Markvart, A.; Song, M.; Kosulnikov, S.; Glybovski, S.; Belov, P.; Simovski, C.; Kapitanova, P.

Metamaterials-inspired resonator for wireless power transfer systems

Published in:
Journal of Physics: Conference Series

DOI:
10.1088/1742-6596/1092/1/012083

Published: 01/01/2018

Document Version
Publisher's PDF, also known as Version of record

Please cite the original version:
Markvart, A., Song, M., Kosulnikov, S., Glybovski, S., Belov, P., Simovski, C., & Kapitanova, P. (2018). Metamaterials-inspired resonator for wireless power transfer systems. *Journal of Physics: Conference Series*, *1092*, Article 012083. https://doi.org/10.1088/1742-6596/1092/1/012083

Journal of Physics: Conference Series

Metamaterials-inspired resonator for wireless power transfer systems

To cite this article: A. Markvart *et al* 2018 *J. Phys.: Conf. Ser.* **1092** 012083

Metamaterials-inspired resonator for wireless power transfer systems

A. Markvart[1], M. Song[1], S. Kosulnikov[1], S. Glybovski[1], P. Belov[1], C. Simovski[2,1], P. Kapitanova[1]

[1]Department of Nanophotonics and Metamaterials, ITMO University, 197101 Saint-Petersburg, Russia
[2]School of Electrical Engineering, Department of Electronics and Nanoengineering, Aalto University, P.O. Box 15500, 00076 Aalto, Finland

E-mail: `a.markvart@metalab.ifmo.ru`

Abstract.
Metamaterial-inspired resonator for a wireless power transfer system is proposed and studied numerically. The resonator consists of two orthogonal wire layers separated by a short distance. To reduce the resonant frequency from several hundreds of MHz it is placed in a background dielectric material with high permittivity. By tuning the permittivity of the background material, the radiation losses can be significantly reduced resulting in a high Q-factor of 900. The wireless power transfer efficiency greater than 80% from the wire resonator to a small loop receiver has been numerically demonstrated at the frequency of 19 MHz. The large area of the proposed resonator (50 cm × 50 cm) offers a possibility to charge multiple receivers simultaneously.

1. Introduction

Wireless power transfer (WPT) through magnetic resonance coupling is thought to be a popular and safe way for charging consumer electronic devices [1,2]. Traditionally the system utilizes a transmitter and receiver operating at the same resonant frequency which are coupled through the magnetic fields. Two main parameters to be optimized to improve the WPT efficiency are the Q-factors and the couping coefficient between the transmitter and receiver [2]. Usually, metallic coils or planar spiral resonators are used as a transmitter and receiver. Their Q-factors are normally limited due to the Ohmic loss and do not exceed 500 [3–5]. Metamaterials are artificial periodic structures which can realize unique electromagnetic (EM) properties that does not exist in nature. A variety of metamaterials have been both theoretically [8–10] and experimentally [11,12] verified to improve the couping coefficient between the transmitter and receiver in a WPT system. Wire medium is a volumetric metamaterial which has been extensively investigated in recent years for controlling the propagation of the EM waves and has been used to realize subwavelength imaging [6]. The metasurface (2D metamaterial) composed of an array of wires has been proposed to enhance the uniformity of the magnetic field in magnetic resonance tomography [7]. In this work, we propose a metamaterials-inspired resonator which is composed of two orthogonal wire layers separated by a short distance placed in a background material with high permittivity. We perform numerical studies to show that a high Q-factor of the resonator can be achieved with the optimization of the background material permittivity.

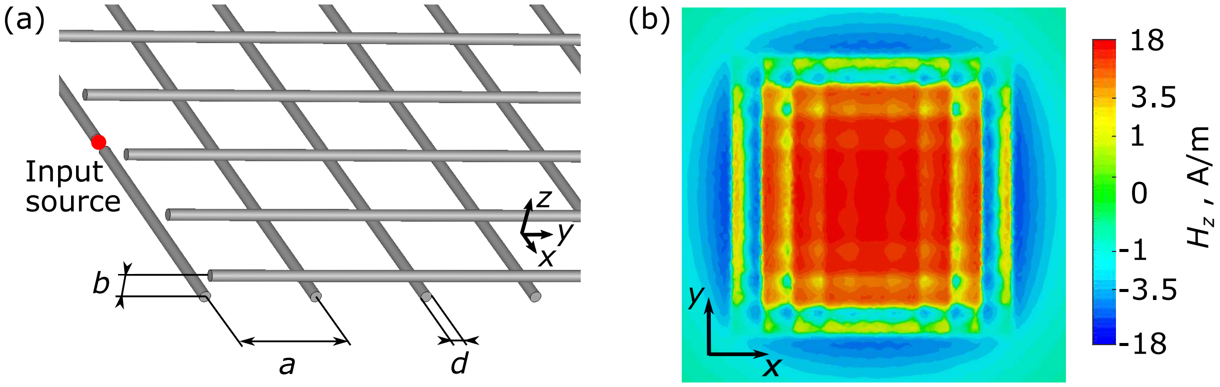

Figure 1. (a) Design of the metamaterials-inspired resonator. (b) The z-component of magnetic field distribution on the plane 12 mm above the resonator formed by 10 × 10 wires.

Moreover, the magnetic field distribution over the resonator is quasi-uniform which can be used to charge several devices placed on it simultaneously. Finally, the WPT efficiency from the proposed transmitter resonator to a loop receiver at the operational frequency of 19 MHz is studied.

2. The Resonator Design and Results of Numerical Simulations

The metamaterials-inspired resonator under study is demonstrated in figure 1(a). In principle the proposed resonator structure can be consisted of two orthogonal layers formed by an arbitrary number of wires with an arbitrary length L, periodicity a, and diameter d, which are separated by a spacing b. Taking into consideration the practical resonator size, e.g. for a WPT charging pad use, we chose 10 × 10 copper wires with $a = 5.55$ cm, $b = 6$ mm, $d = 2$ mm and $L = 50$ cm. We performed numerical simulations in CST Microwave Studio 2017. First, the eigenmode solver was used to analyze the modes which exist in such resonator. We observed a series of eigenmodes corresponding to certain current directions in the wires. For WPT application, a uniform magnetic field over the whole area of the resonator is preferable for charging multiple receivers. The fundamental mode of the resonator meets this requirement. Next, to excite the fundamental mode of the resonator, a discrete port with 50 Ohm impedance was embedded in to a gap of a lateral wire, as shown in Fig.1(a). The frequency domain solver of CST Microwave Studio 2017 was used to numerically study the input admittance and the field distribution of the resonator. From the simulated Y-parameter a resonant peak at $f = 150$ MHz was observed. The magnetic field distribution simulated at this frequency is demonstrated in figure 1(b), in which a quasi-uniform magnetic field is generated in the central area of the resonator. Thus, one may conclude that the fundamental mode is excited in the resonator. The uniformity of the magnetic field over the resonator could be favorably utilized to charge multiple small receivers. The classical 3 dB method to determine the Q-factor of the resonator from the Y-parameter spectrum was used and the Q-factor of the resonator operating at the fundamental mode was obtained as $Q = 13$. The low value of the Q-factor can be explained by the strong radiation losses of the resonator.

It is absolutely clear, that the current resonator design can not be used in a WPT system due to the low Q-factor. Moreover, the operational frequency determined by the wires length is beyond 100 MHz. With respect to the AirFuel Alliance standard the resonator system shall operate at 6.78 MHz. So, for the practical application of the proposed design it is important to reduce the resonant frequency and radiation losses. To solve these problems, we propose to immerse the resonator into a high permittivity background material. As an initial study,

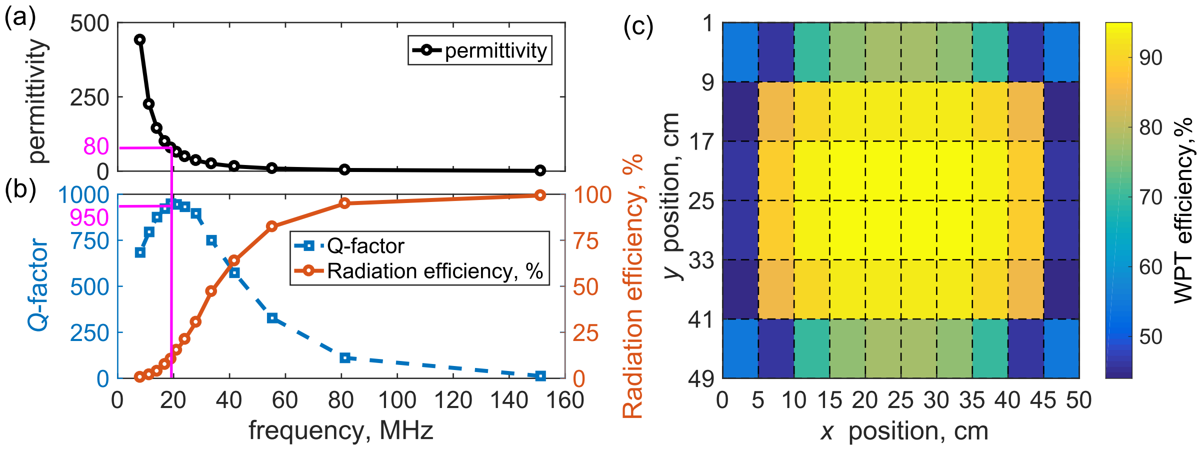

Figure 2. (a) The permittivity of the background material as a function of the corresponding resonant frequency. (b) Q-factor and the radiation efficiency as a function of the resonant frequency. (c) Calculated WPT efficiency as a function of the location of the receiving loop. Grid dotted lines represent the position of the receiving loop.

the resonator was situated inside a lossless dielectric material with the overall dimensions of 50 cm × 50 cm × 2 cm. The resonant frequency can be tailored by tuning the permittivity of the dielectric material as plotted in figure 2(a). The resonant frequency decreases as the permittivity of the dielectric material increases. At the same time, we observe the radiation efficiency also decreases (see figure 2(b)). It can be explained by the fact that the physical dimension in terms of wavelengths became much smaller leading to the reduced of the radiation efficiency. However, as the permittivity increases, the Q-factor does not increase monotonically. There exists a maximal Q-factor $Q = 950$ at $f = 19$ MHz corresponding to an optimal permittivity of $\varepsilon = 80$ as shown in figure 2(b). This is because of the overall capacitance between the wire layers increases significantly for the high permittivity values, which reduces the Q-factor. Water is a natural material characterized by a permittivity of $\varepsilon = 78.4$ at the frequency of 19 MHz. As a further investigation, the loss of the water is taken into consideration. The numerical study for Q-factor was conducted when the water conductivity was set as $\sigma = 5.55 \times 10^{-6}$ S/m, which resulted in a slightly reduced Q-factor from 950 to 900. However, the obtained Q-factor value is still higher then metallic coils or planar spiral resonators. Finally, the embedding of the metamaterials-inspired resonator inside the water helped to significantly improve the Q-factor, decrease the resonant frequency keeping the resonator dimensions the same (50 cm × 50 cm × 2 cm).

Now we proceed to investigate the WPT efficiency of the optimized metamaterials-inspired resonator design. For generality, we employ a copper rectangular loop with the dimensions of 5 cm × 8 cm. A 50 Ohm discrete port was embedded in a loop gap as a load. The loop size corresponds to a typical dimensions of a mobile phone. The receiver is placed in $x - y$ plane 5 mm above the dielectric surface of the resonator. The WPT efficiency for different positions of the receiver above the transmitter was calculated via the simulated S-parameters of the WPT system as $\eta = |S_{21}|^2$. Note that this equation is valid only when the impedance matching conditions at both ports are satisfied, i.e. $|S_{11}| = |S_{22}| = 0$ at the resonant frequency. Thus, additional matching networks at both ports were employed for all the receiver positions. The calculated WPT efficiency is shown in figure 2(c). In the central area of the metamaterials-inspired resonator, the WPT efficiency of more than 80% is obtained, whereas the efficiency of 50% is still achievable as the receiver approaches the edges.

3. Conclusion

The design of metamaterial-inspired resonator for planar WPT system has been proposed. The quasi-uniform magnetic field generated in the resonator has been numerically demonstrated. To improve the resonator's Q-factor the structure has been optimized by tuning the background material permittivity. The optimized design of the metamaterials-inspired resonator with the dimensions of 50 cm × 50 cm × 2 cm offered a Q-factor of 900 at the resonant frequency of 19 MHz. The power transfer from the metamaterial-inspired resonator to the metallic loop has been numerically investigated. The WPT efficiency of more than 80% in the central area of the resonator has been demonstrated. The further optimization of the resonator to meet the AirFuel Alliance standard operational frequency of 6.78 MHz can be achieved by adjusting the wire length.

4. Acknowledgment

The work was supported by the Russian Science Foundation (Project No. 17-79-20379).

References

[1] Kurs A, Karalis A, Moffatt R, Joannopoulos J D, Fisher P and Soljacich M 2007 *Science* **317** 83–86
[2] Song M, Belov P and Kapitanova P 2017 *Appl. Phys. Rev.* **4** 021102
[3] Tierney B B and Grbic A 2014 *IEEE Trans. Antennas and Propag.* **62** 3310–20
[4] Jolani F, Yu Y and Chen Z 2014 *IEEE Antennas Wireless Propag. Lett.* **13** 1648–51
[5] Klein A and Katz N 2011 *Curr. Appl. Phys.* **11** 1188–91
[6] Simovski C R, Belov P A, Atrashchenko A V and Kivshar Y S 2012 *Adv. Mater.* **24** 4229–48
[7] Slobozhanyuk A P, Poddubny A N, Raaijmakers A J, van den Berg C A, Kozachenko A V, Dubrovina I A, Melchakova I V, Kivshar Y S and Belov P A 2016 *Adv. Mater.* **28** 1832–38
[8] Zhu L, Luo X and Ma H 2016 *Appl. Phys. Lett.* **109** 024103
[9] Zhao Y and Leelarasmee E 2014 *Microwave Opt. Technol. Lett.* **56** 867–75
[10] Urzhumov Y and Smith D 2011 *Phys. Rev.* B **83** 205114
[11] Wu Q, Li Y H, Gao N, Yang F, Chen Y Q, Fang K, Zhang Y W and Chen H 2015 *Europhys. Lett.* **109** 680005
[12] Yoo Y J, Yi C, Hwang J S, Kim Y J, Park S Y, Kim K W, Rhee J Y and Lee Y P 2016 *Sci. Rep.* **6** 33416