Flexible wireless power transfer system based on closed-loop magnetoinductive waveguides: solution to misaligned and rotational systems

Fralett Suárez Sandoval, Saraí M. Torres Delgado, Ali Moazenzadeh, and Ulrike Wallrabe

1. Laboratory for Microactuators, Department of Microsystems Engineering - IMTEK, University of Freiburg, Georges-Koehler-Allee 102, 79110, Freiburg, Germany
2. Laboratory for Simulation, Department of Microsystems Engineering - IMTEK, University of Freiburg, Georges-Koehler-Allee 103, 79110, Freiburg, Germany
E-mail: wallrabe@imtek.uni-freiburg.de

Abstract. We present the characterization of a circular, 1D wireless power transfer system based on magnetoinductive waves travelling through an array of coupled LC resonators. This work builds upon the linear array that we have introduced in our former publications. The use of high quality double-spiral coils combined with an arrangement of 50% of overlapping between consecutive resonating cells renders low attenuation of the travelling wave. Thus, a receiver device located in the near field of the array is able to be powered from the energy travelling through the array. The newly-introduced flexibility of the array provides an additional degree of freedom for its end-application. We measured unoptimized system efficiencies of up to 60% for 1 mm of radial separation at 13.56 MHz. We present the measurement results of the transfer efficiency between the array and a receiver device for two terminating impedances of the array. We also discuss the feasibility of not implementing an impedance modulation scheme when the receiver device revolves inside the array. It was found that one can obtain small output voltage ripples for rotational frequencies as low as 207 revolutions per minute without a modulation scheme. The system is envisaged to recharge in- and on-body devices whose position cannot be directly controlled. The rotational wireless power transfer system could present an alternative to slip rings which are subjected to mechanical wear.

1. Introduction

Wireless power transfer (WPT) via magnetoinductive waves travelling through resonating arrays of one dimension have been demonstrated before as a method to supply to a receiver device in the near-field of the array. However, standing waves in the arrays shift the transferred power and consequently the transfer efficiency to high and low values [2]. As a way to counteract the effects of standing waves one can either adjust the length of the array or change the operating frequency of the array according to the receiver position. An investigation on the dependence of the transmission parameter and transfer efficiency while varying these two parameters according to the receiver position has been reported in [3]. In former publications [4, 5], we formulated a control method based on inexpensive circuitry which permitted to shift in real time the standing waves along a magnetoinductive wave device to prevent the receiver to stand over a resulting
power null. This control method was implemented either at the resonance frequency of the transmitter array [4] or at a different operating frequency [5] inside the bandwidth of the array.

The present work experimentally investigates the efficiency characteristics of an 1D resonating array whose last cell is overlapped with the first, making a circular, closed-loop array. A flexible, closed-loop wireless charger tolerable to misalignment could, potentially, be applied to recharge batteries of implanted medical devices, such as a microstimulator for the vagus nerve [6] or equip every day use items like a backpack [7] with the possibility to recharge electronic devices that are just thrown in it. We also present a case study in terms of a rectified output voltage measured at the receiver device when the device is revolving inside the flexible wireless power transmitter array.

2. 1D resonating array for WPT

2.1. Efficiency of an open-loop array

This work builds upon the open-loop array of LC resonators that we have proposed in [4] as exemplified in figure 1. There we demonstrated how the array based on double-spiral coils renders a low attenuation of the travelling wave along the array due to the optimized quality factor of the coils. In [5], we compared the effect the double-spiral geometry has over the coupling coefficient between two consecutive cells for a lateral displacement sweep between these cells. The array of figure 1 is formed by two rigid double-sided printed circuit boards, both boards have 4 resonating cells, as shown in figure 1(a). The double-spiral coil of each cell is connected in series to a capacitor, thus driving them to resonate at 13.56 MHz. The boards were arranged by placing them on top of each other as shown in figure 1(b), making neighboring cells to have 50% of overlap.

To characterize the system we connected port one of a vector network analyzer (ZVL, Rohde & Schwarz GmbH & Co KG, Germany) in series with the first cell of the array, as shown in figure 1(a) and measure the two-port scattering parameters. The measurement was done for a logarithmic frequency sweep of 801 points between 1 MHz and 100 MHz. Port two of the analyzer is acting as the load impedance (50 Ω) in series with the receiver resonator, which has the same geometry as the cells of the transmitter array. The receiver is moved above the array at an axial separation of 6.5 mm. The system efficiency was calculated using equation (7) of [5]. Figure 2 shows the efficiency with respect to the receiver displacement. Note that the transferred
Figure 3. The closed-loop 1D array is demonstrated with a three-layer flexible printed circuit board on a polyimide substrate. Copper of 35 µm in thickness acts as the conducting material. Resonant behavior is achieved with surface-mount capacitors. The array is excited at the first cell and the last cell is overlapped 50% with the first.

2.2. Efficiency of a closed-loop array

A closed-loop system can be made by overlapping the last cell of a planar array with the first while maintaining the same 50% of overlapping between the last and the first cell. To investigate the behavior of the system with this closed-loop configuration we fabricated the array shown in figure 3. The array has three layers of conducting material (one layer less than the array of figure 1) on a polyimide substrate. The most inner conductor layer is reserved for the capacitors (not present in figure 3) of each cell. Then one layer with four double-spiral coils is stacked over the conducting traces for the capacitors. The layer stack-up extends radially outwards with a second layer of four double-spiral coils displaced by 50% with respect to the first layer. There exist an isolation layer of 39 µm-thick polyimide between consecutive copper layers. The most inner and outer conducting layers are isolated as well, therefore, only the contact pads are exposed.

There is a solid-state relay connected in series with the last cell of the array, the relay can be controlled to set an impedance state for this cell. When the relay is activated, the last cell of

Figure 4. (a) Efficiency between the array of figure 3 with a closed circuit termination at its last cell and a receiver revolved inside the array. The radial separation is 1 mm and the measurement frequency is 13.56 MHz. (b) Efficiency on the surface of the closed-loop array.

Figure 5. (a) Efficiency between the array of figure 3 with an open circuit termination at its last cell and a receiver revolved inside the array. The radial separation is 1 mm and the measurement frequency is 13.56 MHz. (b) Efficiency on the surface of the closed-loop array.
the array is in operation (a closed circuit). When the solid-state relay is deactivated, the series circuit of the last cell is opened, therefore, the active diameter of the array is reduced by one cell. We characterized the system efficiency similarly to the planar array using the two-port scattering parameters. A receiver resonator was revolved inside the array with a radial separation of 1 mm following the trajectory depicted in figure 3. The result of this measurement is shown in figure 4(a) in a linear representation and in figure 4(b) as a surface plot showing the efficiency variation around the surface of the flexible array. Figure 4 depicts the efficiency when the array has all its cells in operation (closed circuit in the last cell). When the last cell is deactivated the efficiency varies as shown in figure 5. Both figures correspond to an excitation frequency of 13.56 MHz.

The efficiency behavior differs between figures 4 and 5 because when the solid-state relay is in the active mode, the last cell of the array is coupled to the first cell with the same coupling factor as the rest of pairs made with consecutive cells. Hence, the wave can continue travelling in the same direction once it reaches the end of the array. Since the coupling between the penultimate cell and the first cell in figure 3 is considerably lower than that between the first and the last cell of the same figure, once the wave reaches the last cell, most of it reflects through the same path it was travelling. We presented in [4, 5] how to sense the actual position of the receiver device and, from that position, adjust the length of the array so that the zero-efficiency spots are avoided. Note that although there exist the same number of zones with low efficiency in figures 4 and 5, the width of these zones is considerably smaller in figure 4 than those of figure 5, at the expense of reaching lower efficiency peaks in comparison to figure 5.

3. Delivering wireless power to a rotatory device
A method to modulate the active diameter of the closed-loop array is useful when the potential receiver device could be displaced from a fixed position but it is not foreseen for it to be in constant revolution. If power needs to be transferred to a revolving device a modulation scheme might not be even needed.

To investigate this hypothesis, we measured the output voltage after rectification as shown in figure 6. The output voltage is depicted in figures 7 and 8 for two different termination impedances. To record these figures the transmitter array was kept still while the receiver was revolved inside the array with a radial separation of 3 mm by mounting it to the axle of a stepper motor. The insets of each figure denote the waveform of the output voltage for different rotational frequencies. As expected, for a fixed RC output filter, in this case 470 µF and 1 kΩ, the larger the rotation frequency, the less the ripple of the output voltage, regardless of the termination impedance state.

4. Conclusion
We presented a flexible, circular, 1D wireless power transfer system based on magnetoinductive waves propagating through LC resonating arrays. It can transmit wireless power in misaligned-presumable configurations like body-worn devices. We measured unoptimized system efficiencies of up to 60% for a receiver device separated 1 mm in the radial direction at an excitation frequency of 13.56 MHz. The termination impedance modulation schemes that we have presented before could be applied as well to the closed-loop transmitter array. Nevertheless,
Figure 7. Recorded $V_{\text{out}}$ of figure 6 with a termination impedance of the transmitter array shown in figure 3 set to an open circuit. The receiver device is revolved inside the transmitter array with varying rotation speeds. A smaller output voltage ripple is observed with increasing rotation speed.

Figure 8. Recorded $V_{\text{out}}$ of figure 6 with a termination impedance of the transmitter array shown in figure 3 set to closed circuit. The receiver device is revolved inside the transmitter array with varying rotation speeds. A smaller output voltage ripple is observed with increasing rotation speed.

modulation might not even be needed if the receiver is revolved inside the array with a sufficient rotational frequency and some output voltage ripple is admissible.

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