Dynamic performance analysis of T network impedance matching

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Abstract: - Harmonic rejection ability and reflection coefficient are the most important factors in the design of impedance matching network. However, dynamic stability of impedance matching should be taken into account in applications existing working frequency drift, load impedance variation and components deviation due to tolerances and process variation. In order to study the dynamic performance of T network impedance matching, theoretical analysis is conducted in accordance with the Q (quality)-based design method. The relationships between the matching result (reflection coefficient) and components deviation, load impedance variation and operating frequency drift are obtained. The analysis results suggest that higher Q value produces worse dynamic stability and that matching result is more sensitive to load impedance variation when the load reflection coefficient of static state is larger. In designing a T network, it is need to make the tradeoff between dynamic stability and harmonic rejection ability. The analysis results provide theoretical basis for the design and characteristics analysis of T network impedance matching.

Keywords: - Impedance Matching, Circuit Analysis, Dynamic Performance, Component Tolerance, Frequency Drift, Circuit Design

1 Introduction

Impedance matching using a passive network is very important in the design of RF and microwave circuits to achieve maximum power transfer, minimum reflection, and adequate harmonic rejection [1-4]. By matching the load impedance to the complex conjugate of the source impedance, the load can obtain maximum power from the source. When a transmission line is used to transfer power to the load, the wave power is completely absorbed by the load, and reflection is minimized by matching the impedance of the load to the characteristic impedance of the transmission line [2–4].

The single-frequency (narrow-band) impedance matching circuits represented by L, T and Pi networks are the common-used passive impedance matching networks by virtue of their simplicity [3, 4]. In practical application, the values of the passive components (such as inductors and capacitors) in impedance matching networks often deviate from the theory design value influenced by nominal value tolerances, parasitic and manufacturing process variations [5-12]. For example, capacitance can vary up to ±20% for a metal–insulator–metal capacitor due to process variation [13]. These components deviations can cause the impedance matching networks to deviate from perfect matches. In addition to component deviation, variation of load impedance and working frequency drift in applications such as the piezoelectric ultrasonic transducers [14, 15] and cell phone antenna [11] can also cause deviation from perfect matches.

Broadband impedance matching and dynamic matching are solutions to this problem [16–19]. However, the single frequency matching adopted in L, Pi and T networks is preferred due to its simplicity and manufacturing feasibility in many applications, such as in small type systems. Hence, investigating the dynamic performance of the commonly-used single-frequency impedance-matching networks is of utmost significance.

The influence of load impedance variation on the performance of L network is analyzed by Chung [20]. Chen and Weber [11] presented a process variation-insensitive network with matched passive components. Sun and Fidler discussed component tolerance and parasitic sensitivities of frequency response of Pi network in [21].

The most important performance of impedance-matching networks, in many applications, is the resulting reflection coefficient, which represents the effect of impedance matching. In the present work, the dynamic performance of T network impedance matching is theoretically analyzed using the reflection coefficient as the performance parameter.

The remainder of this paper is organized as follows. The Q-based design method of T network impedance matching is introduced in Section 2. Impacts of components deviation caused by tolerances and process variations on matching performance of the T network are analyzed in Section 3. Impacts of load variation and frequency drift on the matching performance are analyzed in Section4 and Section 5 respectively. The discussions and conclusions are presented in Section 6.

2 Q-based design method of T network impedance matching

2.1 Design process

The easy-to-use Q-based design method is often adopted in designing impedance matching networks for its simplicity [3, 22]. In order to theoretically analyze the dynamic performance of T network, we introduce the Q-based design method in this section. For simplicity, the source impedance and load impedance of the T network in Fig. 1 were considered as pure resistance, which are denoted by R_1 and R_2 respectively. Defining $Q_1=X_{L1}/R_1$, $Q_2=X_{L2}/R_2$ and $k=R_1/R_2$, the loaded quality factor Q_0 can be defined as $Q_0 = (Q_1+Q_2)/2$. The design process is as follows [22]:

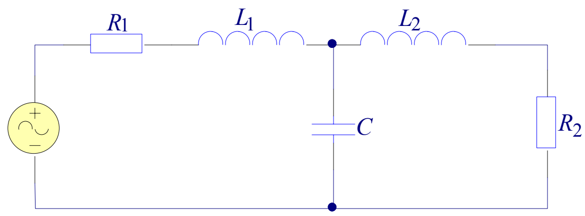

Fig. 1 A T network for pure resistance matching

a. An appropriate Q_0 for the network is selected, which meets the designable condition of:

$$Q_0 \geq Q_{0(\min)} = \frac{1}{2}\sqrt{k-1} \quad \text{for } R_1 \geq R_2 \ (k \geq 1)\,, \quad (1)$$

$$Q_0 \geq Q_{0(\min)} = \frac{1}{2}\sqrt{1/k - 1} \text{ for } R_1 \leq R_2 \ (k \leq 1) \quad (2)$$

and other conditions, such as harmonic rejection.

b. Q_1 and Q_2 are calculated using Eqs. 3 and 4. ($k \neq 1$) given by:

$$Q_1 = \frac{2Q_0 - \sqrt{4kQ_0^2 - (k-1)^2}}{1-k} \quad \text{and} \quad (3)$$

$$Q_2 = \frac{2kQ_0 - \sqrt{4kQ_0^2 - (k-1)^2}}{k-1}. \quad (4)$$

c. Components L_1, L_2, and C of the network are calculated using Eqs. 5 to 7 given by:

$$L_1 = \frac{R_1 Q_1}{\omega_0}, \quad (5)$$

$$L_2 = \frac{R_2 Q_2}{\omega_0} \text{ and} \quad (6)$$

$$C = \frac{2Q_0}{\omega_0 R_1 (1 + Q_1^2)} = \frac{2Q_0}{\omega_0 R_2 (1 + Q_2^2)}, \quad (7)$$

where ω_0 is the matching angular frequency.

2.2 Selection of Q_0

As shown in the design process above, the key in designing a T network impedance matching is to select the appropriate loaded quality factor Q_0 for each network. In [20] and [22], the guidance of selection considers the harmonic rejection of the network. Defining the voltage transfer function as $H(S) = V_2/V_s$, the complex frequency response $H(j\omega)$ can be obtained using circuit analysis, and then substituting $S=j\omega$. The magnitude frequency response $|H(j\omega)|$ is derived using Eq. 8 expressed as:

$$\left|H(j\omega)\right| = \frac{2(k+1)Q_0 - 2p}{\left\{ \begin{array}{l} 4\left[(k+1)^2 Q_0 - (k+1)p - (k-1)^2 Q_0 \omega_p^2\right]^2 \\ + \left[(k-1)^2(3\omega_p - \omega_p^3) + \left(2(k+1)Q_0 - 8kQ_0^2\right)(\omega_p - \omega_p^3)\right]^2 \end{array} \right\}^{\frac{1}{2}}}, \quad (8)$$

where $p = 4kQ_0^2 - (k-1)^2$, $\omega_p = \omega/\omega_0$.

The n-order harmonic rejection can be calculated by 20 log[$|H(jn\omega_0)|/|H(j\omega_0)|$] for specified Q_0 and k. Fig. 2 shows the plots of the second and third harmonic rejection performances with respect to the loaded Q_0 of the network, respectively when k=0.5. The harmonic rejection ability of T network is proportional to the value of Q_0. A suitable Q_0 can be selected according to the requirement of harmonic rejection when designing a T network impedance matching.

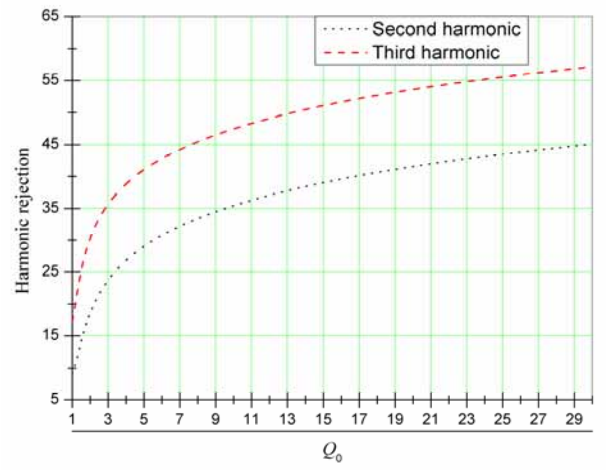

Fig. 2. Harmonic rejection performance of a T impedance matching network

3 Impacts of components deviation on the matching performance

The passive components such as inductors and capacitors are the key components in T network impedance matching. Affected by tolerances and manufacturing process variations, the values of the passive components in practical circuits are different from the theory design value. In addition, the small variation of components parameters can be caused by working environment factors such as temperature. These deviations from the theory design values prove to affect the matching effect of T network. The impacts of the deviation of components L_1, L_2 and C on the matching performance of T network are analyzed in this section.

Considering the T network in Fig. 1, the equivalent impedance Z_e of matched load at working frequency is demonstrated as

$$Z_e = j\omega_0 L_1 + \frac{1}{j\omega_0 C + \frac{1}{j\omega_0 L_2 + R_2}}. \quad (9)$$

For the ideal condition, the equivalent impedance Z_e at working frequency is matched to be equal to R_1 by the T network and the resulting reflection coefficient is zero.

3.1 Deviation of inductor L_1

Considering a small deviation ΔL_1 from the design value of inductor L_1 due to process variation or tolerance in Fig.1, the practical inductance of L_1 is given by

$$L_1' = L_1 + \Delta L_1 = L_1(1 + dL_1), \quad (10)$$

where L_1 is determined by Eq. 5 and $dL_1 = \Delta L_1/L_1$, the relative deviation of inductor L_1.

The practical equivalent impedance of matched load at working frequency becomes

$$Z_e' = Z_e + j\omega_0 \Delta L_1 = R_1 + jR_1 Q_1 dL_1. \quad (11)$$

The changed equivalent impedance will result in a deviation from perfect match. The reflection coefficient caused by the deviation of inductance L_1 can be calculated by

$$\Gamma' = \frac{Z_e' - R_1}{Z_e' + R_1} = \frac{jQ_1 dL_1}{jQ_1 dL_1 + 2}. \quad (12)$$

Eq. 12 suggests that the deviation of inductance L_1 from its theory design value can make the matching effect worse and the magnitude of resulting reflection coefficient |Γ'| is proportional to the relative deviation dL_1 and Q_1. Fig.3 shows the relationship between the magnitude of resulting reflection coefficient |Γ'| and Q_1 when dL_1=0.1. Tolerance of 10% in inductor L_1 can cause the resulting reflection coefficient to be 0.5 when the selected Q_1 reaches to 11.7. Eq. 12 can be used to calculate the resulting reflection coefficient caused by the deviation of inductor L_1 for arbitrary quality factor.

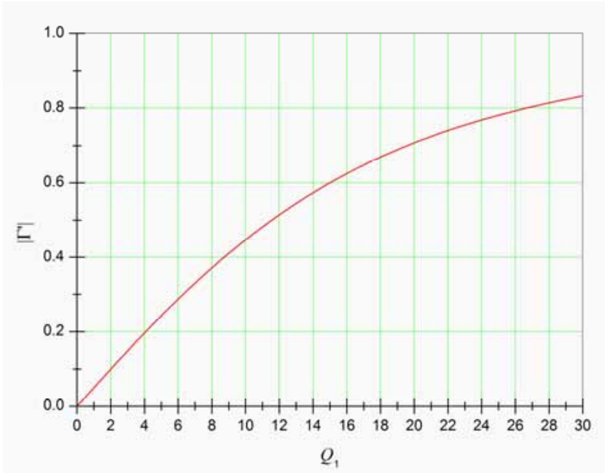

Fig.3 Relationship between magnitude of reflection coefficient |Γ'| and Q_1 (dL_1=10%)

3.2 Deviation of inductor L_2

Considering a small deviation ΔL_2 from the design value of inductor L_2 due to process variation or tolerance in Fig.1, the practical inductance of L_2 is given by

$$L_2' = L_2 + \Delta L_2 = L_2(1 + dL_2), \quad (13)$$

where L_2 is determined by Eq. 6 and $dL_2 = \Delta L_2/L_2$, the relative deviation of inductor L_2.

The practical equivalent impedance of matched load at working frequency is demonstrated by

$$Z'_e = j\omega_0 L_1 + \frac{1}{j\omega_0 C + \frac{1}{j\omega_0 L'_2 + R_2}}. \qquad (14)$$

Substituting Eqs. 5-7 into Eq. 14, the resulting reflection coefficient Γ' caused by the deviation of inductance L_2 can be derived as

$$\Gamma' = \frac{Z'_e - R_1}{Z'_e + R_1} = -\frac{A + jB}{A - jB} \cdot \frac{jQ_2 dL_2}{2 + jQ_2 dL_2}, \qquad (15)$$

where $A = (k-1)^2$, $B = 4kQ_0 - p(k+1)$.

Eq. 15 suggests that the deviation of inductance L_2 can make the matching effect worse and the magnitude of resulting reflection coefficient |Γ'| is proportional to the relative deviation dL_2 and Q_2. It is obvious to see that Eq. 15 is similar with Eq. 12 and the relationship between the magnitude of resulting reflection coefficient and Q_2 is identical with Fig.3. Similarly, tolerance of 10% in inductor L_2 can cause the resulting reflection coefficient to be 0.5 when the selected Q_2 reaches to 11.7.

3.3 Deviation of capacitor C

For the ideal condition where the passive components are the designed ideal value, the reflection coefficient in front of the capacitor is zero. Such condition indicates that the equivalent load impedance looking into the front of the capacitor C is equal to $R_1 - j\omega_0 L_1$ at working frequency.

With regard to the small deviation of ΔC in Fig. 1, the inductance of C is given by

$$C' = C + \Delta C = C(1 + dC), \qquad (16)$$

where C is determined by Eq. 7 and $dC = \Delta C/C$ is the relative deviation of inductor C.

The changed equivalent impedance of matched load at working frequency is

$$Ze' = j\omega_0 L_1 + \frac{1}{j\omega_0 \Delta C + \frac{1}{R_1 - j\omega_0 L_1}} \qquad (17)$$

Substituting Eqs. 5 and 6 into Eq. 17, the resulting reflection coefficient caused by deviation of capacitor can be derived as

$$\Gamma' = \frac{(Q_1 + j)Q_0 dC}{(-Q_1 + j)(-Q_0 dC + j)}. \qquad (18)$$

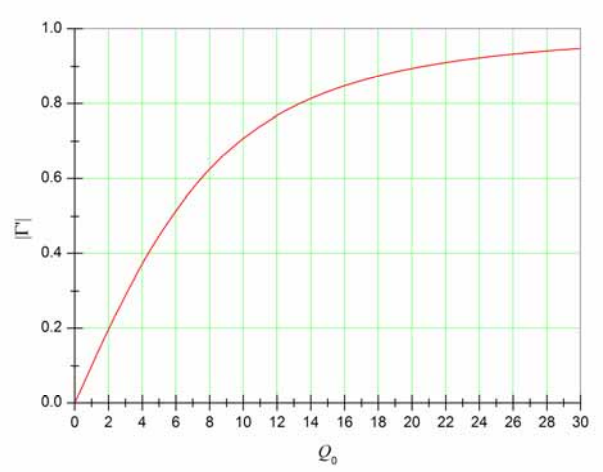

Fig.4 Relationship between magnitude of reflection coefficient |Γ'| and Q_0 (dC=10%)

Eq. 18 suggests that the deviation of capacitance C can make the matching effect worse and the magnitude of resulting reflection coefficient |Γ'| is proportional to the relative deviation dC and Q_0. Fig. 4 shows the relationship between the magnitude of resulting reflection coefficient |Γ'| and Q_0 when dC=0.1. Tolerance of 10% in capacitor C can cause the resulting reflection coefficient to be 0.5 when the selected Q_0 reaches to 5.8.

4 Impact of load impedance variation on the matching performance

In practical application, the load impedance to be matched varies dynamically due to change of the working environment. This load impedance variation can make the matching performance of T network worse or even produces impedance mismatch. In order to analyze the impact of load impedance variation on the matching performance, the load reflection coefficient Γ_l should be defined as the reflection coefficient of the load side. The function of T network is to reduce the resulting reflection coefficient Γ to zero.

A small change of Γ_d in load impedance can result in a changed load reflection coefficient, which is expressed as:

$$\Gamma_l' = \Gamma_l + \Gamma_d \qquad \Gamma_l' \leq 1. \tag{19}$$

The changed load impedance Z_l' can be also expressed in terms of load reflection coefficient Γ_l'.

$$Z_l' = \frac{1+\Gamma_l'}{1-\Gamma_l'} R_1 = \frac{1+\Gamma_l+\Gamma_d}{1-\Gamma_l-\Gamma_d} R_1 \tag{20}$$

The equivalent impedance Z_e' after impedance matching is obtained by:

$$Z_e' = j\omega L_1 + \frac{1}{j\omega C + \frac{1}{j\omega L_2 + Z_l'}}. \tag{21}$$

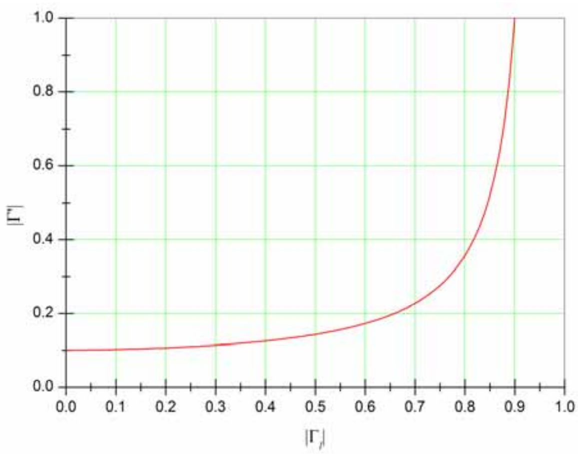

Fig. 5. Relationship between magnitude of reflection coefficient |Γ'| and magnitude of load reflection coefficient $|\Gamma_l|$ (Γ_d=0.1)

Substituting Eqs. 5-7 into Eq. 21, the resulting reflection coefficient Γ' can be derived through analytic derivation, which leads to

$$\Gamma' = \frac{(Q_1 + j)(Q_2 + j)\Gamma_d}{(Q_1 - j)(Q_2 - j)\left(1 - \Gamma_l \Gamma_d - \Gamma_l^2\right)}. \tag{22}$$

Eq. 22 suggests that the dynamic variation of load impedance can make the matching effect worse and the magnitude of resulting reflection coefficient |Γ'| is proportional to the variation of load reflection coefficient Γ_d and the load reflection coefficient Γ_l of static state and independent of the loaded quality factor Q_0. The quality factor Q_1 and Q_2 are proportional to the phase angle of resulting reflection coefficient. Fig.5 shows the relationship between the magnitude of resulting reflection coefficient |Γ'| and the magnitude of static load reflection coefficient $|\Gamma_l|$ when Γ_d=0.1. The resulting reflection coefficient is doubled to 0.2 when the load reflection coefficient reaches to 0.66. Larger load reflection coefficient of static state means poorer dynamic stability to load impedance variation. A small variation in the load impedance will cause a large deviation from perfect match when the impedance difference between load and source is quite large. This problem should be specially considered in designing T network impedance matching.

5 Impact of frequency drift on the matching performance

In applications where small frequency drift is inevitable, the deviation of the reflection coefficient from zero should be considered although the bandwidth is not the main concern of single-frequency impedance matching networks.

Considering the circuit in Fig. 1, for a small frequency drift $\Delta\omega$, the drifted working frequency ω' can be defined as:

$$\omega' = \omega + \Delta\omega = \omega(1 + d\omega), \quad (23)$$

where $d\omega = \Delta\omega/\omega$, the relative change of working frequency.

Similarly, as in the analysis above, the equivalent impedance can be demonstrated as:

$$Z_e = j\omega' L_1 + \frac{1}{j\omega' C + \frac{1}{j\omega' L_2 + R_2}}. \quad (24)$$

Substituting Eq. 23 and Eqs 5-7 into Eq. 24, the resulting reflection coefficient Γ in terms of Q_0, k and $d\omega$ can be obtained as:

$$\Gamma' = \frac{\left(-jQ_0Q_1Q_2M + 2Q_0^2 - 2Q_1\right)\left(M^2 - 1\right)}{\left(jQ_0Q_1Q_2M + 2Q_0^2\right)\left(M^2 - 1\right) - 2jQ_0M + Q_1Q_2 - 1}, \quad (25)$$

where Q_1 and Q_2 are defined by Eqs. 1 and 2 and $M = 1 + d\omega$.

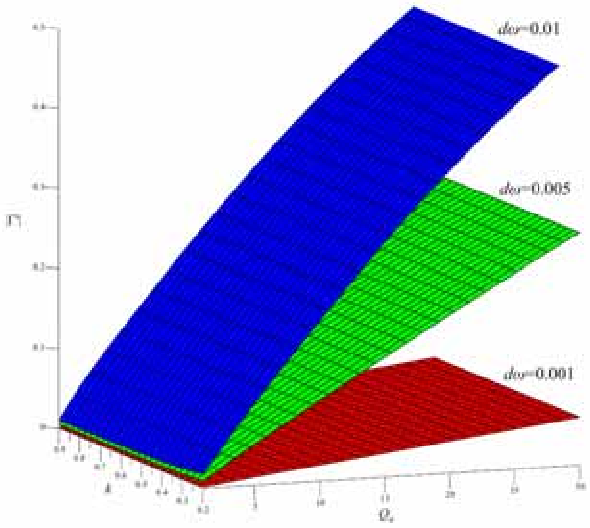

Fig. 6. 3D graph of magnitude of resulting reflection coefficient caused by frequency drift

With the three variables Q_0, k and $d\omega$, Eq. 25 is quite complicated. However, it can be demonstrated by 3D graph for specified $d\omega$. Fig. 6 shows the magnitude of resulting reflection coefficient caused by frequency drift when $d\omega$ equals to 0.001, 0.005 and 0.01 respectively. From Fig. 6, we can see that the value of k has a negligible effect on |Γ'| for $Q_0 > Q_{0(\min)}$. Hence, k can be taken as a constant to analyze the reflection coefficient caused by frequency drift $d\omega$. When k is set to 1, Eq. 25 becomes:

$$\Gamma' = -\frac{jQ_0M\left(M^2 - 1\right)}{1 + jQ_0M\left(M^2 - 1\right)}. \quad (26)$$

Eq. 26 shows that the magnitude of resulting reflection coefficient caused by frequency drift is proportional to $d\omega$ and Q_0. Fig. 7 shows how $d\omega$ influences |Γ'| when Q_0 is set to various values. The magnitude of resulting reflection coefficient |Γ'| is proportional to Q_0 and this is consistent with the circuit theory. A circuit with higher quality factor has higher selectivity and is more sensitive to frequency drift (i.e. poorer dynamic stability). |Γ'| increases rapidly for a small change of working frequency when $Q_0 \geq 5$.

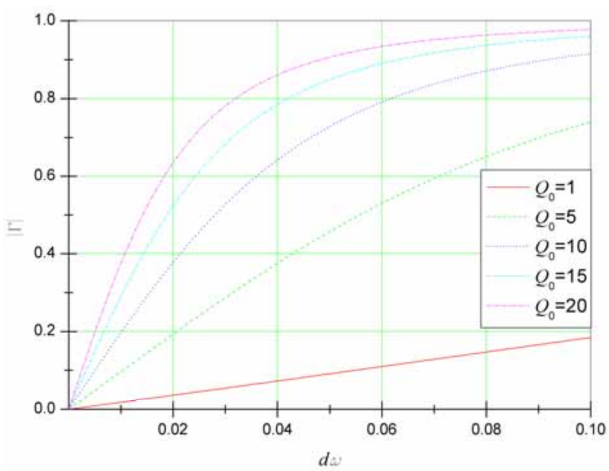

Fig. 7. Relationship between frequency drift $d\omega$, Q_0, and magnitude of reflection coefficient |Γ|

6 Discussions and Conclusions

a) In practical application, the components deviation, load impedance variation and working frequency drift can make the matching effect worse (i.e. make the reflection coefficient deviate from zero).

b) For a T network with larger quality factor value, the matching effect is more sensitive to components deviation, load impedance variation and working frequency drift and the dynamic stability is worse.

c) In the application of load impedance dynamically varying, if the static load reflection coefficient is larger (i.e. the impedances of source and load are mismatched significantly), the matching effect is more sensitive to load impedance variation (i.e. the dynamic stability is worse).

d) In designing T network impedance matching, the quality factor can not be too high in order to ensure good dynamic performance. However, the harmonic rejection ability is proportional to quality factor. Therefore, it is need to make the tradeoff between dynamic stability and harmonic rejection ability.

e) The formulas to calculate reflection coefficient presented in this paper can be used to determine whether the T network is suitable for dynamic application.

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8 References

[1] Zhang S W. *High frequency electronic circuits*. Beijing: Higher Education Press, 2004: 44-64.
[2] Matthaei, G L, Young L, Jones E M T. *Microwave filters, impedance matching network and coupling structure*. Norwood: Artech House, 1980: 255-272.
[3] Bowick C. *RF circuit design*. London: Newnes, 1997: 63-102.
[4] Motorola application note AN-721. Impedance matching networks applied to RF power transistors. *Motorola Inc.* 1993.
[5] Thompson M, Fidler JK. Determination of the impedance matching domain of impedance matching networks. *IEEE Trans. Circuits Syst. I: Regular Papers* 2004; 51(10):2,098–2,106.
[6] Gao S J, Wang Z B, and Park C W. A novel RF tunable impedance matching network for correcting the tested result deviation from simulated result. *IEEE Asia-Pacific Conf. App. Electromag.* (APACE). 2010(11):1-4.
[7] van Bezooijen, A., de Jongh, M.A., Chanlo, C., et. al. RF-MEMS based adaptive antenna matching module. *IEEE Radio Frequency Integr. Circuits (RFIC) Symp.*, 2007(7):573-576.
[8] van Bezooijen, A., de Jongh, M.A., Chanlo, C., et. al. A GSM/EDGE/WCDMA adaptive series-LC matching network using RF-MEMS switches. *IEEE Journal of Solid-State Circuits*, 43(10), 2259-2268.
[9] Serban A, Karlsson M, Gong S. Component tolerance effect on ultra-wideband low-noise amplifier performance, *IEEE Trans. Adv. Packag.* 2010, 33 (3): 660-668.
[10] Nieuwoudt A, Ragheb T, Nejati H, et al. Variation tolerant design methods for wideband low noise amplifiers. *Analog Integr. Circ. S.*, 2009, 58(1): 49-54.
[11] Chen F, Weber R J. A novel process-variation insensitive network for on-chip impedance matching. communications and information technology. *IEEE Int. Symp. Commun. Inf. Technol.* (ISCIT), 2004(1): 43-46.
[12] Liao R J, Tan J W, Wang H. Q-based design method for impedance matching network considering load variation and frequency drift. *Microelectron. J.* 2011, 42 (2): 403-408.
[13] Hastings A. *The art of analog layout*. New Jersey: Prentice-Hall Inc.; 2001: 200–203.
[14] Ramesh R, Ebenezer D D. Equivalent circuit

for broadband underwater transducers. *IEEE Trans. Ultrasonics, Ferroelectrics and Frequency Control.* 2008, 55(9): 2079-2083.

[15] Dogra VS, Zhang M, Bhatt S. High-intensity focused ultrasound (HIFU) therapy applications. Ultrasound Clin 2009; 4(3):307–21.

[16] Bezooijen A, Jongh M A, Straten F, et al. Adaptive impedance-matching techniques for controlling L networks. *IEEE Trans. Circuits Syst. I*, 2010, 57(2): 495-505.

[17] Kong Q, Zhao C L, Tan J W. On-line detection of ultrasound transducer impedance angle. *Measurement & control technology*, 2009, 28(3): 16-19.

[18] Bao S H. Dynamic matching for a piezoelectric transducer. *Applied acoustics*, 1998, 17(2): 16-20.

[19] Bennett B J. Broad-band impedance matching of ladder loads. *IEEE Trans. Circuits Syst.*, 1985, 32(12): 1201-1208.

[20] Chung B K. Variability analysis of impedance matching network. *Microelectron. J.* 2006, 37(11): 1419-1423.

[21] Sun Y, Fidler J K. Design method for impedance matching networks, *IEE Conf. Proc. Circuits Devices Syst.* 1996, 143(4): 186-194.

[22] Chung B K. Q-based design method for T network impedance matching. *Microelectronics J.* 2006, 37(9): 1007-1011.

9 Biographies

Liao Ruijin was born in 1963. He received his master's and doctor's degrees of Electrical Engineering from Chongqing University and Xi'an Jiaotong University respectively. In 1988 he began his career with college of electrical engineering, Chongqing University. He is currently professor and the general secretary of college of electrical engineering and deputy director of the State Key Laboratory of Power Transmission Equipment & System Security and New Technology, Chongqing University.

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