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Efficiency Enhancement in Mid-Range RWPT Systems by GRIN Metasurface Lenses

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Abstract—The Magnetic Resonant Wireless Power Transfer (RWPT) is one of the best suitable techniques for mid-range applications. Therefore, there are different approaches to enhance RWPT efficiency, many of them based on metamaterial devices. In this work, the GRAdient-INdex (GRIN) technique is applied to increase the coupling between transmitter and receiver coils and collimate the magnetic field, reducing its dispersion. This proposed lens topology operates at 28 MHz and is formed by a 5x5 planar and periodic arrangement of Split Ring Resonators (SRR) unit cells. In each one, a lumped capacitor is added to reduce the lens's size and radially create a refractive index gradient. Then, a four-coil RWPT system is designed at the same operating frequency. Finally, the coils and lenses are prototyped, and the RWPT efficiency is measured in three cases: without any lenses, with a conventional (uniform) metasurface, and with the proposed GRIN lens. The experimental results demonstrate that the RWPT efficiency, which is about 8% without any lenses, becomes almost four times higher (33%) after the inclusion of metasurface GRIN lenses. When the same measurement is carried out with a uniform lens, typical topology in literature, the obtained efficiency is 17.59%, nearly half of the obtained with the proposed metasurface.

Keywords—ceramics, coaxial resonators, delay filters, delay lines, power amplifiers.

I. INTRODUCTION

For the past decades, there has been a remarkable increase in the number of publications and patents related to Wireless Power Transfer (WPT). The evolution of electronics that enabled the design of ultra-low-power devices, the modern techniques of applied electromagnetism that led to the physical realization of materials with properties that were not found in nature, and the boost in the computational capacity of processors that favours high-performance computer-aided designs and high-precision simulations can be listed as some of the main factors that allowed this fast development. In addition to them, the concept of the Internet of Things (IoT) with many electronic devices and sensors connected in a network applied for both industrial and consumer electronics makes wireless energy not only a desire but a requirement for its entire establishment.

Due to its commercial appeal and potentialities, the mid-range Resonant Wireless Power Transfer (RWPT) has been investigated from different aspects by many research institutions, universities, and technology corporations. In this way, there are various enhancement methods focused on

electromagnetic analysis [1], power electronic circuits [2], novel materials development [3], control system [4], electromagnetic compatibility [5], among other fields.

An innovative approach that has gained visibility over time is applying metamaterial structures for increasing the coupling between transmitter and receiver resonators in an RWPT system. This class of novel electromagnetic artificial materials presents remarkable properties that cannot be found in conventional structures; for instance, they can exhibit negative refractive index, perfect absorbing effects, and overcome the diffraction limit by collimating evanescent waves [6].

In the context of RWPT systems, once the evanescent fields are magnetic, and the separation between the unit cells is much smaller than the wavelength, the double negative requirement can be relaxed, and only $\mu < 0$ is required in order to design a metamaterial lens [7]. For this reason, different topologies and techniques for metamaterial lenses have been applied to RWPT systems. In general, these devices enhance the coupling between transmitter and receiver, leading to higher efficiency levels [8].

This paper's novelty is in the application of the GRAdient-INdex (GRIN) technique [9], recurrent in optics and photonics [10], to design a metasurface lens that can focus the magnetic field. In previous papers, conventional lenses are designed with a periodic and uniform distribution of unit cells, all with the same effective refractive index [11], [12]. Instead, in this paper, the unit cells are designed and positioned to radially create a gradual variation in the refractive index, which leads to magnetic field collimation. This technique has been already applied to far-field wireless power transfer [13]; however, in near-field RWPT, it enables combining the coupling enhancement with field focusing, thus achieving even higher efficiency.

II. GRIN METASURFACE LENS DESIGN

The first step to project a metasurface is to design a unit cell in which induced currents emulate atomic resonances. In order to achieve this operation, it is required that the unit cell size shall be less than a tenth of the free-space wavelength. Nevertheless, in this work, subwavelength unit cells (size $\ll \lambda_0$) are designed.

Two major design constraints for the unit cell design are established. First, the unit cell size is limited to 4 mm to assure the unit cell periodicity without having large full structures. This constraint is important since the losses in the dielectric substrate as well in its conductive layer increase with its size. In addition to it, the entire system, that is, the RWPT resonator

and the metamaterial slabs, must operate at 28 MHz. This specific frequency was chosen because it allows having subwavelength cells without leading to a constructively prohibitive size.

One of the most commonly used unit cell topologies is the Split Ring Resonator (SRR). However, to operate at the specified frequency, this topology itself would be prohibitively large. Therefore, a lumped capacitor is added to the SRR gap to get a more compact structure [14]. Consequently, the resonant frequency and the metamaterial parameters can be adjusted by varying the SRR dimensions and the lumped capacitance C . The unit cell and the full structure were designed and optimized using the software Computer Simulation Technology (CST[®]) to get $\mu < 0$ [7] in 28 MHz. The optimization method applied is the Covariance Matrix Adaptation Evolutionary Strategy (CMA-ES), with the standard deviation (sigma parameter) equal to 0.9 to force the method to be more global. The proposed square SRR topology is presented in Fig. 1a.

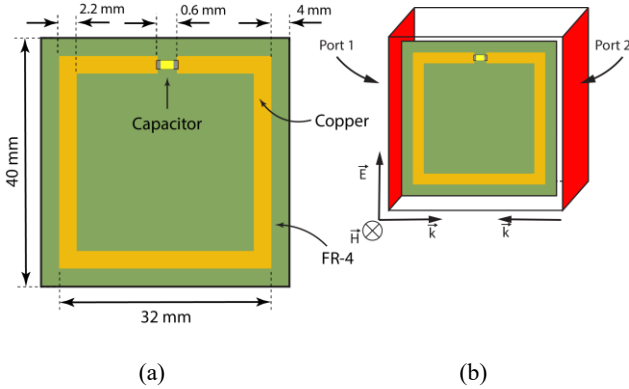


Fig. 1. Metamaterial lens unit cell: (a) Topology and optimized dimensions; (b) ports and boundary assignment.

The excitation and boundaries must be judiciously chosen according to the application properties in the simulation and optimization of metamaterials. For the present case, the designed structures were centred between two parallel waveguide ports; perfect electrically conducting boundary conditions were set on the faces that are perpendicular to the electric field \vec{E} and perfect magnetically conducting boundary conditions on the faces that are perpendicular to the magnetic field \vec{H} [15], as indicated in Fig. 1b, in which \vec{k} is the wave vector. Therefore, it is guaranteed that the magnetic field is normally incident upon the metamaterial lens, and this configuration enables the metamaterial parameter extraction function in CST[®]. Based on this unit cell, a full metamaterial structure constituted by a 5x5 unit cell arrangement was simulated and built on a single-side FR-4 substrate through an etching process; this prototype can be seen in Fig. 2.

Once the metasurface is designed, the refractive index gradient can be reproduced in two ways: by changing the unit cell size or by varying the value of the capacitor added to it. Table I presents the parametric analysis result of the real part of the effective refractive index $\Re(n)$ at the resonant frequency as a function of the lumped capacitance for three different

commercial values. It must be pointed out that, for all three cases $\mu < 0$ at the resonant frequency. As can be seen, the refractive index reduces as the capacitance increases. Therefore, the GRIN metasurface lens was built with these three different capacitance values, one at each layer indicated by the red dashed line in Fig. 2. In addition, for the sake of comparison, a conventional (uniform) metamaterial lens in which all unit cells were loaded with a 680 pF capacitor was prototyped.

Table 1. Simulation results for the effective refractive index as a function of the unit cell's lumped capacitances.

Capacitance (pF)	$\Re(n)$
560	146.1182
680	127.5067
820	120.3740

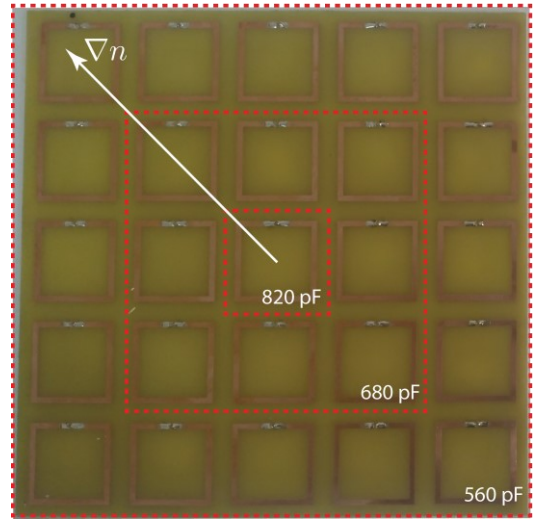


Fig. 2. Prototypes of the designed GRIN lenses.

III. RWPT SYSTEM DESIGN

In order to verify the behaviour of the proposed lens, a four-coil RWPT system is designed. The transmitter/receiver is composed of a double-sided FR-4 board so that the driver/sink coil is placed in one copper layer and the transmitting/receiving resonator is in the opposite layer. The square topology is chosen for both resonators since it leads to higher coil quality factors [16]. First, the dimensions of each resonator are optimized using the CMA-ES algorithm in CST[®] with the same settings described in section II, with the optimization goal set to minimize the VSWR at 28 MHz. Moreover, to get a compact structure, the resonators are designed in an FR-4 board with the same size as the designed metamaterial lenses, 200x200 mm. The designed coil with its optimized dimensions is presented in Fig. 3.

The reflection coefficient was measured, and the result is presented in Fig. 4 as well as the simulated one. As it can be seen, the measured S_{11} parameter corroborates with the simulation, and it satisfies the design requirement with a VSWR equal to 3.57.

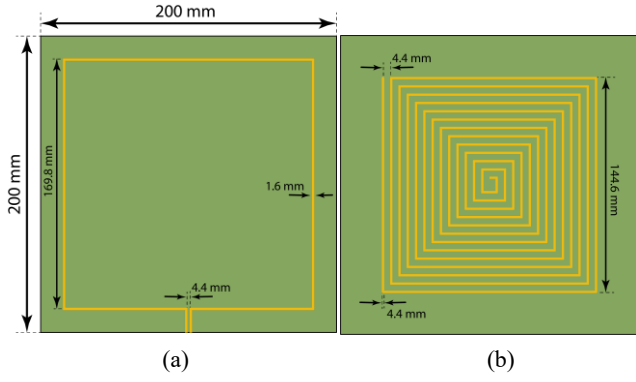


Fig. 3. Optimized dimensions for a four-coil RWPT resonator: (a) Driver/Sink coil; (b) Transmitting / Receiving resonator.

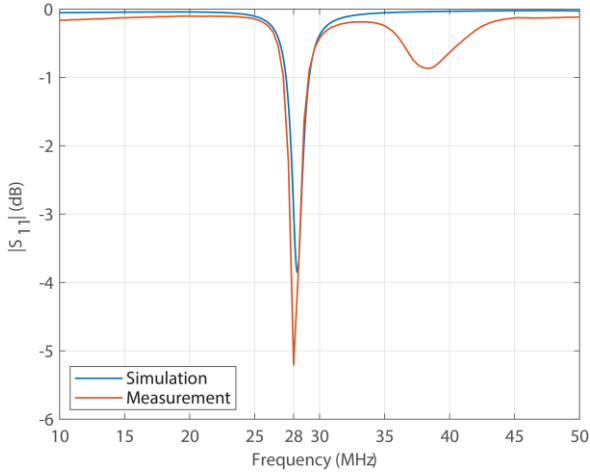


Fig. 3. Simulated and measured reflection coefficient for the designed resonator.

IV. RESULTS

In order to analyze and compare the behaviour of the RWPT system with different lenses, the measurement was set up as indicated in Figure 5 with the transmitter coil (driver coil with transmitting resonator) connected to Port 1 and the receiver (sink coil with receiving resonator) to the Port 2 of a Vector Network Analyzer (VNA). For all cases, the lens was positioned 5 cm apart from the transmitter coil. Then, the scattering-parameter matrix was measured in a frequency range from 10 MHz to 50 MHz. This measurement is performed by varying the distance between transmitter and receiver coils from 10 cm to 60 cm in 10 cm steps.

From the scattering parameters matrices, it is possible to evaluate the efficiency of an RWPT system. Assuming that the RWPT system is perfectly matched, the forward complex transmission coefficient S_{21} is related to the RWPT efficiency η_{RWPT} , according to the equation $\eta_{RWPT} = |S_{21}|^2$ [17]. Based on the measurements, the efficiency was calculated for three cases: without any lens, with a conventional lens, and with the proposed GRIN lens. The obtained results are presented in 6. As can be noticed, only with the RWPT resonators the achieved efficiency is about 8% at the frequency of 28 MHz with a distance between resonators equal to 20 cm.

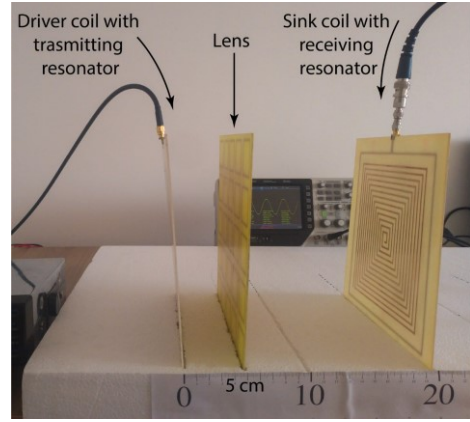


Fig. 4. Setup of the RWPT system with the lenses for efficiency measurements.

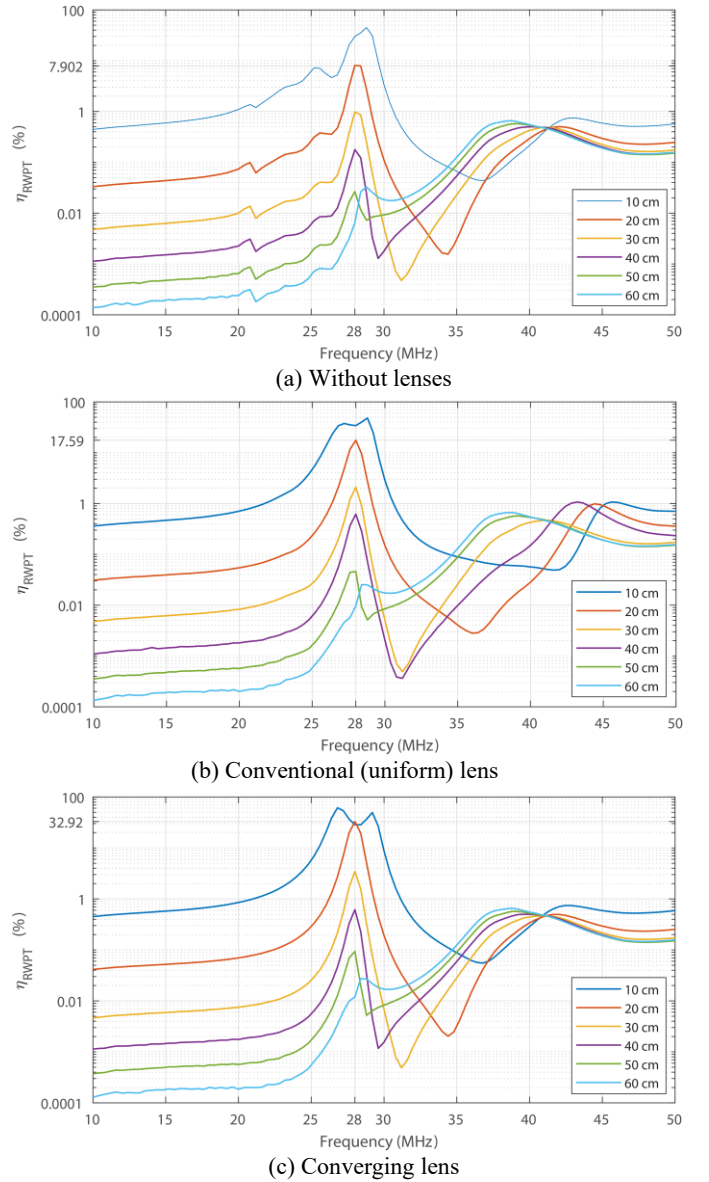


Fig. 5. Measured results for the efficiency of the four-coil RWPT prototype.

However, when the GRIN lens is included, this efficiency increases to almost 33%. By way of comparison, the exact measurement with a conventional lens leads to an efficiency of 17.59%.

These results can be explained by the fact that both uniform (conventional) and GRIN lenses significantly increase the coupling between transmitter and receiver coils, leading to higher efficiency. However, the GRIN lenses reduced the magnetic field dispersed by focusing it at the centre of the receiver resonator, thus increasing even more the amount of power that reaches the sink coil.

Even though the proposed GRIN lenses' efficiency is significantly higher than the conventional metamaterial lenses, it is limited by some loss sources. First, at the frequency in which the real part of the effective magnetic permeability becomes negative, the imaginary part, related to the losses, reaches its peak. In addition, most commercial capacitors have an expressive uncertainty in their nominal values, and as resonant metamaterials usually have a reduced bandwidth, it can also detune the system. However, even with these inherent sources, the RWPT efficiency can be improved by including an impedance matching network at the input and output of the system, reducing thus the reflection losses between the transmitter/receiver and the source/load respectively. Besides that, active GRIN lenses also allow better control of the metamaterial properties, and consequently, improve the performance of the RWPT system.

Moreover, it is possible to see that when the separation between transmitting and receiving resonator is equal to 10 cm, the system is on the over-coupling region, and the frequency splitting phenomena can be observed for both lenses. In this case, instead of achieving a higher efficiency at 28 MHz, the maximum efficiency is shifted to 26.8 MHz and 29.20 MHz. As the coupling enhancement is higher for the GRIN lens, the frequency splitting is even more expressive. However, at this distance, the system is outside the mid-range zone in which it was intended to operate, and this phenomenon does not happen for further distances.

V. CONCLUSION

There are various techniques in literature to improve the efficiency of resonant wireless power transfer systems. Among them, the applications of metasurfaces enable a significant enhancement in the coupling between transmitter and receiver coils. The standard approach to designing these metasurfaces is periodically assembling unit cells with negative effective magnetic permeability at the coils' resonant frequency and uniform refractive index.

In this work, the gradient-index technique is applied to design a metasurface lens that increases the coupling and reduces the dispersed magnetic field by focusing it on the receiver resonator. It is done by design unit cells with different refractive indexes and positioning them to create a radial gradient of this electromagnetic parameter.

The experimental results revealed that a wireless power transfer efficiency of approximately 33% had been reached with the novel lens proposed in this work, which is four times

higher than verified with the system without the lens and twice the efficiency measured with the conventional, uniform metasurface lenses. Future works aim to present a theoretical analysis for resonant wireless power transfer with this technique and additional results that demonstrate the field collimation.

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