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Impedance-Matched Sensor-Tag Antenna Design Using Genetic Algorithm Optimization

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***Abstract*— Optimal matching between tag antenna and integrated circuit is crucial for maximizing delivered power in remotely-powered sensor systems. The method maximizes conjugate matching between antenna with inductive reactive impedance and an integrated circuit with capacitive reactive impedance. Obtaining the desired conjugate impedance by the intrinsic antenna impedance excludes the need of an impedance matching network. This enables fully integrated sensor systems with further miniaturization. In this study the design of a meandered slot antenna with genetic algorithm optimization for an operation frequency of 2.45 GHz is proposed. Investigations on constraints limiting the power link efficiency between reader and tag antenna at system level outline possible design actions and give rise to the design flow of the antenna. Simulation results on the proposed architecture verify the performance of the designed miniaturized antenna.**

I. INTRODUCTION

Advances in integrated circuit technology enable realization of miniaturized and implantable wireless sensor systems. Performance evaluation of these systems relies on the quality of data communication and the efficiency of power transmission. In the scope of this study the wireless power transmission efficiency is highlighted.

Wireless sensor systems can acquire energy in two different schemes: a) powered by a battery and b) by scavenging available energy from the environment. Although employing a battery instantly delivers the required energy, the size of the integrated system increases which makes it undesirable for strict dimension constraints. Besides, continuity of operation of the sensor system depends on the battery lifetime which increases maintenance costs for longer deployment. On the other hand exploiting energy from the environment (e.g. solar, thermoelectric, electromagnetic, and mechanical vibration) is more advantageous than a battery due to the aforementioned facts. Therefore such a system benefits from reduced maintenance costs and miniaturization of the system.

The power transfer mechanism of these sensors can be analyzed in the context of wireless remote powering of passive RFID tags. Since fundamentals of passive RFID tags are well established [1], the analogy between these systems can be exploited to model the behavior of wireless sensor systems. Therefore remote powering can be utilized using an antenna as in the case of passive RFID tags.

Various antenna solutions provide different input impedance characteristics considering high frequency electromagnetic coupling in UHF and microwave frequencies. In addition, a rectifier, which converts the AC signal received by the antenna into DC, can have different range of complex input impedance depending on its design and fabrication technology. These two facts come up with the problem of impedance matching of antenna and the rectifier in order to maximize the efficiency of power transmission. Impedance matching can be performed by a passive matching network that requires additional circuit components. This method brings further costs and overall system size increment. Therefore a systematic antenna design methodology for specific rectifier impedance becomes necessary to sustain miniaturization and to reduce overall costs.

This work shows the analysis of delivered power from an electromagnetic energy source to a receiving tag antenna emphasizing the significance of impedance matching between the antenna and the chip. The work provides design directions of a miniaturized impedance-matched tag antenna with genetic algorithm optimization in Section III. Simulation results of the designed antenna are given in Section IV and results are discussed in Section V.

II. IMPEDANCE MATCHING FOR WIRELESS POWER TRANSMISSION

The power received by an antenna which is emitted by another antenna under ideal conditions at a given distance d can be calculated by well-known Friis transmission equation for free space,

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

where P_{EIRP} is the equivalent isotropic radiated power by the source, λ is the wavelength of the transmission frequency and $G_{RX(R)}$ is the realized gain of the receiver antenna. The realized gain of the receiver antenna $G_{RX(R)}$ remains as the only variable for the received power once the frequency and separation distance is fixed.

By looking at (1) it is clear that the wavelength therefore the frequency of transmission impacts the received power.

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The received power in UHF frequencies (e.g. 870 MHz) is approximately eight times greater than the received power at microwave frequency of 2.45 GHz. Implantable systems require small antennas which can result with complex antenna structures such as three dimensional antennas for UHF applications [2]. However increasing frequency to microwave frequency such as 2.45 GHz provides size reduction thanks to the wavelength even with simple antenna geometries. Therefore utilization of 2.45 GHz necessitates the maximization of the efficiency in the power transfer even for limiting the irradiation.

In order to maximize the amount of delivered power from the antenna to the chip, it is essential to have optimal impedance matching between the receiver antenna and the chip input. Referring to (1) the realized gain of the antenna $G_{RX(R)}$ can be defined by,

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

where G_{RX} is the intrinsic gain of the antenna and τ is power transmission coefficient which represents the ratio of power delivered from the antenna to the chip and it is defined by [3],

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

given that Z_{CHIP} and Z_{ANT} are the complex impedances of the antenna and the chip in the form of $Z = R \pm jX$.

A remotely powered integrated circuit with a rectifier as an input stage has a capacitive input reactance [4]. As a result of this, the input impedance of the antenna has to be inductive for conjugate matching with the rectifier. Depicted in Fig. 1, a tag antenna outside its self-resonance frequency has flat impedance characteristic which provides the desired bandwidth with impedance matching.

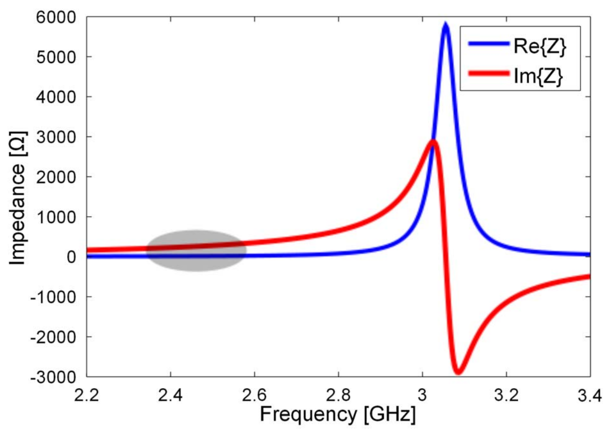

Fig. 1. Real and imaginary impedance of slot antenna

Geometric optimization of antennas for complex impedance matching has been applied to different antenna types. For instance, dipole antennas are matched with the chip by being loaded with resistive and inductive stubs [5]. Moreover, slot antennas are used for complex impedance matching in the form of nested-slot or meandered-slot dipole [6] thanks to their non-resonant inductive behaviors [7]. These antennas are known to have quasi-omnidirectional radiation patterns which make them favorable for being robust to lateral and angular misalignments on moving objects.

Meandered-slot antennas based on nested-slot antennas possess geometry optimized using automated optimization tools. An impedance matched tag antenna for UHF RFID tags is given in [8] where the tag antenna geometry is optimized with genetic algorithm (GA). Next section describes the design procedure of a miniaturized meandered-slot antenna for microwave frequency of 2.45 GHz.

III. Tag Antenna Design with GA

Utilization of genetic algorithm optimization on the design of meandered-slot antenna can provide maximum size shrinking while trying to reach the optimal impedance matching with the chip impedance which is determined by the rectifier. Although numerous iterations of the simulations consume considerable amount of computation time, the algorithm can finally reach the desired solution.

Generic layout of a meandered-slot antenna with N number of slots in Cartesian coordinate system is shown in Fig. 2. The layout of the antenna is chosen to be symmetric with respect to y-axis. In order to enable optimization of the antenna layout, upper and lower coordinates of each slot is parameterized by $S_{N,UP}$ and $S_{N,DN}$ respectively. The widths of all slots are identical and the lengths of the slots are limited to L_{SLOT}.

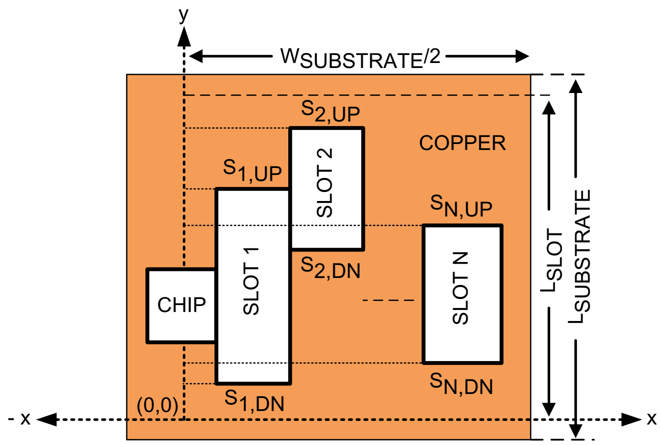

Fig. 2. Generic layout of meandered slot antenna

Since all slots have to be merged in the antenna layout, the coordinates of the slots have to be constrained for successive layout generation where the successor slot (N) is generated with respect to the previous slot (N-1). To guarantee this, the upper and lower coordinates are defined by the dimensional constraints as,

$$S_{(N-1),DN} \leq S_{(N),UP} \leq L_{SLOT}$$
$$0 \leq S_{(N),DN} \leq max(S_{(N),UP}, S_{(N-1),UP}) \quad (4)$$

To prevent the generation of the zero length slots, it is recommended to set the minimum slot length to ensure the convergence of the optimizer. The condition that applies this action becomes valid when,

$$S_{(N),UP} - S_{(N),DN} < \Delta L \quad (5)$$

where ΔL can be as short as the manufacturing limitations.

Referring to (3) the objective is to maximize τ by matching real and imaginary parts of antenna and chip resistance. The fitness function which is desired to be maximized defined by,

$$F = \tau(f) \quad (6)$$

where f is the single frequency of interest for performing the optimization.

The population size to generate the coordinates of each $S_{N,UP}$ and $S_{N,DN}$ has an impact on the total simulation time. Choosing a small population takes less simulation time than a bigger population however it can diverge from the optimal solution. On the other hand a bigger population can find an accurate solution with increased simulation time since each iteration takes greater number of simulations time to generate new population.

Based on the given methodology and the constraints, a meandered slot antenna layout with $N = 30$ in Fig. 3 is generated with integrated GA optimization for a chip impedance of $Z_{CHIP} = 15 - j250\ \Omega$ at 2.45 GHz operation frequency.

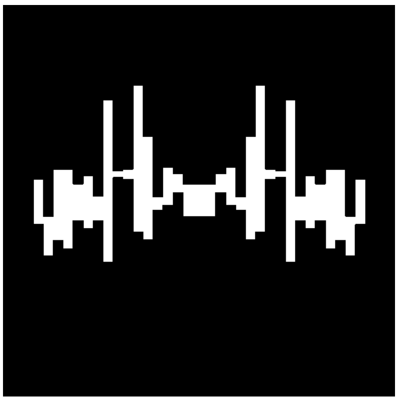

Fig. 3. Optimized antenna layout for $Z_{CHIP} = 15 - j250\ \Omega$

The antenna layout is optimized for a printed circuit board with dimensions of 24 mm×24 mm with a slot width of 0.6 mm and ΔL of 0.5 mm. Once an optimization cycle is finished it is possible to fine tune the antenna layout to achieve greater power transmission coefficient. Therefore, a second optimization cycle can be performed with a narrow range coordinates which were calculated in the previous optimization cycle. Given in Fig. 4, a second optimization step for the designed antenna with 5% of variability in the slot coordinates is demonstrated.

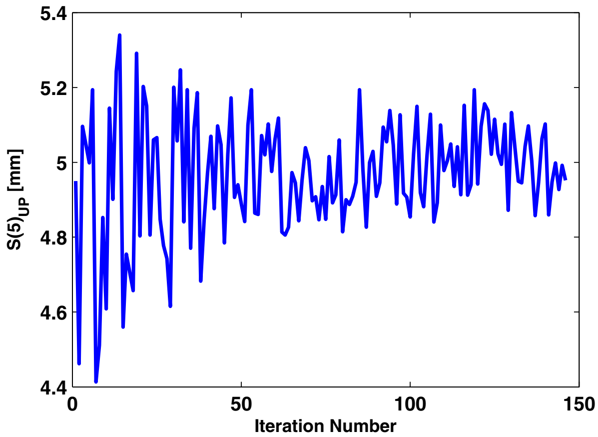

Fig. 4. Convergence of slot coordinate with lower mutation rate

It can be seen that after certain number of iterations the coordinate value is converged for the desired optimizer goal.

IV. Simulation Results

The design of a meandered slot antenna for 2.45 GHz operation frequency is carried out with GA optimization on a Rogers RT/Duroid 5880 PCB which has a dielectric constant of $\varepsilon_r = 2.2$ and dielectric thickness of 0.8 mm. The impedance of the optimized antenna is desired to be matched with the chip impedance $Z_{CHIP} = 15 - j250\ \Omega$.

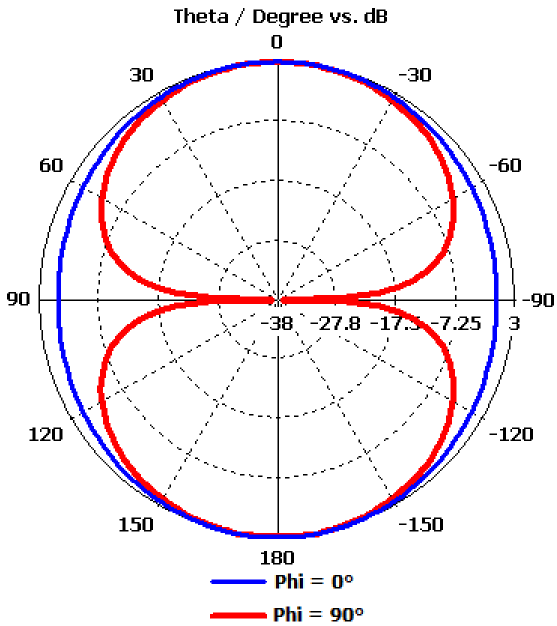

Fig. 5. Far-field radiation pattern of the antenna

Design optimization and electromagnetic simulations of the antenna are performed with CST Microwave Studio [9]. As shown in Fig. 5, the far-field gain G_{RX} at 2.45 GHz is found to be 2.8 dB. The power transmission coefficient τ is found to be 0.9 meaning that 90% of the power received by the antenna is delivered to the rectifier. It is more useful to calculate the realized gain of the antenna $G_{RX(R)}$ by performing a broadband far-field simulation. The realized gain is depicted in Fig. 6.

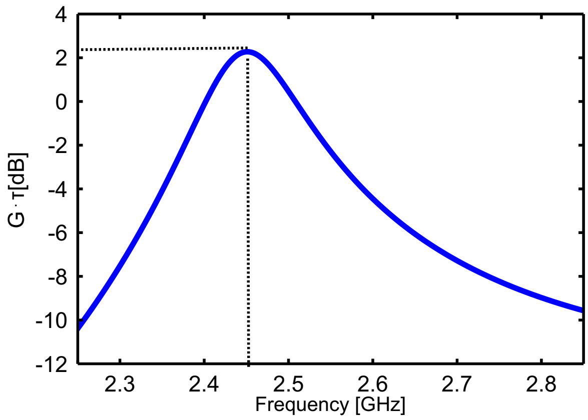

Fig. 6. Realized gain of the antenna versus frequency

The maximum realized gain is found as 2.25 dB at 2.45 GHz. A bandwidth of 100 MHz from 2.4 GHz to 2.5 GHz is spanned by a realized gain of $G_{RX(R)}$ greater than 0 dB.

V. Conclusion

This work has presented the design of a 2.45 GHz miniaturized meandered-slot antenna with genetic algorithm optimization which was previously published for UHF RFID systems. The trade-off between operation frequency and antenna design complexity in the context of wireless remote powering of sensor-systems is explained. Elimination of the impedance matching network between the proposed antenna and rectifier is emphasized. The design methodology of the meandered-slot antenna geometry is explained in detail for successive slot generation. Optimization of the meandered-slot antenna with the dimensions of 24 mm x 24 mm x 0.8 mm and a total volume of 460 mm^3 is optimized for a chip impedance $Z_{CHIP} = 15 - j250\ \Omega$ resulting with a power transmission coefficient τ of 0.9. The maximum realized gain of the antenna is found to be 2.25 dB. The bandwidth of realized gain which is greater than 0 dB is found as 100 MHz.

It is shown that the genetic algorithm optimization can be used as a tool to design custom miniaturized antennas for different chip impedances while eliminating the need of a matching network.

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