Design of a Miniaturized Omni-Directional RF-to-dc IR-WPT

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***Abstract*—This paper proposes the design and experimental validations of a 13,56 MHz IR-WPT link with a conformal transmitter (Tx) and a miniaturized (about 1 cubic centimeter) receiver (Rx). The Rx is composed of three receiving coils wrapped around a miniaturized sphere and mutually orthogonal, arranged in such a way that quasi-constant dc-output voltage and efficiency are obtained, regardless of the receiver orientation in 3-D. The conformal transmitter is designed to maximize the coupling coefficient, at a reference distance of 5 cm, and is about 7×10^{-3}. The quasi-constant output voltage is obtained by connecting each Rx coil to its class-E rectifiers, optimized together with the rest of the system, and by series-connecting their dc output ports, thus de-facto removing any possible dark zone. With a 10-V input source, the dc-output voltage is always above 2.7 V and an average conversion efficiency of 13% for any possible 3-D receiver orientation is obtained.**

***Index Terms*—Implantable device, IR-WPT, Inductive Powering, Class-E rectifier.**

I. Introduction

The wireless powering of implants has been addressed with increasing interest [1], which would provide a safe and less invasive alternative to the replacement of batteries through surgery. Issues related to system reliability are still under investigation, for both near-field (reactive) and far-field (radiative) implementations.

This work proposes a near-field resonant inductive system operating at $13.56\,\mathrm{MHz}$, designed with the goal of being insensitive to every 3-D Rx rotation, which is usually unknown, and to achieve a reasonable efficiency with a miniaturized receiver, having a volume of the order of a cubic centimeter. Previous attempts to solve this problem are available in the literature [2], [3], but miniaturization and omni-directionality constraints, necessary for implantable devices, have not been fully solved. Indeed, most proposed links are designed assuming a known receiver position, rarely taking into account possible movements or misalignments; when the coil rotates, the shared flux varies significantly and thus the output power and voltage. A successful attempt to reduce energy transfer variation to a small implants has been recently demonstrated in [4], but for a rotation in a 2-D plane only. Moreover, in [4], the receiver is larger, the working frequency lower ($6.78\,\mathrm{MHz}$), but a comparable efficiency is achieved.

In this work, a 3-D miniaturized Rx is adopted to realize the quasi-constant output dc-voltage and power for any possible receiver rotation. It consists of three orthogonal coils wrapped around a plastic sphere, which acts as the capsule; each coil is connected to its own optimized class-E rectifier and the three dc outputs are series-connected. This solution demonstrates a reduced output voltage ripple for any possible Rx orientation, ensuring the continuous powering of the implant. The system design, from the Tx coil to the Rx dc-load, is carried out by

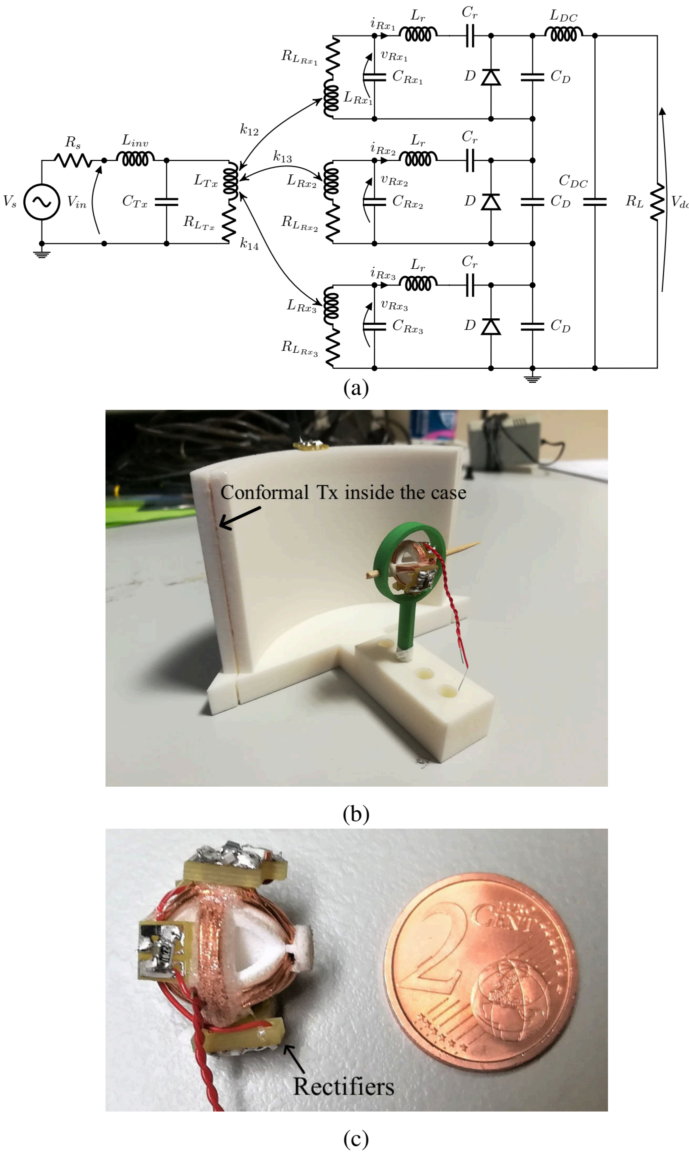


Fig. 1. (a), circuit equivalent of the RF-to-dc link; (b), picture of the realized prototype with the 3-D printed hosting setup; (c) miniaturized receiver compared to a 2 euro cent coin.

means of EM/nonlinear co-simulation [5].

The results confirm that the proposed solution allows to remotely provide at least $2.7\,\mathrm{V}$ at $5\,\mathrm{cm}$ on an optimum load of 2700 Ohm, corrisponding to a dc-power of 2,5 mW. These values are fully compatible with state-of-the-art implantable devices needs of power and turn-on voltage. The prototype and first experimental validations are provided.

II. RF-to-dc Link design

The design of the omni-directional and optimized WPT link starts with the Tx coil input, excited by a voltage source with a $50\,\Omega$ internal impedance at $13.56\,\mathrm{MHz}$. Fig. 1(a) shows the equivalent circuit model of the designed IR-WPT system, Fig. 1(b) pictures the first prototype realized by 3-D printing and Fig. 1(c) displays the dimensions of the 3-D Rx coils. For this version of the prototype the rectifiers are mounted on pcb and glued on the coils. In the ultimate version the circuitry will be hosted inside the sphere.

A. The RF-to-RF link

A large transmitter is geometrically optimized to maximize the shared flux, thus the kQ [6], in the direction of the miniaturized Rx receiver axis and at the distance of $5\,\mathrm{cm}$. This operating distance is chosen to be comparable to the distance between the skin and the left ventricular apex or the digestive tract. The optimized geometrical parameters are: h and w_1, chosen in order to obtain a conformal coil adaptable to be lean on the body surface, as for example the abdomen. The Rx is composed of three orthogonal coils, thus enabling to receive power in any 3-D position, regardless of the Tx-Rx orientation (see Fig. 1(b)). By full-wave EM simulation, during which the RX position has been varied by rotating the receiver around the three orthogonal axes, different sets of RF-to-RF links are calculated. The full exploitation of the 3-D Rx rotations highlights several θ-ϕ combinations, showing dichotomic performance.

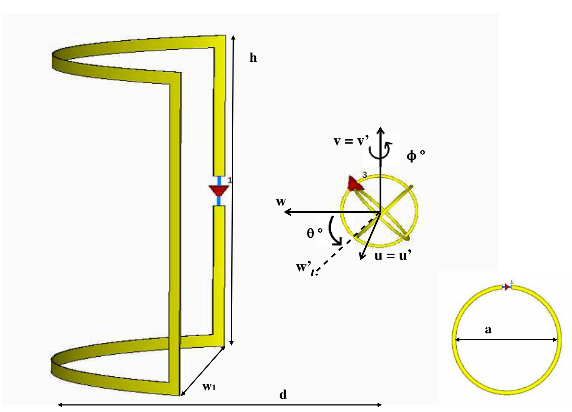


Fig. 2. Rotation angles θ-ϕ. The Tx dimensions are: $h = 52\,\mathrm{mm}$, $w_1 = 100\,\mathrm{mm}$. The Rx coil dimensions are: $a = 12\,\mathrm{mm}$ and the operating distance is $d = 50\,\mathrm{mm}$. Single-loop receiving coils are displayed only for visualization purposes, to enable a clearer description of the angles.

The equivalent circuit parameters of Fig. 1(a) are derived and the coupling coefficients are listed in Table I and Table II for θ= 45° and θ= 60°, respectively. Although the self-inductances do not vary, the coupling coefficients clearly show significant different operating conditions. This behaviour is overcome by the proposed 3-D structure and the rectifiers topologies, which guarantee an almost constant overall Tx-to-Rx coupling, regardless the Tx and Rx reciprocal orientation.

TABLE I
Equivalent circuit parameters of the RF-to-RF link at θ= 45°, for various ϕ

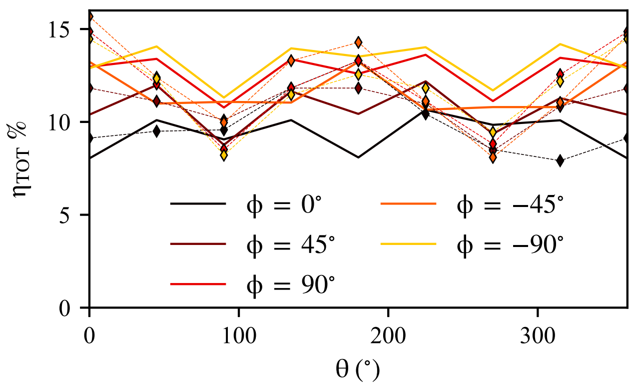
ϕ	k_{12}	k_{13}	k_{14}
0	-5.05×10^{-3}	-4.82×10^{-6}	-4.95×10^{-3}
45	-3.48×10^{-3}	-5.09×10^{-3}	-3.48×10^{-3}
90	3.19×10^{-6}	-0.707×10^{-2}	1.00×10^{-5}
135	3.48×10^{-3}	-4.82×10^{-3}	3.59×10^{-3}
180	5.04×10^{-3}	1.94×10^{-6}	5.14×10^{-3}
225	3.62×10^{-3}	4.97×10^{-3}	4.97×10^{-3}
270	-5.09×10^{-6}	0.71×10^{-2}	-0.83×10^{-6}
315	-3.61×10^{-3}	5.09×10^{-3}	-3.53×10^{-3}

TABLE II
Equivalent circuit parameters of the RF-to-RF link at θ= 60°, for various ϕ

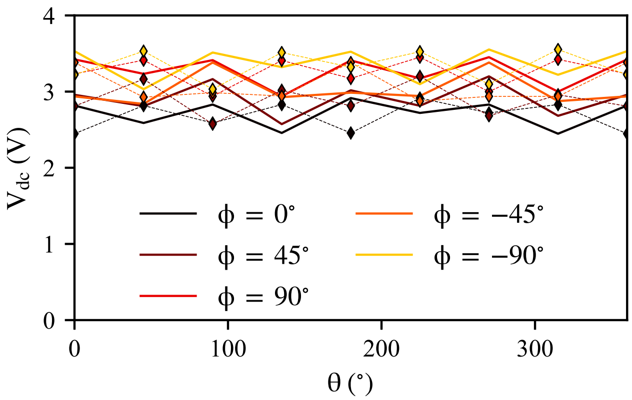
ϕ	k_{12}	k_{13}	k_{14}
0	3.58×10^{-3}	-5.22×10^{-6}	-6.03×10^{-3}
45	-2.48×10^{-3}	-5.12×10^{-3}	-4.32×10^{-3}
90	1.84×10^{-6}	-0.71×10^{-2}	0.924×10^{-5}
135	2.50×10^{-3}	-4.94×10^{-3}	4.41×10^{-3}
180	3.60×10^{-3}	-1.00×10^{-5}	6.26×10^{-3}
225	2.54×10^{-3}	4.96×10^{-3}	4.41×10^{-3}
270	-4.36×10^{-6}	0.71×10^{-2}	6.75×10^{-7}
315	-2.58×10^{-3}	5.16×10^{-3}	-4.32×10^{-3}

B. Design of the RF-to-dc receiver

A proper receiver topology can be realized by connecting each Rx coil with its own rectifier and then connecting the dc outputs in series. With this approach, the output voltage dark-zones are avoided and fluctuations are strongly reduced. The RF-to-dc conversion is performed by a Class-E rectifier, shown in Fig. 1(a), connected to each receiving coil through a LC filter, which ensures a sinusoidal input current. The three outputs are then dc-combined and share the same dc filter, where the inductance L_{DC} provides also a high RF impedance of the dc-combining path. This allows to separate the PCBs of the three rectifiers and thus to freely position the dc filter, without any unwanted spurious RF coupling from the dc line. The equivalent circuit of the transmitter consists in a $50\,\Omega$ voltage source, linked to the resonant Tx coil through the inductance L_{inv}: in this way, the RF-to-RF link acts as a transformer, thus obtaining the source load proportional to the system load. This solution is suitable for sources with high internal series resistance, as in the case of low-power devices powering. The three identical rectifiers are optimized, by means of the Harmonic Balance technique, embedded in the rest of the WPT system, thus accounting for the actual termination impedances. The nonlinear regime is described with 7 harmonics (plus dc), with the goals of maximizing



(a)



(b)

Fig. 3. (a), total efficiency (η_{TOT}), (b), output dc voltage (V_{dc}). Both are relative to $V_s = 10\,\text{V}$. The measured data are included using diamonds.

the total efficiency (see Eq. (1)) and of minimizing the output voltage (V_{dc}) variations for any possible angle. The optimization variables are C_D and the dc-load R_L, which resulted to be $10\,\text{pF}$ and $2.7\,\text{k}\Omega$, respectively. Finally, several voltage source amplitudes are considered to analyze the dynamic behaviour of the proposed design.

III. Prototype and Obtained Results

An early prototype is designed as shown in Fig. 1(b). The three-loop coils are wrapped around three 3D-printed orthogonal disks which are able to rotate around the 3 axis through a Cardan suspension. The optimized components are listed in Table III.

TABLE III
Optimized components values

L_{inv}	140 nH	C_{Rx_3}	890 pF	f	13.56 MHz
$R_{L_{inv}}$	26 mΩ	$R_{L_{Tx}}$	200 mΩ	D	HSMS-2822
L_{Tx}	322 nH	$R_{L_{Rx_1}}$	100 mΩ	C_D	10 pF
C_{Tx}	430 pF	$R_{L_{Rx_2}}$	100 mΩ	L_{DC}	22 µH
L_{Rx_1}	155 nH	$R_{L_{Rx_3}}$	100 mΩ	$R_{L_{DC}}$	20 mΩ
L_{Rx_2}	155 nH	L_r	140 nH	C_{DC}	20 µF
L_{Rx_3}	155 nH	R_{L_r}	20 mΩ	R_L	2700 Ω
C_{Rx_1}	890 pF	C_r	1 nF	R_s	50 Ω
C_{Rx_2}	890 pF				

The proposed 3-D Rx configuration results in a limited voltage variation, with values always above $2.7\,\text{V}$, for a voltage source of 10 V. For any orientation in 3-D a dc-power of at least 2.5 mW is obtained, which is usually sufficient to power an implant [1]. For a 10 V source the current flowing into the transmitter is around 4 mA, therefore the magnetic field in proximity of the receiver is quantified to be around 0.018 A/m, which is in compliance with the ICNIRP guidelines. In Fig. 3(a) the overall efficiency η_{TOT} is plotted for various θ-ϕ rotations and computed starting from the simulated results and defined as in [7]:

$$\eta_{TOT} = \eta_{RF-RF} \ * \eta_{RF-dc} = \frac{P_{dc}}{P_{in}}, \tag{1}$$

with:

$$\eta_{RF-RF} = \frac{P_{Rx_1} + P_{Rx_2} + P_{Rx_3}}{P_{in}}, \tag{2}$$

$$\eta_{RF-dc} = \frac{P_{dc}}{P_{Rx_1} + P_{Rx_2} + P_{Rx_3}}. \tag{3}$$

and

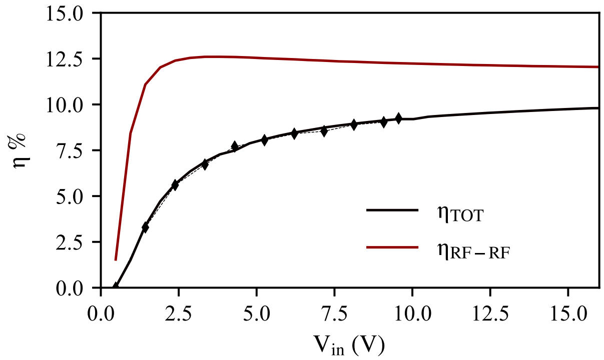
$$P_{Rx_i} = \text{Re}\left\{\frac{v_{Rx_i} i^*_{Rx_i}}{2}\right\} \text{ with } i = 1, 2, 3. \tag{4}$$

where P_{in} is the RF power entering the Tx coil, which is always around 20 mW, and P_{dc} is the power delivered to the Rx load. Fig. 3(b) shows the corresponding dc output voltage for any possible azimuthal and longitudinal rotations.

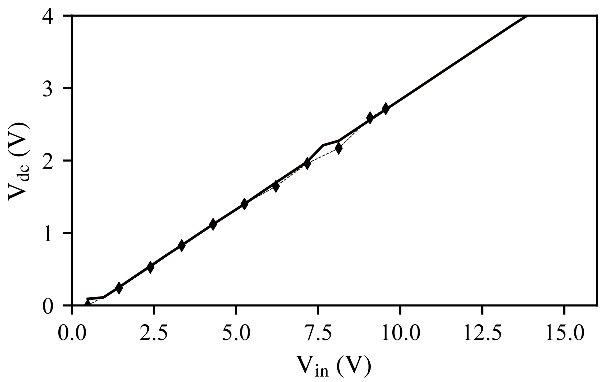
Finally, Fig. 4(a) considers a reference RX configuration, with (θ, ϕ) = $(45°, 45°)$ and the efficiency obtained by varying the V_{in} is plotted: when V_{in} is above the diodes threshold ($\sim 1.5\,\text{V}$) the performances strongly improve, while if it exceeds $10\,\text{V}$ the improvements are reduced due to the diodes nonlinear behaviour. For very low voltage source values, the η_{TOT} degradation is unavoidable since the rectifiers input impedances are far from the optimum ones. On the other hand, when higher source voltages are provided, the rectifiers input impedance has no significant variations and the efficiency is maximized, according to kQ [8]. In the same figures the preliminary measurement results are superimposed and compared with the predicted ones, confirming the accuracy of the design procedure.

IV. Conclusion

The analytical and numerical design of a tiny, omni-directional $13.56\,\text{MHz}$ IR-WPT, suitable for implantable applications, has been presented. A set of three circular coils are arranged in a 3-D orthogonal setup, with specific concerns on miniaturization and omni-directional capabilities: the miniaturized coils radius is only $6\,\text{mm}$. Three orthogonal coils are wrapped around a conformal 3D-printed empty plastic sphere, which will host the rectifier circuits in a future prototype. They guarantee the absence of dark zones, allowing the receiver to be freely oriented in the 3-D space and ensuring a WPT link with almost constant performance. The transmitter is designed using a large conformal coil, which is optimized to maximize the coupling at a reference distance of $5\,\text{cm}$.



(a)



(b)

Fig. 4. (a), simulated (lines) and measured (dots) η_{RF-RF} and η_{TOT}, (b), simulated and measured output dc voltage (V_{dc}). Both are obtained for different V_{in} at (θ, ϕ) = $(45°, 45°)$ and $d = 5\,\mathrm{cm}$.

The power received from each coil is rectified separately and the dc output are combined in series. The output voltage is always above $2.7\,\mathrm{V}$. The total RF-to-dc efficiency has an average value of 13% for all the possible rotations around the three axis.

V. Acknowledgment

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References

[1] K. Agarwal, R. Jegadeesan, Y.-X. Guo, and N. V. Thakor, “Wireless power transfer strategies for implantable bioelectronics: Methodological review,” *IEEE Reviews in Biomedical Engineering*, pp. 1–1, 2017.

[2] G. Joung and B. Cho, “An energy transmission system for an artificial heart using leakage inductance compensation of transcutaneous transformer,” in *PESC Record. 27th Annual IEEE Power Electronics Specialists Conference*. IEEE, 1996.

[3] A. Pacini, A. Costanzo, S. Aldhaher, and P. D. Mitcheson, “Load- and position-independent moving MHz WPT system based on GaN-distributed current sources,” *IEEE Transactions on Microwave Theory and Techniques*, vol. 65, no. 12, pp. 5367–5376, dec 2017.

[4] A. Pacini, F. Benassi, D. Masotti, and A. Costanzo, “Design of a rf-to-dc link for in-body ir-wpt with a capsule-shaped rotation-insensitive receiver,” in *IEEE MTT-S International Microwave Symposium (IMS)*, 2018.

[5] V. Rizzoli, A. Costanzo, and G. Monti, “General electromagnetic compatibility analysis for nonlinear microwave integrated circuits.” IEEE.

[6] T. Ohira, “The kQ product as viewed by an analog circuit engineer,” *IEEE Circuits and Systems Magazine*, vol. 17, no. 1, pp. 27–32, 2017.

[7] A. Costanzo, M. Dionigi, D. Masotti, M. Mongiardo, G. Monti, L. Tarricone, and R. Sorrentino, “Electromagnetic Energy Harvesting and Wireless Power Transmission: A Unified Approach,” *Proceedings of the IEEE*, vol. 102, no. 11, pp. 1692–1711, nov 2014.

[8] K. V. Schuylenbergh and R. Puers, *Inductive Powering: Basic Theory and Application to Biomedical Systems*. Springer, 2009.