April 2, 2019

Introduction to Surface Acoustic Wave (SAW) Devices

Part 4: Resonator-Based RF Filters

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Contents

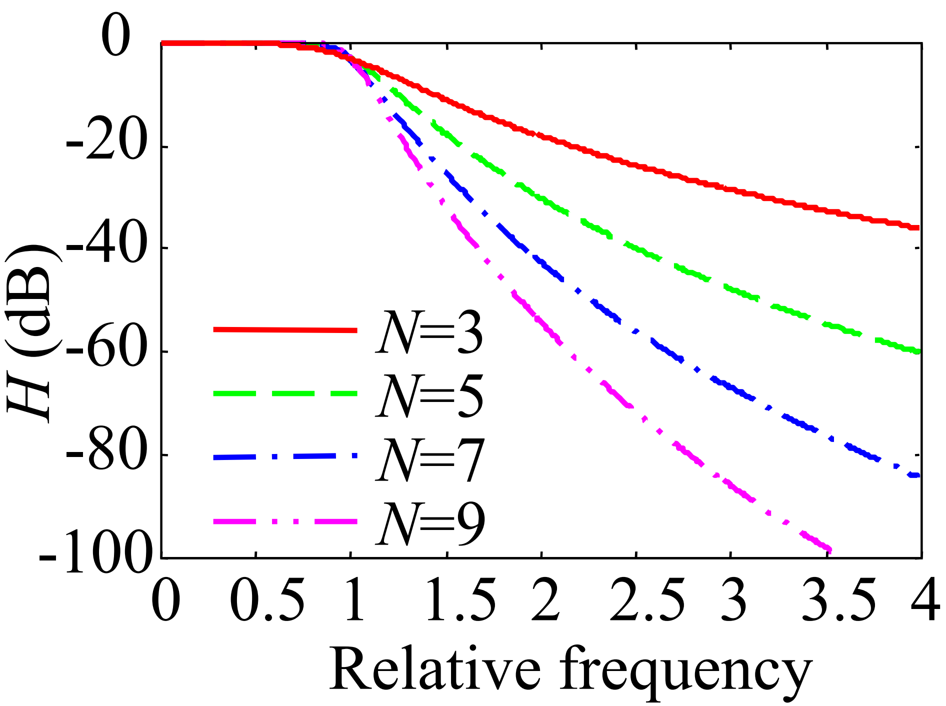
Contents

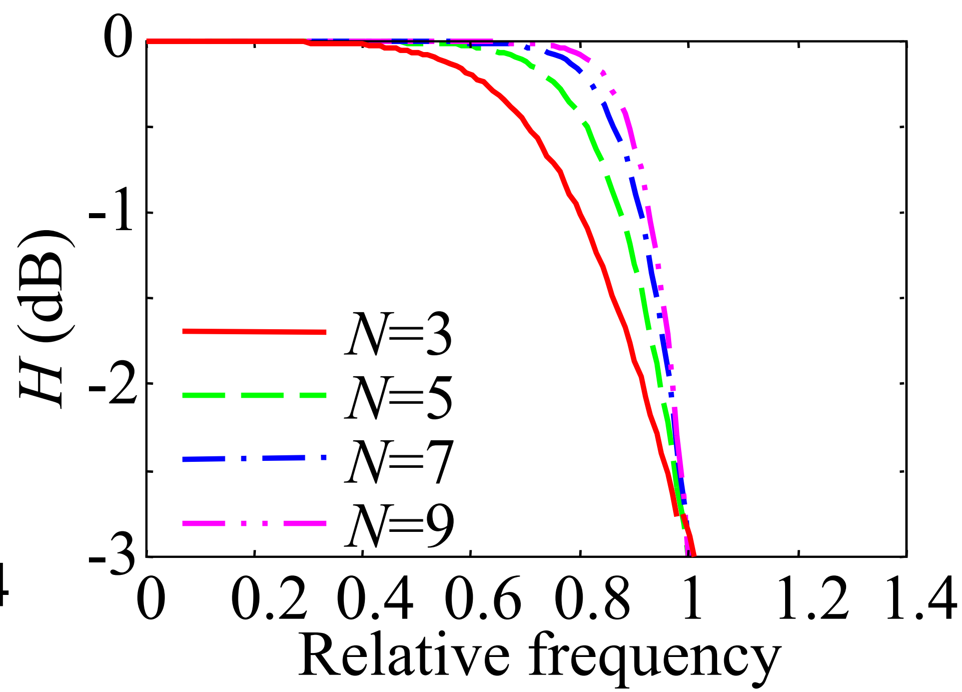
- Basic Filter Design

N-th Order Butterworth Filter

Maximally Flat Response: $H^{(n)}(0)=0$ for $n=1,2,\text{---}N$

$$\left|H(\omega)\right|^2 = \frac{1}{1+(\omega/\omega_0)^{2N}}$$





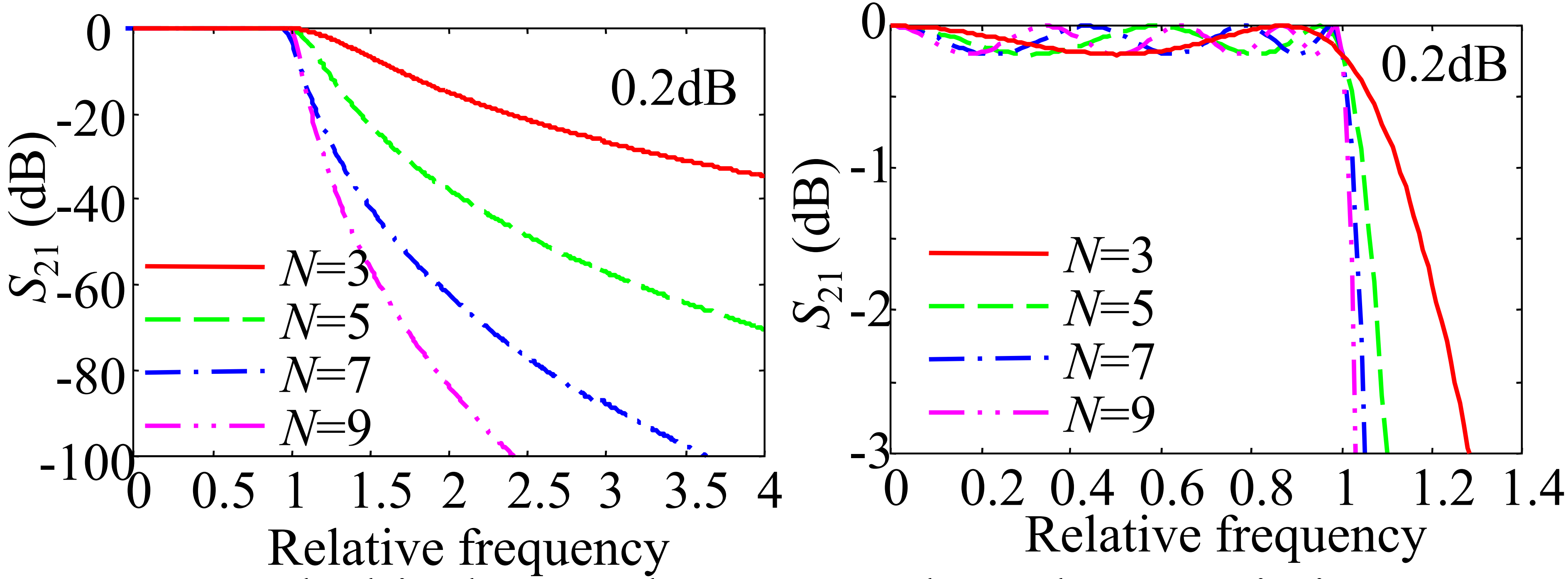
Gradual Skirt & Group Delay Characteristics

N-th Order Chebyshev Filter

Equal-Ripple Characteristics (ε: parameter)

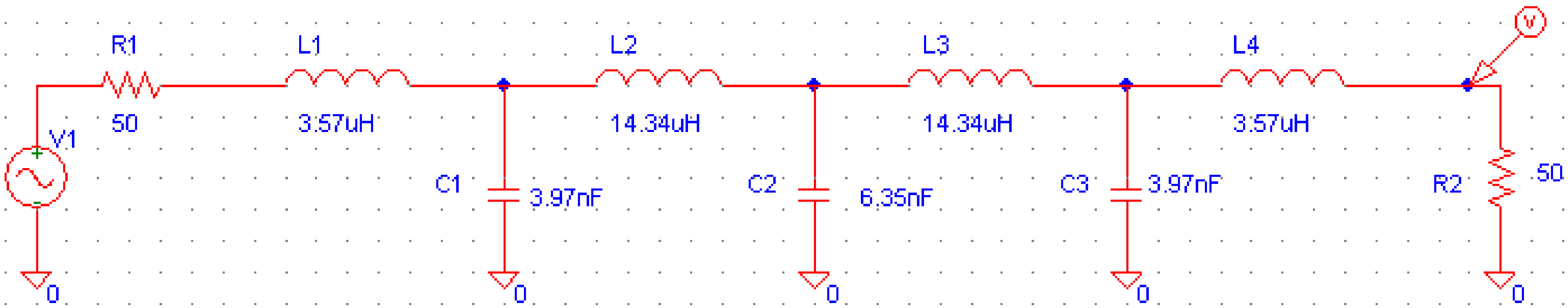
$$\left|H(\omega)\right|^2 = \frac{1}{1+\varepsilon^2 T_N(\omega/\omega_0)^2}$$

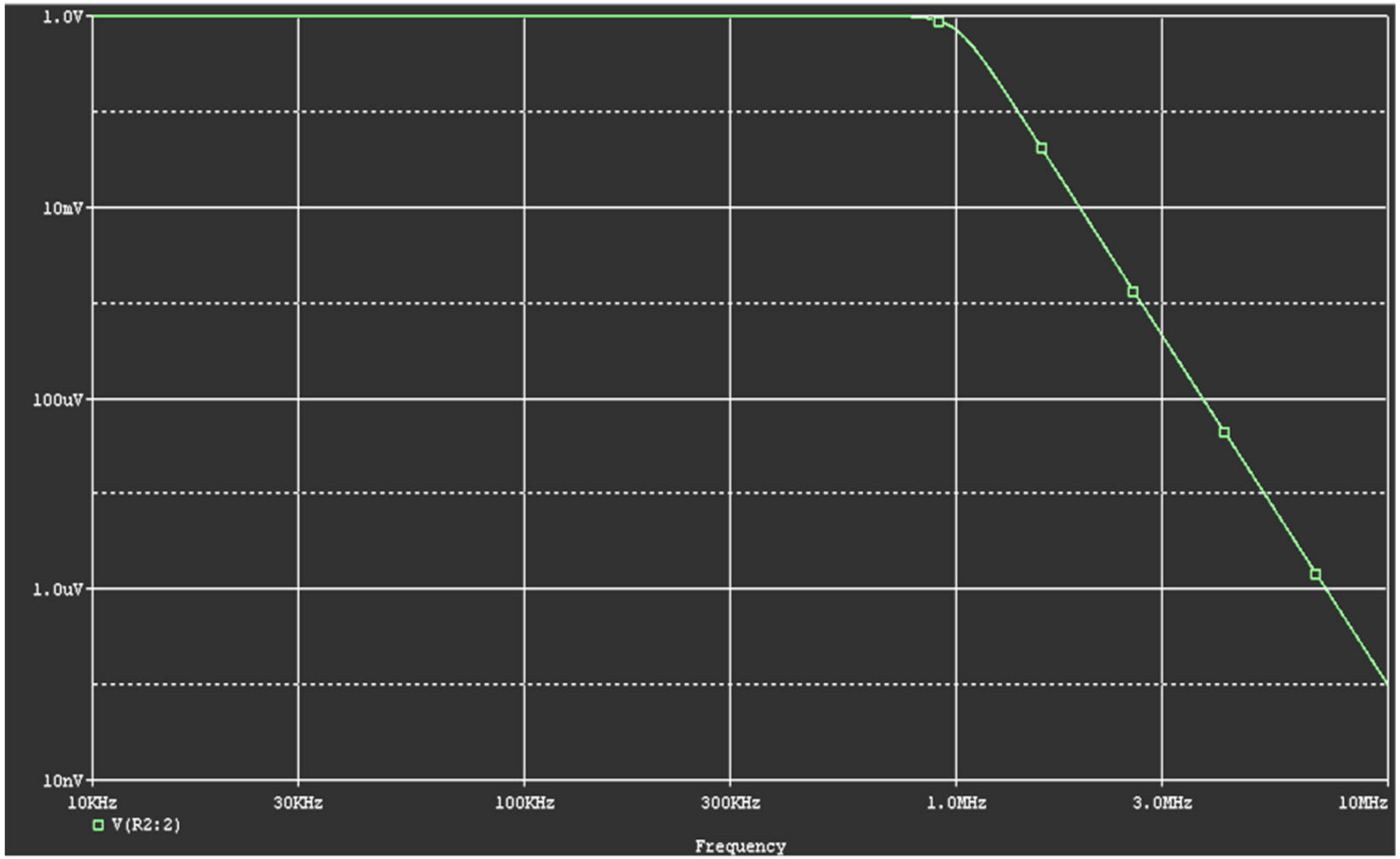
Chebyshev polynomial $$T_N(x) = \begin{cases} \cos(N\cos^{-1}x) & |x| \le 1 \\ \cosh(N\cosh^{-1}x) & |x| \ge 1 \end{cases}$$



Good Skirt but Bad Group Delay Characteristics

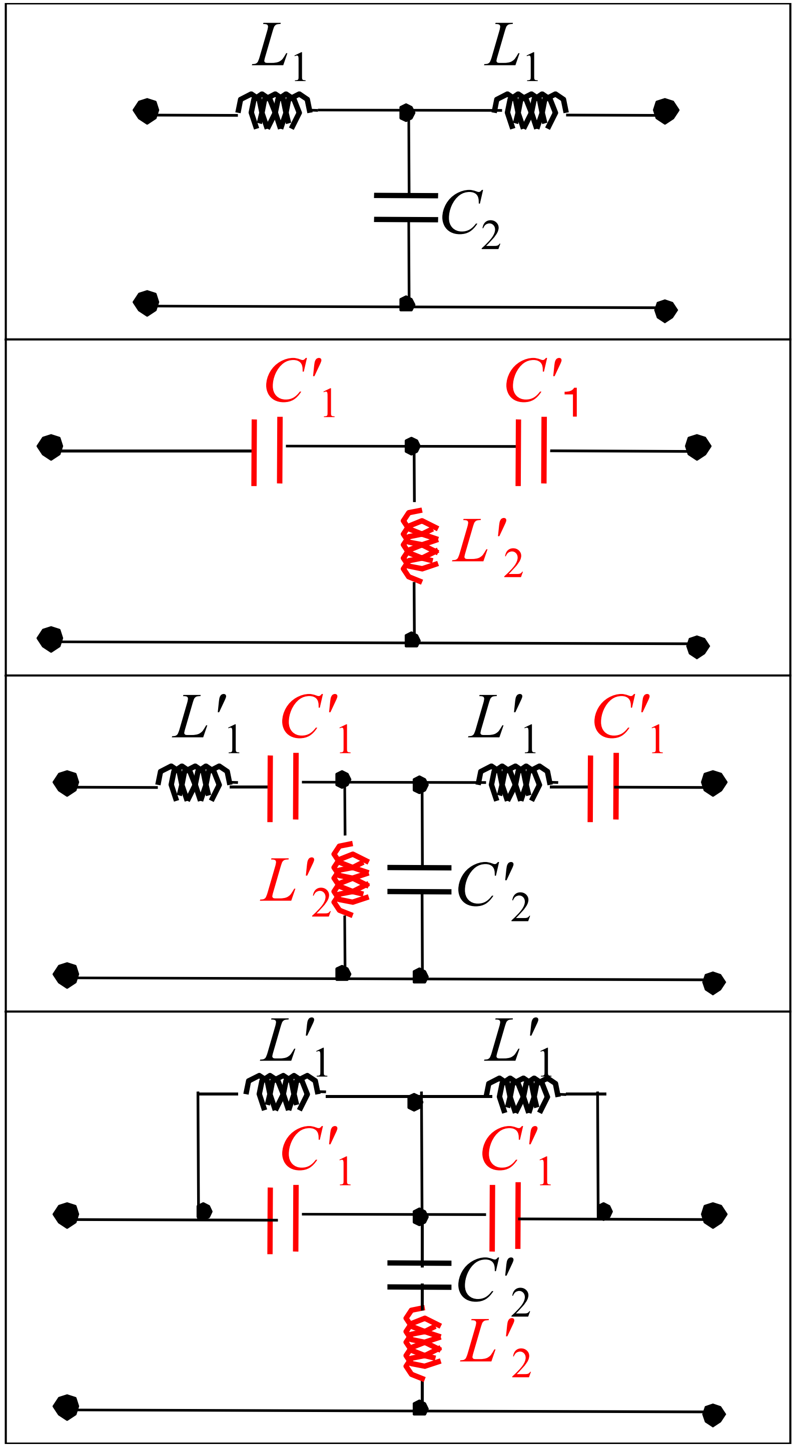
7 Element T-type Butterworth LPF





Various values

R_0=50Ω,
f_0=1MHz



- Original LPF

(Cut-off ω_c)

- LPF to HPF

$$\omega_c C'_1 = 1/\omega_c L_1$$

$$\omega_c L'_2 = 1/\omega_c C_2$$

- LPF to BPF

$$\omega_0^2 L'_1 C'_1 = 1,\ \ \omega_0^2 L'_2 C'_2 = 1$$

$$(\omega_0+\omega_c)L'_1 - 1/(\omega_0+\omega_c)C'_1 = \omega_c L_1$$

$$(\omega_0+\omega_c)C'_2 - 1/(\omega_0+\omega_c)L'_2 = \omega_c C_2$$

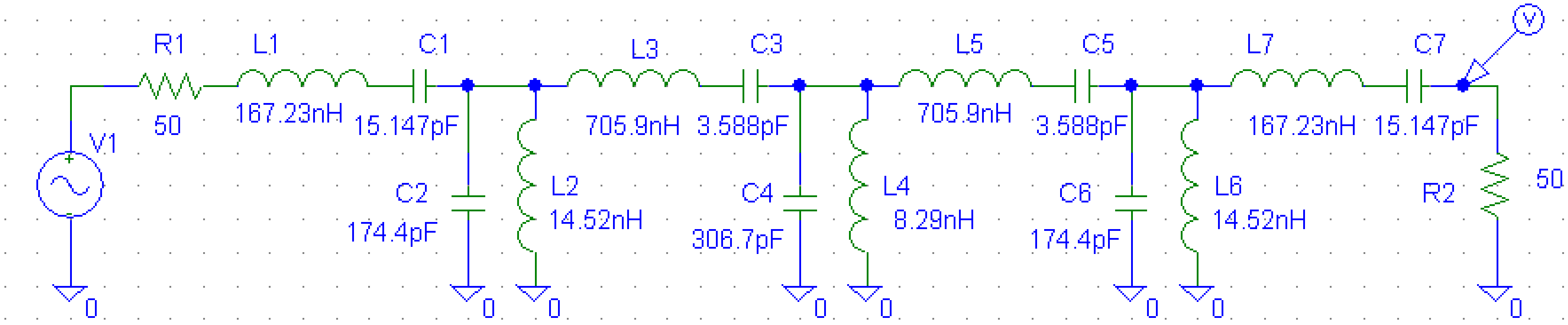
- LPF to BEF

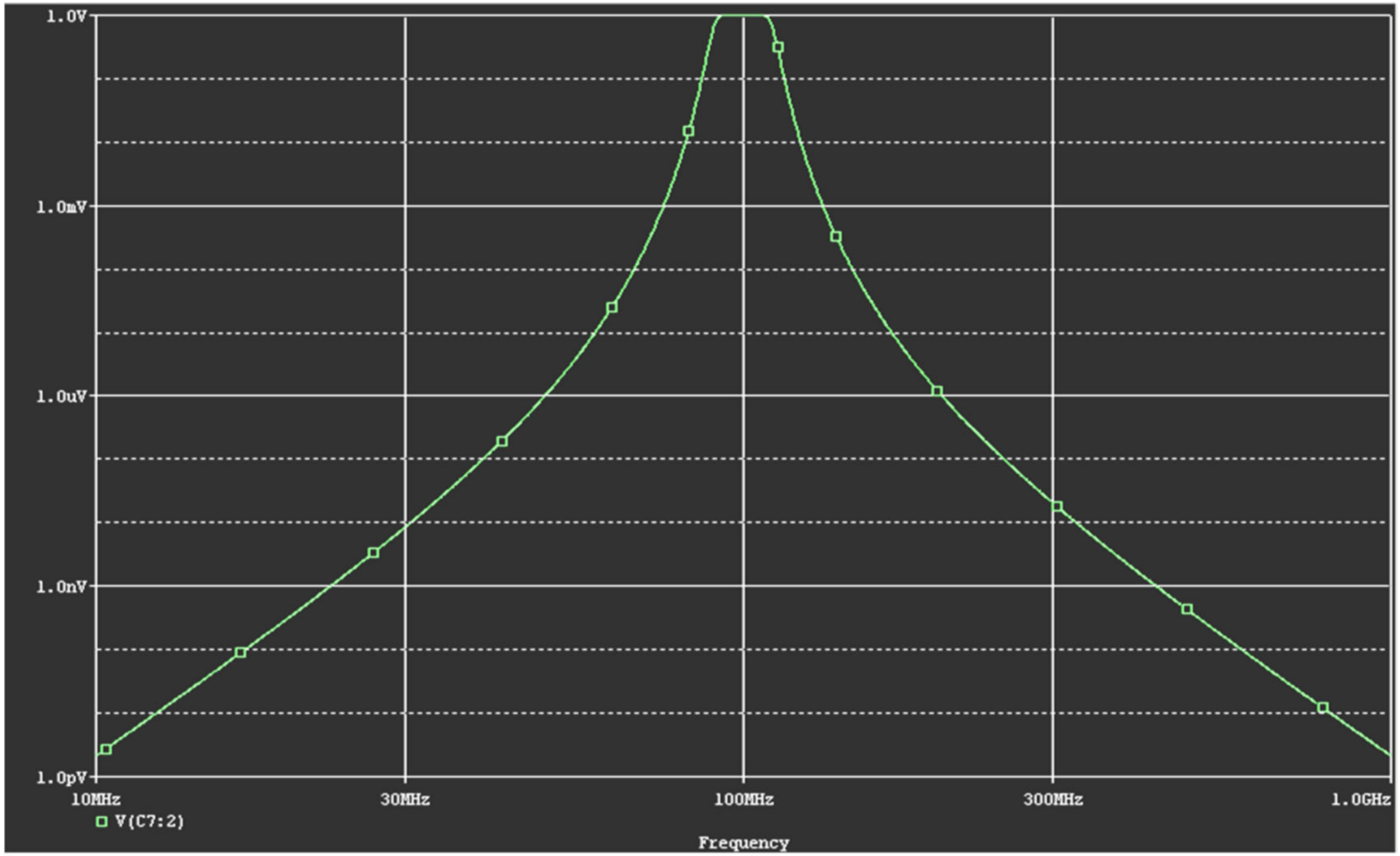
$$\omega_0^2 L'_1 C'_1 = 1,\ \ \omega_0^2 L'_2 C'_2 = 1$$

$$(\omega_0+\omega_c)C'_1 - 1/(\omega_0+\omega_c)L'_1 = 1/\omega_c L_1$$

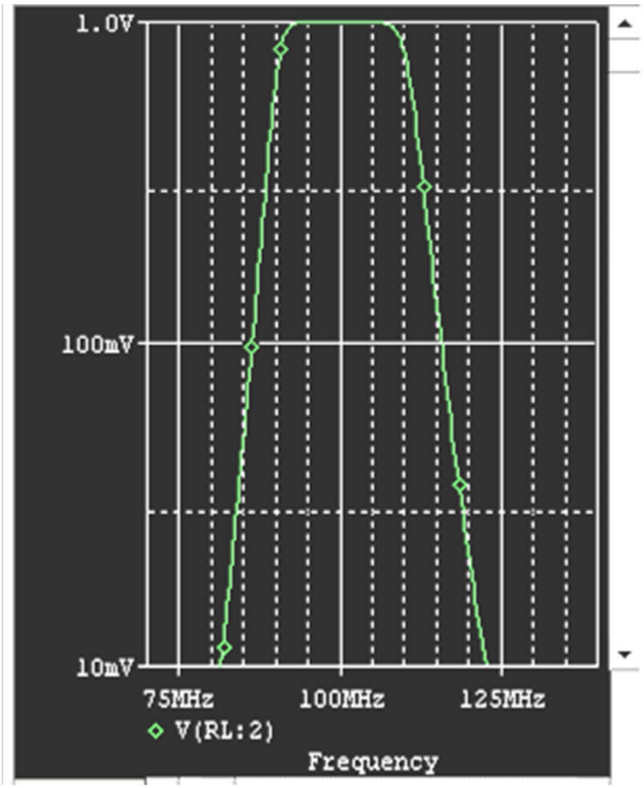
$$(\omega_0+\omega_c)L'_2 - 1/(\omega_0+\omega_c)C'_2 = 1/\omega_c C_2$$

$R_0=50\Omega,\ \Delta=1\%,\ f_c=100\text{MHz}$

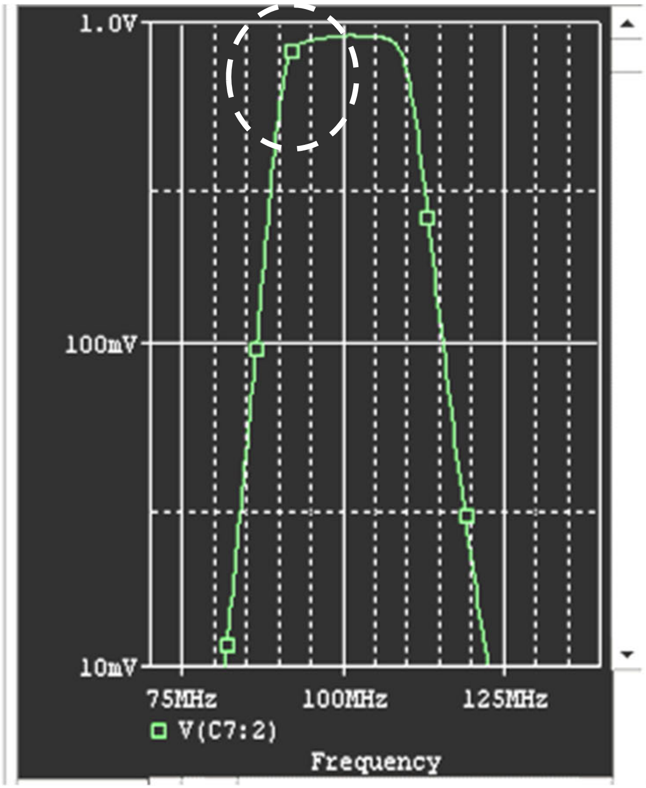




Infinite Q

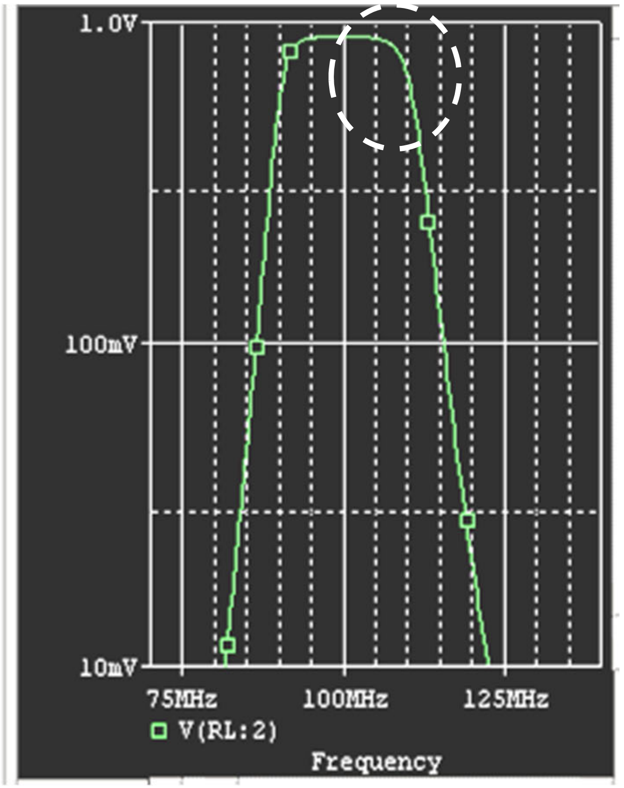


Q=100 for Parallel-L



Round Left Shoulder

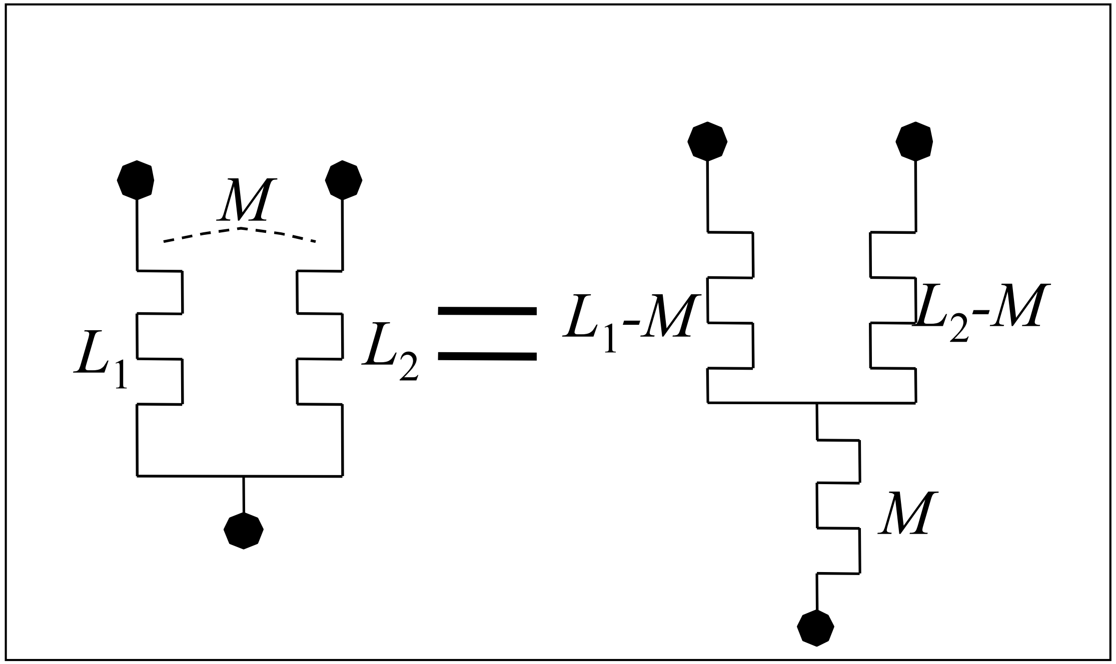
Q=100 for Series-L



Round Right Shoulder

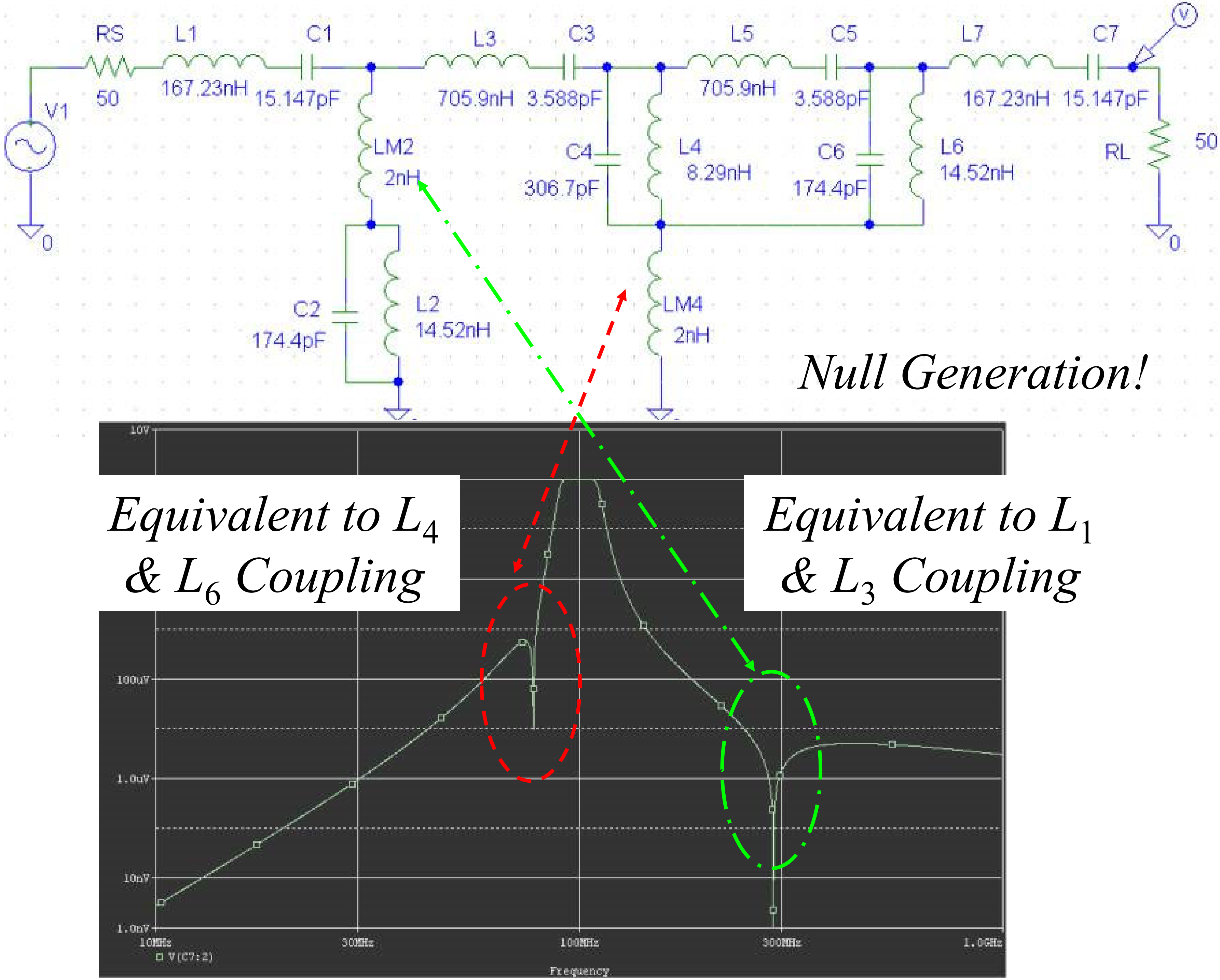
Increased Insertion Loss

Influence of Mutual L

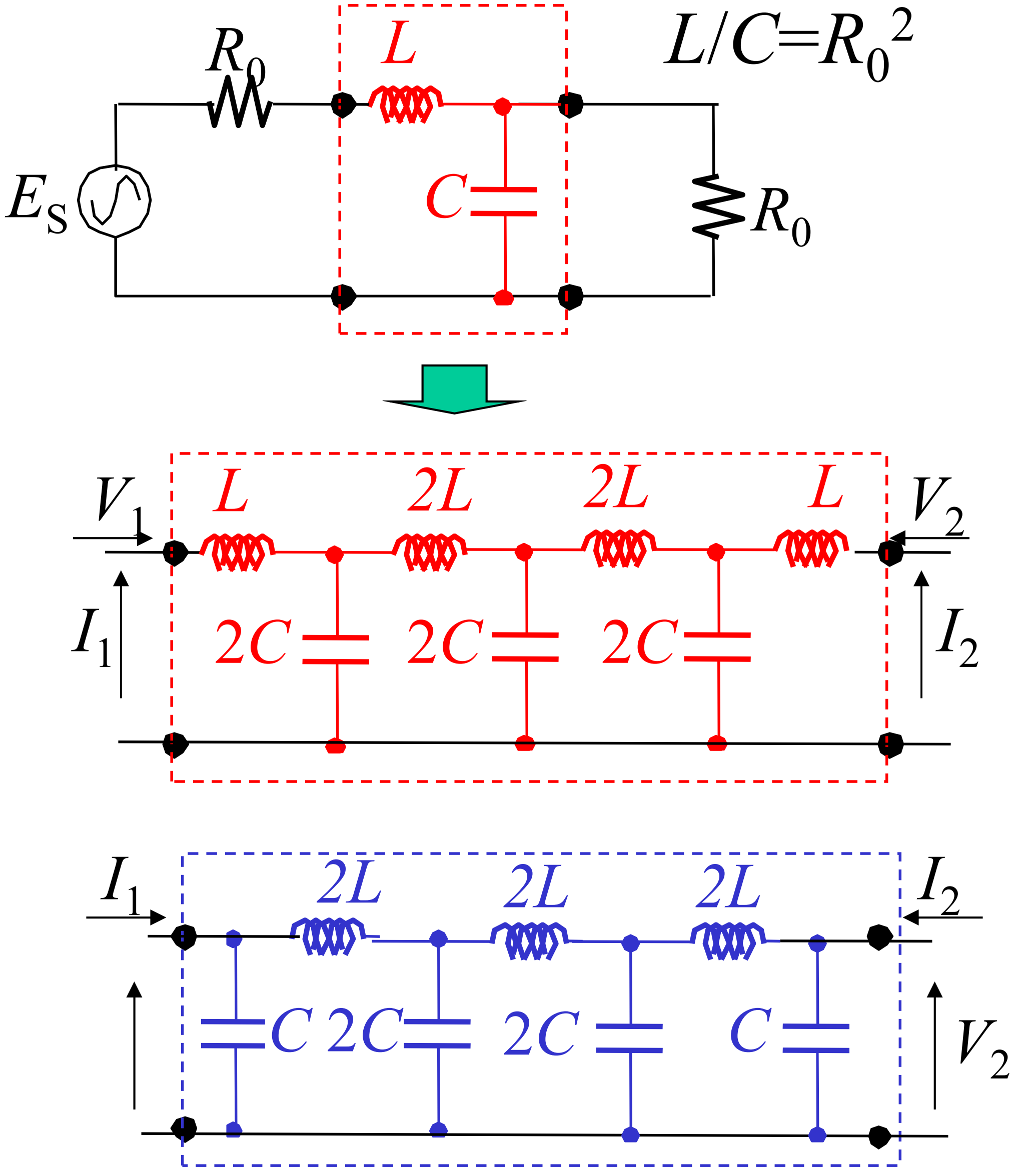


$$V_1 = L_1 \frac{dI_1}{dt} + M \frac{dI_2}{dt} = (L_1 - M)\frac{dI_1}{dt} + M \frac{d}{dt}(I_1 + I_2)$$

$$V_2 = M \frac{dI_1}{dt} + L_2 \frac{dI_2}{dt} = (L_2 - M)\frac{dI_2}{dt} + M \frac{d}{dt}(I_1 + I_2)$$


RS
50
L1
167.23nH
C1
15.147pF
L3
705.9nH
C3
3.588pF
L5
705.9nH
C5
3.588pF
L7
167.23nH
C7
15.147pF
V1
LM2
2nH
C4
306.7pF
L4
8.29nH
C6
174.4pF
L6
14.52nH
RL
50
C2
174.4pF
L2
14.52nH
LM4
2nH
0
Null Generation!
Equivalent to L_4 & L_6 Coupling
Equivalent to L_1 & L_3 Coupling
10V
100uV
1.0uV
10nV
1.0nV
10MHz
30MHz
100MHz
300MHz
1.0GHz
V(C7:2)
Frequency

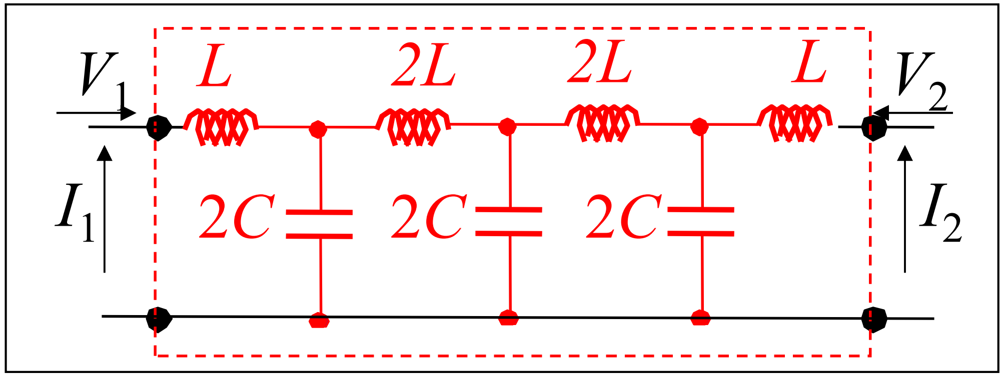
Constant K Filter



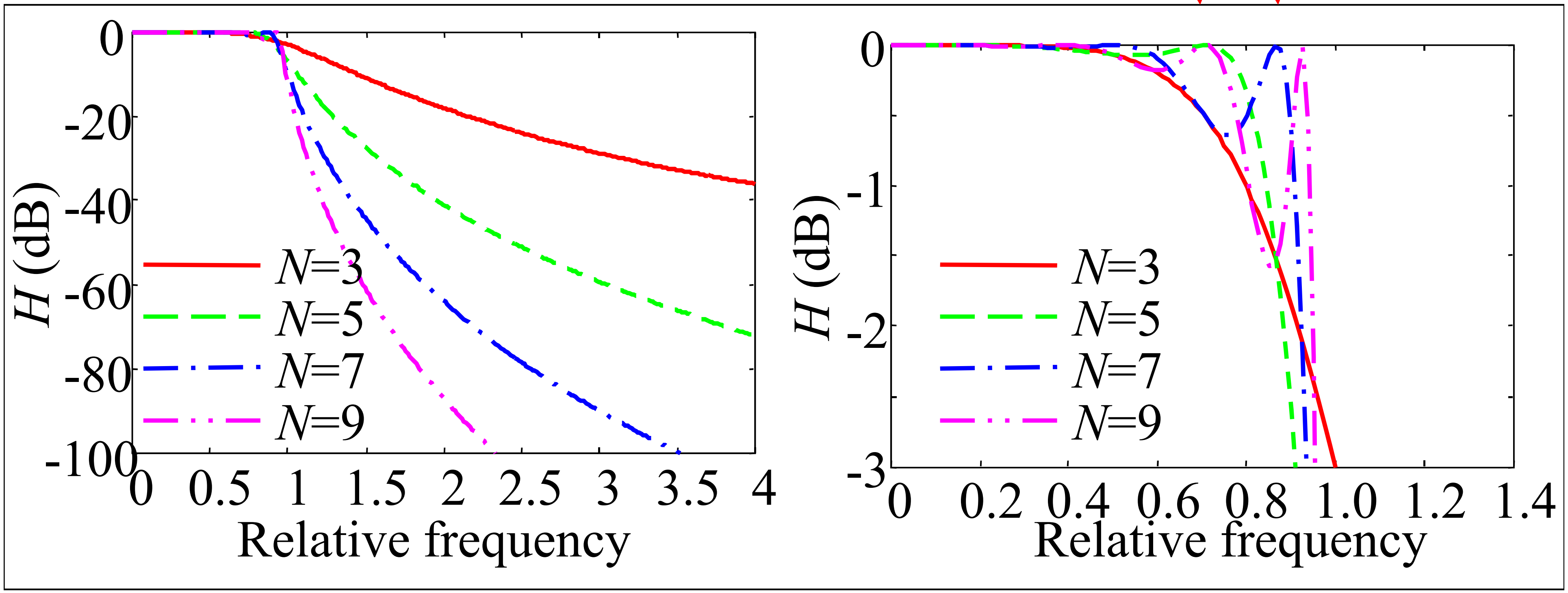
Uniform Impedance Values

Cascade-Connection with Inversion

(Equivalent Circuit for Transmission Line)

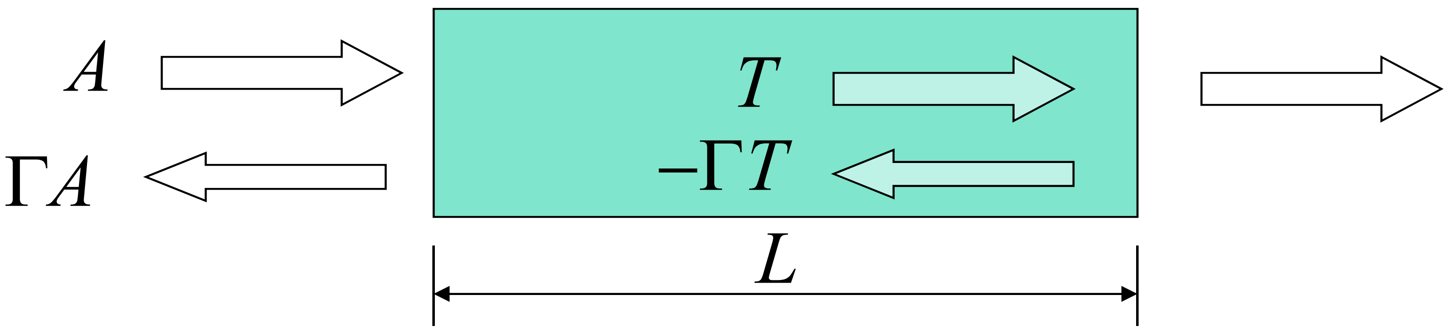


$|H|=1$ When Equivalent Transmission Line Length is $n\lambda/2$



Similar Response to Butterworth Filter

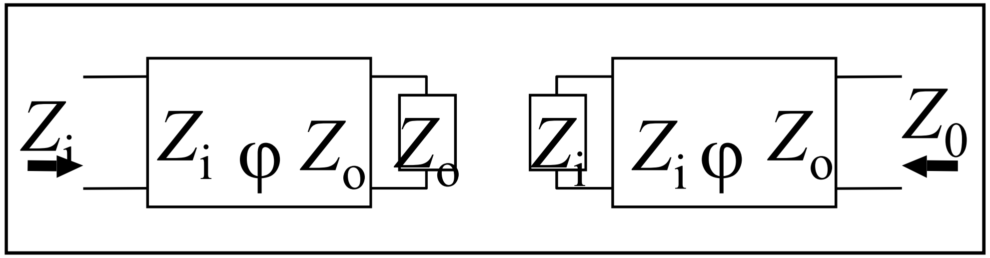
Fabry-Perot Resonator



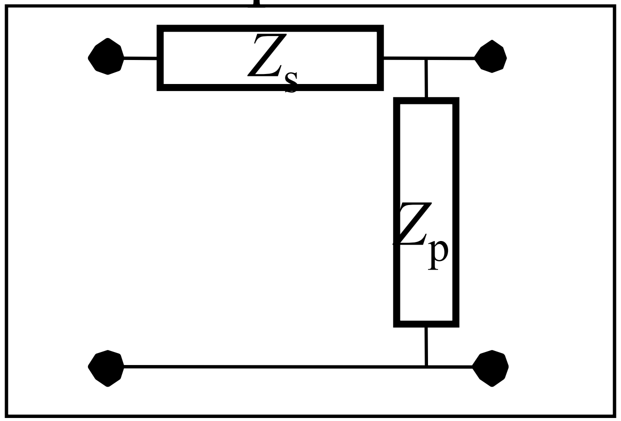
Interference Between Two Reflected Waves

100% Transmit When $L=n\lambda/2$

Image Parameter Z_i, Z_o & φ



Example

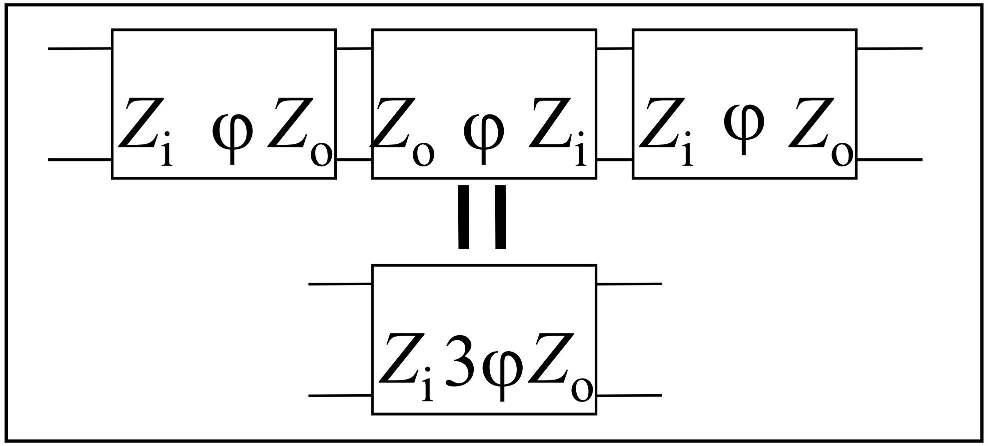


$$Z_i = \sqrt{Z_s(Z_s + Z_p)}$$

$$Y_o = Z_o^{-1} = \sqrt{Y_p(Y_p + Y_s)}$$

$$\varphi = \sinh^{-1}\left(\sqrt{Z_s / Z_p}\right)$$

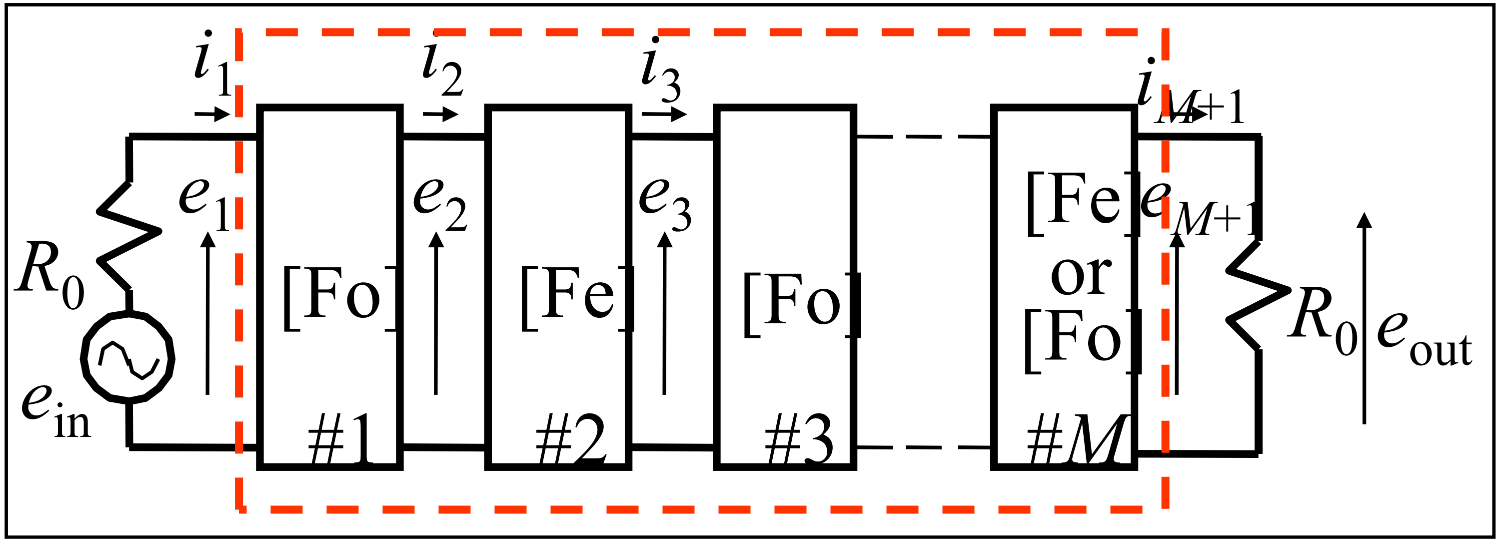
Cascade Connection with Inversion



$$\mathbf{F} = \begin{bmatrix} \xi^{-1}\cosh\varphi & Z_i\xi^{-1}\sinh\varphi \\ Z_i^{-1}\xi\sinh\varphi & \xi\cosh\varphi \end{bmatrix}$$

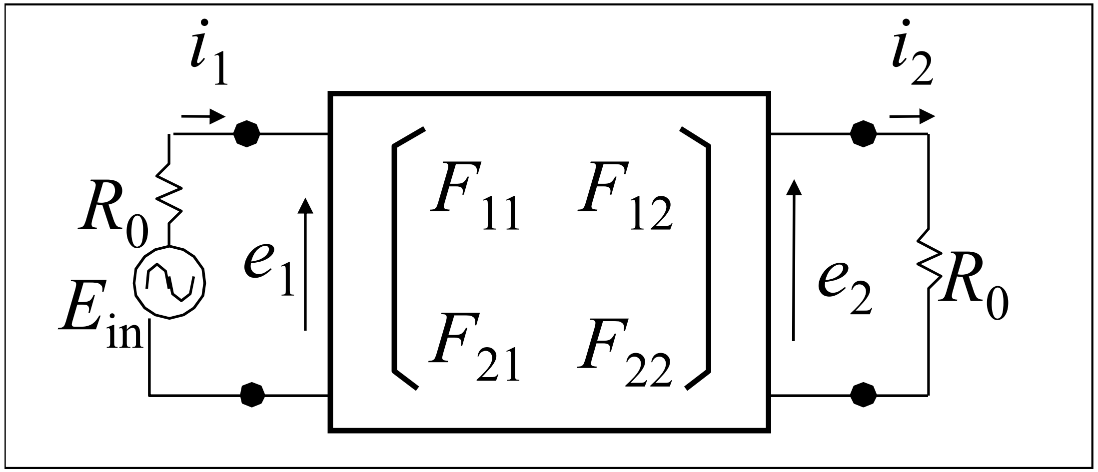
where $\xi = Z_i/Z_o$

Analysis



Cascade Connection with Inversion

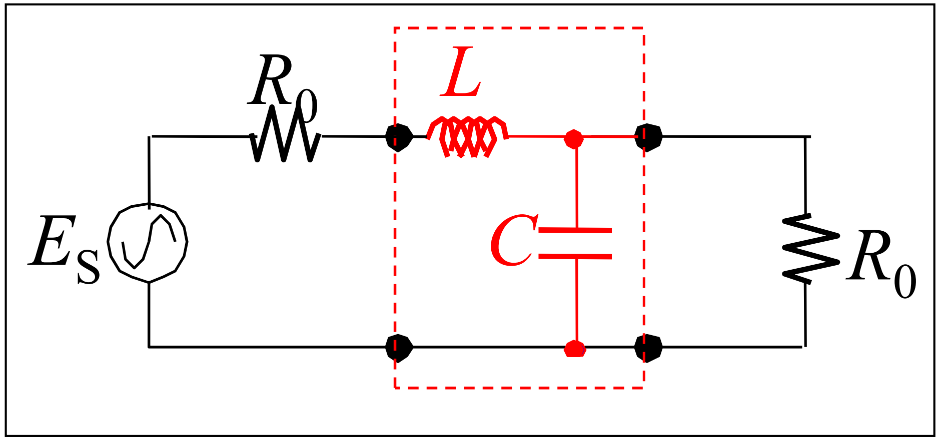
$$\mathbf{F} = \begin{cases} \begin{bmatrix} \xi^{-1}\cosh M\varphi & Z_i \xi \sinh M\varphi \\ Z_i^{-1}\xi \sinh M\varphi & \xi \cosh M\varphi \end{bmatrix} & (M : \text{odd}) \\ \begin{bmatrix} \cosh M\varphi & Z_i \sinh M\varphi \\ Z_i^{-1} \sinh M\varphi & \cosh M\varphi \end{bmatrix} & (M : \text{even}) \end{cases}$$



$$S_{21} = \frac{2}{F_{11} + F_{22} + R_0 F_{21} + G_0 F_{12}}$$

$$= \begin{cases} \dfrac{2}{(\xi + \xi^{-1})\cosh M\varphi + (Z_i \xi^{-1} / R_0 + R_0 \xi / Z_i)\sinh M\varphi} & (M : \text{odd}) \\ \dfrac{2}{2\cosh M\varphi + (Z_i / R_0 + R_0 / Z_i)\sinh M\varphi} & (M : \text{even}) \end{cases}$$

When $\varphi = jn\pi / M$, $|S_{21}| = 1$



$$Z_i = K\sqrt{1-(\omega/\omega_c)^2}$$

$$Z_o = K/\sqrt{1-(\omega/\omega_c)^2}$$

$$\varphi = j\sin^{-1}(\omega/\omega_c)$$

$$K=\sqrt{L/C},\omega_c = 1/\sqrt{LC}$$

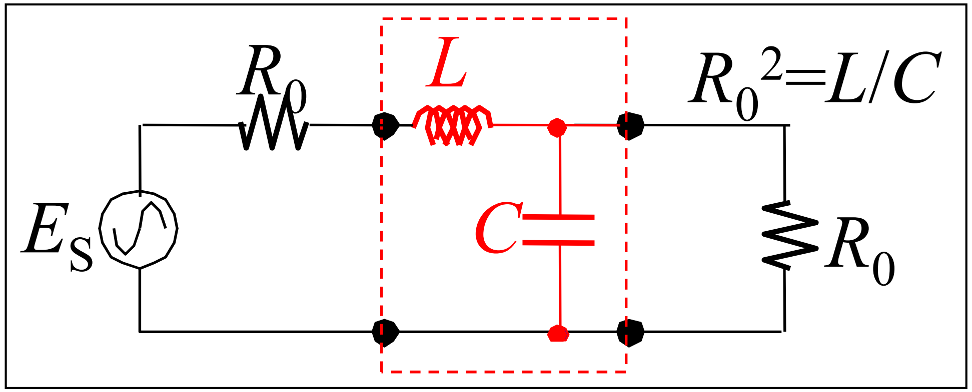
When $\omega<\omega_c$, φ Imag., Z_i & Z_o Real $\Rightarrow$ Passband

When $\omega>\omega_c$, φ Real, Z_i & Z_o Imag. $\Rightarrow$ Rejection band

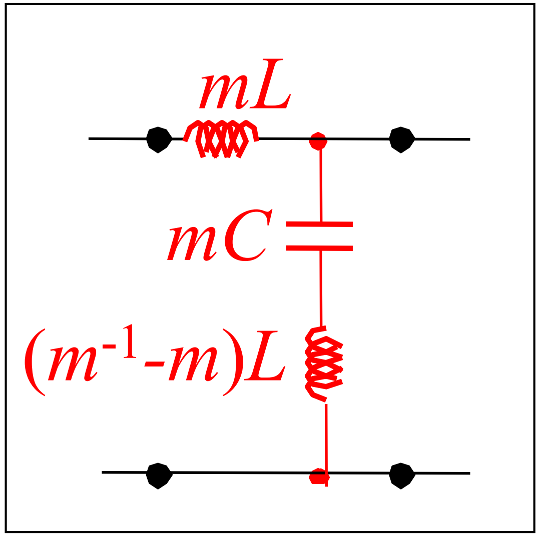
Zero Insertion Loss

$\varphi = jn\pi/M \Rightarrow \omega/\omega_c = \sin(n\pi/M)$

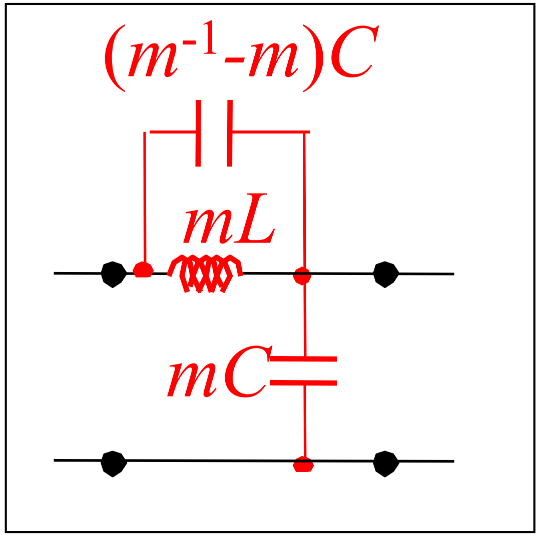
Derived m Filter



Constant K Filter



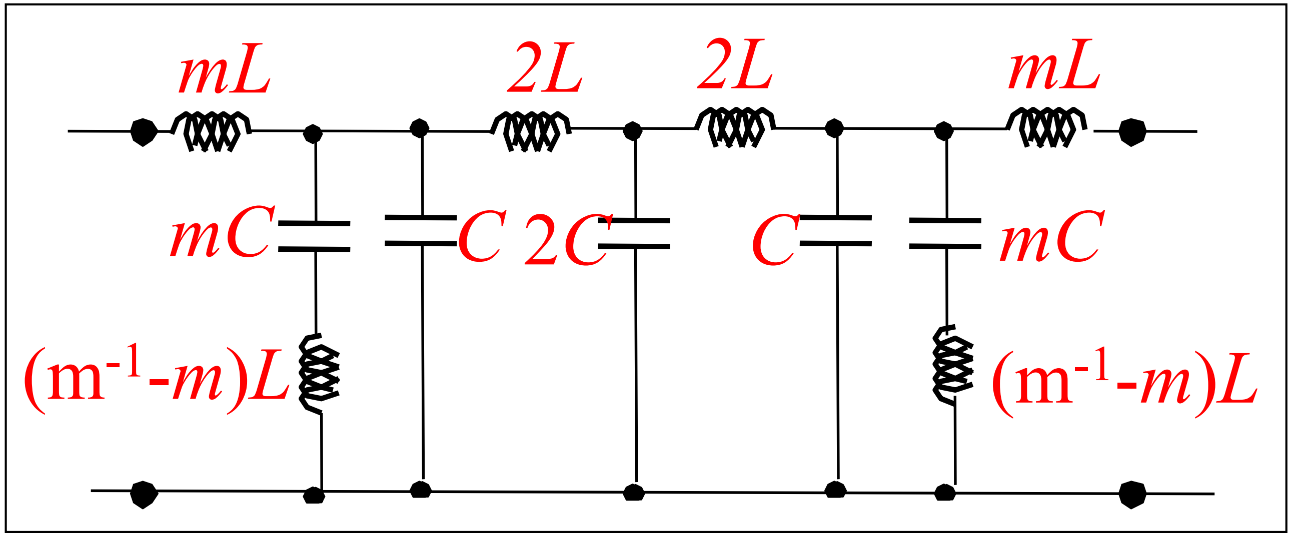
Null Due to Series Resonance



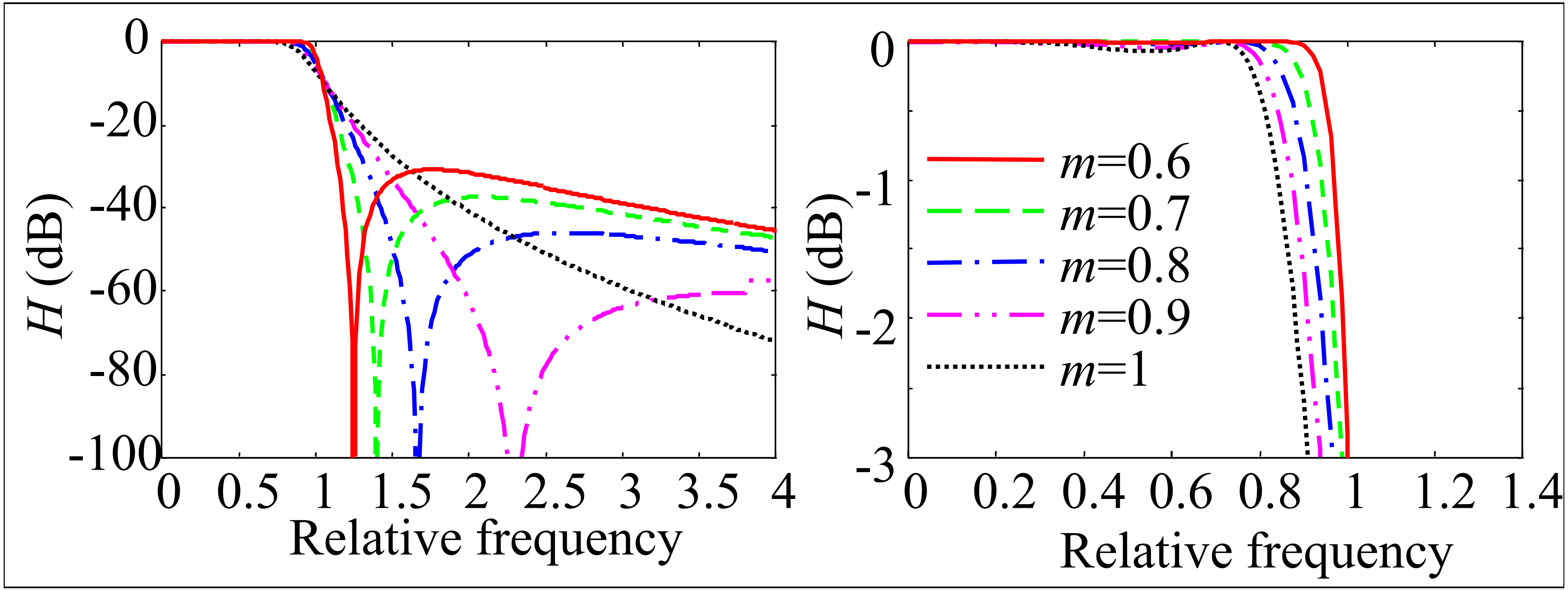
Null Due to Parallel Resonance

$R_0^2=L/C$

$0 \le m \le 1$



Combination of Derived *m* and Constant *K* Filters

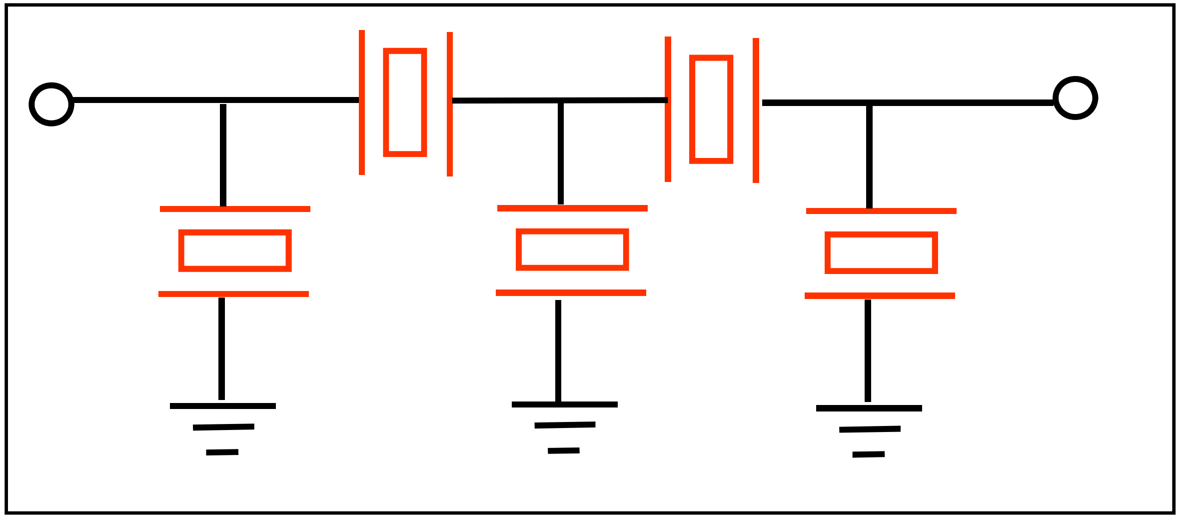


Steep Skirt and Good Out-Band Rejection

Contents

- Ladder Type Filter Design

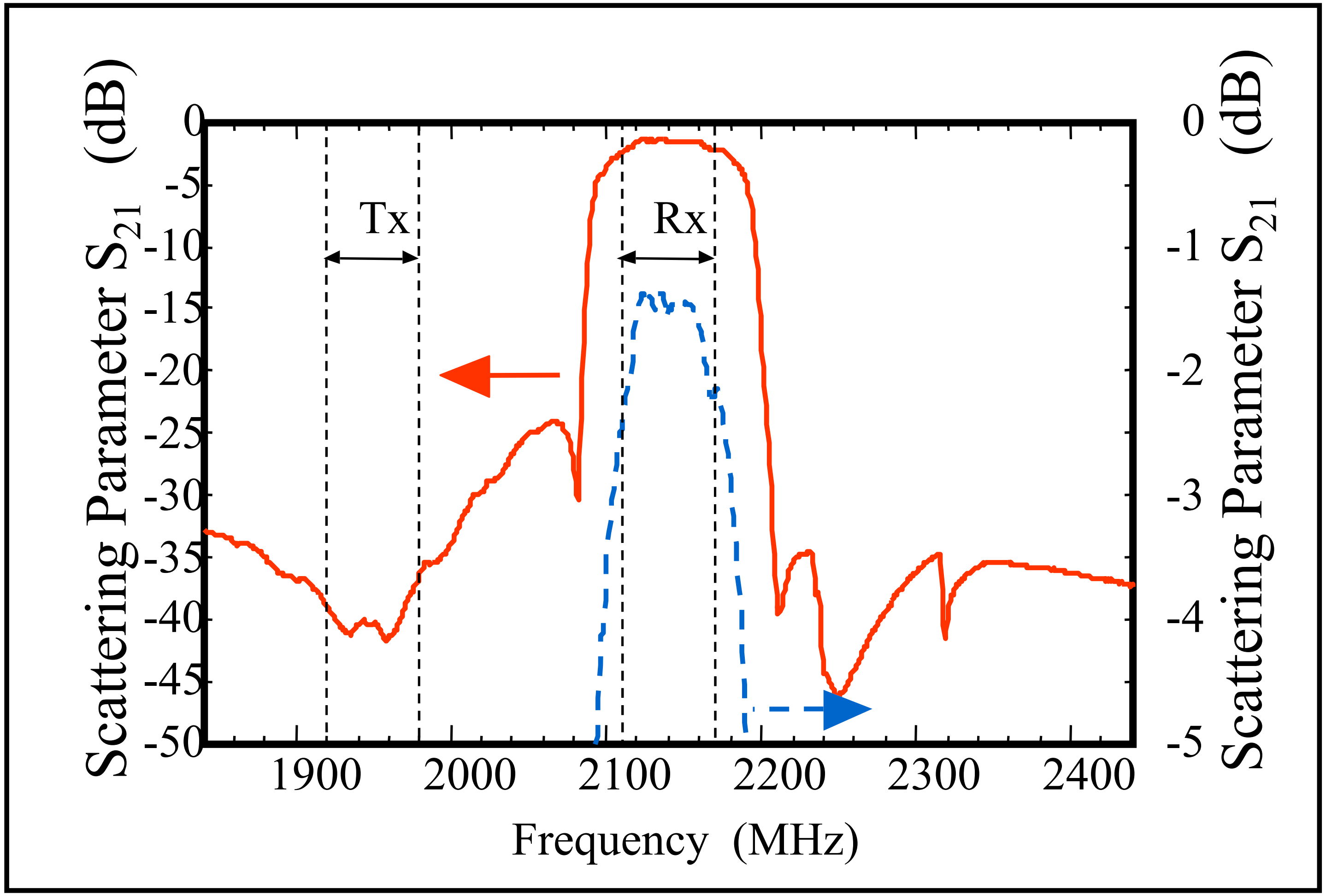
Ladder-Type Filter



Configuration (Resonator-Based Constant K Filter)

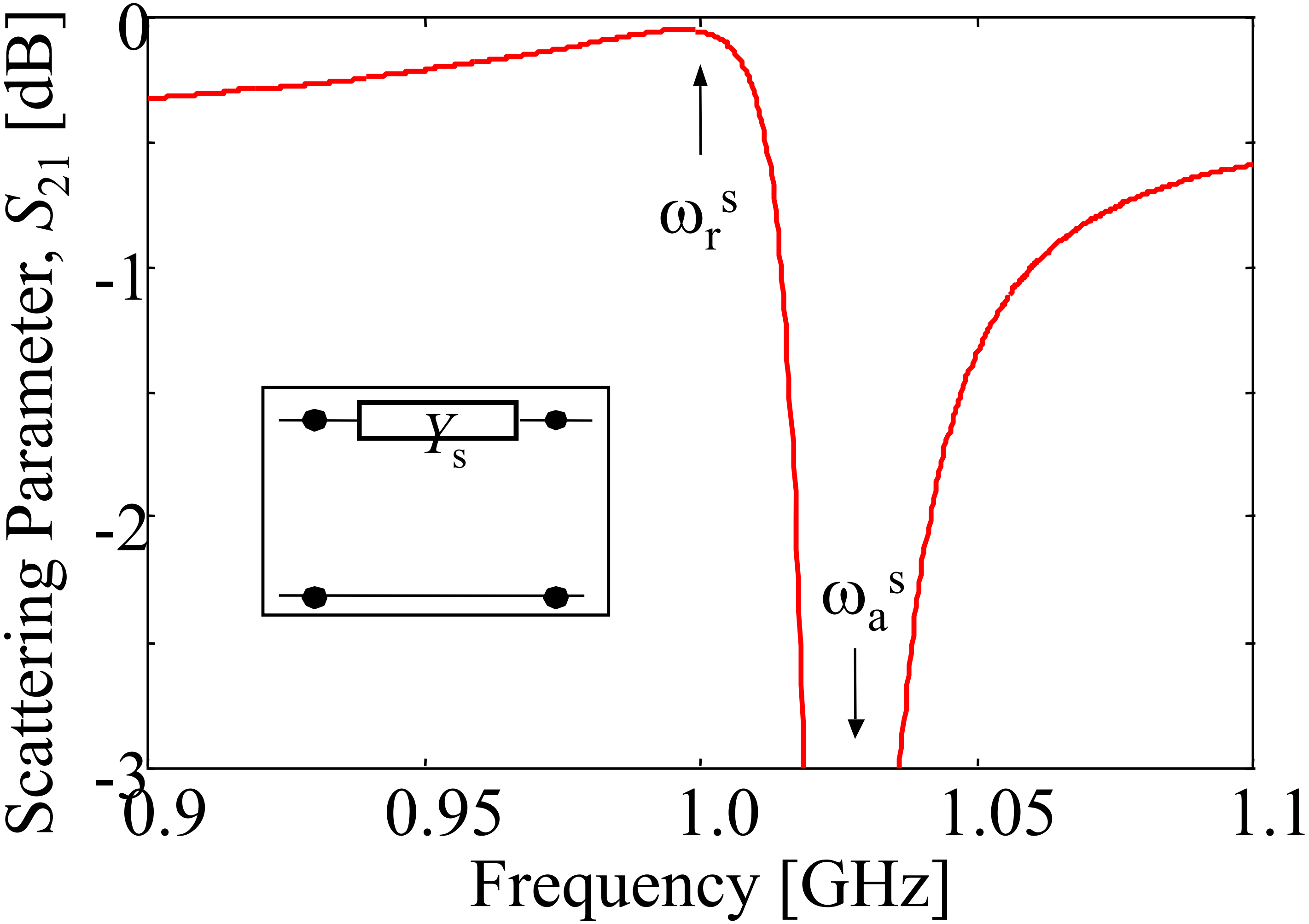
- Fabrication of Multiple Resonators on a Chip
- Low Loss
- High Power Durability
- Moderate Out-of-Band Rejection

Performance of Ladder-Type SAW Filter

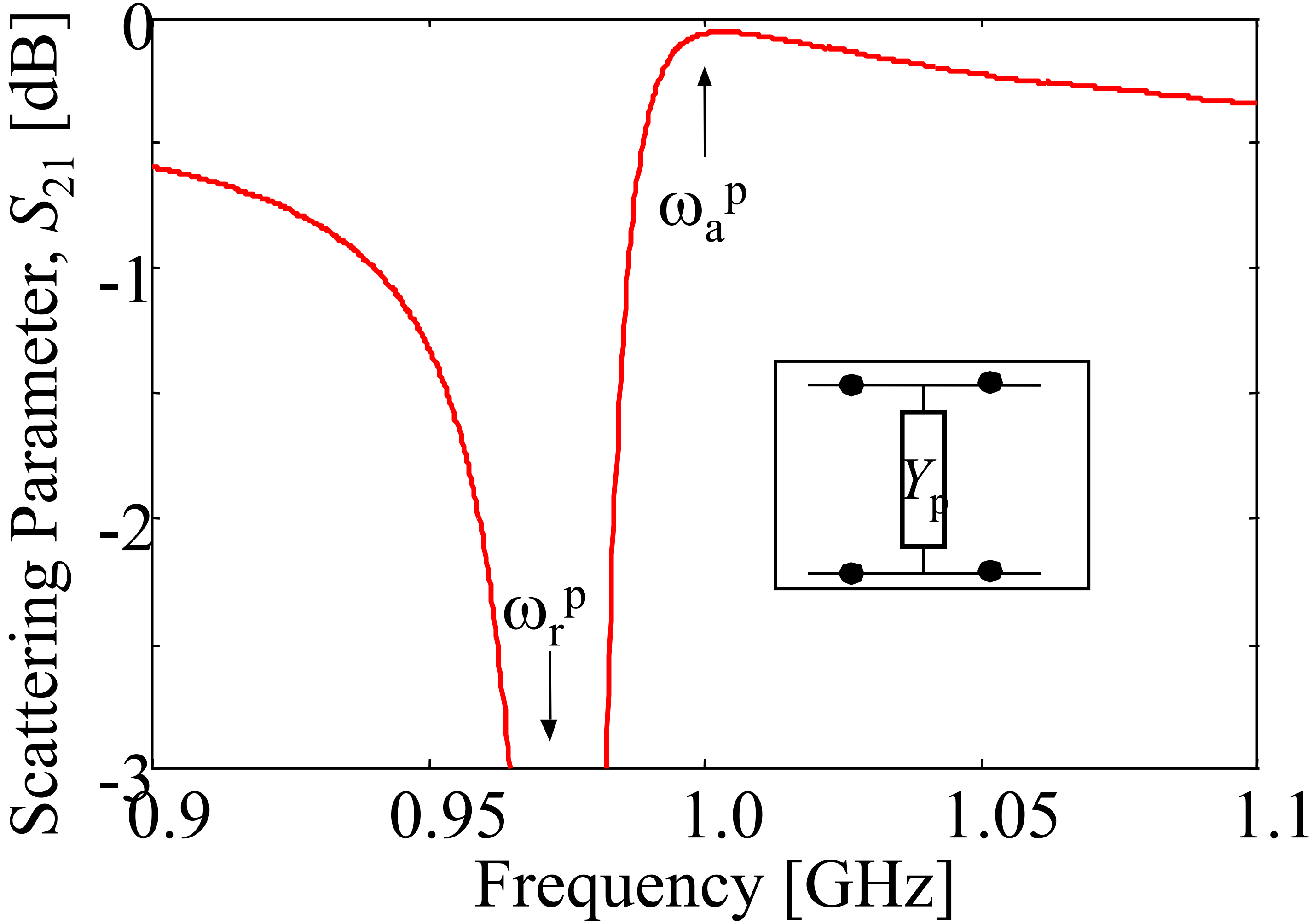


Fujitsu FAR-F6CP-2G1400-L21M

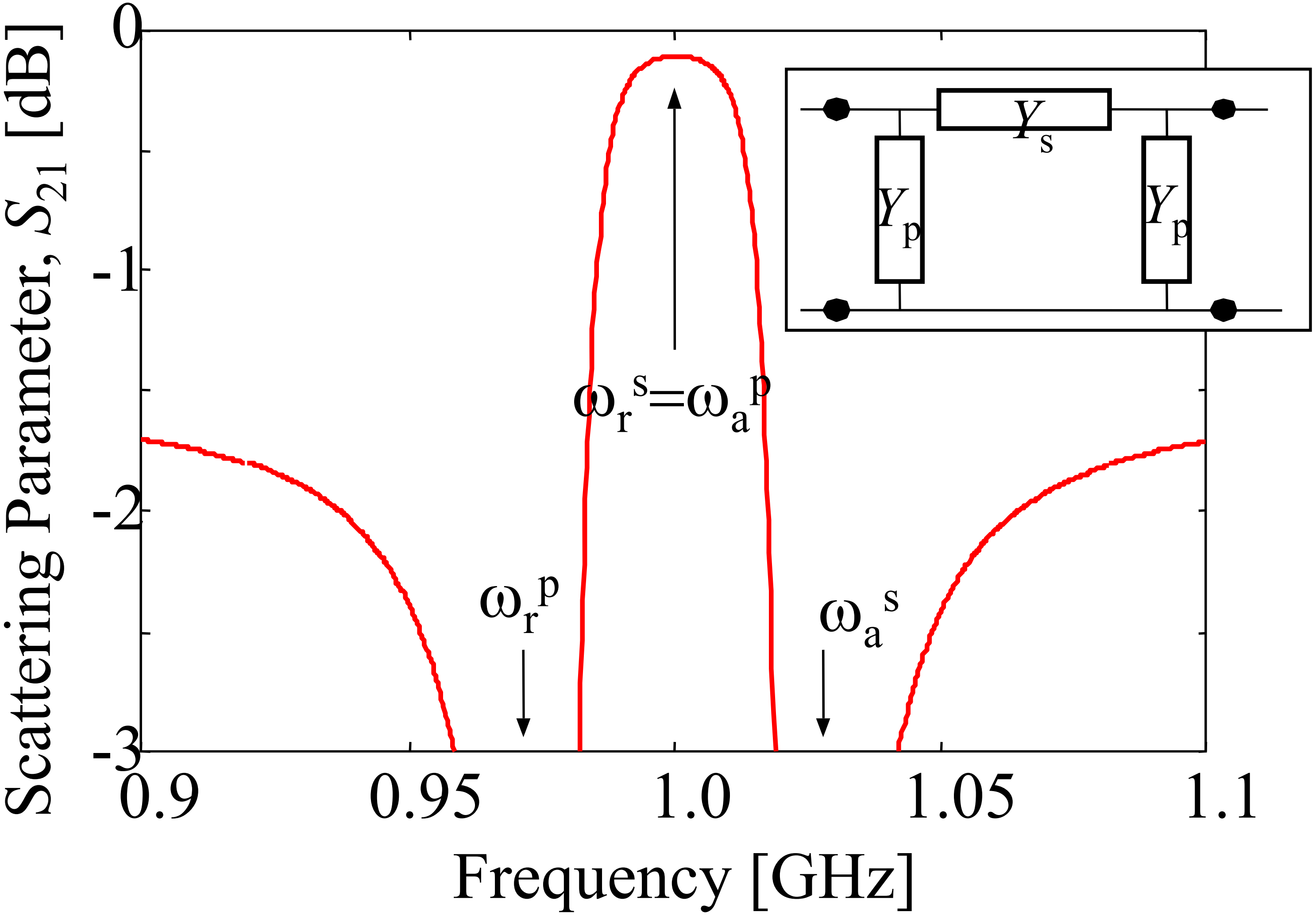
W-CDMA-Rx



Scattering Parameter, S_{21} [dB]
0
-1
-2
-3
0.9
0.95
1.0
1.05
1.1
Frequency [GHz]
ω_r^s
ω_a^s
Y_s



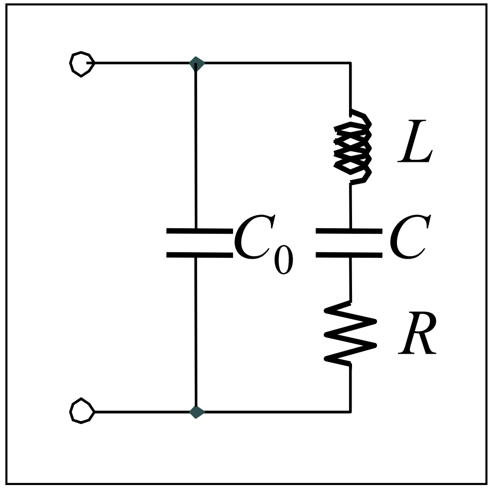
Scattering Parameter, S_{21} [dB]
0
-1
-2
-3
0.9
0.95
1.0
1.05
1.1
Frequency [GHz]
ω_a^p
ω_r^p
Y_p



Scattering Parameter, S_{21} [dB]
0
-1
-2
-3
0.9
0.95
1.0
1.05
1.1
Frequency [GHz]
$\omega_r^s=\omega_a^p$
ω_r^p
ω_a^s
Y_s
Y_p
Y_p

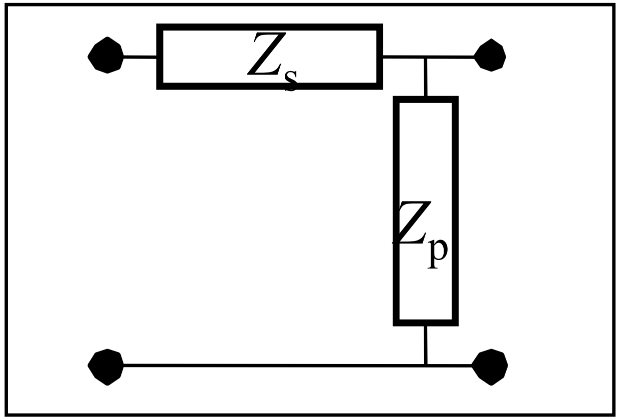
Resonator Model for Y_p & Y_s

$$Y = j\omega C_0 \frac{(j\omega/\omega_a)^2 + 1 + (j\omega/\omega_a)/Q_r}{(j\omega/\omega_r)^2 + 1 + (j\omega/\omega_r)/Q_r}$$



Assumption 1. γ & Q_r Identical for Z_s & Z_p

2. $\omega_r^s = \omega_a^p$

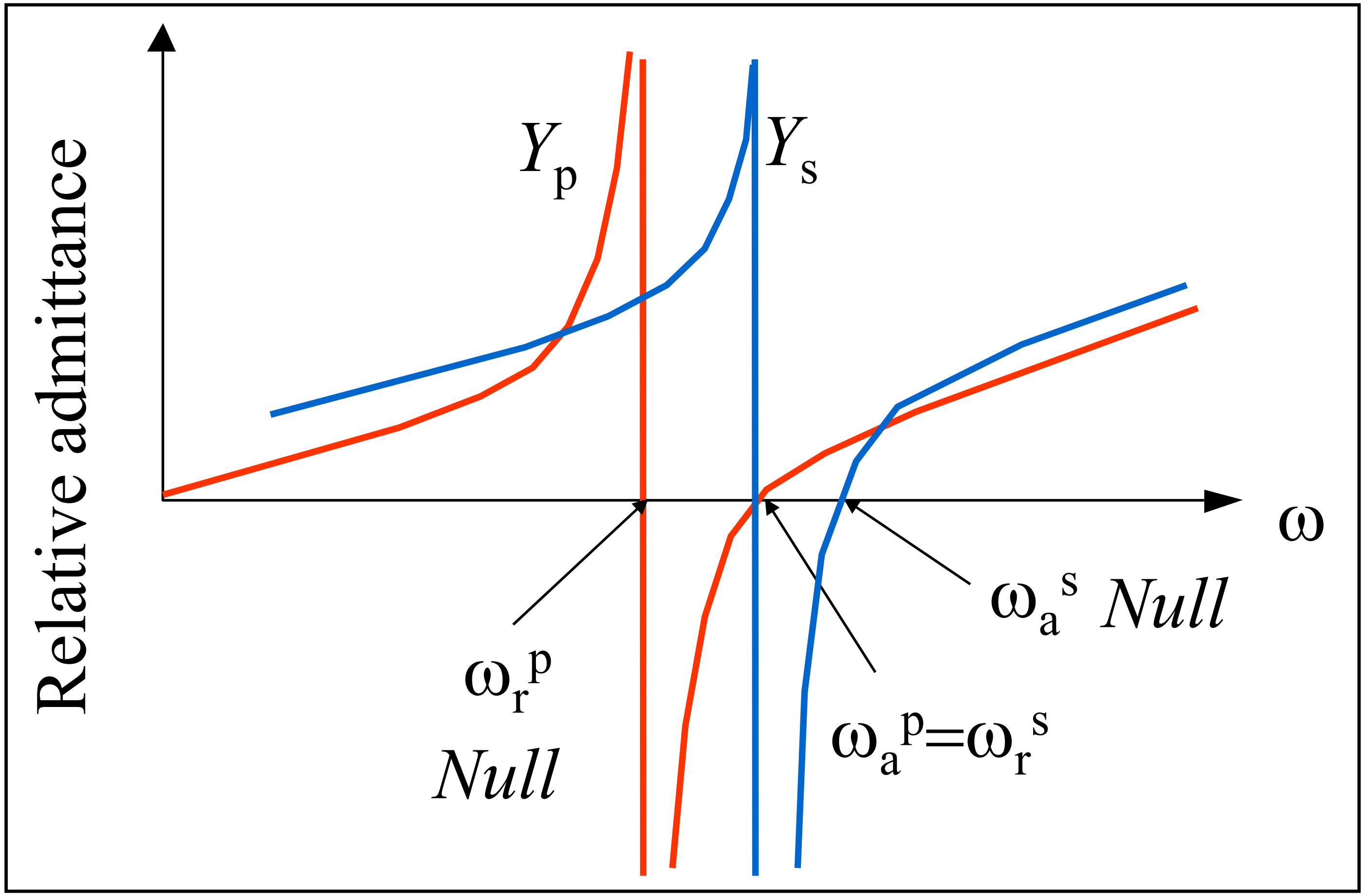


$$Z_i = \sqrt{Z_s(Z_s + Z_p)}$$

$$Y_o = Z_o^{-1} = \sqrt{Y_p(Y_p + Y_s)}$$

$$\varphi = \sinh^{-1}\left(\sqrt{Y_p / Y_s}\right)$$

Passband When $-1 < Y_p/Y_s < 0$ (Either Y_s or Y_p Inductive)



Passband When $-1 < Y_p / Y_s < 0$ (Either Y_s or Y_p Inductive)

Larger Y_s Offers Wide Bandwidth

$$S_{21} = \begin{cases} \dfrac{2}{(\xi + \xi^{-1})\cosh M\varphi + (Z_i \xi^{-1} / R_0 + R_0 \xi / Z_i)\sinh M\varphi} & (M : \mathrm{odd}) \\[2ex] \dfrac{2}{2\cosh M\varphi + (Z_i / R_0 + R_0 / Z_i)\sinh M\varphi} & (M : \mathrm{even}) \end{cases}$$

At the Resonance(φ=0)

$$S_{21}\Big|_{\omega=\omega_r^s} \cong \frac{2}{2 + N(Z_s / R_0 + R_0 / Z_p)}$$

$$\cong \frac{2}{2 + NrM^{-1}(\eta^{-1} + \eta)}$$

where

$$\eta = R_0 \omega \sqrt{C_0^s C_0^p}$$

$$r = \sqrt{C_0^p / C_0^s}$$

$$M = Q_r / \gamma \ \text{(FOM)}$$

Loss Minimum Condition **η=1**

$$\Rightarrow \quad S_{21}\Big|_{\substack{\omega=\omega_r^s \\ \eta=1}} \cong \frac{1}{1 + NrM^{-1}}$$

Low Loss When $NrM^{-1} \ll 1$

Bandwidth

$$\frac{2\delta\omega}{\omega_r^s} \cong \sqrt{1+\frac{1}{\sqrt{\gamma(1+\gamma)(1+r^2)}}} - \sqrt{1-\frac{1}{\sqrt{\gamma(1+\gamma)(1+r^2)}}}$$

$$\cong \frac{1}{\sqrt{\gamma(1+\gamma)(1+r^2)}} \cong \frac{1}{\gamma\sqrt{1+r^2}}$$

where $r = \sqrt{C_0^p / C_0^s}$

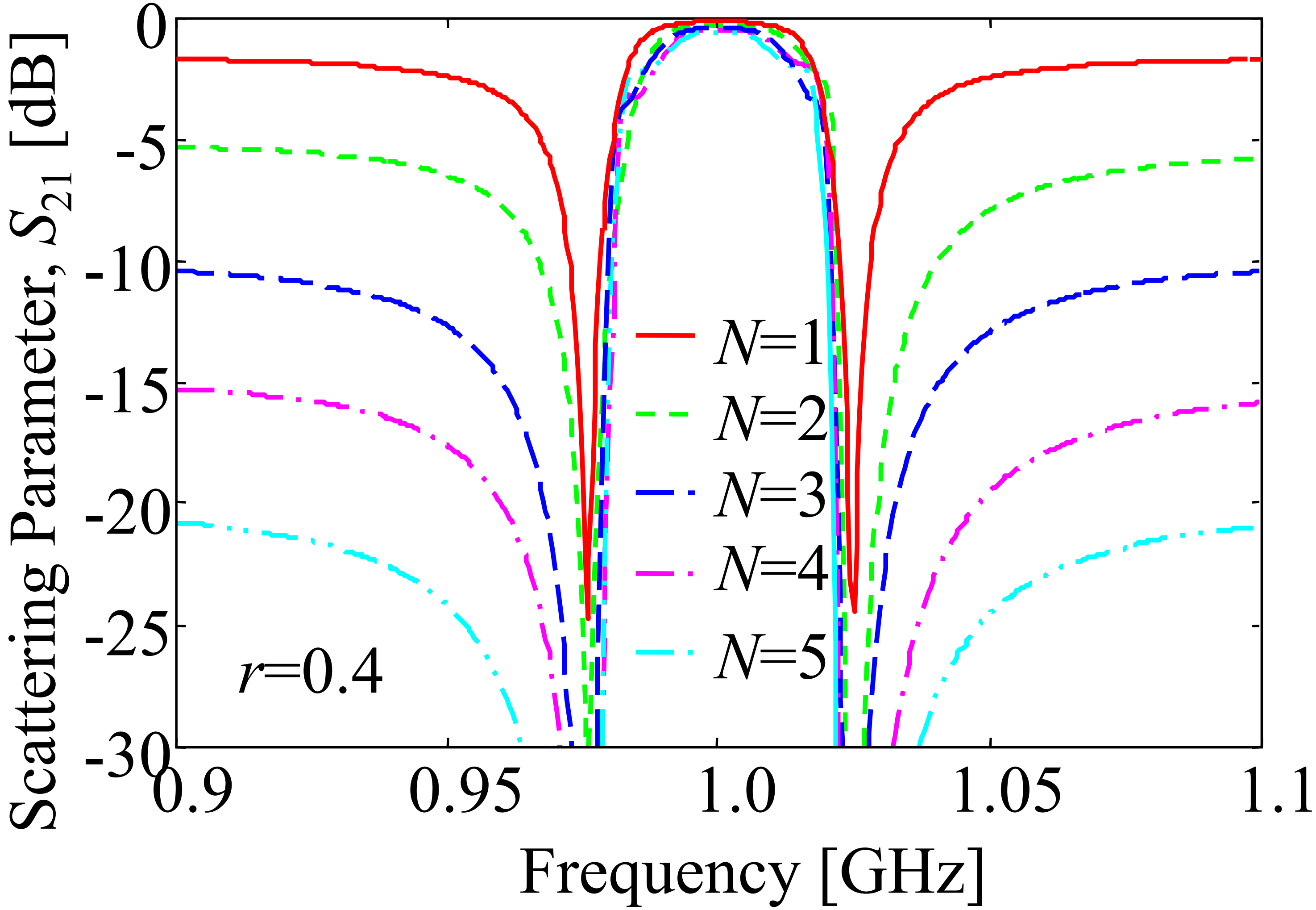
Out-of-Band Rejection

When η=1, $S_{21} \cong \frac{1}{\cosh(N\varphi)} = \frac{1}{T_N\left(\sqrt{r^2+1}\right)}$

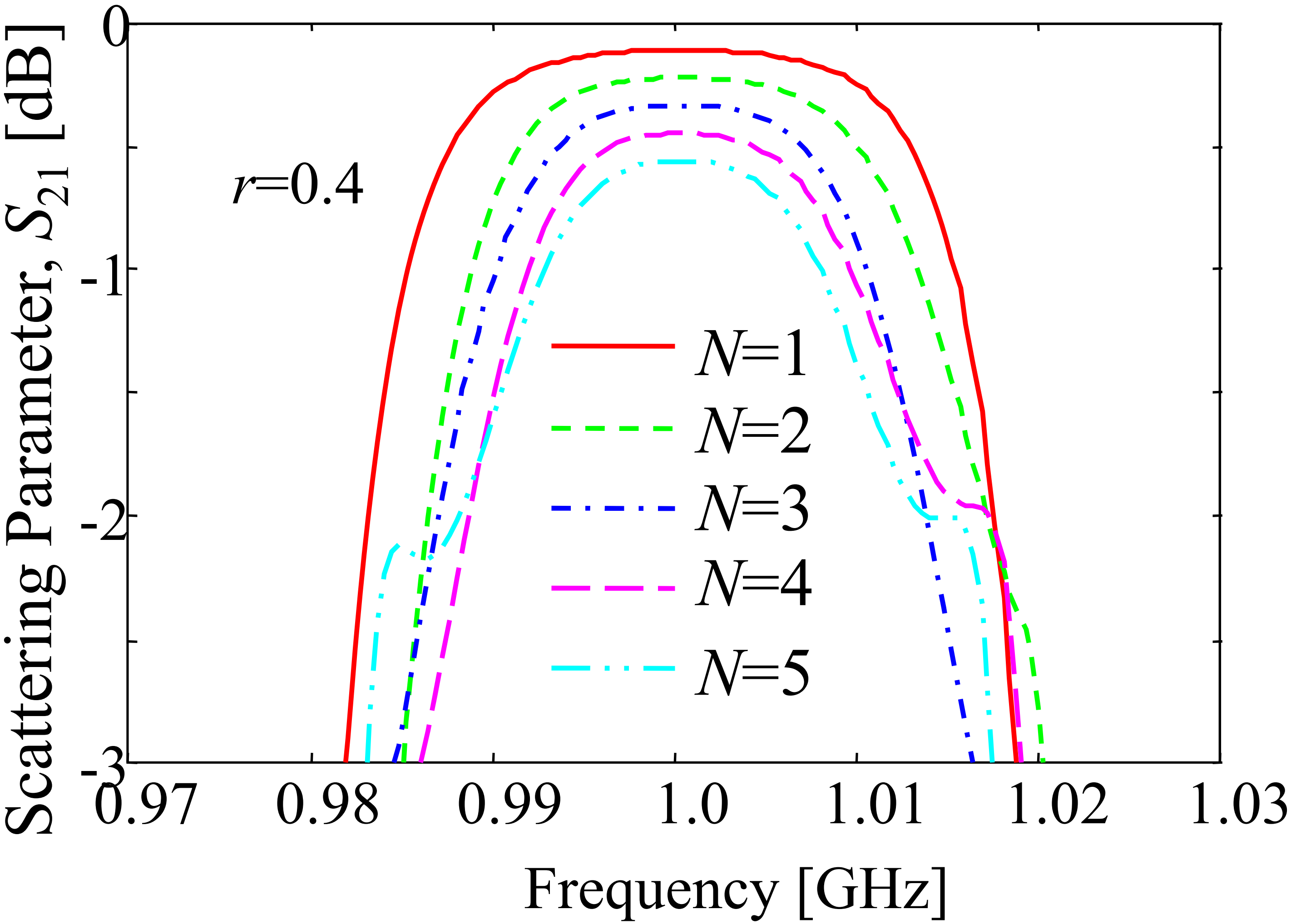
where $T_N(x)=\cosh(N\cosh^{-1}x)$: Chebyshev Polynomial

N Influences IL and OoB Rejection

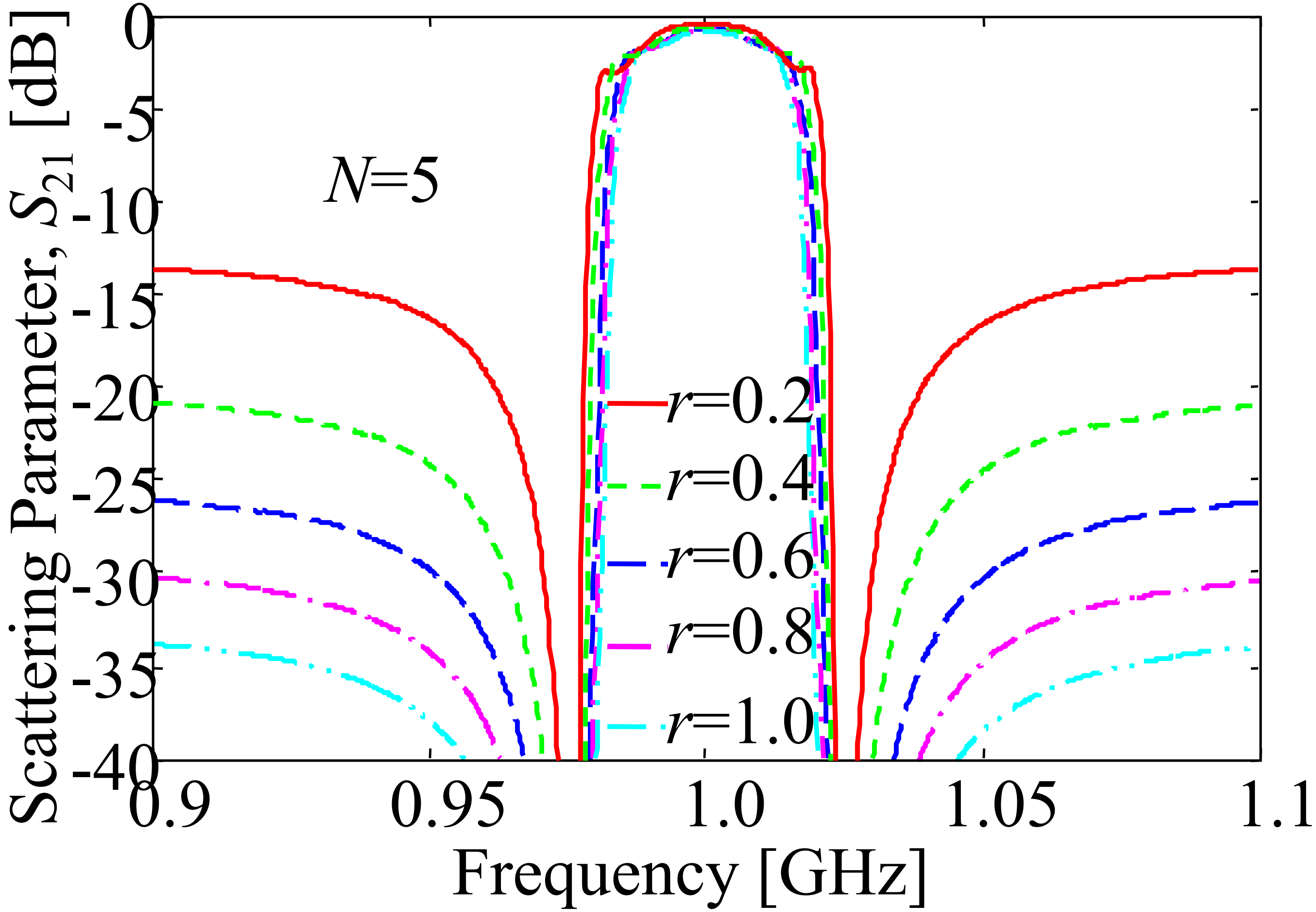
r Influences IL, Bandwidth and OoB Rejection



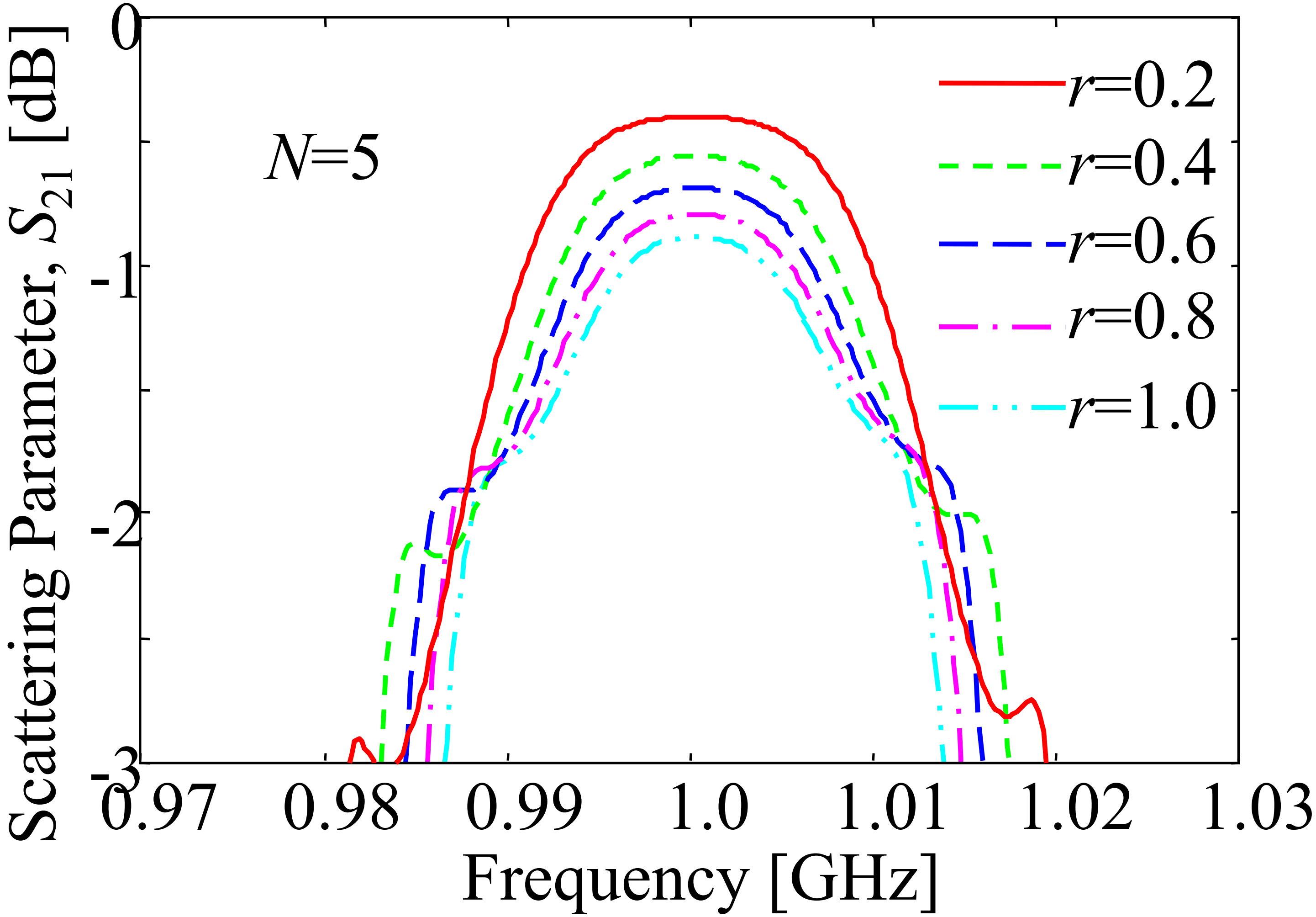
0
-5
-10
-15
-20
-25
-30
Scattering Parameter, S_{21} [dB]
0.9
0.95
1.0
1.05
1.1
Frequency [GHz]
N=1
N=2
N=3
N=4
N=5
r=0.4

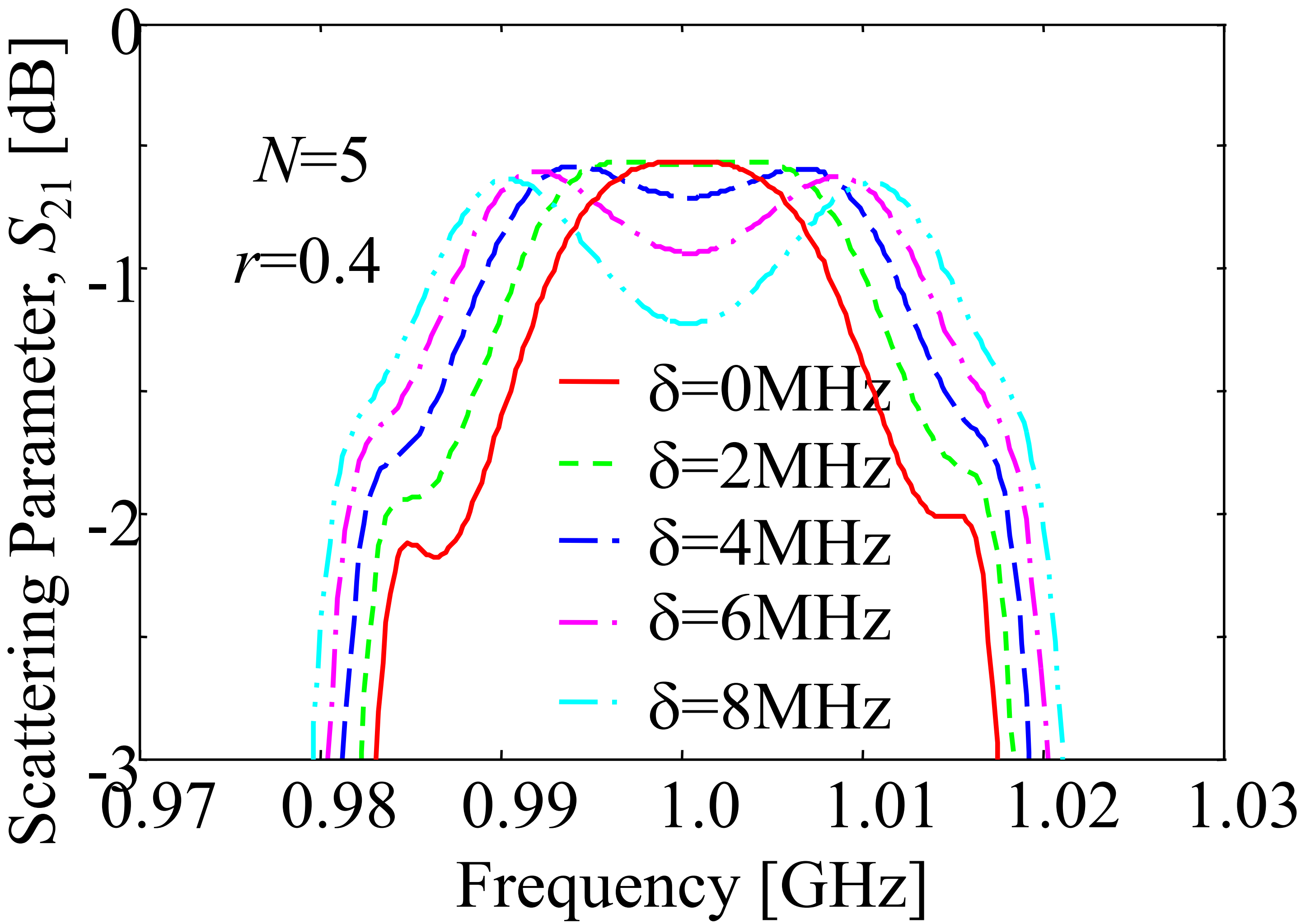


r=0.4
N=1
N=2
N=3
N=4
N=5
0
-1
-2
-3
0.97
0.98
0.99
1.0
1.01
1.02
1.03
Scattering Parameter, S21 [dB]
Frequency [GHz]

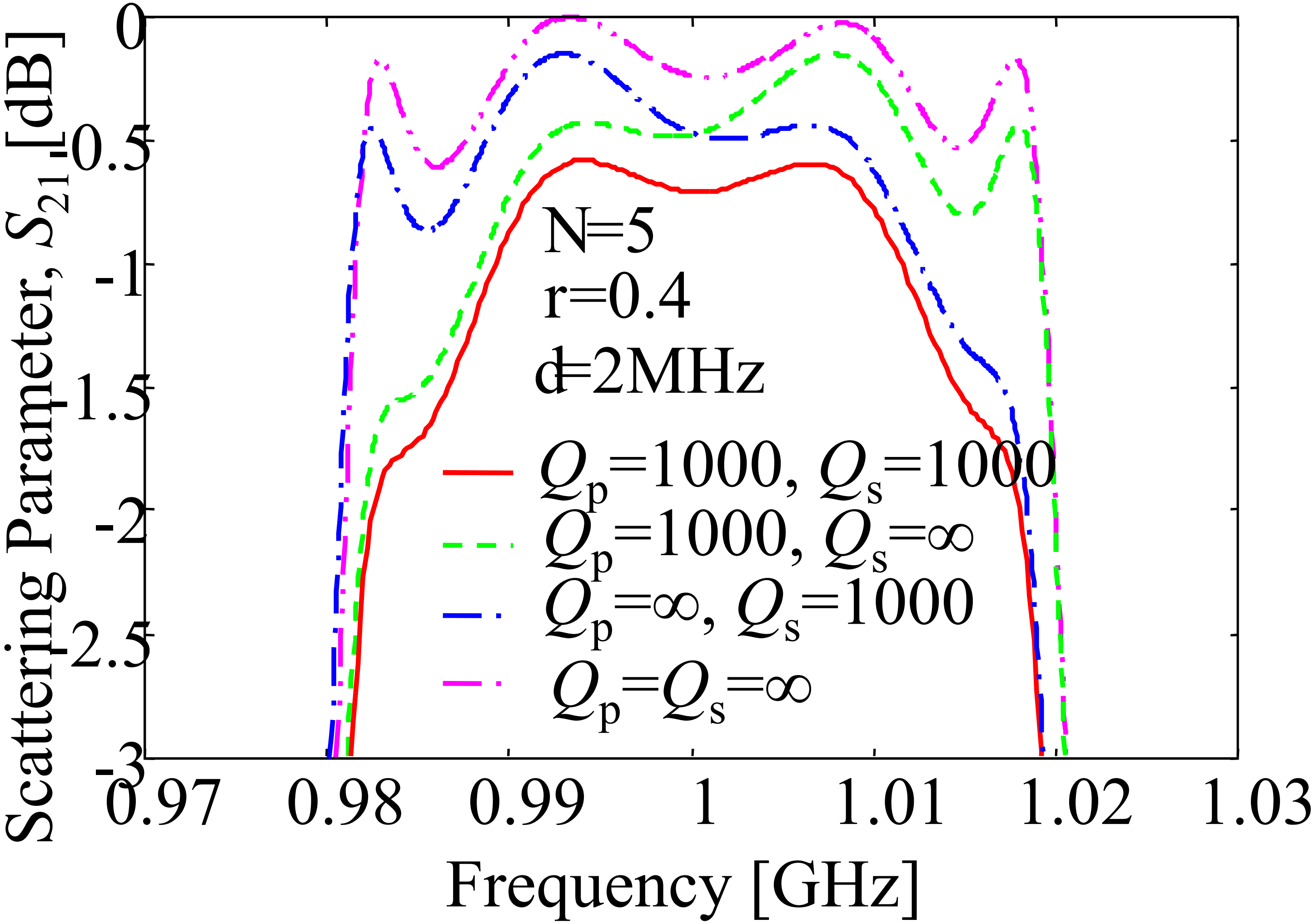


Scattering Parameter, S_{21} [dB]
0
-5
-10
-15
-20
-25
-30
-35
-40
N=5
r=0.2
r=0.4
r=0.6
r=0.8
r=1.0
0.9
0.95
1.0
1.05
1.1
Frequency [GHz]


Scattering Parameter, S_{21} [dB]
0
-1
-2
-3
0.97
0.98
0.99
1.0
1.01
1.02
1.03
Frequency [GHz]
N=5
r=0.2
r=0.4
r=0.6
r=0.8
r=1.0

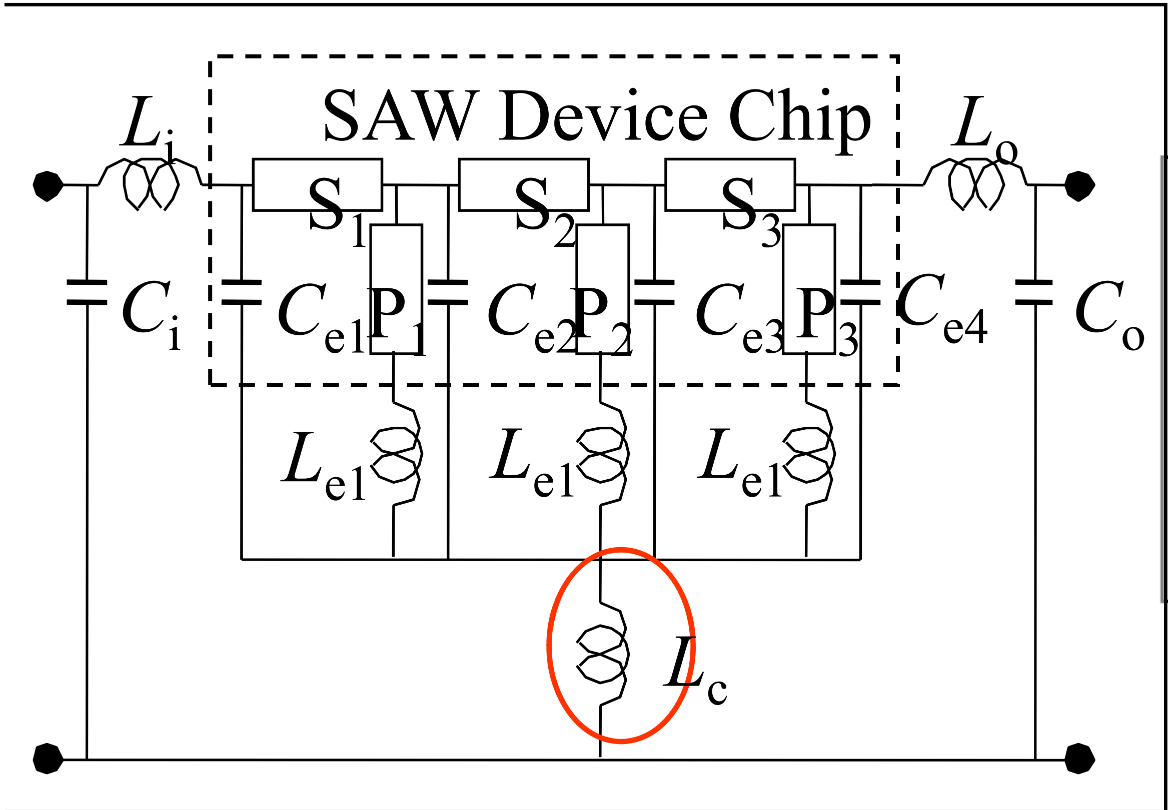


Scattering Parameter, S_{21} [dB]
0
-1
-2
-3
0.97
0.98
0.99
1.0
1.01
1.02
1.03
Frequency [GHz]
N=5
r=0.4
δ=0MHz
δ=2MHz
δ=4MHz
δ=6MHz
δ=8MHz

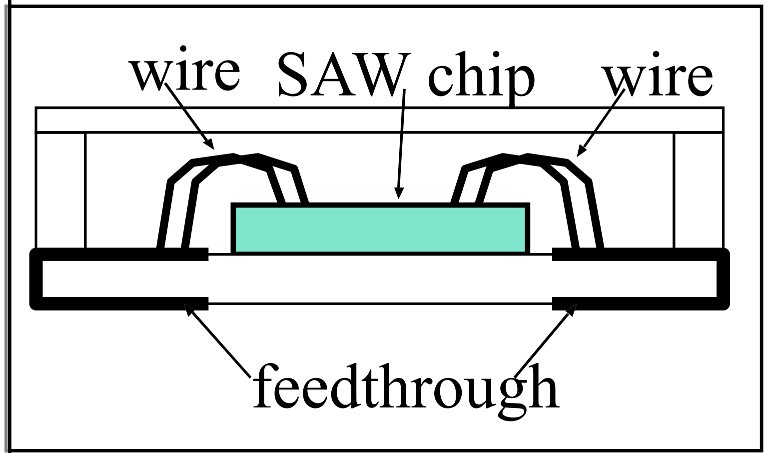


0
-0.5
-1
-1.5
-2
-2.5
-3
0.97
0.98
0.99
1
1.01
1.02
1.03
Frequency [GHz]
Scattering Parameter, S_{21} [dB]
N=5
r=0.4
d=2MHz
Q_p=1000, Q_s=1000
Q_p=1000, Q_s=∞
Q_p=∞, Q_s=1000
Q_p=Q_s=∞

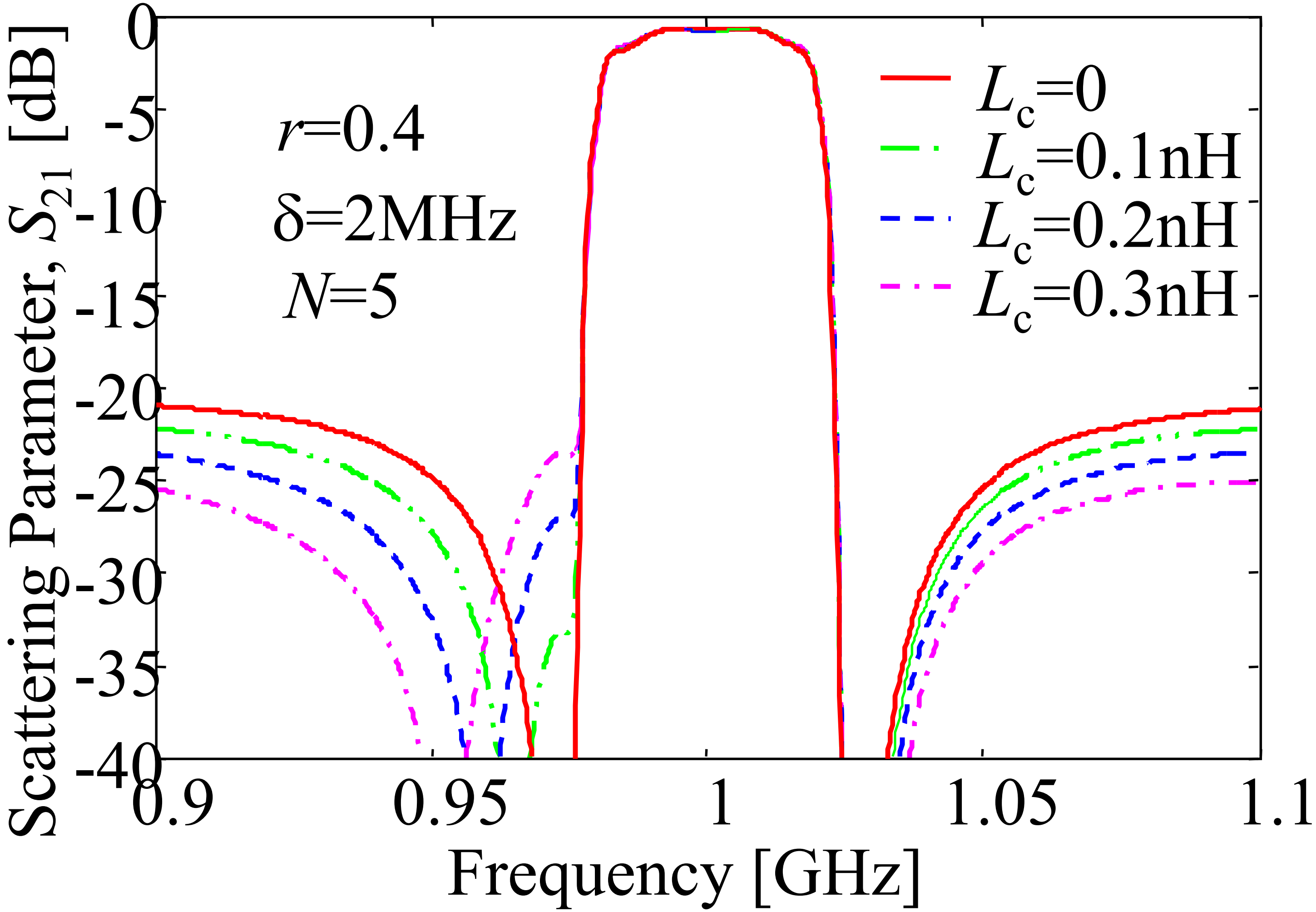
Influence of Common Impedance



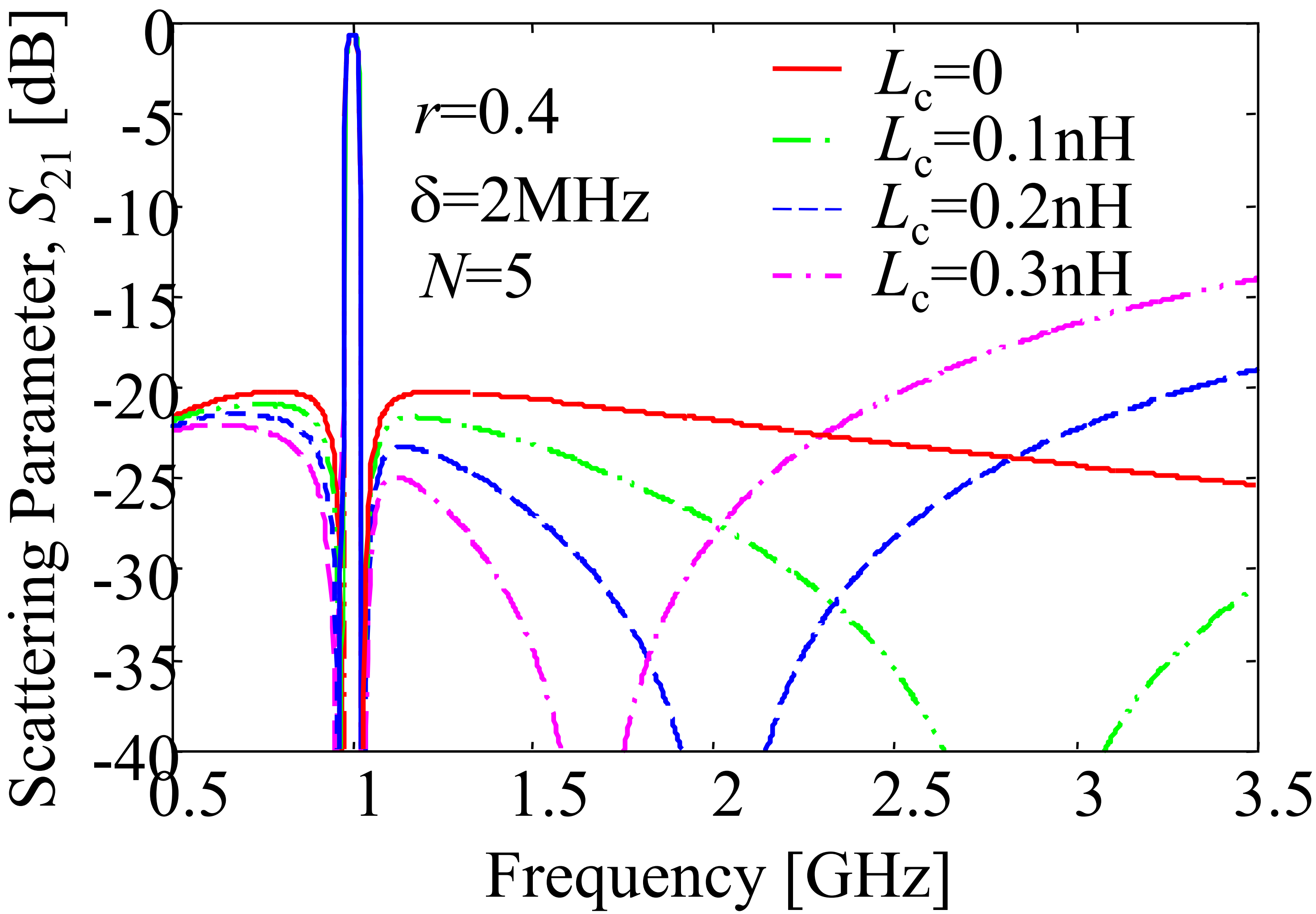
Equivalent Circuit



Origin of L_c



Scattering Parameter, S_{21} [dB]
0
-5
-10
-15
-20
-25
-30
-35
-40
0.9
0.95
1
1.05
1.1
Frequency [GHz]
r=0.4
δ=2MHz
N=5
L_c=0
L_c=0.1nH
L_c=0.2nH
L_c=0.3nH



Scattering Parameter, S_{21} [dB]
0
-5
-10
-15
-20
-25
-30
-35
-40
0.5
1
1.5
2
2.5
3
3.5
Frequency [GHz]
r=0.4
δ=2MHz
N=5
L_c=0
L_c=0.1nH
L_c=0.2nH
L_c=0.3nH

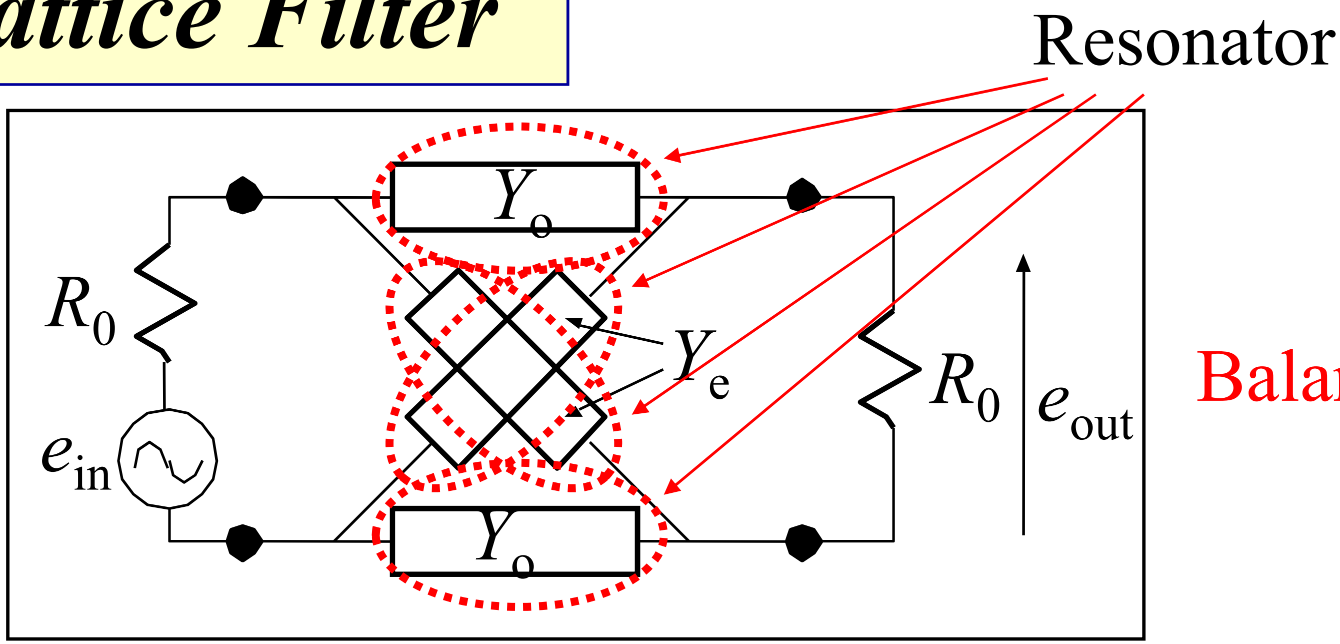
Design of Ladder-type Filters

- Resonator γ Limits Achievable Band Width
- For IL Minimization, $\omega_r^2 C_0^p C_0^s R_S^2 \approx 1$
- For Wide bandwidth, ω_r^s should be a little larger than ω_a^p
- With smaller $r = \sqrt{C_0^p / C_0^s}$, IL and Band Width Improved but OoB Rejection Deteriorated.
- With N, OoB Rejection Improved but IL Increases
- *IL* is Very Sensitive to Motional Resistance of Y_s
- Very Sensitive to Parasitics
- Q Influences IL and Shoulder Characteristics

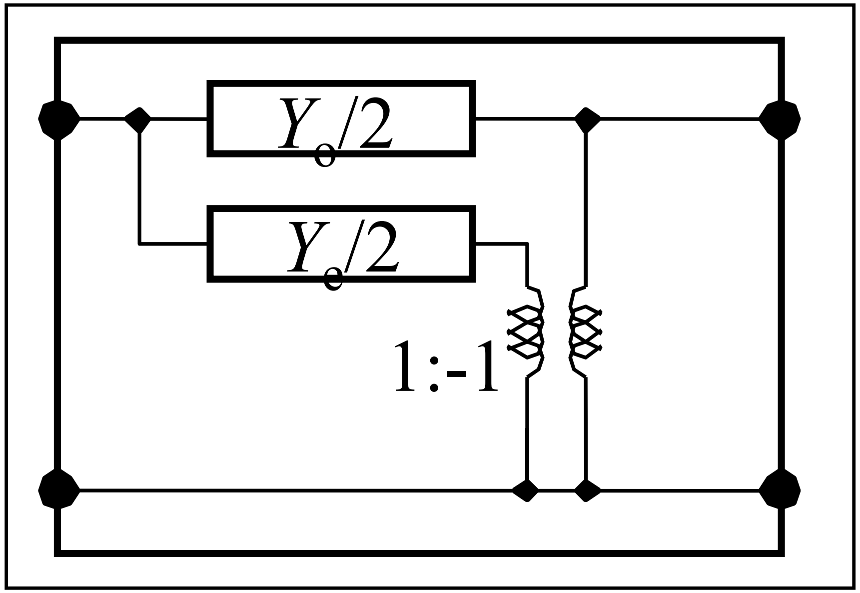
Contents

- Lattice Filter Design

Lattice Filter

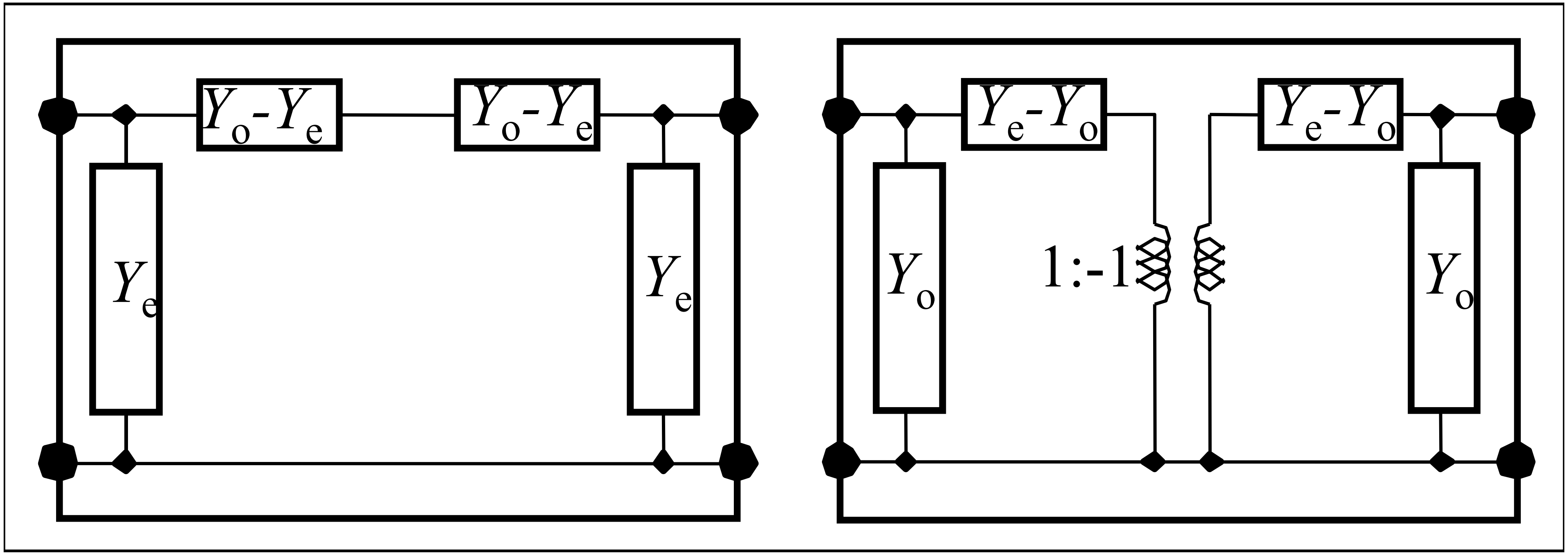


Balanced I/O



Equivalent Circuit

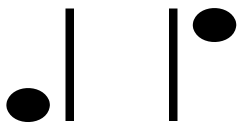
Unbalanced I/O



Modified Equivalent Circuit

Equivalent to 2-Stage Cascaded *L*-type (or π-type) Filter

Res. Freq. for Series Arm



Anti-Res. Freq. for Parallel Arm

$Y_e=\infty$, $Y_o=0$
or
$Y_o=\infty$, $Y_e=0$

Resonance Condition

Res. Freq. for Y_o || Anti-Res. Freq. for Y_e Or Res. Freq. for Y_e || Anti-Res. Freq. for Y_o

$$S_{21} = \frac{R_0(Y_o - Y_e)}{(1+Y_eR_0)(1+Y_oR_0)}$$

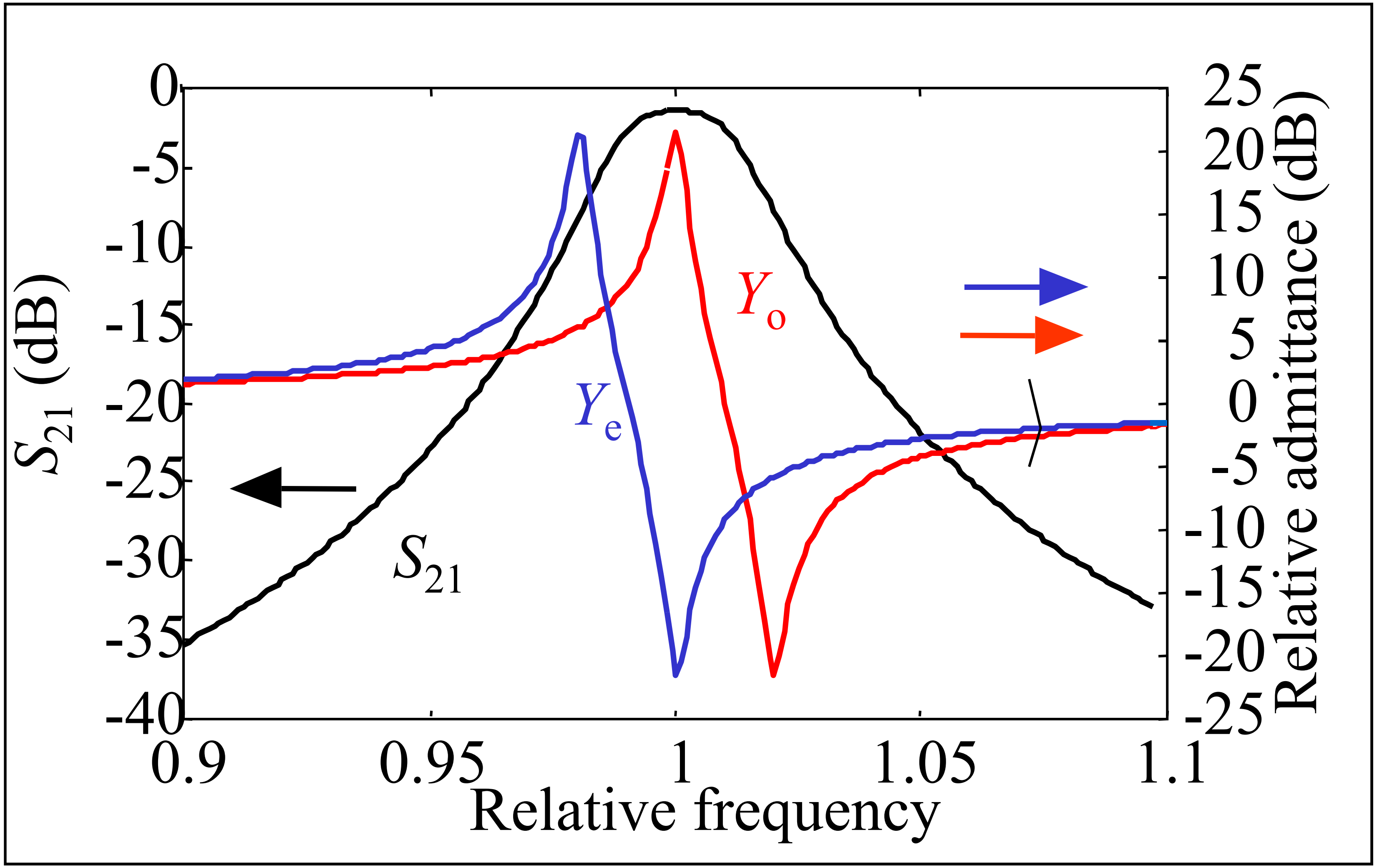
At Resonance

$$S_{21}\Big|_{\omega=\omega_r^o} \cong \frac{\eta(M^{-1}-M)}{\eta^2+\eta(M^{-1}+M)+1}$$

Where $M=Q_r/\gamma$, $\eta=\omega C_0R_0$

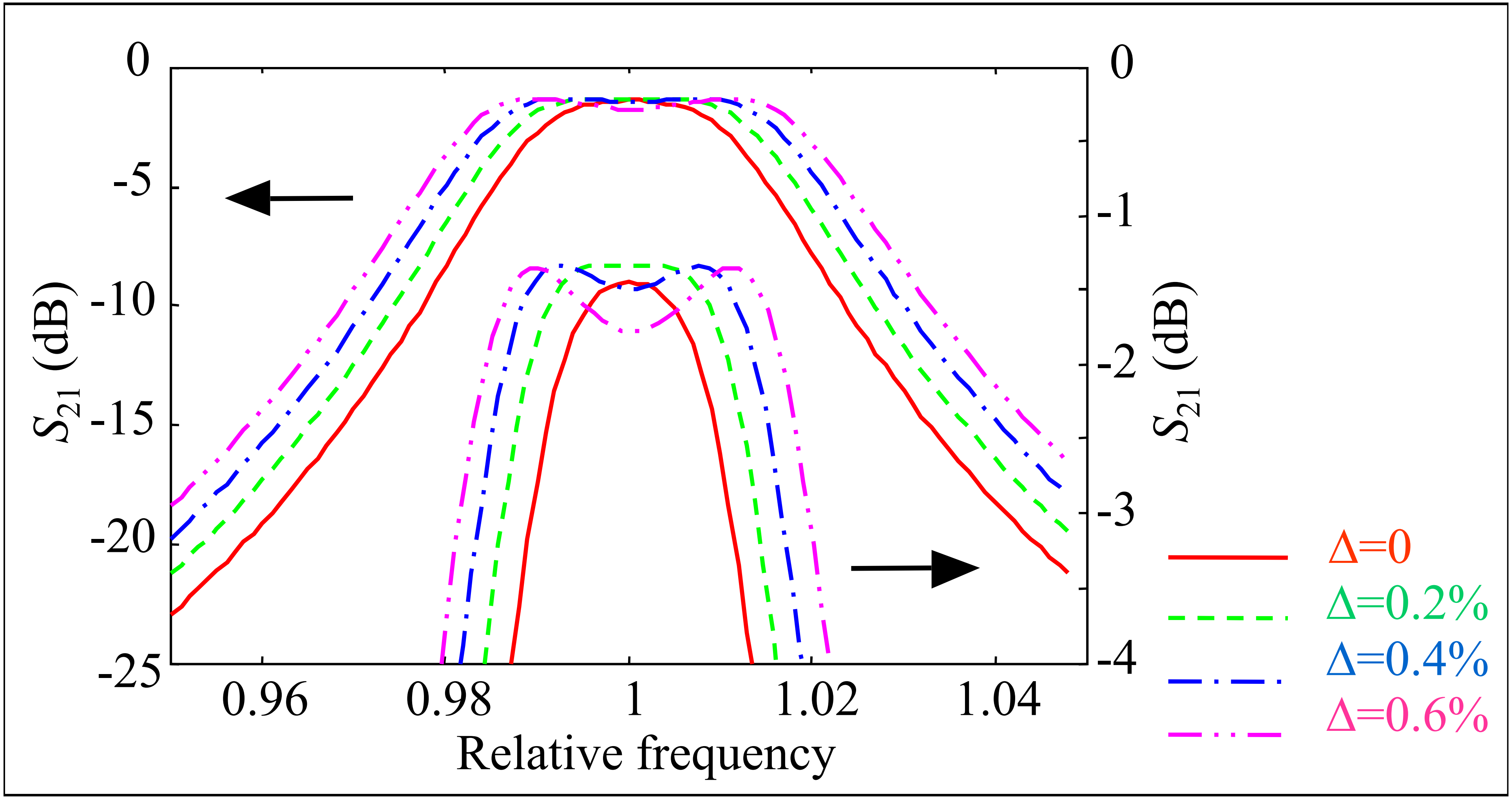
IL Min. Condition η=1 ⇨ $S_{21}\Big|_{\omega=\omega_r^o} \cong \dfrac{1-M}{1+M}$

Frequency Response

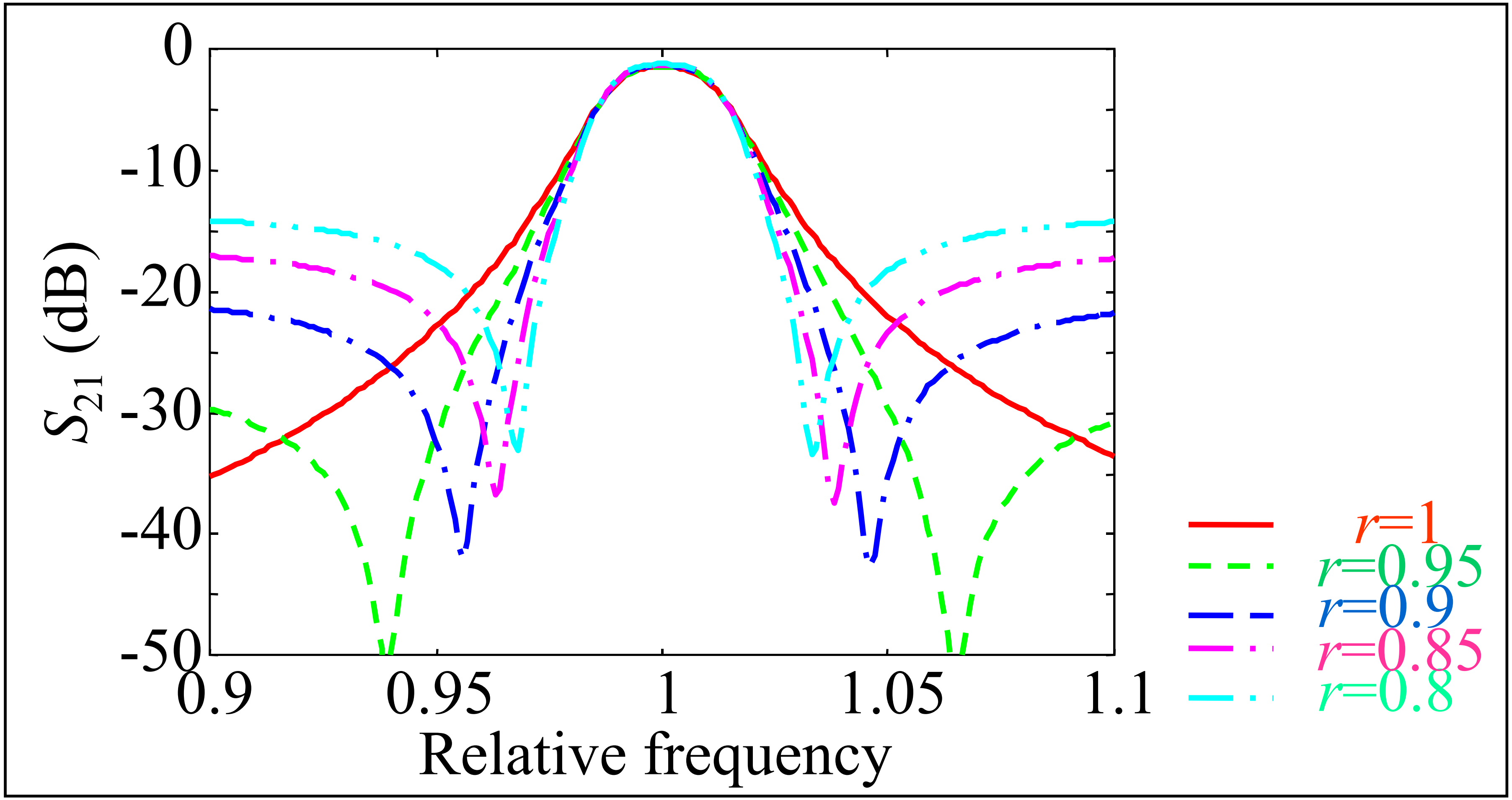


Good OoB Rejection

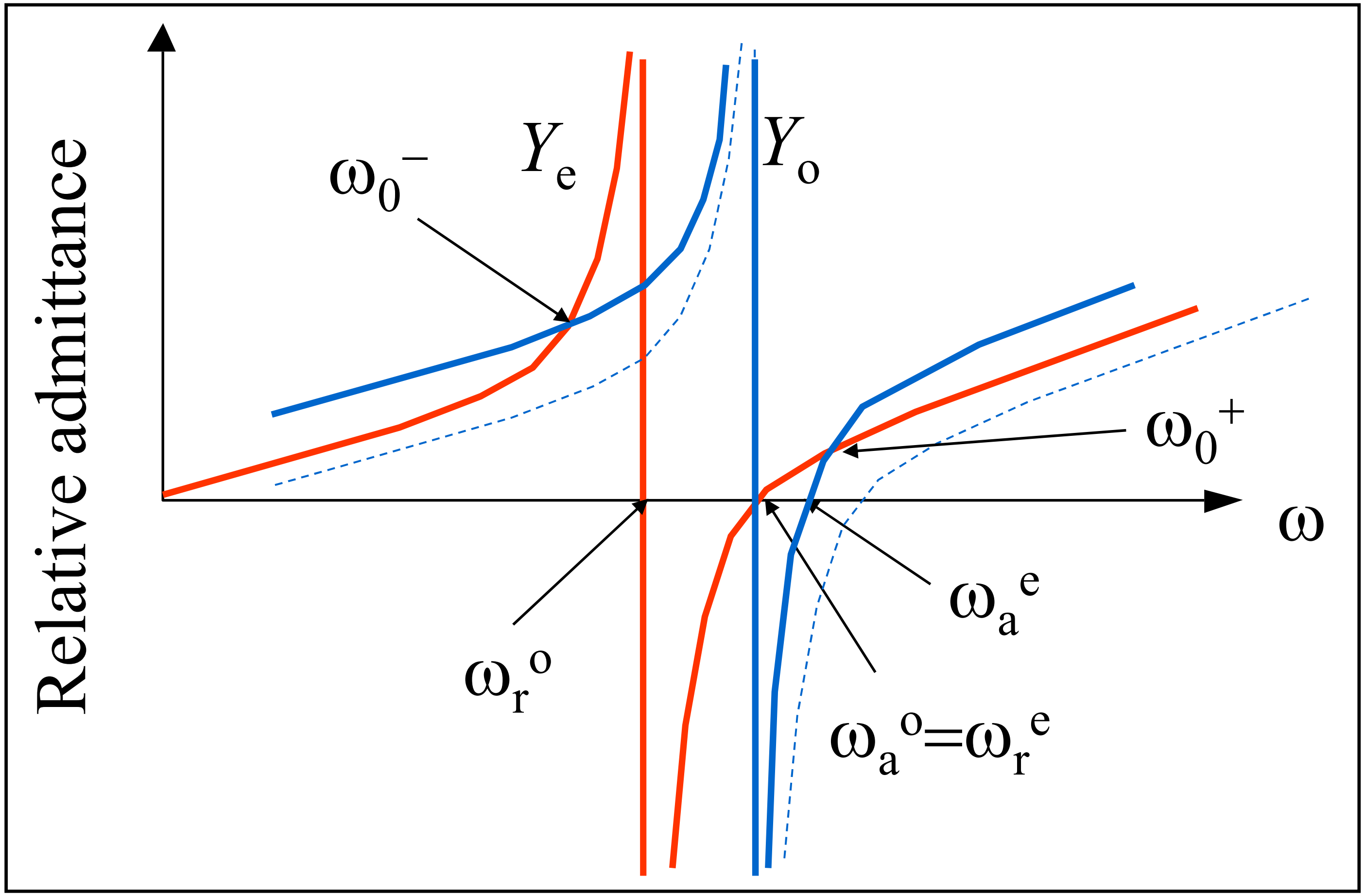
Wideband When $\omega_r^o > \omega_a^e$



Better OoB Rejection When $C_0^o > C_0^e$



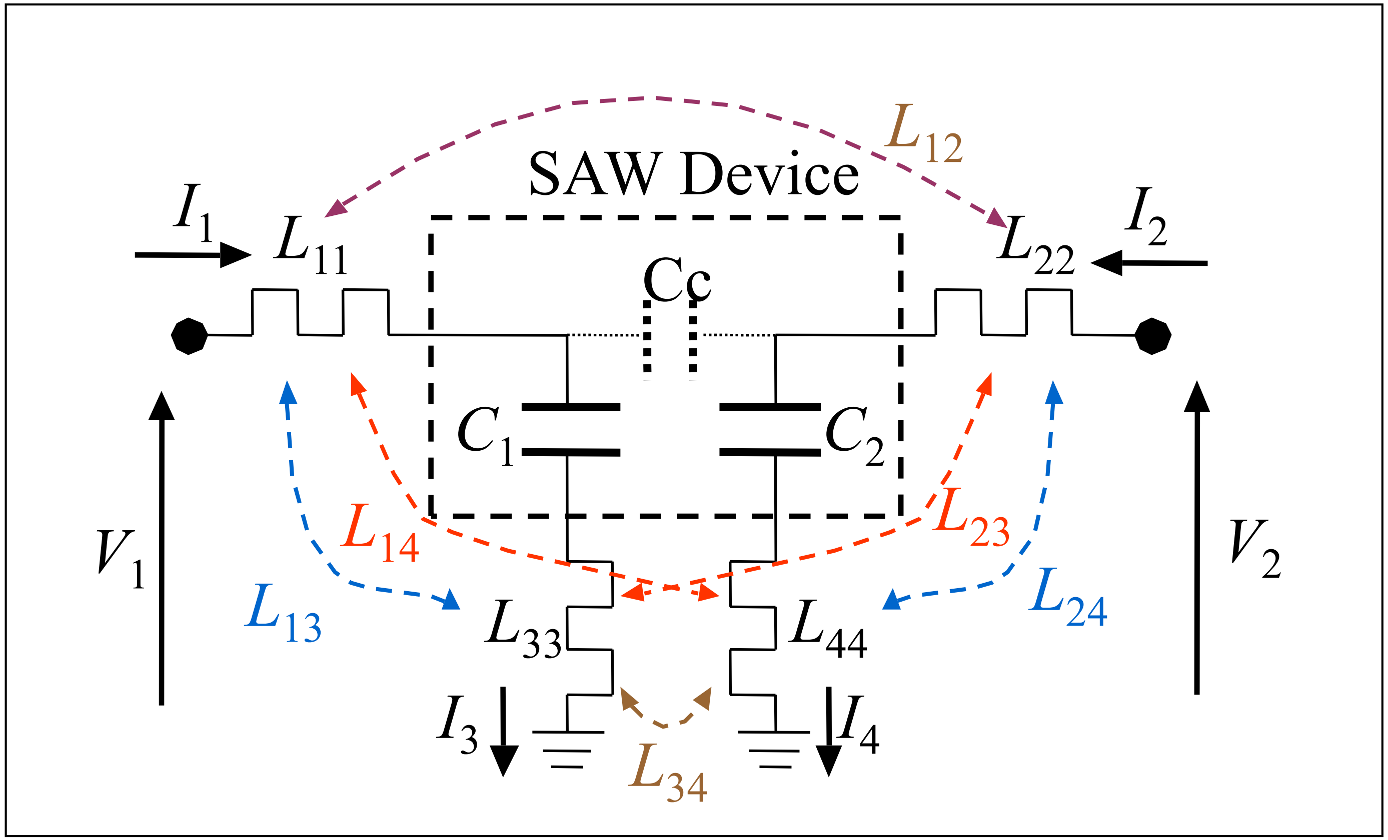
Null Generation Near Passband



$$S_{21} = \frac{R_0(Y_o - Y_e)}{(1 + Y_e R_0)(1 + Y_o R_0)}$$

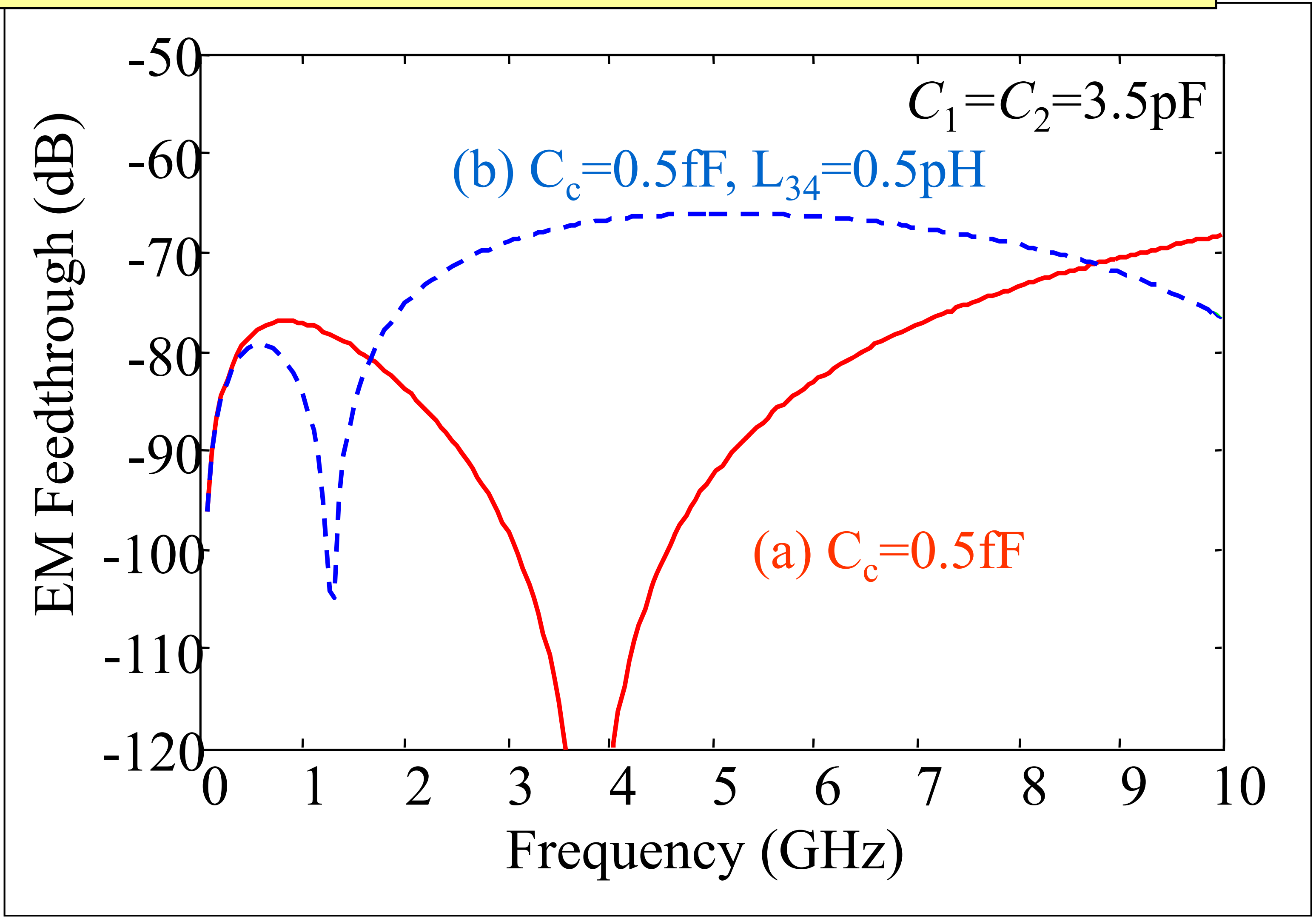
Null Generation When
$Y_e = Y_o$

Influence of Mutual Coupling



Very Small Values but May Not Negligible

Influence of Inductive Coupling

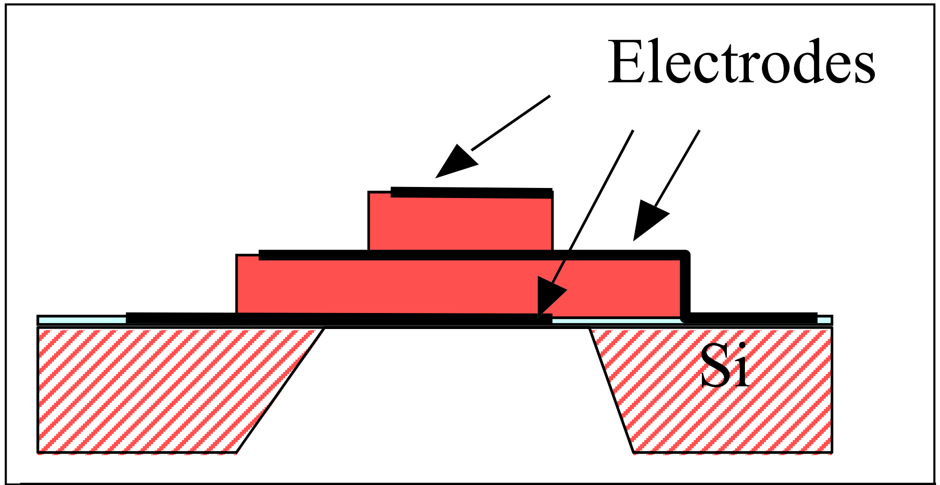


Tiny Coupling Gives Significant Influence

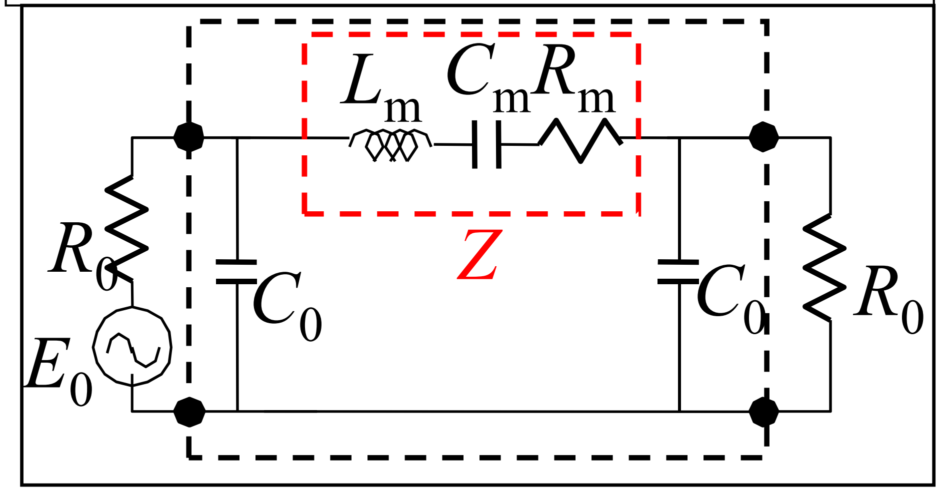
Contents

- Stacked Resonator Filter Design

Stacked FBAR Filter



- Good OoB Rejection
- Moderate IL



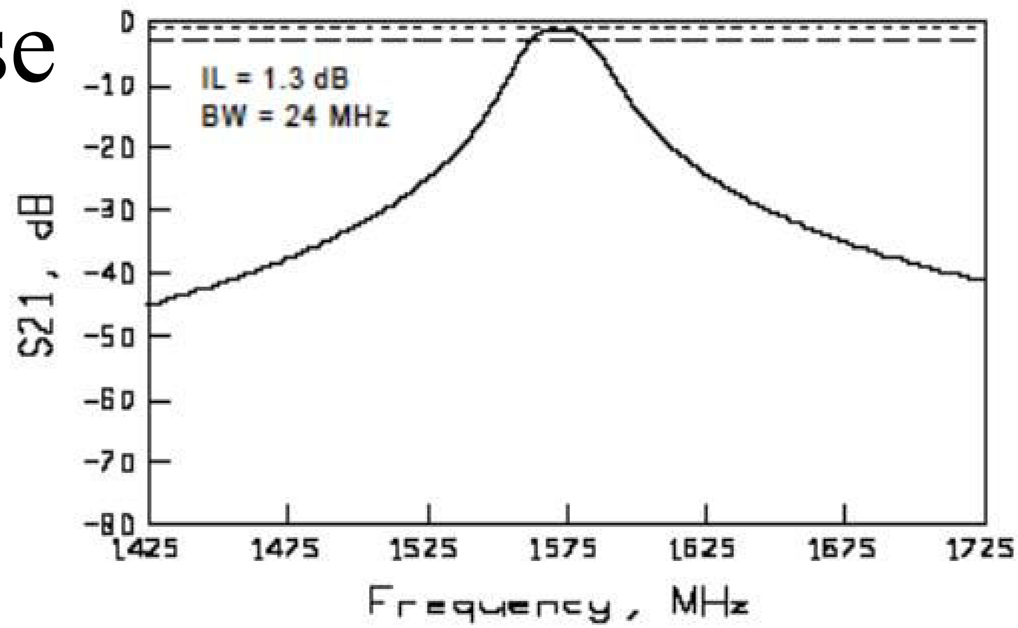
Equivalent Circuit for Fundamental Resonance

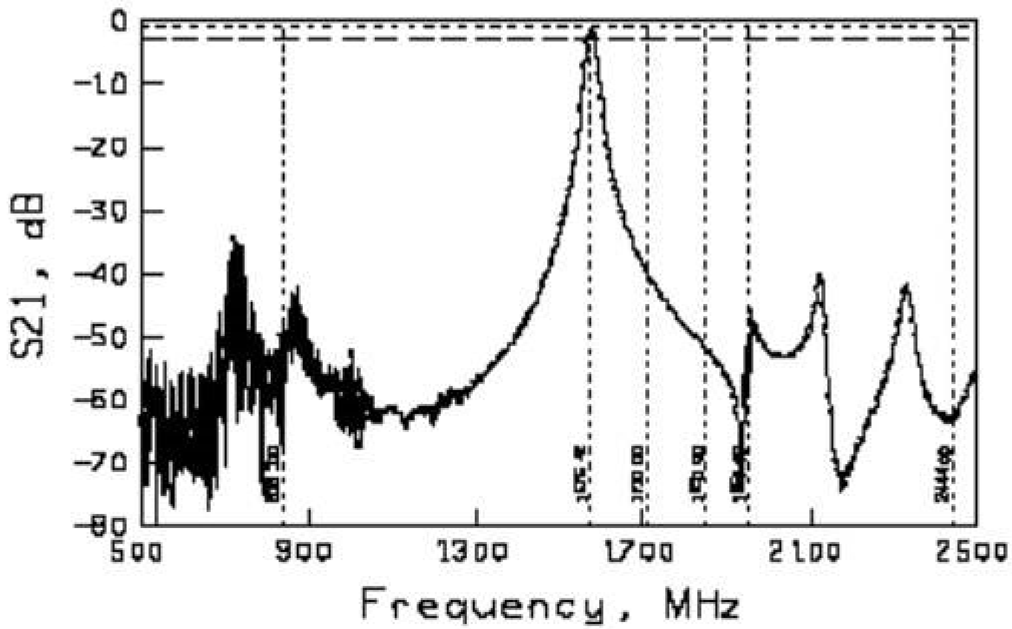
Static Capacitance When Parallel-Connected

1-Port Resonator When Parallel-Connected with Inversion

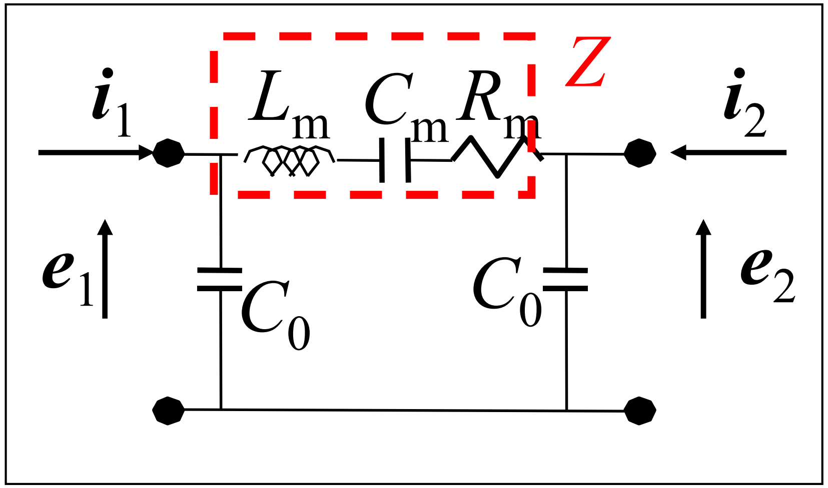
Frequency Response of Stacked Resonator Filter

GPS 2-POLE SCF





From TFR Technologies



$$\begin{pmatrix} i_1 \\ i_2 \end{pmatrix} = \begin{pmatrix} Y_{11} & Y_{12} \\ Y_{12} & Y_{11} \end{pmatrix} \begin{pmatrix} e_1 \\ e_2 \end{pmatrix}$$

Where $Y_{11} = j\omega C_0 + Z^{-1}$

$$Y_{12} = -Z^{-1}$$

$$Z = j\omega L_m + R_m + 1/\, j\omega C_m$$

Transfer Function

$$S_{21} = \frac{2}{(1 + j\omega C_0 R_0)\{Z R_0^{-1}(1 + j\omega C_0 R_0) + 2\}}$$

Ideal Case (R_m=0), $2 + Z R_0^{-1}(1 + j\omega C_0 R_0) = 2/(1 - j\omega C_0 R_0)$

At ω_0 Satisfying $Z = \dfrac{2 j\omega_0 C_0 R_0^2}{1 + (\omega_0 C_0 R_0)^2}$

$$S_{21} = \frac{1 - j\omega_0 C_0 R_0}{1 + j\omega_0 C_0 R_0}$$ → $|S_{21}| = 1$ (Loss Less)

$$Z \approx 2j(\omega - \omega_0)L + R_m + \frac{2j\omega_0 C_0 R_0^2}{1 + (\omega_0 C_0 R_0)^2} \quad \text{Gives}$$

$$S_{21} \approx \frac{G_0}{(G_0 + j\omega C_0)^2 [j(\omega - \omega_0)L + R_m / 2 + G_0 / \{G_0^2 + (\omega C_0)^2\}]}$$

$$\left| S_{21} \right|_{\omega=\omega_0} \approx \frac{1}{R_m \{1 + (\omega_0 C_0 R_0)^2\} / 2R_0 + 1}$$

$$\gamma = C_0 / C_m$$

$$Q = \frac{1}{\omega_0 C_m R_m} = \frac{\omega_0 L_m}{R_m}$$

$$M = Q / \gamma$$

IL Min. Condition $\omega_0 C_0 R_0 = 1$

$$\Rightarrow \left| S_{21} \right|_{\omega=\omega_0} \approx \frac{1}{1 + \omega_0 C_0 R_m} = \frac{1}{1 + M^{-1}}$$

Determined by M

When $\omega_0 C_0 = G_0$ $$S_{21} \approx \frac{1}{j[2j\gamma(\omega-\omega_0)/\omega_0 + M^{-1}+1]}$$

When $\omega = \omega_{\pm} = \omega_0[1 \pm \gamma^{-1}(1+M^{-1})/2]$ $$|S_{21}| \approx \frac{1}{\sqrt{2}}\frac{1}{[1+M^{-1}]}$$

-3dB Bandwidth

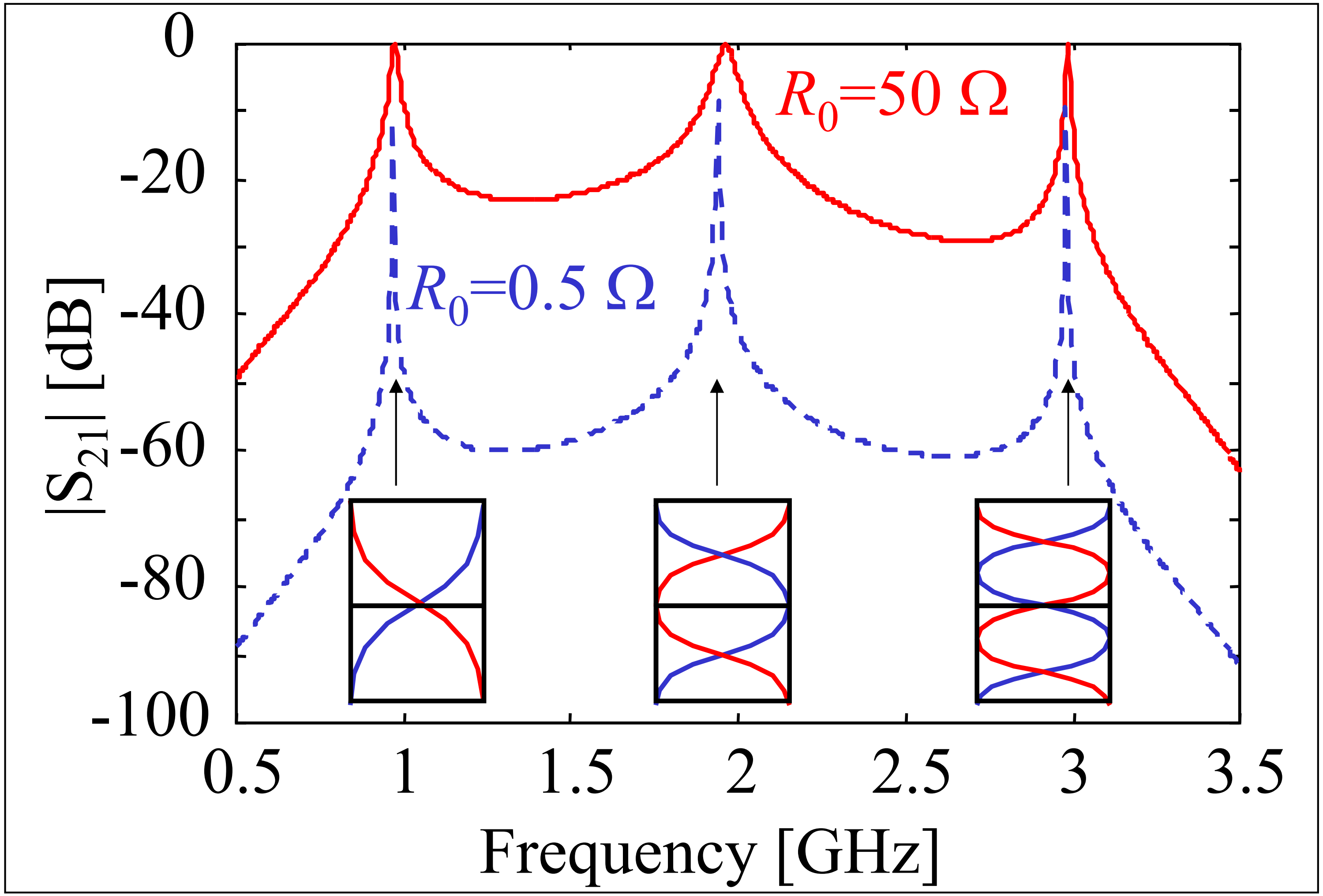
$$\frac{\omega_+ - \omega_-}{\omega_0} = \gamma^{-1}(1+M^{-1})$$

$$\Rightarrow |S_{21}|_{\omega=\omega_0} \bullet \frac{\omega_+ - \omega_-}{\omega_0} \approx \gamma^{-1}$$

Determined by M and γ

$$\gamma = C_0 / C_m$$
$$Q = \frac{1}{\omega_0 C_m R_m} = \frac{\omega_0 L_m}{R_m}$$
$$M = Q/\gamma$$

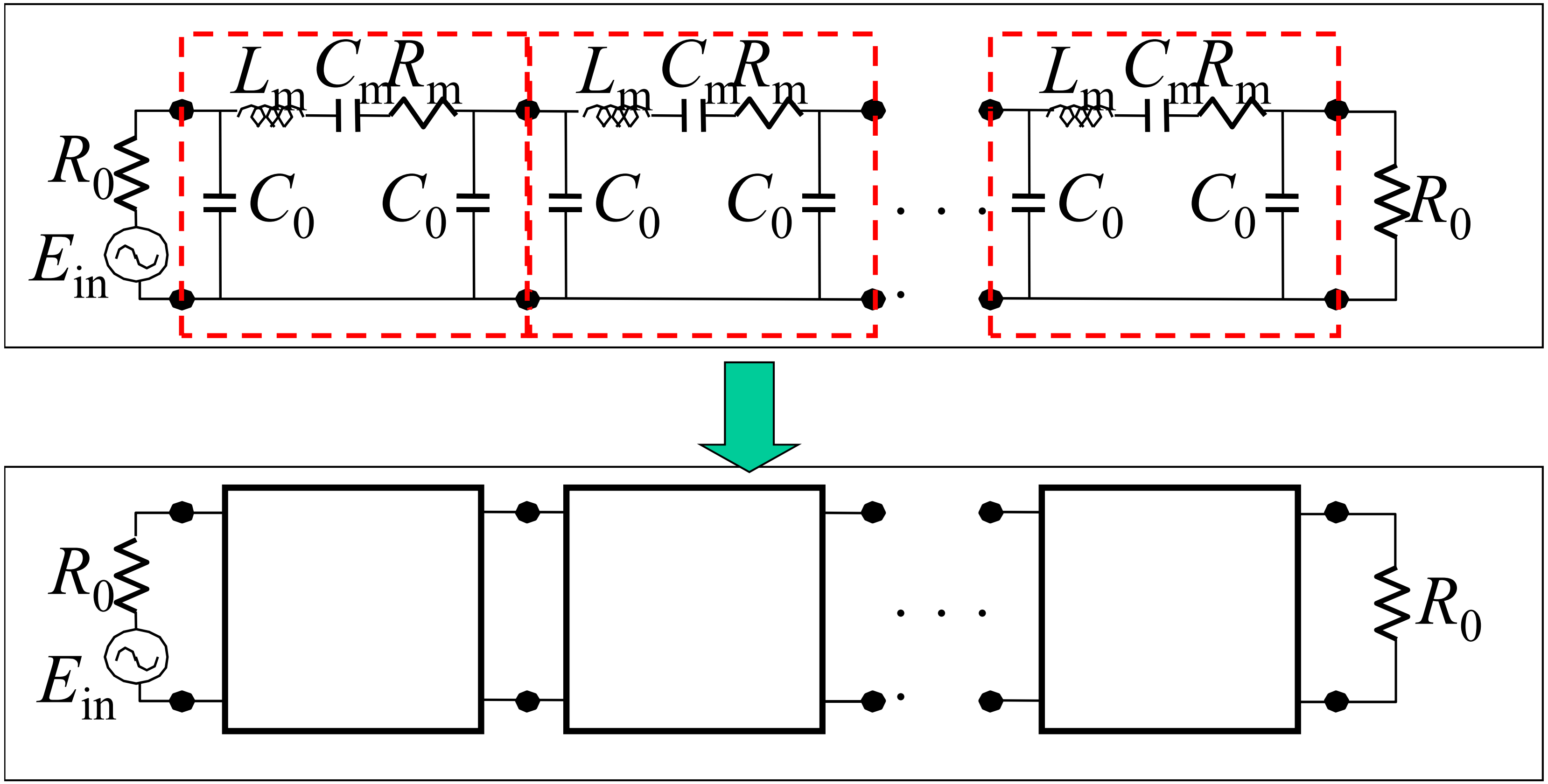
Response of Stacked Resonator Filter



ZnO (L=1.6 μm, S=160×160 μm^2)

S is Set to Z-Match at 2GHz

Cascaded Stacked Resonator Filters



$$\mathbf{F}^N = \begin{pmatrix} \cos\theta & jR_e \sin\theta \\ jR_e^{-1}\sin\theta & \cos\theta \end{pmatrix}^N = \begin{pmatrix} \cos N\theta & jR_e \sin N\theta \\ jR_e^{-1}\sin N\theta & \cos N\theta \end{pmatrix}$$

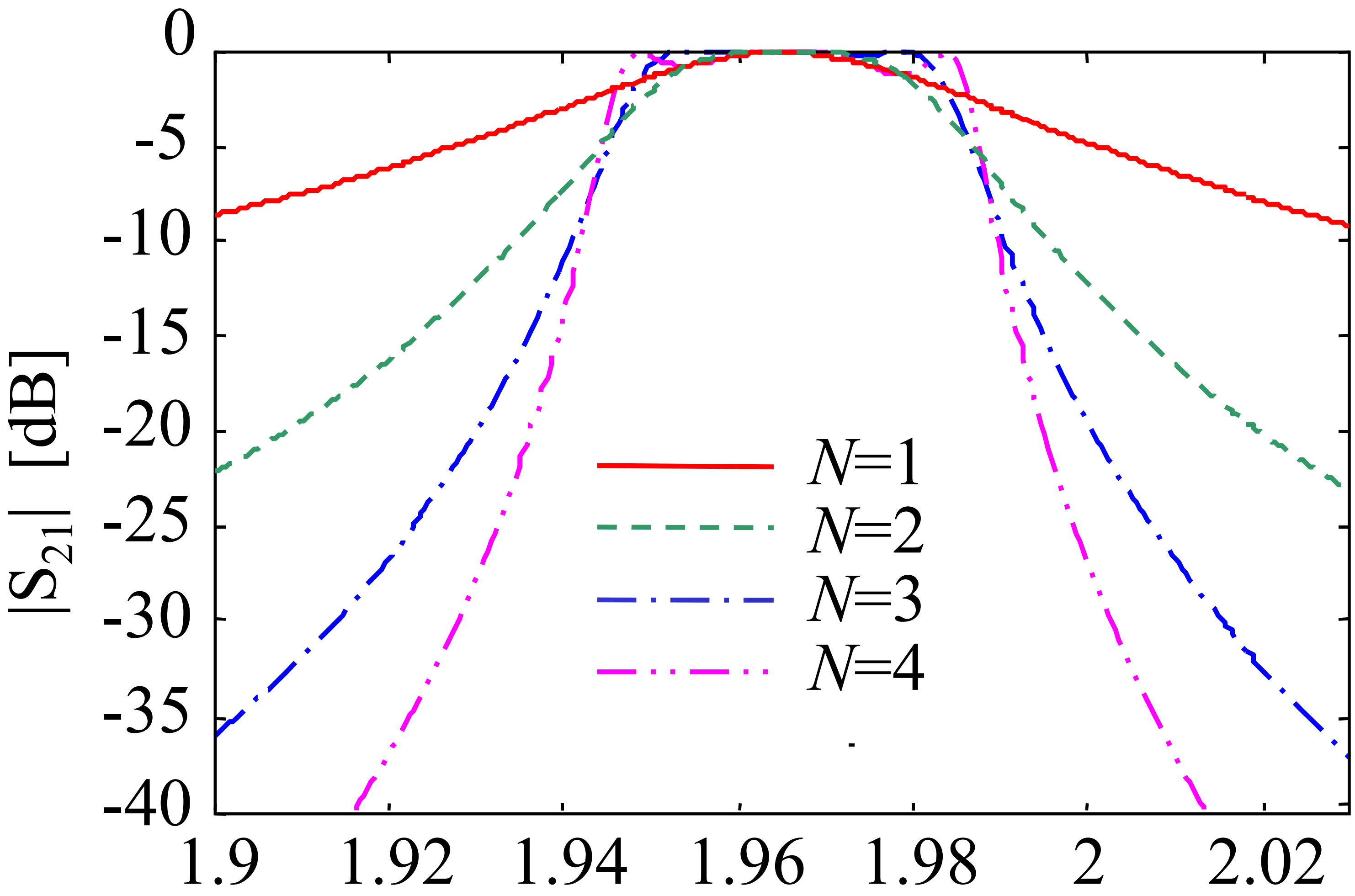
where

$$\cos\theta = 1 + j\omega C_0 Z$$

$$jR_e \sin\theta = Z$$

$$jR_e^{-1}\sin\theta = j\omega C_0(2 + j\omega C_0 Z)$$

$$Z = j\omega L_m + R_m + 1/j\omega C_m$$



ZnO (L=1.6 μm, S=160×160 μm^2)

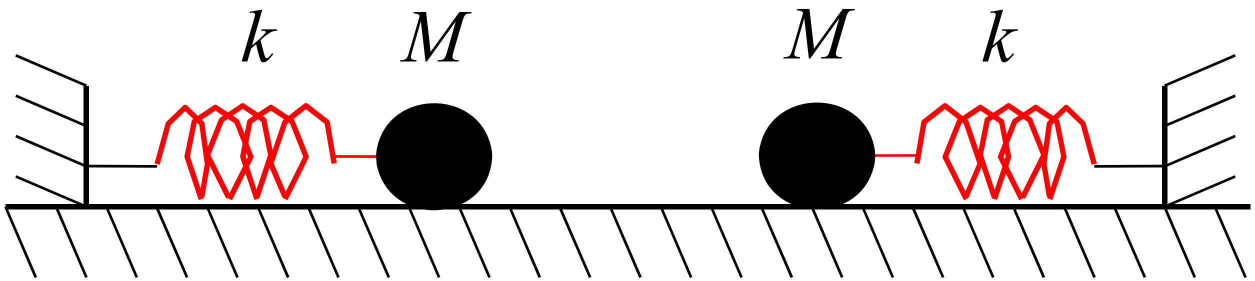
Widened Passband

Steeper Skirt Characteristics

Contents

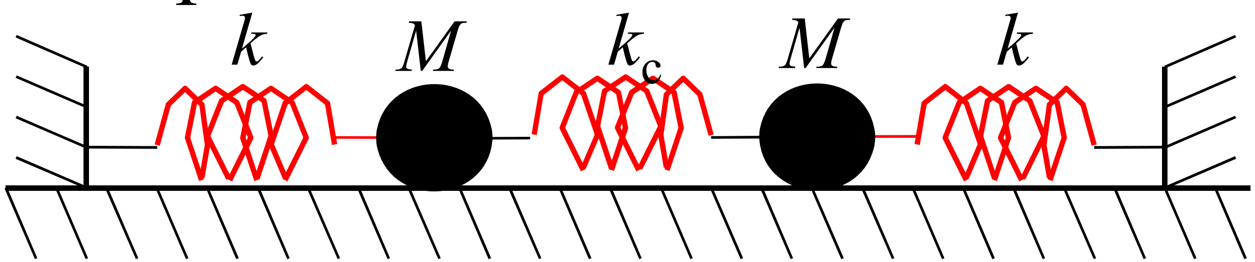
- Coupled Resonator Filter Design

Uncoupled State



Resonance Frequency: $\omega_r=(k/M)^{0.5}$

Coupled State

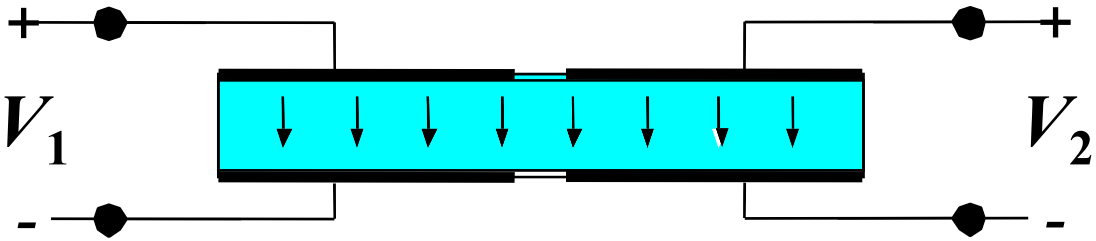


Resonance Frequency

Symmetric Resonance: $\omega_{rs}=\{(k+2k_c)/M\}^{0.5}$

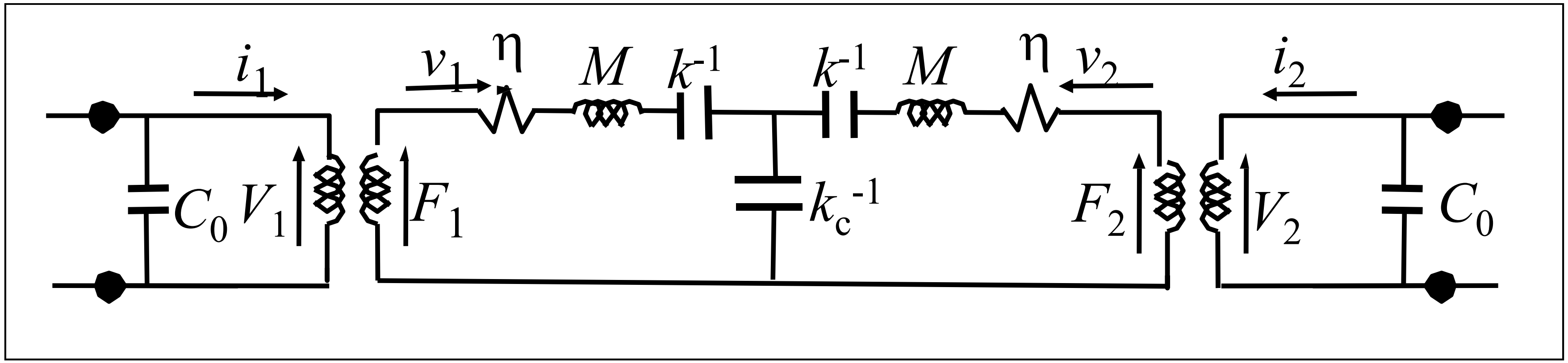
Antisymmetric Resonance: $\omega_{ra}=(k/M)^{0.5}$

Coupled Resonator

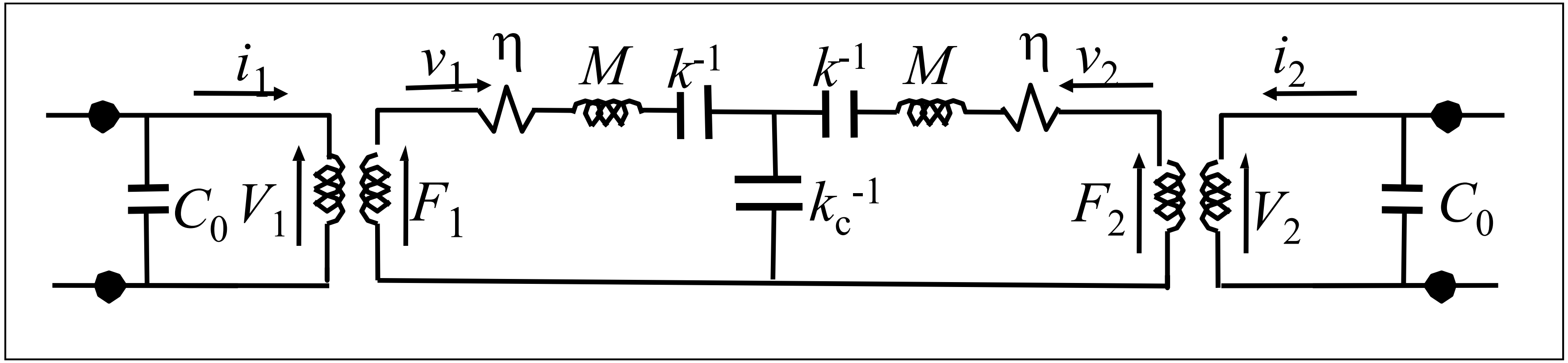


$$M\frac{dv_1}{dt}+\eta v_1+k\int v_1 dt+k_c\int (v_1+v_2)dt \propto V_1$$

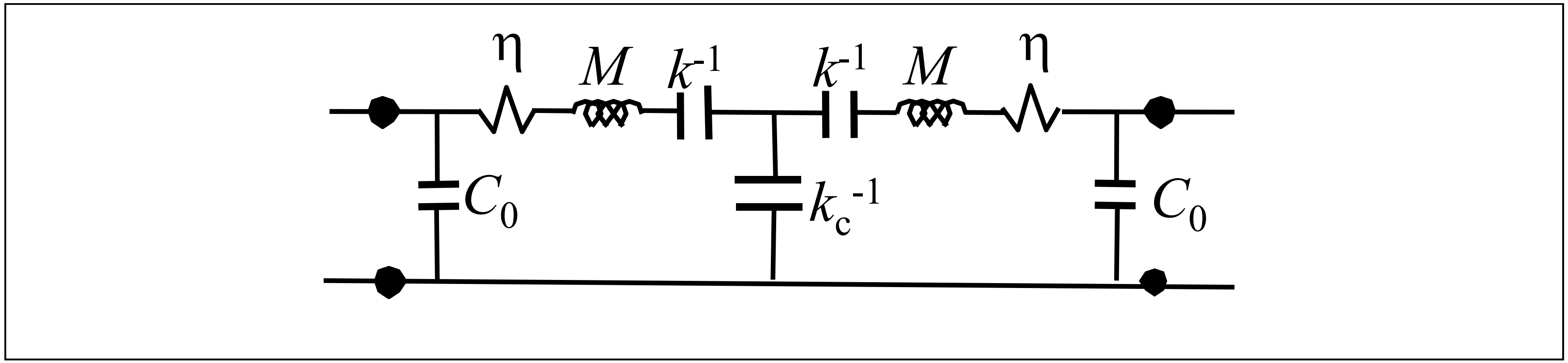
$$M\frac{dv_2}{dt}+\eta v_2+k\int v_2 dt+k_c\int (v_1+v_2)dt \propto V_2$$



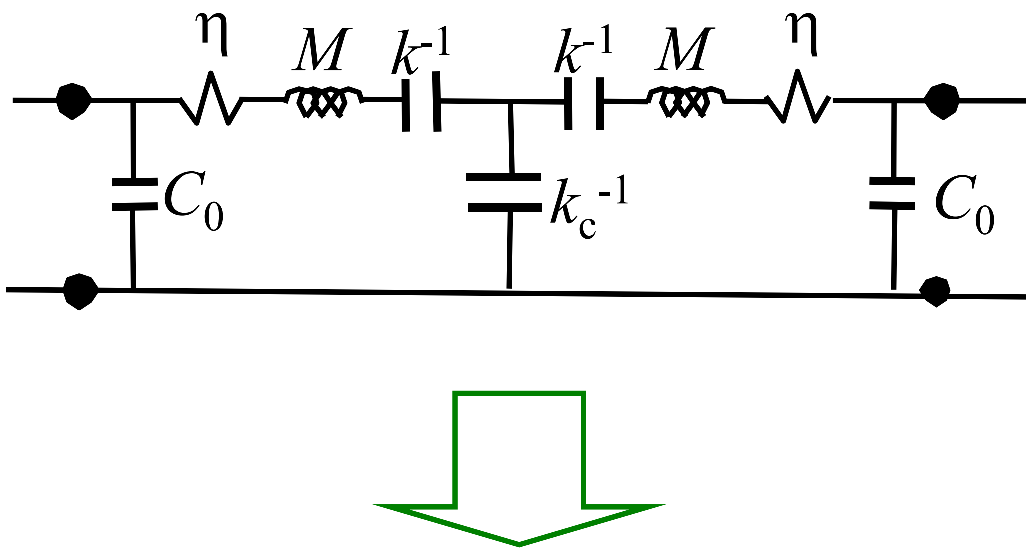
(a) Electric + Mechanical Circuit

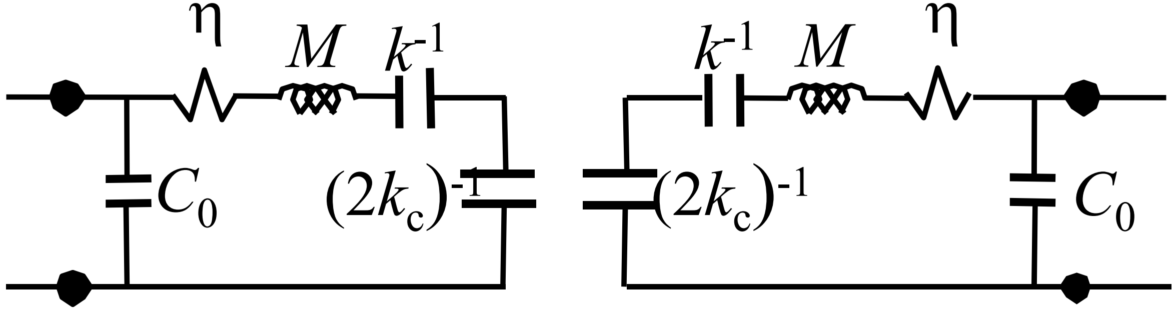


(a) Electric + Mechanical Circuit

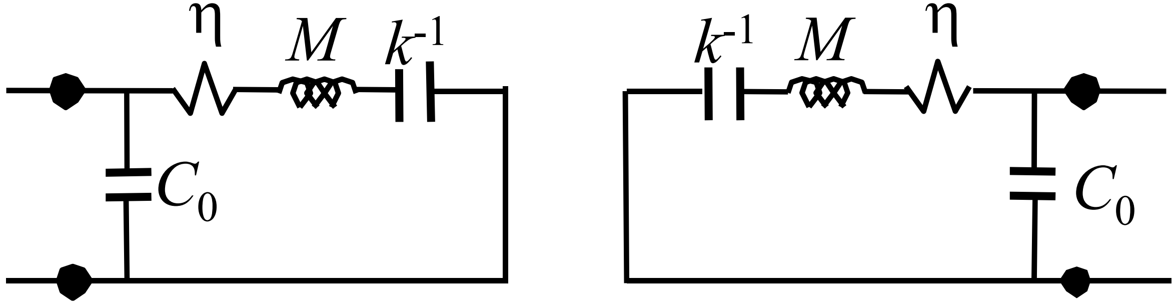


(b) Mechanical Circuit



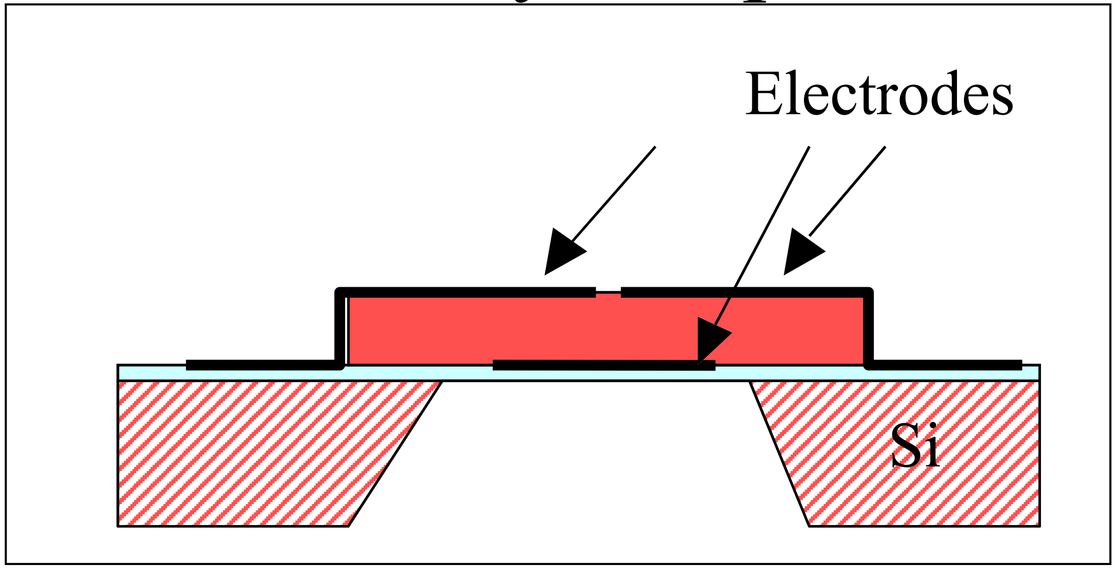


(a) Symmetric Resonance

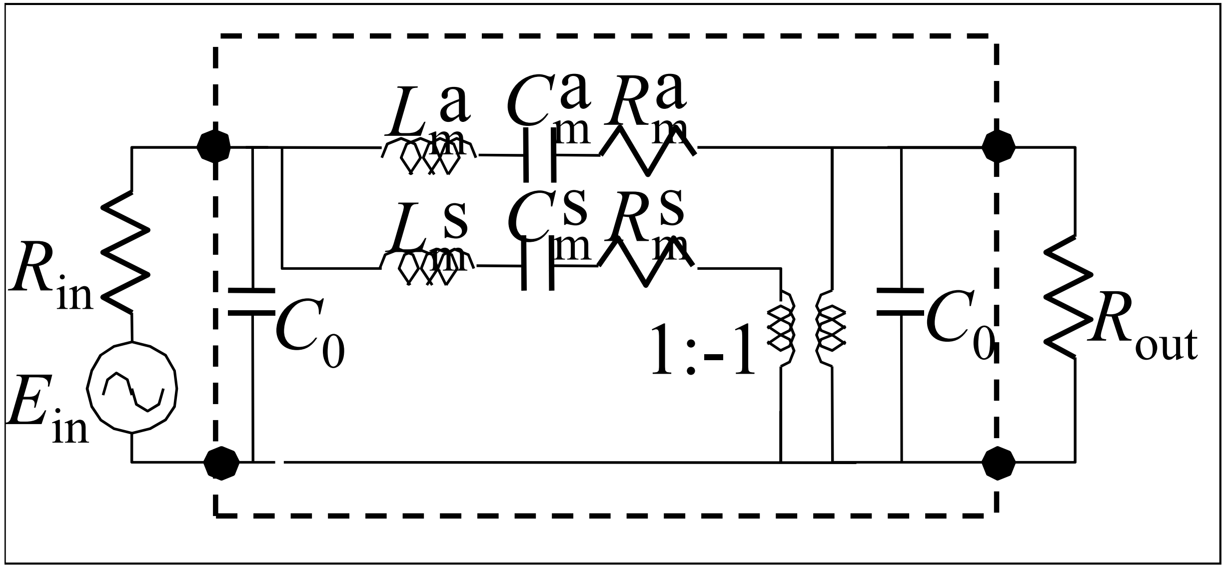


(b) Antisymmetric Resonance

Transversally Coupled Double-Mode Filter



Symmetrical & Antisymmetrical Resonances

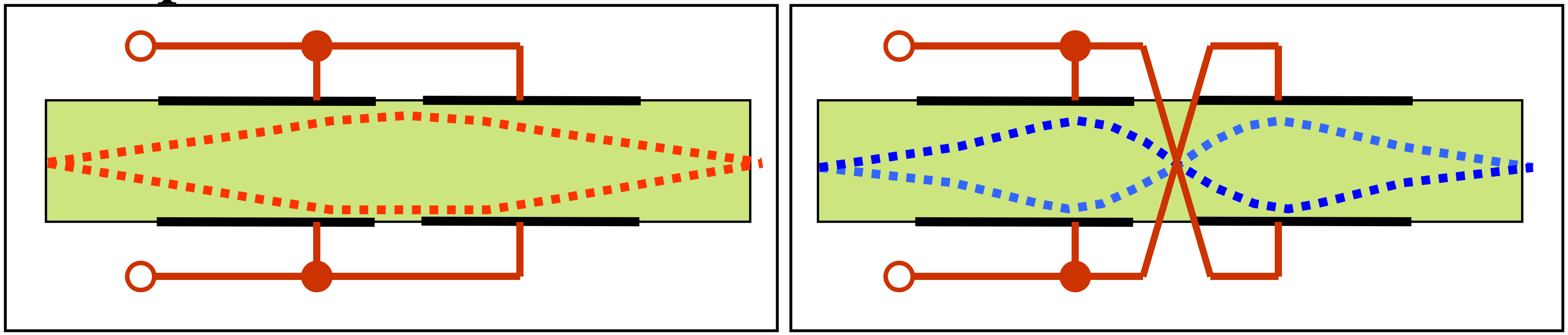


Equivalent Circuit

1-Port Resonator When Parallel-Connected

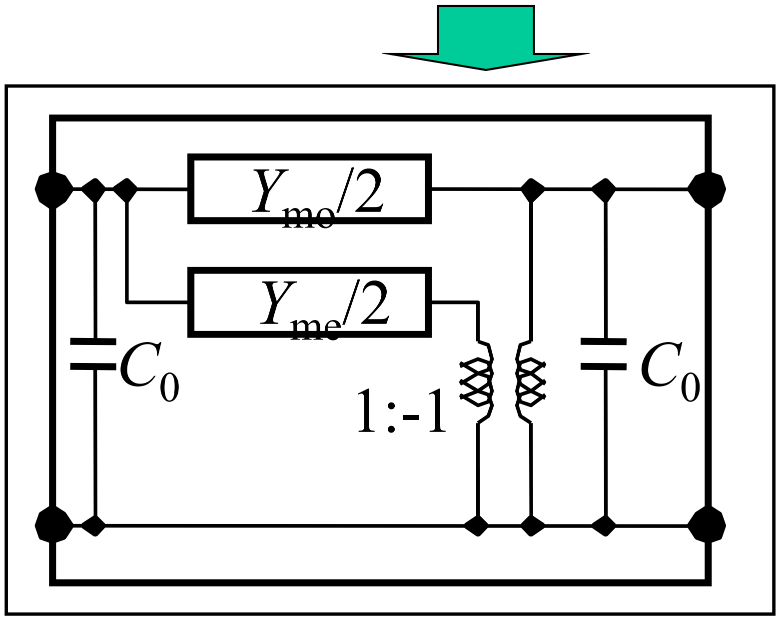
Another 1-Port Resonator When Parallel-Connected with Inversion

Equivalent Circuit of Double-Mode Filter

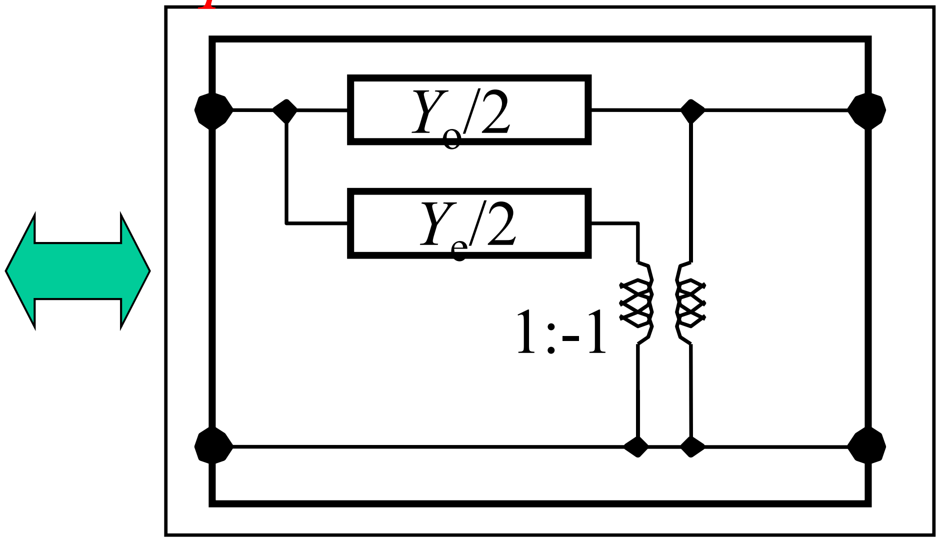


$2Y_e = 2(Y_{me} + j\omega C_0)$ $\quad$ $2Y_o = 2(Y_{mo} + j\omega C_0)$

Y_{me}, Y_{mo}:Motional Y, $j\omega C_0$:Static Capacitances

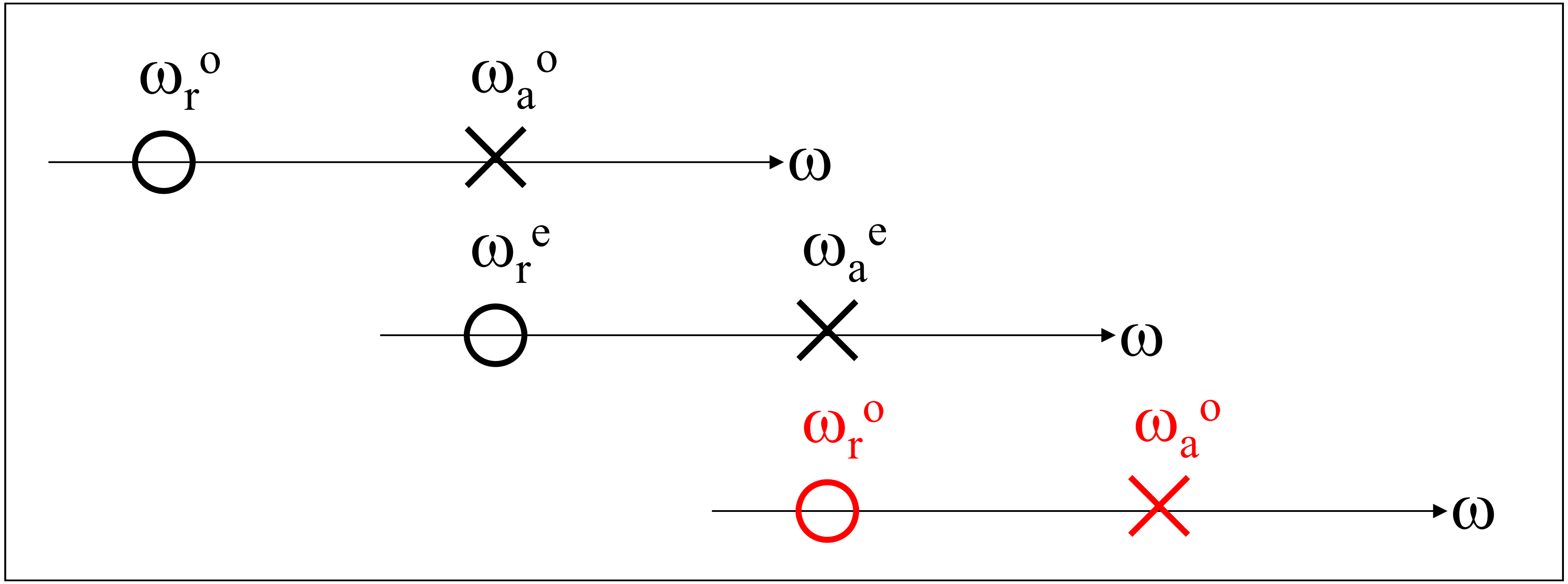


Equivalent to Lattice Filter



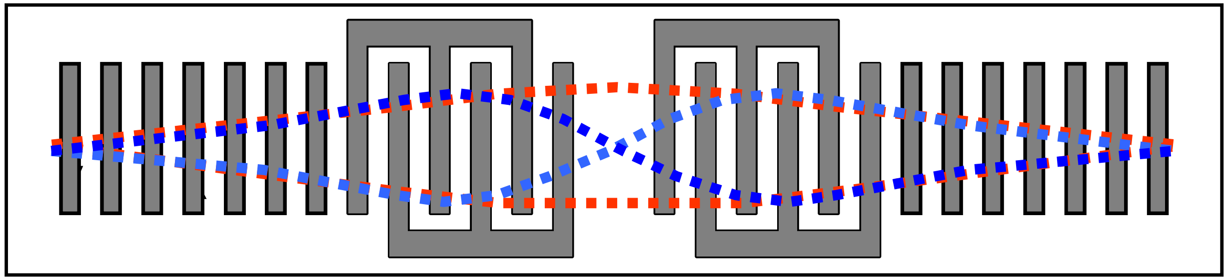
Design Principle of Wideband DMS Filters

Coincidence of Multiple Resonance ω for Y_e (or Y_o) with Antiresonance ω for Y_o (or Y_e)

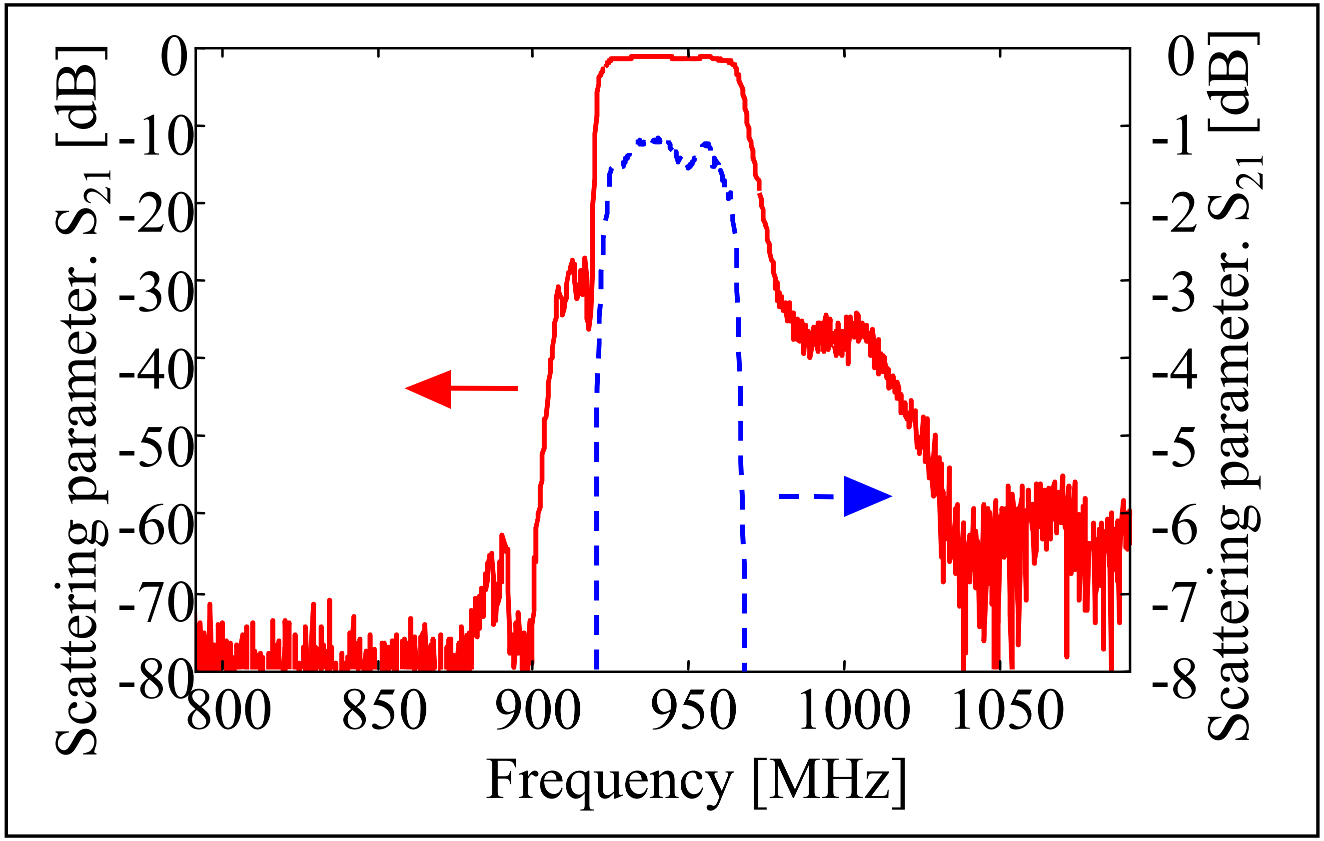


Employing More Resonances Results in More Bandwidths

Double Mode SAW (DMS) Filter

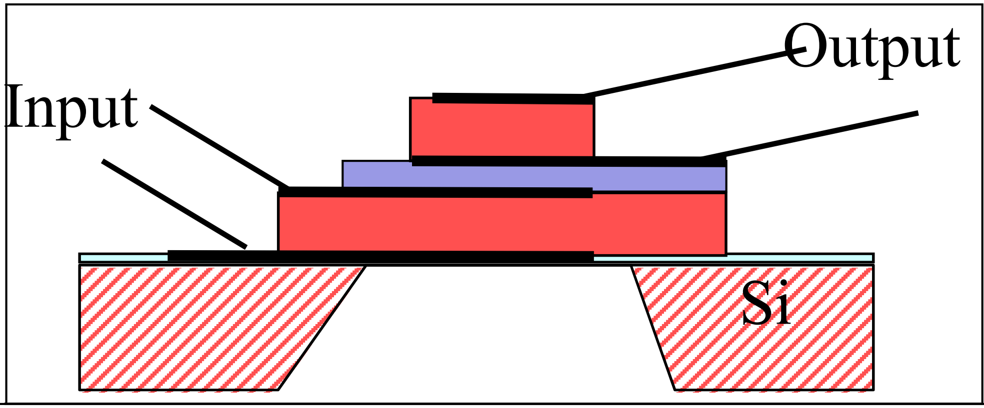


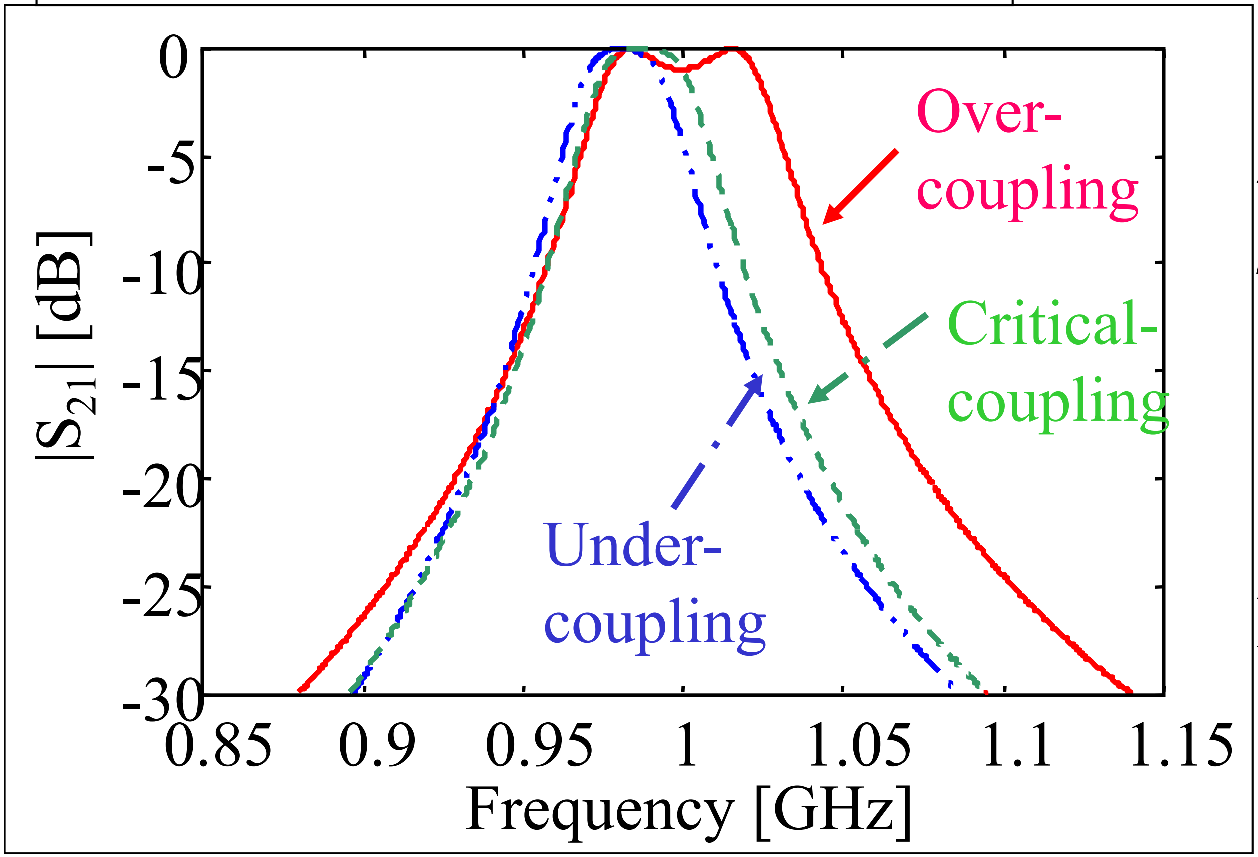
Symmetrical & Anti-symmetrical Resonances



Fujitsu FAR-F5EB-942M50-B28E

Coupled Resonator Filter (CRF)

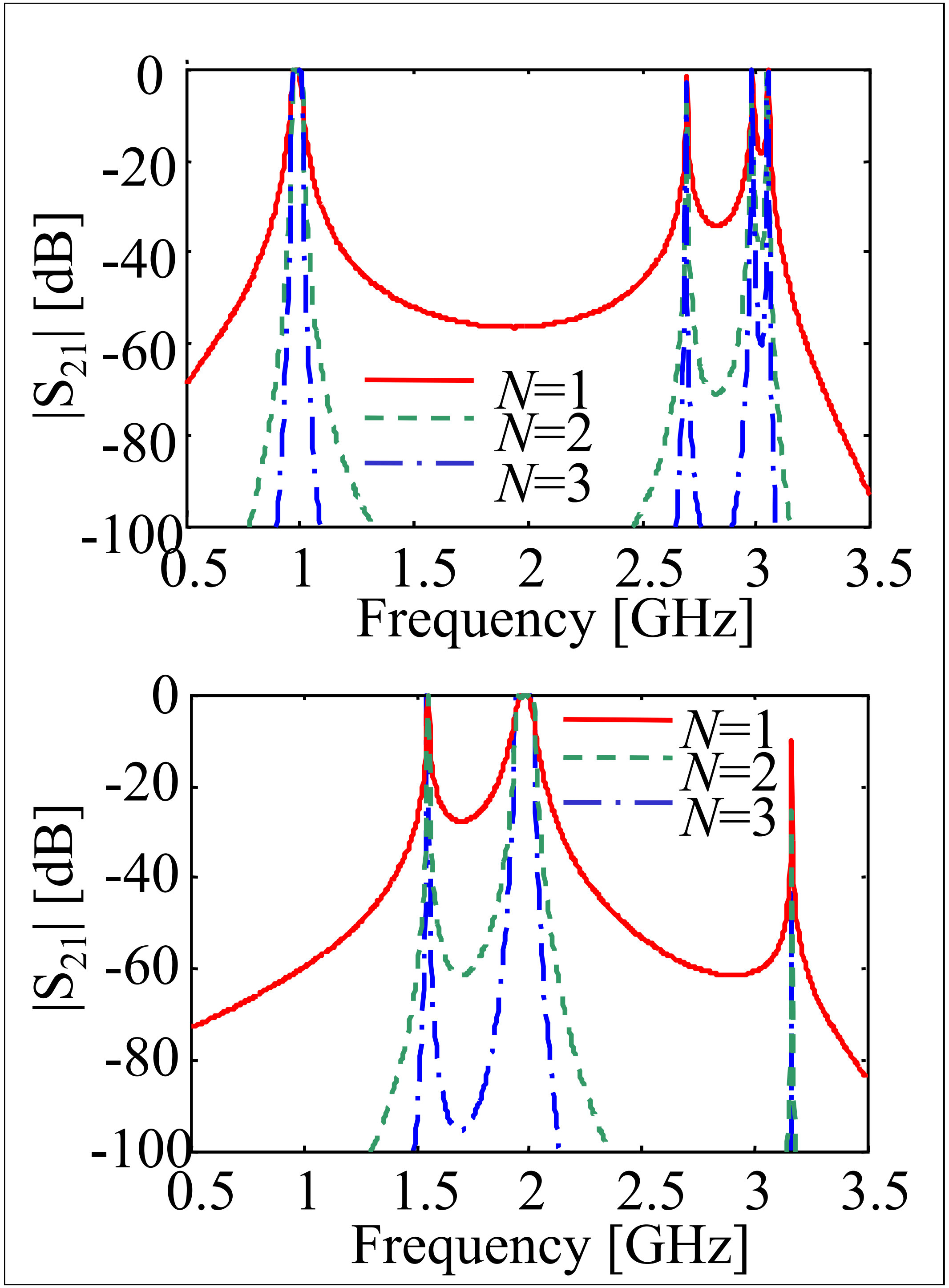




ZnO (L=1.6 μm, S=220×220 μm^2)

Coupler R=2GRayls (Very hard), 0.18λ

How to Realize?



Cascaded CRF

ZnO (L=1.6 μm, S=220×220 μm^2)

Coupler 2 GRayls, 0.18 λ

Extremely hard

ZnO (L=1.6 μm, S=160×160 μm^2)

Coupler 1 MRayls, 0.1 λ

Extremely soft

Design of Coupled Resonator Filters

- Band Width Governed by γ
- For Loss Minimization, $\omega_r C_0 R_S \approx 1$
- Coupling Layer Should be Designed to Adjust Multiple Poles to Coincide with Nulls (But Very Critical!)
- Slight Difference Between Poles & Nulls Effective
- Cascade-Connection is Effective
- IL is Sensitive to Motional Resistances & Parasitics