Design of a RF-to-dc Link for in-body IR-WPT with a Capsule-shaped Rotation-insensitive Receiver

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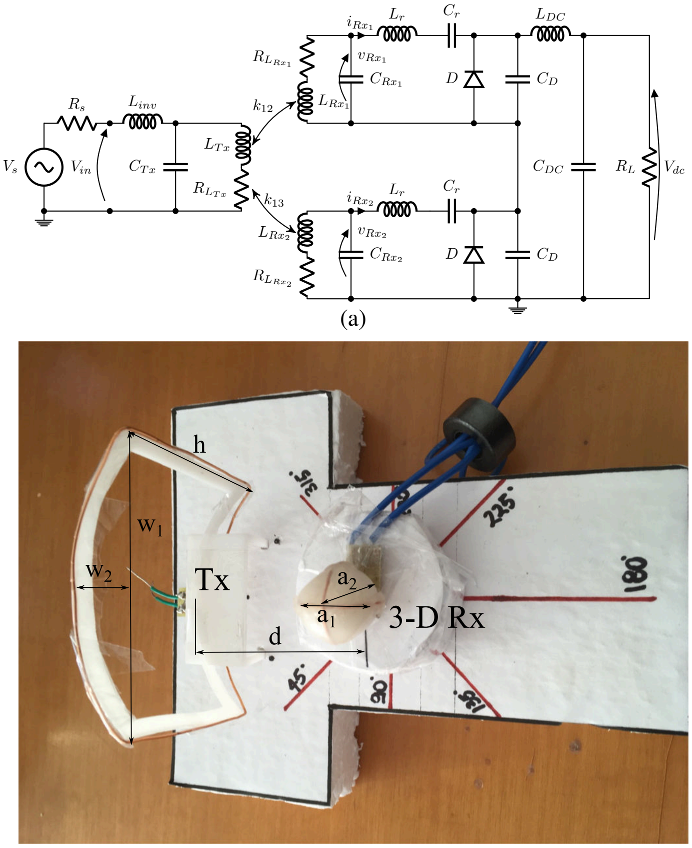
***Abstract*—This paper proposes the design and experimental validations of a 6.78 MHz IR-WPT with one conformal transmitter (Tx) and a couple of receiver (Rx) coils, suitable for powering implantable devices. The Rx coils are arranged in such a way that quasi-constant dc-output voltage and conversion efficiency are obtained, regardless of the receiver rotation, with respect to the transmitter. A 3-D miniaturized receiver, consisting of two elliptical coils wrapped around a capsule and orthogonal to each other, is faced to a conformal transmitter designed to maximize the magnetic flux in the receiver region. In order to avoid dark areas for energy transfer, due to unknown capsule rotations, each Rx coil is connected to one rectifier and the dc output ports are series-connected.**

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



(a)

(b)

Fig. 1. (a), circuit equivalent of the RF-to-dc link; (b), picture of the realized prototype. Two orthogonal coils are wrapped around an ellipsoid plastic capsule with major and minor axes of $a_1 = 24\,\mathrm{mm}$ and $a_2 = 18\,\mathrm{mm}$ mm, respectively. The other dimensions are: $h = 52\,\mathrm{mm}$, $w_1 = 78.54\,\mathrm{mm}$, $w_2 = 12\,\mathrm{mm}$ and $d = 5\,\mathrm{cm}$ to $7\,\mathrm{cm}$ with a $1\,\mathrm{cm}$ step.

I. INTRODUCTION

In recent years, the problem of wireless powering implants has been addressed with increasing interest [1], but a number of issues related to system reliability are still under investigation, for both near-field (reactive) and far-field (radiative) implementations. In this study a near-field inductive powering system at 6.78 MHz for an implanted capsule is designed with the goal of being insensitive to the Rx rotation, which is usually unknown. Previous attempts to solve this problem are available in the literature [2], but miniaturization constraints, necessary for implantable devices, are not addressed.

High efficiencies have been demonstrated in [3], in particular for short distances between the coils. However, most proposed links are optimized for static and known positions, rarely taking into account possible movements or misalignments. Indeed, when the coils rotate, the shared flux varies significantly and thus the output power and voltage.

To realize almost constant output dc- voltage and power, for any possible receiver rotation, a 3-D configuration at the Rx side is adopted. It consists of two orthogonal coils wrapped around an ellipsoid plastic capsule; each one is connected to its own rectifier circuit and their dc outputs are series-connected. In this way a reduced output voltage ripple is obtained for any possible Rx rotation, ensuring continuous powering of the implant. The system design, from the Tx coil to the Rx dc-load, is carried out by means of EM/nonlinear co-simulation. The experimental results, firstly performed for several distances in open air, confirm that the proposed solution allows to remotely provide the minimum required dc-power and voltage to energizing the implantable device, independently of its rotation with respect to the transmitter.

II. RF-TO-DC LINK DESIGN

In order to get rid of dark rotations, the design of the WPT link starts from the Tx coil input, excited by an ideal power source at 6.78 MHz. Fig. 1(a) shows the equivalent circuit model of the designed IR-WPT system, while Fig. 1(b) shows the first prototype photo.

A. The RF-to-RF link

A large transmitter is optimized to maximize the shared flux, and thus the kQ [4], in the direction of the miniaturized Rx receiver axis location. The optimized geometrical parameters are: h, w_1, w_2 and are chosen in such a way to obtain a conformal coil adaptable to be lean on the human body, for example the abdomen, to energize an implantable device in the digestive tract. The Rx side consists of a 3-D structure with orthogonal coils wrapped around an ellipsoid plastic capsule of fixed dimensions (see Fig. 1(b)). From the EM simulations of a set of RF-to-RF links, one for any possible rotation (a 0° rotation corresponds to one coil facing the transmitter and the other one orthogonal to it), the associated equivalent circuits parameters of Fig. 1(a), including the losses, are derived and are listed in Table I. While the self-inductances are unchanged, the coupling coefficients clearly show the different operating conditions of each Rx coil with respect to its position: for a 0°-rotation the k_{12} is maximum but k_{13} is negligible, while for a 90°-rotation the coupling coefficients are almost interchanged. A first idea could be to series connect the two Rx coils, but this would simply shift the problem of zero-coupling to other rotations, where k_{12} and k_{13} have the same absolute value with opposite signs, leading to an almost zero-coupling. This is shown in Fig. 2 where the coupling coefficients of the series-connected coils [5], [6] are plotted against rotation for several distance d.

TABLE I
EQUIVALENT CIRCUIT PARAMETERS OF THE RF-TO-RF LINK, FOR VARIOUS RX ROTATIONS

Rotation (°)	k_{12}	k_{13}
0	1.85×10^{-2}	-1.4×10^{-5}
45	1.34×10^{-2}	1.34×10^{-2}
90	-1.88×10^{-5}	1.86×10^{-2}
135	-1.32×10^{-2}	1.35×10^{-2}
180	-1.84×10^{-2}	-3.0×10^{-6}
225	-1.32×10^{-2}	-1.33×10^{-2}
270	1.5×10^{-5}	-1.81×10^{-2}
315	1.34×10^{-2}	-1.33×10^{-2}

L_{Tx}	135 nH
L_{Rx_1}	47 nH
L_{Rx_2}	47 nH
$R_{L_{Tx}}$	45 mΩ
$R_{L_{Rx_1}}$	30 mΩ
$R_{L_{Rx_2}}$	30 mΩ

B. Design of the RF-to-dc receiver

A suitable receiver topology can be realized by connecting each Rx coil with its own rectifier and by connecting in series the dc outputs. In this way, large output voltage variations and zero-zones are avoided. A class-E rectifier, shown in Fig. 1(a), is connected to the Rx coil through an LC filter, in order to guarantee a sinusoidal input current. The rectifiers outputs share the same low-pass filter. The transmitter equivalent circuit is represented with a 50-Ohm voltage source connected to the resonant Tx coil through the inductance L_{inv}: in this way the RF-to-RF link acts as a transformer so that source load is 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. All the circuit elements, including the capacitances C_D, connected at the rectifiers outputs, and the dc load, are optimized by means of Harmonic Balance technique, using 7 harmonics plus dc. This is a multi-circuit non-linear optimization since, for each rotation, different coupling factors are used in the equivalent circuit. Furthermore, several voltage source amplitudes are considered. The optimum obtained load is 320 Ω.

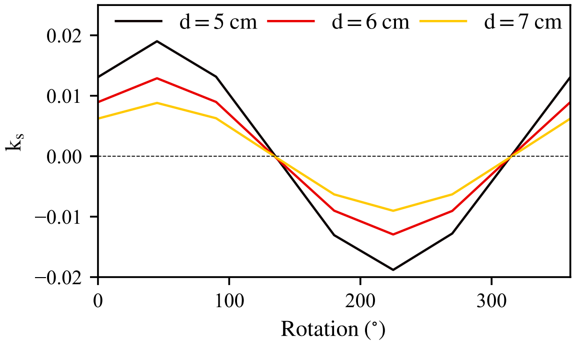


Fig. 2. EM simulations of the coupling coefficient of the RF-to-RF link, resulting from series connection of the two Rx coils, versus Rx rotations.

III. SIMULATED AND MEASURED RESULTS

A first prototype, resulting from the multi-circuit optimization, that is from the Tx input port to the dc output, is built and a photo is reported in Fig. 1(b). The final component values are listed in Table II: the resistances representing the coils losses are verified using an RLC meter. The measurement setup is shown in Fig. 3: the Tx input is connected to a 6.78 MHz voltage source and the dc output to a multimeter. An oscilloscope controls input voltage and the voltage across $R_{L_{inv}}$.

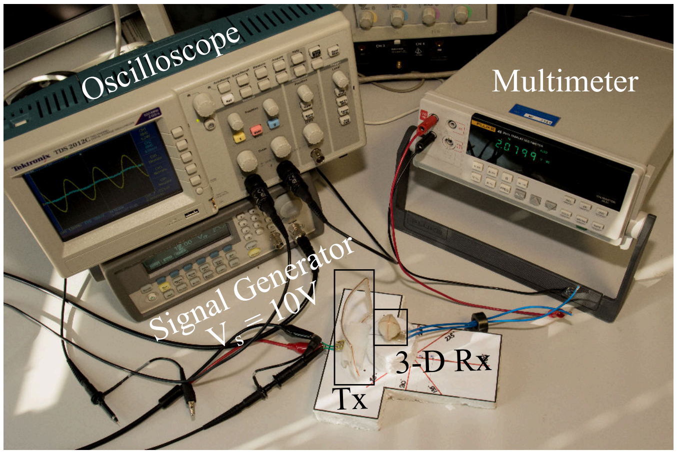


Fig. 3. Measurement setup.

TABLE II
PROTOTYPE COMPONENTS VALUES

L_{inv}	140 nH	C_{Rx_2}	10 nF	D	HSMS-2822
$R_{L_{inv}}$	1 Ω	$R_{L_{Tx}}$	50 mΩ	C_D	50 pF
L_{Tx}	141 nH	$R_{L_{Rx_1}}$	35 mΩ	L_{DC}	50 µH
C_{Tx}	3.9 nF	$R_{L_{Rx_2}}$	35 mΩ	$R_{L_{DC}}$	2 Ω
L_{Rx_1}	53.2 nH	L_r	140 nH	C_{DC}	20 µF
L_{Rx_2}	55.1 nH	R_{L_r}	1 Ω	R_L	320 Ω
C_{Rx_1}	10.3 nF	C_r	3.9 nF	R_s	50 Ω
		f	6.78 MHz		

Fig. 4 reports the simulated and measured dc-voltage on the Rx optimum load, for a Tx-to-Rx distance of 5 cm and a voltage source V_s of 10 V: they are in very good agreement and both show the effectiveness of the proposed design which ensures reduced outputs variation with capsule rotation. This is highlighted by the comparison with the results obtained with a one-coil configuration which shows several rotations where providing a rectified voltage is not possible.

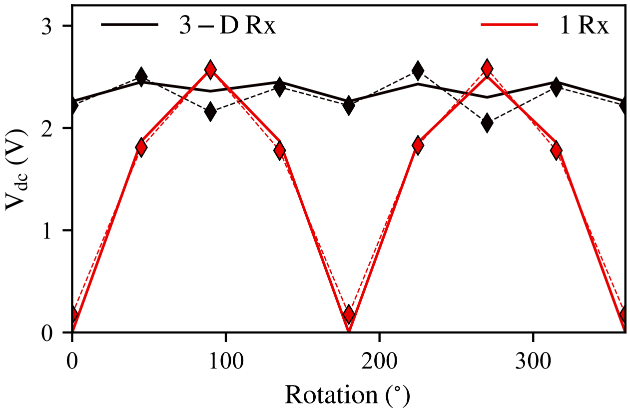


Fig. 4. Rectified output voltage obtained by a system with one Rx coil (red) and by the proposed solution (black). The distance d is 5 cm, diamonds represent measurements. $V_s = 10\,\text{V}$.

On the other hand, the proposed 3-D Rx configuration results in a limited voltage variation (less than 20%) with values always above 2 V, therefore sufficient to power an implant in every rotation.

In Fig. 5 the overall efficiency η_{TOT}, defined as in [7], [8], is tested over rotation, for various distances (d), and defined as in :

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

with:

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

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

and

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

where: P_{in} is the RF power entering the Tx coil and P_{dc} is the power delivered to the Rx load. As the distance increases, the efficiency decreases since the coupling coefficient decreases, but the variability with rotation is limited.

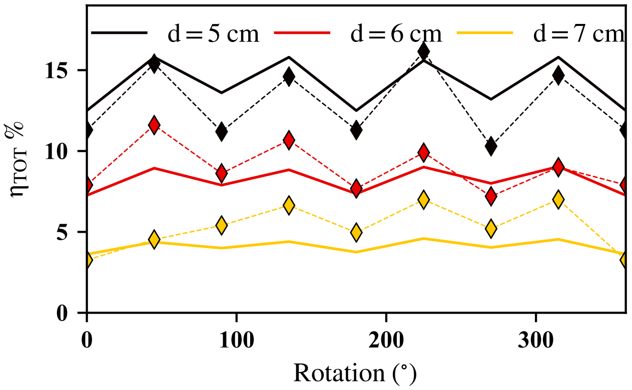


Fig. 5. η_{TOT} predicted and measured for increasing Tx-Rx distances: diamonds are measurements ($V_s = 10\,\text{V}$).

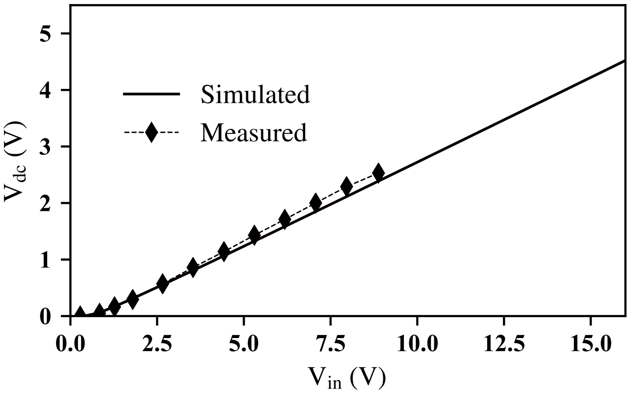


Fig. 6. Simulated and measured V_{dc} vs V_{in}

Finally the system efficiency, varying V_{in}, is tested and the results are summarized in Fig. 7, where the predicted and measured η_{TOT} are plotted for a 45°-Rx rotation: better performances are obtained once V_{in} is well above the diodes threshold ($\sim$ 1 V). At lower levels of the source, η_{RF-RF} is low because the rectifiers input impedances are far from the designed one. While at higher levels of the source, the rectifiers input impedance does not change significantly and the efficiency is maximized, according to kQ [9].

IV. CONCLUSION

The design and experimental validation of a 6.78 MHz IR-WPT, suitable for implantable applications, has been presented. A couple of miniaturized Rx coils are wrapped around a capsule orthogonal to each other, while a large conformal transmitter (Tx) is used. To solve the problem of dark zones, occurring when the capsule rotation is casual, the received power from each coil is rectified separately and the dc outputs are combined in series. The validation of the prototype, optimized for a

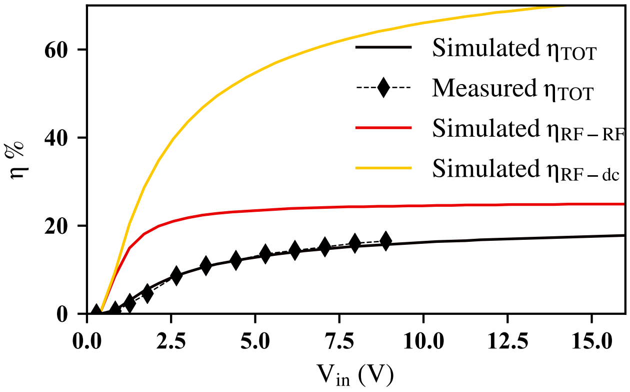


Fig. 7. η_{TOT}, η_{RF-RF} and η_{RF-dc} for different V_{in} at 45° and $d = 5\,\text{cm}$.

reference Tx-to-Rx of 5 cm, is carried out in open air, for different distances and it is shown that a voltage source of 10 V is sufficient to remotely provide the dc power to activate an implantable device.

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