Incorporation of DNG Metamaterial for Enhancing Efficiency of RF WPT

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***Abstract*—This paper presents the incorporation of a double-negative metamaterial (MTM) into a radio frequency wireless power transfer (WPT) system. In particular, an MTM slab was placed in between two coupled resonators which subsequently led to the power transfer efficiency (PTE) enhancement. In this instance, it is worth noting that the resonators, oscillating at 900 MHz, are constructed using the defected ground structure approach. Two coupled resonators and MTM possess a miniature board area of 30-by-30 sq. mm. Finally, it should be highlighted that the MTM integration resulted in the PTE improvement by 17%.**

***Index Terms*—Double negative (DNG) metamaterial, near-field coupling, radio frequency (RF), wireless power transfer (WPT).**

I. Introduction

Wireless power transfer (WPT) systems have become renowned in fields such as biomedical implants, low-power sensors, and consumer electronics [1]–[3]. The fact that RF WPT can transmit power without connections has sparked a lot of interest. Nowadays, a variety of approaches exist for the WPT systems' development, with one notable method being the defected ground structure (DGS) that is acclaimed for its design simplicity and compact circuitry [2], [4]. However, DGS-based WPT often suffers from small power transfer efficiency (PTE) over large distances [4]. In this regard, metamaterial (MTM) offers a potential solution to enhance PTE.

Generally, MTM refers to engineered material that displays extraordinary properties characterized by negative permeability (μ) and/or permittivity (ϵ) [3], [5], [6]. It is worth noting that MTMs with both negative μ and ϵ are termed double-negative (DNG). These DNG MTMs hold significant promise for WPT applications due to their ability to manipulate magnetic field lines [5], [6]. In detail, MTM allows the direction of magnetic field lines toward the receiver, positively influencing PTE.

This paper aims to investigate the integration of an MTM slab exhibiting DNG characteristics into a near-field RF WPT system. Initially, the focus centers on the DGS-based WPT system development operating within the industrial, scientific, and medical frequency bands. Then, DNG MTM is designed which is composed of a single unit cell and possesses the same size as resonators. Finally, PTE of WPT was increased by 17%, when MTM was placed in between DGS-based resonators separated by 40 mm.

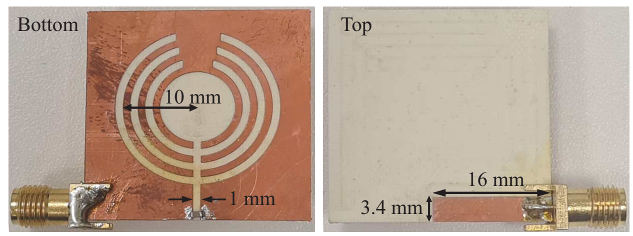


Fig. 1. The DGS-based resonator.

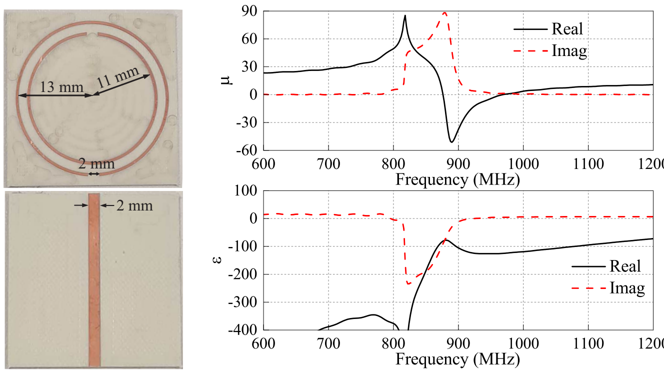
II. Coupling-based WPT Development

This section elaborates on the near-field RF WPT development which is achieved by coupling two identical resonators, where one functions as a transmitter and the second as a receiver. Here, the resonators are developed using the DGS approach, represented by a three-layer structure comprising a 1.54 mm RO4350B substrate covered by 0.035 mm copper layers on both sides. Fig. 1 presents the proposed resonator design of 30-by-30 sq. mm area. Afterward, the implementation of WPT is executed by coupling the designed resonators at a 40 mm transmission range. It is crucial to highlight that impedance matching is essential for maximizing power delivery, and this is achieved through the precise selection of the microstrip line length ($l = 16$ mm), shown at the top layer. Furthermore, to attain the targeted resonant frequency, a lumped capacitor with a value of 0.3 pF is integrated into the circuit. It is worth noting that Eq. (1) is utilized in calculations of the circuit's key parameters [4], [7].

$$L = \frac{\mathrm{Im}(Z_{11})}{2\pi f_r},\ f_r = \frac{1}{2\pi\sqrt{LC}},\ \text{and}\ C_s = \frac{\tan(\beta l)}{2\pi f_r Z_0}. \quad (1)$$

III. MTM Design and Incorporation

In general, the MTM slabs are composed of repeating and periodic basic building blocks known as unit cells. In this section, the design of DNG MTM is demonstrated. To be more specific, MTM consists of a single unit cell measuring 30×30 sq. mm in size. In the design, a split-ring resonator structure is used to attain negative characteristics. Detailed schematics of the second MTM composed of three layers are presented in Fig. 2. The top layer contains two coils, each with a 0.5 mm width and a separation space of 1.5 mm. The second layer consists of the substrate, while the bottom layer comprises a metallic wire



(a) (b)

Fig. 2. Obtained results: (a) permeability; (b) permittivity.

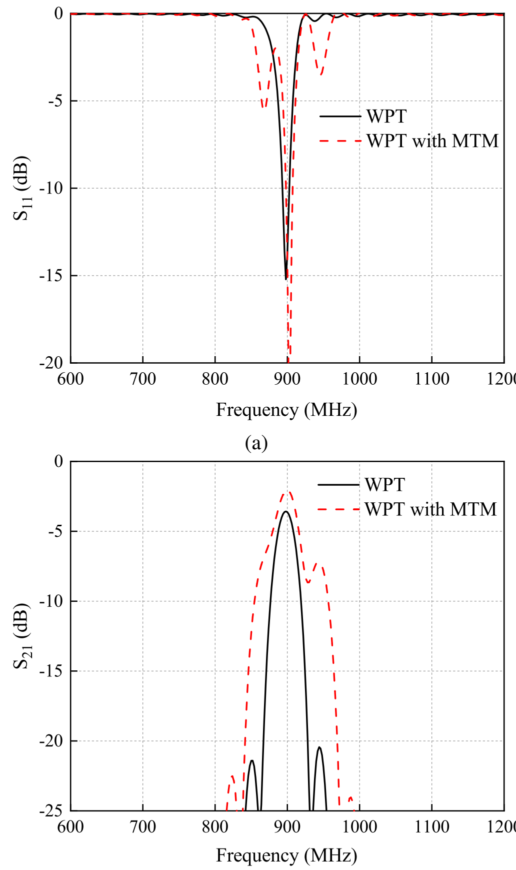
measuring 2 mm in width and 30 mm in length. Furthermore, it should be noted that MTM is developed using the same Rogers' substrate that was utilized for the DGS-based resonator design. In addition, Fig. 2b depicts the obtained results of the MTM slab. It is apparent that real parts of both μ and ϵ are negative, at the opted frequency of 900 MHz, which essentially verifies that the designed MTM has DNG properties. As a result, the developed MTM slab can be aptly employed to improve the overall PTE of coupling-based near-field WPT systems.

Prior to discussing the MTM inclusion procedure, it is necessary to mention that PTE of WPT can be calculated using Eq. (2) [7]. The integration process of the MTM slab starts by placing it between two resonating structures. In detail, the transmitter and receiver resonators based on DGS are separated by a 40 mm, and the MTM slab is positioned precisely in the middle. The subsequently obtained results of the WPT system with and without integrated MTM are depicted in Fig. 3. It is clear from Fig. 3a that the S_{11} value falls below -10 dB for both cases, referring to a good impedance match. In addition, WPT presents $S_{21} = -3.58$ dB, corresponding to PTE of 44%. It is also apparent from the presented results that the integration of DNG MTM into the designed system led to a significant PTE improvement to 61%. This essentially reveals that achievable PTE was increased by 17%. Lastly, it is possible to state that the addition of DNG MTM validates its usefulness in the performance improvement strategy of the WPT system.

$$\text{PTE} = \frac{|\,S_{21}\,|^2}{1-|\,S_{11}\,|^2} \times 100\%. \tag{2}$$

IV. Conclusion

This paper has presented the RF WPT system design and performance improvement through the incorporation of DNG MTM. The designed MTM slab was placed in the middle of two DGS-based resonators. Furthermore, it should be noted that the developed WPT system worked at practical 900 MHz. Finally, the MTM slab assisted in the WPT's PTE enhancement to 17%.



(a)

(b)

Fig. 3. WPT system results with and without MTM.

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