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回路素子損失を考慮したT型整合回路に関する研究

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Abstract: In this report, a novel design method for a T-section impedance matching circuit which is composed of lumped elements with ohmic loss is proposed. The T-section matching circuit has three unknown reactances to be found when the ohmic loss of all reactances, i.e. Q factor is known. In order to find these reactances, the proposed design method assumes that one unknown reactance is a part of load impedance and the remaining two unknown reactances are obtained from so-called conjugate matching condition. The remaining one unknown reactance is readily available from the load impedance and known Q factor of the reactance. Numerical simulation demonstrates the performance of the proposed method.

Keyword: Impedance matching circuit, Q-factor, Ohmic loss, Efficiency

1. Introduction

According to advances of a wireless power transfer (WPT) system in recent decades, extensively efforts have been dedicated to design of impedance matching circuits. One of the most popular impedance matching circuits are L-section, T-section, and Π-section matching circuits. The L-section is composed of two unknown reactance which are uniquely found from so-called conjugate matching condition. According to its minimum degrees of freedoms for design the L-section is only capable of keeping the conjugate matching condition for only one specific load impedance. As a result, the L-section circuit is unable to design harmonic rejection and bandwidth performance which are sensitive to ohmic loss of circuit components [2].

On the other hand, the T and Π section have three degrees of freedoms and are capable of designing its performance such as bandwidth. Another advantage of the T and Π sections is its wide applicability to any load impedance [1, 3, 5].

In this report, a novel design method for a T-section impedance matching circuit is proposed. The proposed method enables to include ohmic loss of reactance, i.e. Q factor, for the design of the T-section impedance matching circuits. According to a circuit theory, a T-section is equivalent to a Π section. Therefore, the Π section can be designed in the same manner with the proposed method. A loaded quality factor Q_n is introduced to evaluate the efficiencies of T-section matching circuits which are composed of reactance w/ or w/o ohmic loss.

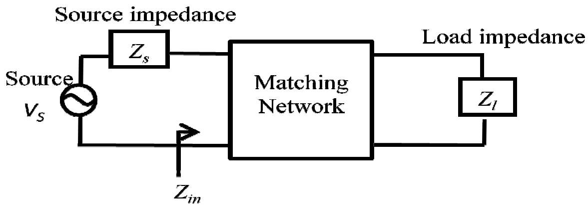

Fig.1 An example of impedance matching circuit between source and load impedance.

2. Conjugate matching condition and formulation

2.1 The ohmic loss of reactance

As we know, the design of impedance matching networks, with particular attention to the T-section matching circuit, is studied on conjugate matching with any two impedance not only can achieve maximum power transmission efficiency but also can meet a specified loaded quality factor Q_n. And furthermore, the most of research for lumped matching networks which designed by inductors and capacitors is without consideration of their ohmic losses. In particular, in an accurate design, the ubiquitous actual ohmic losses have to be considered. It has been shown that the efficiency of WPT system has reduced due to the ohmic loss of inductors and capacitors [4]. So to design a T-section circuit, there is one more parameter, Q-factor. The Q-factor is used to define the ohmic loss of inductor and capacitor as:

$$Q_B = \frac{|B|}{G} \; or \; Q_X = \frac{|X|}{R} \tag{1}$$

where using R to represent the ohmic loss of X and G that of B.

2.2 The formulation

The L-section matching circuit which consists of two reactive components is the basic one of the lumped matching circuit. Certainly, L-section matching circuit will be easily extended to T-section or Π-section matching circuit. So both T-section and Π-section matching circuit can be calculated on the foundation of L-section's equations. L-section can be divided into two kind circuits, BX-L and XB-L circuit [1]. Here, we choose BX-L section as the calculation basis of T-section. So we will firstly discuss the L-section matching circuit without ohmic loss to carry out the basic formula

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derivation. Consider the complex load impedance terminated lossless L-section matching circuit in Fig.2. Using Z_s to represent the source impedance (usually 50Ω), Z_l is the load impedance, and denoting:

$$Z_s = R_s \quad Z_l = R_l + jX_l \tag{2}$$

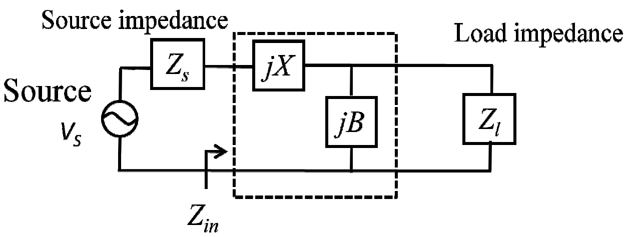


Fig.2 BX-L section matching circuit

So the design problem can be described as: given Z_s and Z_l, determine component values of the reactance X [Ω] and susceptance B [S] to satisfy the conjugate impedance matching condition. The circuit can achieve maximum power transmission when the input impedance (Z_{in}) seen by the load is equal to the complex conjugate of the source impedance (Z_s^*).

$$Z_{in} = Z_s^* \tag{3}$$

The above equation is called as the matching condition. As Fig.2, we can obtain the input impedance Z_{in}:

$$Z_{in} = \frac{1}{\frac{1}{Z_l} + jB} + jX \tag{4}$$

To solve the equation set of (2), (3) and (4), the B and X can be readily formulated as:

$$\mathrm{B} = -\mathrm{B_l} \pm \sqrt{\mathrm{G_l G_s} - \mathrm{G_l^2}} \tag{5}$$

$$\mathrm{X} = \pm \frac{\sqrt{\mathrm{G_l G_s} - \mathrm{G_l^2}}}{\mathrm{G_l G_s}} \tag{6}$$

here, G_s is the reciprocal of R_s, G_l and B_l are the conductance and susceptance of Z_l. And then, we can obtain the value of inductor L and capacitor C by the table 1.

Table 1 calculation method of L and C

	> 0	< 0
Shunt B	$j\omega C$	$\frac{-j}{\omega L}$
Series X	$j\omega L$	$\frac{-j}{\omega C}$

As it should be, a precise approach to design a impedance matching circuit must consider the ohmic loss of inductor and capacitor. This moment, by introducing equation (1) into (4), the Z_{in} is

$$Z_{in} = \frac{1}{\frac{1}{Z_l} + \frac{|B|}{G} + jB} + \frac{|X|}{R} + j \tag{7}$$

Then B and X also can be calculated by solving equations of (2) (3) (7) easily when we know the Q-factor of inductor and capacitor.

2.3 The Q_n-based design method of T-section

The basic two-component L-section is that when given a load impedance to be matched, can only provide a unique solution. Compared with L-section, T-section circuit adds a component variable so we require one more condition to solve the equation set. It is just the loaded quality factory Q_n as a design parameter. The Q_n is extremely useful that we can first determine the value of X_2 in Fig.3 according to the equation (8) below of Q_n.

$$Q_n = \frac{|X_2 + X_l|}{R_l} \tag{8}$$

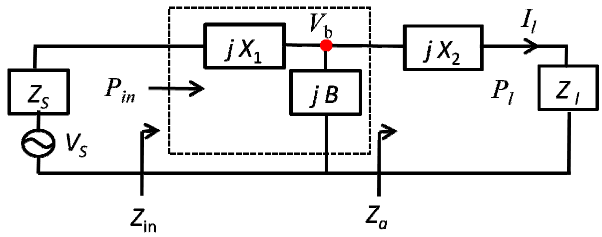


Fig.3 T-section matching circuit

And then, the T-section in Fig.3, which can be considered to L-section when we treat Z_a as the load impedance just like the equation (9) is directly designed following the same procedure as that for the L-section. Therefore, the component values of T-section matching circuit can be calculated on the foundation of L-section's equations no matter with ohmic loss or not.

$$Z_a = Z_l + jX_2 \tag{9}$$

3 Results

3.1 Matching results when with and without loss

For the T-section matching circuit in Fig.3, we set the design parameters as source impedance Z_s=R_s=50 [Ω] and load impedance Z_l are 100+j50 [Ω], 10-j10 [Ω], 1+j6 [Ω], 10+j50 [Ω], 5-j1000 [Ω]. Firstly, the component values in T-section matching circuit will be calculated without considering the ohmic loss of matching elements. And we can get the results as shown in table 2 when the loaded Q_n is equal to 10. All of Z_{in} are equal to Z_s to satisfy the matching condition precisely. This is, all Z_l can be matched to Z_s by means of the design method of T-section circuit in terms of the loaded quality factor Q_n.

Table 2 Impedance matching performance of designed T-section circuits and their reactances obtaind using the proposed method (w/o ohmic loss)

Z_l [Ω]	X_1 [Ω]	B [S]	X_2 [Ω]	Z_{in} [Ω]
100+j50	708.87	2.39E-03	950	50.00
	-708.87	-2.39E-03	-1050	50.00
10-j10	219.09	1.42E-02	110	50.00
	-219.09	-1.42E-02	-90	50.00
1+j6	50.5	1.09E-01	4	50.00
	-50.5	-1.09E-01	-16	50.00
10+j50	219.09	1.42E-02	50	50.00
	-219.09	-1.42E-02	-150	50.00
5-j1000	150.83	2.58E-02	1050	50.00
	-150.83	-2.58E-02	950	50.00

Now, the component values also need to be calculated with the ohmic loss of matching elements when the Q-factor of inductor and capacitor is equal to 100 and the loaded Q_n is still equal to 10. The result is shown in the following table 3. As seen, all the Z_{in} also can be matched to 50Ω. And the last column in the table3 shows that the Z_{in} cannot be matched to 50Ω when ignoring the ohmic loss.

Table 3 Impedance matching performance of designed T-section circuits and their reactances obtained using the proposed method (with ohmic loss, $Q_B = Q_X = 100$)

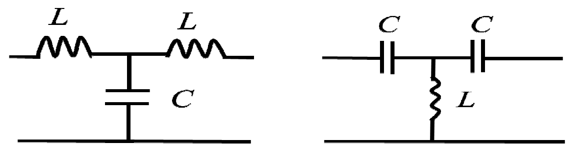
Z_l [Ω]	X_1 [Ω]	B [S]	X_2 [Ω]	Z_{in} [Ω]	Z_{in} [Ω] w/o loss
100+j50	616.78	2.51E-03	1055.56	50.00-j1.48E-05	31.17-j2.17
	-619.44	-2.50E-03	-1166.67	50.00-j6.49E-05	30.82+j2.25
10-j10	211.81	1.33E-02	122.22	50.00-j8.99E-07	38.18-j4.50
	-209.69	-1.35E-02	-100	50.00-j2.37E-06	38.89+j4.64
1+j6	47.45	1.05E-02	4.44	50.00-j1.52E-06	49.72-j7.34
	-53.34	-9.41E-02	-17.78	50.00+j1.71e-07	48.30+j13.11
10+j50	205.38	1.40E-02	55.56	50.00-j9.07e-06	40.39-j3.84
	-215.97	-1.29E-02	-166.67	50.00+j8.72e-06	36.81+j5.64
5-j1000	257.64	9.69E-03	1166.67	50.00-j9.79E-06	13.10-j11.98
	-233.42	-1.14E-02	863.64	50.00-j1.97E-05	16.30+j11.42

3.2 Efficiency effects when with and without loss

The efficiency η [%] in this paper is defined as the below equation:

$$\eta = \frac{P_l}{P_{in}} \qquad (10)$$

where the P_l represents the power consumption of the load impedance Z_l and P_{in} is the available maximum power delivered into the matching circuit as shown by Fig.3. Therefore, the efficiencies versus frequency for Z_l =100+j50 [Ω] and 10-j10 [Ω] are illustrated by Fig.5, 6. The efficiencies are computed in both of cases, without loss and with loss, when the center frequency is 6 MHz and the loaded Q_n is 10. Certainly, when considering the ohmic loss, the Q-factor is equal to 100. For the both cases of Z_l=100+j50 [Ω] and 10-j10 [Ω], the matching circuits plotted in Fig.4 are possible used for calculating and comparing the efficiencies of (a) and (b) section circuit. (a) section circuit is series L shunt C and (b) is series C shunt L.



(a) Series L, Shunt C (b) Series C, Shunt L

Fig.4 Two different T-section matching circuits for design

The efficiency results in Fig.5, 6 show that both of (a) and (b) can be matched at the center frequency and efficiencies reduced significantly because of the ohmic loss. The bandwidth of (b) is wider than that of (a) and the efficiency of (a) and (b) at the same frequency point, (b) is the higher one.

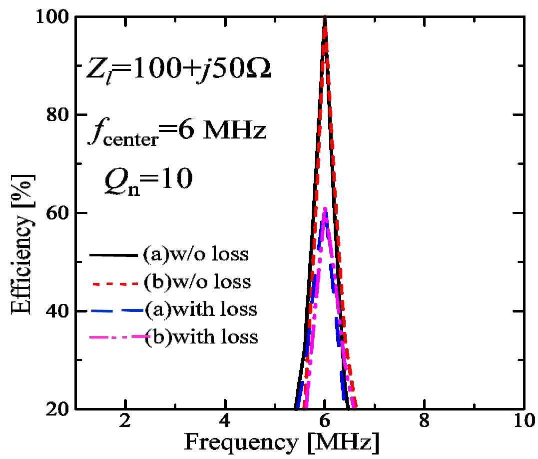


Fig.5 Efficiency of Z_l=100+j50[Ω]

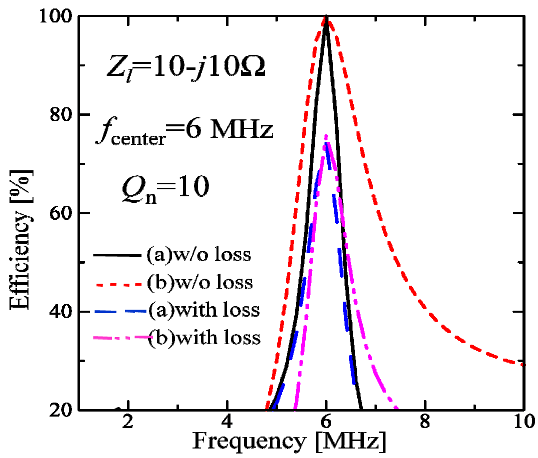


Fig.6 Efficiency of Z_l=10-j10[Ω]

3.3 Efficiency of (b) section versus Q-factor and the loaded Q_n

The efficiencies of (b) section circuit versus Q-factor are exemplified by Z_l =10- j10 [Ω], 10+ j50 [Ω] and 100+ j50 [Ω]. Accurate computation of the ohmic loss effects is also possible. The results are plotted in Fig.7. All of efficiencies improve along with the increase of Q value as shown in Fig.7. So the results can confirm that the Q-factor has a great influence on efficiency. That is, the consideration of the ohmic loss in matching elements is greatly important for an exact design of impedance matching circuit.

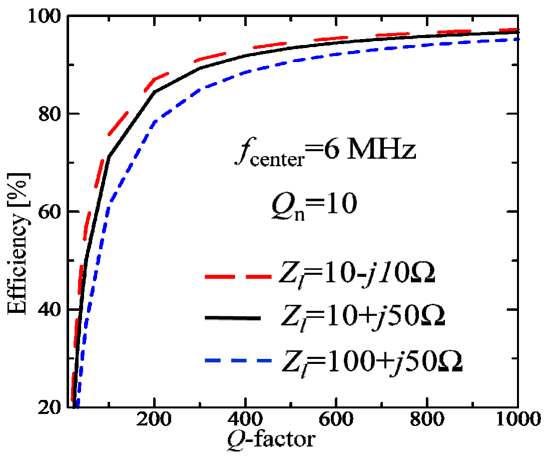


Fig.7 Efficiency versus Q-factor

Furthermore, the efficiencies versus Q_n are drawn in Fig.8, 9. The Fig.8 is plotted by Z_l =100+ j50 [Ω] at the center frequency of 6 MHz when (b) section matching circuit is designed without the ohmic loss of matching elements. Fig.9 is when (b) is designed at the presence of the ohmic loss and the Q-factor is equal to 100. As can be seen in Fig.8, 9, the efficiency is highest and the bandwidth is widest when the loaded Q_n is equal to 3. The result shows that the matching bandwidth become narrow and the efficiencies reduce gradually when the value of Q_n increase. The reason for the decline in efficiencies in Fig.9 is that according to the equations of (1) and (8), X_2 increase since Q_n increase and the ohmic loss R_2 of X_2 will increase when X_2 increase.

Finally during the design of T-section matching circuit, there is one problem of how to select the Q_n that have to be considered. And in this paper, we do not discuss the problem [2, 3].

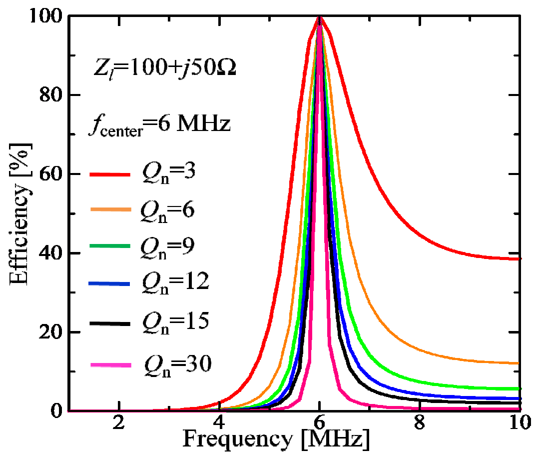


Fig.8 Efficiency of (b) section versus Q_n without loss

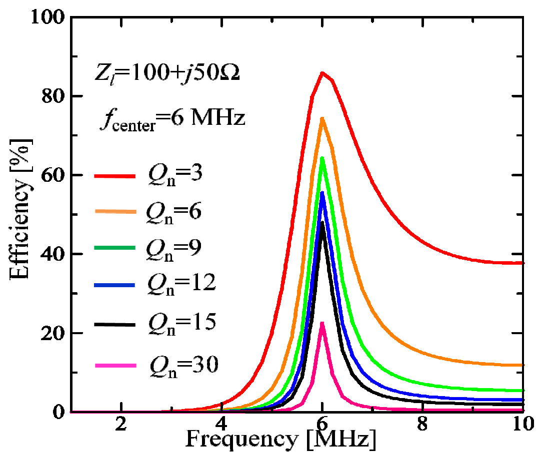


Fig.9 Efficiency of (b) section versus Q_n with loss

4 Conclusion

In this paper, an accurate design method for T-section matching circuit has been introduced, illustrating the circuit's capabilities in terms of Q-factor and the loaded quality factor Q_n. The proposed method has been confirmed for any two different impedances to be possibly conjugated matched at any frequency precisely. The results of some examples in the paper also show that the Q-factor has a great influence on efficiency and the further flexibility in selecting the Q_n for T-section matching circuit design.

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