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Dual-Mode Resonator for the Dual-Band System of Wireless Energy Transfer with Simultaneous Data Transmission

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Abstract—Original resonant structures for improving efficiency of wireless charging system with the possibility of data exchange are presented. Characteristics of two different dual-mode spiral resonators were obtained by electromagnetic and circuit simulations. Based on these results, an optimum design for highly efficient data and energy transfer was suggested.

1. INTRODUCTION

Wireless energy transmission systems are widely used for power-supply of different electronic devices such as mobile phones, remote control devices etc. This technology improves the reliability of consumer electronics and makes it more convenient for users. Extremely important are medical applications of wireless charging systems. In this case, implanted into biological medium antennas interact effectively with a reader on its surface [1].

Generally, wireless power supply systems are based on using magnetic induction providing coupling between transmitting and receiving parts. The main elements of such systems are transmitting and receiving radiators (antennas) that can be represented as resonant circuits operated at the specified frequency. Possibilities of wireless charging systems can be expanded if at the same time the data transmission is provided [2]. In known systems [2–4], data and energy exchange is based on the near-field magnetic coupling in the kHz- or MHz-frequency range. There are some drawbacks in such systems. Particularly, the data transfer rate and the energy transmission efficiency are remarkably limited. Moreover, design of radiators becomes a challenging task because the additional components for providing a sufficient decoupling level between data and energy transfer channels are required.

Such difficulties can be avoided, if data exchange is realized at much higher frequencies (for example, using RFID or Wi-Fi bands at frequencies around 900 MHz and 2.4 GHz respectively) keeping low frequency for the energy transfer. Using high frequency makes it possible to increase the data rate and reduce the noise, generated by high power transmission channel. The problem of miniaturization can be solved by using a single two-band radiator operating in two frequency bands simultaneously (e.g., 13.56 MHz and 2400 MHz).

2. MATCHING AND DECOUPLING CIRCUITS FOR DATA AND ENERGY TRANSFER CHANNELS

The dual-band resonator designed for simultaneous transmission of energy and data has been investigated in the previous work [5]. The considered design consists of a resonator, matching and decoupling networks (Figure 1). Planar multi-turn spirals were used as transmitting and receiving resonators due to a highly efficient energy transmission by such structures.

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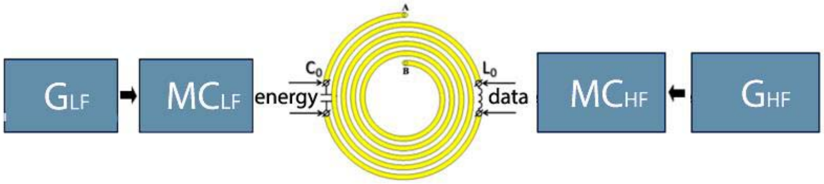


Figure 1. The structure of a dual-band radiator. Here $\mathrm{G_{LF}}/\mathrm{G_{HF}}$ and $\mathrm{MC_{LF}}/\mathrm{MC_{HF}}$ are the generator and matching circuits for low/high frequency channels.

Mutual coupling between the channels can be effectively suppressed if operating frequencies are widely separated in the frequency range. For this purpose, the inductance should be installed in parallel with the input port of the higher frequency RF channel while the capacitor is installed in parallel with the terminal of the lower frequency circuit. This approach allows designing the matching circuits for both channels independently. LC-baluns based on lumped elements [6] were used in both channels of energy and data transfer for matching the balanced resonator input with an unbalanced 50-Ω feed line.

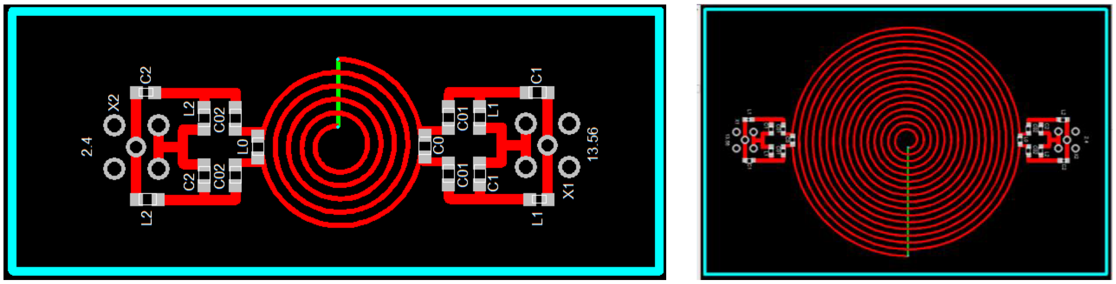
3. SPIRAL RADIATOR FOR SIMULTANEOUS TRANSMISSION OF ENERGY AND INFORMATION

As noted above, the system under consideration comprises transmitting and receiving loop antennas shaped as spiral resonators. Power transmission between two resonators is based on the magnetic induction. The efficiency of this system is mainly determined by the coupling coefficient between these resonators that is proportional to the generated magnetic field intensity [7]. The current flowing along the spiral should have the uniform amplitude and phase distribution for maximizing the magnetic field intensity generated by this resonator. This condition is satisfied if the length of the spiral does not exceed one half of the operating wavelength.

In the case of quite large diameter (of the order of few centimeters) this condition is satisfied only in kHz- and MHz-frequency bands, but it is violated at higher frequency range. As a result, the inevitable periodic undulations of the current distribution along the resonator will appear, that can significantly decrease the coupling between the receiving and transmitting parts of the system.

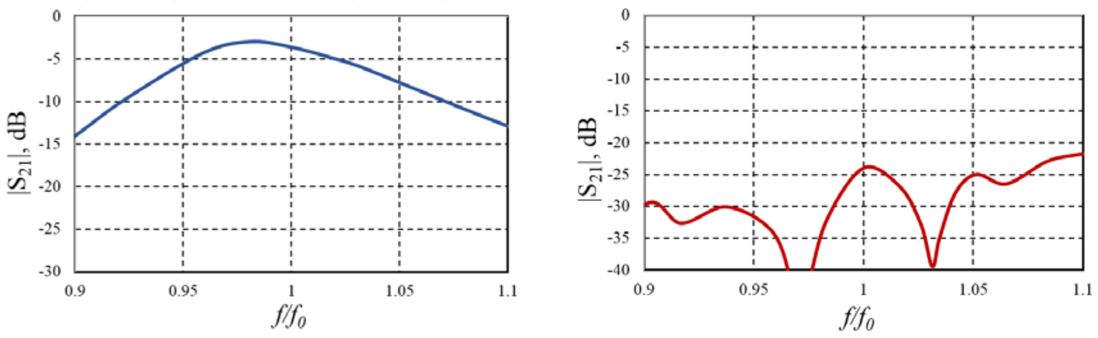
To demonstrate this effect the system consisting of transmitting and receiving spiral resonators was experimentally investigated. The layouts of manufactured resonators with decoupling and matching circuits are shown in Figure 2 (scales for (a) and (b) are different).

The optimum dimensions of the resonators were found using the approach described in [5]. The diameter of the transmitting resonator is $2r_1 = 70\,\mathrm{mm}$, the number of turns is $N_1 = 16$, the width of the wire is $a_1 = 1\,\mathrm{mm}$; the diameter of the receiving resonator is $2r_2 = 20\,\mathrm{mm}$, the number of turns is $N_2 = 5$, the width of wire is $a_2 = 0.5\,\mathrm{mm}$, the metallization thickness is $b = 35\,\mu\mathrm{m}$. The thickness of the dielectric substrate is $h = 2\,\mathrm{mm}$ (FR4 was used with dielectric permittivity $\varepsilon_r = 4.8$). All installed SMD components are of 0603 package size. Values of lumped elements in matching and decoupling



(a) (b)

Figure 2. Printed layout of receiving (a) and transmitting (b) radiators.



(a) (b)

Figure 3. Frequency dependence of measured transmission coefficient between two single spiral resonators separated by 15 mm for central frequencies, (a) $f_0 = 13.56$ MHz and (b) $f_0 = 2400$ MHz.

circuits are as follows: $L_0 = 30$ nH, $C_0 = 10$ pF, $L_1 = 75$ nH, $L_2 = 5.5$ nH, $C_{01} = 390$ pF, $C_{02} = 2$ pF, $C_1 = 1800$ pF, $C_2 = 0.8$ pF (for receiving resonator) and $L_0 = 20$ nH, $C_0 = 5.1$ pF, $L_1 = 330$ nH, $L_2 = 6.8$ nH, $C_{01} = 390$ pF, $C_{02} = 5.1$ pF, $C_1 = 1800$ pF, $C_2 = 3$ pF (for transmitting resonator). These parameters provide higher than 10 dB return loss in operating frequency ranges.

Experimental investigation of fabricated resonators was performed using the vector network analyser Agilent E5071C with a function of balanced measurements.

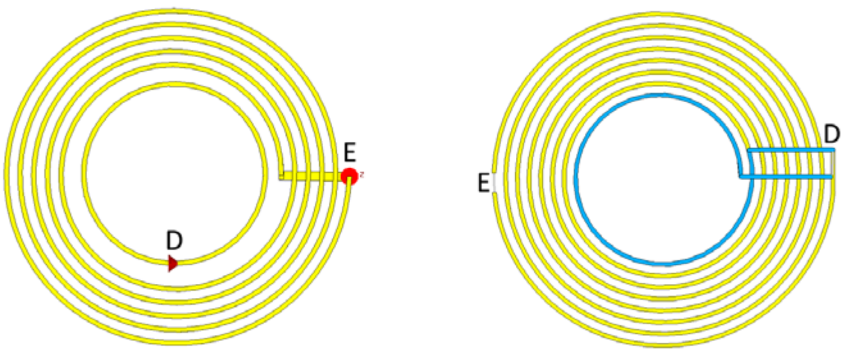
The measured in both frequency ranges magnitude of transmission coefficient between two radiators separated by 15 mm is presented in Figure 3.

According to expectation, the transmission coefficient at frequency 2400 MHz is quite low — only about -24 dB. The efficiency of the energy transfer at frequency 13.56 MHz is 50%. This value is lower than the simulated one (70%). This fact can be explained by nonperfect matching that results in additional 10 dB losses for both receiving and transmitting parts of the system.

4. DUAL-BAND RADIATORS WITH MODIFIED HIGH FREQUENCY PART

The electrical length of the radiating high frequency part of the spiral resonator should be reduced to improve the efficiency of the system at higher frequencies. This can be achieved in two ways without increasing the size of the system:

- design the high-frequency part of the resonator separately from the low-frequency one and place it inside, so as to keep the overall dimensions of the system (Figure 4(a));



(a) (b)

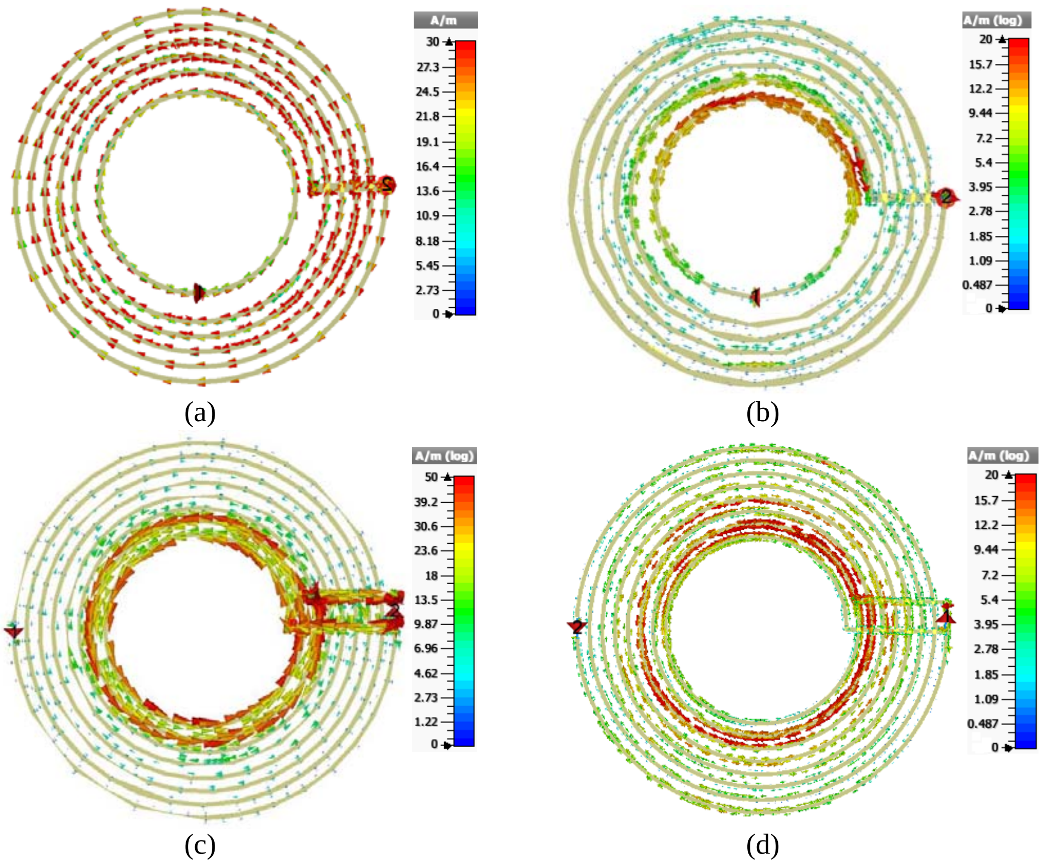
Figure 4. (a) Modified resonators: high-frequency part is electrically isolated from the low-frequency part, (b) connecting bridges are made in the bottom layer to form the high-frequency resonator. Here **D** is the data transfer channel and **E** is the energy transfer channel.

- apply connecting bridges, which are installed in the bottom layer of PCB. In this case, the length of the spiral between the connection points becomes equal to the half wavelength at the required frequency (Figure 4(b)).

The dimensions of the resonators were found using the same approach as in the previous case. The diameter of the transmitting resonator is $2r_1 = 70\,\text{mm}$, the number of turns is $N_1 = 16$, the width of wire is $a_1 = 0.5\,\text{mm}$; the diameter of the receiving resonator is $2r_2 = 20\,\text{mm}$, the number of turns is $N_2 = 8$, the width of wire is the same $a_2 = 0.5\,\text{mm}$, the metallization thickness for both resonators is $b = 35\,\mu\text{m}$. The thickness of the dielectric substrate is $h = 2\,\text{mm}$ (FR4 was used with the dielectric permittivity $\varepsilon_r = 4.8$). The distance between the resonators is $s = 15\,\text{mm}$.

The current distribution at the frequencies 13.56 MHz and 2400 MHz obtained by electromagnetic simulation of the proposed designs is presented in Figures 5(a), (b), (c), (d).

As follows from Figure 5(a), the current along the isolated high-frequency part (the internal turn) of the resonator flows in opposite direction with respect to the low-frequency part (external turns) at frequency 13.56 MHz, which can significantly reduce the energy transmission efficiency. Whereas, in the case of resonator with the modified connecting bridges, the current distribution at low frequency is almost uniform (Figure 5(c)). However, at higher frequency both modifications provide high performance, because the maximum current density is localized in the internal turns. (Figures 5(b), (d)). Thus, such spiral can be considered as an equivalent loop with short electrical length. One may conclude that the modified system with bridges should be more effective in the both frequency ranges.



(a) (b)

(c) (d)

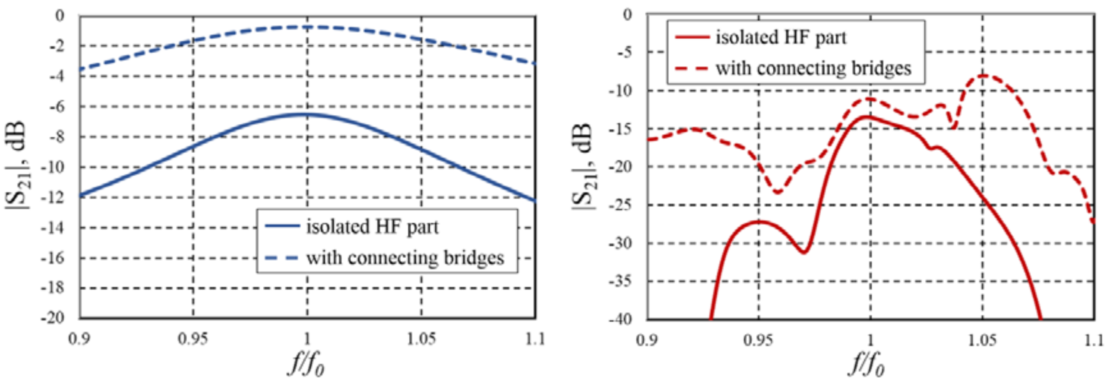
Figure 5. Current distribution along two-mode resonators, (a), (b) with the isolated high-frequency part and (c), (d) with the modified connecting bridges at frequencies (a), (c) 13.56 MHz and (b), (d) 2400 MHz.

5. EFFICIENCY OF THE SYSTEM CONSISTING OF COUPLED RESONATORS

Primarily, electromagnetic simulation by using CST Microwave Studio [8] was performed to analyse the coupling coefficient of the system consisting of receiving and transmitting radiators spaced apart by the distance s. The obtained scattering parameters (S-parameters) were exported to another software (AWR Microwave Office [9]) for further circuit analysis, which is necessary for calculating the nominal lumped elements in matching and decoupling circuits. Division of tasks such as 3-D electromagnetic simulation and circuit analysis enabled to significantly reduce the computation time.

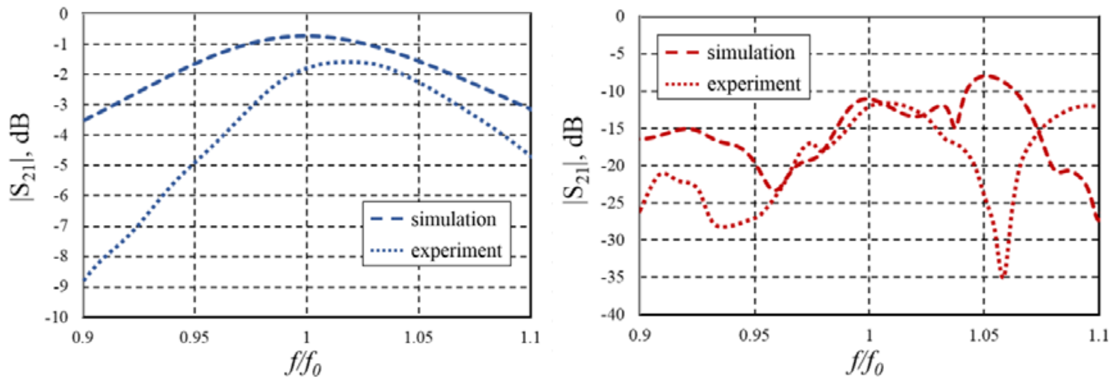
The frequency dependent transmission coefficient between proposed resonators with the isolated high-frequency part and with the modified arrangement of bridges are shown in Figure 6 for two different frequency ranges.

As it follows from the simulation results, both modifications demonstrate quite good performance (around -10 dB) at frequency 2400 MHz, which is enough for reliable data exchange (Figure 6(b)). However, the efficiency of energy transfer at 13.56 MHz is too low (no more than 30%) in the case of the first resonator modification. As discussed above, this follows from the opposing currents in the inner and outer parts of the spiral resonator; as a result, the total intensity of the magnetic field created by such resonator is reduced. At the same time, the improved structure with connecting bridges provides



(a) (b)

Figure 6. Transmission coefficient between two resonators with modified connecting bridges and the isolated high-frequency part versus frequency with central frequencies, (a) $f_0 = 13.56$ MHz and (b) $f_0 = 2400$ MHz.



(a) (b)

Figure 7. Frequency dependence of measured (dotted lines) and simulated (dashed lines) transmission coefficient between two resonators with modified arrangement of bridges separated by 15 mm for central frequencies, (a) $f_0 = 13.56$ MHz and (b) $f_0 =$2400 MHz.

a highly efficient energy transfer (about 80%) at lower frequency. Thus, this design of resonators can be recommended for use in the system of simultaneous energy and data transmission.

The measured in both frequency ranges transmission coefficients between resonators with modified arrangement of bridges separated by 15 mm is presented in Figure 7 in comparison with simulated results.

As expected, the transmission coefficient at frequency about 2400 MHz became much higher (-10 dB) in comparison with previous measurements of single spiral resonators. Moreover, the efficiency of the energy transfer at frequency 13.56 MHz also increased up to 60%. This effect is mainly connected with improved matching due to more accurate selection of lumped elements.

6. CONCLUSION

A possibility of implementation of highly effective dual-band system of wireless energy transfer and data transmission using a dual-mode resonators operating at two different widely separated frequencies, was discussed in this article. Two novel designs of receiving and transmitting resonators that provide an enhancement of the magnetic field intensity were proposed. Simulations of the considered multifunctional system demonstrated that such modified resonators allow increasing performance at high frequencies used for data exchange, providing at the same time highly efficient energy transfer at lower frequency.

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