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Parametric study of metamaterial-inspired resonator for wireless power transfer

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Abstract. A metamaterial-inspired resonator for free-positioning wireless charging of several devices is proposed and numerically studied. The resonator is based on orthogonal metallic wires arrays deposited on a high permittivity low loss dielectric substrate. Given a fixed area of 50×50 cm, its resonant frequency can be tuned in a wide frequency band from 5 MHz to 45 MHz. A parametric study is performed to reveal the influence of resonant frequency, dielectric permittivity and number of wires on Q -factor.

1. Introduction

Recently, magnetic resonance wireless power transfer (WPT) technology has been intensively investigated [1, 2]. One of the main directions is charging multiple receivers simultaneously. Conventionally, a large metallic coil is used as a transmitter and several small metallic coils as receivers [3, 4]. However, the generated near electric field in such WPT systems can be dangerous, especially on the human health due to the temperature heating and nerve electrostimulation [5, 6]. As soon as the transmitted power is restricted by several watts for such systems the decrease of the electromagnetic exposure of human tissues is a challenging task [7, 8, 9, 10, 11].

Recently, the concept of a metasurface-based smart table for wireless power transfer has been proposed and experimentally demonstrated [12]. The metasurface consisting of wires supports propagating surface modes and helps to transfer energy with high efficiency between two devices placed above it. Another design of a metamaterial-inspired resonator which can be used as a part of the smart table for free-charging of multiple devices has been demonstrated [13]. It consists of two orthogonal wire layers embedded to high-permittivity dielectric. For that particular design the authors used water as a hosting media. The quasi-uniform magnetic field distribution over 50×50 cm area has been demonstrated at the frequency 19 MHz. Nevertheless, optimization of the resonator's operational frequency to the WPT standard and achieving high Q -factor are important for practical application, but have not been considered yet. Here we propose an improved design and demonstrate the parametric study to reveal the influence of resonant frequency, dielectric permittivity and number of wires on Q -factor.



2. Resonator Design

The design of the proposed metamaterial-inspired resonator is shown in Fig.1(a). It consists of two orthogonal wire arrays deposited from both sides of a high-permittivity dielectric substrate. Each wire array consists of N parallel copper wires with length L , width w and thickness t . The profile of the wire array takes a square shape satisfying the condition $(N - 1) \times d = L$, where d is the spacing between adjacent wires. The dimensions of the dielectric layer are $a \times a \times b$. One of the lateral wires was used as an excitation element by applying electromotive force between the halves of the wires. Frequency Domain Solver of CST Microwave Studio 2017 was used for full wave electromagnetic simulation of the proposed resonator. We revealed the quasi-uniform magnetic field generated at the first resonant mode of the structure (similar to Ref. [13]). At this mode the vertical component of the magnetic field had only one maximum in the center.

We performed a thorough parametric study to investigate the influence of wire number N , dielectric permittivity ε and the dielectric slab thickness b on the resonant frequency and Q -factor. We swept the permittivity from 50 to 900 for different number of wires $N=6, 10, 20, 30, 40$ and simulated the frequency dependence of the resonator's input impedance.

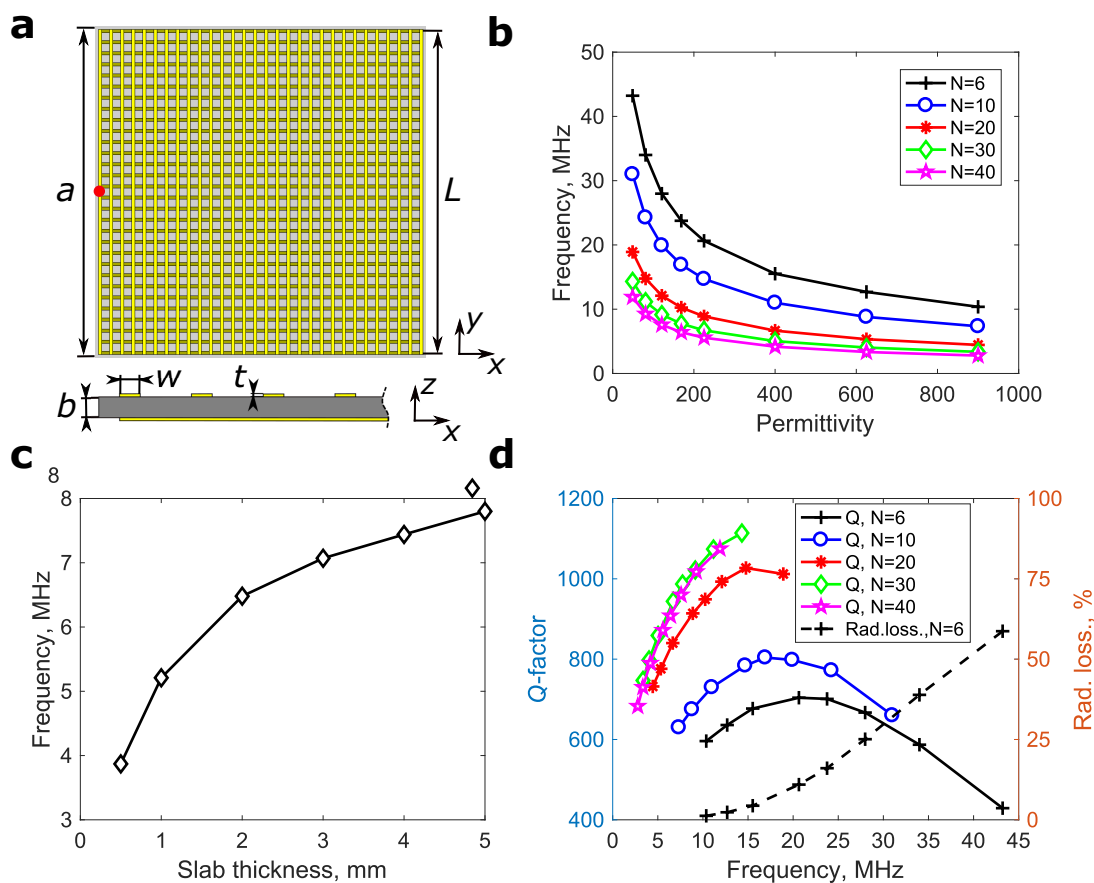


Figure 1. (a) Geometry of the resonator with number of wires in each layer $N = 30$. Red label corresponds to the source input; (b) simulated operational frequency as a function of the substrate permittivity for different number of wires N ; (c) the operational frequency of the resonator as a function of the slab thickness; (d) Q -factor and the radiation losses as functions of the resonant frequency for different N .

The other resonator parameters were set as: $L=50.5$ cm, $w=5$ mm, $t=1$ mm, $a=51.5$ cm, $b=5$ mm. The dielectric loss tangent was chosen as $\tan(\delta)=3\times 10^{-4}$ [14]. The resonant frequency was determined as the first local minimum of the input impedance spectrum $Z(\omega)$ that corresponds to the serial resonance. The Q -factor was calculated by:

$$Q = \frac{\omega_0 |Z'(\omega_0)|}{2\text{Re}(Z(\omega_0))} \quad (1)$$

where ω_0 is the resonant frequency [15]. The results of numerically simulated operational frequency of the resonator for different permittivity values are presented in Fig. 1(b). The resonant frequency decreases drastically with increasing of number of wires N and permittivity ε . Thus, it is possible to optimize the operational frequency within a wide frequency band. For example, the following parameters result in the resonator's operational frequency of 6.78 MHz described by AirFuel standard: $N=20$, $\varepsilon=390$; $N=30$, $\varepsilon=221$; $N=40$, $\varepsilon=154$.

Figure 1 (d) shows the Q -factor as a function of frequency extracted from the numerical results using Eq.(1). For any LC resonator, the Q -factor can be expressed by formula $Q = \omega L/R$. In the lower frequency range, where the wavelength is much larger than the characteristic dimension of the resonator, the Q -factor is linearly growing up as frequency increases. However, when the wavelength decreases, the resonator becomes more and more electrically large resulting in an increased radiation resistance and radiation losses. Therefore, there is an optimal frequency to achieve the highest Q -factor. On the other hand, the number of wires N also influences the Q -factor. With increasing of N the self-inductance increases leading to the Q -factor increase. In our case it has maxima for wire number between $N = 30$ and $N = 40$. This is due to the proximity effect of multiple wires.

An additional degree of freedom for operational frequency optimization can be reached by the dielectric slab thickness. As an example, the numerical simulation of the resonator's operational frequency was done for the case of $N = 30$, $\varepsilon = 169$, and the results are depicted in Fig. 1(c).

3. Conclusions

The design approach of the wire array resonator has been proposed. The required resonant frequency can be achieved in a wide frequency band by tailoring the dielectric permittivity, number of wires and dielectric slab thickness. Also, the Q -factor optimization can be done for the each frequency by choosing the optimal number N . The proposed resonator enables high Q -factor based on high permittivity low loss dielectric and opens up possibilities for free-positioning multiple charging WPT systems in low MHz frequency range.

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