,

$$P_{OUT} = P_{TX} \cdot G_{TX} \cdot G_{RX(R)} \cdot \left[\frac{\lambda}{4\pi d}\right]^2 \cdot \eta \qquad (1)$$

where P_{TX} is the delivered power to the transmitting antenna, G_{TX} is the gain of the transmitting antenna, λ is the wavelength of the electromagnetic wave and $G_{RX(R)}$ is the realized gain of the receiver antenna. The parameter d is the distance between the two antennas and η is the rectifier efficiency. The realized gain $G_{RX(R)}$ of the receiving antenna can be written as,

$$G_{RX(R)} = G_{RX} \cdot \tau \qquad (2)$$

with G_{RX} is the far-field gain of the antenna. τ is the power transmission coefficient between the antenna and the load which is given by [3],

$$\tau = \frac{4 \cdot R_{CHIP} \cdot R_{ANT}}{|Z_{CHIP} + Z_{ANT}|^2} \leq 1 \qquad (3)$$

where Z_{CHIP} and Z_{ANT} are the complex impedances of the chip and the antenna respectively. Maximizing the power transfer from the tag antenna to the rectifier, requires the condition $Z_{ANT} = Z^*_{CHIP}$ to be fulfilled. Hence, tag antenna design must give rise to an inductive input impedance characteristic in the frequency of interest in order to match the capacitive input impedance of the chip.

III. Determining Non-Linear Rectifier Impedance

The impedance matching between tag antenna and rectifier determines how much of the incident power on the tag antenna is delivered to the rectifier. To this end, standalone measurements and trimming methods, aimed at maximizing the impedance matching, are often expensive and time consuming [4], [5]. On the contrary, large signal s-parameter (LSSP) simulations quickly determine the design conditions for an optimal input impedance of a rectifier. Similarly, full wave electromagnetic simulations obtain input impedance and far-field gain of the antenna. As a result, the overall gain of the rectenna can be evaluated by combining the rectifier and antenna into a single block.

In this work we utilized the BSIM model of the zero-V_T transistors used to build NMOS bridge rectifier as shown in Fig.1. The zero threshold voltage can provide high power conversion efficiency since the voltage drop on these diode connected transistors is zero. Simulations account for the parasitic components of the rectenna such as bondwires used to connect the chip to the antenna. The test circuit includes a single tone source at 2.45 GHz with variable output power when it is matched to its load.

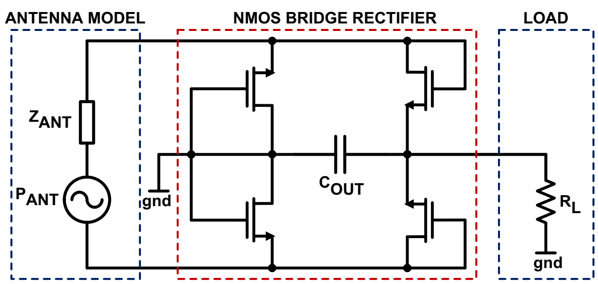

Fig. 1. Antenna driving NMOS bridge rectifier

The use of the built-in optimizer of ADS determines the matching of source and rectifier impedance as required to obtain correct input impedance of the rectifier. The tool minimizes the reflection coefficient between the source and the load which therefore maximizes τ by finding conjugate input impedance with the given input power. Fig.2 shows simulation results of the input impedance of the rectifier versus frequency for input power ranging from -6 dBm to 6 dBm where R_L = 10 kΩ. Each point of the curve corresponds to a matched source impedance as determined by the optimizer. The family of curves represents real and complex impedance variation with input power.

IV. Miniaturized Tag-Antenna Design

A. Antenna with Inductively Coupled Feed

An inductively coupled loop fed meandered dipole antenna [6] shown in Fig.3 is chosen as the the receiving tag antenna. While having an inductive behaviour for conjugate matching with rectifier impedance, its meandered geometry enables miniaturized antenna geometry. The real and imaginary parts of the antenna impedance are given by,

$$R_{ANT} = \frac{(2\pi f M)^2}{R_{RB}}$$
$$X_{ANT} = 2\pi f L_{loop} \tag{4}$$

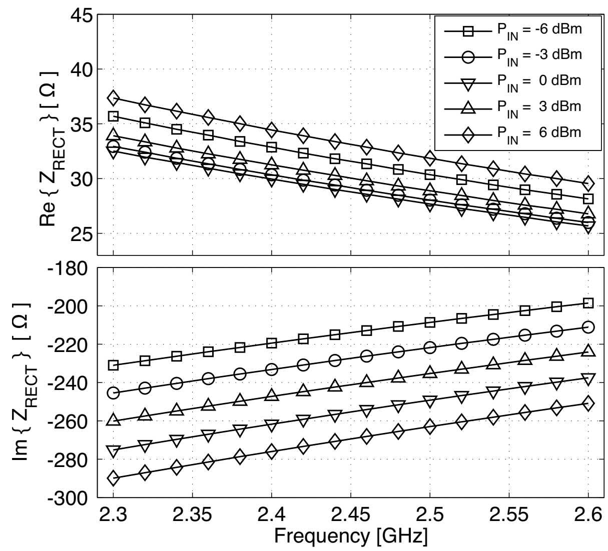

Fig. 2. Simulated input impedance of rectifier (R_L = 10 kΩ)

where M is the mutual inductance between the radiating body of the antenna and the feed loop, L_{loop} is the inductance of the feed loop and R_{RB} is the resistance of the radiating body at its resonance frequency. Notice that the input resistance of the antenna depends on mutual inductance M, while input reactance is the inductance of the feed loop L_{loop}.

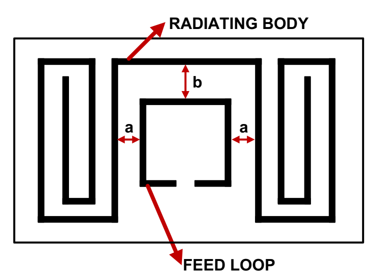

Fig. 3. Inductively coupled loop antenna layout

A complex impedance with large phase angle is the sign of having low input resistance with high reactance. This requires longer feed loop for high inductance as well as increasing parameters a and b in order to reduce the resistance by reducing the mutual inductance. This shows that the antenna dimension is determined by the resonance frequency and its input impedance. Therefore it is necessary to combine the size constraints of the antenna, which results in limited impedance range, with design directions for maximum impedance matching with the rectifier.

B. Case Study

The result of Fig.2 shows that an antenna impedance of $Z_{RECT} = 30 + j250\Omega$ allows a wide input power range with good impedance matching coefficient. The above specifications and the use of CST Microwave Studio gave rise to the design and simulated performance of the antenna. The maximum simulated gain is -2.9 dB. The experimental implementation of the antenna, fabricated on Rogers RO4003 substrate ($\epsilon_r = 3.55$), has dimensions of $16{\times}8$ mm^2 with a substrate thickness of 0.5 mm. Fig.4 shows the photograph of the fabricated antenna.

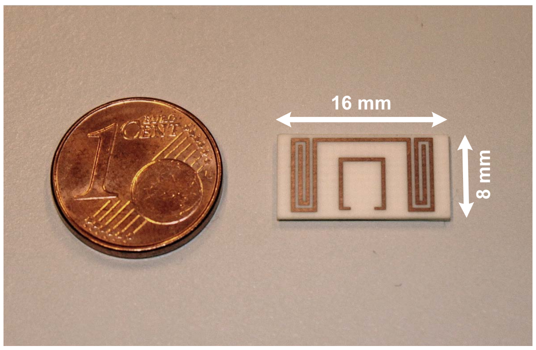

Fig. 4. Tag antenna fabricated on Rogers RO4003 substrate

V. Measurement Results

Experimental tests verify the effectiveness of the fabricated antenna by measuring the output power of the rectifier. The electromagnetic energy is radiated on the tag antenna by a coaxial-fed linearly polarized patch antenna that operates as transmitter antenna. The two antennas are placed at 12 cm distance, facing each other. In order to ensure that the correct amount of power is delivered from transmitter antenna to the tag antenna, transmitter antenna is characterized by using identical patch antennas facing each other as illustrated in Fig. 5. Thus the transmitter antenna gain G_{TX} is measured and used for tag antenna calculations. To characterize the transmitter antenna, different loss contributors are taken into account. In addition to the free-space path loss there are also the losses of other elements in the communication link affecting the performance. Considering the measurement setup for the transmitter antenna, the losses can be accounted for with link budget equation given by

$$P_{RX} = P_{TX} + G_{TX} - L_{TX} - L_{FS} + G_{RX} - L_{RX} \quad (5)$$

where P_{TX}, G_{TX} and G_{RX} are previously defined parameters, L_{FS} is free-space path loss defined by $(\lambda/4\pi d)^2$. The coaxial cable and mismatch losses of the transmitter and receiver antennas are denoted as L_{TX} and L_{RX} respectively.

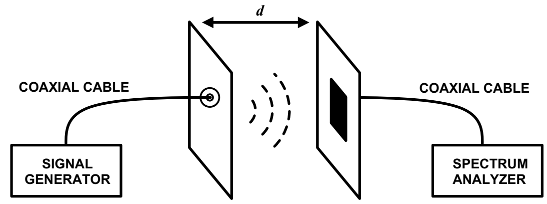

Fig. 5. Setup used to determine transmitter patch antenna gain

A. Gain of TX Antenna G_{TX}

The gain measurement of transmitting antenna verifies the accuracy of simulations. The experiment uses two identical transmitting antennas, then knowing the cable loss and reflection coefficients, the Friis transmission equation gives rise to the following relation,

$$P_{RX(T)} = P_{TX} \cdot G_{TX}^2 \cdot \left[\frac{\lambda}{4\pi d}\right]^2 \quad (6)$$

where $P_{RX(T)}$ is the received power by the receiving transmitter antenna. By using (6) including cable loss and reflection coefficient, the measured peak gain of transmitter antenna G_{TX} results 6.5 dB. The measurement results are in good agreement with simulations where G_{TX} is 6.4 dB.

B. Measurement of the Power Link

The wire bonding of the tag antenna and the rectifier, integrated using a $0.18\mu m$ technology makes the rectenna. Fig.6 shows the micro-photograph of the chip. Accounting for gain of the tag antenna and input impedances of the antenna and the rectifier, the combined efficiency of the system is

$$G_{TAG} = G_{RX(R)} \cdot \eta = \frac{P_{OUT}}{P_{TX} \cdot G_{TX} \cdot \left[\frac{\lambda}{4\pi d}\right]^2} \quad (7)$$

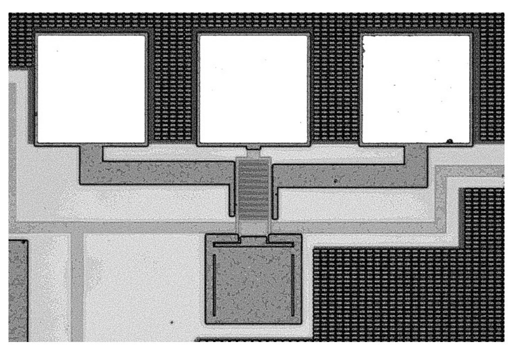

Fig. 6. Micrograph of the fabricated NMOS bridge rectifier

The experimental measurements, performed with transmitter and receiver at 12cm distance and compensation for the transmitter losses, did not verify the gain of the tag antenna calculated by output power where expected

P_{OUT} is 1.25 mW instead the measured one was 0.3 mW. From Fig.2 notice the impact of the input power on the relative change of rectifier impedance which is greater on the imaginary part than the real part. Therefore we tried to rule out the poor impedance matching possibility by testing the rectifier with set of antennas having imaginary impedances ranging from j110Ω to j400Ω while the real part is kept constant at 30Ω. The output power of different antennas with same experiment setup is depicted in Fig.7. The maximum measured output power is $560\mu W$ with $Z_{ANT} = 30 + j180\Omega$ which is still lower than the expected P_{OUT}.

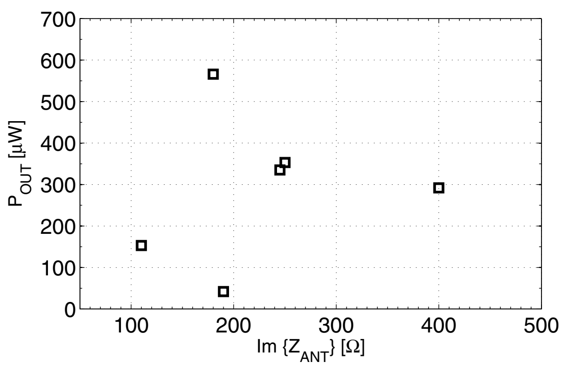

Fig. 7. Measured output power of the rectifier versus X_{ANT}

Since using different antennas with varying imaginary impedance did not improve the efficiency of the rectenna significantly, it is worthwhile to analyze the rectifier efficiency. As custom integrated circuits are subject to process variations, the rectifier is simulated for process corners. We found that the rectifier constructed with zero-V_T transistors is highly sensitive to process variations, which exhibits simulated power efficiency of 75% in best case and 1.1% in worst case. Additionally, the input impedance of the rectifier is also dependent on the process corner of the fabricated rectifier. Table I summarizes the rectifier efficiency and input impedance for different process corners.

TABLE I
RECTIFIER CHARACTERISTICS WITH PROCESS CORNERS

Corner	$Z_{ANT} = Z^*_{CHIP}[\Omega]$	Efficiency (%)
SS (Slow)	15 + j285	78
TT (Typ.)	33 + j260	35
FF (Fast)	98 + j41	1.1

The corner analysis show that characterization of a small antenna with the output power of a rectifier with a custom integrated circuit should be avoided where the rectifier performance is highly sensitive to the process corners. We can conclude that not only the impedance matching but also the rectifier efficiency with respect to fabrication process affect the overall gain of the system.

Experiments show that the maximum gain of the rectenna G_{TAG} is -13.7 dB where the simulated rectenna gain was -7.8 dB. The summary of the measured parameters of the remote powering link with the rectenna is summarized in Table II.

TABLE II
SUMMARY OF REMOTE POWERING LINK MEASUREMENTS

Parameter	Value
Frequency	2.45 GHz
$P_{EIRP}(P_{TX} \cdot G_{TX})$	2 W
Distance (d)	12 cm
P_{OUT} (max)	560 μW
$G_{TAG}(\eta \cdot G_{RX,R})$	-13.7 dB

VI. CONCLUSION

In this work a simulation oriented methodology for the design of a miniaturized antenna and an integrated rectifier is presented. Performing simple measurements determines the parameters of the power link with the emphasis on the transmitter antenna in order to ensure that correct amount of power is transmitted. The introduced method allows characterization of the power link easier than the time consuming experimental and costly measurements. Analysis and measurements indicate that precise characterization of the rectifier in terms of power efficiency and input impedance determines accurate characterization of the miniaturized tag antenna with the proposed method. Therefore, the use of a rectifier having less sensitivity to process variations can facilitate more accurate characterization of the fabricated tag antenna.

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