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損失性インピーダンス整合回路を用いた無線電力伝送効率の研究

鄭　立飛，佐藤　弘康，陳　強（東北大学大学院工学研究科）

Abstract: this paper proposed an exact approach to enhance the transmission efficiency of wireless power transfer(WPT) by connecting two-side impedance matching network with the consideration of losses from components in matching circuits. Lossy T-section impedance matching circuits are used at both the transmitting and receiving sides of a 2-dipole WPT system to satisfy the condition of impedance conjugate matching and maximize the transmission efficiency. And the maximize transmission efficiency is calculated by S parameters. Moreover, the effect of losses from the components in matching circuit on transmission efficiency will be investigated.

Keyword: Wireless Power Transfer, Lossy Impedance Matching Circuit, *Q*-factor, Transmission Efficiency

1. Introduction

Wireless power transfer is the process which electromagnetic energy is transmitted from a source to a load without lines. Presently, the popular WPT technology is the microwave power transfer. However, the microwave power transfer has a low transmission efficiency because it uses radiation to transfer power. And a WPT technology using impedance matching network can enhance the transmission efficiency.

The impedance matching network is usually designed as L-section, T-section and Π-section circuit to maximum the transmission efficiency. The equivalent circuit of the WPT system with impedance matching networks is shown in Fig.1. Two dipole antennas displayed the transmitting and receiving antennas respectively. And the impedance matching circuits have designed by using series or parallel inductors and capacitors with consideration their losses.

A fundamental study about lossy L-section impedance circuit has been reported in [1]. The results of [1] showed the transmission efficiency is reduced greatly because of the losses of matching circuit components. But there is a limitation of the L-section impedance matching circuit due to matching area.

In this paper, an exact approach to design T-section impedance matching circuit to enhance the transmission efficiency of a 2-antenna WPT system at 13.56MHz with the consideration losses of matching circuit components.

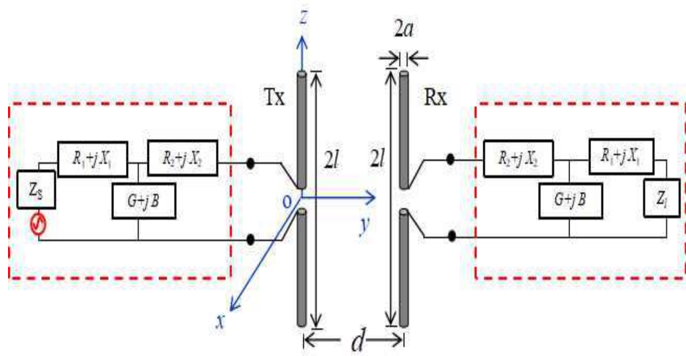

Fig.1 two-antenna WPT system with two-side lossy T-Section impedance matching circuits

2. Analysis model and method

2.1 Maximum efficiency calculation of WPT system with S parameters

The 2-dipole WPT system can be studied as two-port network theory, which is shown in Fig.2. And the maximum transmission efficiency can be calculated by S parameters.

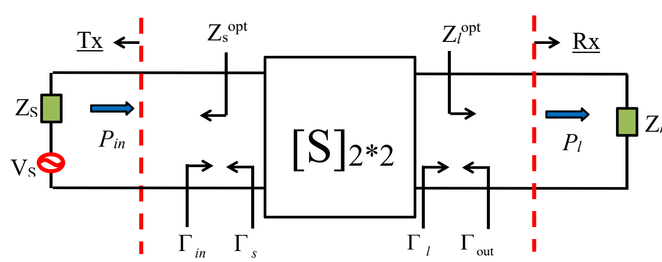

Fig.2 The equivalent circuit of two-port network

As discuss in [2], the conjugate matching condition at two ports is expressed as equation (1).

$$\Gamma_{in} = \Gamma_s^* \qquad \Gamma_{out} = \Gamma_l^* \tag{1}$$

Where Γ_{in} and Γ_{out} is the input and output reflection coefficients at ports. And Γ_s and Γ_l is the reflection coefficient at source Z_s and load Z_l.

Γ_{in} and Γ_{out} in terms of S-parameter are defined in the following equation (2).

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$$\begin{aligned}\Gamma_{in} &= S_{11} + \frac{S_{12}S_{21}\Gamma_l}{1 - S_{22}\Gamma_l} = \Gamma_s^* \\ \Gamma_{out} &= S_{22} + \frac{S_{12}S_{21}\Gamma_s}{1 - S_{11}\Gamma_s} = \Gamma_l^*\end{aligned} \tag{2}$$

From (1) and (2), the optimal Γ_s and Γ_l can be written as (3).

$$\begin{aligned}\Gamma_s^{opt} &= \frac{B_1 \pm \sqrt{B_1^2 - 4|C_1|^2}}{2C_1} \\ \Gamma_l^{opt} &= \frac{B_2 \pm \sqrt{B_2^2 - 4|C_2|^2}}{2C_2}\end{aligned} \tag{3}$$

where,

$$\begin{aligned}B_1 &= 1 + |S_{11}|^2 - |S_{22}|^2 - |\Delta|^2 \\ B_2 &= 1 + |S_{22}|^2 - |S_{11}|^2 - |\Delta|^2 \\ C_1 &= S_{11} - \Delta S_{22}^* \\ C_2 &= S_{22} - \Delta S_{11}^*\end{aligned}$$

From the optimal Γ_s and Γ_l , the optimal source impedance Z_s and optimal load impedance Z_l can be obtained as equation (4).

$$\begin{aligned}Z_s^{opt} &= Z_0 \frac{1 + \Gamma_s^{opt}}{1 - \Gamma_s^{opt}} \\ Z_l^{opt} &= Z_0 \frac{1 + \Gamma_l^{opt}}{1 - \Gamma_l^{opt}}\end{aligned} \tag{4}$$

where, Z_0 is a characteristic impedance (normally chosen to be 50Ω).

Finally, maximum transmission efficiency of the two antenna WPT system can be calculated by using S parameters as (5).

$$\eta_{max} = \eta \big|_{\Gamma_{in}=\Gamma_s^*, \Gamma_{out}=\Gamma_l^*} = \frac{1}{1 - |\Gamma_s|^2} |S_{21}|^2 \frac{1 - |\Gamma_l|^2}{|1 - S_{22}\Gamma_l|^2} \tag{5}$$

2.2 The calculation of the value of components in lossy impedance matching circuits

In order to realize two ports conjugate matching condition in WPT system, the T-section matching circuit could be connected with the source and load impedance in series. The source impedance Z_s and T-section matching circuit can be regarded as the optimal source impedance Z_s^{opt} such as Fig.3. The X_1, X_2 and B are components of T-section matching circuit. Their value can be obtained from equation (6).

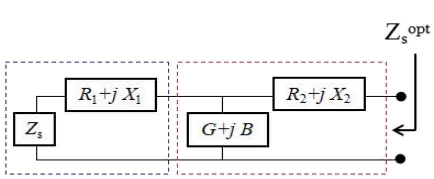


Fig.3 The equivalent circuit of Z_s^{opt}

$$\begin{cases} Z_s^{opt} = \dfrac{1}{\dfrac{1}{R_s + R_1 + jX_1} + G + jB} + R_2 + jX_2 \\ Q_n = \dfrac{|X_1|}{R_s + R_1} \\ Q_{X_1} = \dfrac{|X_1|}{R_1} \quad Q_{X_2} = \dfrac{|X_2|}{R_2} \quad Q_B = \dfrac{|B|}{G} \end{cases} \tag{6}$$

where Q-factor is used to defined the losses R_1, R_2 and G of component X_1, X_2 and B respectively and Q_n represents the loss of the sum of load impedance Z_l and component X_2. The matching circuit at transmitting terminal is the same as that of the receiving terminal. Because the transmitting antenna and receiving antenna are exactly the same dipole.

2.3 The model of two-antenna WPT system

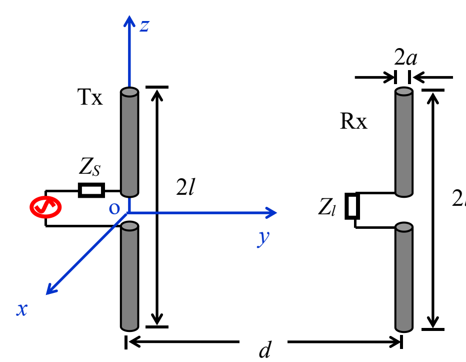


Fig.4 two-dipole system

Two dipole are used as transmitting and receiving antenna. The dipoles are made of perfect electrical conductor (PEC). The parameters of model in this paper is described in Table 1.

Table 1. parameters of two dipole model

Parameters	
frequency	13.56 MHz
$2l$	λ/2
$2a$	0.2 mm
d	0.01λ～0.2λ
material	Copper or PEC

3 Results

3.1 Maximum transmission efficiency

By using the distance d between the transmitting and receiving antennas in Fig.4 as a parameter, we could obtain the S parameter from the FEKO software and examine the change of the transmission efficiency.

The power transferred to load will be a maximum when the conjugate matching condition at two ports is satisfied. The results of maximum transmission efficiency are shown in Fig.5 where the distance d is 0.01λ and 0.1λ and two dipole is made of copper. The solid lines in Fig.5 are the maximum transmission efficiency calculated by using equation (5) and the dashed lines are transmission efficiency when both of source impedance and load impedance is 50Ω.

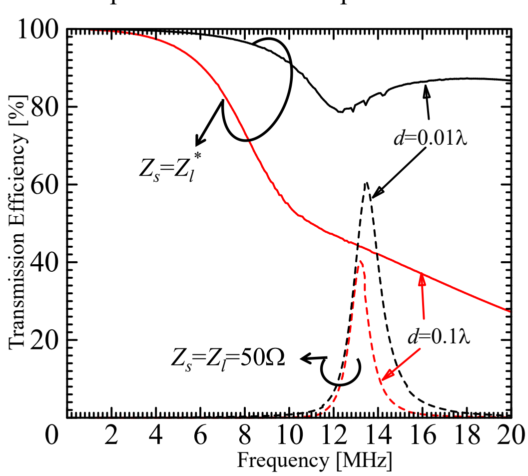


Fig.5 Transmission efficiency of two-dipole model

From Fig.5, it is clear that if the conjugate matching condition is satisfied at the low frequency band, the transmission efficiency can be about 100% and when the distance d between the transmitting and receiving antennas increased, the transmission efficiency decreased.

3.2 Transmission efficiency with consideration of losses of matching circuit components

The transmission efficiency is also researched when two lossy T-section impedance matching circuits in Fig.7 are connected to two dipole antennas which made of PEC and copper. The results is shown in Fig.8 and Fig.9 respectively. when the distance d between transmitting and receiving antennas is 0.01λ and the Q_n is equal to 3 at 13.56 MHz.

From Fig.8(a) and Fig.9(a), it is shown that the losses of the matching circuit components decreased and the transmission efficiency increased when the Q value increased. And the Fig.8(b) and Fig.9(b) show that the bandwidth became larger when the Q_n value became smaller. That is, Q_n can control the bandwidth when design a lossy T-section impedance matching circuit. And compare Fig.8 and Fig.9, it is shown that the transmission efficiency became smaller when the WPT system has antenna loss

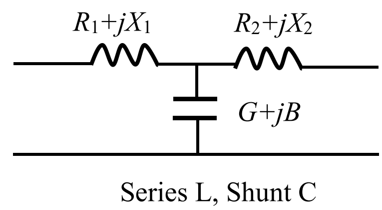
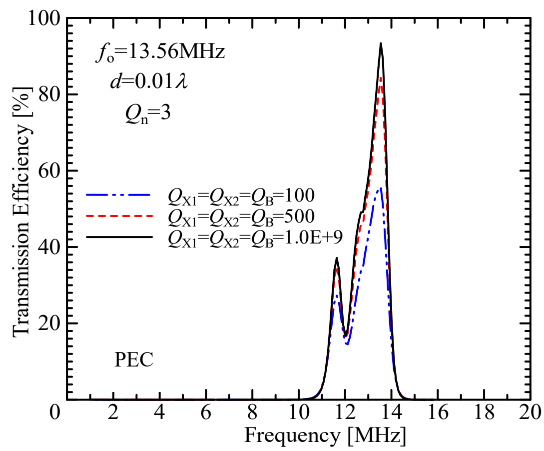
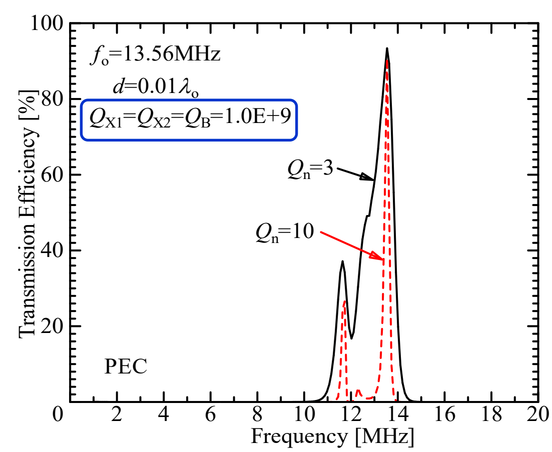


Fig.7 Lossy T-section impedance matching circuit

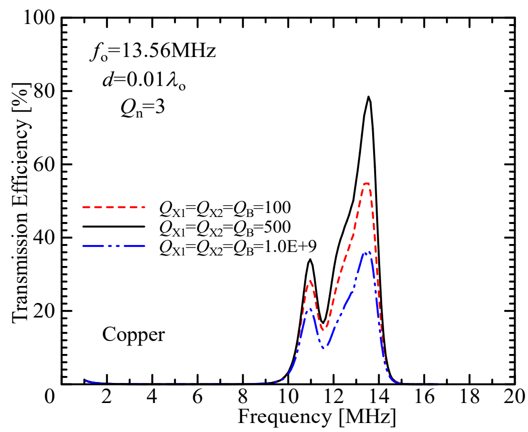


(a) Transmission efficiency versus Q when Q_n is 3

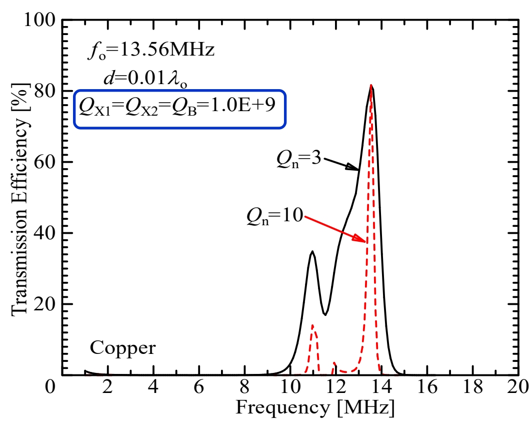


(b) Transmission efficiency versus Q_n when Q is 1.0E+9

Fig.8 Transmission efficiency of two-dipole model which made of PEC with two-side lossy impedance matching circuits



(a) Transmission efficiency versus Q when Q_n is 3



(b) Transmission efficiency versus Q_n when Q is 1.0E+9

Fig.9 Transmission efficiency of two-dipole model which made of copper with two-side lossy impedance matching circuits

Finally, the transmission efficiency is also studied when to design the impedance matching circuits with and without the consideration of losses of matching circuit components.

The result in Fig.10 shows that the transmission efficiency with considering losses of matching circuit components is about 55%, and it is about 18% when without the consideration. Compared to the transmission efficiency without considering the losses, the improvement of transmission efficiency with consideration is about 37%.

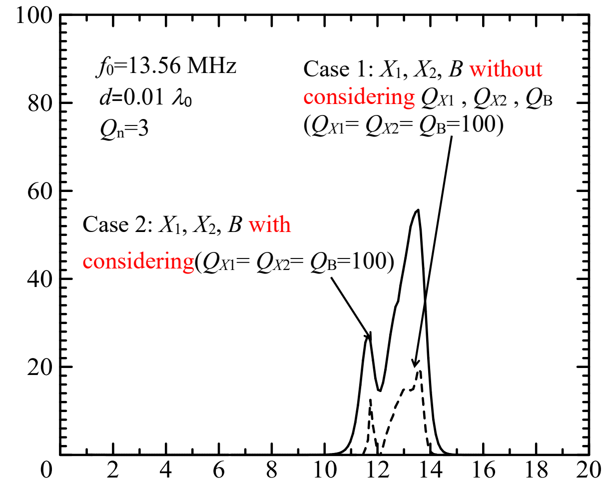


Fig.10 The transmission efficiency when with considering losses of matching circuit components and without the consideration.

4 Conclusion

In this paper, a wireless power transfer system with two-side impedance matching circuits was studied by two dipole model. And this paper also demonstrated how to design two-side impedance matching circuits to get the maximum transmission efficiency on the load by using S parameters to get the optimal source impedance and the optimal load impedance at both of transmitting and receiving ports. Moreover, the results of transmission efficiency in this paper also showed that the Q-factor has a great influence on transmission efficiency and the Q_n factor can affect the bandwidth.

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