Wireless Power Transfer Through Coupled Magnetic Resonance With Conventional and Superconducting Metamaterials

Transferência de energia sem fio através de Ressonância Magnética Acoplada com Metamateriais Convencionais e Supercondutores

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ABSTRACT
Wireless Power Transfer (WPT) is an option to gain mobility and convenience while charging electrical devices. Metamaterials are used to increase the energy transmission efficiency by coupled magnetic resonance. A WPT system was implemented in a 3D electromagnetic solver, where three configurations were simulated: initially without Metamaterials, with Split Ring Resonators, and with a superconductor spiral line (superconducting Metamaterials) that was designed in this work. An investigation of the power and efficiency of these systems was carried out through simulations. The distance between the coils was increased from 4 until 10 cm, and the horizontal misalignment varied up to 3 cm. The metamaterials showed themselves efficient as can be seen in the results.

Keywords: Wireless Power Transfer, Strongly Coupled Magnetic Resonance, Metamaterials, Superconductivity.

RESUMO
A transferência de energia sem fio abstrata (WPT) é uma opção para ganhar mobilidade e conveniência enquanto carrega dispositivos elétricos. Os metamateriais são usados para aumentar a eficiência da transmissão de energia por ressonância magnética acoplada. Um sistema WPT foi implementado em um solver eletromagnético 3D, onde três configurações foram simuladas: inicialmente sem Metamateriais, com Ressonadores de Anel Dividido, e com uma linha espiral de supercondutores (Metamateriais supercondutores) que foi projetada neste trabalho. Uma investigação da potência e eficiência destes sistemas foi realizada através de simulações. A distância entre as bobinas foi aumentada de 4 a 10 cm, e o desalinhamento horizontal variou até 3 cm. Os metamateriais se mostraram eficientes como pode ser visto nos resultados.

Palavras-chave: Transferência de energia sem fio, Ressonância magnética fortemente acoplada, Metamateriais, Supercondutividad .

1 INTRODUCTION

The Wireless Power Transfer (WPT) is a technology able to transmit electromagnetic energy from a source to an electrical charge between a gap in the air. It can offer energy to small devices [1], biomedical implants, portable devices, networks sensors, Internet of Things (IoT), robots and electrical vehicles [2].

This technology is an option to replace the traditional methods of transmission by cables. It features advantages over security in low frequency, mobility, and convenience. Furthermore, it increases flexibility on devices whose battery replacement is expensive or dangerous [3].

There are many techniques for WPT, among them the strongly coupled magnetic resonance (SCMR) that was used in this work. This technique works over the magnetic field oscillation between two coupled coils that operate in resonance.

However, the WPT has some problems regarding the cost of implementation and the power decay with distance. The efficiency decay comes from the increase of the distance between the source and load, misalignment between the transmitter and receiver, and inherent problems like radial propagation and reflection.

In order to mitigate losses in WPT, and consequently increase the transmission distance and efficiency, the application of metamaterials (MMs) has been studied. MMs are made by natural elements and can present unnatural properties. When properly arranged and submitted to electromagnetic fields, they work like perfect absorbers.

There are two types of MMs. The “conventional metamaterials”, such as the Split Ring Resonators (SRRs) and the thin wires (TWs), and currently “superconducting metamaterials” have been developed. In these two forms, the MMs have been employed to increase the electromagnetic waves absorptivity capturing the magnetic flux dispersed in the air.

In this work, an investigation of the applicability of metamaterials is made. The behavior of conventional and superconducting MMs in wireless power transfer by strongly coupled magnetic resonance SCMR is evaluated when there are load variation and misalignment. A spiral line of superconducting MM was projected. The system is simulated without MM and with conventional MM. An investigation of the power and efficiency behavior according to the increase in the distance between the transmitter and receiver coils and to the horizontal misalignment between them, for all system configurations, is also made.

Section II presents the theory of conventional and the called superconducting MMs. Section III presents the simulated systems and the design of the superconducting MM unit cell. Section IV presents the results and the Conclusion is in Section V.

2 METAMATERIALS

MMs are artificial structures effectively homogeneous, that is, their average cell size is much smaller than the wavelength. Because of it, the refractive phenomenon overlaps to the scattering and diffraction in the propagation of the wave [4].

MMs are also called Left-handed materials (LHM) because they do not obey the “right-hand rule”. Furthermore, these elements can present a negative refractive index (NRI), and for that, they can change the behavior of the wave according to the reversal of Snell’s law. In order to obtain an NRI, a metamaterial must have at least the electric permittivity or the magnetic permeability negative in the same frequency range.

A. Conventional Metamaterials

Among the so-called conventional metamaterials, there are two very used models: Thin Wires and Split Ring Resonators. The TWs models have a negative electric permittivity, and the SRRs have a negative magnetic permeability. In this work, it is used SRR in simulations because of the SCMR technique, where the magnetic part of the evanescent fields prevails.

The ring resonators have a cut to operate at a resonance frequency in which the wavelength is significantly greater than its diameter.

B. Superconducting Metamaterials

The superconducting MMs are different in their constructive characteristics comparing to the conventional ones. To exhibit superconducting behavior, the material must be below the critical temperature (T_c), when the MM can present the Meissner effect and have its resistivity considerably reduced and no magnetic flow inside the conductor.

Low losses are achieved in superconducting MMs, higher quality factor, and smaller wavelength when compared with the conventional MMs [5]. Furthermore, superconducting MMs can be miniaturized, and then they can be applied in small and medium-sized devices.

In this paper, the two types of metamaterials and their respective behaviors in the simulated system of WPT are investigated.

3 SIMULATED SYSTEMS

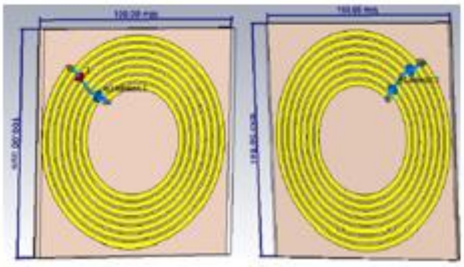
This section are presented the general data for the three system configurations simulated. In this work, a superconducting metamaterial unit cell was also projected.

A. General data

The system was simulated on CST® Studio software using the Finite Integration Technique (FIT) in time domain. The transmitter and receiver copper coils are flat and have 7 loops, width of 2.49 mm, spacing of 1.0 mm, inner radius of 22 mm, outer radius of 47 mm. Furthermore, this system has an inductance of 4.73 µH, relative electrical permittivity (ε_R) of 4.3, tangent loss (δ) of 0.015, as shown in Fig. 1. These data and geometry were obtained in [6]. These coils are in an Flame Retardant 4 (FR4) substrate with dimensions of 100 mm x 100 mm x 1.5 mm.

In the transmitter coil was used a discret port of voltage, defined by a starting point and an endpoint. These two points were connected by a perfectly conducting wire (visualized by a thick blue line) and the respective port source (indicated by a red cone) in the center of this wire, as shown in Figures 1 and 2. This port type realizes an ideal voltage source, exciting with constant voltage amplitude. This discret port is used in all simulations, c.a., with a peak voltage of $V_{max} = 100\ V$. In the receiver coil, a resistor of 100 Ω is used (in the without misalignment simulations between the coils).

Fig. 1. (a) Transmitter coil (b) Receiver coil.



The operating frequency in which the system was projected is 1 MHz. In this frequency, there are many applications in WPT such as self-resonant structures [7] and biomedical implants [8].

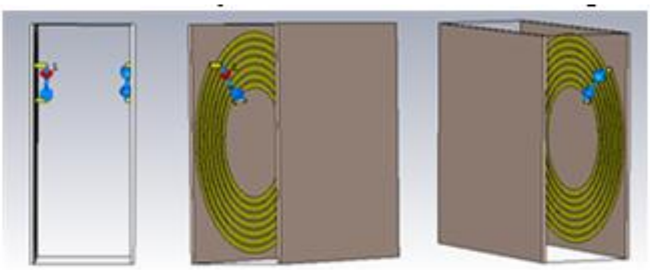
The percentage efficiency (η %) can be calculated through the relation between the load power (P_L) and source power (P_S), both in watts:

$$\eta\ (\%) = \frac{P_L}{P_S} \cdot 100\% \qquad (1)$$

B. SCMR without any Metamaterial

Initially, the system was simulated with the transmitter and receiver coils with only air between them, as shown in Fig. 2.

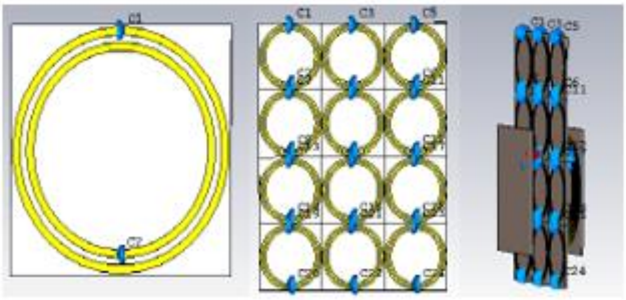
Fig. 2. SCMR system without metamaterial: (a) Complete system. Lateral view showing details of transmitter coil (b) and receiver coil (c).



C. SCMR with conventional metamaterial

The SRR model simulated in this work is based on the prototype of [4]. The metamaterial slab has 12 unit cells arranged in 3 columns and 4 lines, 300 cm² in total and it is placed at halfway between the coils, as shown in Fig. 3.

Fig. 3. SCMR with conventional metamaterial: (a) Unit cell of SRR (b) Slab of conventional metamaterial (c) Complete system.



Every unit cell of the slab has two copper rings presenting width of 1.63 mm, spacing of 1.47 mm, height of 0.02 mm, inner radius of 19.87 mm, with overall of 50 mm x 50 mm x 1.5 mm and one capacitor of 47 nF in each ring.

D. Design of the Superconducting Metamaterial Unit Cell

A superconductor unit cell was designed in this work. Its dimensions were reduced when compared with conventional MM. The substrate of $LaAlO_3$ has dielectric constant of 25, tangent losses (δ) of 0.0005, and critical current density of $4.7x10^6\ A/cm^2$ in 77 K. Furthermore, its dimensions were defined with an average size (p) much smaller than the wavelength (λ) to respect the effective homogeneity principle [4]. The dimensions for every cell are 40 mm x 40 mm x 0.5 mm, and the area of the whole slab is 144 cm² (9 unit cells in 3 lines and 3 columns, 52% lower the conventional slab simulated), as shown in Fig. 4.

The superconductor metamaterial has a spiral line geometry of YBCO, a superconductor material that generally is used in a critical temperature of 90 K. After the definition of the unit cell, the dimensions of the spiral line were defined after computer simulations and analysis: an outer radius of 38 mm and an inner radius of 2 mm.

The equivalent circuit of a superconducting MM is an RLC circuit and it is necessary to place capacitors to achieve the resonance. From [9] we have:

$$C(pF) = 0.035D_o(mm) + 0.06 \qquad (2)$$

where C is the capacitance in pF, with a value of 1.39 pF in this case.

After that, the geometric inductance (L_g) was defined from:

$$f = \frac{1}{2\pi\sqrt{L_g C}} \qquad (3)$$

obtaining $L_g = 0.0182\ H$, where f is the resonance frequency.

The number of loops (N) of the spiral conductor is determined by:

$$N = \sqrt{\frac{2L_g\left[\left(\frac{2.46}{a}+0{,}2a^2\right)\right]}{D_{avg}\mu_0}} \qquad (4)$$

where the factor a is:

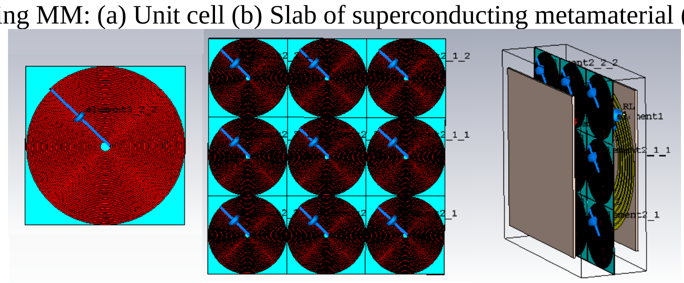
$$a = \frac{(D_o - D_i)}{(D_o + D_i)}\,. \qquad (5)$$

In (5) D_o is the outer diameter, D_i is the inner diameter and the average diameter is calculated as:

$$D_{avg} = \frac{(D_o - D_i)}{2}\,. \qquad (6)$$

It was obtained N = 43.37, which was considered N=43. The designed unit cell is shown in Fig. 4 (a) and the complete system in Fig. 4 (b).

Fig. 4. Superconducting MM: (a) Unit cell (b) Slab of superconducting metamaterial (c) Complete System.



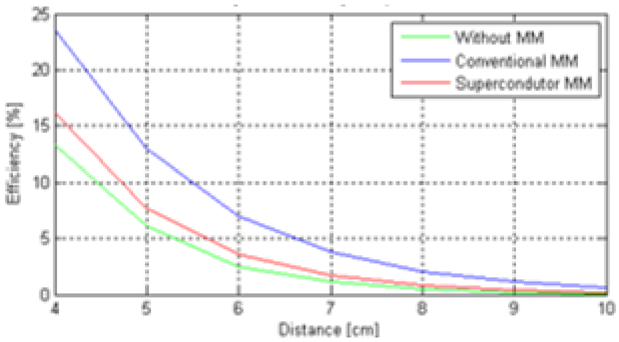
4 RESULTS

The results of the simulations and the comparison between them are presented in this Section. The system was simulated without MM, with Conventional and Superconducting MM.

A. Comparison of the configurations without misalignment

The distance between the coils varied from 4 cm to 10 cm. The system was simulated without MM, and with conventional and superconducting MM. The comparison can be seen in Fig. 5.

Fig. 5. Efficiency comparison.



The best results were at 4 cm of distance between the transmitter and receiver coil. Without the MM, the power in the load resistor was 45.14 W, and the efficiency of 13.23%.

With the conventional metamaterial, the power in the load was 69.59 W and efficiency of 23.46% in the transmission, as shown in Table I. There was an increase of 77.32% in the efficiency and 54.16% in the power after inserting the conventional MM. In the presence of the superconducting metamaterial, the efficiency was 16.11% (an increase of 21.76%) and the power was 49.34 W (an increase of 9.30%) when compared to the simulations without metamaterial.

The MMs were responsible to direct the disperse magnetic flux. Both types of MM were able to increase the power flux and transmission efficiency.

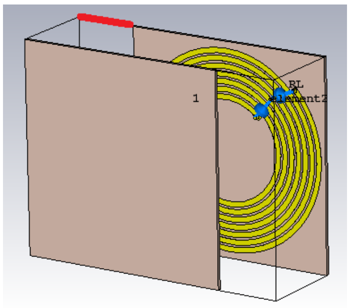
TABLE I. EFFICIENCY AND POWER COMPARISON

1 MHz	**Without MM**		**Conventional MM**		**Superconduct. MM**	
Distance (cm)	P (W)	η (%)	P (W)	η (%)	P (W)	η (%)
4	45.14	13.23	69.59	23.46	49.34	16.11
5	21.03	6.12	48.00	18.64	23.10	7.65
6	8.86	2.52	24.15	14.62	10.71	3.63
7	3.99	1.13	13.61	10.75	4.97	1.73
8	1.66	0.47	7.21	7.44	2.32	0.82
9	0.64	0.18	4.07	5.54	1.09	0.39
10	0.26	0.07	2.34	4.17	0.51	0.19

B. Comparison of the configurations with misalignment

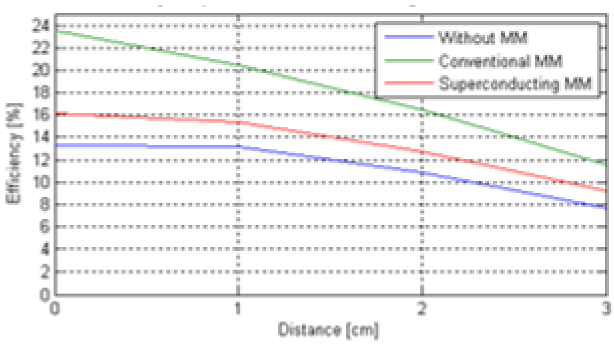
An investigation was carried out on the horizontal misalignment between the transmitter and receiver coils. It is important in cases where there is no absolute certainty about the position of the recipient (biomedical implants, for example). The coils were initially with their centers 4 cm apart and then there was a horizontal displacement from 1 to 3 cm, as shown in Fig. 6. The simulations, again, occurred without MM, with the conventional and superconducting MM and there was a comparison between them.

Fig. 6. Displacement of the receiver unit.



The system efficiency shows an increase after the insertion of the metamaterial as can be seen in Fig.7.

Fig. 7. Efficiency comparison with misalignment between coils.



Even with 3 cm of displacement, the efficiency was increased with metamaterials: 49.41%, from 7.67 to 11.46% with the conventional and 20.33%, from 7.67 to 9.23% with the superconductor, as shown in Table II.

TABLE II. EFFICIENCY AND POWER COMPARISON WITH MISALIGNMENT

1 MHz	**Without MM**	**Conventional MM**	**Superconduct. MM**
Misalignment (cm)	η (%)	η (%)	η (%)
0	13.23	23.52	16.11
1	13.14	20.45	15.33
2	10.81	16.51	12.69
3	7.67	11.46	9.23

Although the system is very sensitive to the misalignment, it still presents a better efficiency compared to no MM setup. Thus, the MM was able to increase efficiency in wireless power transfer even with horizontal misalignment between coils.

5 CONCLUSION

After inserting the two configurations of MMs and comparing their results with the simulations without MM, it was verified an increase of 77.32% and 21.76% in the efficiency with conventional and superconducting respectively. Even with a horizontal misalignment of 3 cm between the transmitter and receiver coils the efficiency was also increased after inserting the MM.

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REFERENCE

[1] Z. Zhang, B. Zhang, “Angular-Misalignment Insensitive Omnidirectional Wireless Power Transfer”, IEEE Transactions on Industrial Electronics, v. 67, n. 4, p. 2755-2764, 2020.

[2] J. Gao, G. Yan, “Design and Implementation of a Clamper-Based and Motor-Driven Capsule Robot Powered by Wireless Power Transmission”, IEEE Access, v.7, p. 138151-138161, 2019.

[3] Y. Li, J. Hu, X. Li, R. Mai, Z. Li, M. Liu and Z. He, “Efficiency Analysis and Optimization Control for Input-Parallel Output-Series Wireless Power Transfer Systems”, IEEE Transactions on Power Electronics, v. 35, n. 1, p. 1074-1085, jan. 2020.

[4] C. Caloz, T. Itoh, “Electromagnetic metamaterials: transmission line theory and microwave applications”, John Wiley & Sons, 2006.

[5] P. Jung, A. V. Ustinov, S. M. Anlage, “Progress in Superconducting Metamaterials”, Superconductor Science & Technology, v. 27, n. 7, jul. 2014.

[6] D. C. Corrêa, U. C. Resend and F. S. Bicalho, “Experiments With a Compact Wireless Power Transfer System Using Strongly Coupled Magnetic Resonance and Metamaterials”, IEEE Transactions on Applied Magnetics, vol. 55, n. 8, pp. 1-4, Aug. 2019, Art n. 8401904

[7] A. L. F. Stein, P. A. Kyaw and C. R. Sullivan, “Wireless Power Transfer Utilizing a High-Q Self-Resonant Structure”, IEEE Transactions on Power Electronics, v. 34, n. 7, p. 6722-6735, jul. 2019.

[8] I. A. Mashhadi, M. Pahlevani, S. Hor, H. Pahlevani and E. Adib, “A New Wireless Power-Transfer Circuit for Retinal Prosthesis”, IEEE Transactions on Power Electronics, v. 34, n. 7, p. 6425-6439, jul. 2019.

[9] X. Wang, Y. Wang, Y. Hu, Y. He and Z. Yan, “Analysis of Wireless Power Transfer Using Superconducting Metamaterials”, IEEE Transactions on Applied Superconductivity, v. 29, n. 2, p. 1-2, mar. 2019.