Analysis of Radiation Efficiency of Asymmetrical Wireless Power Transmission System

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Abstract

The radiation efficiency of asymmetrical mu-zero resonators (MZRs) for wireless power transmission (WPT) is analysed. The radiation efficiency of two coupled resonators can be calculated by the weighted arithmetic mean of the radiation efficiencies of the transmitter and receiver. To prove our approaches, the WPT efficiency, radiation efficiency, and radiated power are theoretically calculated and simulated. The compared data show good agreements.

Keywords : Wireless Power Transmission Asymmetrical WPT system Radiation Efficiency

1. Introduction

A wireless power transmission (WPT) technology has been proposed using magnetic resonance coupling between two resonators [1]. This technology is capable of transmitting power for distances which are a few times longer than a diameter of transmitting or receiving resonators. In addition, this technology is safer than a WPT technology using electromagnetic radiation because it is non-radiative and a human body is made up of non-magnetic material. However, the radiated power in WPT systems should be considered for practical applications due to the electromagnetic interference (EMI) problem.

Recently, the efficient WPT system using a mu-zero resonator (MZR) is studied [2-3]. In the WPT system consisted of symmetrical MZRs, which means that the same resonators are used as a receiver and a transmitter, the radiation efficiency is equal to that of an isolated MZR because two identical resonators have the same radiation efficiencies. The radiated power is easily calculated by multiplying the total power loss by the radiation efficiency where the total power loss is determined by subtracting the transmitted power from the incident power. For example, if the input power, transmitted power, and radiation efficiency are 10 W, 6 W, and 0.5, respectively, the radiated power is equal to 2 W. On the other hand, the asymmetric case is quite different due to the different radiation efficiencies of two resonators.

In this paper, the radiation efficiency of asymmetrical WPT systems is analyzed by the radiation efficiencies and the WPT efficiency of asymmetrical WPT systems. The equation of the radiation efficiency for asymmetric WPT systems is derived. To prove our approaches, the radiation efficiencies and WPT efficiency are analytically calculated and simulated by adjusting the resonance frequency of asymmetrical MZRs. Also, the transmitted, dissipated (by ohmic loss), and radiated power of the system are obtained and compared.

2. Radiation Efficiency of Asymmetrical Mu-zero Resonators

Figure 1 shows the WPT system using asymmetric MZRs. Each one-cell MZR consists of series inductance and capacitance which are induced by a square loop and a lumped capacitor, respectively [3-4]. In Fig. 1, $a_{1,2}$, $t_{1,2}$, and D are the lengths of the MZR$_1$ and MZR$_2$, the thicknesses of the wire of the MZR$_1$ and MZR$_2$, and the distance between two resonators, respectively.

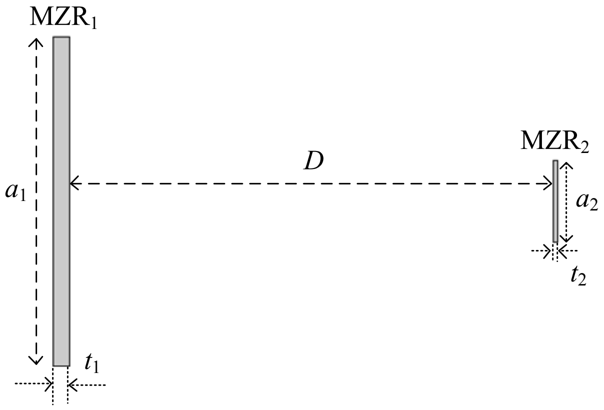

Figure 1: Asymmetric MZRs

Since the figure of merit of a WPT system is $\kappa\sqrt{Q_1Q_2}$ and the coupling coefficient of κ is independent of the resonance frequency [1], the efficient WPT system can be designed at a certain optimum resonance frequency where the square root of Q_1Q_2 is maximized. In case of the symmetrical WPT system, the optimum resonance frequency of the system is equal to that of the single resonator because two coupled resonators have the same quality factor of Q [3]. Similarly, it can be intuitively expected that the radiation efficiency of the symmetrical WPT system is equal to that of the resonator. On the other hand, in case of the asymmetrical system, the radiation efficiencies of the MZR$_1$ and MZR$_2$ are different at a certain resonance frequency. If the WPT efficiency is close to 100%, the transmitter and receiver will exchange the same amount of energy [4]. During a period of the energy exchange, each resonator will radiate, by turns, some power which is calculated by multiplying the total power loss by the radiation efficiency of each resonator. Therefore, the radiation efficiency of the asymmetrical WPT system can be calculated using the arithmetic mean of the radiation efficiencies of the MZR$_1$ and MZR$_2$. However, when the WPT efficiency is less than 100%, the radiation efficiency can be calculated by the following equation with the weighted arithmetic mean of the radiation efficiencies of the asymmetric MZRs

$$\eta_{rad} = \frac{w_1\eta_{rad1} + w_2\eta_{rad2}}{w_1 + w_2} \tag{1}$$

where η_{rad1} and η_{rad2} are the radiation efficiencies of the MZR$_1$ and MZR$_2$, respectively. w_1 and w_2 are the weighting factors which contains the energy of the MZR$_1$ and MZR$_2$. If the MZR$_1$ and MZR$_2$ are transmitter and receiver, respectively, the weighting factors of w_1 and w_2 can be defined as 1 and WPT efficiency of η_{WPT}.

To calculate the WPT efficiency and the radiation efficiency of asymmetrical MZRs, the MZRs with the following dimensions are analytically calculated [3] and simulated by Ansoft's HFSS: a_1 = 20 cm, a_2 = 5 cm, t_1 = 1 cm, and t_2 = 0.25 cm. The theoretical optimum frequencies of the MZR$_1$, MZR$_2$, and the asymmetrical WPT system with the MZR$_1$ and MZR$_2$ are 31 MHz, 151 MHz, and 40 MHz, respectively. Note that the capacitances of the simulated MZR$_1$ and MZR$_2$ varies from 23 pF to 625 pF and from 101 pF to 2500 pF, respectively, to sweep the corresponding resonance frequency from 10 MHz to 50 MHz.

Figure 2 shows the theoretical and simulated WPT efficiencies versus the resonance frequency of asymmetrical MZRs. To compare the theoretical and simulated radiation efficiencies, the theoretical and simulated WPT efficiencies are set to be 0.1, 0.5, and 0.9 at 40 MHz by adjusting κ and D. At fixed values of κ and D, the WPT efficiency is lower than the maximum WPT efficiency if the resonance frequency is lower or higher than the optimum resonance frequency of 40 MHz. The theoretical and simulated WPT efficiencies are in good agreement, as shown in Fig. 2.

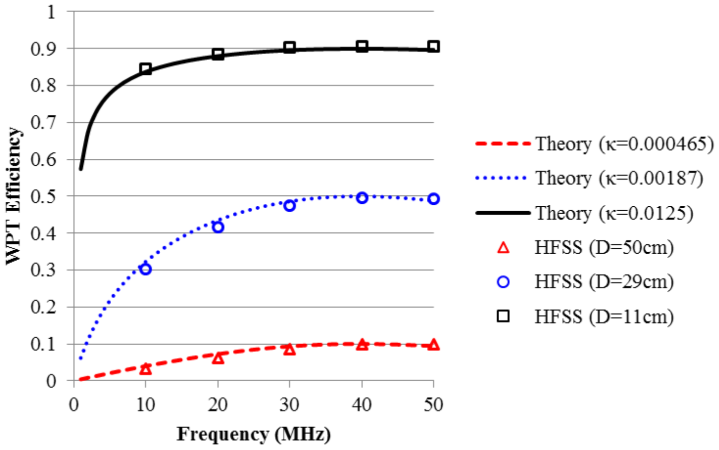

Figure 2: WPT Efficiency of asymmetric MZRs

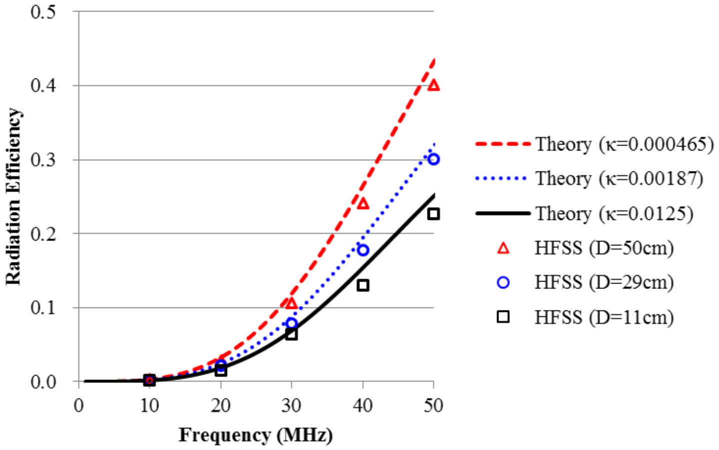

Figure 3: Radiation Efficiency of asymmetric MZRs

Figure 3 shows the theoretical and simulated radiation efficiencies versus the resonance frequency in the asymmetrical WPT system. The theoretical and simulated results are calculated by (1) and Ansoft's HFSS, respectively. As shown in Fig. 3, the theoretical and simulated radiation efficiencies are in good agreements. The radiation efficiency of the MZR_2 is much smaller than that of the MZR_1 due to its small size at the same resonance frequency [2]. If the WPT efficiency increases as κ increases or D decreases, the radiation efficiency of the asymmetrical WPT system decreases because the weight of w_2 is close to 1.

Table 1: Power Loss of asymmetric MZRs (W)

Frequency (MHz)	Theory (κ = 0.000465) HFSS (D = 50 cm)			Theory (κ = 0.00187) HFSS (D = 29 cm)			Theory (κ=0.0125) HFSS (D = 11 cm)		
	P_{WPT}	P_{diss}	P_{Rad}	P_{WPT}	P_{diss}	P_{Rad}	P_{WPT}	P_{diss}	P_{Rad}
10	0.40	9.57	0.03	3.23	6.75	0.02	8.37	1.63	0.00
	0.32	9.65	0.03	3.22	6.95	0.01	8.45	1.55	0.00
20	0.73	8.97	0.30	4.35	5.51	0.14	8.80	1.18	0.02
	0.62	9.11	0.27	4.17	5.70	0.13	8.86	1.12	0.02
30	0.94	7.98	1.08	4.86	4.69	0.45	8.96	0.97	0.07
	0.85	8.17	0.98	4.73	4.85	0.41	9.02	0.92	0.06
40	1.00	6.62	2.38	5.00	4.03	0.97	9.00	0.85	0.15
	1.00	6.83	2.17	4.97	4.14	0.89	9.07	0.81	0.12
50	0.94	5.14	3.92	4.87	3.49	1.63	8.96	0.78	0.26
	1.00	5.39	3.61	4.94	3.53	1.52	9.05	0.73	0.22

[Incident Power: 10 W]

In Table 1, when the incident power is 10 W, the WPT power, the dissipated power by heat loss, and the radiated power in the asymmetric WPT system are calculated using the theoretical and simulated results in Fig. 2 and Fig. 3, respectively. If the κ and D are fixed, the radiated power decreases as the resonance frequency decreases. However, the dissipated power increases because the radiation efficiency decreases. In case of the same resonance frequency, the radiated and dissipated power decrease as the κ increases or the D decreases because the total loss decreases. As the κ increases (or the D decreases), the radiated power decreases because the total loss and radiation efficiency decrease at the same resonance frequency. The dissipated power by heat loss also decreases due to the decreased total loss. If an EMI problem is caused by the radiated power in the asymmetrical WPT system, it can be solved by decreasing the designed resonance frequency and/or distance between the resonators. Therefore, the trade-off between the resonance frequency and WPT efficiency of the system should be considered.

3. Conclusion

The radiation efficiency of the WPT system using asymmetrical MZRs is analysed by using the weighted arithmetic mean of the radiation efficiencies of resonators. Since the radiated power is calculated by multiplying the total power loss by the radiation efficiency, an EMI problem can be solved by decreasing the designed resonance frequency and/or distance between the resonators. The simulated WPT efficiency, radiation efficiency, and radiated power show good agreement with the theoretical results.

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