Microwave Filter Design

Chp5. Lowpass Filters

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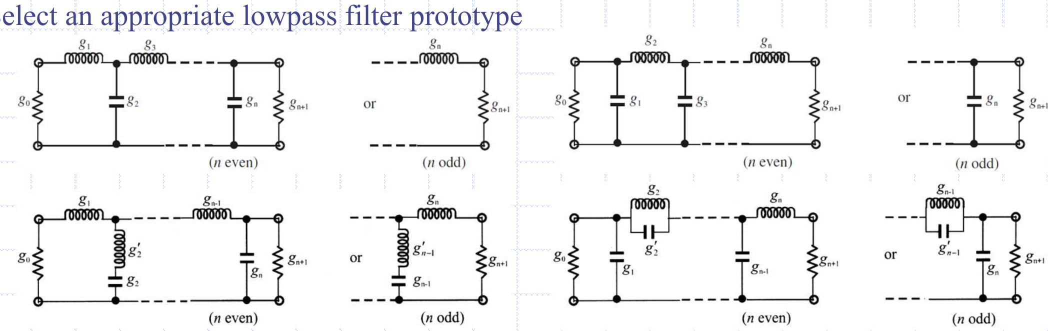
Lowpass Filters

Design steps

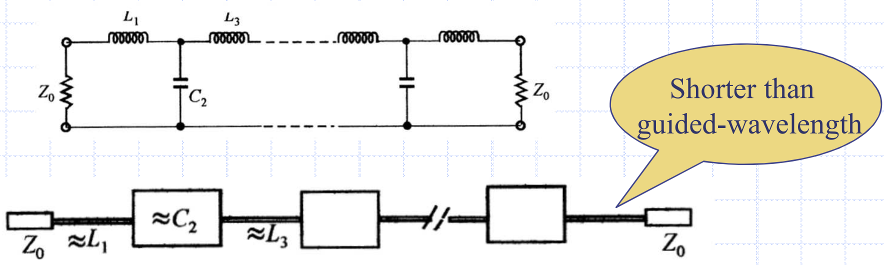
- Select an appropriate lowpass filter prototype



- The choice of the type of response including passband ripple and the number of reactive elements
  - Butterworth (Maximally Flat) Response
  - Chebyshev (Equal-Ripple) Response
  - Gaussian Response
  - Elliptic Function Response
- Find an appropriate microstrip realization
  - Stepped-Impedance LPF
  - LPF using open-circuited stubs
  - Semilumped LPF having finite-frequency attenuation poles

Stepped-Impedance LPF

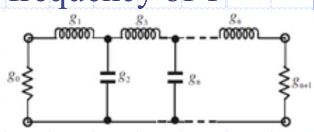
- General structure – cascaded structure of high- and low-impedance TML



- Design considerations
  - $Z_{0C} < Z_0 < Z_{0L}$, where Z_{0C} and Z_{0L} denote the characteristic impedances of the low and high impedane lines, respectively, and Z_0 is the source impedance, which is usually 50 ohms.
  - Lower Z_{0C} results in a better approximation of a lumped-element capacitor, but the resulting line width W_C must not allow any transverse resonance to occur at operation frequency.
  - Higher Z_{0L} leads to a better approximation of a lumped-element inductor, but Z_{0L} must not be so high that its fabrication become difficult, or its current-carrying capability becomes a limitation.

Example
- Stepped-impedance LPF

- Design a three-order LPF with 0.1 dB ripple and cutoff frequency of 1 GHz. The source/load impedance of the filter is 50 Ω.



  - Step 1 – Find out the required L/C element values

For passband ripple $L_{Ar} = 0.1$ dB ($g_0 = 1.0, \Omega_c = 1$)

n	g_1	g_2	g_3	g_4	g_5	g_6
1	0.3052	1.0				
2	0.8431	0.6220	1.3554			
3	1.0316	1.1474	1.0316	1.0		
4	1.1088	1.3062	1.7704	0.8181	1.3554	

$$L_1 = L_3 = \left(\frac{Z_0}{g_0}\right)\left(\frac{\Omega_c}{2\pi f_c}\right) g_1 = 8.209 \times 10^{-9}\ \text{H}$$

$$C_2 = \left(\frac{g_0}{Z_0}\right)\left(\frac{\Omega_c}{2\pi f_c}\right) g_2 = 3.652 \times 10^{-12}\ \text{F}$$

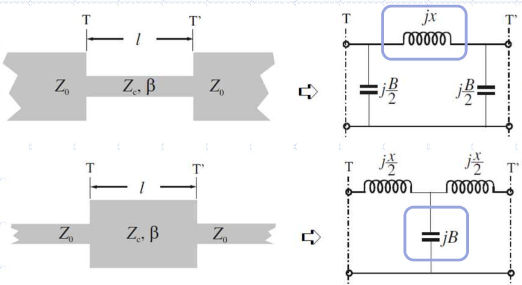
  - Step 2 – Choose the adequate design parameters of microstrip lines

Characteristic impedance (ohms)	$Z_{0C} = 24$	$Z_0 = 50$	$Z_{0L} = 93$
Guided wavelengths (mm)	$\lambda_{gC} = 105$	$\lambda_{g0} = 112$	$\lambda_{gL} = 118$
Microstrip line width (mm)	$W_C = 4.0$	$W_0 = 1.1$	$W_L = 0.2$

fabricated on a substrate with a relative dielectric constant of 10.8 and a thickness of 1.27 mm.

Example
- Stepped-impedance LPF

- Step 3 – physical length of the high- and low-impedance lines



$$x = Z_c \sin\left(\frac{2\pi}{\lambda_g} l\right) \qquad \frac{B}{2} = \frac{1}{Z_c}\tan\left(\frac{\pi}{\lambda_g} l\right)$$

$$B = \frac{1}{Z_c}\sin\left(\frac{2\pi}{\lambda_g} l\right) \qquad \frac{x}{2} = Z_c \tan\left(\frac{\pi}{\lambda_g} l\right)$$

- Initial guess for the physical length

$$l_L = \frac{\lambda_{gL}}{2\pi}\sin^{-1}\left(\frac{\omega_c L}{Z_{0L}}\right)$$

$$l_C = \frac{\lambda_{gC}}{2\pi}\sin^{-1}(\omega_c C Z_{0C})$$

$\Rightarrow$ $l_L = 11.04$ mm, $l_C = 9.75$ mm

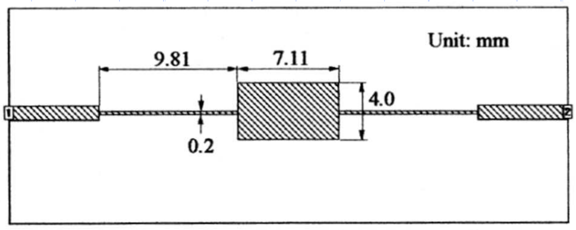
- Compensate the parasitic elements

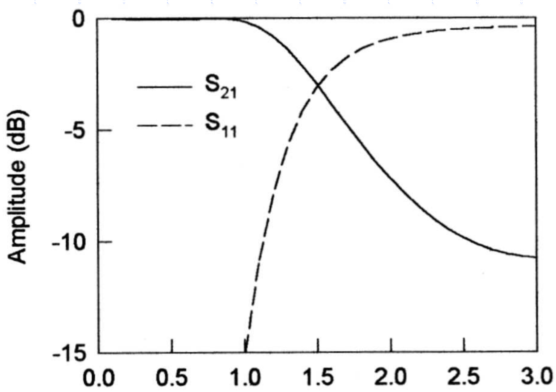
$$\omega_c L = Z_{0L}\sin\left(\frac{2\pi l_L}{\lambda_{gL}}\right) + Z_{0C}\tan\left(\frac{\pi l_C}{\lambda_{gC}}\right)$$

$$\omega_c C = \frac{1}{Z_{0C}}\sin\left(\frac{2\pi l_C}{\lambda_{gC}}\right) + 2\times\frac{1}{Z_{0L}}\tan\left(\frac{\pi l_L}{\lambda_{gL}}\right)$$

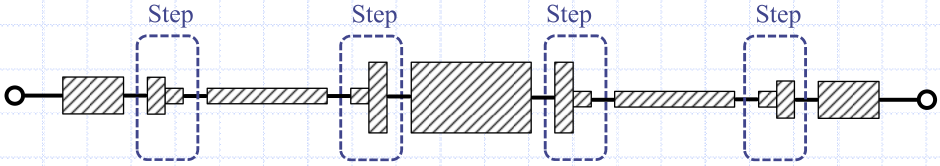
$\Rightarrow$ $l_L = 9.81$ mm, $l_C = 7.11$ mm

Example
- Stepped-impedance LPF



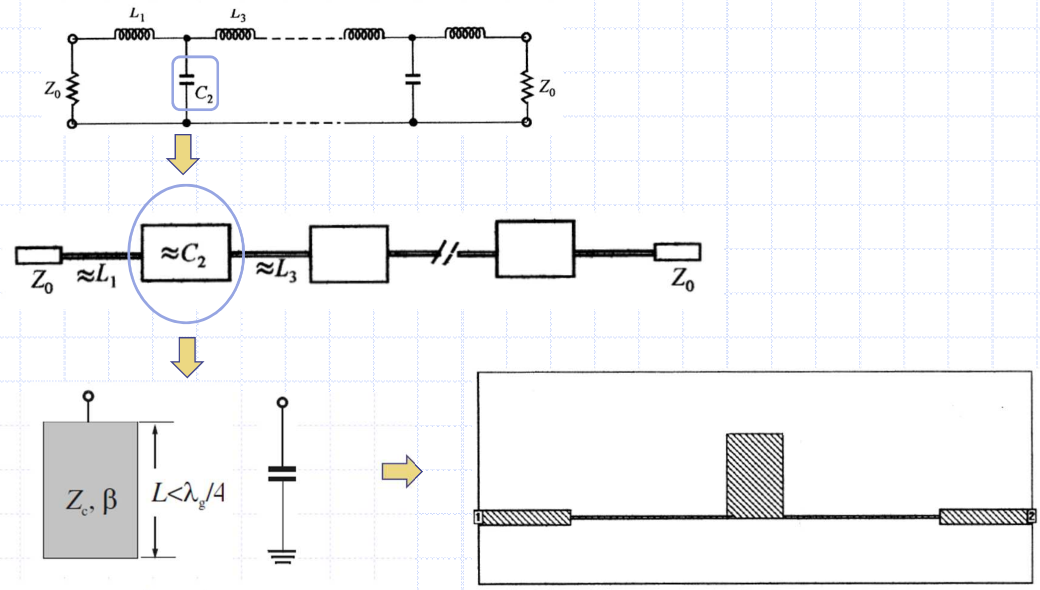


- Step 4 – take discontinuities into account as circuit simulator is used



LPF using open-circuited stubs

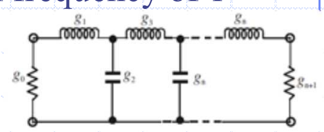
- General structure – high-impedance TML and open-circuited stubs



$$\omega C = \frac{1}{Z_0}\tan\left(\frac{2\pi}{\lambda_g}l\right) \qquad \text{for } l < \lambda_g/4$$

Example
- LPF with open-circuited stubs

- Design a three-order LPF with 0.1 dB ripple and cutoff frequency of 1 GHz. The source/load impedance of the filter is 50 Ω.



- Step 1 – Find out the required L/C element values

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n	g_1	g_2	g_3	g_4	g_5	g_6
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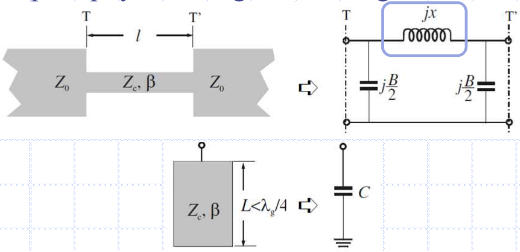
- Step 2 – Choose the adequate design parameters of microstrip lines

Characteristic impedance (ohms)	$Z_{0C} = 24$	$Z_0 = 50$	$Z_{0L} = 93$
Guided wavelengths (mm)	$\lambda_{gC} = 105$	$\lambda_{g0} = 112$	$\lambda_{gL} = 118$
Microstrip line width (mm)	$W_C = 4.0$	$W_0 = 1.1$	$W_L = 0.2$

fabricated on a substrate with a relative dielectric constant of 10.8 and a thickness of 1.27 mm.

Example
- LPF with open-circuited stubs

- Step 3 –physical length of the high- and low-impedance lines



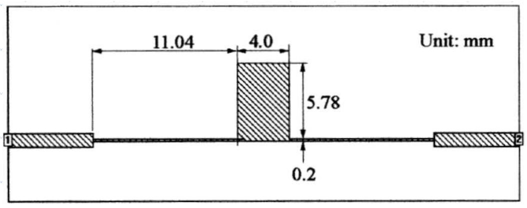
$$x = Z_c \sin\left(\frac{2\pi}{\lambda_g} l\right) \qquad \frac{B}{2} = \frac{1}{Z_c} \tan\left(\frac{\pi}{\lambda_g} l\right)$$

$$\omega C = \frac{1}{Z_0} \tan\left(\frac{2\pi}{\lambda_g} l\right) \qquad \text{for } l < \lambda_g/4$$

- Initial guess for the physical length

$$l_L = \frac{\lambda_{gL}}{2\pi} \sin^{-1}\left(\frac{\omega_c L}{Z_{0L}}\right) = 11.04 \text{ mm}$$

$$l_C = \frac{\lambda_{gC}}{2\pi} \tan^{-1}(\omega_c C Z_{0C}) = 8.41 \text{ mm}$$



- Compensate the discontinuities
  1. parasitic effect on high-impedance line

$$\omega_c C = \frac{1}{Z_{0C}} \tan\left(\frac{2\pi l_C}{\lambda_{gC}}\right) + 2 \times \frac{1}{Z_{0L}} \tan\left(\frac{\pi l_L}{\lambda_{gL}}\right) \Rightarrow l_C = 6.28 \text{ mm}$$

  2. open-end

$$\Delta l = \frac{c Z_c C_p}{\sqrt{\varepsilon_{re}}} = 0.5 \text{ mm} \Rightarrow l_C = 6.28 - 0.5 = 5.78 \text{ mm}$$

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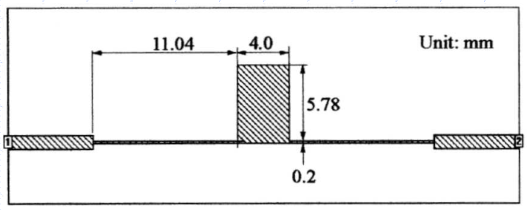
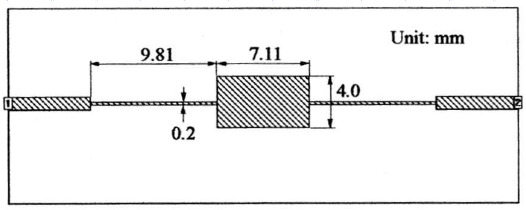
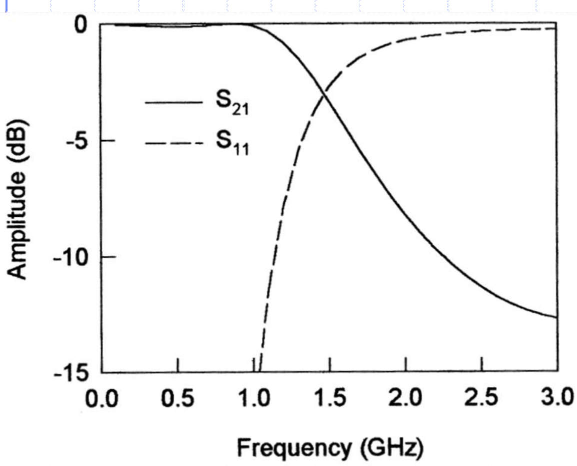
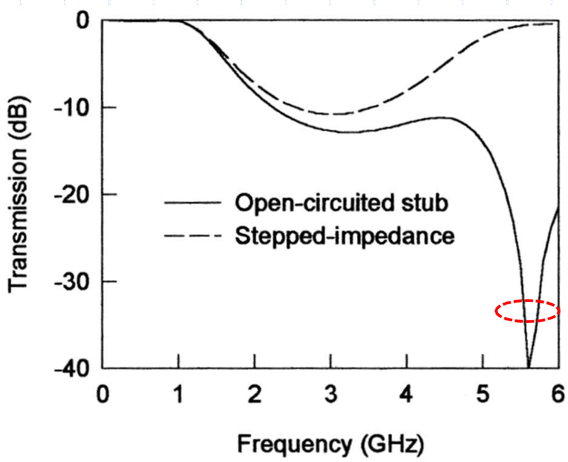
Example
- Results and comparisons

- LPF with open-circuited stubs can exhibit a better stopband characteristic.



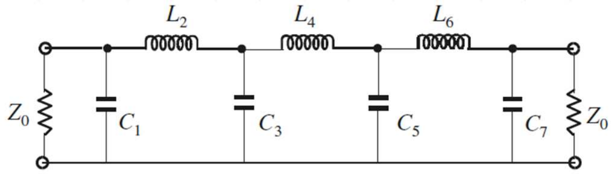






Example
- LPF with open-circuited stubs

- To obtain a sharper rate of cutoff, a seven-order LPF is designed with 0.1 dB ripple and cutoff frequency of 1 GHz. The source/load impedance of the filter is 50 Ω.



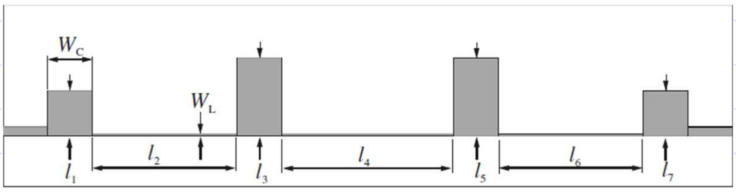
$Z_0 = 50$ ohm

$L_2 = L_6 = 11.322$ nH

$L_4 = 12.52$ nH

$C_1 = C_7 = 3.7596$ pF

$C_3 = C_5 = 6.6737$ pF



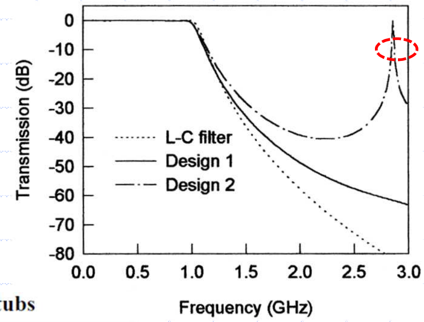
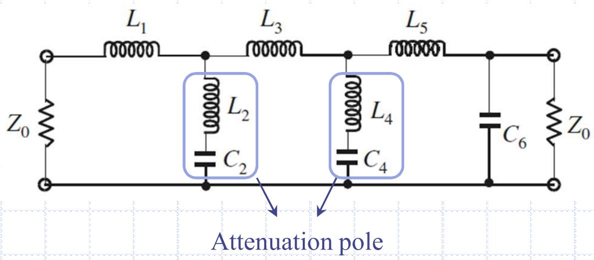


TABLE 5.2 Two microstrip lowpass filter designs with open-circuited stubs

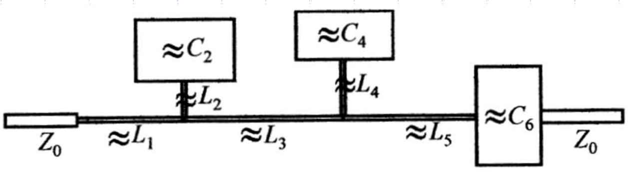
Substrate ($\varepsilon_r = 10.8$, $h = 1.27$ mm) $W_C = 5$ mm	$l_1 = l_7$ (mm)	$l_2 = l_6$ (mm)	$l_3 = l_5$ (mm)	l_4 (mm)
✓ Design 1 ($W_L = 0.1$ mm)	5.86	13.32	9.54	15.09
Design 2 ($W_L = 0.2$ mm)	5.39	16.36	8.67	18.93

LPF with attenuation poles (transmission zeros)

- To obtain an sharper rate of cutoff, attenuation poles are required to achieve the frequency response.
  - Prototype filter with elliptic function response



  - General structure – cascaded structure of open-circuited stubs, high- and low-impedance TML



Example
- LPF with attenuation poles

- Design a six-order elliptic LPF with a passband ripple L_{Ar} = 0.18 dB and a minimum stopband attenuation L_{As} = 38.1 dB at Ω_s = 1.194 for cutoff Ω_c = 1. The filter is designed at cutoff frequency f_c = 1 GHz and the source/load impedance of the filter is 50 Ω.
  - Step 1 – Find out the required L/C element values

θ	Ω_S	A_S[db]	L_1	L_2	C_2	Ω_2	L_3	L_4	C_4	Ω_4	L_5	C_6	θ
56	1.252 921	42.7	0.8705	0.3221	1.147	1.645 294	1.269	0.5941	1.024	1.281 971	1.172	1.140	56
57	1.237 179	41.5	0.8587	0.3377	1.132	1.617 530	1.249	0.6274	0.9957	1.265 189	1.159	1.139	57
58	1.222 145	40.4	0.8466	0.3541	1.116	1.590 725	1.229	0.6629	0.9668	1.249 136	1.145	1.138	58
59	1.207 787	39.3	0.8342	0.3712	1.100	1.564 828	1.209	0.7008	0.9375	1.233 777	1.131	1.137	59
60	1.194 077	38.1	0.8214	0.3892	1.084	1.539 791	1.188	0.7413	0.9077	1.219 083	1.117	1.136	60
61	1.180 985	37.0	0.8081	0.4081	1.067	1.515 571	1.167	0.7848	0.8775	1.205 023	1.103	1.134	61
62	1.168 486	35.9	0.7945	0.4280	1.049	1.492 126	1.146	0.8317	0.8468	1.191 572	1.088	1.133	62
63	1.156 557	34.8	0.7804	0.4490	1.032	1.469 414	1.125	0.8823	0.8157	1.178 704	1.074	1.131	63
64	1.145 175	33.7	0.7659	0.4712	1.013	1.447 401	1.103	0.9372	0.7843	1.166 396	1.058	1.130	64
65	1.134 320	32.6	0.7509	0.4947	0.9940	1.426 049	1.081	0.9970	0.7524	1.154 626	1.043	1.128	65

$g_0 = g_7 = 1.000$

$g_{L1} = g_1 = 0.8214$

$g_{L2} = g_2' = 0.3892$

$g_{C2} = g_2 = 1.0840$

$g_{L3} = g_3 = 1.1880$

$g_{L4} = g_4' = 0.7413$

$g_{C4} = g_4 = 0.9077$

$g_{L5} = g_5 = 1.1170$

$g_{C6} = g_6 = 1.1360$

$$L_i = \frac{1}{2\pi f_c} Z_0 g_{Li}$$

$$C_i = \frac{1}{2\pi f_c}\frac{1}{Z_0} g_{Ci}$$

$L_1 = 6.53649$ nH

$L_3 = 9.45380$ nH

$L_5 = 8.88880$ nH

$C_6 = 3.61600$ pF

$L_2 = 3.09716$ nH

$C_2 = 3.45048$ pF

$L_4 = 5.89908$ nH

$C_4 = 2.88930$ pF

Attenuation poles

$$f_{p1} = \frac{1}{2\pi\sqrt{L_4 C_4}} = 1.219 \text{ GHz}$$

$$f_{p2} = \frac{1}{2\pi\sqrt{L_2 C_2}} = 1.540 \text{ GHz}$$

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Example
- LPF with attenuation poles

- Step 2 – Choose the adequate design parameters of microstrip lines

Characteristic impedance (ohms)	$Z_{0C} = 14$	$Z_0 = 50$	$Z_{0L} = 93$
Microstrip line width (mm)	$W_C = 8.0$	$W_0 = 1.1$	$W_L = 0.2$
Guided wavelength (mm) at f_c	$\lambda_{gC}(f_c) = 101$	$\lambda_{g0} = 112$	$\lambda_{gL}(f_c) = 118$
Guided wavelength (mm) at f_{p1}	$\lambda_{gC}(f_{p1}) = 83$		$\lambda_{gL}(f_{p1}) = 97$
Guided wavelength (mm) at f_{p2}	$\lambda_{gC}(f_{p2}) = 66$		$\lambda_{gL}(f_{p2}) = 77$

- Step 3 – Initial physical length of the high- and low-impedance lines

$$l_{Li} = \frac{\lambda_{gL}(f_c)}{2\pi}\sin^{-1}\left(2\pi f_c \frac{L_i}{Z_{0L}}\right)$$

$$l_{Ci} = \frac{\lambda_{gc}(f_c)}{2\pi}\sin^{-1}(2\pi f_c Z_{0C} C_i)$$

$l_{L1} = 8.59$ $\quad l_{L2} = 3.96$

$l_{L3} = 13.01$ $\quad l_{C2} = 4.96$

$l_{L5} = 12.10$ $\quad l_{L4} = 7.70$

$l_{C6} = 5.20$ $\quad l_{C4} = 4.13$

- Step 4 – Compensate the parasitic elements
  1. For L_5 and C_6

$$2\pi f_c L_5 = Z_{0L}\sin\left(\frac{2\pi l_{L5}}{\lambda_{gL}(f_c)}\right) + Z_{0C}\tan\left(\frac{\pi l_{C6}}{\lambda_{gC}(f_c)}\right)$$

$$2\pi f_c C_6 = \frac{1}{Z_{0C}}\sin\left(\frac{2\pi l_{C6}}{\lambda_{gC}(f_c)}\right) + \frac{1}{Z_{0L}}\tan\left(\frac{\pi l_{L5}}{\lambda_{gL}(f_c)}\right)$$

$l_{L5} = 11.62$ mm

$l_{C6} = 4.39$ mm

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Example
- LPF with attenuation poles

- Step 4 – Compensate the parasitic elements
  2. For L_2 and C_2 or L_4 and C_4 (fixed l_{L1}, l_{L2}, and l_{L3})

$$\frac{1}{(2\pi f L_2) - 1/(2\pi f C_2)} = B_2(f) + \Delta B_{123}(f) \qquad \text{for } f = f_c \text{ and } f_{p2} \quad \Rightarrow \quad l_{L2} = 2.98 \text{ mm}, \quad l_{C2} = 5.61 \text{ mm}$$

where

$$B_2(f) = \cfrac{1}{Z_{0L}\sin\left(\frac{2\pi l_{L2}}{\lambda_{gL}(f)}\right) + Z_{0C}\tan\left(\frac{\pi l_{C2}}{\lambda_{gC}(f)}\right) - \cfrac{1}{\frac{1}{Z_{0C}}\sin\left(\frac{2\pi l_{C2}}{\lambda_{gC}(f)}\right) + \frac{1}{Z_{0L}}\tan\left(\frac{\pi l_{L2}}{\lambda_{gL}(f)}\right)}}$$

$$\Delta B_{123}(f) = \frac{1}{Z_{0L}}\tan\left(\frac{\pi l_{L1}}{\lambda_{gL}(f)}\right) + \frac{1}{Z_{0L}}\tan\left(\frac{\pi l_{L2}}{\lambda_{gL}(f)}\right) + \frac{1}{Z_{0L}}\tan\left(\frac{\pi l_{L3}}{\lambda_{gL}(f)}\right)$$

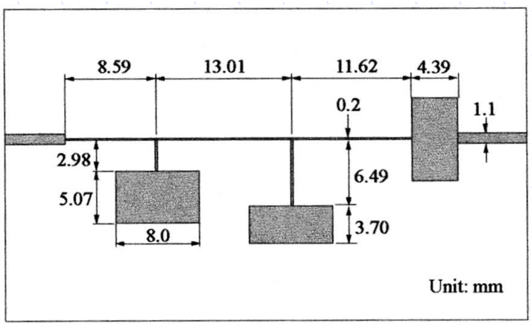
The same method can be applied to L_4 and C_4 and the corrected length are l_{L4} = 6.49 mm and l_{C4} = 4.24 mm.

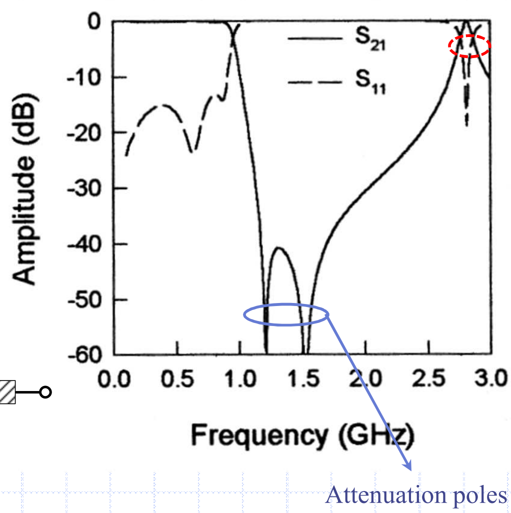
  3. l_{C2} and l_{C4} on open-end effect

$$\Delta l = \frac{c Z_c C_p}{\sqrt{\varepsilon_{re}}} = 0.54 \text{ mm} \quad \Rightarrow \quad l_{C2} = 5.61 - 0.54 = 5.07 \text{ mm}, \quad l_{C4} = 4.24 - 0.54 = 3.70 \text{ mm}$$

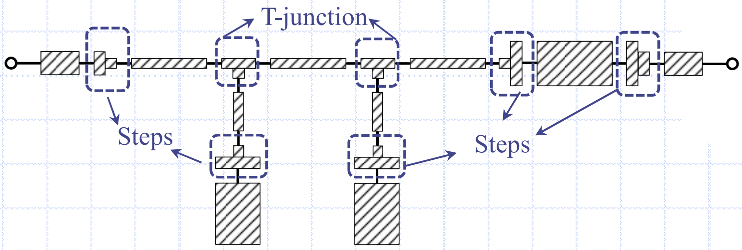
Example
- LPF with attenuation poles

- A sharp rate of cutoff with two attenuation poles is designed
  - The unwanted transmission peak could be moved away up to a higher frequency if higher characteristic impedance could be used for the inductive lines.





- Step 5 – take discontinuities into account



HW II

Please design a LPF based on Chebyshev prototype with following specifications:

1. Passband ripple < 0.0432 dB
2. Cutoff frequency : 1 GHz
3. Insertion loss > 30 dB at 3 GHz.

The properties of the substrate is FR4 with $\varepsilon_r = 4.2$ and loss tangent 0.01. The substrate thickness is 1.6 mm. The high and low impedance used in this design is 90 ohm and 25 ohm, respectively. (Note: Please consider the parasitic effects and discontinuities)

a. Please decide the order of the LPF and calculate the lumped element values of L and C.
b. Based on step impedance approach, please plot the layout of the LPF, and calculate (and denote) the corresponding geometry dimensions.
c. Plot the return loss and insertion loss for the designed LPF using ADS.
d. Simulate the return loss and insertion loss for the designed LPF using full-wave simulator (CST or HFSS), and compare the results with those modeled in (c). Please also discuss the reasons for the discrepancy between them.
e. Based on the open-circuited stubs approach, please repeat steps (b) to (d).