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Effects of parasitic elements on L-type LC/CL matching circuits
Satoshi Tanaka*, Fellow Takeshi Yoshida*, Member, and Minoru Fujishima†, Fellow

SUMMARY L-type LC/CL matching circuits are well known for their simple analytical solutions and have been applied to many radio-frequency (RF) circuits. When actually constructing a circuit, parasitic elements are added to inductors and capacitors. Therefore, each L and C element has a self-resonant frequency, which affects the characteristics of the matching circuit. In this paper, the parallel parasitic capacitance to the inductor and the series parasitic inductor to the capacitance are taken up as parasitic elements in L and C, and a series VSWR-Vs characteristics are reported. When a parasitic element is added, each characteristic basically tends to deteriorate as the self-resonant frequency decreases. However, as an interesting feature, we found that the combination of resonant frequencies determines the VSWR and passband characteristics, regardless of whether it is the inductor or the capacitor.

keywords: Matching circuit, Parasitic element, Analytical solution, LC/CL, Matching network

1. Introduction

The L-type LC/CL matching circuit is well known for its simple analytical solution and has been applied to many radio frequency (RF) circuits [1]. A lot of research has been done on the design method when this is multi-staged [2-10]. In the actual circuit, parasitic elements are added to inductors and capacitors. When designing amplifiers, they are combined with transistors, and the input/output capacitor of the transistors can also be regarded as a kind of parasitic elements. However, the effect of adding a parasitic element to each element has not been studied much [11]. Of course, with today’s advanced simulators, it is easy to design matching circuits that take into account the effects of parasitic elements. However, analytical understanding of the effects of parasitic elements is very effective in solving problems during design.

The design including parasitic elements is illustrated in Fig. 1. Fig.1(a) shows the interstage matching circuit of a typical integrated multistage complementary metal-oxide-semiconductor field effect transistor (CMOSFET) amplifier [12]. The CMOSFET has a gate-to-source capacitance CGS, gate-to-drain capacitance CGD, and drain-to-source capacitance CDS. The two FETs are connected by a r-type matching circuit consisting of LCL. Drain bias and gate bias are applied through the respective inductors L1 and L2; the drain output impedance and gate input impedance of the CMOSFETs are both complex impedances. As shown in Fig. 1(b), the drain output impedance can be simply represented by the parallel connection of the output resistor RH and the output capacitor CDP. The gate input impedance can be represented by the series connection of the input resistor RL and the input capacitor CPG. When integrated capacitance is applied, a series parasitic inductor LP is added due to the presence of series wiring. When integrated inductors are used, parallel parasitic capacitance is added due to the presence of capacitance between wires [13]. These parasitic effects must also be taken into account in the design. Although the interstage matching circuit exists between two CMOSFETs, it is appropriate to add CDP and CPD to the matching circuit components and terminate both ends with RHI and RL as shown in Fig. 1 (b) in order to study the bandwidth. Thus, a realistic matching circuit should include parasitic elements.

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in this case, and confirmed the effects of changes in the parasitic element values on the $S_{11}$, voltage standing wave ratio (VSWR), and $S_{11}$ characteristics.

The element value was changed by changing the self-resonant frequency of each matching element when the parasitic element was included, rather than by directly changing the value of the parasitic element.

2. L-type LC/CL matching circuits

Table 1 summarizes the circuit configuration of the LC/CL matching circuit and analytical matching conditions [9, 14, 15]. The LC matching circuit shown on the left in Table 1 is a matching circuit with low-pass characteristics, and is an L-type matching circuit consisting of a series inductor $L$ and grounding capacitance $C$. The CL matching circuit shown on the right side of Table 1 is a matching circuit with high-pass characteristics, and is an L-type matching circuit consisting of a series capacitor $C$ and a grounded inductor $L$. Input termination resistor $R_L$ and output termination resistor $R_H$ are connected to both matching circuits, and when $R_L < R_H$, matching can be achieved with appropriate $L$ and $C$ values.

Table 1 The circuit configuration of the LC/CL matching circuit and analytical matching conditions. Copyright © 2023, IEEE [14].

<table>
<thead>
<tr>
<th>TYPE</th>
<th>LC matching circuits</th>
<th>CL matching circuits</th>
</tr>
</thead>
<tbody>
<tr>
<td>Circuits</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$R_L$</td>
<td>$L$</td>
<td>$L$</td>
</tr>
<tr>
<td>$C$</td>
<td>$1/\omega_0 \sqrt{R_H (R_H - R_L)}$</td>
<td>$1/\omega_0 \sqrt{R_L (R_H - R_L)}$</td>
</tr>
<tr>
<td>$L$</td>
<td>$1/\omega_0 \sqrt{R_L (R_H - R_L)}$</td>
<td>$1/\omega_0 \sqrt{R_H (R_H - R_L)}$</td>
</tr>
<tr>
<td>Matching condition</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$L = \frac{1}{\omega_0} \sqrt{R_L (R_H - R_L)}$</td>
<td>$C = \frac{1}{\omega_0} \sqrt{R_H (R_H - R_L)}$</td>
<td></td>
</tr>
</tbody>
</table>

In order to compare the characteristics of the LC/CL matching circuits, $S_{11}$ on the input terminal side was calculated and shown in Fig. 2, assuming $R_L = 5 \Omega$ and $R_H = 15 \Omega$ under the conditions normalized to the matching frequency $f_0 = 1$ Hz. In the case of the LC matching circuit, the impedance of the series inductor is sufficiently small at low frequencies, and $R_H$ can be seen directly. As the frequency increases, the reactance passes through the negative region and approaches $R_L$, and at 1 Hz, it can be matched to $R_L$. As the frequency rises further, the impedance of the inductor increases, and the reactance component passes through the positive region and becomes $\infty$.

In the case of the CL matching circuit, the impedance of the series capacitance becomes sufficiently small, and $R_H$ can be seen directly through the region where the reactance component is positive.

Fig. 3 shows the frequency dependence of the VSWR characteristics. Here we assume that the target specification is VSWR<1.2. LC matching circuits that approach $R_H$ at frequencies lower than 1 Hz satisfy the target specification over a wider bandwidth than CL matching circuits when compared below 1 Hz. Conversely, a CL matching circuit that approaches $R_H$ at a frequency higher than 1 Hz satisfies the target specification over a wider bandwidth than an LC matching circuit when compared to a CL matching circuit at over 1 Hz.

Table 2 summarizes the comparison of the characteristics of LC/CL matching circuits.
LC/CL matching circuits. The element value that realizes the matching condition at the same frequency is small for the element of the LC matching circuit. The fractional bandwidth (FBW) that satisfies VSWR<1.2 or $S_{21}>-0.3$ dB are almost the same for both. As for $S_{21}$, it can be seen that the CL matching circuit has a wider bandwidth (BW) defined by the difference between the maximum frequency $f_{\text{max}}$ and the minimum frequency $f_{\text{min}}$ that satisfy the conditions. However, since the center frequency $f_c$ of the band shifts to the region of $f_c<1$ Hz in the LC matching circuit and shifts to the region of $f_c>1$ Hz in the CL matching circuit, they are almost the same when compared in terms of FBW.

![Fig. 4 $S_{21}$ characteristics of LC/CL matching circuits.](image)

### Table 2 Parameter & performance comparison of LC/CL matching circuits.

<table>
<thead>
<tr>
<th>Type</th>
<th>Items</th>
<th>$f_c$ (Hz)</th>
<th>Min (Hz)</th>
<th>Max (Hz)</th>
<th>X (Hz)</th>
<th>FBW (%)</th>
<th>BW (Hz)</th>
</tr>
</thead>
<tbody>
<tr>
<td>LC</td>
<td>VSWR&lt;1.2</td>
<td>1.125</td>
<td>0.918</td>
<td>1.098</td>
<td>0.997</td>
<td>15.0</td>
<td>0.162</td>
</tr>
<tr>
<td></td>
<td>$S_{21}$&gt;0.3 dB</td>
<td>1.689</td>
<td>0.931</td>
<td>1.084</td>
<td>1.007</td>
<td>15.2</td>
<td>0.153</td>
</tr>
<tr>
<td>CL</td>
<td>VSWR&lt;1.2</td>
<td>1.125</td>
<td>0.918</td>
<td>1.098</td>
<td>0.997</td>
<td>15.0</td>
<td>0.162</td>
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<td>1.689</td>
<td>0.931</td>
<td>1.084</td>
<td>1.007</td>
<td>15.2</td>
<td>0.153</td>
</tr>
</tbody>
</table>

### 3. Analytical solutions with parasitic elements

Table 3 summarizes the connection of parasitic elements. A parallel parasitic capacitance $C_P$ is added to the inductor, and a series parasitic inductor $L_P$ is added to the capacitor.

<table>
<thead>
<tr>
<th>Element without parasitic</th>
<th>Element with parasitic</th>
</tr>
</thead>
<tbody>
<tr>
<td>$L$</td>
<td>$L$</td>
</tr>
<tr>
<td>$C$</td>
<td>$C$</td>
</tr>
</tbody>
</table>

Conditions for the element values to be the same:

- $f_{\text{RL}} = \frac{1}{\omega L} = \frac{1}{\sqrt{L_C C_P}}$
- $f_{\text{RL}} = \frac{1}{\omega L} = \frac{1}{\sqrt{L_C C_P}}$
- $f_{\text{RL}} = \frac{1}{\omega L} = \frac{1}{\sqrt{L_C C_P}}$
- $f_{\text{RL}} = \frac{1}{\omega L} = \frac{1}{\sqrt{L_C C_P}}$

Analytical solutions:

- $L = L \left(1 - \frac{w_L}{w_C}ight)$
- $C = \left(1 - \frac{w_L}{w_C}\right)$
- $L_P = \frac{1}{\sqrt{C P}}$
- $L_P = \frac{1}{\sqrt{C P}}$

As shown in the third row of Table 3, the following two conditions must be satisfied at $f_c=1$ Hz in order to satisfy the matching condition even if the parasitic element is added.

1. The first is that the impedance of the parallel connection of the capacitors $C_P$ and $L_P$ matches the original $L$. The second is that the impedance of the series connection of $L_P$ and $C_P$ matches the original $C$.

4. Effects of parasitic elements on L-type LC matching circuit characteristics

Table 5 summarizes changes in the VSWR characteristics and passband characteristics ($S_{21}$) when the LC matching circuit has a self-resonant frequency due to the addition of parasitic elements. Four conditions are set for the
self-resonant frequency $f_{RL}$ of the inductor: 2 Hz, 3 Hz, 4 Hz, and $\infty$ (in the absence of parasitic elements).

Table 5 FBW of VSWR and $S_{21}$ performances with parasitic elements on LC matching circuit.

<table>
<thead>
<tr>
<th>$RL$</th>
<th>$RC$</th>
<th>$f_{min}$</th>
<th>$f_{max}$</th>
<th>$f_{center}$</th>
<th>$f_{min}$</th>
<th>$f_{max}$</th>
<th>$f_{center}$</th>
<th>$f_{min}$</th>
<th>$f_{max}$</th>
<th>$f_{center}$</th>
<th>$f_{min}$</th>
<th>$f_{max}$</th>
<th>$f_{center}$</th>
<th>FBW (%)</th>
<th>FBW (%)</th>
<th>FBW (%)</th>
<th>FBW (%)</th>
<th>FBW (%)</th>
<th>FBW (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>2</td>
<td>3</td>
<td>4</td>
<td>$\infty$</td>
<td>$\infty$</td>
<td>$\infty$</td>
<td>$\infty$</td>
<td>$\infty$</td>
<td>$\infty$</td>
<td>$\infty$</td>
<td>$\infty$</td>
<td>$\infty$</td>
<td>$\infty$</td>
<td>$\infty$</td>
<td>9.49</td>
<td>10.9</td>
<td>13.3</td>
<td>15.9</td>
<td>18.5</td>
<td></td>
</tr>
<tr>
<td>3</td>
<td>4</td>
<td>2</td>
<td>0.94</td>
<td>0.96</td>
<td>1.00</td>
<td>0.94</td>
<td>0.96</td>
<td>1.00</td>
<td>0.94</td>
<td>0.96</td>
<td>1.00</td>
<td>0.94</td>
<td>0.96</td>
<td>34.7</td>
<td>36.0</td>
<td>38.2</td>
<td>40.1</td>
<td>42.0</td>
<td></td>
</tr>
<tr>
<td>4</td>
<td>2</td>
<td>3</td>
<td>1.05</td>
<td>1.06</td>
<td>1.00</td>
<td>1.05</td>
<td>1.06</td>
<td>1.00</td>
<td>1.05</td>
<td>1.06</td>
<td>1.00</td>
<td>1.05</td>
<td>1.06</td>
<td>14.2</td>
<td>14.9</td>
<td>15.6</td>
<td>16.9</td>
<td>18.5</td>
<td></td>
</tr>
</tbody>
</table>

Four conditions are set for the self-resonant frequency $f_{RC}$ of the capacitor: 2 Hz, 3 Hz, 4 Hz, and $\infty$ (in the absence of parasitic elements). By combining these, the characteristics were confirmed under a total of 16 conditions. The frequency response was calculated with 50 points per octave, and the frequencies that satisfy the specifications of VSWR ≤ 1.2 and $S_{21} \geq -0.3$ were obtained by linear completion.

The band that satisfies VSWR ≤ 1.2 (minimum frequency $f_{min}$ and maximum frequency $f_{max}$), its center frequency $f_{center}$ and FBR (fractional bandwidth), and the band that satisfies $S_{21} \geq -0.3$ dB (minimum frequency $f_{min}$ and maximum frequency $f_{max}$) and its center frequency $f_{center}$ and FBW were confirmed.

It can be seen that both bands widen as the self-resonant frequency increases. It was also found that when the self-resonant frequency is four times or less than the design frequency, band deterioration due to parasitic elements becomes apparent. An interesting characteristic is that even if the combination of $f_{RL}=2$ Hz, $f_{RC}=3$ Hz and the combination of $f_{RL}=3$ Hz, $f_{RC}=2$ Hz are different, if the combination of self-resonant frequencies is the same, the characteristics will be the same (although there are small calculation errors in the results in Table 5).

The details of the characteristics are explained using Fig. 5-8 [14]. Fig. 5 shows the $S_{11}$ characteristics on the input side. The frequency was varied in the range of 0.01-10.0 (Hz). In the absence of parasitic elements, as shown in Fig. 2, the input resistance is 15 Ω when the frequency is 0, 5 Ω when the frequency is 1 Hz, and converges to $\infty$ when the frequency increases.

As shown by the purple curve, when $f_{RL}=2$ Hz and $f_{RC}=3$ Hz, it shifts outward at frequencies below 1 Hz and shifts inward at frequencies above 1 Hz compared to the case without parasitic elements. It becomes $\infty$ at $f=f_{RL}=2$ Hz. At $f=f_{RC}=3$ Hz, the output resistor $R_{RL}$ is terminated to GND (See also Table 3), and the input impedance becomes the capacitive impedance of the parallel resonant circuit of $L_{a}$ and $C_{P}$. As shown by the green curve, when $f_{RL}=3$ Hz and $f_{RC}=2$ Hz, it shifts inward at frequencies below 1 Hz and shifts outward at frequencies above 1 Hz compared to the case without parasitic elements. At $f=f_{RC}=2$ Hz, the output resistor $R_{RL}$ is terminated to the GND and the input impedance becomes the inductive impedance of the parallel-resonant circuit of $L_{a}$ and $C_{P}$. The input impedance becomes $\infty$ at $f=f_{RL}=3$ Hz.

As shown by the orange curve, when $f_{RL}=f_{RC}=2$ Hz, it follows the locus without parasitic elements as the frequency changes. However, the input impedance becomes $\infty$ at $f=2$ Hz. As the frequency is further increased, it gradually approaches the origin, matching 5 Ω at $f=f_{RL}=4$ Hz, and as the frequency is further increased, it approaches 15 Ω.
Next, focus on the VSWR frequency characteristics shown in Fig. 6 and the \( S_{11} \) frequency characteristics shown in Fig. 7. With parasitic elements, the band that satisfies VSWR \( \leq 1.2 \) and \( S_{11} \geq -0.3 \) dB becomes narrower than without parasitic elements.

The VSWR and \( S_{11} \) characteristics are the same for \( f_{RL}=2 \) Hz, \( f_{RC}=3 \) Hz and \( f_{RL}=3 \) Hz, \( f_{RC}=2 \) Hz, where the trajectories on \( S_{11} \) are different. The narrowest band is obtained under the condition of \( f_{RL}=f_{RC}=2 \) Hz where the locus on \( S_{11} \) overlaps with the case without parasitic elements.

Fig. 8 shows the expanded frequency range of the frequency characteristics of \( S_{21} \). Under the conditions of \( f_{RL}=2 \) Hz, \( f_{RC}=3 \) Hz and \( f_{RL}=3 \) Hz, \( f_{RC}=2 \) Hz. Under the condition of \( f=2, 3 \) Hz, \( S_{21} \) is 0 in true value and theoretically \(-\infty\) dB in dB expression. This is due to the parallel and series resonance of the elements including their respective parasitic elements. It also has a large attenuation between 2 Hz and 3 Hz.

It should be noted that the combination of matching characteristics differs depending on the items to be evaluated.

5. Effects of parasitic elements on L-type LC matching circuit characteristics

Table 6 summarizes changes in the VSWR characteristics and passband characteristics \( (S_{11}) \) when the CL matching circuit has a self-resonant frequency due to the addition of parasitic elements. Four conditions are set for the self-resonant frequency \( f_{RL} \) of the inductor: 2 Hz, 3 Hz, 4 Hz, and \( \infty \) (in the absence of parasitic elements). Four conditions are set for the self-resonant frequency \( f_{RC} \) of the capacitor: 2 Hz, 3 Hz, 4 Hz, and \( \infty \) (in the absence of parasitic elements).

Using the same notation as in Table 4, by combining these, the characteristics were confirmed under a total of 16 conditions. It can be seen that both bands widen as the self-resonant frequency increases. It was also found that when the self-resonant frequency is four times or less than the design frequency, band deterioration due to parasitic elements becomes apparent. An interesting characteristic is that even if the combination of \( f_{RL}=2 \) Hz, \( f_{RL}=3 \) Hz and the combination of \( f_{RC}=3 \) Hz, \( f_{RL}=2 \) Hz are different, if the combination of self-resonant frequencies is the same, the characteristics will be the same.
The details of the characteristics are explained using Fig. 9-12. Fig. 9 shows the $S_{11}$ characteristics on the input side. The frequency was varied in the range of 0.01-10.0. In the absence of parasitic elements, as shown in Fig. 2, the input resistance is $\infty$ when the frequency is 0, 5 $\Omega$ when the frequency is 1 Hz, and as the frequency is further increased, the impedance converges to 15 $\Omega$.

Table 6 FBW of VSWR and $S_{11}$ performances with parasitic elements on CL matching circuit.

<table>
<thead>
<tr>
<th>$f_{RL}$</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>$\infty$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$f_{RC}$</td>
<td>0.96</td>
<td>0.98</td>
<td>0.95</td>
<td>0.95</td>
</tr>
<tr>
<td>FBW (%)</td>
<td>0.96</td>
<td>0.98</td>
<td>0.95</td>
<td>0.95</td>
</tr>
</tbody>
</table>

As shown by the purple curve, when $f_{RC}=2$ Hz and $f_{RL}=3$ Hz, it shifts inward at frequencies below 1 Hz and shifts outward at frequencies above 1 Hz compared to the case without parasitic elements. Further increasing the frequency, the impedance increases after one rotation within a region where reactance is positive, eventually approaching $\infty$.

As shown by the green curve, when $f_{RC}=3$ Hz and $f_{RL}=2$ Hz, it shifts outward at frequencies below 1 Hz and shifts inward at frequencies above 1 Hz compared to the case without parasitic elements. The frequency is further increased, the impedance moves from the area where reactance is positive to the negative, makes one rotation, and then returns to the area where reactance is positive again.

As shown by the orange curve, when $f_{RC}=f_{RL}=2$ Hz, it follows the locus without parasitic elements as the frequency changes. However, the input impedance becomes 15 $\Omega$ at $f=2$ Hz. As the frequency is further increased, the impedance moves into the negative reactance region and is again matched to 5 $\Omega$ at $f=4$ Hz. With further increase in frequency, reactance returns to the positive region again.

Next, focus on the VSWR frequency characteristics shown in Fig. 10 and the $S_{11}$ frequency characteristics shown in Fig. 11. With parasitic elements, the band that satisfies $\Omega$ matches within a region.
With parasitic elements, the band that satisfies VSWR $\leq 1.2$ and $S_{21} \geq -0.3$ dB becomes narrower than without parasitic elements.

The VSWR and $S_{21}$ characteristics are the same for $f_{RC}=2$ Hz, $f_{RL}=3$ Hz and $f_{RC}=3$ Hz, $f_{RL}=2$ Hz, where the trajectories on $S_{11}$ are different. The narrowest band is obtained under the condition of $f_{RC}=f_{RL}=2$ Hz where the locus on $S_{11}$ overlaps with the case without parasitic elements.

Fig. 12 shows the expanded frequency range of the frequency characteristics of $S_{21}$. Under the conditions of $f_{RL}=2$ Hz, $f_{RC}=3$ Hz and $f_{RL}=3$ Hz, $f_{RC}=2$ Hz, After $S_{21}=0$ dB at 1 Hz, $S_{21}$ decreases as frequency is increased, then increases again, and finally decreases. Under the conditions of $f_{RC}=f_{RL}=2$ Hz, $S_{21}$ becomes 0 dB at $f=1.4$ Hz. After $S_{21}=0$ dB at 1 Hz, $S_{21}$ decreases as the frequency is increased, then increases again, and then $S_{21}=0$ dB again at 4 Hz. Further increasing the frequency causes $S_{21}$ to finally decrease.

6. Conclusion

We have confirmed the change in characteristics when a parasitic element is added to the L-type LC/CL matching circuit. A self-resonant frequency is generated in the inductor and the capacitor by adding the parasitic capacitance and the parasitic inductor, respectively. As a common feature, when checking the bands of VSWR and $S_{21}$, it can be seen that both bands become narrower as the self-resonant frequency of the constituent elements is lowered. In addition, when the self-resonant frequency is changed from 2 to 4 times and confirmed, it was found that the frequency band of VSWR and $S_{21}$ is the same with the same frequency combination regardless of whether the element is L or C.

In this first study, we analytically confirmed the details of the effect of parasitic elements added to the matching elements in the L-type LC/CL matching circuit, which is the basis of the matching circuit, and as a future issue, we will extend this study to a multistage LC/CL matching circuit as shown in Fig. 1. Note that the newly added L and C are treated here as parasitic elements. However, in harmonic control of power amplifiers, these elements may be intentionally added to the LC/CL matching circuit in order to short-circuit or open-circuit second-order or higher-order harmonics [18-22]. We believe this study is applicable to this case as well.

Acknowledgments

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References


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