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Distance and Efficiency Improvement in Wireless Power Transfer Systems through Steering Magnetic Field using Metasurface with Negative Permeability

Said CHOUKRI*[†], Hakim TAKHEDMIT*, Otman EL MRABET[†], Mahdi HAMIDOUCHE*, Laurent CIRIO*

*Univ Gustave Eiffel CNRS, ESYCOM F-77454 Marne-la-Valle, France

[†]LaSiT Lab, the Faculty of Sciences, Abdelmalek Essaadi University, BP 2121, Tetouan, Morocco

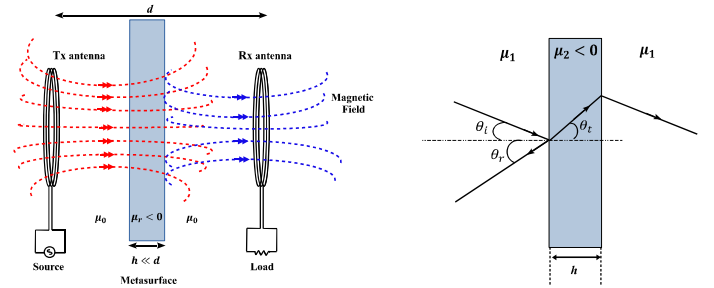
*said.choukri@univ-eiffel.fr

Abstract—This work presents a new Wireless Power Transfer (WPT) system with improved transfer distance and power efficiency. The enhancement of power transmission is provided by integrating a metasurface with negative permeability in the middle of the transfer distance between the Tx and Rx antennas. A new design of magnetic dipole antenna is done, and used for both Tx and Rx sides. Simulation and measurement results show that the Power Transfer Efficiency (PTE) of the Tx/Rx elements achieves 29 % and 27.30 %, respectively, while when integrating the metasurface the PTE is about 72.67 % and 57.77 %, respectively, hence 30.47 % of PTE improvement is achieved in experiments at the transfer distance of 60 mm.

Index Terms—Wireless Power Transfer, Metamaterials, Metasurfaces, Negative Permeability, Magnetic Field.

I. INTRODUCTION

The story was started when the American physicist Nikola Tesla proposed the idea of transmitting energy between two distant points without any wired connection by transmitting electromagnetic waves. Today, physicists and engineers are still chasing Tesla's most ambitious idea of Wireless Power Transfer (WPT) and making tantalizing progress. WPT systems found their applications in healthcare [1], automotive charging [2], Defense [3] and industry [4]. Some existing WPT systems use the Inductive Coupling (IC) approach where the transfer distances still in the near field region between the Tx and Rx coils [5]. In the other hand, WPT systems based on Magnetic Resonance Coupling (MRC) are operating in middle-range, where the transfer distances are multiple of the transmitting coil radius [6]. Still one of the limitations of both WPT systems, as the receiving coil move away from the power source, the strength of the field drops off very quickly, and every time we double the distance, the field drops off by a power of six [7]. As a result of this physical issue, the transfer distance is restricted and the Power Transfer Efficiency (PTE) also decays. Aiming to overcome the limitations of MRC-WPT systems, researchers have used metamaterials to enhance the PTE over considered transfer distances. Most recently in [8], a WPT system based on magnetic coupling between two identical loops, considered as Tx and Rx elements, and a high permittivity metamaterial slab. The PTE enhancement is about 9% at the transfer distance of 30 mm. Y. Cho *et al* proposed in their work [9] a thin hybrid metamaterial slab with negative



(a) Illustration of the proposed WPT System.

(b) Field Refraction.

Fig. 1: Magnetic field steering in the proposed WPT System.

and zero permeability for PTE enhancement, where this later has been improved with 7.2% at the resonance frequency of 6.78 MHz. In the present work, we propose a new WPT system based on two identical magnetic dipoles antennas coupled with metasurface array that has negative permeability. The power transfer between the Tx and Rx elements is carried by the magnetic field, whereas the PTE enhancement is justified by steering the magnetic field into the physical area of the receiving antenna.

II. THEORETICAL EXPLANATION OF MAGNETIC FIELD STEERING PROCESS

Fig. 1a illustrates the principle of operation of the proposed WPT system, where two identical antennas are used as the Tx and Rx parts of the system. The Rx antenna is located either in the near or the far-field region of the Tx antenna with respect to the distance d . Between the two antennas, is placed a thin ($h \ll d$) metamaterial slab that exhibits negative permeability within the frequency band of interest. The transmitting antenna is excited by an harmonic Continuous Wave (CW) source, while the receiving antenna is directly connected with a load that almost represents the input impedance of the rectifying circuit. Fig. 1b depicts the reflection and refraction of the magnetic field when passing through the metamaterial slab with negative permeability. The reflection coefficient at the

interface medium 1/medium 2 can be expressed as follows :

$$\Gamma = \frac{\sqrt{\frac{\mu_2}{\varepsilon_2}} \cos \theta_i - \sqrt{\frac{\mu_1}{\varepsilon_1}} \cos \theta_t}{\sqrt{\frac{\mu_2}{\varepsilon_2}} \cos \theta_i + \sqrt{\frac{\mu_1}{\varepsilon_1}} \cos \theta_t} \quad (1)$$

Assuming that minimum reflections occurs ($\Gamma \approx 0$), means that the energy reflected back to the Tx antenna is neglected, then we obtain :

$$\cos \theta_i = \sqrt{\frac{\mu_1 \varepsilon_2}{\mu_2 \varepsilon_1}} \cos \theta_t$$

Using Snell's law of refraction, leading to the following expression :

$$\frac{\tan \theta_i}{\tan \theta_t} = \frac{\mu_2}{\mu_1} \quad (2)$$

Eq. (2) represents a new formulation of snell's law, it could be used to determine the direction of propagation of the incoming wave when traversing the medium 2 (assumed with negative permeability), this direction could simply be reversed two times, in the first refraction then in the second refraction, leading to converge the magnetic fields in the other side.

III. DESIGN AND NUMERICAL STUDIES OF THE WPT SYSTEM

A. Magnetic Dipole Antenna Design

The top view of the proposed magnetic dipole antenna design is shown in Fig. 2a. it is an electrically small antenna ($kD \leq 1$), where k is the wavenumber and D is the radius of the smallest enclosing radian sphere. It consists of a circular loop excited between its two pads, and its design were done at the top of a non-grounded Rogers Duroid RT5880 dielectric substrate having a relative permittivity of $\varepsilon_r = 2.2 \times (1 - j0.0009)$. The overall size of the antenna is $\lambda_0/5 \times \lambda_0/5 \times 1.6 \text{ mm}^3$. The geometrical parameters were optimized, and the resonance frequency was chosen to be around 513 MHz. As shown in Fig. 3, the antenna presents good input matching around this operating frequency. The simulated radiation pattern characteristics are depicted in Fig. 4, where The property of quasi-omnidirectional propagation is clearly shown in the H-plane (Elevation plane) and E-plane (Azimuthal plane) with slight directive behavior in the azimuthal plane due to the open feeding gap.

B. Metamaterial Uni-Cell Design and Analysis

The proposed metamaterial unit-cell design is illustrated in Fig. 2b. The unit-cell is also shaped on the top of non-grounded Rogers Duroid RT5880 substrate. It consists of several square rings with two etched gaps on each ring, the interspacing between two rings is kept much small to create strong coupling between different elements. This configuration is adopted to have a strong magnetic resonance response when the unit-cell is excited by an external magnetic field perpendicular to the plane containing the cell. The unit-cell has been analyzed using the electromagnetic full-wave simulator CST Microwave Studio, where PEC boundary condition has been applied in y direction, PMC boundary condition in z

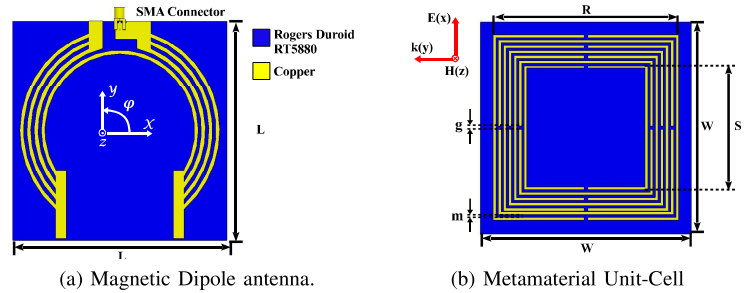


Fig. 2: Schematic design of the proposed dipole antenna with the metamaterial unit-cell, the geometrical parameters values are : $L = 120 \text{ mm}$, $W = 55 \text{ mm}$, $g = 1 \text{ mm}$, $m = 1 \text{ mm}$, $R = 50.91 \text{ mm}$, $S = 33.94 \text{ mm}$

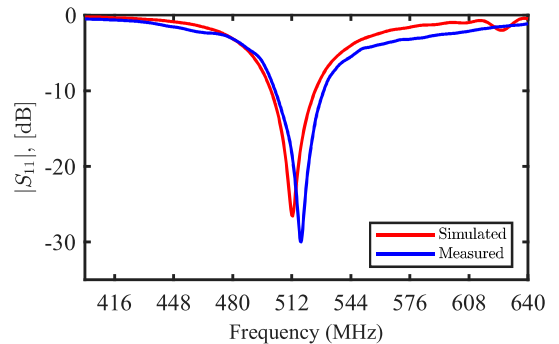


Fig. 3: Reflection coefficient of the magnetic dipole antenna as a function of frequency.

direction and two excitation ports in $-x$ and $+x$ directions. By applying these boundary conditions, the unit-cell is excited by a TEM plane wave with its magnetic field perpendicular to the plane containing the metamaterial unit-cell. The unit-cell characteristics of reflection and transmission are shown in Fig. 5, and the Kramers-Kronig Techniques [10] has been used to extract the relative magnetic permeability of the unit-cell which its real and imaginary parts are plotted in Fig. 6. The relative permeability can be expressed by :

$$\mu_r = \mu_r' + j\mu_r'' = \mu_r' (1 + j \tan \delta_m) \quad (3)$$

Where $\tan \delta_m$ represents the magnetic loss tangent. From Fig. 6, one can clearly notice that the unit-cell exhibits reactive permeability with negative values for the real part, while the imaginary part remains constant with values equal to zero within the operating frequency band, which means that practically the metamaterial structure presents zero magnetic loss tangent.

IV. ANALYSIS OF THE WPT SYTEM : SIMULATION AND MEASUREMENT RESULTS

In this section, we study the performances of the global WPT system. the proposed system consists of two Tx/Rx antennas coupled through the negative permeability metasurface. The proposed magnetic dipole antenna, presented in section

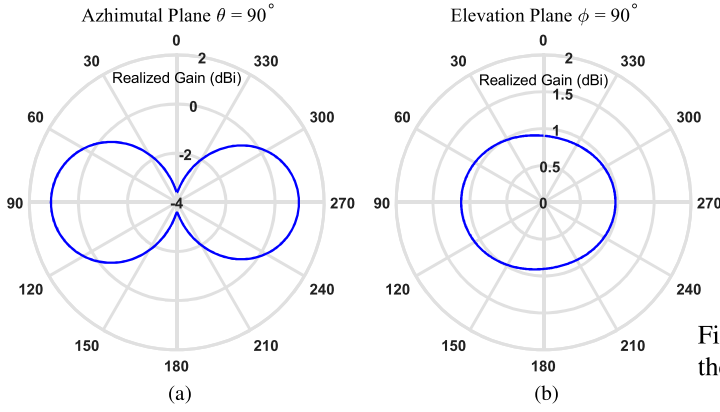


Fig. 4: Simulated Radiation Pattern of the proposed antenna.

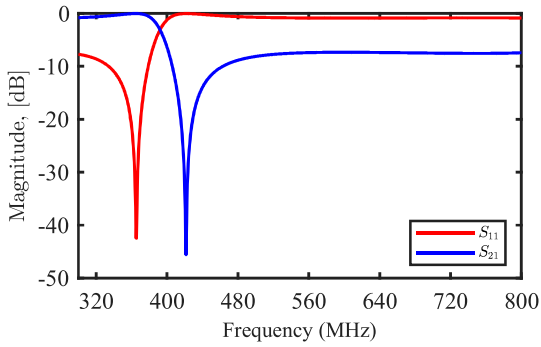


Fig. 5: Reflection and Transmission characteristics of the metamaterial unit-cell.

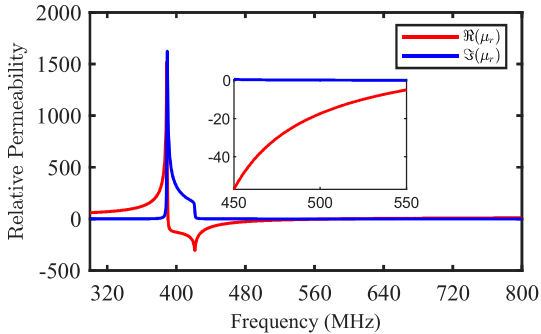


Fig. 6: Unit-cell relative permeability with its real and imaginary parts as a function of frequency

III-A, has been used as the same Tx/Rx element to tune the system at the same resonance frequency (513 MHz). The negative permeability metasurface is constructed by an array of 4×4 unit-cells. Fig. 7 describes the WPT system, where the distance between the two antennas is represented by d and the metasurface is placed between the Tx and Rx elements within the optimal distance chosen to be $d/2$. The distances manipulated here are practically located in the radiative near field and the far field regions of the transmitting antenna and

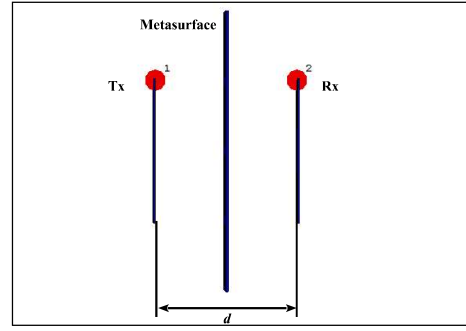


Fig. 7: The magnetic dipole Tx/Rx antennas coupled by using the metasurface with negative permeability.

they satisfy the following conditions :

$$d = \begin{cases} d^{FF} \geq \frac{2D^2}{\lambda_0} \\ 0.62\sqrt{\frac{D^3}{\lambda_0}} \leq d^{NF} \leq \frac{2D^2}{\lambda_0} \end{cases}$$

Where D is the diameter of the smallest enclosing radian sphere that can encompasses the antenna, d^{FF} and d^{NF} are respectively, the far and near field distances, and λ_0 is the wavelength at the resonance frequency. Fig. 8a, shows the fabricated WPT system as well as the measurement bench used to test the performances of the system. Firstly, the performances of the Tx/Rx system alone were analyzed, where we kept the same configuration shown in Fig. 7 without the presence of the metasurface. Then, the metasurface has been intergrated with the Tx/Rx system for further comparison between the two WPT systems. Fig. 8b, shows a comparison between the simulated and measured PTE as a function of frequency. The PTE of both systems has been calculated, which can be defined as the ratio of the recieved power to the accepted power by the Tx element, and it is given as follows :

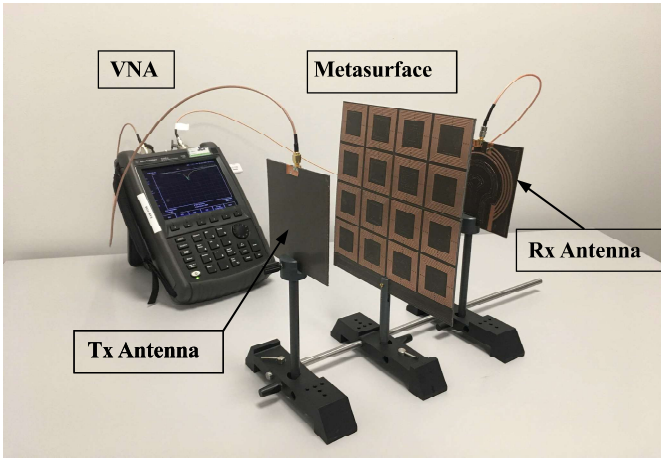
$$\text{PTE} = \frac{P_r}{P_a} = \frac{|S_{21}|^2}{1 - |S_{11}|^2} \quad (4)$$

With good input matching of the Tx antenna, the PTE can be simplified to the following expression :

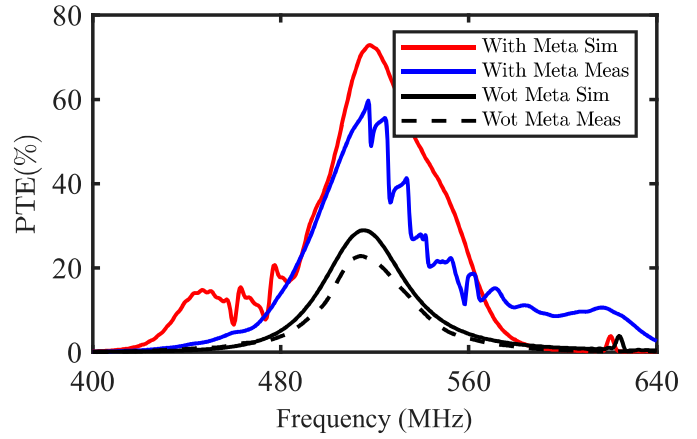
$$\text{PTE}(\%) \approx |S_{21}|^2 \times 100 \quad (5)$$

The comparison between the PTE of the WPT system, with and without the presence of the metasurface, show that the global WPT system becomes more efficient with the presence of the metasurface, where the measured PTE of the Tx/Rx alone is about 22.32 %, while when intergating the metasurface it becomes 56.57 %, hence, 34.25 % of PTE improvement is brought at the transfer distance of $d = 80 \text{ mm}$.

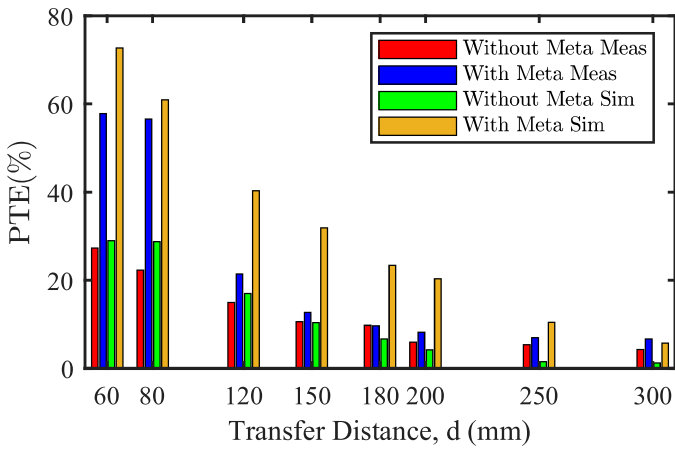
Also shown in Fig. 8c, a comparison between the measured and simulated PTE of each system when varying the transfer distance d , we can see that the WPT system with metasurface maintains high PTE compared to the Tx/Rx system alone, but for distances higher than 300 mm the performances of both



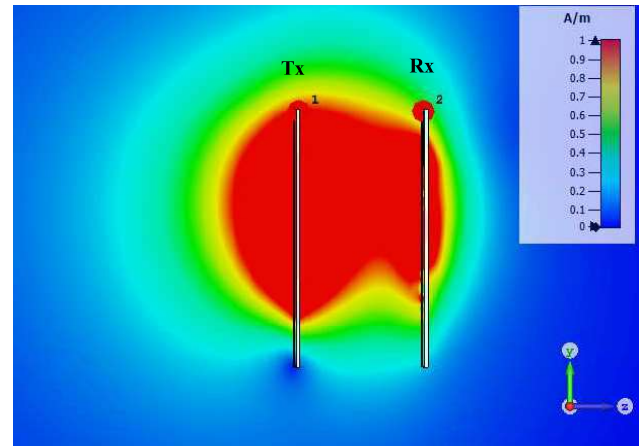
(a) Prototypes and measurement Setup



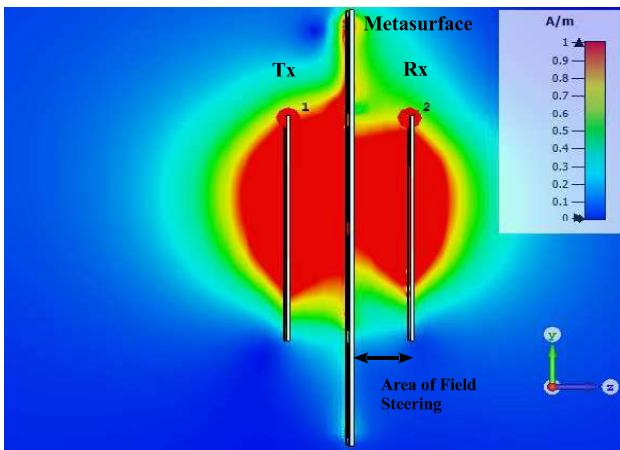
(b) PTE of the WPT system with and without metasurface as a function of frequency : comparison between simulated and measured results, the transfer distance is $d = 60 \text{ mm}$



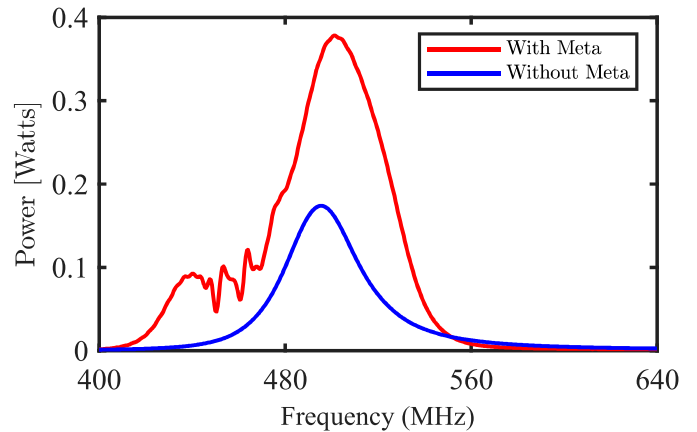
(c) PTE of the WPT system with and without metasurface as a function of the transfer distance



(d) Magnetic field distribution of the Tx/Rx elements alone at the resonance frequency.



(e) Magnetic field distribution of the global WPT system, with metasurface, at the resonance frequency.



(f) Received average power across the feeding pads of the Rx antenna, the transmitted power was fixed at 0.5 W .

Fig. 8: Global performances of the WPT system with and without negative permeability metasurface.

TABLE I: Comparison between the WPT system proposed in this work and some others reported in the literature

Reference	Operation Frequency (MHz)	Metasurface Property	Metasurface Slabs	Transfer Distance (mm)	PTE(%)	PTE improvement (%)
[7]	472.6	Electric with high permittivity	Two Slabs at both sides of Tx and Rx	30	60.8	8.6
[9]	6.78	Magnetic with hybrid Metamaterials	Single Slab Near to Tx side	150	41.7	7.2
[11]	1.3	Magnetic with Metamaterials	Single Slab	40	24	-
This work	492	Magnetic with Negative permeability	Single Slab between TX and Rx elements	60	57.77	30.47

systems are the same with less than 5 % of the PTE. Fig. 8d and Fig. 8e, show the magnetic field distribution of the Tx/Rx elements alone and with the metasurface, respectively. We can see that the presence of the metasurface enhance the radiated field into the steering area of the Rx antenna, this is justified by the negative values of the magnetic permeability. This property of the proposed metasurface allows it to converge the magnetic field, radiated by the Tx antennas and pointing out of the region where the Rx antenna is presenting, to the steering area of the receiving antenna where the maximum power could be captured by this later. Fig. 8f, shows the frequency evolution of the received power by the Rx antenna when exciting the Tx antenna by an average power of 0.5 W, with and without the presence of the metasurface. It is seen that the maximum average value of the received power (0.375 W) occurs at the resonance frequency, which confirm the 72.67 % of PTE calculated before from simulation results. Table I gives comparison between the performances of the WPT system presented in this paper and some recent WPT systems based on metasurfaces in the literature. Which confirm that the proposed WPT system brought an improvement in terms of PTE and transfer distance.

V. CONCLUSION

In this paper, a new WPT system was proposed with improved transfer characteristics in terms of PTE and transfer distance. Fully planar PCB technology has been used in the design of the Tx and Rx parts as well as the metasurface, where earlier proposed works often use wired bulky coils as Tx/Rx elements. Measurement results showed that the PTE is improved from 27.67 % to 57.77 % when coupling the metasurface with the Tx/Rx elements at the transfer distance of 60 mm

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