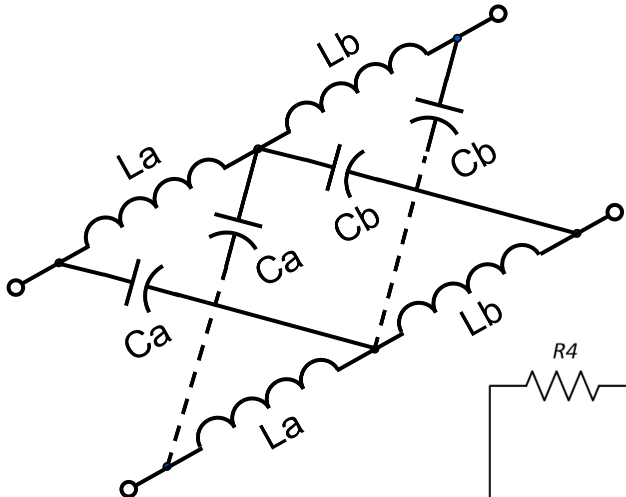
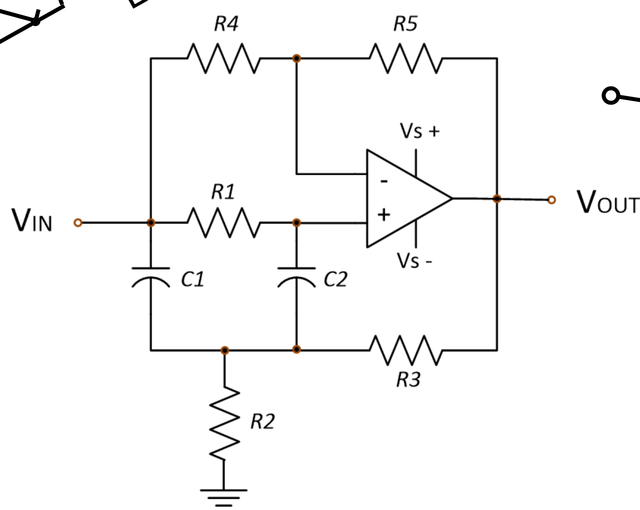
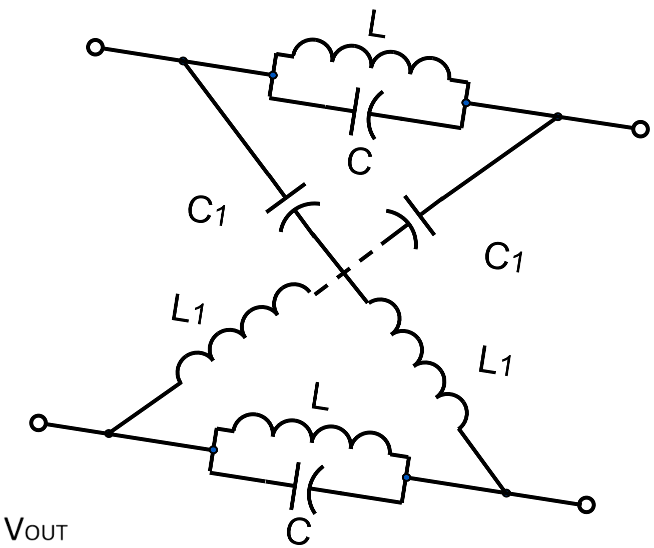
Filters for SSB Direct Conversion Transceivers





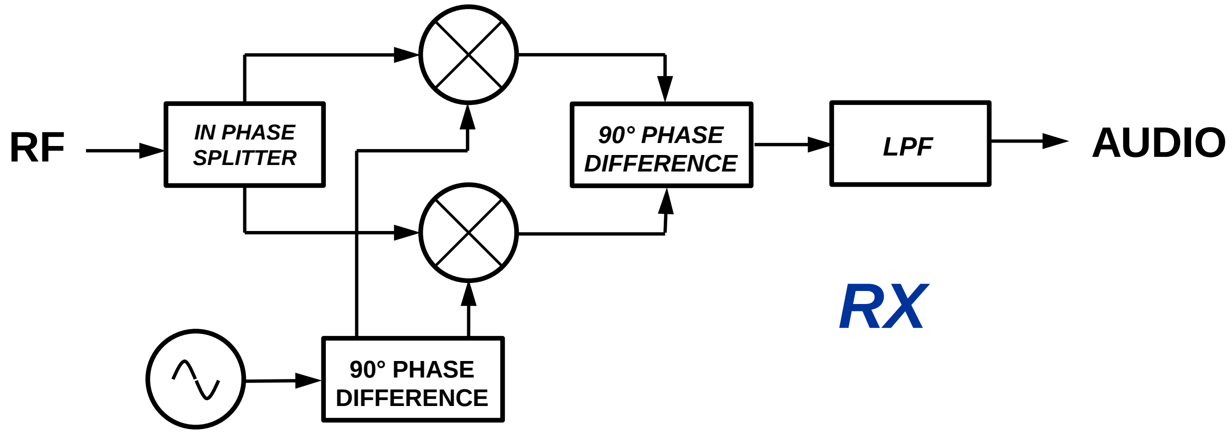


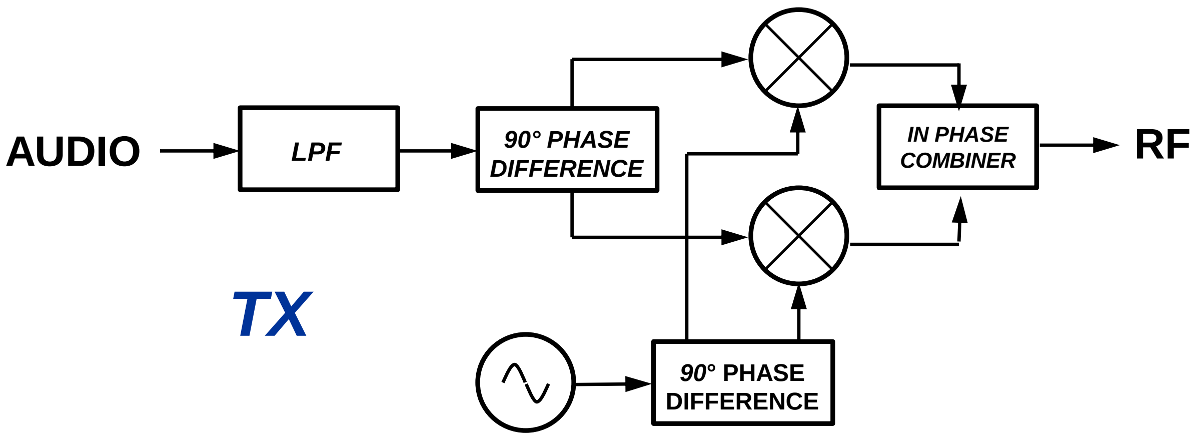
K5TRA

OVERVIEW

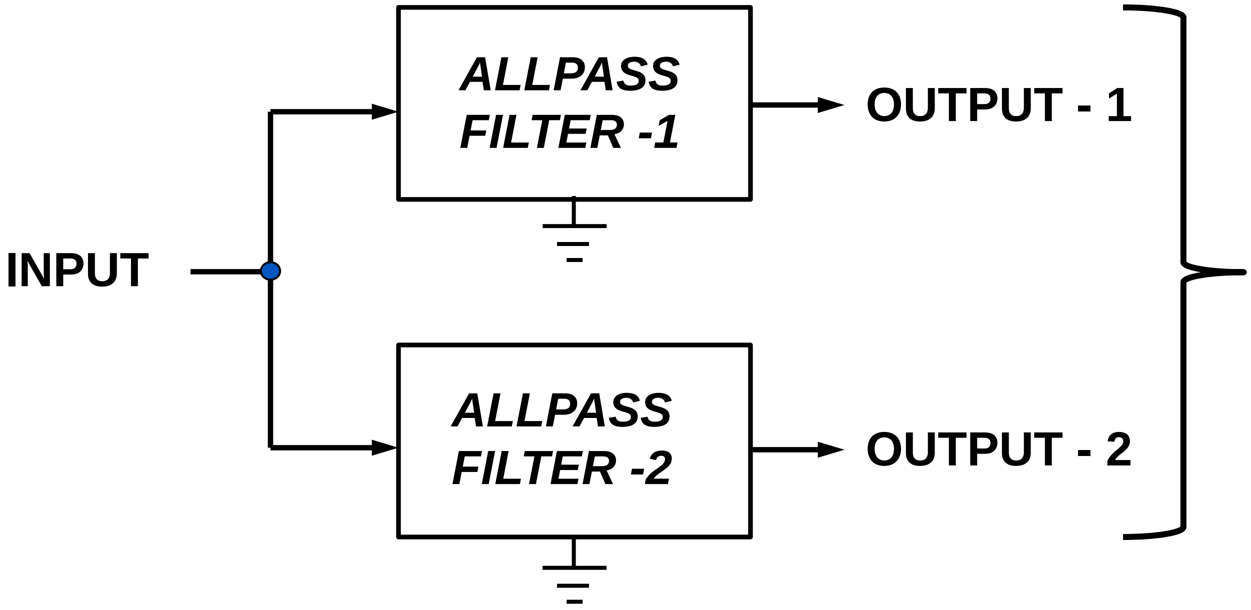
- SSB (Image Reject) direct conversion – phasing method
- Allpass approach to constant phase difference
  - Active Filters
  - Biquad cascades
- Low sensitivity approaches
- Audio phase difference networks
- Audio band limiting LPF (or BPF) low sensitivity filters

TX / RX SSB DIRECT CONVERSION





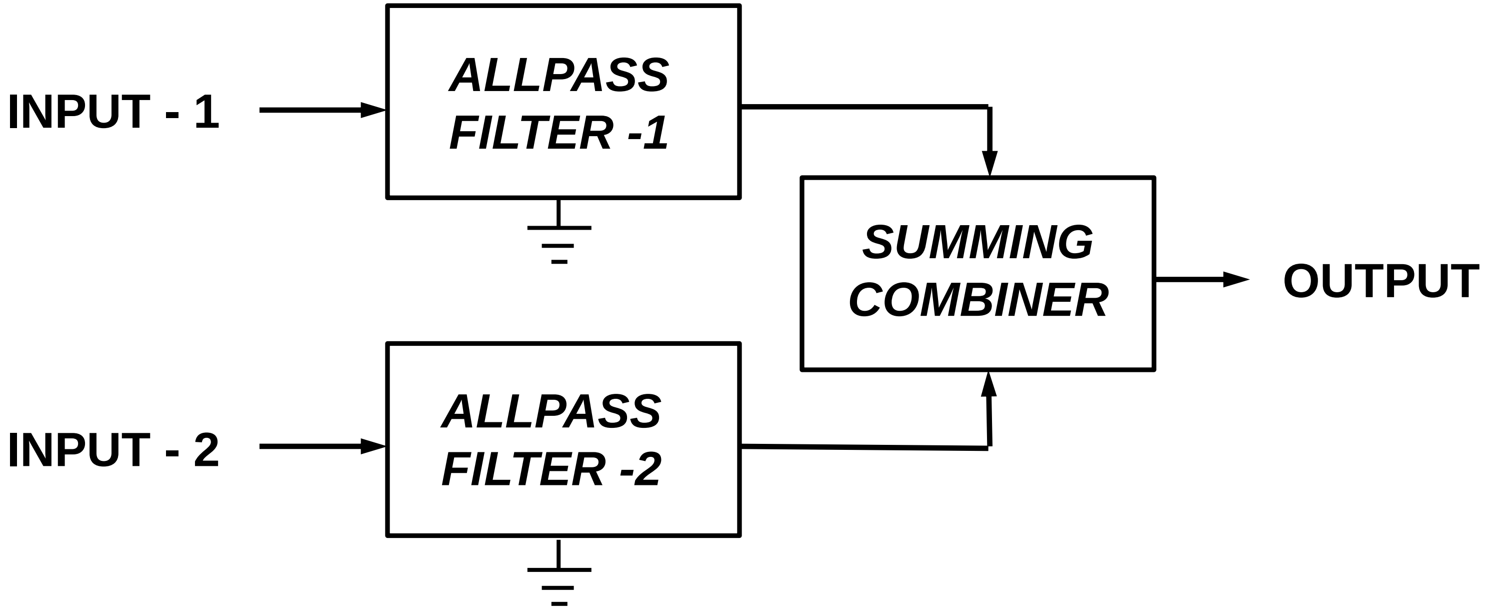
DUAL ALLPASS 90° PHASE SPLITTER



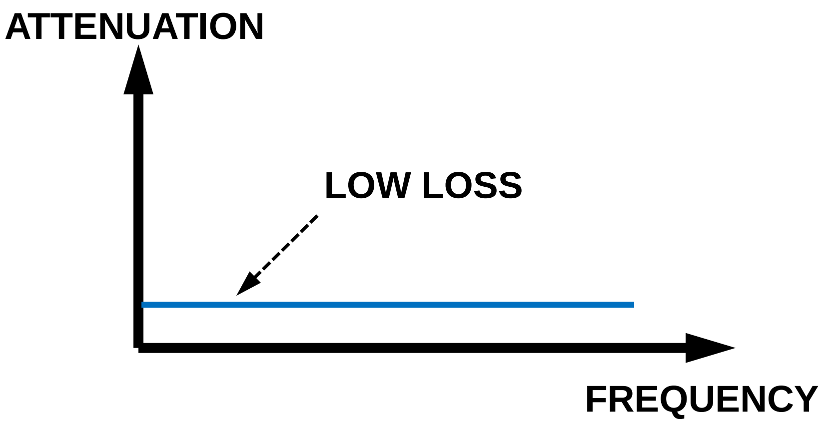
90° PHASE DIFFERENCE,

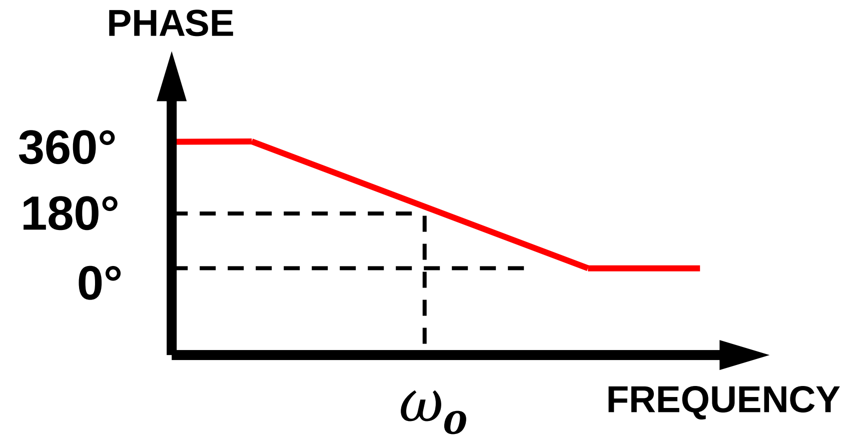
EQUAL AMPLITUDE

DUAL ALLPASS 90° PHASE COMBINER



ALLPASS FILTER RESPONSE



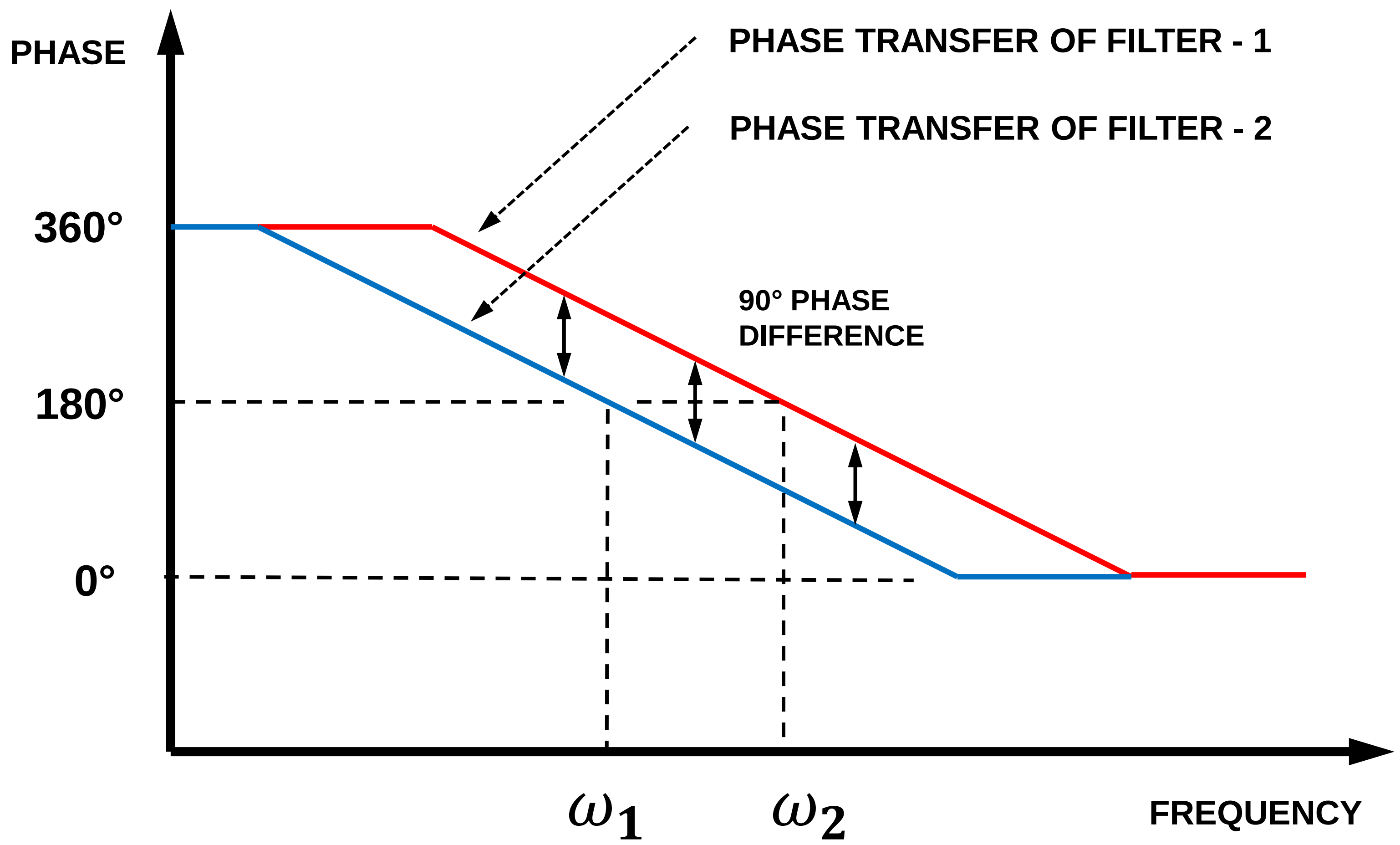


$$\frac{V_{output}}{V_{input}} = \frac{-\omega^2 - j\,\frac{\omega_o}{Q}\,\omega + \omega_o{}^2}{-\omega^2 + j\,\frac{\omega_o}{Q}\,\omega + \omega_o{}^2}$$

$\omega = 2\pi\, frequency$

ω_o and Q are constants

DUAL ALLPASS PHASE RESPONSE



SECOND ORDER FILTER FUNCTIONS (BIQUADS)

FILTER RESPONSE TYPE	TRANSFER FUNCTION
LOW PASS	$K \dfrac{1}{S^2 + \frac{\omega_o}{Q} S + {\omega_o}^2}$
HIGH PASS	$K \dfrac{S^2}{S^2 + \frac{\omega_o}{Q} S + {\omega_o}^2}$
BAND PASS	$K \dfrac{S}{S^2 + \frac{\omega_o}{Q} S + {\omega_o}^2}$
BAND REJECT	$K \dfrac{S^2 + {\omega_o}^2}{S^2 + \frac{\omega_o}{Q} S + {\omega_o}^2}$
ALLPASS **(DELAY EQUALIZER)**	$K \dfrac{S^2 - \frac{\omega_o}{Q} S + {\omega_o}^2}{S^2 + \frac{\omega_o}{Q} S + {\omega_o}^2}$

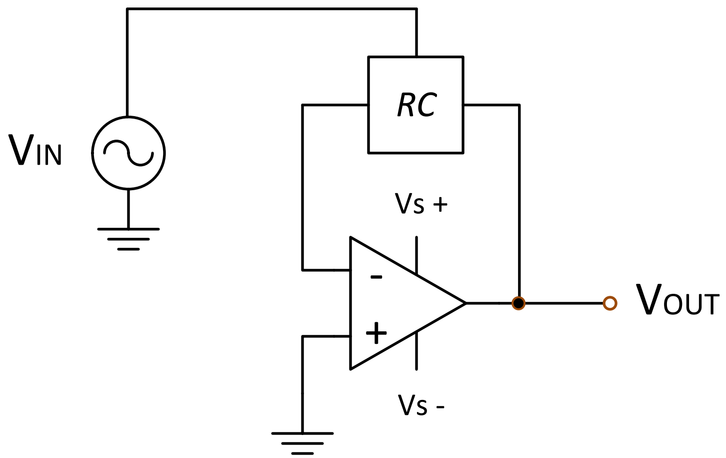
BIQUAD TRANSFER FUNCTION

$$T(S) = \frac{S^2 + \frac{\omega_Z}{Q_Z} S + \omega_Z{}^2}{S^2 + \frac{\omega_P}{Q_P} S + \omega_P{}^2}$$

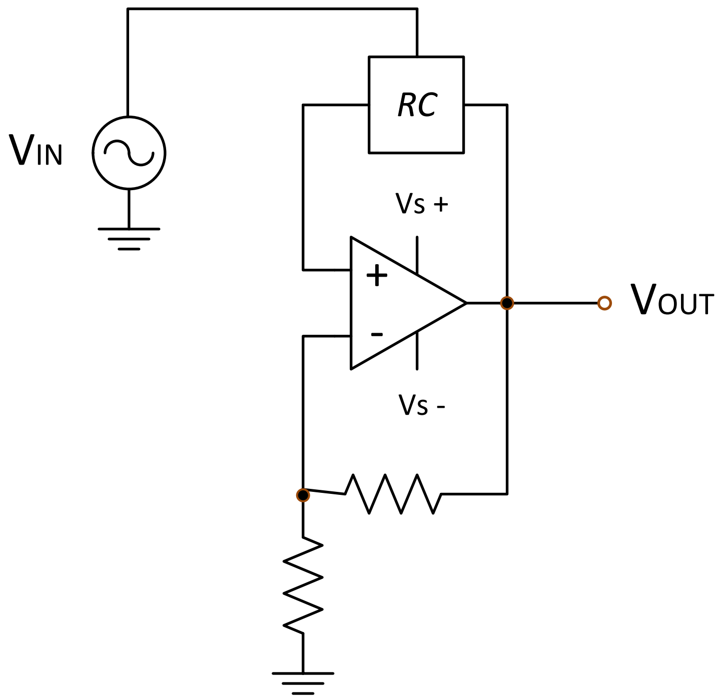
ω_Z and ω_P are zero and pole frequencies

Q_Z and Q_P are zero and pole Qs

ACTIVE FILTER BIQUAD REALIZATIONS

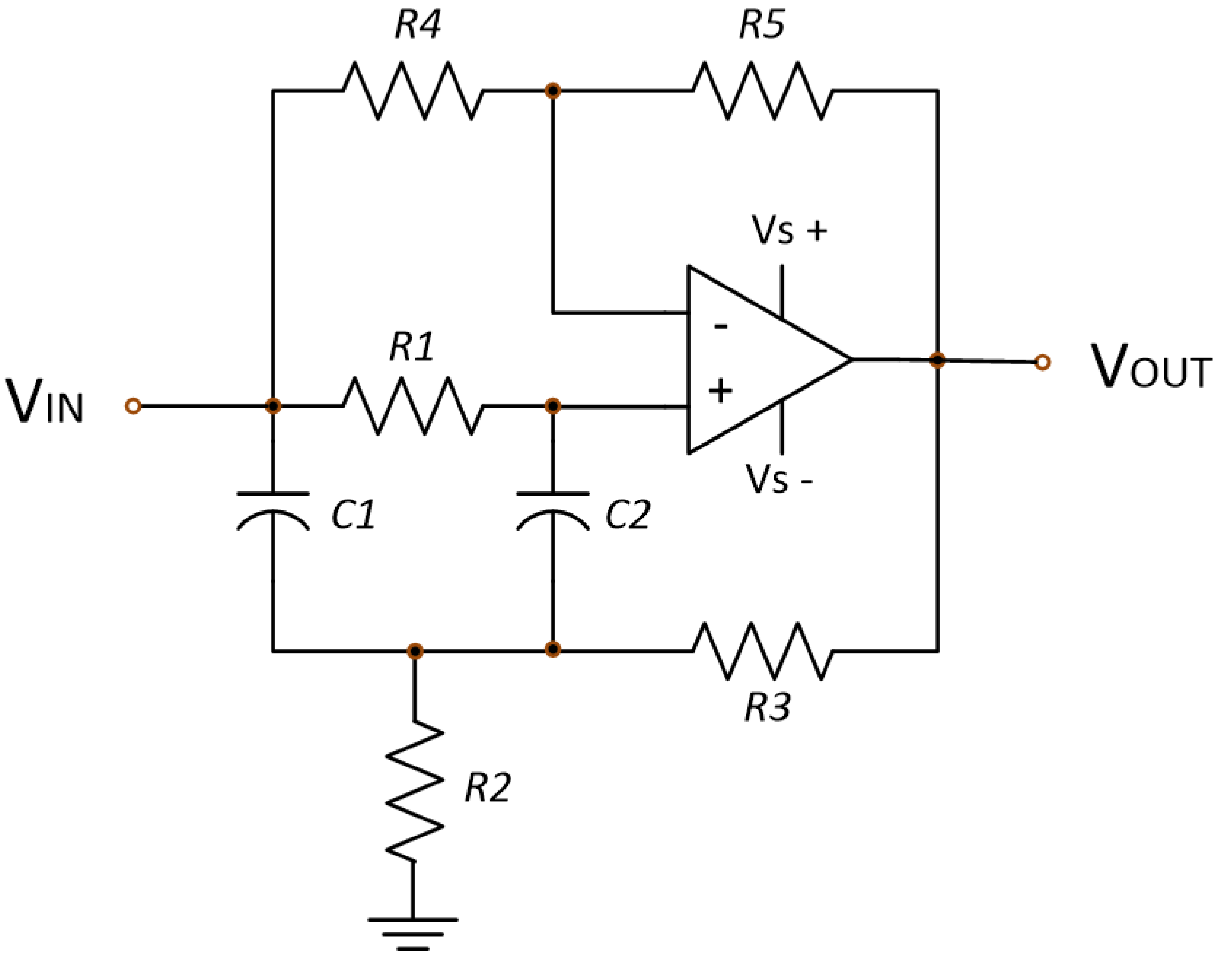


NEGATIVE FEEDBACK TOPOLOGY



POSITIVE FEEDBACK TOPOLOGY

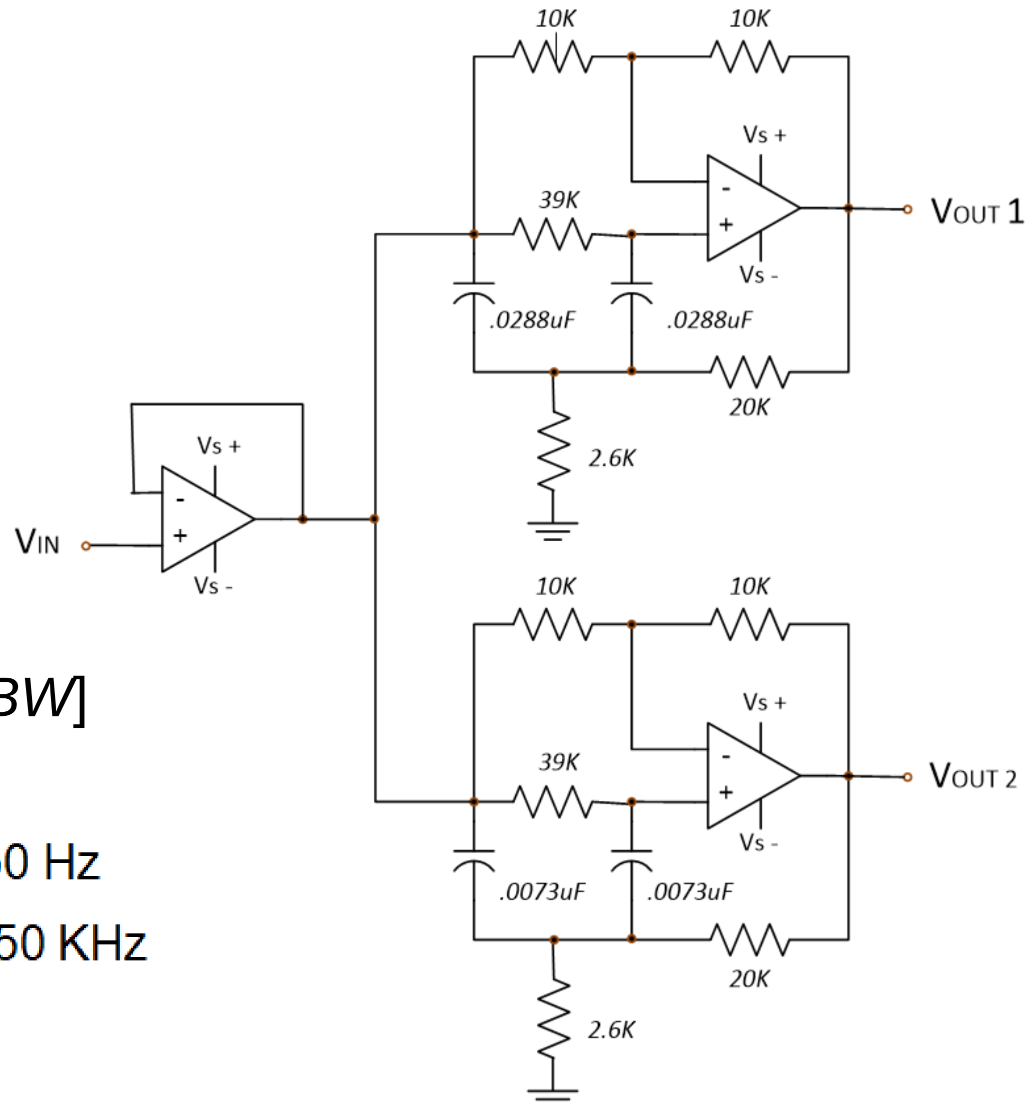
STEFFEN ALLPASS FILTER



STEFFEN ALLPASS TRANSFER FUNCTION

$$\frac{V_{out}}{V_{in}} = \frac{-\omega^2 - j\omega\left[\frac{R_4}{R_5}\left(\frac{1}{R_2}+\frac{1}{R_3}\right)\frac{1}{C_1} - \frac{1}{R_1C_1} - \frac{1}{R_1C_2}\right] + \frac{1}{R_1C_1C_2}\left(\frac{1}{R_2}+\frac{1}{R_3}\right)}{-\omega^2 + j\omega\left[\frac{1}{R_1C_2} + \frac{1}{R_1C_1} + \left(\frac{1}{R_2}+\frac{1}{R_3}\right)\frac{1}{C_1} - \frac{1}{R_3C_1}\left(1+\frac{R_4}{R_5}\right)\right] + \frac{1}{R_1C_1C_2}\left(\frac{1}{R_2}+\frac{1}{R_3}\right)}$$

STEFFEN DUAL ALLPASS FILTERS



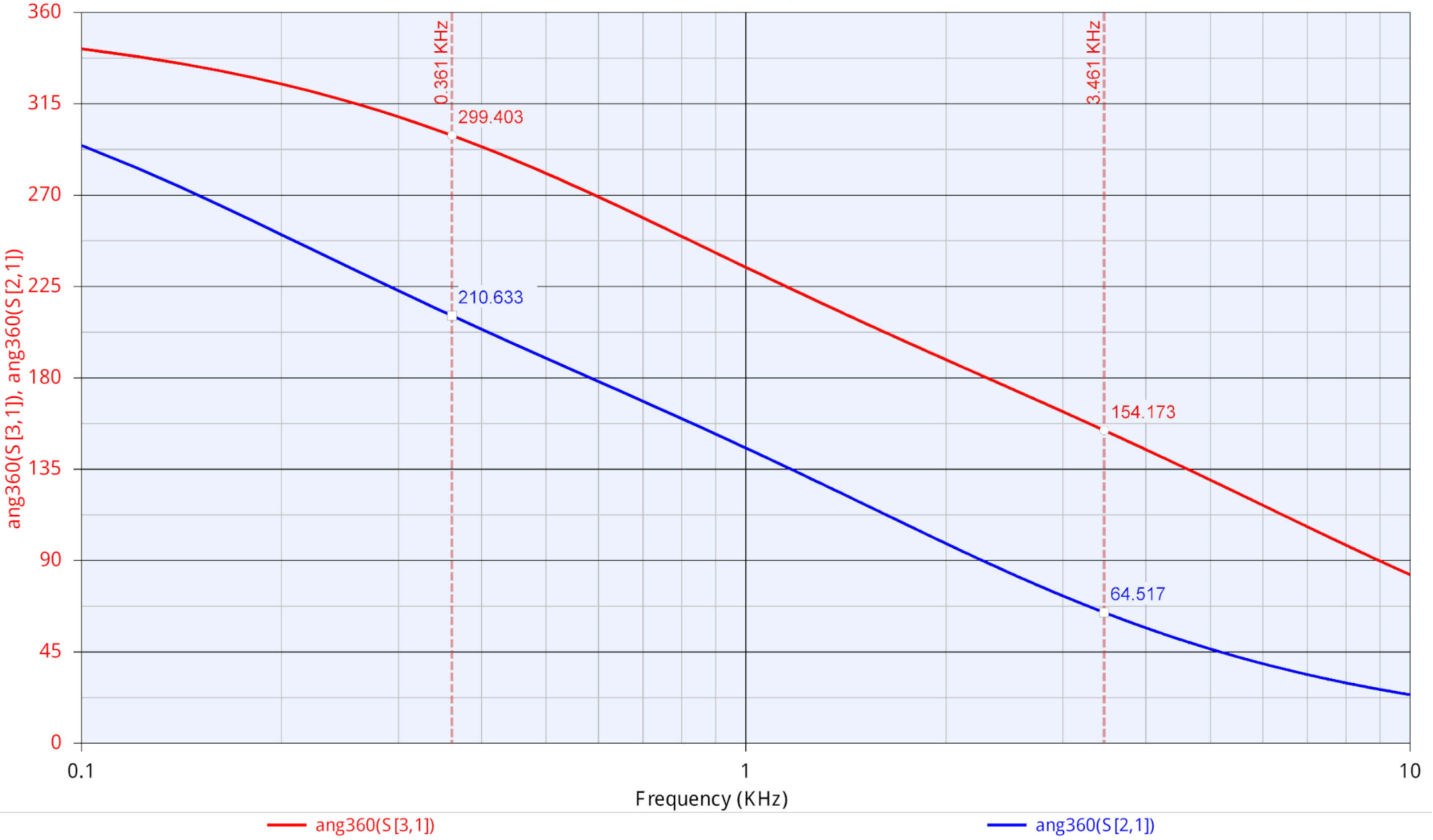
[*for decade BW*]

Q = 0.27553

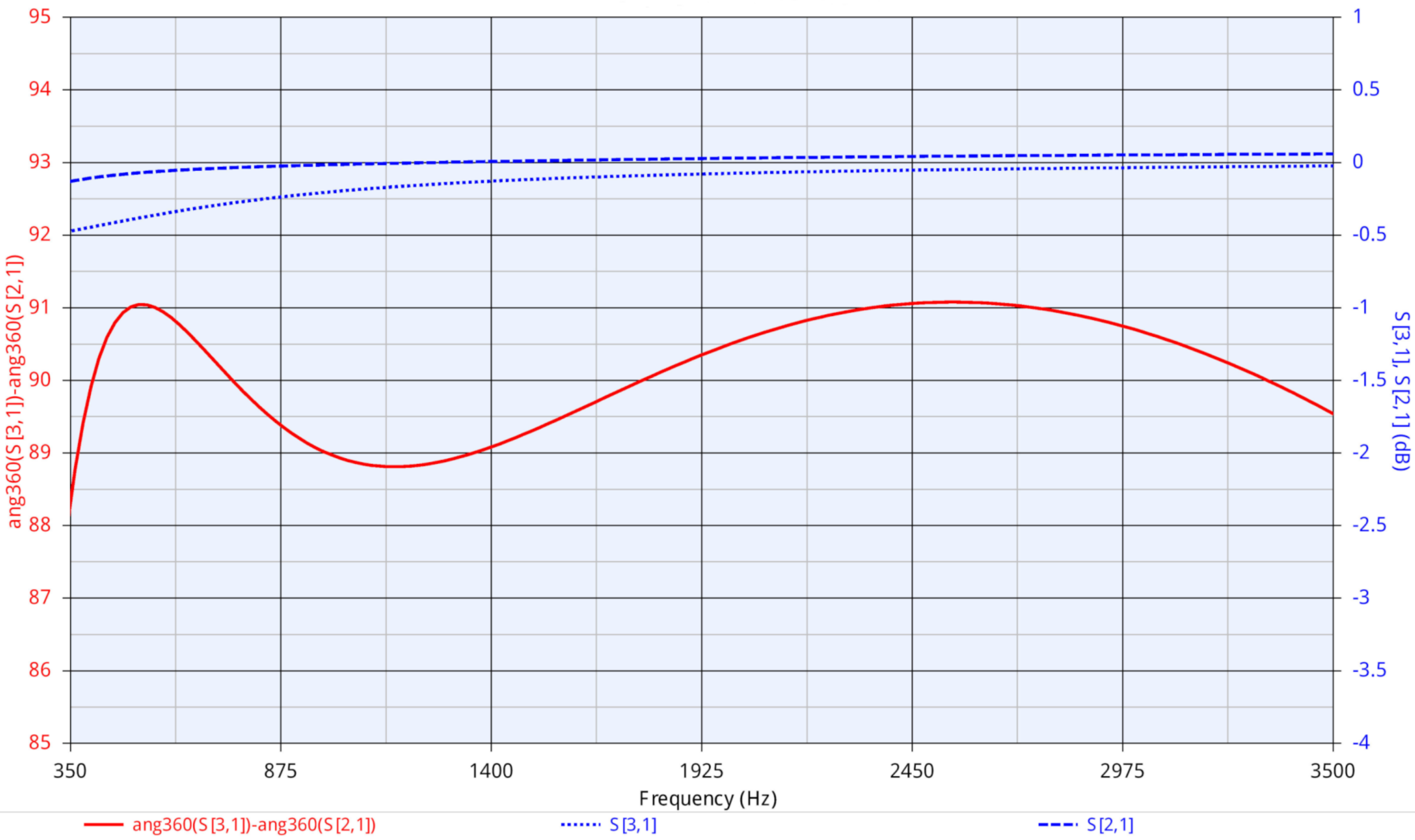
$\omega_1 = (2\pi)$ 350 Hz

$\omega_2 = (2\pi)$ 3.50 KHz

DUAL ALLPASS FILTER – PHASE RESPONSES



DUAL ALLPASS FILTER – RESPONSE COMPARISON



NORMALIZED PROTOTYPE PARAMETERS

SECOND ORDER PROTOTYPE

BW RATIO	Q	ω_1	ω_2	PHASE ERROR
3	0.31011	0.53488	1.87003	0.074°
4	0.30348	0.52811	1.89315	0.178°
5	0.29767	0.52381	1.90940	0.308°
6	0.29206	0.51853	1.92700	0.455°
8	0.28334	0.50984	1.95934	0.770°
10	0.27553	0.50292	1.98650	1.080°
15	0.26010	0.48829	2.04241	1.910°
20	0.25003	0.47960	2.08534	2.550°

$$T_1(S) = \frac{S^2 - \frac{\omega_1}{Q_1}S + \omega_1{}^2}{S^2 + \frac{\omega_1}{Q_1}S + \omega_1{}^2}$$

$$T_2(S) = \frac{S^2 - \frac{\omega_2}{Q_2}S + \omega_2{}^2}{S^2 + \frac{\omega_2}{Q_2}S + \omega_2{}^2}$$

$$\omega_0 = \sqrt{\omega_1\omega_2} = 1$$

THIRD ORDER PROTOTYPE

BW RATIO	Q1	ω_1	γ_1	Q2	ω_2	γ_2	PHASE ERROR
6	0.19231	0.5500	0.7310	0.19206	1.81750	1.3700	0.020°
8	0.18354	0.5458	0.7200	0.18347	1.83064	1.3880	0.040°
10	0.17560	0.5420	0.7110	0.17652	1.84217	1.4100	0.070°

$$T_1(S) = \left(\frac{S^2 - \frac{\omega_1}{Q_1}S + \omega_1{}^2}{S^2 + \frac{\omega_1}{Q_1}S + \omega_1{}^2}\right)\left(\frac{\gamma_1 - S}{\gamma_1 + S}\right) \qquad T_2(S) = \left(\frac{S^2 - \frac{\omega_2}{Q_1}S + \omega_2{}^2}{S^2 + \frac{\omega_2}{Q_2}S + \omega_2{}^2}\right)\left(\frac{\gamma_2 - S}{\gamma_2 + S}\right)$$

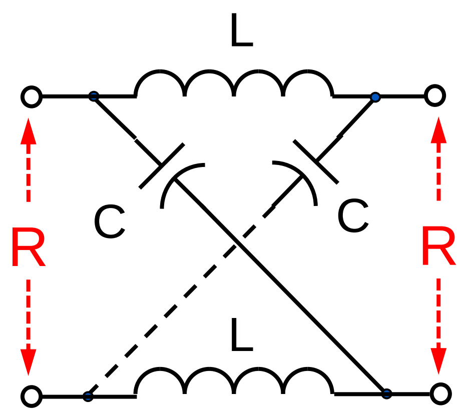
$$\omega_0 = \sqrt{\omega_1\omega_2} = 1 \qquad \gamma_0 = \sqrt{\gamma_1\gamma_2} = 1$$

ALLPASS FILTER CONSIDERATIONS

- Baseband audio filters
  - Active biquad designs, like Steffen
  - Low Q poles and zeros
- RF filters
  - Passive filters
  - Non-minimum phase transfer cannot be realized as ladder
    - ✓ Lattice networks with baluns
    - ✓ Bridge-T networks
- Allpass filters always have pole-zero symmetry *WRT* $j\omega$ axis
- First order: $T(S) = \left(\frac{\gamma - S}{\gamma + S}\right)$
- Second order: $T(S) = \frac{S^2 - \frac{\omega_0}{Q_0}S + {\omega_0}^2}{S^2 + \frac{\omega_0}{Q_0}S + {\omega_0}^2}$
- Third order: $T(S) = \left(\frac{S^2 - \frac{\omega_0}{Q_0}S + {\omega_0}^2}{S^2 + \frac{\omega_0}{Q_0}S + {\omega_0}^2}\right)\left(\frac{\gamma - S}{\gamma + S}\right)$

LATTICE ALLPASS FILTERS

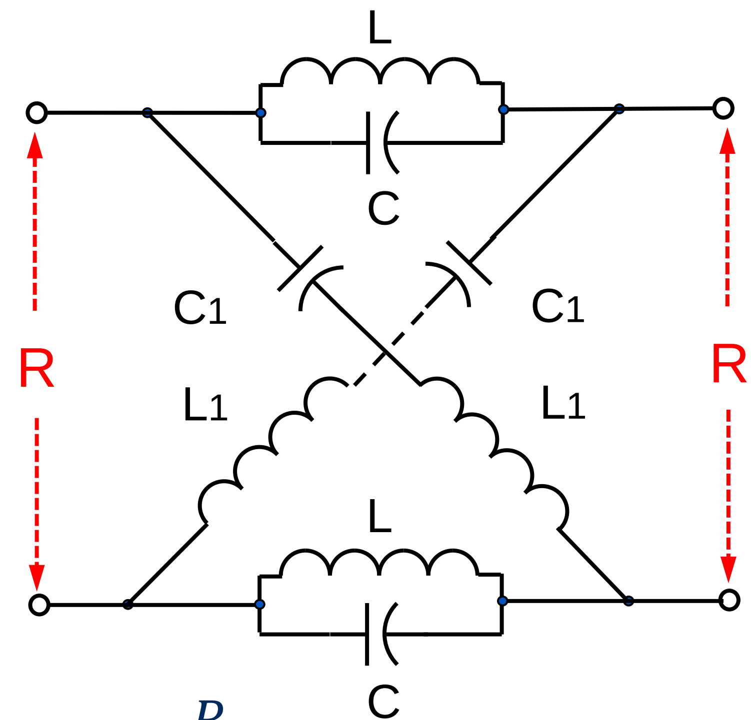
FIRST ORDER



$$L = \frac{R}{\gamma}$$

$$C = \frac{L}{R^2}$$

SECOND ORDER



$$L = \frac{R}{\varpi_o}$$

$$L_1 = C R^2$$

$$C = \frac{1}{L\,\varpi_o{}^2}$$

$$C_1 = \frac{L}{R^2}$$

CASCADE 1st ORDER to 2nd ORDER LATTICE

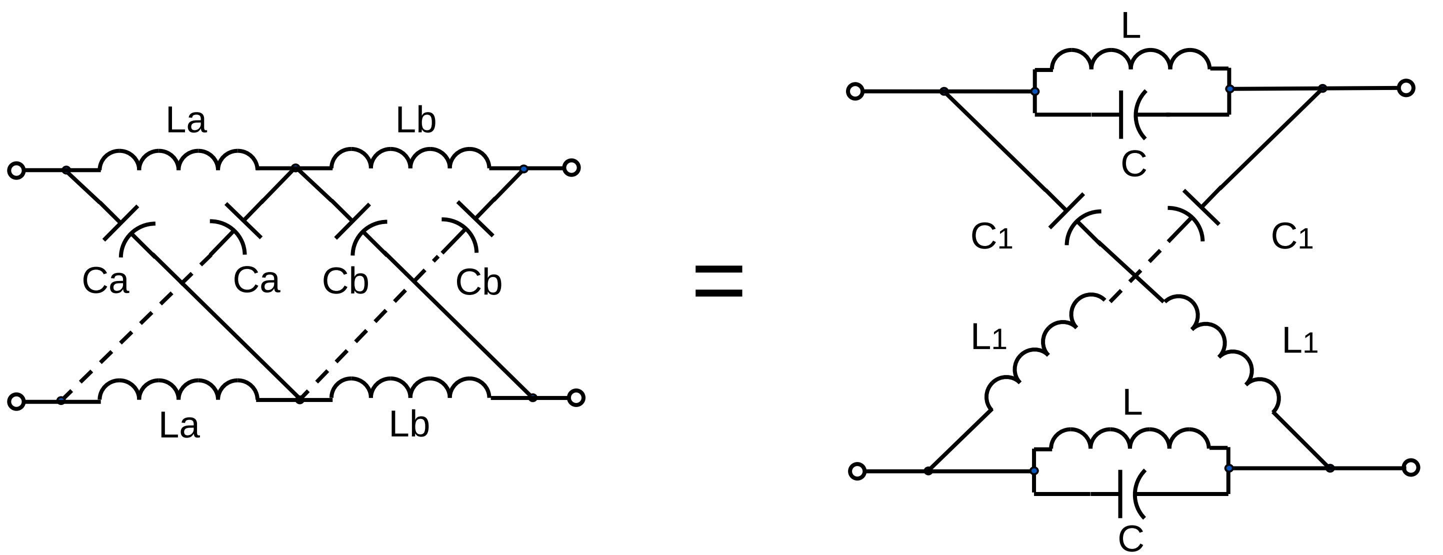
- For applications here, the pole / zero Q is always < 0.5
- System is over-damped; so, poles and zeros are real and distinct
- Allows: 2nd order lattice equivalence to cascaded 1st order lattices

$$T(S) = A(S)B(S) = \left(\frac{S_a - S}{S_a + S}\right)\left(\frac{S_b - S}{S_b + S}\right)$$

$$T(S) = \frac{S^2 - (S_a + S_b)S + S_aS_b}{S^2 + (S_a + S_b)S + S_aS_b}$$

$$\varpi_o = \sqrt{S_aS_b} \qquad Q = \frac{\sqrt{S_aS_b}}{S_a + S_b} \qquad \frac{\varpi_o}{Q} = S_a + S_b$$

CASCADE 1st ORDER to 2nd ORDER LATTICE

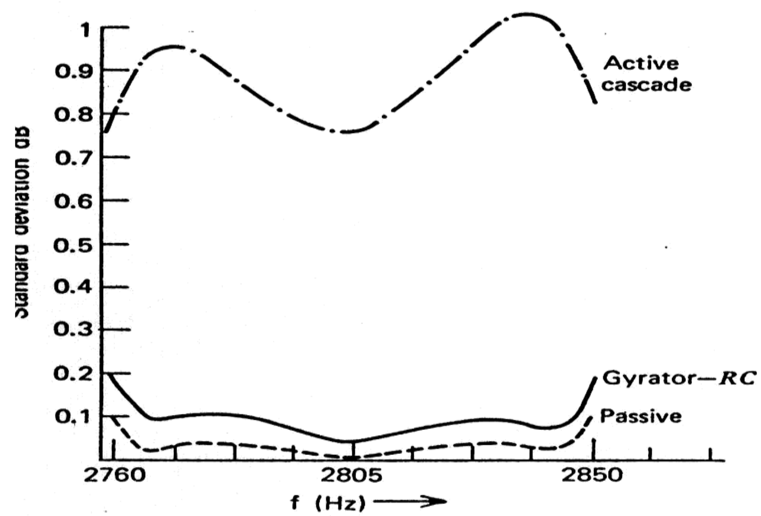


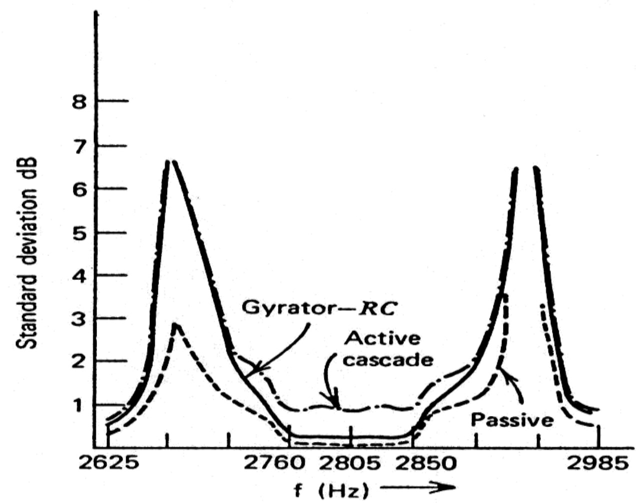
$$L = L_a + L_b \qquad C_1 = C_a + C_b$$

$$C = \frac{C_a C_b}{C_a + C_b} \qquad L_1 = \frac{L_a L_b}{L_a + L_b}$$

LOWPASS BASEBAND AUDIO FILTER

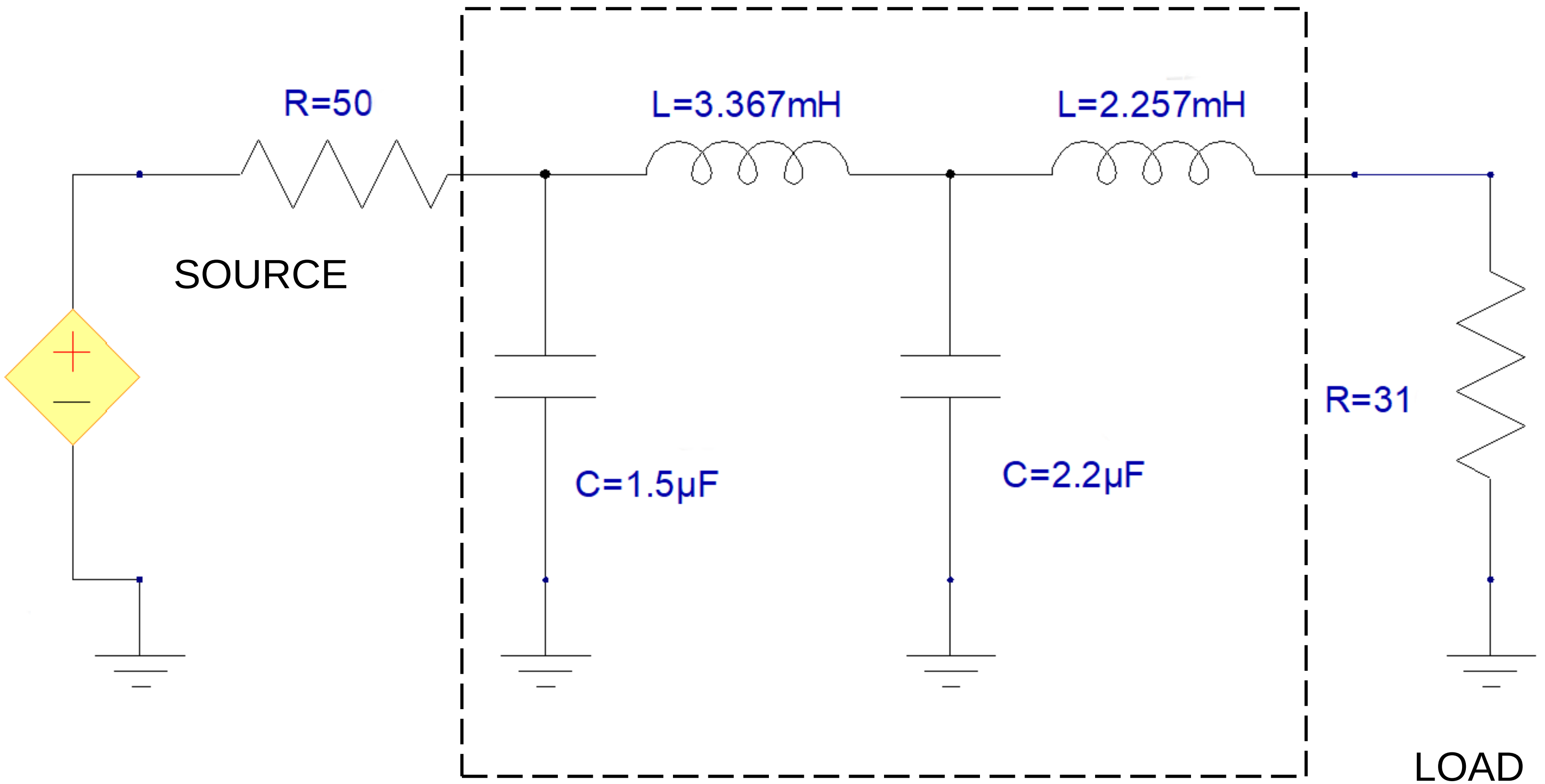
- Lowpass active filters have high Q poles



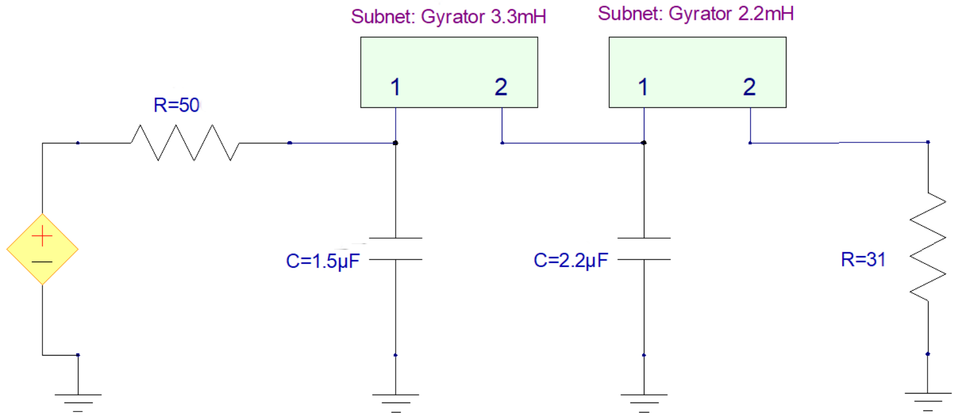


- Cascaded biquad blocks are have higher sensitivity than passive
- Active filters based on passive designs have lower sensitivity:
  - Gyrator substitution for inductors
  - Frequency Dependent Negative Resistor (FDNR)

FOURTH ORDER PASSIVE BPF

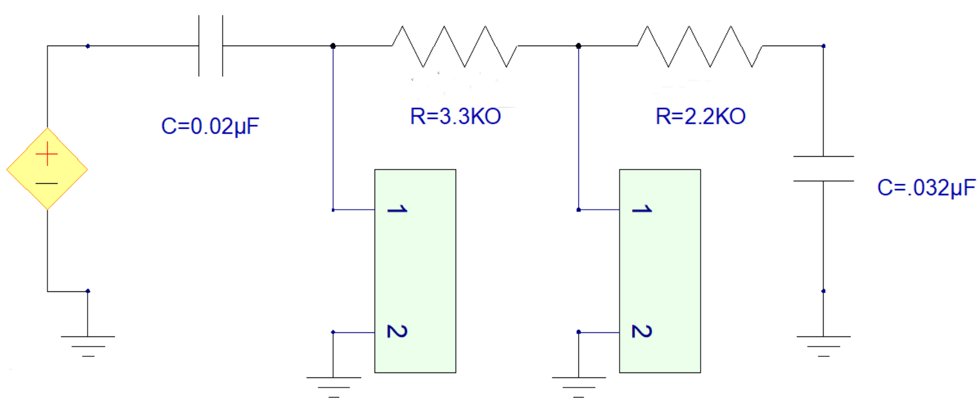


PASSIVE BASED ACTIVE BPF



GYRATORS PROVIDE INDUCTOR EQUIVALENT BY INVERTING CAPACITOR IMPEDANCE

$$L_{eqv} = K^2\, C$$

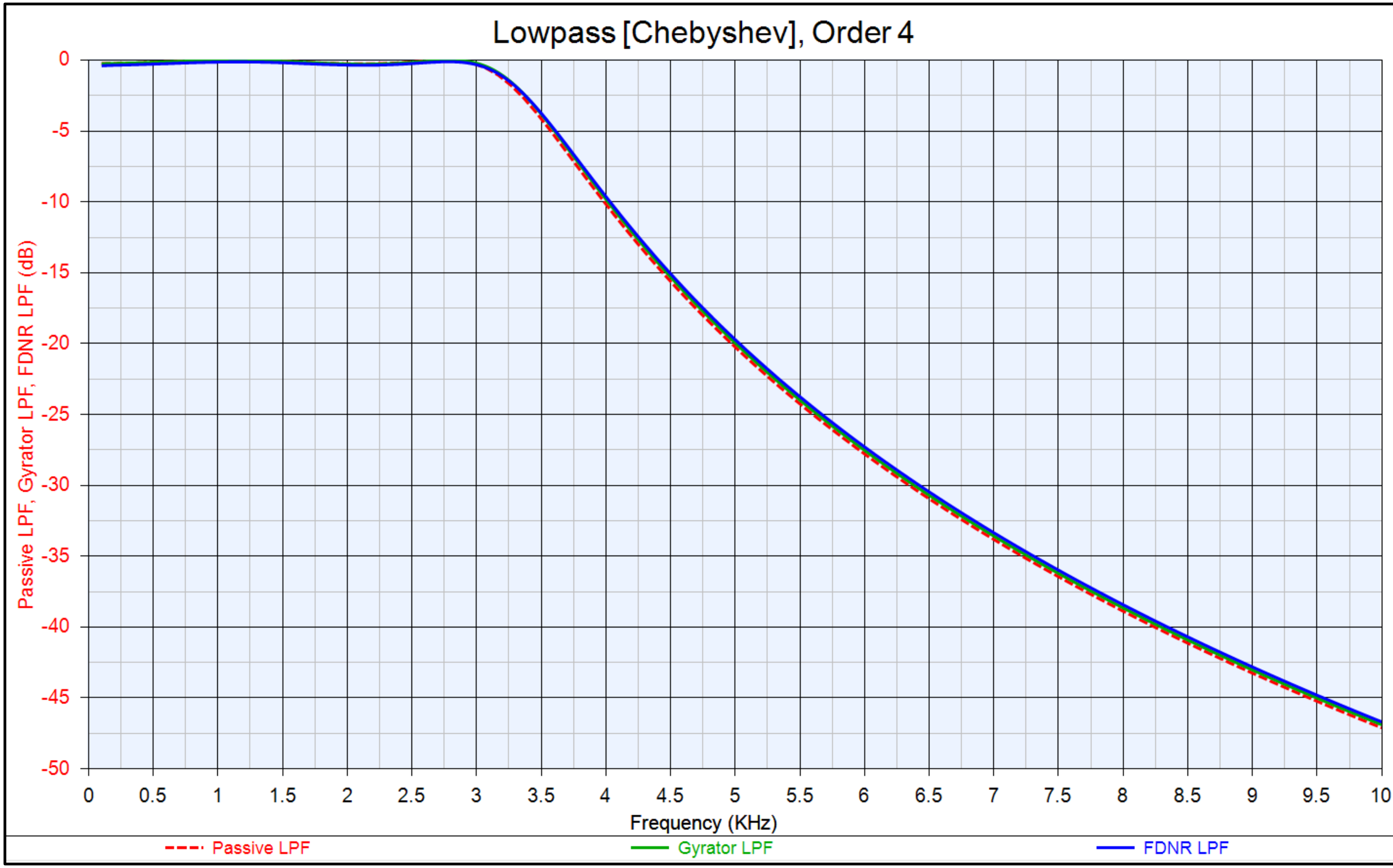


FDNR SOLUTION OBTAINED BY Z-SCALING PASSIVE LADDER ELEMENTS BY: K / S

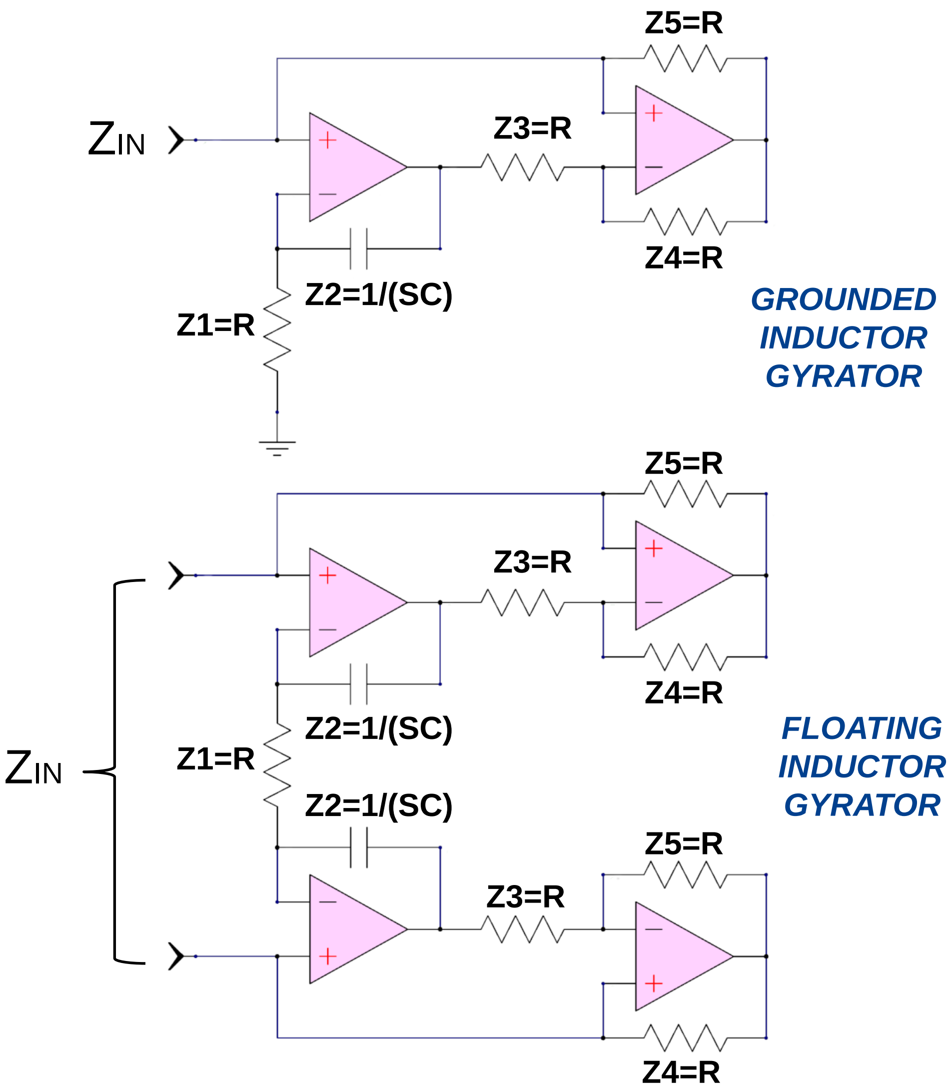
PASSIVE		FDNR
R	$\Longrightarrow$	$\dfrac{R\,K}{S}$
$S\,L$	$\Longrightarrow$	$L\,K$
$\dfrac{1}{S\,C}$	$\Longrightarrow$	$\dfrac{K}{S^2\,C} = \dfrac{1}{S^2 D}$

K5TRA

LPF RESPONSE



RIORDAN'S GYRATOR – AS INDUCTOR



$$Z_{IN} = \frac{Z_1 Z_3 Z_5}{Z_2 Z_4}$$

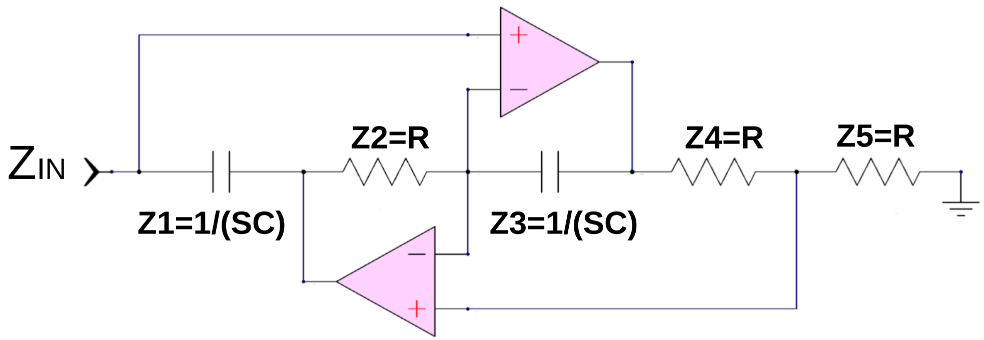
$$Z_2 = (C\ S)^{-1}$$

$$Z_1 = Z_3 = Z_4 = Z_5 = R$$

$$Z_{IN} = SCR^2$$

$$\mathbf{L_{eff} = CR^2}$$

BRUTON'S FDNR



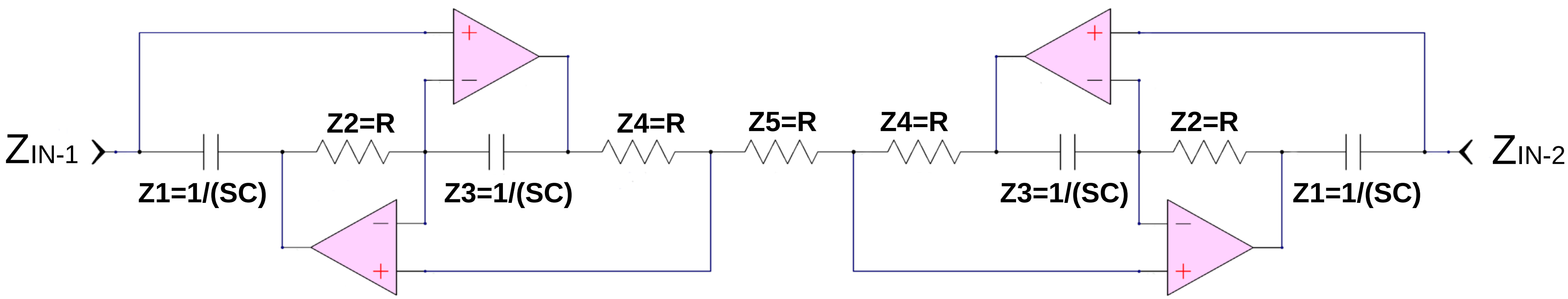
GROUNDED FDNR

$$Z_{IN} = \frac{Z_1 Z_3 Z_5}{Z_2 Z_2}$$

$$Z_1 = Z_3 = (C_D\ S)^{-1}$$

$$Z_2 = Z_4 = Z_5 = R_D$$

$$Z_{IN} = \frac{1}{S^2 R_D {C_D}^2} = \frac{1}{S^2 D}$$



FLOATING FDNR

SUMMARY

- SSB (image reject) direct conversion blocks
- Audio band limiting filter is key to setting selectivity
- Phase difference networks are obtained from a pair of allpass delay equalizers
- Audio phase difference networks are realized with Steffen allpass filters
- Wideband RF passive phase difference networks are realized as a pair of 2nd order lattice filters (with balun)
- Active filter sensitivity discussed
- Audio band limiting active filters based on passive ladders are preferred for low sensitivity.