Microwave Filter Design

Chp6. Bandstop Filters

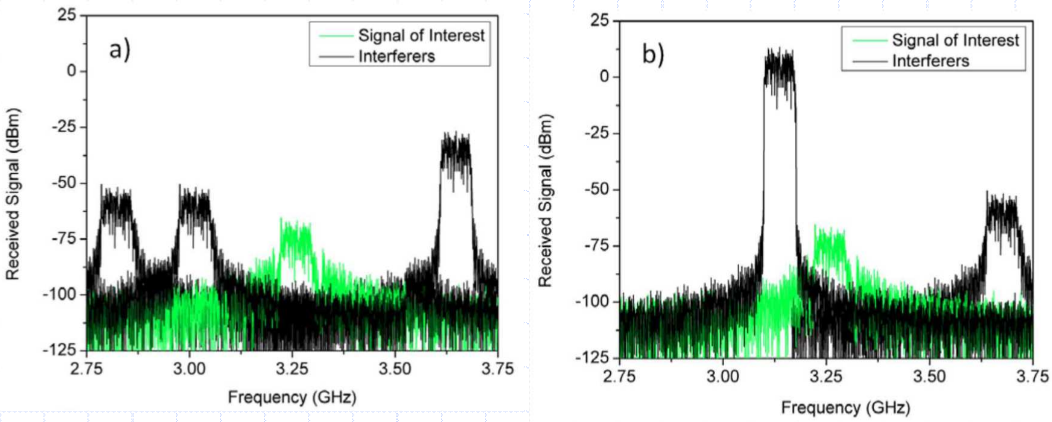
Prof. Tzong-Lin Wu

Department of Electrical Engineering
National Taiwan University

Bandstop Filters

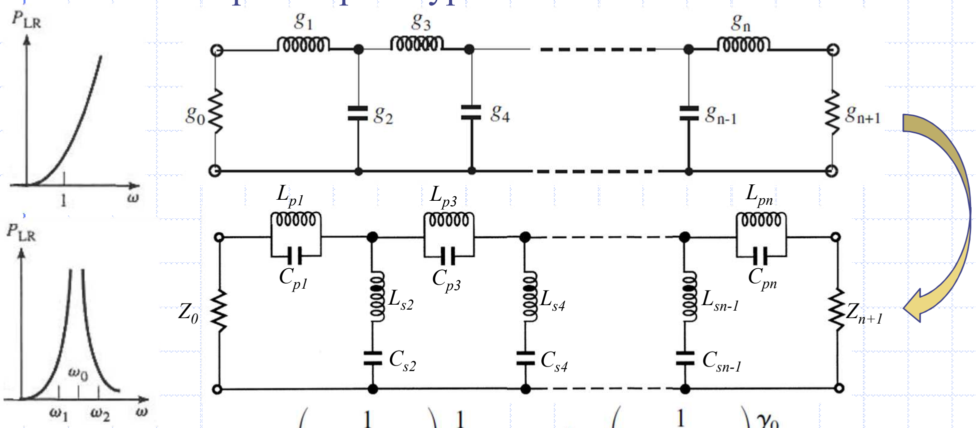
- Bandstop filter V.S. Bandpass filter
  - Use bandpass filters to discriminate against wide ranges of frequencies outside the passband.
  - Use bandstop filters when some unwanted interfering frequencies be particularly strong; or when high attenuation may be needed only at certain frequencies.

Bandpass Filter　　　　Bandstop Filter



Bandstop Filters

- Bandstop filter prototype



Bandstop Transformation

$$\Omega = \frac{\Omega_c FBW}{(\omega_0/\omega - \omega/\omega_0)}$$

$$\omega_0 = \sqrt{\omega_1 \omega_2}$$

$$FBW = \frac{\omega_2 - \omega_1}{\omega_0}$$

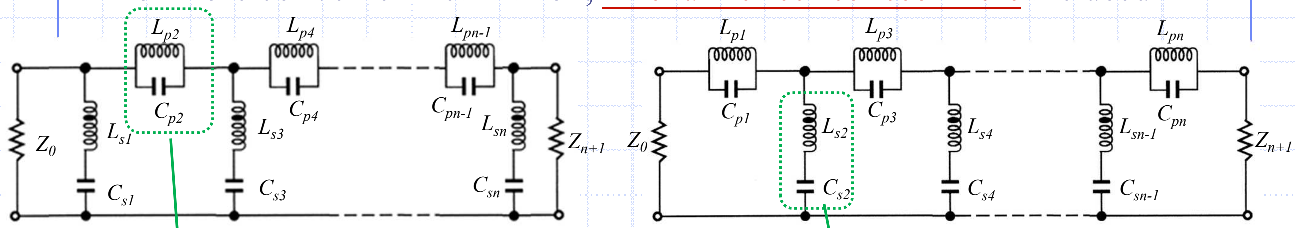
$$C_p = \left(\frac{1}{FBW\omega_0\Omega_c}\right)\frac{1}{\gamma_0 g} \qquad L_s = \left(\frac{1}{FBW\omega_0\Omega_c}\right)\frac{\gamma_0}{g}$$

$$L_p = \left(\frac{\Omega_c FBW}{\omega_0}\right)\gamma_0 g \qquad C_s = \left(\frac{\Omega_c FBW}{\omega_0}\right)\frac{g}{\gamma_0}$$

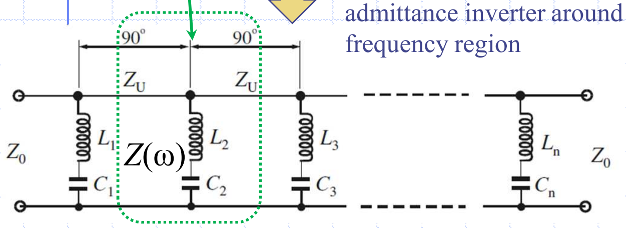
- Find an appropriate microstrip realization
  - Narrowband Bandstop Filter (electric couplings and magnetic couplings)
  - Bandstop Filters with Open-circuited Stubs
  - Optimum Bandstop Filter
  - Bandstop Filters for RF chokes

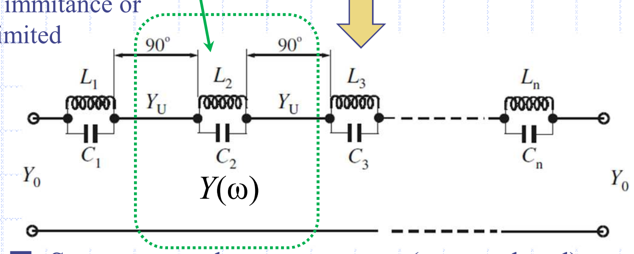
Narrowband Bandstop Filters

- For more convenient realization, all shunt or series resonators are used



Quarter-wavelength TML as immitance or admittance inverter around limited frequency region





- Reactance slope parameters (narrow-band)

$$x_i = \frac{\omega_0}{2}\frac{dZ(\omega)}{d\omega}\bigg|_{\omega_0} = \omega_0 L_i = \omega_0 Z_u^2 C_{pi} = \omega_0 Z_u^2 \frac{1}{\omega_0 \Omega_c FBW Z_0 g_i}$$

$$= Z_0\left(\frac{Z_u}{Z_0}\right)^2 \frac{1}{\Omega_c FBW g_i} \qquad \text{i = even}$$

$$x_j = \frac{\omega_0}{2}\frac{dZ(\omega)}{d\omega}\bigg|_{\omega_0} = \omega_0 L_{sj} = \omega_0 \frac{Z_0}{\omega_0 \Omega_c FBW g_j} = Z_0 \frac{1}{\Omega_c FBW g_j}$$

j = odd ⟷

- Susceptance slope parameters (narrow-band)

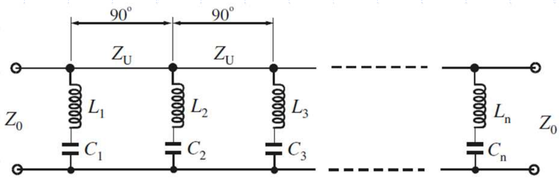
$$b_i = \frac{\omega_0}{2}\frac{dY(\omega)}{d\omega}\bigg|_{\omega_0} = \omega_0 C_2 = \omega_0 Y_u^2 L_{s2} = \omega_0 Y_u^2 \frac{Z_0}{\omega_0 \Omega_c FBW g_i}$$

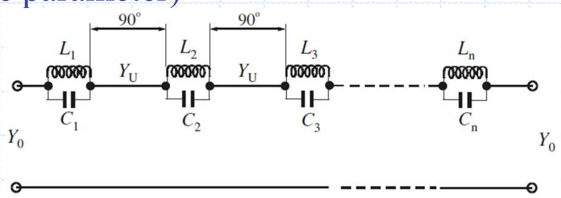
$$= Y_0\left(\frac{Z_u}{Y_0}\right)^2 \frac{1}{\Omega_c FBW g_i} \qquad \text{i = even}$$

$$b_j = \frac{\omega_0}{2}\frac{dY(\omega)}{d\omega}\bigg|_{\omega_0} = \omega_0 C_j = \omega_0 \frac{1}{\omega_0 \Omega_c FBW Z_0 g_j} = Y_0 \frac{1}{\Omega_c FBW g_j}$$

Narrowband Bandstop Filters

- Approximate Design parameters (slope parameter)





$$\left(\frac{Z_U}{Z_0}\right)^2 = \frac{1}{g_0 g_{n+1}} \qquad Z_0 = Z_u$$

$$x_i = \omega_0 L_i = \frac{1}{\omega_0 C_i} = Z_0\left(\frac{Z_U}{Z_0}\right)^2 \frac{g_0}{g_i \Omega_c FBW}$$

for $i = 1$ to n

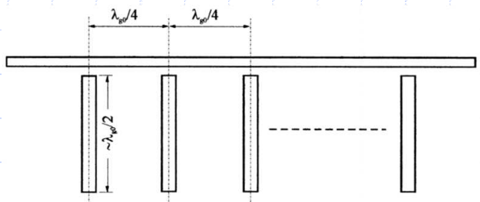
$$\left(\frac{Y_U}{Y_0}\right)^2 = \frac{1}{g_0 g_{n+1}} \qquad Y_0 = Y_u$$

$$b_i = \omega_0 C_i = \frac{1}{\omega_0 L_i} = Y_0\left(\frac{Y_U}{Y_0}\right)^2 \frac{g_0}{g_i \Omega_c FBW}$$

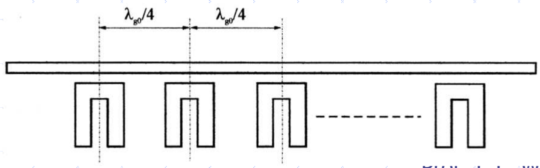
for $i = 1$ to n

- General structure – $\lambda_g/2$ resonators are spaced $\lambda_g/4$ apart

Electric coupling

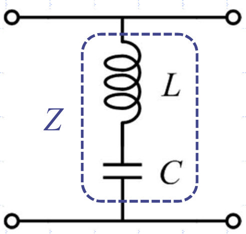


Magnetic coupling



Extraction of slope parameters (1)

- Consider two-port network with a single shunt branch



$$Z = j\omega L + 1/j\omega C$$

$$x = \frac{\omega_0}{2}\frac{dZ(\omega)}{d\omega}\bigg|_{\omega_0} = \omega_0 L$$

- Transmission parameter terminated with Z_0

$$S_{21} = \frac{1}{1+\dfrac{Z_0}{2Z}}$$

Narrowband case, $\Delta\omega << \omega_0$

$\omega = \omega_0 + \Delta\omega,\ \ Z \approx j\omega_0 L\left(\frac{2\Delta\omega}{\omega_0}\right)$

$$|S_{21}| = \frac{1}{\sqrt{1+\left[\dfrac{1}{4(x/Z_0)}\dfrac{\omega_0}{\Delta\omega}\right]^2}}$$

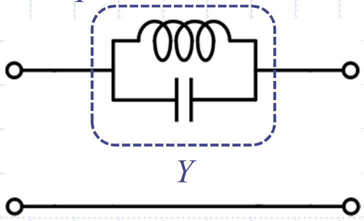
- Choose the 3 dB bandwidth of $|S_{21}|$

from EM simulator

$$\frac{1}{4(x/Z_0)}\frac{\omega_0}{\Delta\omega_\pm} = \pm 1 \Rightarrow \Delta\omega_{3\text{dB}} = \Delta\omega_+ - \Delta\omega_- = \frac{\omega_0}{2(x/Z_0)} \Rightarrow \left(\frac{x}{Z_0}\right) = \frac{\omega_0}{2\Delta\omega_{3\text{dB}}} = \frac{f_0}{2\Delta f_{3\text{dB}}} \quad (1)$$

Extraction of slope parameters (2)

- Consider two-port network with a single shunt branch



$$Y = j\omega C + 1/j\omega L$$

$$\Rightarrow b = \frac{\omega_0}{2}\frac{dY(\omega)}{d\omega}\bigg|_{\omega_0} = \omega_0 C$$

- Transmission parameter terminated with Z_0

$$S_{21} = \frac{1}{1+\frac{Y_0}{2Y}} \xrightarrow{\text{Narrowband case, } \Delta\omega \ll \omega_0} S_{21} = \frac{1}{\sqrt{1+\left[\frac{1}{4(b/Y_0)}\frac{\omega_0}{\Delta\omega}\right]^2}}$$

$$\omega = \omega_0 + \Delta\omega, \quad Y = j\omega_0 C\left(\frac{2\Delta\omega}{\omega_0}\right)$$

- Choose the 3 dB bandwidth of $|S_{21}|$

from EM simulator

$$\frac{1}{4(b/Y_0)}\frac{\omega_0}{\Delta\omega_\pm} = \pm 1 \Rightarrow \Delta\omega_{3dB} = \Delta\omega_+ - \Delta\omega_- = \frac{\omega_0}{2(b/Y_0)} \Rightarrow \left(\frac{b}{Y_0}\right) = \frac{\omega_0}{2\Delta\omega_{3dB}} = \frac{f_0}{2\Delta f_{3dB}} \quad (2)$$

- Both the normalized reactance and susceptance slope parameter can be determined from the above design equations, namely (1) and (2), regardless of actual structures of microwave bandstop resonators and regardless of whether the couplings are electric, magnetic, and mixed.

Example
- A narrow-band bandstop filter with L-resonators

- Design a five order microstrip bandstop filter in chebyshev prototype with passband ripple of 0.1 dB. The desired band-edge frequencies to equal-ripple points are f_1 = 3.3 GHz and f_2 = 3.5 GHz. Choosing Z_0 = 50 ohm.
  - Step 1 – Find out the required information for design of a filter

$$f_0 = \sqrt{f_1 f_2} = 3.3985\ GHz \Rightarrow FBW = \frac{f_2 - f_1}{f_0} = 0.0588$$

For passband ripple L_{Ar} = 0.1 dB

n	g_1	g_2	g_3	g_4	g_5	g_6	g_7	g_8
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			
5	1.1468	1.3712	1.9750	1.3712	1.1468	1.0		
6	1.1681	1.4040	2.0562	1.5171	1.9029	0.8618	1.3554	

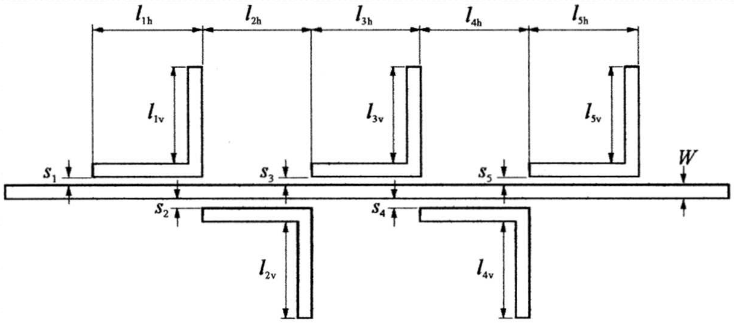
  - Step 2 – look up table to find the desired design parameters (slope parameters)

$$Z_U = Z_0 \qquad \frac{x_3}{Z_0} = 8.6038$$

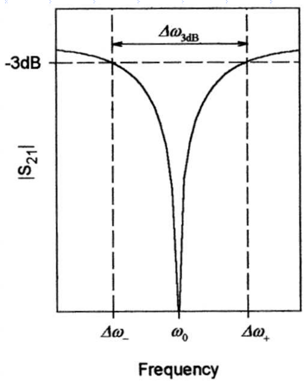
$$\frac{x_1}{Z_0} = \frac{x_5}{Z_0} = 14.8170 \qquad \frac{x_2}{Z_0} = \frac{x_4}{Z_0} = 12.3924$$

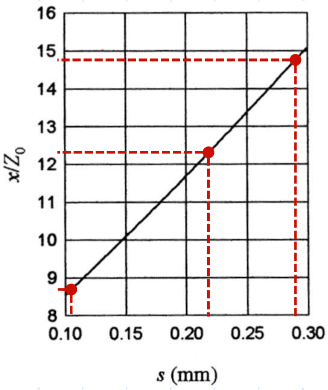
Example
- A narrow-band bandstop filter with L-resonators

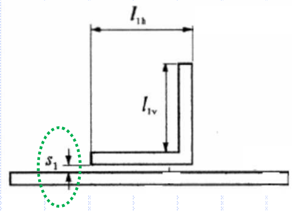
- Step 3 – determine the physical size of the L-resonators



- Length of L-resonators
  l_h = 8.9 mm and l_v = 8.9 mm
  (half guided wavelength)
- Spacing of main line and resonators
  $\frac{f_0}{2\Delta f_{3dB}}$ from EM simulator
  $s_1 = s_5 = 0.292$ mm
  $s_2 = s_4 = 0.292$ mm
  $s_3 = 0.292$ mm

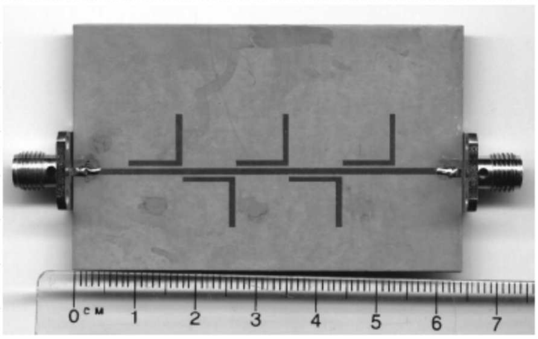


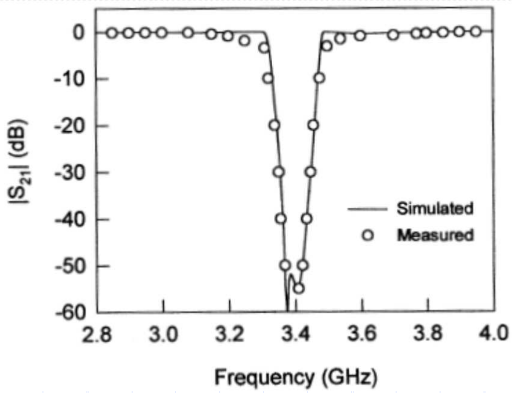




Prof. T. L. Wu

Example
- A narrow-band bandstop filter with L-resonators





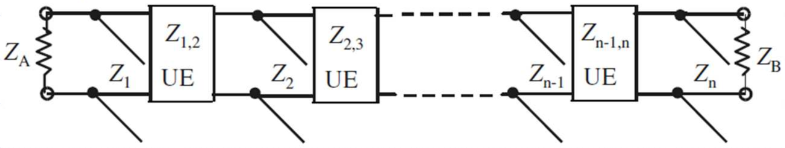
The microstrip is designed on a substrate with a dielectric constant of 10.8 and a thickness of 1.27 mm

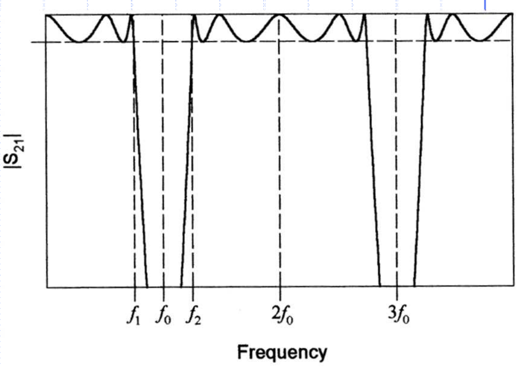
- Note:
  1. This measured filter is enclosed in a copper housing to reduce radiation losses, otherwise the stopband attenuation around the midband would be degraded.
  2. Frequency tuning is normally required for narrowband bandstop filters to compensate for fabrication tolerances. The length l_v could be slightly trimed.

Prof. T. L. Wu

Bandstop Filters with Open-Circuited Stubs

- General structure – shunt $\lambda_g/4$ open-circuited stubs are separated by unit elements ($\lambda_g/4$ long at mid-stopband frequency)



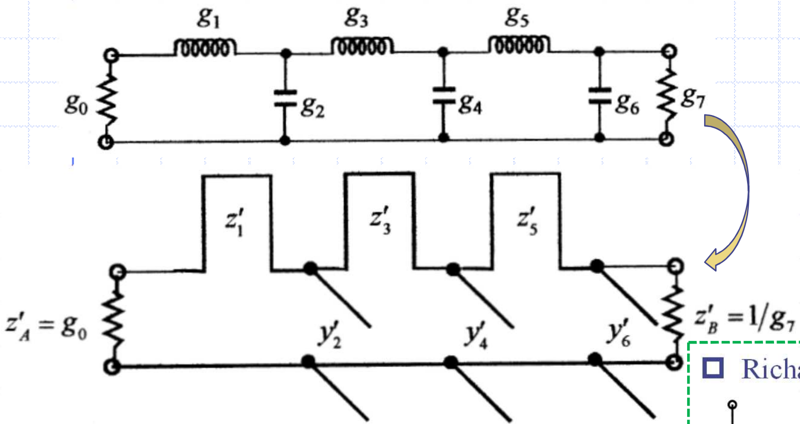


- Characteristic of this filter
  - This filter depends on design of characteristic impedances for the open-circuited stubs, and characteristic impedances $Z_{i,i+1}$ for the unit elements, as well as two terminating impedance.
  - Suitable for wide-band bandstop filters due to the difficulty of realization of narrow line.
  - The bandstop filter of this type have spurious stop bands periodically centered at frequencies that are odd multiples of f_0.

Prof. T. L. Wu

Bandstop Filters with Open-Circuited Stubs (1/3)

- Design procedures (for n=6)



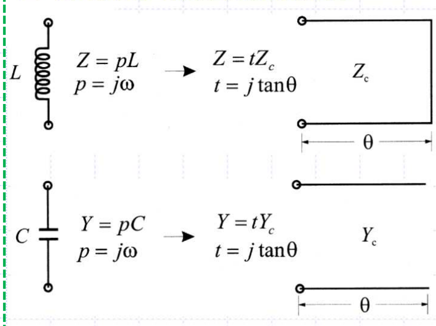
- Frequency Mapping of the LPF

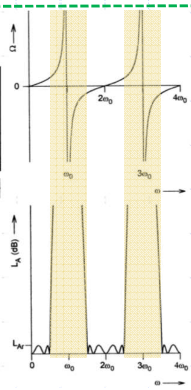
$$\Omega = \Omega_c \alpha \tan\left(\frac{\pi}{2}\frac{f}{f_0}\right)$$

$$\alpha = \cot\left[\frac{\pi}{2}\left(1 - \frac{FBW}{2}\right)\right] = \cot\left(\frac{\pi}{2}\frac{f_1}{f_0}\right)$$

$$FBW = \frac{f_2 - f_1}{f_0} \qquad f_0 = \frac{f_1 + f_2}{2}$$

- Richard Transformations



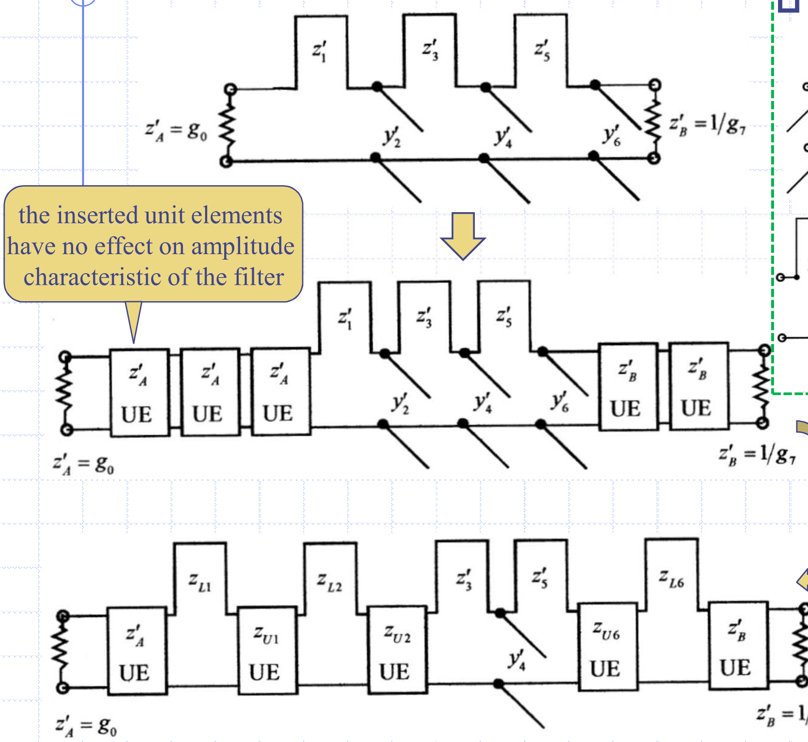


- Normalized characteristic impedance and admittance (all the stubs are $\lambda_g/4$)

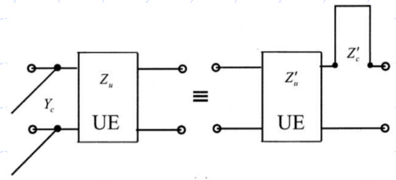
$$z'_i = \Omega_c \alpha g_i \quad \text{for } i = 1, 3, \text{ and } 5$$

$$y'_i = \Omega_c \alpha g_i \quad \text{for } i = 2, 4, \text{ and } 6$$

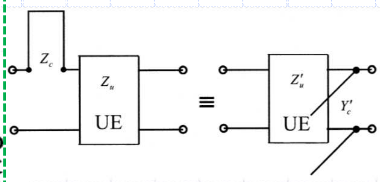
Bandstop Filters with Open-Circuited Stubs (2/3)



- Kuroda's identities



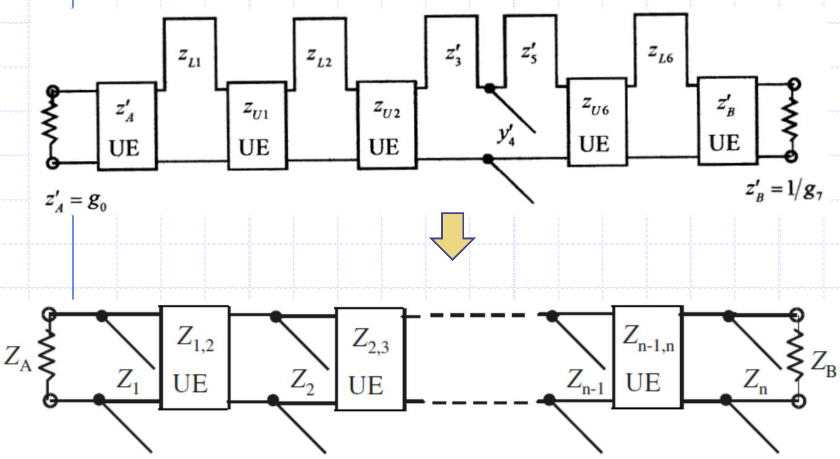
$$Z_c' = \frac{Z_u^2 Y_c}{1+Z_u Y_c} \qquad Z_u' = \frac{Z_u}{1+Z_u Y_c}$$



$$Z_u' = Z_u + Z_c \qquad Y_c' = \frac{Z_c}{Z_u(Z_c+Z_u)}$$

1. $y_{C0} = \dfrac{z_1'}{z_A'(z_A'+z_1')}, \qquad z_{U0} = z_A' + z_1'$
2. $z_{L6} = \dfrac{z_B'^2 y_6'}{1+z_B' y_6'}, \qquad z_{U6} = \dfrac{1+z_B'}{1+z_B' y_6'}$
3. $z_{L2} = \dfrac{z_{U0}^2 y_2'}{1+z_{U0} y_2'}, \qquad z_{U2} = \dfrac{z_{U0}}{1+z_{U0} y_2'}$
4. $z_{L1} = \dfrac{z_A'^2 y_{C0}}{1+z_A' y_{C0}}, \qquad z_{U1} = \dfrac{z_A'}{1+z_A' y_{C0}}$

Bandstop Filters with Open-Circuited Stubs (3/3)



$$Z_A = Z_0 z_A', \qquad Z_B = Z_0 z_B'$$

$$Z_1 = Z_0 z_A' \frac{z_A' + z_{L1}}{z_{L1}}, \qquad Z_{1,2} = Z_0(z_A' + z_{L1})$$

$$Z_2 = Z_0 z_{U1} \frac{z_{U1} + z_{L2}}{z_{L2}}, \qquad Z_{2,3} = Z_0(z_{U1} + z_{L2})$$

$$Z_3 = Z_0 z_{U2} \frac{z_{U2} + z_3'}{z_3'}, \qquad Z_{3,4} = Z_0(z_{U2} + z_3')$$

$$Z_4 = Z_0 / y_4'$$

$$Z_5 = Z_0 z_{U6} \frac{z_{U6} + z_5'}{z_5'}, \qquad Z_{4,5} = Z_0(z_{U6} + z_5')$$

$$Z_6 = Z_0 z_B' \frac{z_B' + z_{L6}}{z_{L6}}, \qquad Z_{5,6} = Z_0(z_B' + z_{L6})$$

- Design equations for other filter order (n=1~5) can be derived in a similar way and are shown in the textbook.(6.28~6.32)

Example
- Bandstop Filters with Open-Circuited Stubs

- Design a three order microstrip bandstop filter in chebyshev prototype with passband ripple of 0.05 dB. The desired band-edge frequencies to equal-ripple points are f_1 = 1.25 GHz and f_2 = 3.75 GHz. Choosing Z_0 = 50 ohm.
  - Step 1 – Find out the required information for designing a filter

$$f_0 = \frac{f_1 + f_2}{2} = 2.5\ GHz \Rightarrow FBW = \frac{f_2 - f_1}{f_0} = 1$$

$$\alpha = \cot\left[\frac{\pi}{2}\left(1 - \frac{FBW}{2}\right)\right] = 1$$

g-values of the prototype

g0 = g4 = 1.0

g1 = g3 = 0.8794

g2 = 1.1132

  - Step 2 – Using the design equations for n=3

$$Z_A = Z_B = 50\ \Omega$$

$$Z_1 = Z_A\left(1 + \frac{1}{\alpha g_0 g_1}\right) = 50\left(1 + \frac{1}{0.8794}\right) = 106.85\ \Omega$$

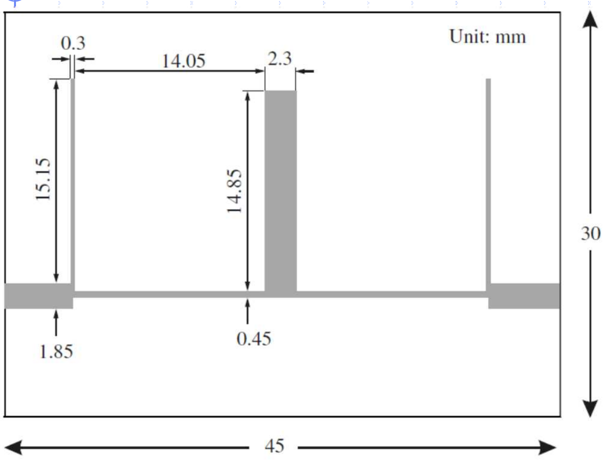
$$Z_2 = \frac{Z_A g_0}{\alpha g_2} = \frac{50}{1.1132} = 44.92\ \Omega$$

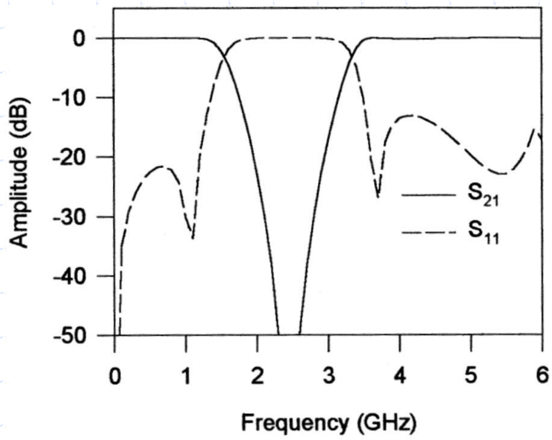
$$Z_3 = \frac{Z_A g_0}{g_4}\left(1 + \frac{1}{\alpha g_3 g_4}\right) = 50\left(1 + \frac{1}{0.8794}\right) = 106.85\ \Omega$$

$$Z_{1,2} = Z_A\left(1 + \alpha g_0 g_1\right) = 50\left(1 + 0.8794\right) = 93.97\ \Omega$$

$$Z_{2,3} = \frac{Z_A g_0}{g_4}\left(1 + \alpha g_3 g_4\right) = 50\left(1 + 0.8794\right) = 93.97\ \Omega$$

Example
- Bandstop Filters with Open-Circuited Stubs



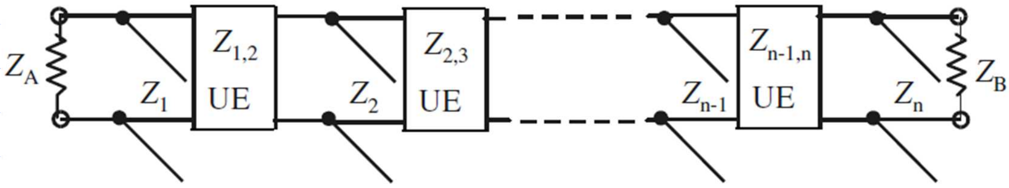


The microstrip is designed on a substrate with a dielectric constant of 6.15 and a thickness of 1.27 mm

- Note:
  1. The open-end and T-junction effects should also be taken into account for determining the final filter dimensions.

Optimum Bandstop Filters

➢ General structure – the same as the previous one



➢ Characteristic of this filter

- The unit elements of the bandstop filter with open-circuited stub are redundant and their filtering properties are not utilized.
- An optimum bandstop filter is realized by incorporating the unit elements in the design.
- Significantly steeper attenuation characteristics can be obtained for the same number of stubs than is possible for filters designed with redundant unit elements.
- A specified filter characteristic can be met with a more compact configuration using fewer stubs if the filter id designed by an optimum method.

Optimum Bandstop Filters

➢ The optimum bandstop filter is synthesized using optimum transfer function

$$|S_{21}(f)|^2 = \frac{1}{1+\varepsilon^2 F_N^2(f)} \quad \text{where} \quad F_N(f) = T_n\left(\frac{t}{t_c}\right) T_{n-1}\left(\frac{t\sqrt{1-t_c^2}}{t_c\sqrt{1-t^2}}\right) - U_n\left(\frac{t}{t_c}\right) U_{n-1}\left(\frac{t\sqrt{1-t_c^2}}{t_c\sqrt{1-t^2}}\right)$$

$$t = j\tan\left(\frac{\pi}{2}\frac{f}{f_0}\right)$$

$$t_c = j\tan\left(\frac{\pi}{4}(2-FBW)\right)$$

$T_n(x) = \cos(n\cos^{-1}x)$ Chebyshev functions of first kinds order n

$U_n(x) = \sin(n\cos^{-1}x)$ Chebyshev functions of second kinds order n

TABLE 6.3 Element values of optimum bandstop filters for $n = 3$ and $\varepsilon = 0.1005$

FBW	$g_1 = g_3$	g_2	$J_{1,2} = J_{2,3}$
0.3	0.16318	0.26768	0.97734
0.4	0.23016	0.38061	0.92975
0.5	0.37754	0.63292	0.83956
0.6	0.46895	0.79494	0.78565
0.7	0.56896	0.97488	0.73139
0.8	0.67986	1.17702	0.67677
0.9	0.80477	1.40708	0.62180
1.0	0.94806	1.67311	0.56648
1.1	1.11601	1.98667	0.51082
1.2	1.15215	2.06604	0.49407
1.3	1.37952	2.49473	0.43430
1.4	1.67476	3.05136	0.37349
1.5	2.07059	3.79862	0.31262

- The impedance of the bandstop filter

$$Z_A = Z_B = Z_0$$
$$Z_i = Z_0/g_i$$
$$Z_{i,i+1} = Z_0/J_{i,i+1}$$

- Element values of the network from two to six stubs are tabulated in Table 6.2 to 6.6 for bandwidth between 30 % and 150 %.

Example
- Optimum Bandstop Filters

- Design an optimum microstrip bandstop filter with three open-circuited stubs and $FBW = 1.0$ at a midband frequency $f_0 = 2.5$ GHz. Assume a passband return loss of -20 dB, which corresponds to a ripple constant $\varepsilon = 0.1005$. Choosing $Z_0 = 50$ ohm.
  - Step 1 – Find out the required information for design of a filter

TABLE 6.3 Element values of optimum bandstop filters for $n = 3$ and $\varepsilon = 0.1005$

FBW	$g_1 = g_3$	g_2	$J_{1,2} = J_{2,3}$
0.3	0.16318	0.26768	0.97734
0.4	0.23016	0.38061	0.92975
0.5	0.37754	0.63292	0.83956
0.6	0.46895	0.79494	0.78565
0.7	0.56896	0.97488	0.73139
0.8	0.67986	1.17702	0.67677
0.9	0.80477	1.40708	0.62180
1.0	0.94806	1.67311	0.56648
1.1	1.11601	1.98667	0.51082
1.2	1.15215	2.06604	0.49407
1.3	1.37952	2.49473	0.43430
1.4	1.67476	3.05136	0.37349
1.5	2.07059	3.79862	0.31262

$$Z_A = Z_B = 50\ \Omega$$

$$Z_1 = Z_3 = \frac{Z_0}{g_1} = \frac{Z_0}{g_3} = 52.74\ \Omega$$

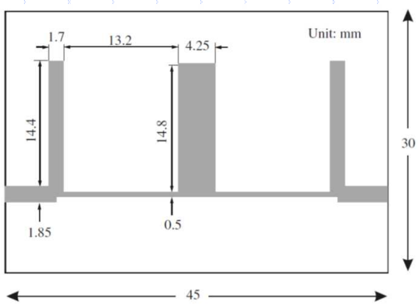
$$Z_2 = \frac{Z_0}{g_2} = 29.88\ \Omega$$

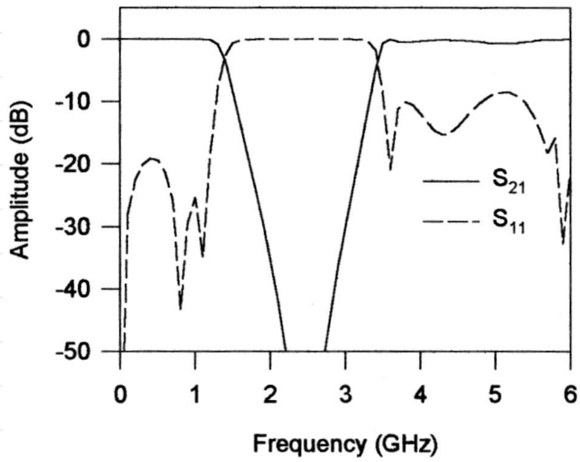
$$Z_{1,2} = Z_A\left(1+\alpha g_0 g_1\right) = 50\left(1+0.8794\right) = 93.97\ \Omega$$

Example
- Optimum Bandstop Filters

TABLE 6.7 Microstrip design parameters for a 3-pole optimum bandstop filter

Line impedance	W (mm)	$\lambda_{g0}/4$ (mm)
Z_1 and Z_3	1.7	14.32
Z_2	4.25	13.73
$Z_{1,2}$ and $Z_{2,3}$	0.528	14.89
Z_A and Z_B	1.85	





The microstrip is designed on a substrate with a dielectric constant of 6.15 and a thickness of 1.27 mm

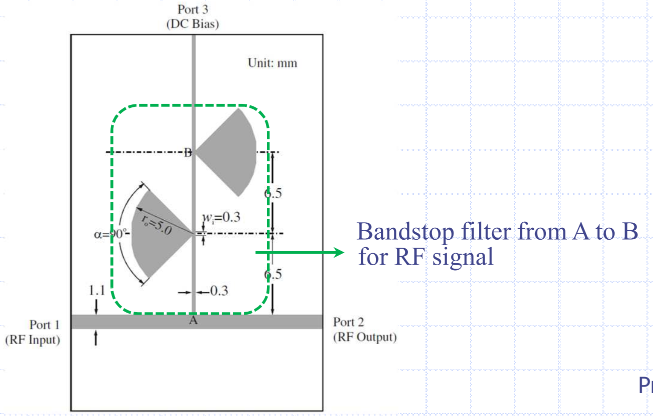
- Note:
  1. The open-end and T-junction effects should also be taken into account for determining the final filter dimensions.
  2. The optimum design demonstrates substantially improved performance with a steeper stopband response.

Bandstop Filters for RF Chokes

- Function of RF choke

  A bandstop filter should function efficiently in a bias network to choke off RF transmission over its stopband, while maintaining a perfect transmission for direct current.

- Basic bias network - Bias T
  1. A bias T is commonly used for feeding dc into active RF components in such a way that the RF behavior is not affected at all by the dc connection.
  2. Bandstop filters are more effective as RF chokes than lowpass filters due to the limited frequency band of RF active components.

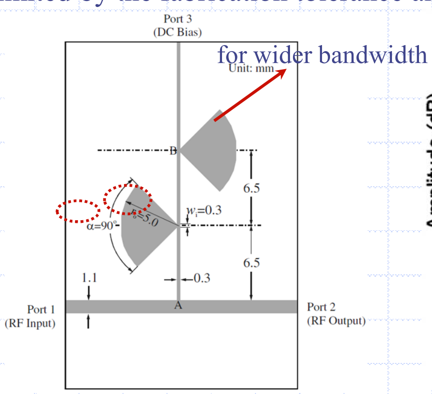


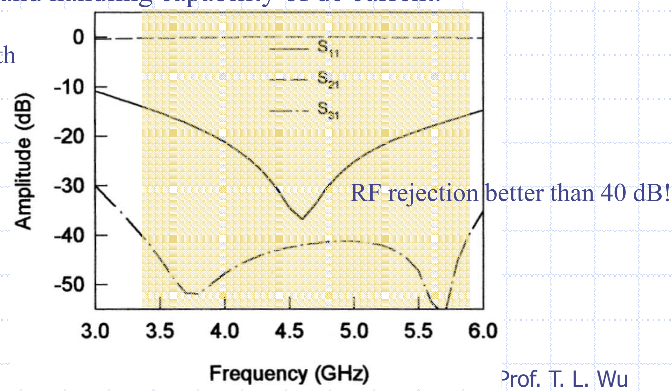
Bandstop Filters for RF Chokes

- Wider stopband

  Conventional quarter-wavelength stubs are replaced with radial stubs for having low impedance level in a wide frequency band.

- Design parameters on the BSF with radial stubs
  1. The radius r_o of a radial stub decide the center frequency of the stopband.
  2. The angle α of a radial stub affect the bandwidth.
  3. The width w_i can have effect on both the center frequency and the bandwidth.
  4. Narrow connecting line can have better performance as a RF choke, but the width is limited by the fabrication tolerance and handling capability of dc current.





The microstrip is designed on a substrate with a dielectric constant of 10.8 and a thickness of 1.27 mm

HW VI

1. Please design a bandstop filter (BSF) based on 3-order Chebyshev prototype with a passband ripple of 0.1 dB using L-shaped resonators. The center frequency is 3.5 GHz and the fractional bandwidth is $FBW = 0.1$. The properties of the substrate is $\varepsilon_r = 4.4$ and loss tangent of 0. The substrate thickness is 1.6 mm.
   a. Calculate the required design parameters (normalized reactance or susceptance slope parameters).
   b. Plot the return loss and insertion loss for the designed BSF with either shunt series-resonant branches or series parallel-resonant branches in ADS environment.
   c. Using the mentioned EM method in this lecture to find the required design parameter and list the chosen dimension.
   d. Plot the return loss and insertion loss for the designed BSF using EM solver.
   e. Discuss frequency responses from ADS and EM solver.

2. Design a BSF using open-circuited stubs based on a 3-order Chebyshev prototype with a passband ripple of 0.1 dB in center frequency 3.5 GHz and $FBW = 0.5$.
   a. Derive the design equations for n = 3 from lowpass filter prototype to the transmission line network with open-circuited stubs.
   b. According to the design equations, plot the return loss and insertion loss for the initial design of this BSF in EM solver. The material is identical to the previous problem.
   c. Consider the discontinuities of the BSF and compare the simulated results with the ones in problem (b).