Enhancing the inductive coupling and efficiency of wireless power transmission system by using metamaterials

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***Abstract*— Over recent years, the interest in using inductive wireless power transmission for many applications has grown. One of the major limitations of this technology is the limited operating distance. Some recent works have suggested using synthesized materials known as metamaterials to improve the power transfer efficiency over distance. Due to their unique electromagnetic properties such as negative permeability, metamaterials can be used to enhance the evanescent waves of the near-field. In the present work, the usage of a magnetic metamaterial to increase the inductive coupling by means of enhanced evanescent waves is studied. Analytical calculations and numerical simulations of the proposed metamaterial and its impact on power transfer efficiency are presented and supported by experimental measurements.**

***Keywords*— metamaterials, wireless energy transmission, magnetic coupling, negative permeability.**

I. Introduction

Wireless power transmission (WPT) by magnetic induction is becoming a reliable technology to power devices without the need of the traditional wiring connections. In such a system, power transfer occurs via inductive coupling between conducting loops serving as transmitter and receiver. However, one of the main constraints to the deployment of this technology is the operating distance that is limited by the size of the loops. The efficiency drops dramatically for distances larger than the diameter of the largest loop.

To solve this problem, the usage of metamaterials has been suggested [1]. Such materials may be used as "superlens" over a limited frequency band to enhance the evanescent waves of the magnetic field strengthening the inductive link.

Previous works can be found in the literature related to the application of metamaterials in super high frequency range (GHz and above), i.e., in the references [2]-[7].

The objective of this work is to evaluate the usage of metamaterials as a mean to ameliorate the coupling between the transmitter and receiver loops, and consequently the operating distance of the system, in high frequency range (MHz).

Thus, a metamaterial arrangement suitable for the frequency range of interest and suitable for inductive WPT is proposed. Analytical calculations and numerical simulations of the properties of the proposed metamaterial and its impact on power transfer efficiency are presented and supported by experimental measurements. The related results are shown and discussed.

II. Wireless power transmission

A. Historical evolution of the wireless power transmission

A crucial point in the history of wireless power transmission took place in 1893 when Nikola Tesla demonstrated that a lamp could be lit remotely without the aid of any conductor. In following years, Tesla devoted much of his time to study telecommunications and wireless power transmission over long distances using earth's electromagnetic field [8].

Recently, studies on WPT field regained attention since MIT's researchers demonstrated in 2007 that efficient non-radiative mid-range WPT was possible. By using strongly coupled loops, they were able to power a 60W light bulb that was 2 meters away from the source, at approximately 45% efficiency [9].

So far, many other works based on inductive WPT has been conducted [10]-[13]. Wireless power transfer has been regarded as a practical solution for recharging electric vehicles, smartphones or implantable medical devices [14] - [15].

B. RLC series circuit

The coils used for the power transmission can be modeled as a RLC circuit, as shown in Figure 1. The parameter L is the self-inductance of the coil, R the resistance of the conductor and C the stray capacitance between the loops. Although the model is well known, a brief description of its theoretical concepts is presented:

The current in the resonance frequency is maximized on the series RLC circuit and it is in phase with the voltage. That is to say, the inductive reactance is equal to the capacitive one with a 180° phase difference. For frequencies below the resonance frequency f_r, the capacitive reactance predominates over the inductive one. For frequencies higher than f_r, the inductive reactance predominates.

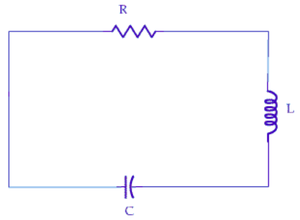

Figure 1- Model RLC of a coil in short circuit [15]

Therefore, at the resonance frequency minimum impedance is achieved and the coupling is maximized.

C. *The quality factor Q*

An ideal coil has no loss independently of the current flowing through it. In practice, these devices have losses caused by the inherent resistivity of the used conductor. This resistance dissipates energy by Joule effect, which mitigates the quality of the system.

The higher this factor is, the closer it approaches to the ideal coil with zero electrical resistance. Thus, the Q-factor is an important design parameter. The efficiency of an inductive system with a weak magnetic coupling can be compensated by a strong Q-factor.

The Q-factor of a serie RLC circuit is given by:

$$Q = \frac{1}{R}\sqrt{\frac{L}{C}} \qquad (1)$$

III. METAMATERIALS

A. *Definition*

Metamaterials are engineered structures usually much smaller than the working wavelength whose electromagnetic properties are obtained from its structure rather than its chemical composition [17].

It has been shown in reference [4] that conducting periodic structures could be synthesized to achieve negative permeability or negative permittivity at a limited frequency range. Such arrangement of scattering elements can be taken as homogeneous if the unit cell dimensions are much smaller than the guided wavelength and effective constitutive parameters $\varepsilon_{eff}(\omega)$ and $\mu_{eff}(\omega)$ can be attributed to the metamaterial slab [18]. Furthermore, being formed by repeated elements, it is possible to study the properties of the slab just by studying the properties of its unit cell [4].

Negative index media are required to create a "superlens" capable of focusing the near-field. However, for inductive WPT systems, this requirement may be simplified. Considering the quasi-static hypothesis of the near-field, its electric and magnetic components can be considered as independents. So a metamaterial presenting $\mu < 0$ only suffices to achieve a similar effect of focusing of the magnetic field. Moreover, by using a single-negative metamaterial the losses are greatly reduced thanks to a simplified structure.

Finally, as metamaterials are resonant, they are dispersive in nature [17].

IV. THE PROPOSED METAMATERIAL ARRANGEMENTS

A. *Prototype*

In Figure 2, the prototype arrangement of the metamaterial unit cell is presented. Its geometrical characteristic are d_{int} = 1cm, d_{ext} = 2cm, s = 1mm, w = 1mm. The lumped capacitor is a 100pF CMS (1.6mm x 8mm). The cell has two holes to connect the capacitor on its backside.

The distance between the centers of each motif is 2.3 cm.

The following equation was used to calculate the total inductance of the unit cell [19]:

$$L = \frac{K_1 \mu_0 n^2 d_{avg}}{1+K_2\rho} \qquad (2)$$

- $\mu_0 = 4\pi 10^{-7}$
- $d_{avg} = 0{,}5(d_{int} + d_{out})$
- $n = 4$
- $\rho = (d_{int} - d_{out})/(d_{int}+d_{out})$
- $K_1 = 2{,}34$
- $K_2 = 2{,}75$

Where n is the number of turns of the square spiral, and K_1 and K_2 are layout coefficients defined in reference [19].

With the proposed dimensions, the calculated inductance is $L = 243nH$.

Table I compares the theoretical and experimental results for the inductance, the capacitance, the resonance frequency and the Q-factor.

V. EXPERIMENTAL PROTOCOL

A. *Verification of the metamaterial parameters*

An impedance analyzer (Agilent Model 4294A 40Hz-110MHz) was used to measure impedance of the metamaterial. These results were compared with the theoretical ones and used to verify their accuracy and validity. The working frequency range of the lumped capacitors was also experimentally verified and confirmed to be in the frequency range of interest.

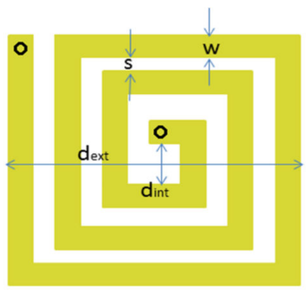

Figure 2- Unit cell of the prototype

B. *Measurement of the energy received*

Spiral resonators based metamaterials are supposed to behave as a magnetic superlens that concentrates the evanescent magnetic field around the slab enhancing the inductive coupling, and by consequence, improving the energy transfer.

The induced voltage in the secondary circuit has been evaluated with and without the metamaterial slab between the coils.

The experiment setup is shown in Figure 3. The transmitter and receiver coils are linked to the Vector Network Analyzer (VNA). The metamaterial is placed between the two coils.

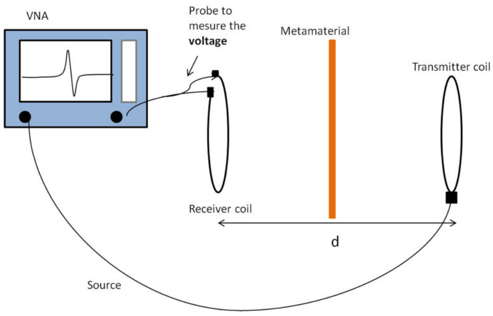

Figure 3- Experimental setup

C. *Experimental results*

The voltage gain at resonance frequency is defined as:

$$G = \frac{V_f - V_i}{V_i} \quad (3)$$

Based on the results of Figure 4, G=4. An enhancement of 400% is achieved in the presence of the metamaterial slab.

	Inductance (nH)	Capacitance (pF)	Resonance frequency (MHz)	Q
Theoretical	246	100	32	180
Experimental	231	115	35.8	-

Table I- Theoretical and experimental parameters of the prototype

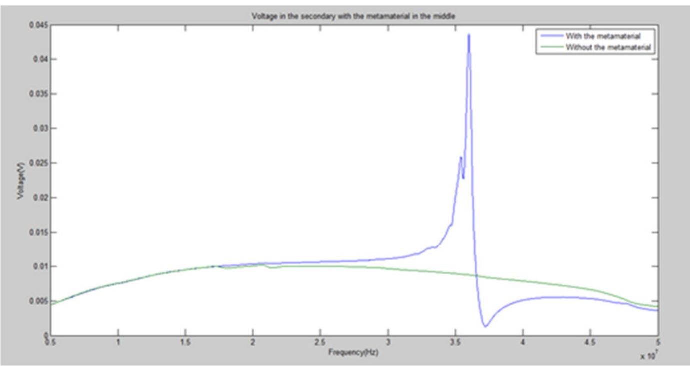

Figure 4- Voltage on the secondary with and without the metamaterial. Distance between the two coils: 15cm.

VI. NUMERICAL SIMULATION

A. *Simulation of the two coils*

The Method of Moments was applied [20].

The coils were 15cm from each other with the metamaterial placed between them. Three substrates had to be defined. The metamaterial was added after the first configuration with two coils only. Based on the fact that the resonance frequency is 35MHz, a simulation between 5MHz and 50MHz was made.

B. *Results of the simulations*

Some results concerning the simulations are presented in this item.

Figures 6 shows the voltage in the secondary without the metamaterial, and Figure 7, the voltage in the secondary with the metamaterial.

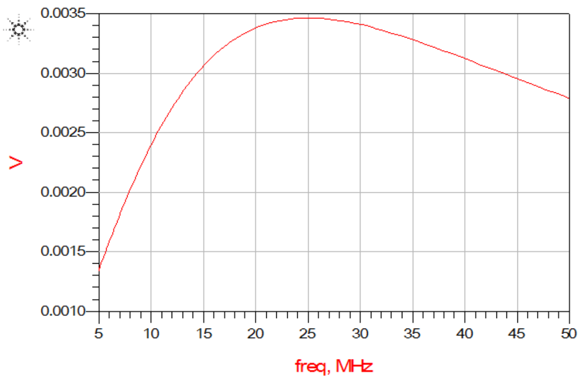

Figure 6- Voltage in the secondary without the metamaterial

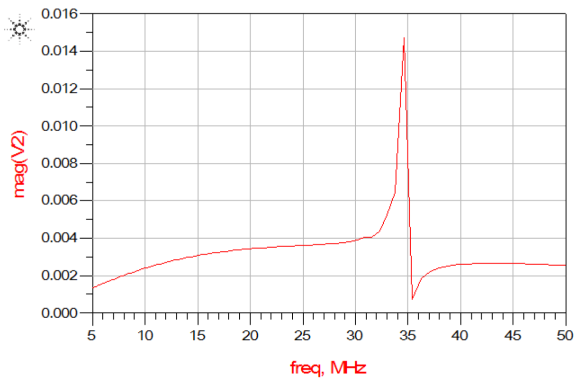

Figure 7- Voltage in the secondary with the metamaterial

According to (3), G = 3.54 for the numerical results. So the experimental and the numerical gain in power transmission in the presence of the metamaterial slab are in an agreement.

Although a difference can be realized concerning the voltage at the resonance, both results show a significant increasing of the received energy.

It should be mentioned that the measured and analytical resonance frequency were 35,9MHz and 34,5MHz, respectively. These results indicate that additional studies in order to examine the influence of the source variation in the accuracy of the theoretical parameters of the model.

Voltage in the resonance frequency	Experiment	Simulation
Without the metamaterial	0.0087363	0.0033
With the metamaterial	0.0437234	0.015
Gain	400%	354%

Table II- Voltage on the secondary with and without metamaterial on the resonance frequency

VII. CONCLUSIONS

The usage of the metamaterial in an inductive coupled system as a mean to improve the magnetic coupling and by doing so increasing the operating distance has been demonstrated. It was considered a frequency range of MHz. Besides the theoretical studies, numerical simulations and experimental measurements were made. During the project other ideas emerged and they will be considered in future works.

It should be mentioned that a first prototype was built and have not shown good results since its Q-factor was too low. To improve the Q factor, it was necessary to enhance the inductance by increasing the number of turns of the unit cell and diminish the capacitance of the lumped capacitor. With a four times larger inductance and a 100 times lower capacitance, the resonance frequency has been also increased. The first prototype had a resonance frequency around 3MHz, 100 times smaller than the second one. Despite the increasing of the resonance frequency, the frequency range was still within the range of interest and the Q-factor has achieved an acceptable value (around 180). The analytical values for the inductance, capacitance and resonance frequency calculated for both prototypes were consistent with the values obtained empirically by using the impedance analyzer.

Both experimental and numerical results indicate an improvement of the voltage in the secondary around 35MHz, which is in agreement with the expected analytical resonance frequency. They have also a gain around 400%, indicating that the numerical simulation represents with good precision the real system.

Concerning future works, the authors can still mention:

a) Studies on the the reduction of the operating frequency. It should be stressed that there is a compromise between the frequency and the Q factor which is an obstacle for reducing the working frequency.

b) Studies on the visualization of the magnetic field in a cross section that can be a helpful tool to better understand the effect of the metamaterial on the repartition of the magnetic field.

c) Additional evaluation of the metamaterial parameter sensibility used in the simulations, as well as the optimization of the position of the metamaterial when placing it close to the secondary and its orientation.

d) Study on the system with double resonance to compensate the reactive power of the emitter and the receptor.

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