Microstrip Notch Filter Design at 3.5 GHz for 5G

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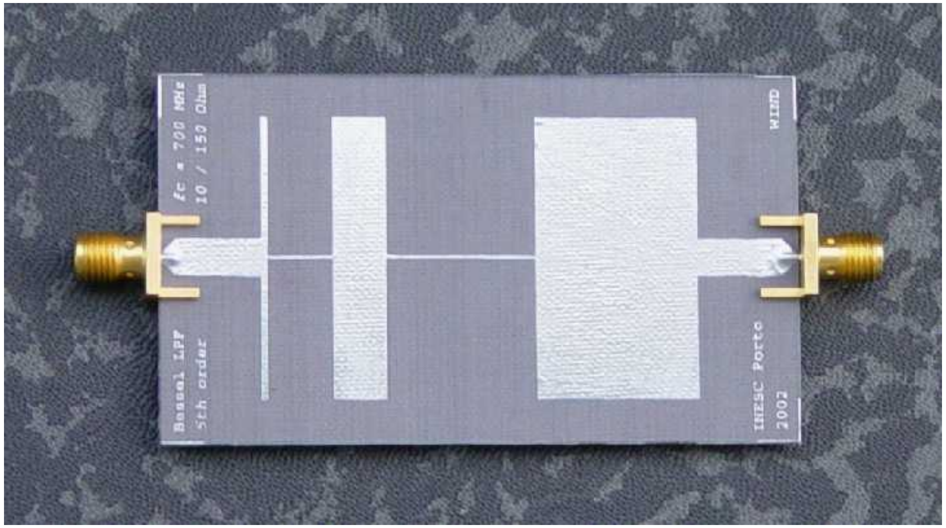
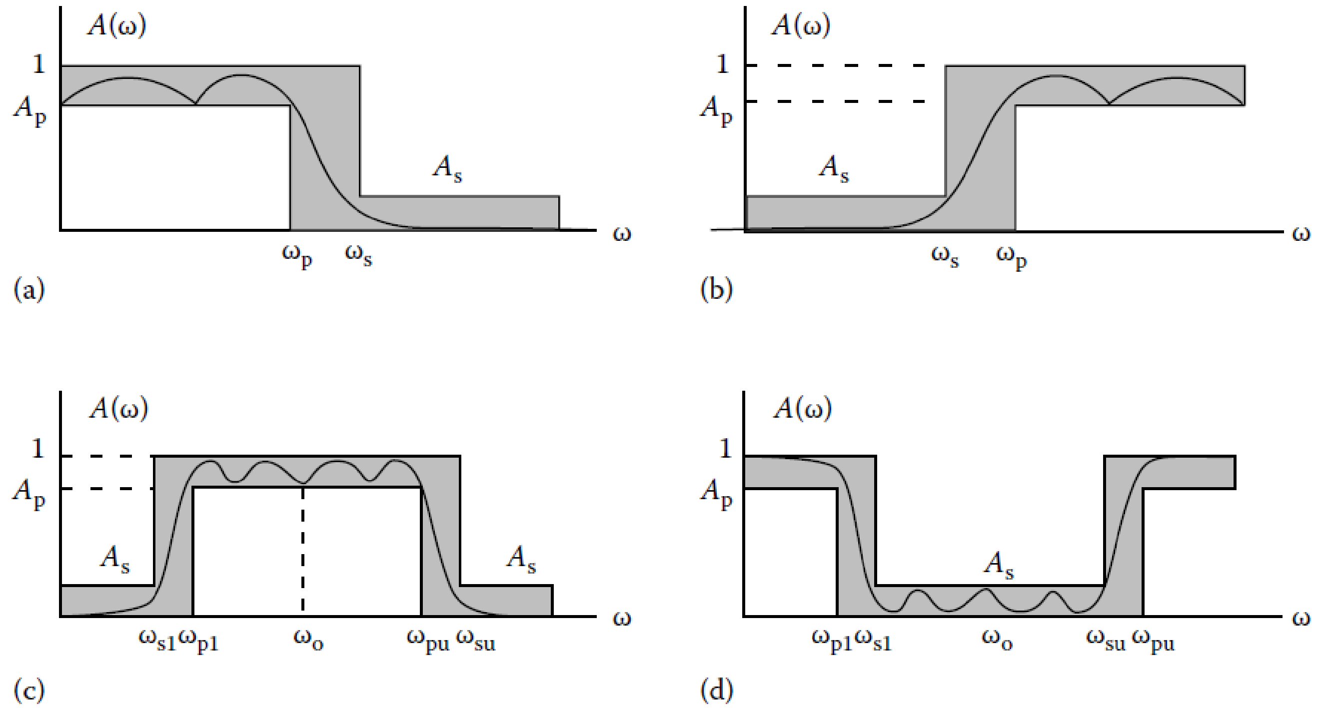
RF and Microwave Filters



- Radio frequency (RF) and microwave filters represent a class of electronic filters designed to work on signals in the megahertz to gigahertz frequency ranges.

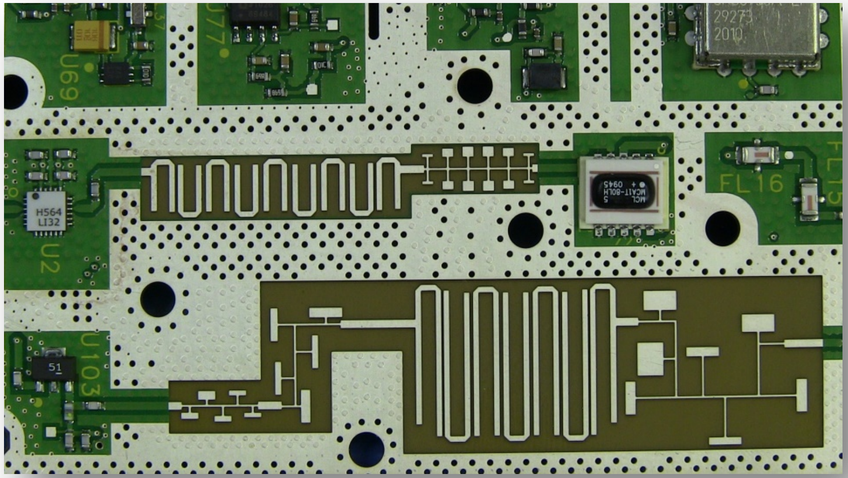
- These are passive circuit components that constitute basic building elements in many areas where RF / Microwave engineering applications are performed.



- Electrical filters are electronic circuits designed to pass signals in a certain band with low attenuation and to reject signals in other bands with high attenuation.

- RF / Microwave filters are electronic circuits designed using distributed parameter circuit modeling techniques to perform the same task at frequencies higher than 500 MHz.

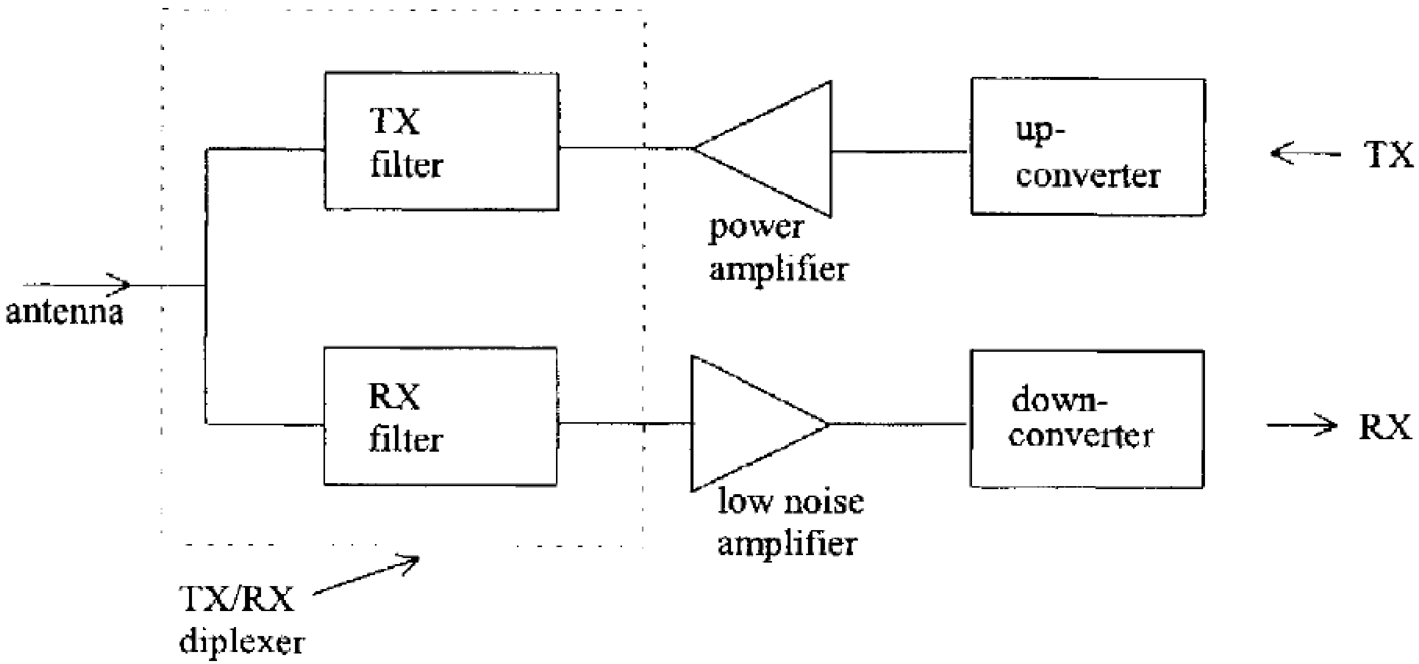
Application Areas of RF and Microwave Filters



- RF / Microwave filters are used in wireless communication, especially in GSM systems and satellite televisions, to civil-military radar applications.

- The use of filters in all systems based on cellular radio broadcasting becomes more critical as technology advances. While maintaining the same importance for 5G systems, it is predicted that filter circuits with higher operating frequency, more sensitive and selective requirements will be required, and more complex structures are expected.

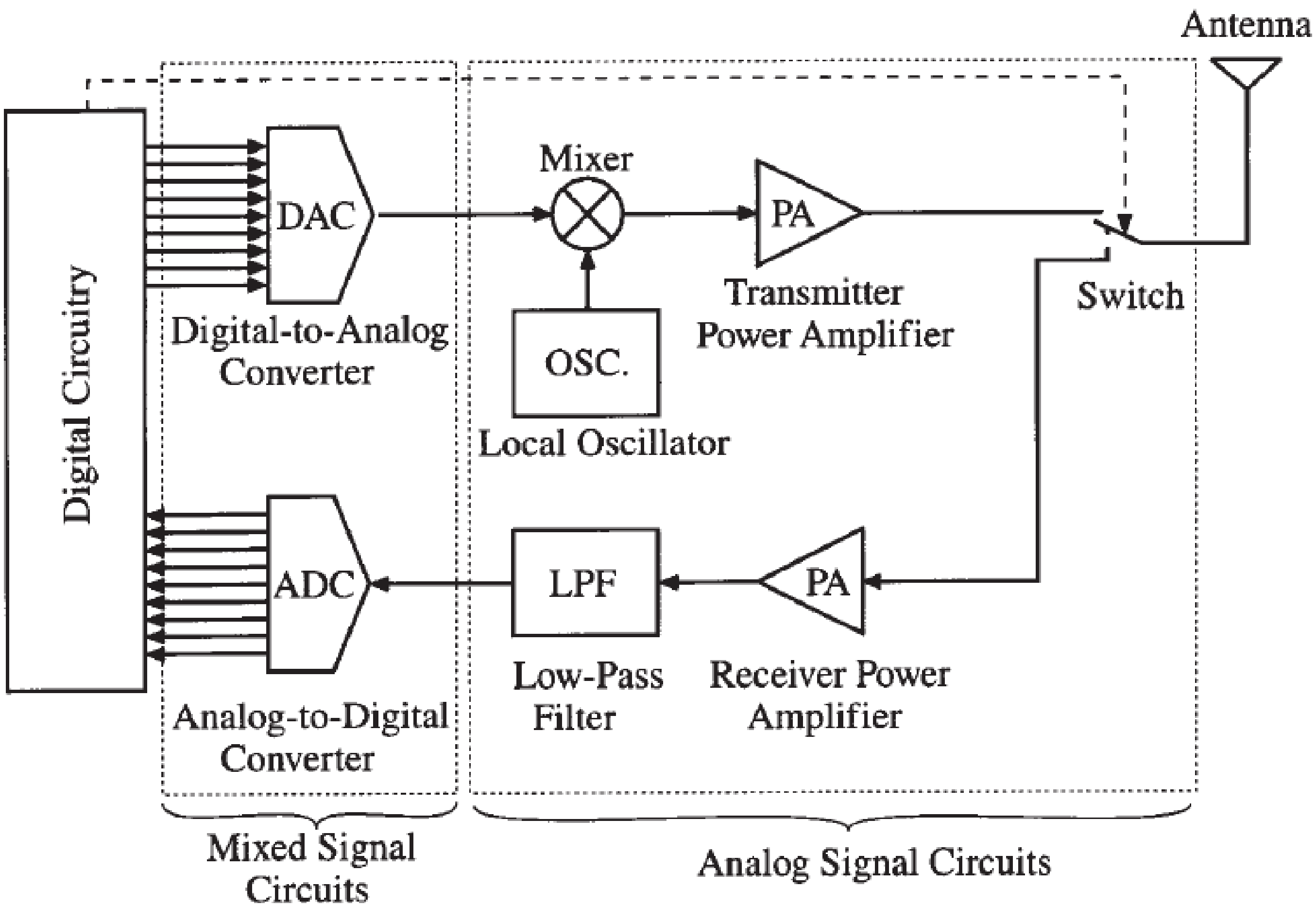
- A typical filter application is the RF front end block diagram of a cellular radio base station.



[Hunter IC. (2001) Theory and Design of Microwave Filters.]

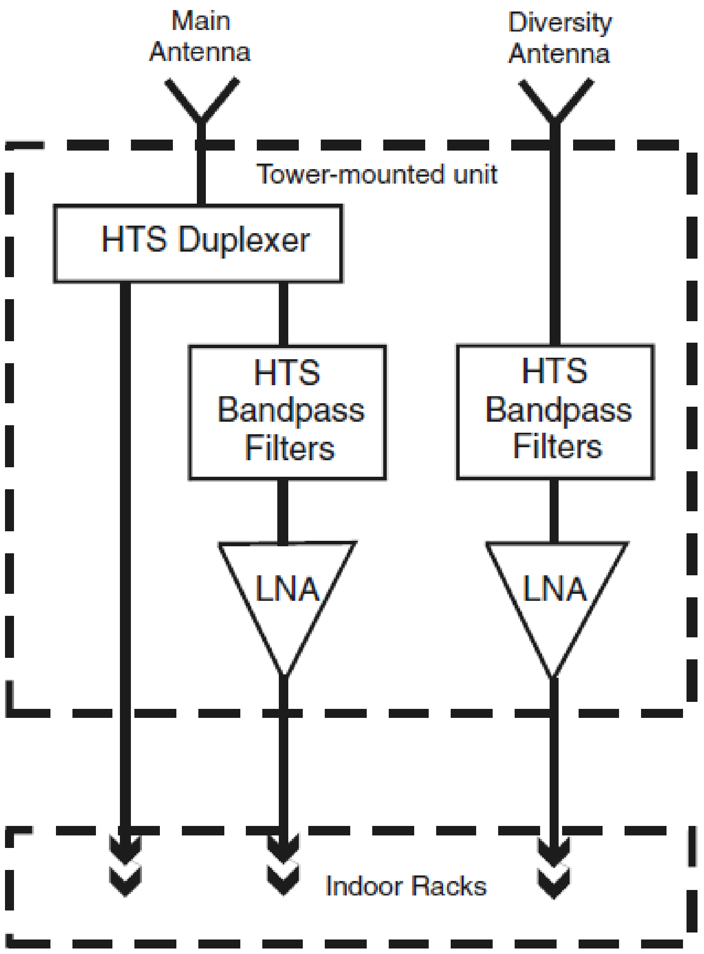
- Diplexer is a 3-port passive device that allows two different devices to share a common communication channel. It consists of two filters (low pass, high pass or band pass) with different operating frequencies connected to a single antenna.

- The transceiver structure, which is a typical application from mobile phone and wireless local area network systems, is given as a block diagram below.



[Ludwing R, Bretchko P. (2000) RF Circuit Design Theory and Applications.]

- The base station sector structure of a typical cellular mobile communication system using the HTS microstrip filter infrastructure is given below as a block diagram.



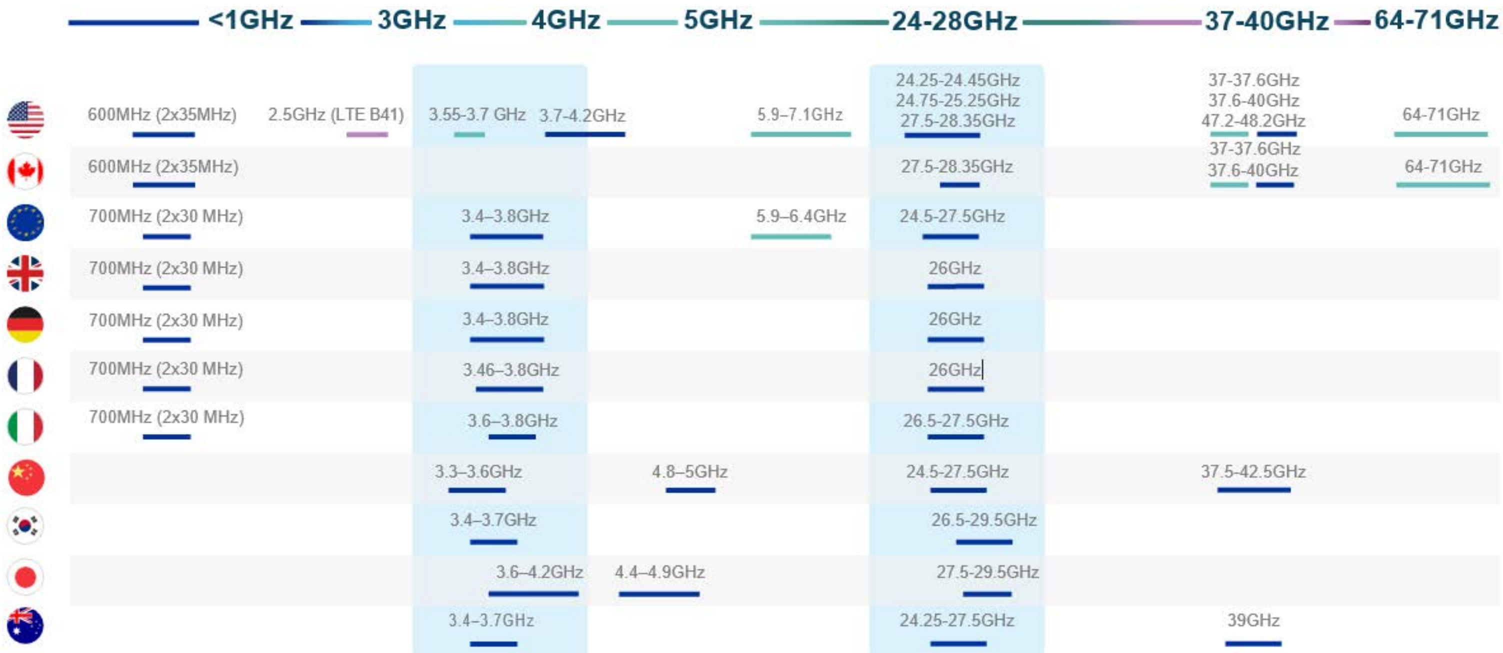
- The duplexer is a 3-port device that allows the transmitter and receiver to use a single antenna while operating at the same / similar frequencies. It is a device that allows two-way communication over a single channel by isolating the receiver from the transmitter while transmitting pulses and isolating the transmitter from the receiver while receiving the pulse, allowing them to share the same antenna. Here, the HTS duplexer consists of two band stop filters.

[Hong JS. (2011) Microstrip Filters for RF Microwave Applications.]

MICROSTRIP FILTERS

- Microstrip filters are classified among microwave filters; They stand out with their features such as high performance, smaller size, lighter and lower cost.
- Previously used rectangular waveguides had limited bandwidth and were expensive, making it difficult to use them in complex microwave systems requiring high power, by developing microstrip transmission lines such difficulties were overcome.
- Microstrip RF filters are generally used in transmitter and receiver circuits operating in the frequency range of 800 MHz - 30 GHz.

5G Targeted Spectrum Uses



This chart shows the targeted frequency bands for 5G deployment in different countries (as of February 2018). Many countries except some have specified low band spectrum (below 1 GHz) to support 5G. Most countries have specified mid-band spectrum (between 1 GHz and 6 GHz) and high band spectrum (above 6 GHz) for 5G use. Blue shading represents the locations of partnerships between countries in spectrum allocation, and ITU's decisions regarding the global harmony of the spectrum. Dark blue stripes; licensed, light blue lines; unlicensed shared, pink scratches; represents the available bands.

A Band Stop Microstrip Filter Design

$n=6$

Design Requirements

Passband ripple $0,05 \leq L_{Ar} \leq 3$ dB

Return loss $L_R = 11$ dB

Stopband attenuation $L_{As} = 32$ dB

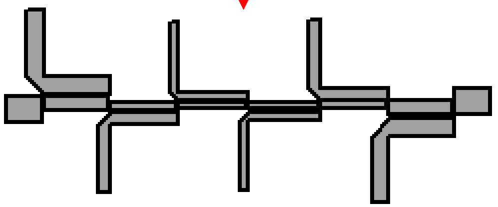
Passband frequency $f_o = 3,55$ GHz

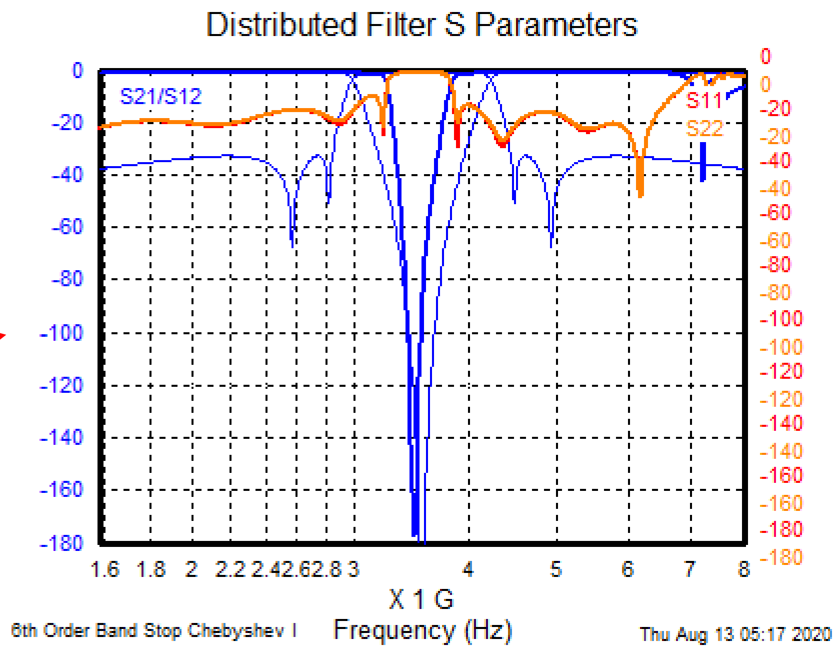
Stopband bandwidth $BW_s = 540$ MHz

Passband bandwidth $BW_p = 800$ MHz

Source and load impedance 50 Ω

Open ended L type Resonator model





Estimated circuit response

Chebyshev Prototype

n=6

Chebyshev approach was used for the Bandstop microstrip filter prototype.

1. Calculating the filter degree

$$N \geq \frac{L_{As} + L_R + 6}{20 \log\left[s + \sqrt{(s^2 - 1)}\right]}$$

$N \geq 5{,}96$, N=6

L_{As} : Minimum stopband attenuation. (32 dB)

L_r : Passband return loss. (11 dB)

s: selectivity [(BW_p)/(BW_s)]

$$s = \frac{BW_p}{BW_s} = \frac{800 \text{ MHz}}{540 \text{ MHz}} = 1{,}48$$

Chebyshev Prototype

n=13

2. Finding prototype filter element values

$$g_0 = 1.0$$

$$L_{Ar} = -10\log(1 - 10^{0.1L_R})$$

$$g_1 = \frac{2}{\gamma}\sin\left(\frac{\pi}{2n}\right)$$

$$g_i = \frac{1}{g_{i-1}} \frac{4\sin\left[\frac{(2i-1)\pi}{2n}\right]\sin\left[\frac{(2i-3)\pi}{2n}\right]}{\gamma^2 + \left(\sin\left[\frac{(i-1)\pi}{n}\right]\right)^2} \quad (i = 2, 3, \dots, n)$$

$$\beta = \ln\left[\coth\left(\frac{L_{Ar}}{17.37}\right)\right]$$

$$\gamma = \sinh\left(\frac{\beta}{2n}\right)$$

$$g_{n+1} = \begin{cases} 1.0 & n \text{ odd} \\ \coth^2\left(\frac{\beta}{4}\right) & n \text{ even} \end{cases}$$

Chebyshev Prototype

n=6

2. Finding prototype filter element values

$$g_0 = g_7 = 1.0$$

$$g_1 = \frac{2}{0{,}221}\sin\left(\frac{\pi}{12}\right) = 2{,}35$$

$$g_2 = \frac{1}{g_1}\frac{4\sin\left[\frac{3\pi}{12}\right]\sin\left[\frac{\pi}{12}\right]}{0{,}221^2 + \left(\sin\left[\frac{\pi}{6}\right]\right)^2} = 1{,}05$$

$$g_3 = \frac{1}{g_2}\frac{4\sin\left[\frac{5\pi}{12}\right]\sin\left[\frac{3\pi}{12}\right]}{0{,}221^2 + \left(\sin\left[\frac{2\pi}{6}\right]\right)^2} = 3{,}27$$

$$g_4 = \frac{1}{g_3}\frac{4\sin\left[\frac{7\pi}{12}\right]\sin\left[\frac{5\pi}{12}\right]}{0{,}221^2 + \left(\sin\left[\frac{3\pi}{6}\right]\right)^2} = 1{,}09$$

$$L_{Ar} = 1{,}25 \text{ dB}$$

$$\beta = 2{,}628334454$$

$$\gamma = 0{,}220783322$$

$$g_5 = \frac{1}{g_4}\frac{4\sin\left[\frac{9\pi}{12}\right]\sin\left[\frac{7\pi}{12}\right]}{1{,}114^2 + \left(\sin\left[\frac{4\pi}{6}\right]\right)^2} = 3{,}15$$

$$g_6 = g_8 = \frac{1}{g_5}\frac{4\sin\left[\frac{11\pi}{12}\right]\sin\left[\frac{9\pi}{12}\right]}{1{,}114^2 + \left(\sin\left[\frac{5\pi}{6}\right]\right)^2} = 0{,}78$$

Richard Transform

n=6

3. Application of Richard transformation of prototype filter element values

$$Z_{in} = jZ_0 \tan(\theta) = SZ_0$$

$$\theta = (\pi/3)(f/f_o)$$

$$S = j\tan(\theta)$$

Richard transformation coefficient.

Richar transformation is performed by taking the pass band lower corner frequency $f_{pL} = 3{,}15$GHz instead of f, and stopband lower corner frequency $f_{sL} = 3{,}28$GHz instead of f_o.

In this way, the richard transformation coefficient has been found.

S= j1,58

$$\lambda_0 = \frac{c}{f_o}$$

the length of the wave in the vacuum

$$\lambda_g = \frac{\lambda_0}{\sqrt{\varepsilon_{re}}}$$

guide wavelength

$$\beta = \frac{2\pi}{\lambda_g}$$

phase constant

electrical length → $\theta = \beta l = \frac{2\pi}{\lambda_g}\frac{\lambda_g}{6} = \frac{\pi}{3}$

Effective physical length

Applicable Filter Circuit

n=6

4. Prototype filter element conversion processes after Richard transform

The inductance and capacitance values of the applicable bandstop filter circuit were calculated by performing element transformation operations such as frequency scaling and impedance scaling on the low-pass prototype filter circuit elements with Richard transformation.

$$L_{pn} = \left(\frac{Z_0}{g_0}\right)\left(\frac{\Omega_c \varphi}{2\pi f_o}\right) g_n \qquad C_{pn} = \left(\frac{g_0}{Z_0}\right)\left(\frac{1}{\varphi 2\pi f_o \Omega_c}\right)\frac{1}{g_n}$$

$$L_{sn} = \left(\frac{Z_0}{g_0}\right)\left(\frac{1}{\varphi 2\pi f_o \Omega_c}\right)\frac{1}{g_n} \qquad C_{sn} = \left(\frac{g_0}{Z_0}\right)\left(\frac{\Omega_c \varphi}{2\pi f_o}\right) g_n$$

$$\varphi = \frac{f_{sH} - f_{sL}}{\sqrt{f_{sH} f_{sL}}}$$

Here φ is fractional bandwidth (FBW).

Applicable Filter Circuit

n=6

4. Prototype filter element conversion processes after Richard transform

n	Chebyshev g_n	Richard g_n	$L_{nn}\,(nH)$	$C_{nn}\,(pF)$	$Z_n\,(\Omega)$	W_n (mm)	l_n (mm)
1	2,3445525	3,697554	3,9854	0,5073	88,640	1,029	13,073
2	1,0451538	1,648294	0,5653	3,5762	12,573	20,98	9,501
3	3,2726552	5,161249	2,85523	0,7081	63,502	2,321	12,122
4	1,0873698	1,714873	0,58814	3,4374	13,081	19,99	9,539
5	3,1455978	4,960869	2,97056	0,68056	66,067	2,132	12,231
6	0,7789992	1,228546	0,42135	4,79805	9,3710	29,87	9,368

Not Applicable

Applicable Filter Circuit

n=6

4. Prototype filter element conversion processes after Richard transform

The high-pass filter response graph in the complex frequency plane can be transformed into a response graph to both the high-pass and band-pass filter in the Richard transform plane. Therefore, the inductance and capacitance values of the applicable Highpass circuit were calculated by performing element transformation operations such as frequency scaling and impedance scaling on the high pass prototype filter element values.

$$L_n = \left(\frac{Z_0}{g_0}\right)\left(\frac{\Omega_c}{2\pi f_c}\right) g_n \qquad C_n = \left(\frac{g_0}{Z_0}\right)\left(\frac{\Omega_c}{2\pi f_c}\right) g_n$$

In the next step, the inductive and capacitive reactance values of the coils and capacitors in the applicable YGMF equivalent circuit model were calculated by substituting these inductance and capacitance values in the following equations.

$$\omega = 2\pi f_o = 2\pi \times 3{,}55 \times 10^9 \qquad X_C(\omega) = \frac{1}{C\omega}\ (\Omega) \qquad X_L(\omega) = L\omega\ (\Omega)$$

Applicable Filter Circuit

n=6

4. Physical dimensions of distributed parameter circuit elements

- Microstrip line widths of the distributed parameter circuit elements whose characteristic impedances, Z_c (Z_0), is found by using the equations given below:

Rogers RT/duroid® 5880 $\varepsilon_r = 2.2$ $h = 1.27$ mm $t = 0{,}018$ mm $\tan\delta = 0{,}0027$

$$W/h = \begin{cases} \dfrac{8e^{A}}{e^{2A}-2} & h/W < 2 \\ \dfrac{2}{\pi}\left[B - 1 - \ln(2B-1) + \dfrac{\varepsilon_r - 1}{2\varepsilon_r}\left\{\ln(B-1) + 0.39 - \dfrac{0.61}{\varepsilon_r}\right\}\right] & h/W > 2 \end{cases}$$

$$A = \frac{Z_0}{60}\sqrt{\frac{\varepsilon_r + 1}{2}} + \frac{\varepsilon_r - 1}{\varepsilon_r + 1}\left(0.23 + \frac{0.11}{\varepsilon_r}\right) \qquad B = \frac{377\pi}{2.Z_c\sqrt{\varepsilon_r}}$$

Applicable Filter Circuit

$n=6$

4. Physical dimensions of distributed parameter circuit elements

After the microstrip line width is calculated, the characteristic impedance of a line of this width is calculated using the equations below, and it is made according to the proximity of the applicable bandstop filter elements to the impedance values.

$$Z_0 = \begin{cases} \dfrac{60}{\sqrt{\varepsilon_e}} \ln\left(\dfrac{8h}{W} + \dfrac{W}{4h}\right) & W/h \le 1 \\ \dfrac{120\pi}{\sqrt{\varepsilon_e\left[W/h + 1.393 + 0.667\ln\left(W/h + 1.444\right)\right]}} & W/h \ge 1 \end{cases}$$

$$\varepsilon_e = \frac{\varepsilon_r + 1}{2} + \frac{\varepsilon_r - 1}{2} \frac{1}{\sqrt{1 + 12\left(h/W\right)}}$$

Applicable Filter Circuit

n=6

4. Physical dimensions of distributed parameter circuit elements

$$W/h = u$$

$$\varepsilon_{re} = \frac{\varepsilon_r + 1}{2} + \frac{\varepsilon_r - 1}{2}\left(1 + \frac{10}{u}\right)^{-ab}$$

the accuracy of the equations is %2, under these circumstances $\varepsilon_r \leq 128$ and $0.01 \leq u \leq 100$.

$$\eta = 120\pi\ \Omega$$

$$a = 1 + \frac{1}{49}\ln\left(\frac{u^4 + \left(\frac{u}{52}\right)^2}{u^4 + 0.432}\right) + \frac{1}{18.7}\ln\left[1 + \left(\frac{u}{18.1}\right)^3\right]$$

$$b = 0.564\left(\frac{\varepsilon_r - 0.9}{\varepsilon_r + 3}\right)^{0.053}$$

$$Z_c = \frac{\eta}{2\pi\sqrt{\varepsilon_{re}}}\ln\left(\frac{F}{u} + \sqrt{1 + \left(\frac{2}{u}\right)^2}\right)$$

$$F = 6 + (2\pi - 6)exp\left(-\left(\frac{30.666}{u}\right)^{0.7528}\right)$$

Rogers RT/duroid® 5880 $\varepsilon_r = 2.2$ $h = 1.27$ mm $t = 0{,}018$ mm $\tan\delta = 0{,}0027$

Applicable Filter Circuit

n=6

4. Physical dimensions of distributed parameter circuit elements

While the physical lengths of microstrip line discontinuities are found, first of all, the relative operating frequency for the microstrip filter is taken as following: $f_o' = 4{,}85$ GHz

$f_o' \cong f_o + (BW_p + BW_s)$

λ_0 is found via the following $\lambda_0 = \frac{c}{f_0}$

Effective dielectric constant of the each microstrip discontinuity is found depend on W/h and ε_r: λ_0 ve ε_{re}

These are put into the following $\lambda_g = \frac{\lambda_0}{\sqrt{\varepsilon_{re}}}$ for finding λ_g

Then λ_g is put into the equaition given below:

$$\beta = \frac{2\pi}{\lambda_g}$$

for getting phase constant β.

Applicable Filter Circuit

n=6

4. Physical dimensions of distributed parameter circuit elements

While the applicable bandstop filter is realized with microstrip discontinuities the electrical lengths of all elements taken as:

$$\theta = (\pi)(f/f_o)$$

and their effective physical lengths, are calculated one by one for each microstrip line discontinuity element from the following equation:

$$\theta = \beta l$$

Here, $f = f_{sL} = 3{,}15$ GHz is stopband low corner frequency,

$f_o = f_{pL} = 3{,}28$ GHz is passband low corner frequency.

Applicable Filter Circuit

n=6

4. Physical dimensions of distributed parameter circuit elements

Due to the fraying effect, the electrical lengths of the microstrip structures behave like longer lines at the cut frequency than their physical dimensions. Therefore the applicable physical lengths of microstrip lines are calculated via:

$$L = L_{eff} - 2\Delta L$$

Here,

$$\Delta L = (0{,}412h)\frac{(\varepsilon_{re} + 0{,}3)\left(\frac{W}{h} + 0{,}264\right)}{(\varepsilon_{re} - 0{,}258)\left(\frac{W}{h} + 0{,}8\right)}$$

is calculated via given formula.

Applicable Filter Circuit

n=6

4. Physical dimensions of distributed parameter circuit elements

n	Chebyshev g_n	Richard g_n	$L_n(nH)$	$C_n(pF)$	$Z_n(\Omega)$	W_n(mm)	l_n(mm)
1	2,3445525	3,697554		3,923	13,523	19,201	9,65
2	1,0451538	1,648294	4,372		82,415	1,256	13,086
3	3,2726552	5,161249		5,476	9,688	28,714	9,510
4	1,0873698	1,714873	4,549		85,744	1,130	13,202
5	3,1455978	4,960869		5,264	10,079	27,389	9,546
6	0,7789992	1,228546	3,259		61,427	2,487	12,253

In order for the low pass filter response to give BDMF response with Richard transform, the electrical lengths of the elements are taken to give half wavelength.

Applicable Filter Circuit

n=6

Frequency scaling and filter behaviors according to Richard transform

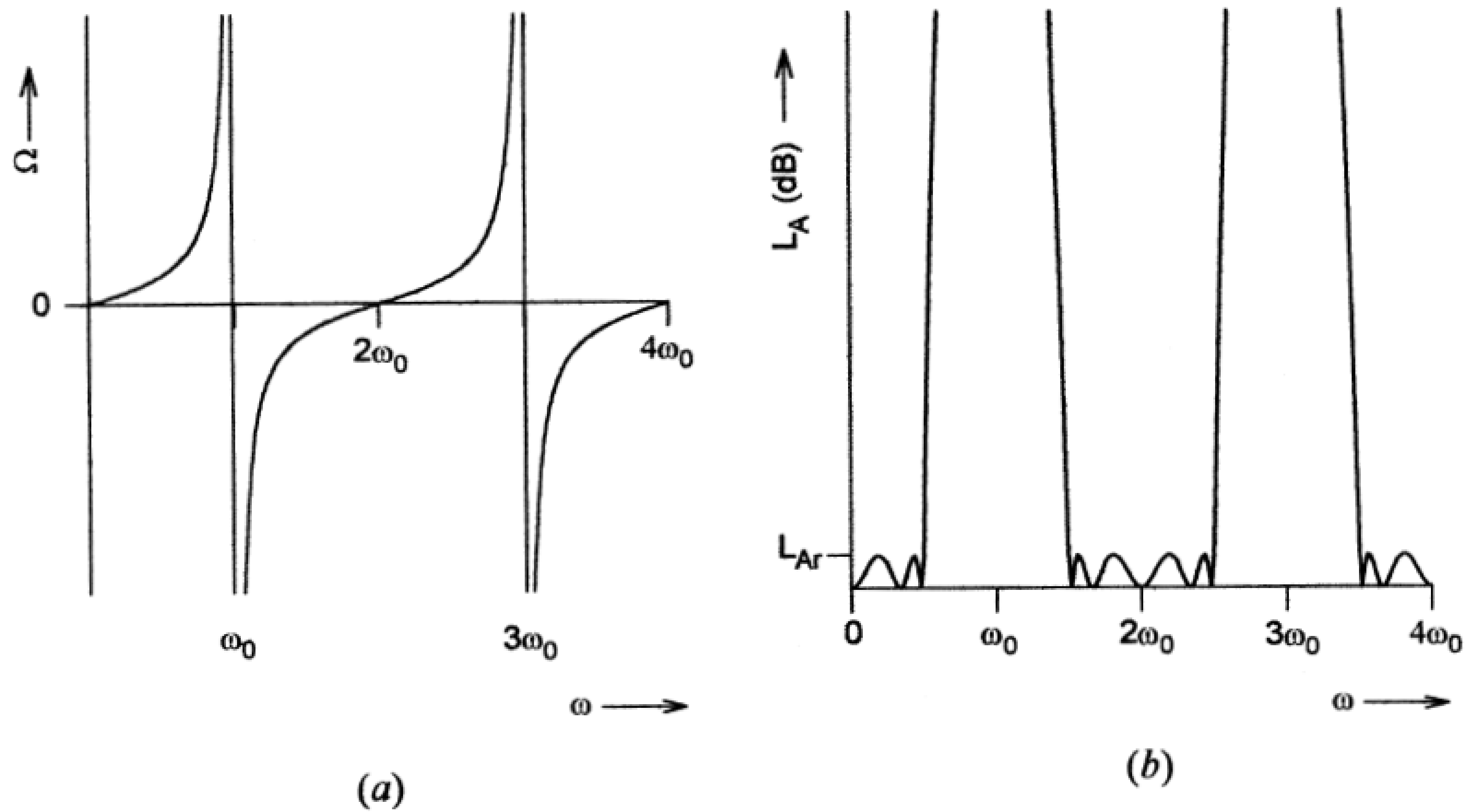


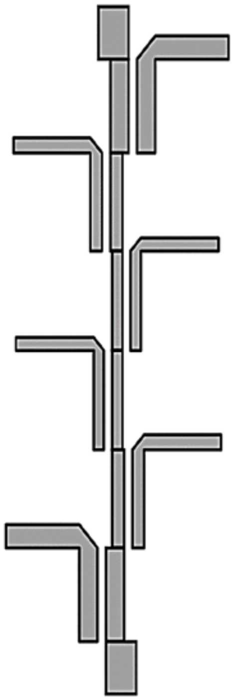
FIGURE 3.23 (a) Frequency mapping between real frequency variable ω and distributed frequency variable Ω. (b) Chebyshev lowpass response using the Richards' transformation.

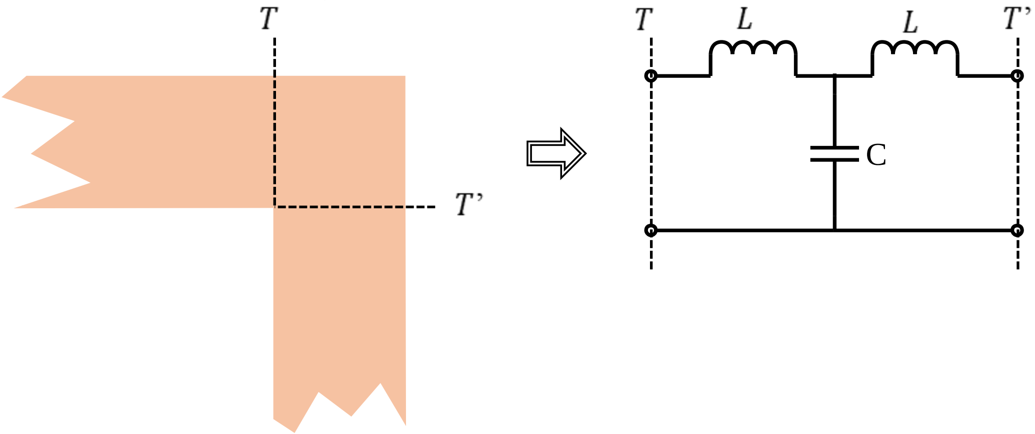
Applicable Filter Circuit

n=6

5. Design layout of bandstop filter elements

The bandstop filter circuit is designed in accordance with the microstrip notch filter model, which consists of coupled microstrip discontinuities and open-ended L-type resonator stages.





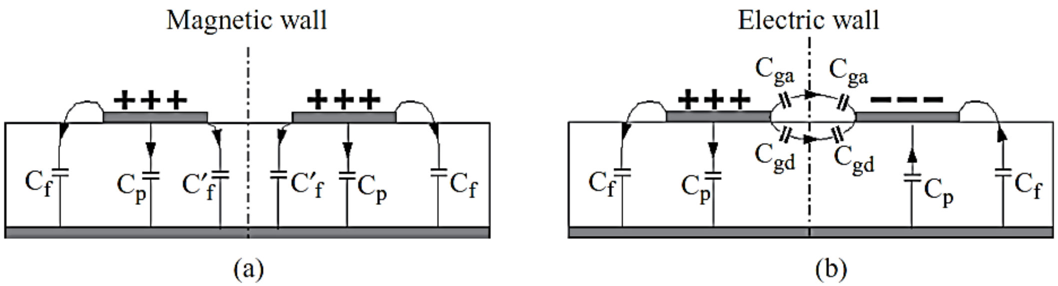


FIGURE 4.3 Quasi-TEM modes of a pair of coupled microstrip lines. (**a**) Even mode; (**b**) odd mode.

Applicable Filter Circuit

n=6

5. Design layout of bandstop filter elements

$$C_e = C_p + C_f + C_f'$$

$$C_o = C_p + C_f + C_{ga} + C_{gd}$$

$$C_p = \varepsilon_0 \varepsilon_r \left(\frac{W}{h}\right)$$

$$2C_f = [\sqrt{\varepsilon_{re}}/(cZ_c)] - C_p$$

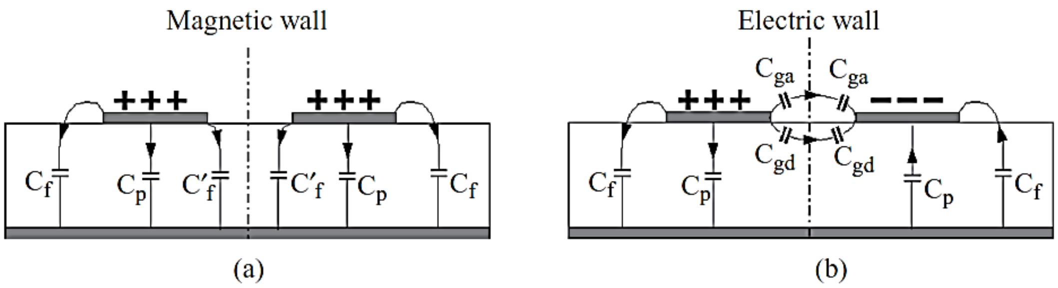


FIGURE 4.3 Quasi-TEM modes of a pair of coupled microstrip lines. (**a**) Even mode; (**b**) odd mode.

$$C_f' = \frac{C_f}{1 + A\left(\frac{h}{s}\right)\tanh\left(\frac{8s}{h}\right)}$$

$$A = exp\left[-0{,}1exp\left(2{,}33 - 2{,}53\left(\frac{W}{h}\right)\right)\right]$$

$$\frac{K(k')}{K(k)} = \begin{cases} \frac{1}{\pi}\ln\left(2\frac{1+\sqrt{k'}}{1-\sqrt{k'}}\right) & 0 \le k^2 \le 0{,}5 \\ \frac{\pi}{\ln\left(2\frac{1+\sqrt{k}}{1-\sqrt{k}}\right)} & 0{,}5 \le k^2 \le 1 \end{cases}$$

$$C_{ga} = \varepsilon_0 \frac{K(k')}{K(k)}$$

$$k = \frac{\left(s/_h\right)}{\left(s/_h\right) + 2\left(W/_h\right)}$$

$$k' = \sqrt{1-k^2}$$

$$C_{gd} = \frac{\varepsilon_0 \varepsilon_r}{\pi}\ln\left[\coth\left(\frac{\pi s}{4h}\right)\right] + 0{,}65C_f\left(\frac{0{,}2\sqrt{\varepsilon_r}}{s/_h}\right) + 1 - \frac{1}{{\varepsilon_r}^2}$$

Applicable Filter Circuit

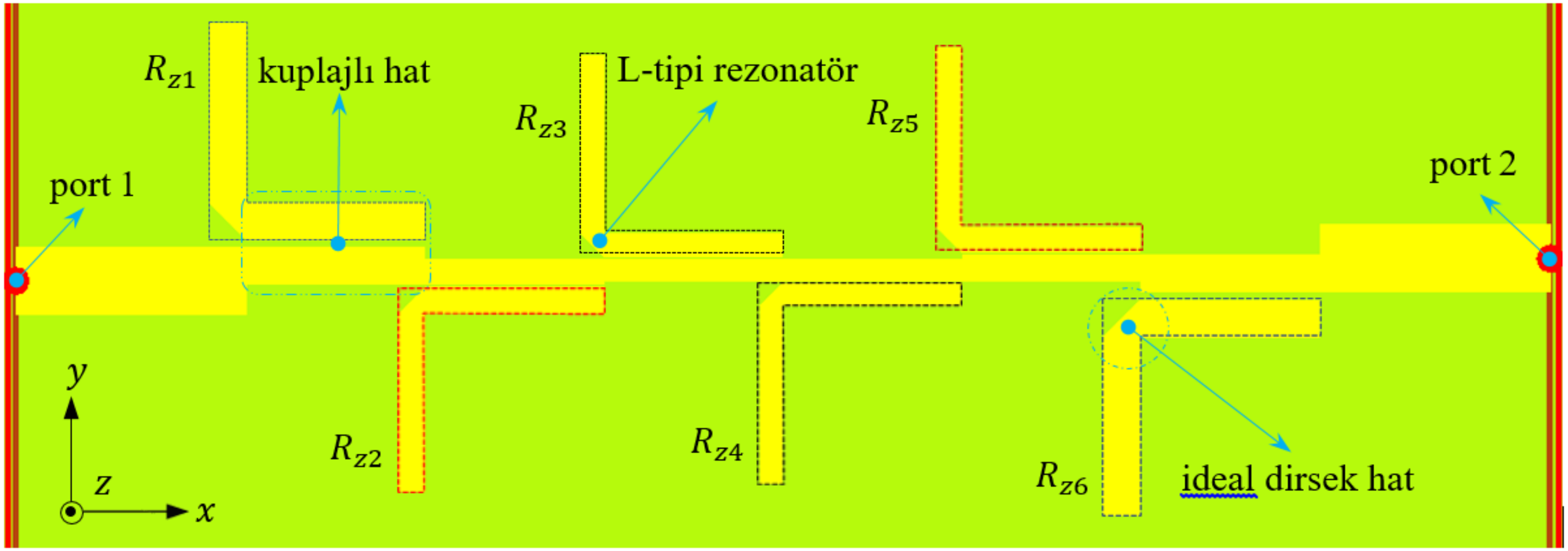
n=13

5. Design layout of bandstop filter elements

The widths of the gaps between coupled microstrip lines were approximated using the quasi-experimental formulas given on the previous page and modifications were made on them according to the simulation results.

L-type R_{z1} $s_1 = 0{,}3449\ mm$, R_{z2} $s_2 = 0{,}05\ m$, R_{z3} $s_3 = 0{,}05\ mm$.

$s_4 = s_3$, $s_5 = s_2$, $s_6 = s_1$

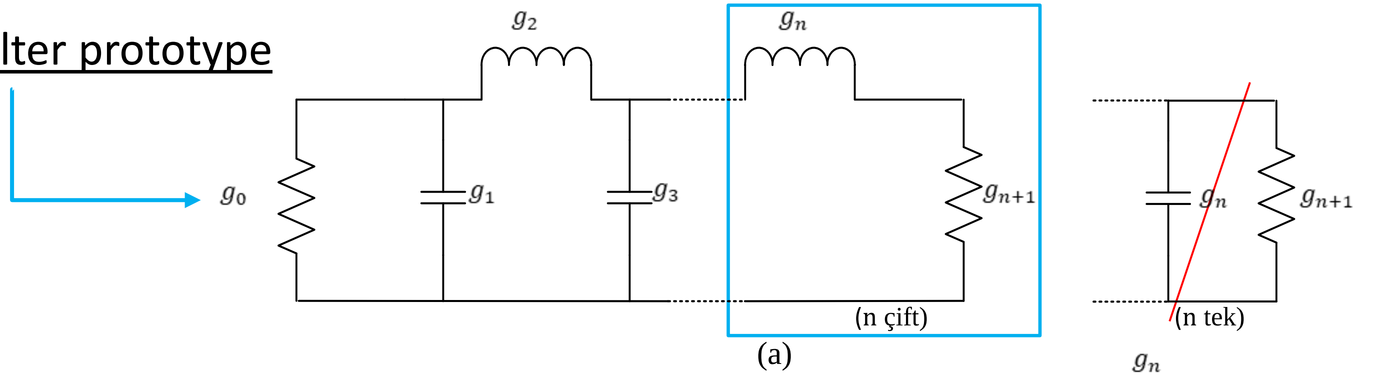


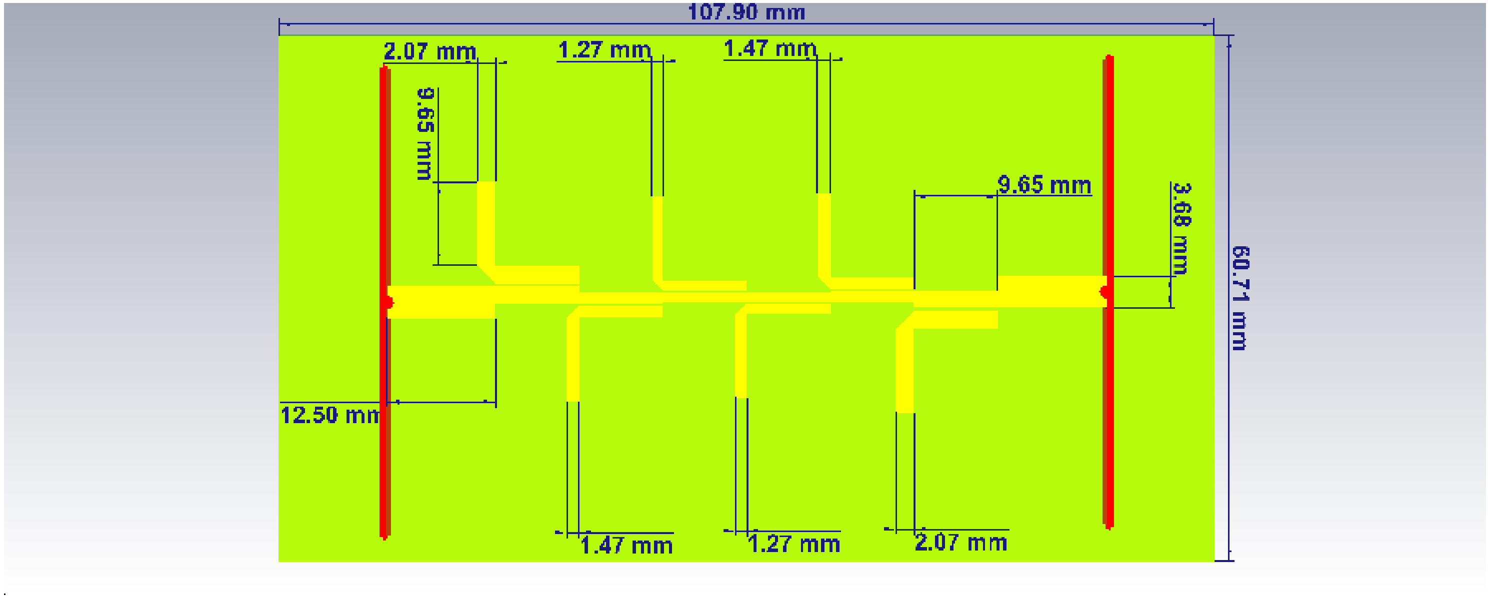
Applicable Filter Circuit

n=6

5. Design layout of bandstop filter elements

Lowpass Filter prototype





Applicable Filter Circuit

n=6

6. High frequency laminate for bandstop filter circuit

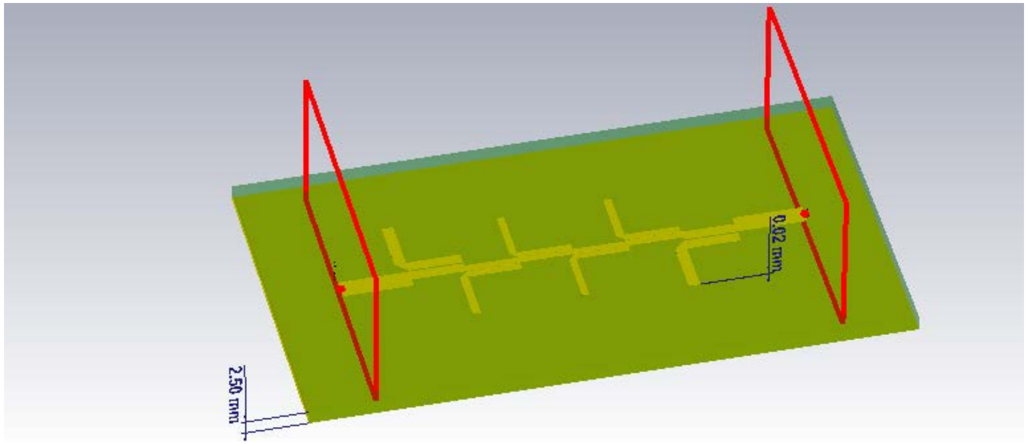
Rogers RT/duroid® 6006

$\varepsilon_r = 6{,}15$

$h = 2{,}5\ \mathrm{mm}$

$t = 0{,}018\ \mathrm{mm}$

$\tan\delta = 0{,}0027$

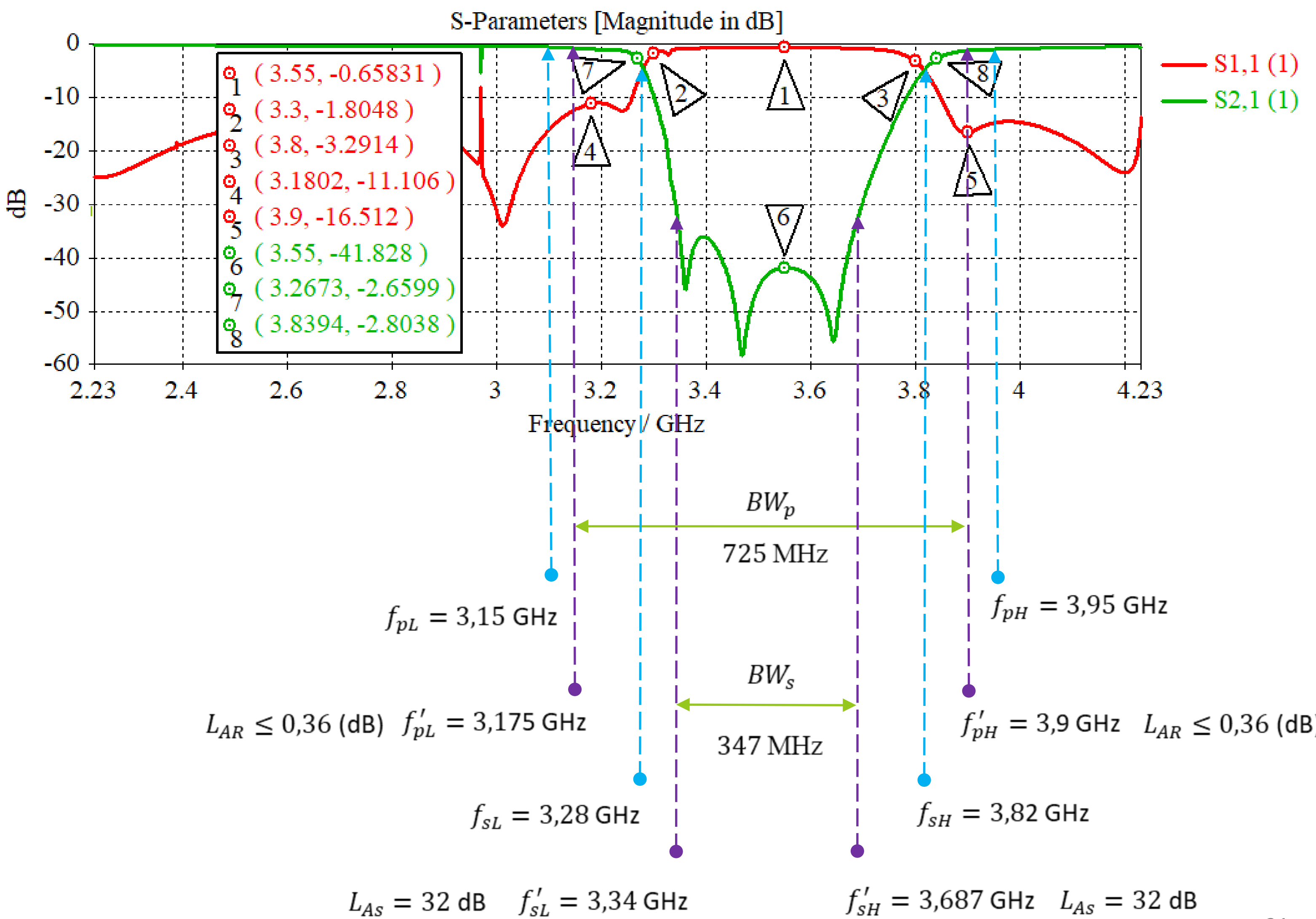


While selecting this material, features that make it possible to design microstrip lines according to TE_{01} basic mode were sought. Here, as the distance between neighboring resonators is more controllable, it is possible to avoid the undesired coupling effect between lines. However, an efficient coupling effect between resonators and the main line is desired. For this reason, it was prefered to choose a material with as large a dielectric constant as possible. In addition, since it is important for the quality factor to keep the surface current at minimum level in filter design, this material with a low value of the surface current loss tangent, loss tan δ as 0,0027 measured at 10 GHz/23°C was preferred.

Applicable Filter Circuit

n=6

7. Amplitude-frequency response of the bandstop microstrip notch filter



CONCLUSIONS

In this study, a bandstop microstrip notch filter that provides the design requirements at 3.4-3.7 GHz, one of the announced 5G frequency spectrum ranges, was designed. Within the scope of the article, the design steps are discussed in detail. The filter response was compared with the specified design requirements and as a result, it was observed that very close values were reached.

THANK YOU