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Multicoil Resonance-Based Parallel Array for Smart Wireless Power Delivery

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Abstract— **This paper presents a novel resonance-based multicoil structure as a smart power surface to wirelessly power up apparatus like mobile, animal headstage, implanted devices, etc. The proposed powering system is based on a 4-coil resonance-based inductive link, the resonance coil of which is formed by an array of several paralleled coils as a smart power transmitter. The power transmitter employs simple circuit connections and includes only one power driver circuit per multicoil resonance-based array, which enables higher power transfer efficiency and power delivery to the load. The power transmitted by the driver circuit is proportional to the load seen by the individual coil in the array. Thus, the transmitted power scales with respect to the load of the electric/electronic system to power up, and does not divide equally over every parallel coils that form the array. Instead, only the loaded coils of the parallel array transmit significant part of total transmitted power to the receiver. Such adaptive behavior enables superior power, size and cost efficiency then other solutions since it does not need to use complex detection circuitry to find the location of the load. The performance of the proposed structure is verified by measurement results. Natural load detection and covering 4 times bigger area than conventional topologies with a power transfer efficiency of 55% are the novelties of presented paper.**

I. Introduction

There are several applications in which electronic device cannot use batteries as primary source of energy, including bio-implantable devices [1-4] and smart animal research systems [5-9]. Implantable devices or head mountable monitoring systems for animal research are examples of such devices. In such applications, power must be delivered wirelessly in air or across the skin through an inductive link formed by mutually coupled coils. Indeed, inductive coupling is among the safest method to power up bioimplants because it avoids risks of infection and prevents any dangerous tethering associated with transcutaneous wires. Inductive power transfer received a lot of attention over the last decade. Such near-field electromagnetic power transfer technique can deliver up to several mill watts of power wirelessly across distances of 10 mm to 200 mm [10-14]. Improving power transfer efficiency (PTE) and achieving larger coupling distances, without increasing the losses and absorption in biological tissues, is the aim of several researchers. Safety imposes a maximum absorption rate that limits magnetic field in human biological tissues, which shows the importance of increasing the PTE [15] in implantable applications. However, inductive links suffer from low efficiency in general due to the low-magnetic coupling (k) between coils, which limits the maximum transferable power. Coupling factor between coils and coils quality factors (Q) have strong impact on the PTE. Increasing the distance between the coils dramatically decreases coupling, and thus the PTE. Moreover, the mutual inductance between coils decreases as a function of d^{-3}, where d is the center-to-center distance between the coils. Improving efficiency in wireless power transfer systems is a key to the development of several novel biomedical applications [4]. For instance, the availability of miniature wireless electronic devices will enable long-term biological monitoring of freely moving laboratory mice, which could drastically contribute to the development of new treatments for chronic diseases, such as Parkinson and epilepsy. Providing sufficient and constant energy to wirelessly powering up such devices will be a huge push forward for the advancement of research.

Arrays made of several coils have been employed to provide energy over surfaces and/or inside chambers (Fig. 1). Detection systems have been proposed to avoid driving every coil in the array at the same time [5], which can create interference and crosstalk, and drastically increase power consumption. In [16], only the coils that encompass the detected magnet are activated. A wireless power transfer coil array based on resonance frequency selectivity is proposed to improve the transfer efficiency [17]. On the other hand, although 2-coil links are an optimal choice for achieving high-power delivery at small coupling distances [14], multicoil topologies have recently been proposed to improve power transfer efficiency at longer coupling distance [10, 12, 14]. In addition, multicoil structures provide more degrees of freedom for optimization of the power link [12, 14].

The proposed system extends the applications of such multicoil links to coil arrays to improve power transfer over a large area and to decrease the circuit design challenge associated with such inductive links. The proposed array is demonstrated in a power chamber application dedicated to a research animal laboratory smart setup.

This work proposes a novel multicoil resonant structure based on a 4-coil inductive link that has several applications in bio-implantable devices and smart animal research systems as well. Among others, such strategy enables to build power surfaces that cover larger areas with only one driver circuit and one primary coil. In the following section, we describe the proposed parallel multicoil power transfer

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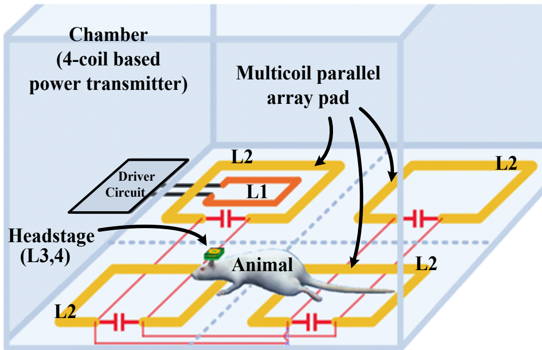

Figure 1. A power chamber structure based on the proposed multicoil array.

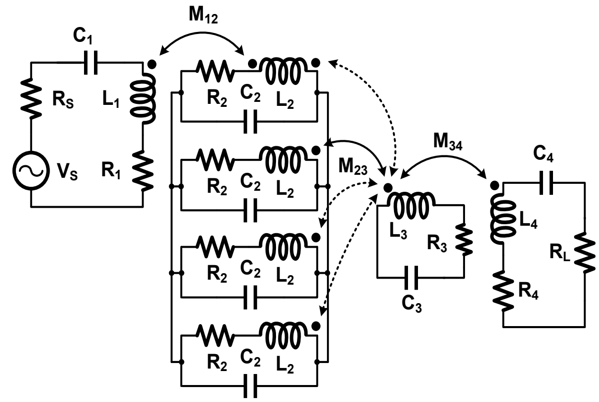

Figure 2. Electrical model of a multicoil parallel array.

array. We then present the simulation and measurement results, and we discuss the adaptive behavior of such a system in Section III. We conclude in the last section.

II. Principle of Parallel Multicoil Array

Multicoil inductive links using 3 and 4-coil topologies have shown significant improvement over conventional 2-coil structures for transferring power transcutaneously across larger distances with higher efficiency [14]. The proposed Parallel multicoil power transmission array is based on a 4-coil inductive link [10]. The transmitter of such an inductive power transfer system uses one primary coil (connected to the driver circuit) and one primary resonance coil, which is made of several coils connected in parallel that form an array, to cover a large area.

The receiver uses one secondary resonance coil and one secondary coil to deliver the recovered power to a load. Such a pseudo-4-coil inductive link has several applications in bio-implantable devices and smart animal research systems (Fig. 1). Such structure enables to build power surface that cover large area with only one driver circuit and one primary coil. Indeed, having only one driver circuit per resonance coil array, instead of one driver per individual resonance coil, like previous systems, is a key for simplicity, higher accuracy and lower cost. A representation of the transmitter for the proposed link topology is shown in Fig. 1. Fig. 2 shows the principle of the proposed multicoil structure. A simple circuit connection scheme is employed. The primary resonance coils are electrically connected in parallel by wires to form an array.

In array configurations (Fig. 2), only one coil has a mutual inductance with the primary coil. The coil coupling factor between the transmitter coil and the receiver are the same for every pair of primary-primary resonance coils. The proposed topology allows the power transmitter to power up a remote system located above the array (Fig. 1), with higher PTE and higher power delivery to the load (PDL), across larger distances, since the proposed topology is based on 4-coil resonance inductive link.

The coil coupling factor, the link efficiency and the delivered power to the load of the proposed power transfer array are simulated, measured and compared with the conventional 4-coil inductive link in next section.

III. Simulation and Measurement Results

A schematic illustrating the connections of the test setup between a network analyzer and the proposed inductive array is shown in Fig. 3. The coil coupling factor corresponds to S21, the scattering parameter between the network analyzer's port 1 and 2 (Fig. 3). The ports of the network analyzer are matched by 50 Ω resistors (Rs=50 Ω). These resistors have a significant effect on the PTE of the link under test. For example, if the coil coupling factor of the link measures -10 dB; it means the PTE equals 10%. Practically, this PTE is much better by using a driver circuit with a lower source resistor. If the effect of the network analyzer ports' resistors is removed (by converting the scattering parameters (S) to Z parameters mathematically [14]), the real PTE of the link under test is obtained, which is close to 80% (when S21=-10 dB). The measurement results obtained by the network analyzer are presented without source resistor cancelation.

In order to measure the performance of the proposed multicoil structure, we have used printed spiral coils fabricated through standard printed circuit board process. Table I shows all specifications of the coils employed for the measurement. Fig. 4 shows a power surface that was built based on the proposed structure. Both the transmitter (coils L_1 and L_2) and the receiver (coils L_3 and L_4) are shown. The primary coil L_1 has mutual inductance with only one paralleled coil element from the primary resonance array. In Fig. 4, the secondary resonance coil array is composed of four paralleled coil elements. This structure covers four times the area of a single coil, with only one driver circuit and one primary coil. Fig. 5 shows the coil coupling factor against the distance between the coil array surface and the receiver, while the receiver is located right above a single parallel coil element of L_2.

Similarly, each coil element of the array, have similar coupling factors and similar mutual inductance with the primary coil L_1. Fig. 6 shows the coil coupling factor between the transmitter and the receiver for the power surface shown in Fig. 4. For this measurement, the distance

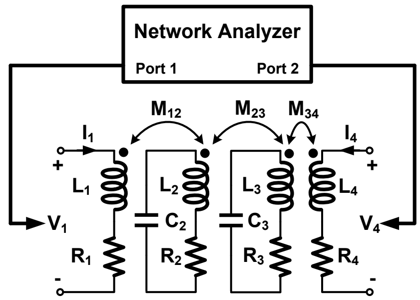

Figure 3: Measurement scheme for testing the inductive link. L_1 (primary coil) and L_4 (secondary coil) are connected to a network analyzer, while L_2 (primary resonance coil) and L_3 (secondary resonance coil) are tuned at a frequency of 13.56 MHz.

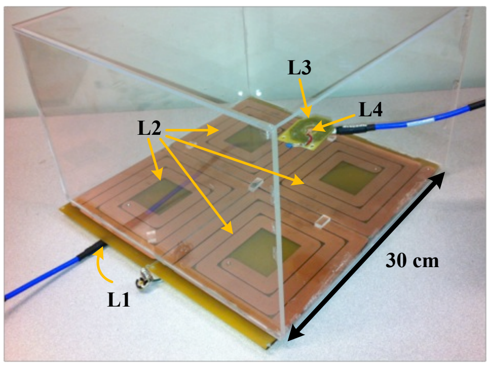

Figure 4. The power surface built based on the proposed structure.

Table I. Specifications of the printed spiral coils at 13.56 MHz.

Parameters	L1	L2	L3	L4
Inductance (µH)	5.165	0.84	0.89	0.54
Parasitic resistance	0.44	0.04	0.15	0.77
Outer diameter (mm)	70	150	41.5	10.5
Inner diameter (mm)	32.5	50	18	3
Line width (µm)	2000	16000	2000	254
Line spacing (µm)	380	1000	380	254
Number of turns	8	3	5	8

between the transmitter and the receiver is constant and equals 4 cm. As mentioned above, it is verified experimentally that only one element from the array has mutual inductance with the primary coil. It shows that the coil coupling factor, thus the electromagnetic field, stays fairly constant everywhere above the parallel coil array (as shown in Fig. 6). The proposed surface has been enclosed in a fiberglass box in order to develop and test a smart animal research system, as shown in Fig. 4.

Coil coupling, PTE and PDL are influenced by the number of coils that are connected in parallel in the primary resonance array. The effect over the aforementioned parameters of adding parallel coils into the primary resonance array of a conventional 4-coil structure is simulated by ADS software and subsequently measured experimentally. PTE and PDL are measured as a function of the number of parallel coils in the array, and compared with the simulation results in Fig. 7. Measurement results show that adding more parallel coils in the array does not significantly affect the PTE and PDL.

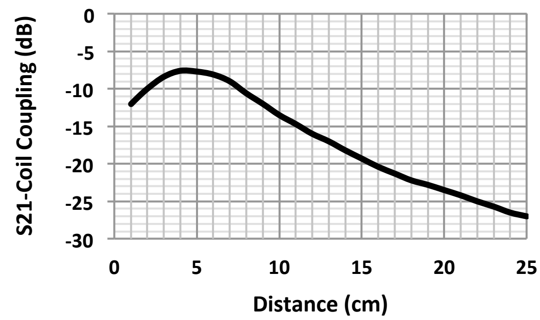

Figure 5. Coil coupling factor as a function of distance for the proposed array structure (measurement results).

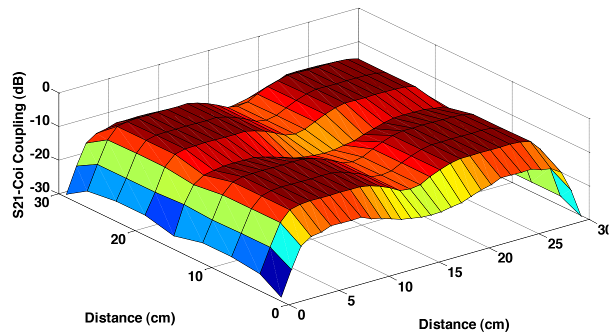

Figure 6. Coil coupling factor above the array structure for d = 4cm (measurement results).

Besides, the proposed parallel multicoil array presents natural adaptive behavior. Indeed, the power transmitted by the primary coil is proportional to the load seen by the coils of the primary resonance array that have mutual inductances with the receiver. Thus, the transmitted power scales with respect to the load of the electric/electronic system to power up, and does not divide equally over every parallel coils that form the array as it could be thought. Instead, the coils of the parallel array that have mutual inductances with the receiver transmit most of the power to the receiver.

Such adaptive behavior enables superior power, size and cost efficiency then previous solutions since it does not need complex circuitry to detect the location of the load. This smart behavior has been verified by sequentially increasing the number of power receivers above the primary resonance array, and measuring the total power drained by the array after adding each additional transmitter. In Fig. 8, the number of loads (on the x axis) tells how many receivers (or loads) are present above the primary resonance array.

Fig. 8 shows the simulated and measured PDL for a four-paralleled coil array, for an increasing number of loads. The delivered power to the load under observation decreases almost from 80 mW to 50 mW when adding a second load above the array, which is close to half of the measured power for a unique load. Subsequently, adding a 3rd and a 4th loads decreases the power delivered to the load under observation to a 3rd and a 4th of the PDL, respectively.

Also, when there are several loads above the array, the total power delivered to the loads equals the sum of the power delivered to each individual load, as shown in Fig. 8

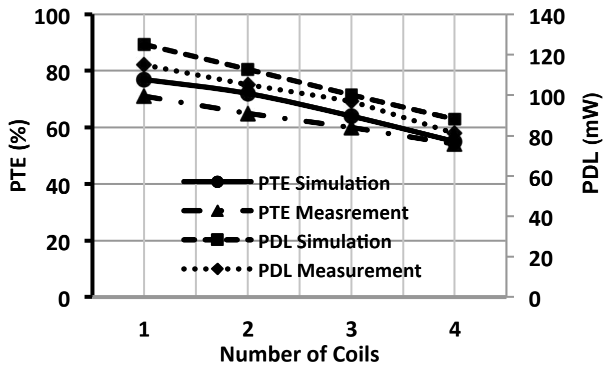

Figure 7. Measurement (d=3cm) and simulation (k23=0.05) results for PTE and PDL, as a function of number of additional paralleled coils.

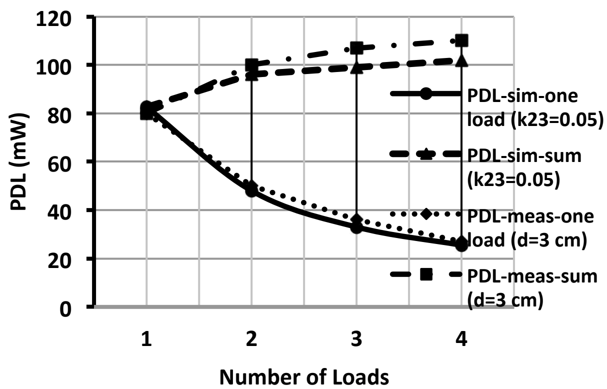

Figure 8. Simulation and measurement results of the PDL as a function of number of loads, regard to the smart system,

as well (upper curves). Thus, in Fig. 8, when x = 2 on the x axis, there is two loads above the array, and the total power delivered to the loads is close to twice the power delivered by each individual load, that is 100 mW. The PTE=PDL/Pin, where Pin (input power) is set constant (150 mW) for all simulations and measurements. Hence, the PTE curves tend to have the same decreasing behavior as for PDL curves of Fig. 8.

In this test, the important point is that the power delivered to the load under observation decreases significantly when putting additional loads above the array. This verifies that the proposed array presents an adaptive behavior without the need for complex control circuitry. Simulation and measurements are in good agreement and both confirm such a behavior.

IV. Conclusion

A novel resonance-based multicoil structure has been proposed to wirelessly and smartly power up apparatus above a surface or inside a chamber. The power transmitted by the driver circuit is proportional to the load seen by the individual coil in the array. Such adaptive behavior avoids the need to use complex detection circuitry to find the location of the load. A simple test has shown that power delivered to the main load decreases significantly when adding more loads, which verifies that the proposed system presents novel load detection ability. Simulation and measurement results have confirmed that only the coils of the transmitter array that have mutual inductance with the receiver coils transmit power (when a load is located above it), and that changing the location of the receiver also changes the location of the active coils in the array. Presented results have been provided to demonstrate the principle of the novel smart power transfer array.

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