Narrower Band Matching with Low Quality Factor Values

Metin Şengül

***Abstract*— In this work, a new approach based on quality factor technique is proposed to design narrower band matching networks. The main idea is to use one series and one parallel lossless one-port LC network between generator and load resistances. In the proposed approach, it is not necessary to use a high quality factor value to get narrower band, it is enough to use the quality factor value defined by generator and load resistances. After explaining the rationale of the new approach, an example is given to compare the performances of the proposed and existing methods in the literature.**

***Index Terms*— LC networks, lossless networks, matching, narrow band, quality factor.**

I. INTRODUCTION

IN the literature, there are lots of narrow band network applications. In [1], the design of some typical passive impedance matching networks for narrow band power-line communications is discussed and basic impedance matching procedures and the necessary power-line environment considerations are outlined. A new adaptive impedance matching network is proposed for narrow band power line communication in [2], and a new model using a digital capacitor and a digital resistor are derived. In [3], a compact narrow band tunable impedance-matching network which consists of a Pi structure with tunable components made of varactors in series with inductors is designed and fabricated. A tunable high quality factor (Q) narrow band triplexer over a large tuning range is demonstrated in [4]. In [5], a design technique is presented to create widely tunable high Q narrow-band filters with bandwidth control by utilizing low Q varactors, while maintaining the high Q of the original filter. In [6], L matching network or impedance transformer is analyzed in detail, and key design equations are derived when source and load impedances are complex. The derivation of the design equations is based on the conjugate matching conditions.

Impedance matching can be grouped as narrowband and broadband impedance matching. In narrowband impedance matching, two-element L networks as shown in Fig. 1 are the most widely utilized and the simplest matching networks, which can be easily designed by means of the following well-known equations [7, 8]:

$$Q_S = Q_P = Q = \sqrt{\frac{R_P}{R_S} - 1}\,, \tag{1a}$$

$$|X_S| = Q_S \cdot R_S\,, \tag{1b}$$

$$|X_P| = R_P / Q_P \tag{1c}$$

where, as shown in Fig. 1, Q_S and Q_P is the quality factor of the series and parallel section, R_S and R_P is the series and parallel termination resistance, X_S and X_P is the series and parallel matching network reactance, respectively.

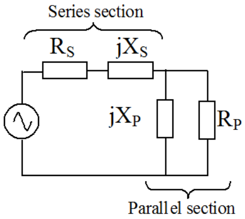

Fig. 1. Narrowband two-element L matching network [8].

L networks are very simple to design and useful for narrowband applications, but they have an important drawback: the designer cannot change the quality factor of the network, which is calculated via (1a), since the series and parallel termination resistances (R_S and R_P , respectively) are given and fixed.

If a narrower band is required, higher quality factor values must be utilized. Three-element Pi or T matching networks seen in Fig. 2 can be used to get higher quality factor values with the same generator and load resistances, where $R_G = R_S$ and $R_L = R_P$. In Pi or T matching network designs, the designer selects a suitable quality factor value in accordance with the desired band, which is greater than the quality factor of L matching network. In other words, the minimum selectable quality factor value in Pi or T matching networks is the quality factor calculated via (1a) in L matching network designs.

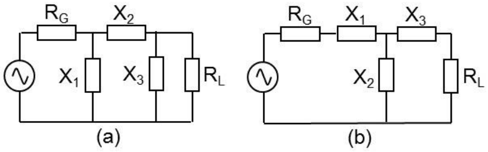

Fig. 2. Three-element Pi and T networks [7, 8].

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Pi (and T) networks can be pictured as two "back-to-back" L networks as seen in Fig. 3. A virtual resistor is utilized between two L networks. So it is clear that the generator and load resistances are matched to the virtual resistance via two L matching networks.

Each L matching section in the Pi (or T) network is designed by using exactly the same quality factor based approach described above.

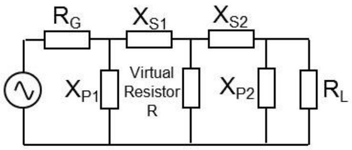

Fig. 3. Pi network as two back-to-back L sections [7, 8].

In the next section, the proposed approach to design narrower band matching networks with low quality factor values is given in detail.

II. RATIONALE OF THE PROPOSED APPROACH

As seen in Fig. 1, in quality factor based narrowband matching approach, we need a series (jX_S) and a parallel (jX_P) reactance, which are realized by using a capacitor or an inductor. If one of them is a capacitor, the other one must be an inductor.

In the proposed approach, using one-port LC networks forms these series and parallel reactance as seen in Fig. 4. If the orders of the series and parallel one-port LC networks are unity, then the network seen in Fig. 1 is reached. As expected, one of the one-port LC networks must be inductive and the other one must be capacitive.

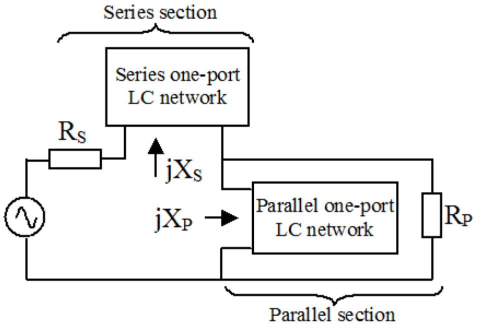

Fig. 4. Narrower band matching network configuration.

In the design process, firstly quality factor (Q) must be calculated via (1a). After selecting the degrees of the series and parallel one-port LC networks, initial values are chosen for the poles and zeros of the input impedances of these networks ($Z_{series}(p)$ and $Z_{parallel}(p)$, where $p = j\omega$ is the frequency variable) in accordance with the selected degrees. Since we have one-port LC networks, the poles and zeros must be simple, they must occur on the $j\omega$-axis in conjugate pairs and must mutually separate each other. Finally quality factors of these networks are calculated via (1b) and (1c), where $jX_S = Z_{series}(j\omega)$ and $jX_P = Z_{parallel}(j\omega)$. The initialized poles and zeros are optimized until the quality factors of the series and parallel one-port LC networks are equal to the calculated quality factor as

$$Q_S = Q_P = Q \,. \tag{2}$$

Then component values are calculated by using the input impedance functions of the one-port LC networks. In the following section, an example is given to compare the performances of the proposed and existing methods in the literature.

III. EXAMPLE

In this section, a matching network is designed between a generator impedance $R_G = 100\Omega$ and a load impedance $R_L = 1000\Omega$ at $100MHz$.

In [7], this problem is solved by using two-element L matching network as seen in Fig. 5.

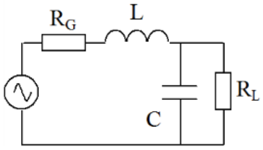

Fig. 5. L matching network, $L = 477nH$, $C = 4.8pF$ [7].

To get a narrower band, the same problem is solved in [7] by using four different Pi matching networks with $Q = 15$ as seen in Fig. 6.

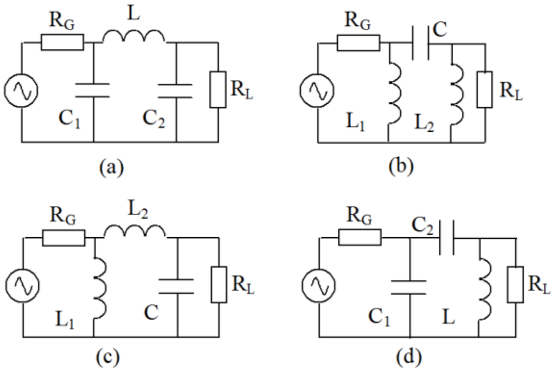

Fig. 6. Pi matching networks [7], a) $C_1 = 73.343pF$, $C_2 = 23.861pF$, $L = 139.861nH$, b) $L_1 = 34.537nH$, $L_2 = 106.16nH$, $C = 18.210pF$, c) $L_1 = 34.537nH$, $L_2 = 73.848nH$, $C = 23.861pF$, d) $C_1 = 73.343pF$, $C_2 = 34.301pF$, $L = 106.16nH$.

In the proposed apprach, for the given generator and load impedances, quality factor is calculated as

$$Q = \sqrt{\frac{R_L}{R_G} - 1} = \sqrt{\frac{1000}{100} - 1} = 3 \,.$$

Normalization resistance and frequency is selected as $R_n = 100\Omega$ and $f_n = 100MHz$, respectively. So normalized generator and load resistances are $r_g = \frac{R_G}{R_n} = \frac{100}{100} = 1$ and

$r_l = \frac{R_L}{R_n} = \frac{1000}{100} = 10$, respectively. In the design process, normalized matching frequency is used as $\omega = 1$.

The orders of the series and parallel one-port LC networks are selected as three, then simple poles and zeros are initialized as $p_1 = j0.6$, $p_2 = -j0.6$, $z_1 = j0.9$, $z_2 = -j0.9$, $z_3 = 0$ and $p_1 = j0.5$, $p_2 = -j0.5$, $p_3 = 0$, $z_1 = j0.1$, $z_2 = -j0.1$, respectively. It is clear that they are on the $j\omega$-axis in conjugate pairs and are mutually separate each other, which are optimized until obtaining the following equality

$$Q_S = \frac{|x_s|}{r_g} = Q_P = \frac{r_l}{|x_p|} = Q = 3\,.$$

where x_s and x_p is the normalized reactance of the series and parallel one-port LC networks, respectively.

After optimization process, the following impedance functions are obtained for series and parallel one-port LC networks

$$z_{series}(p) = \frac{100p^3 + 93.7837p}{3.0721p^2 + 1}\,, \tag{3a}$$

$$z_{parallel}(p) = \frac{250.2259p^2 + 1}{100p^3 + 25.2322p}\,. \tag{3b}$$

If $p = j\omega = j \cdot 1$ is substituted in (3a) and (3b), normalized reactances of series and parallel one-port LC networks are found as

$$jx_s = z_{series}(j \cdot 1) = \frac{100(j)^3 + 93.7837 \cdot j}{3.0721(j)^2 + 1} = j3\,, \tag{4a}$$

$$jx_p = z_{parallel}(j \cdot 1) = \frac{250.2259(j)^2 + 1}{100(j)^3 + 25.2322 \cdot j} = -j3.3333\,. \tag{4b}$$

It is clear that the series one-port LC network is inductive and parallel one-port LC network is capacitive. Quality factors of the designed series and parallel one-port LC networks can be checked by using normalized generator and load resistances as

$$Q_S = \frac{|x_s|}{r_g} = \frac{|3|}{1} = 3\,, \tag{5a}$$

$$Q_P = \frac{r_l}{|x_p|} = \frac{10}{|-3.3333|} = 3\,. \tag{5b}$$

After calculating the component values by using the obtained impedance functions given in (3a) and (3b), series and parallel one-port LC networks shown in Fig. 7 are obtained.

In Fig. 8, transducer power gain (TPG) curves are given to be able to compare the performances of L, Pi and the designed matching networks. It is seen that the narrowest band is obtained from the matching network designed via the proposed approach.

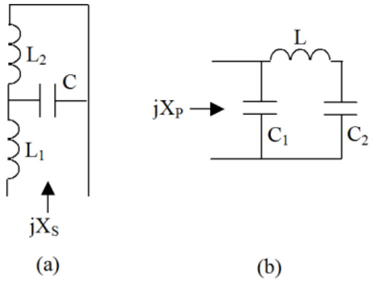

Fig. 7. Designed series and parallel one-port LC networks, a) $L_1 = 5.1807\mu H$, $L_2 = 9.7455\mu H$, $C = 0.79849pF$, b) $C_1 = 6.3604pF$, $C_2 = 395.22pF$, $L = 1.6037\mu H$.

The fractional bandwidth (Δf), which is defined as the ratio of –3 dB bandwidth to the center frequency (f_c), of L, Pi (a,b,c,d) and the designed matching network is computed as 75.79%, 10.506%, 10.657%, 13.43%, 13.574% and 4.225%, respectively.

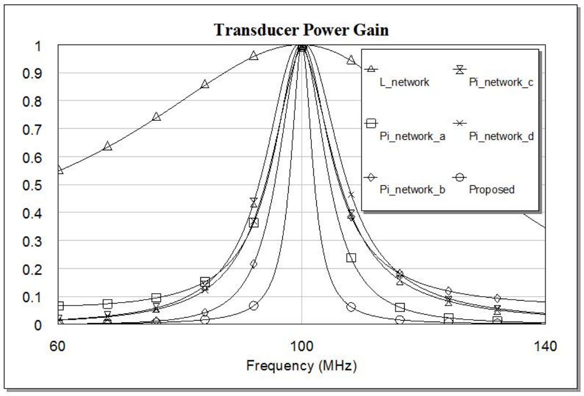

Fig. 8. Transducer power gain curves.

Also note that in Pi matching network design in [7], quality factor is increased to 15 to get a narrower band than the band obtained from L matching network with quality factor of 3. Even though the quality factor is 3 in the proposed approach as in L matching network design, the obtained band is narrower than the band obtained from Pi matching network with quality factor of 15.

If the degrees of the series and parallel one-port LC networks are increased, a narrower band can be obtained with the same quality factor of 3.

TABLE I.
EFFECTS OF COMPONENT VALUE CHANGES FOR L NETWORK.

L network	±10%	f_c (MHz)	Δf (%)
477nH	524.7nH	95.1	75.92
	429.3nH	105.2	75.87
4.8pF	5.28pF	95.09	75.92
	4.32pF	105.2	75.88

In Table I, the values of components used in L network depicted in Fig 5 are changed ±10%, then the center frequency and fractional bandwidth is measured. In a similar manner, the effects of component value changes on the center frequency and fractional bandwidth are given in Table II for the four different Pi networks seen in Fig. 6.

TABLE II.
EFFECTS OF COMPONENT VALUE CHANGES FOR PI NETWORKS.

Pi network a	±10%	f_c (MHz)	Δf (%)
73.343pF	80.677pF	98.9	9.81
	66.008pF	101.3	11.18
23.861	26.1471pF	96.4	10.60
	21.4749pF	103.9	10.30
139.10	153.8471nH	95.1	11.05
	125.8749nH	105.3	9.96
Pi network b	**±10%**	**f_c (MHz)**	**Δf (%)**
34.537nH	37.9907nH	99.0	11.29
	31.0833nH	101.2	9.84
106.16nH	116.776nH	96.5	10.43
	95.544nH	104.1	10.64
18.210pF	20.031pF	95.4	10.11
	16.389pF	105.6	11.25
Pi network c	**±10%**	**f_c (MHz)**	**Δf (%)**
34.537nH	37.9907nH	97.9	14.60
	31.0833nH	100.9	12.32
73.848nH	81.2328nH	96.4	13.06
	66.4632nH	103.1	14.01
23.861pF	26.2471pF	94.9	12.90
	21.4749pF	104.7	14.24
Pi network d	**±10%**	**f_c (MHz)**	**Δf (%)**
73.343pF	80.677pF	99.0	12.45
	66.008pF	101.9	14.75
34.301pF	37.7311pF	97.4	13.90
	30.8709pF	104.2	12.98
106.16nH	116.776nH	95.7	14.16
	95.544nH	105.9	12.83

Finally, for the designed network, a similar measurement is made and the results are noted in Table III.

TABLE III.
EFFECTS OF COMPONENT VALUE CHANGES FOR PROPOSED NETWORK.

Proposed network	±10%	f_c (MHz)	Δf (%)
5180.7nH	5698.77nH	96.8	4.03
	4462.60nH	105.4	4.44
9745.5nH	1072.05nH	98.6	4.50
	8770.95nH	101.7	3.91
0.7985pF	0.87835pF	95.7	4.72
	0.71865pF	105.0	3.71
1603.7nH	1764.07nH	99.9	4.12
	1443.33nH	100.2	4.34
6.3604pF	6.9964pF	99.7	3.76
	5.7243pF	100.4	4.73
395.22pF	433.863pF	100.0	4.225
	355.698pF	100.0	4.225

It is obvious that as the component values change, the center frequency shifts, and fractional bandwidth changes. In Table IV, the differences between the maximum and minimum shifted center frequencies ($f_{c,\max} - f_{c,\min}$), and the differences between that maximum and minimum fractional bandwidths ($\Delta f_{\max} - \Delta f_{\min}$) are given for the networks mentioned above. While maximum differences in center frequency shifts are obtained from Pi networks a, b and d as 10.20 MHz, minimum difference in center frequency shift is obtained from the proposed network as 9.70 MHz. On the other hand, the minimum difference in fractional bandwidth changes is obtained from L network as 0.05%. While the second minimum difference is obtained from the proposed network as 1.02%, it is maximum for Pi network c as 2.30%.

As a result, it can be concluded that the deviation from the center frequency ($f_c = 100MHz$) is minimum for the proposed network as the component values change. Since the fractional bandwidth of L network is very large 75.79%, it is ignored, then the deviation from the obtained fractional bandwidth ($\Delta f = 4.225\%$) is minimum for the proposed network.

TABLE IV.
COMPARISON OF CENTER FREQUENCY AND FRACTIONAL BANDWIDTH DEVIATIONS.

Network Type	$f_{c,\max} - f_{c,\min}$ (MHz)	$\Delta f_{\max} - \Delta f_{\min}$ (%)
L network	10.11	0.05
Pi network a	10.20	1.37
Pi network b	10.20	1.45
Pi network c	9.80	2.28
Pi network d	10.20	2.30
Proposed	9.70	1.02

Microwave Office of Applied Wave Research Inc. (AWR) is utilized in all the simulations [9].

IV. CONCLUSION

In this work, a new narrower band matching approach is proposed. In the matching network, one series and one parallel one-port LC network is connected between the generator and load resistances, which will be matched. In the proposed approach, it is not necessary to use a higher quality factor value to get a narrower band. It is enough to utilize the quality factor value calculated by using the given generator and load resistances to get a narrower band.

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