Filtering
One more look at OpAmps

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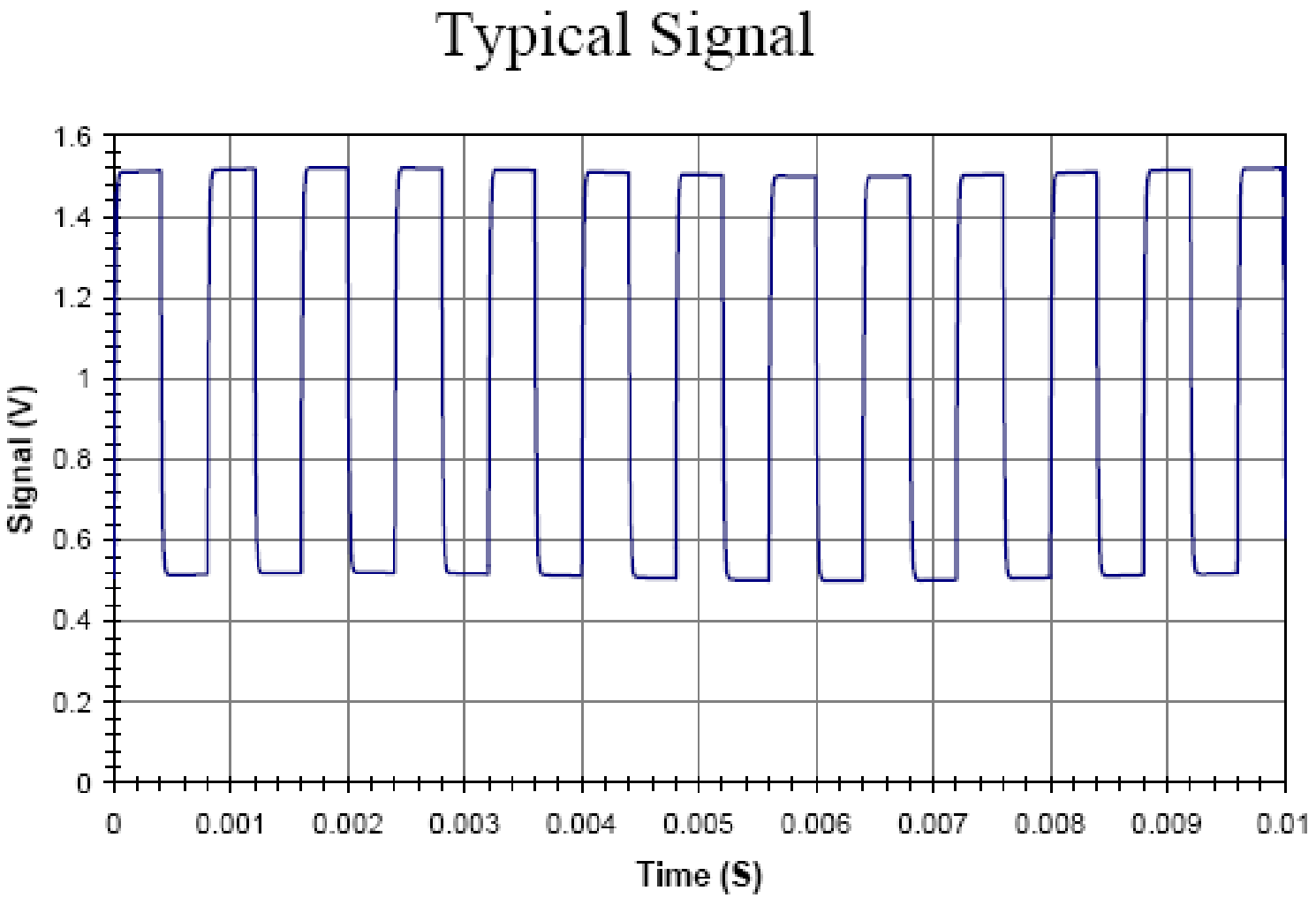
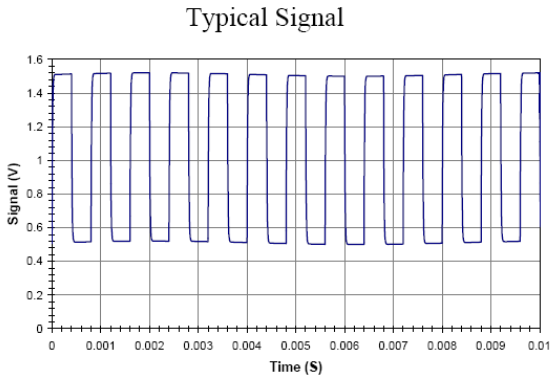
Signal Conditioning

- Amplification
  - Getting a useable signal amplitude?
- Isolation
  - Separating out the interference?
- Identification
  - Which Signal is it?

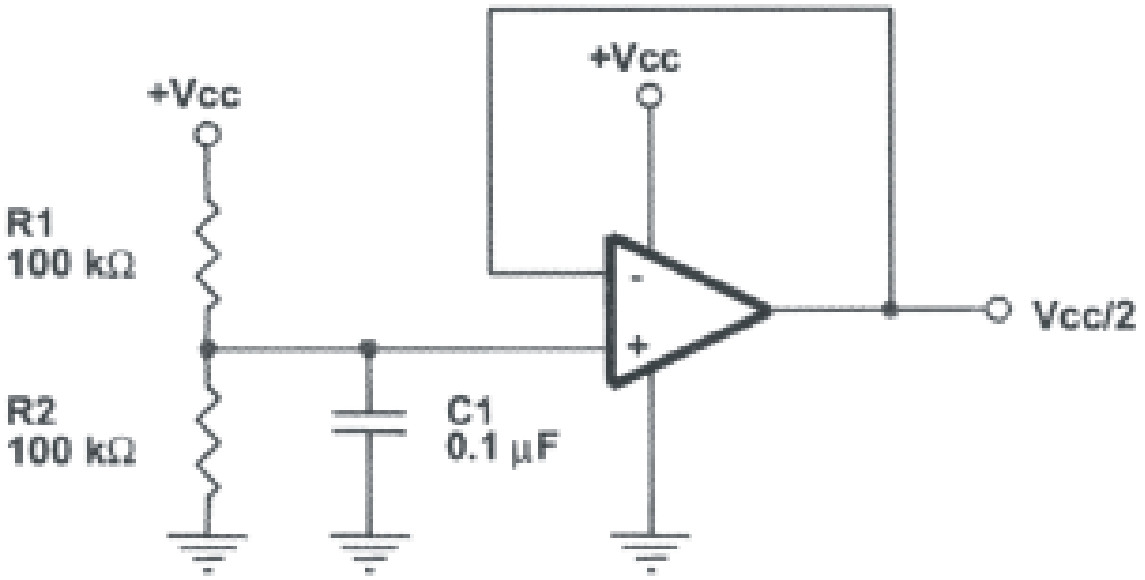
Typical Signal



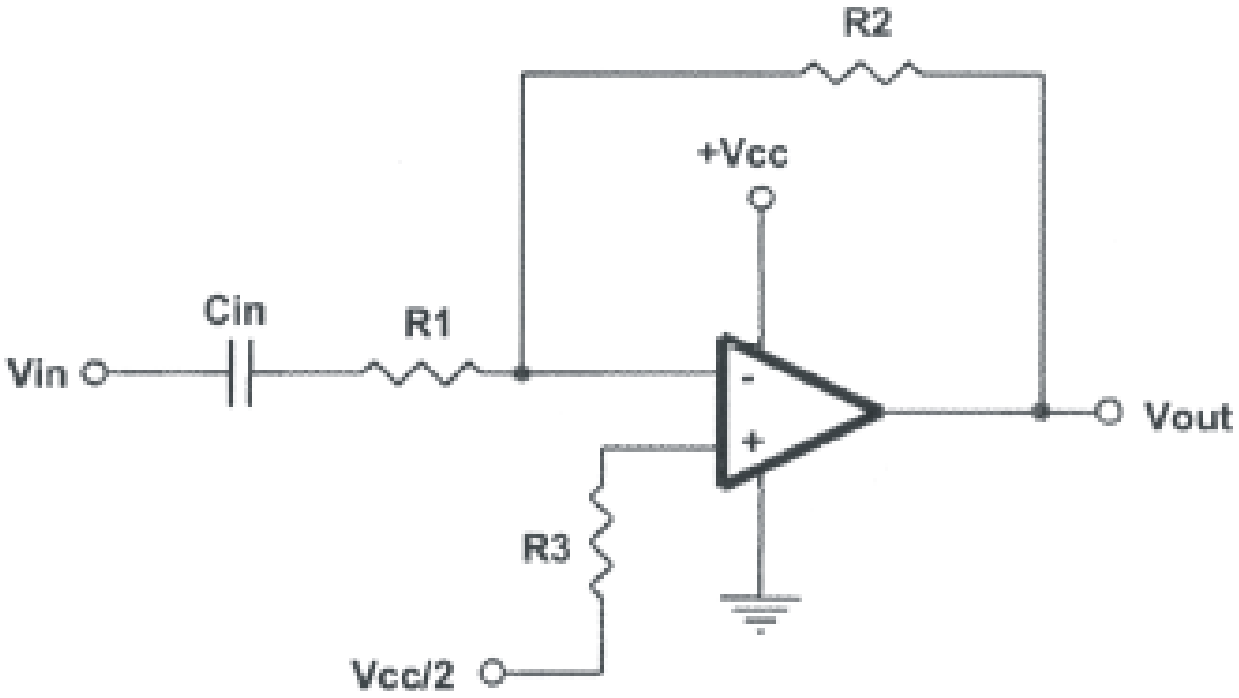
What needs to be done?



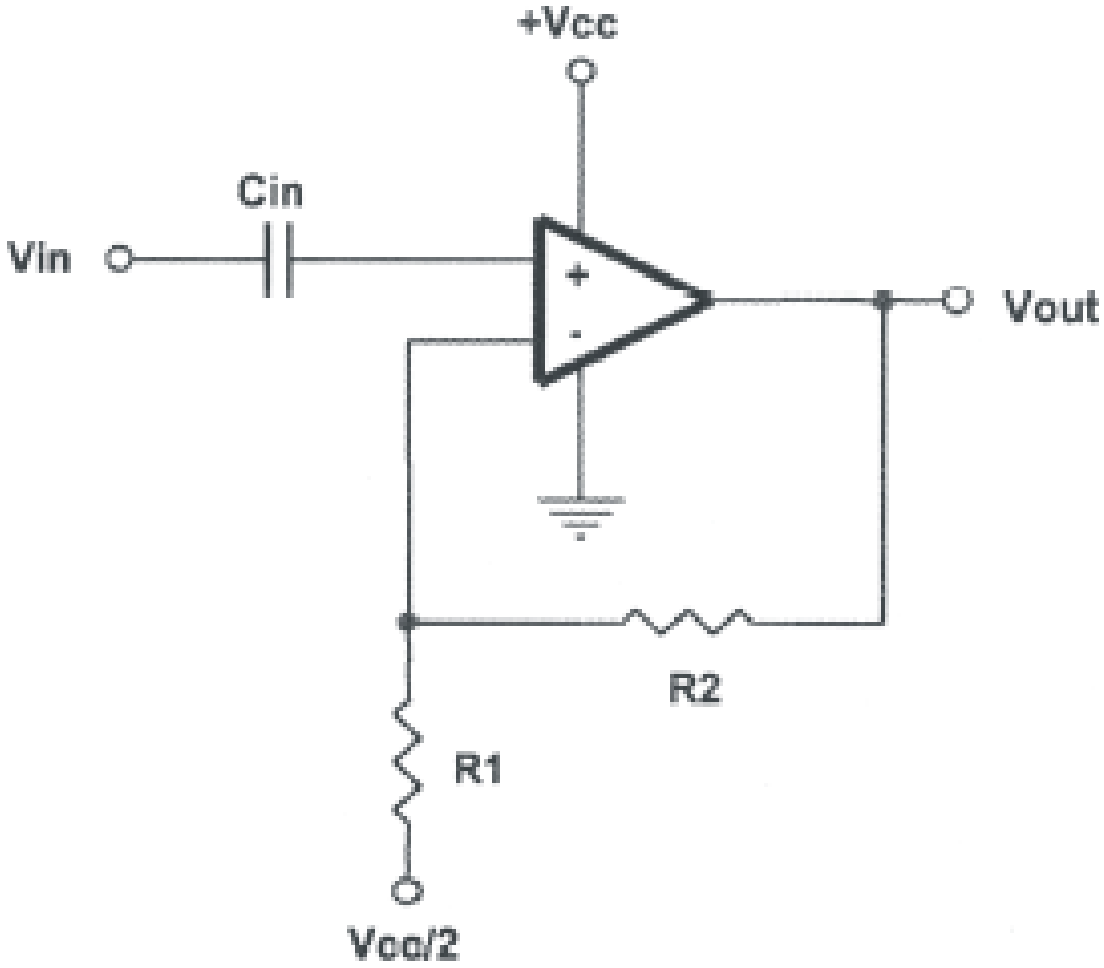
The Virtual Ground Circuit



Inverting Amplifier w/ Virtual Ground



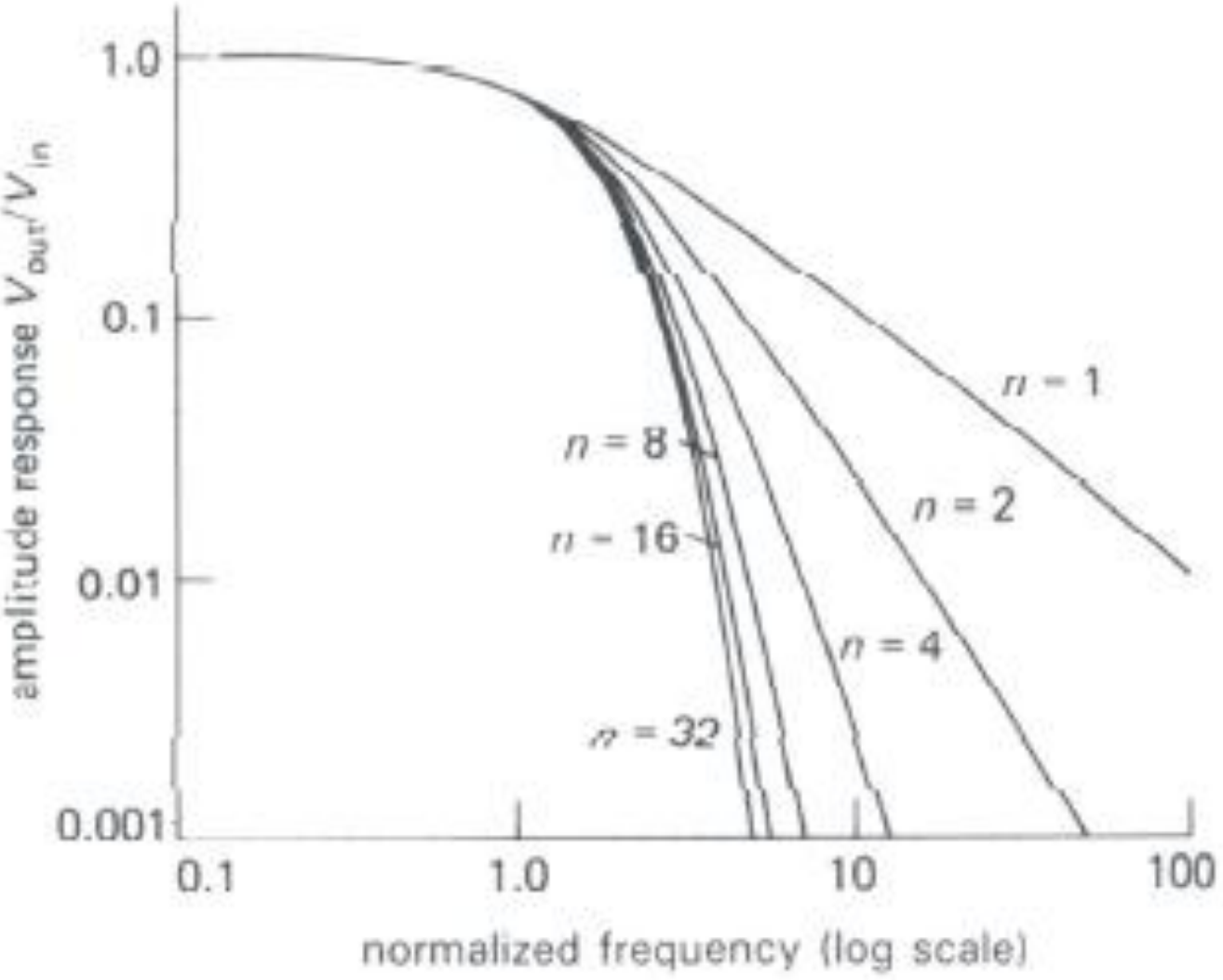
Non-Inverting Amp w/Virtual Ground



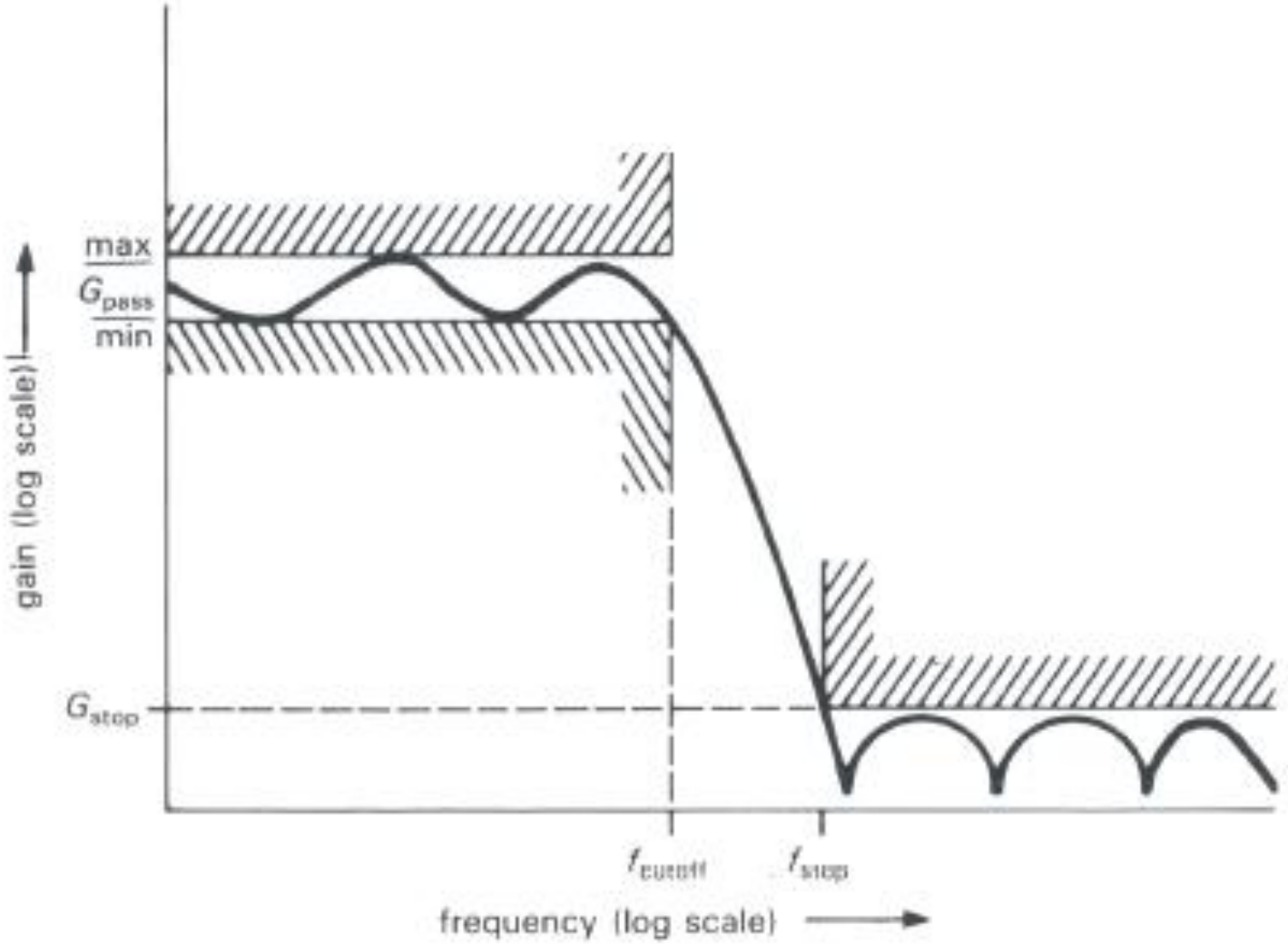
How do we implement a filter?

What if we need more attenuation?

Adding Stages to Increase Attenuation



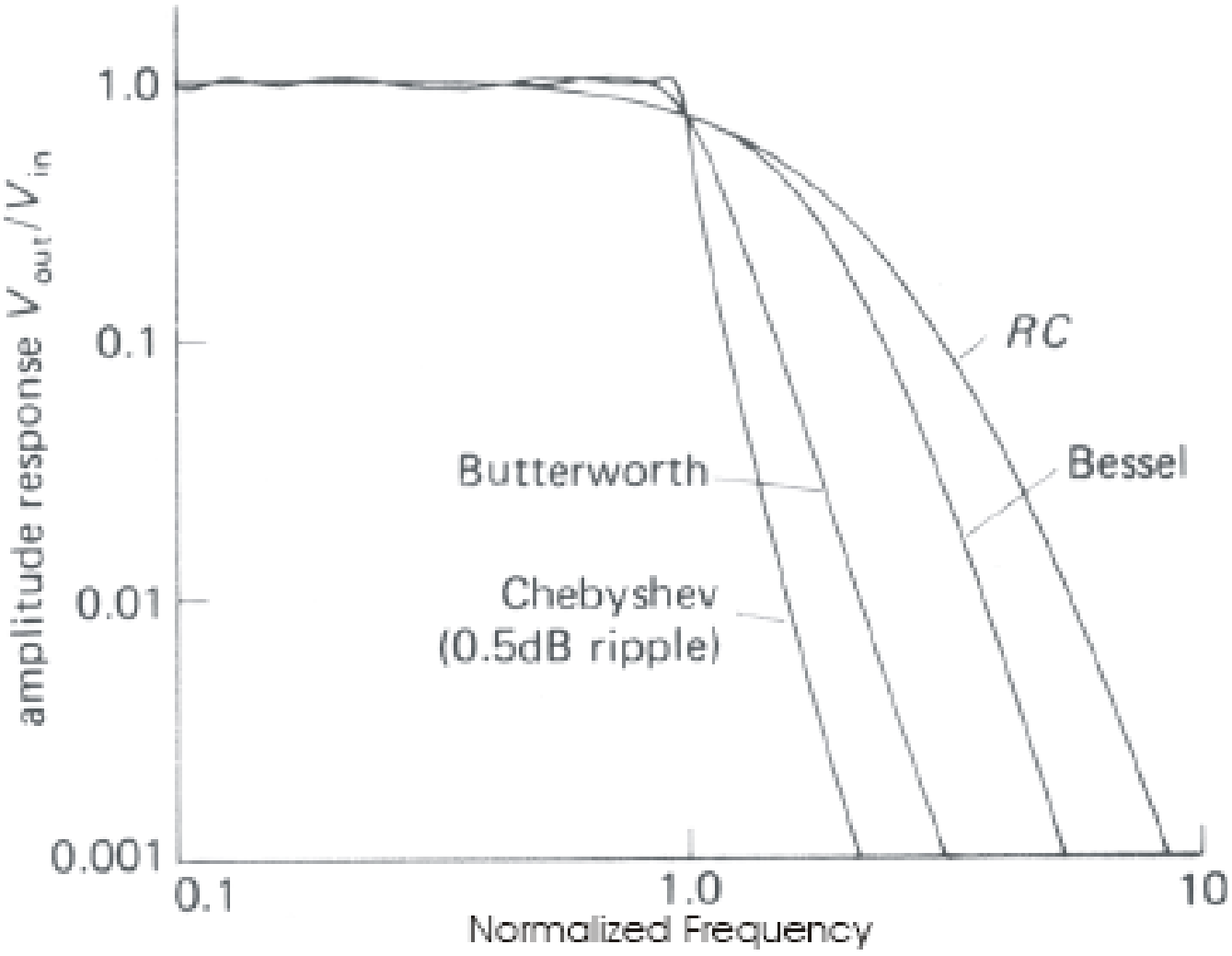
Describing Filter Performance



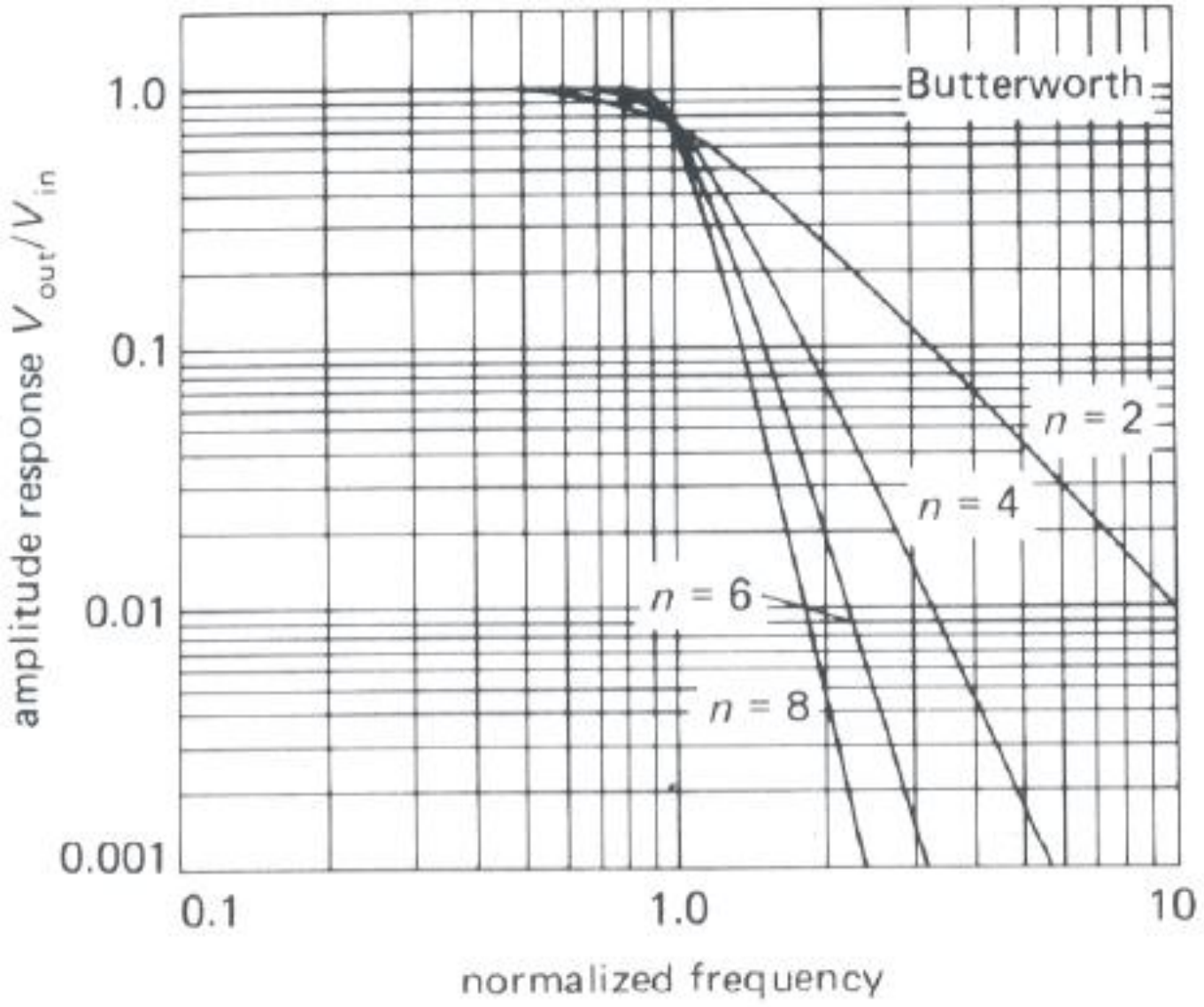
Filter Types

- **Butterworth**
  - Maximally flat: optimizes for pass-band flatness
- **Bessel**
  - Linear phase: optimized for constant delay in the pass-band
- **Chebyshev**
  - Trades ripple in the pass-band for steepness of the rolloff

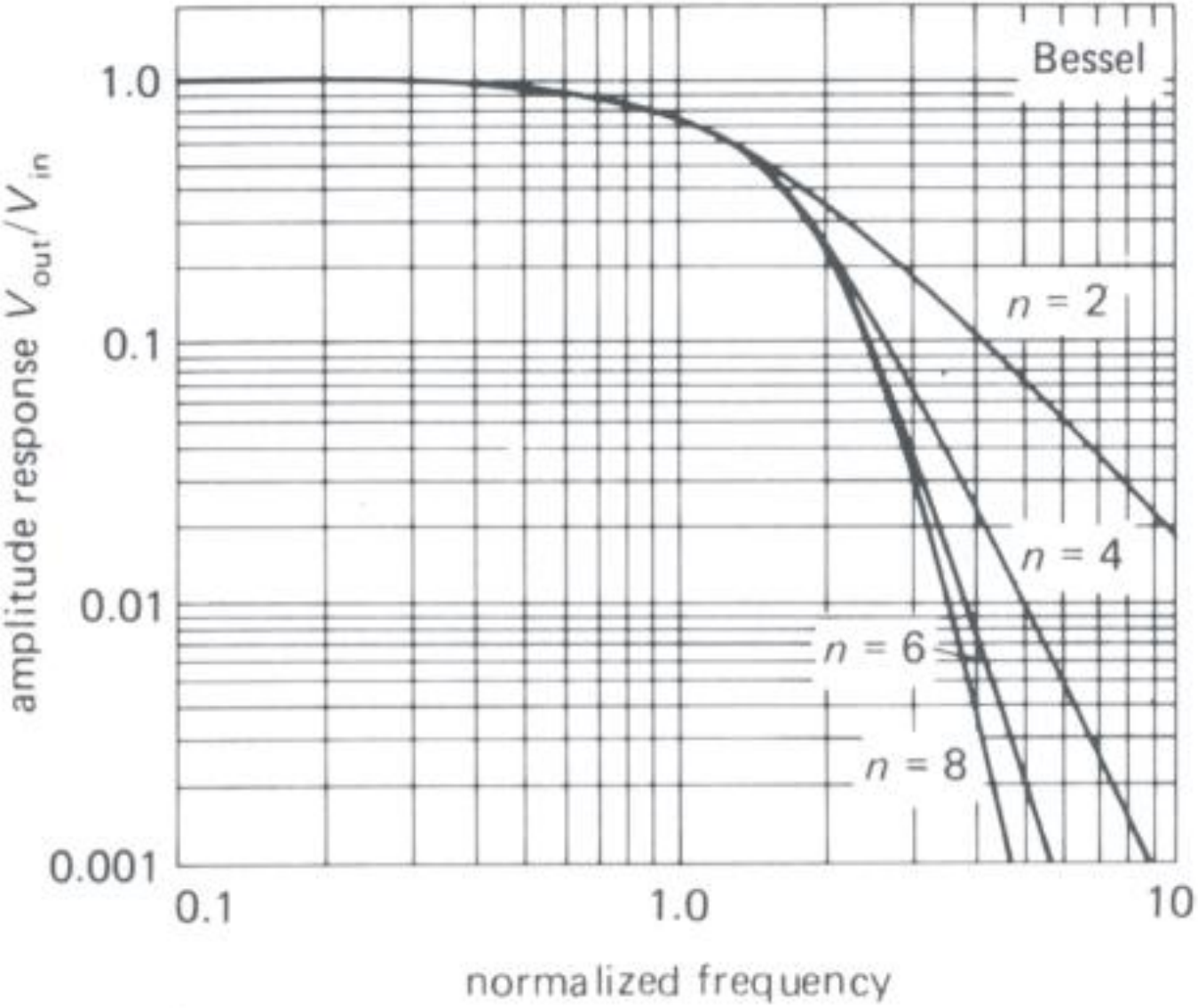
Comparison of 6th Order Filters



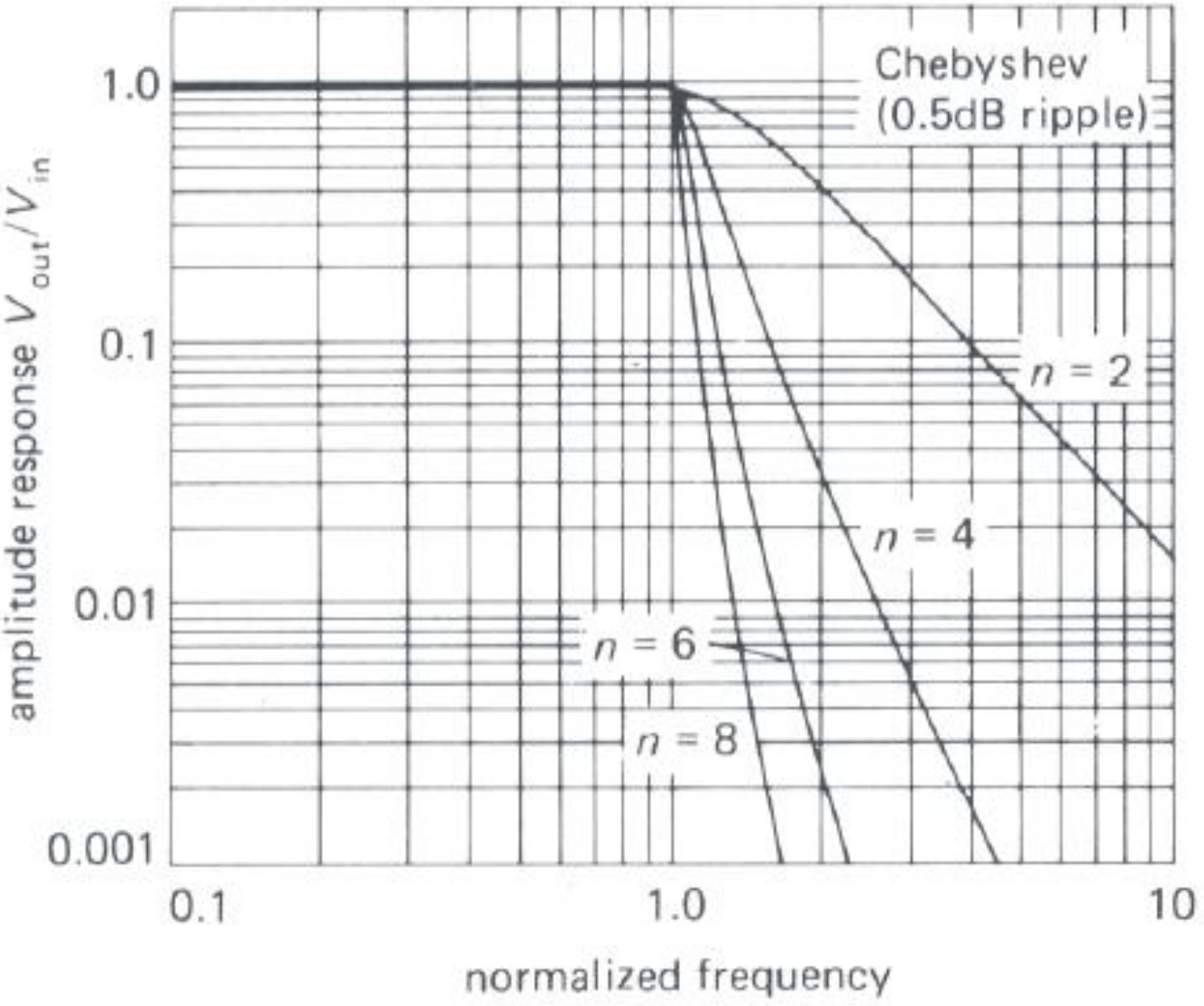
Butterworth Filters



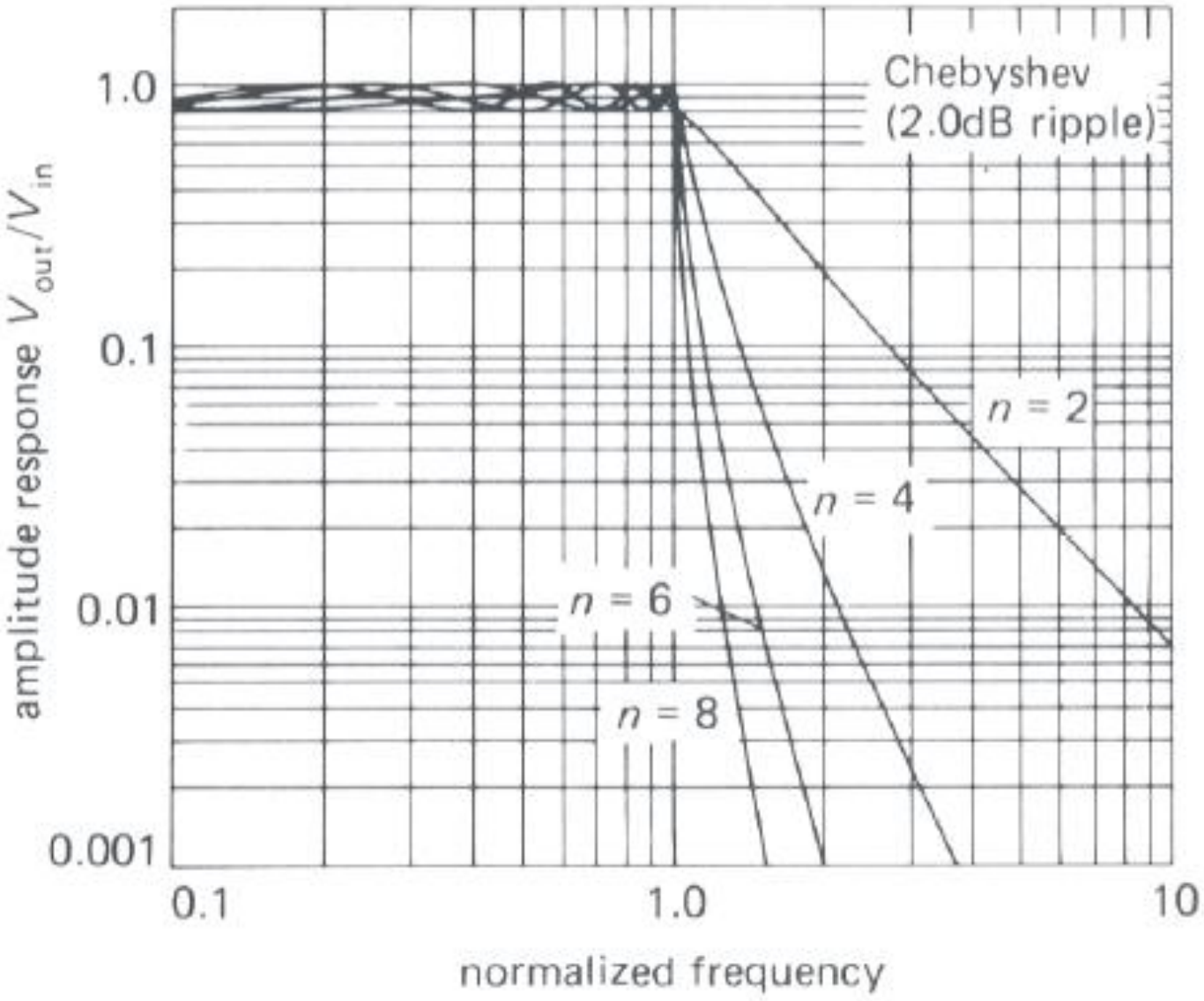
Bessel Filters



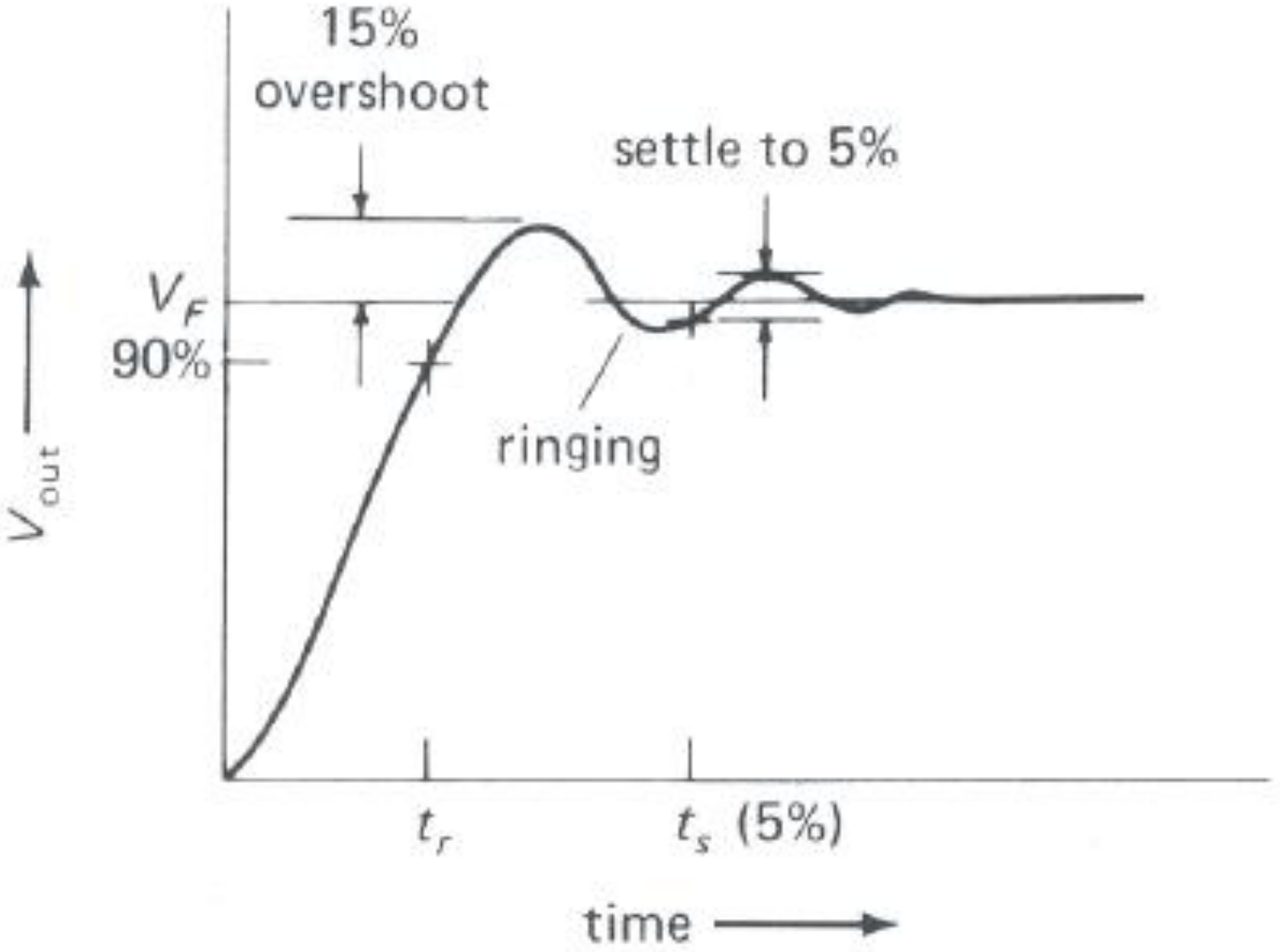
Chebyshev Filter (0.5 dB ripple)



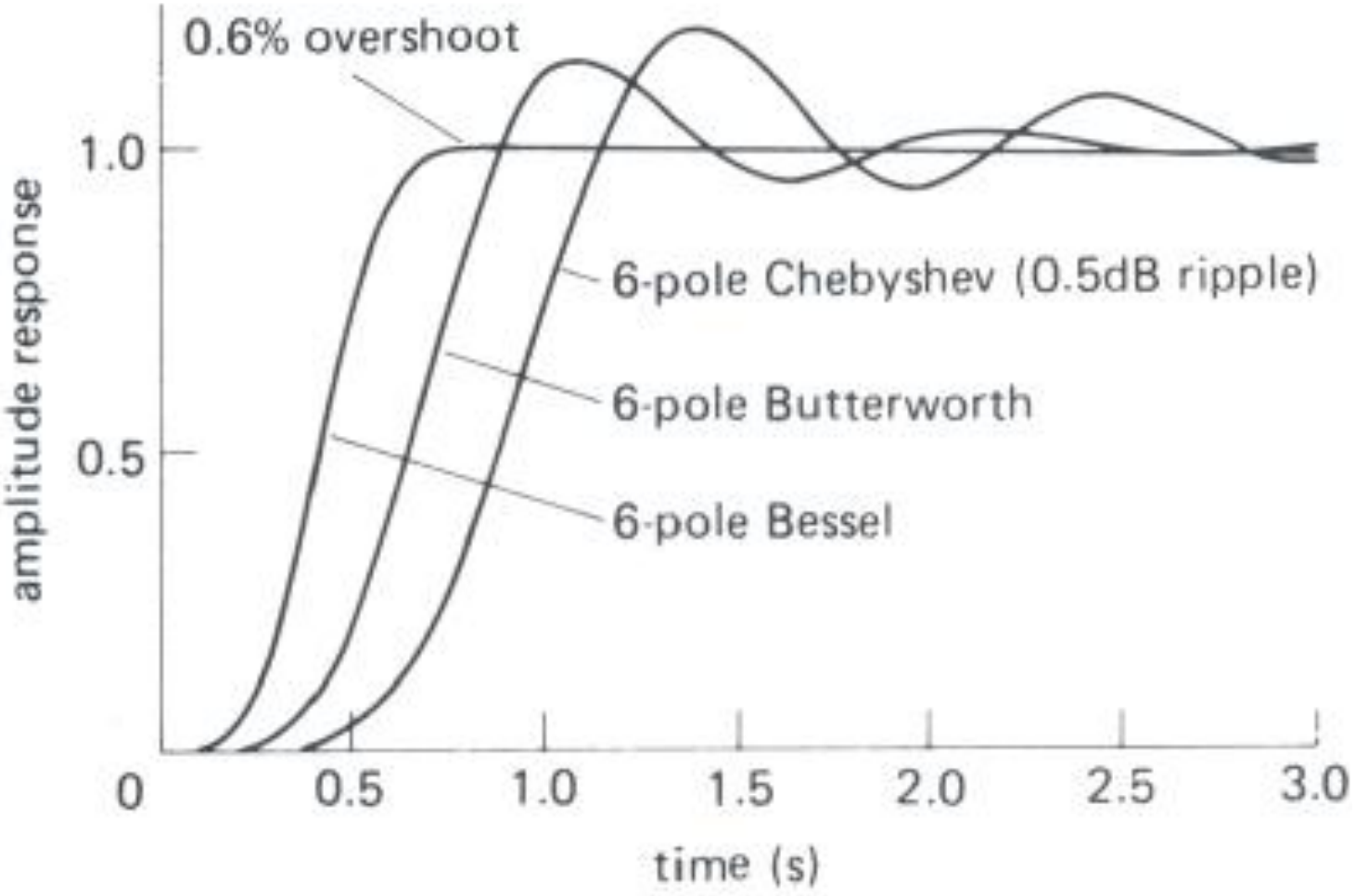
Chebyshev Filter (2.0 dB ripple)



Time Domain Response

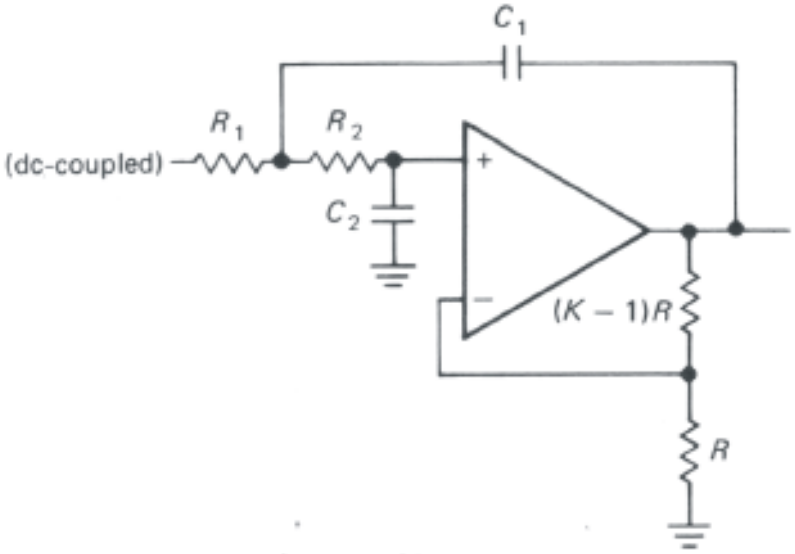


6th Order Filters: Time Domain

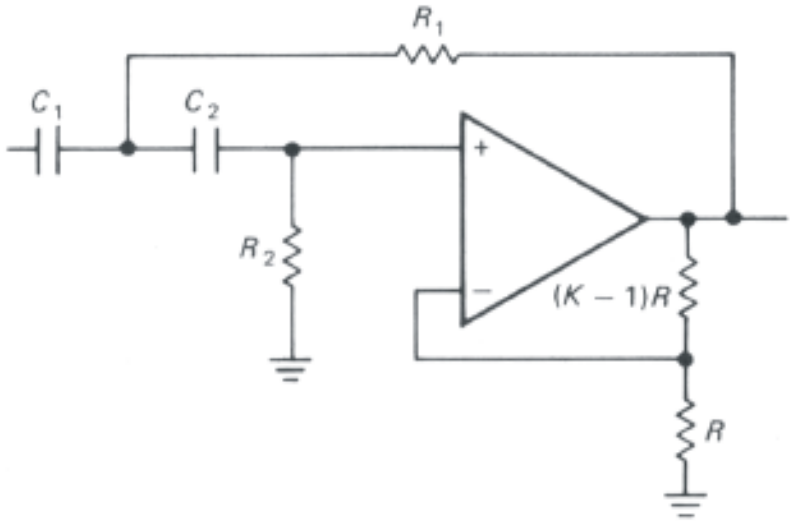


Type	f_{3dB} (Hz)	Poles	Step rise time (0 to 90%) (s)	Over-shoot (%)	Settling time to 1% (s)	Settling time to 0.1% (s)	Stopband attenuation $f = 2f_c$ (dB)	Stopband attenuation $f = 10f_c$ (dB)
Bessel	1.0	2	0.4	0.4	0.6	1.1	10	36
(-3.0dB at	1.0	4	0.5	0.8	0.7	1.2	13	66
f_c = 1.0Hz)	1.0	6	0.6	0.6	0.7	1.2	14	92
	1.0	8	0.7	0.3	0.8	1.2	14	114
Butterworth	1.0	2	0.4	4	0.8	1.7	12	40
(-3.0dB at	1.0	4	0.6	11	1.0	2.8	24	80
f_c = 1.0Hz)	1.0	6	0.9	14	1.3	3.9	36	120
	1.0	8	1.1	16	1.6	5.1	48	160
Chebyshev	1.39	2	0.4	11	1.1	1.6	8	37
0.5dB ripple	1.09	4	0.7	18	3.0	5.4	31	89
(-0.5dB at	1.04	6	1.1	21	5.9	10.4	54	141
f_c = 1.0Hz)	1.02	8	1.4	23	8.4	16.4	76	193
Chebyshev	1.07	2	0.4	21	1.6	2.7	15	44
2.0dB ripple	1.02	4	0.7	28	4.8	8.4	37	96
(-2.0dB at	1.01	6	1.1	32	8.2	16.3	60	148
f_c = 1.0Hz)	1.01	8	1.4	34	11.6	24.8	83	200

Better Filter Stages



low-pass filter



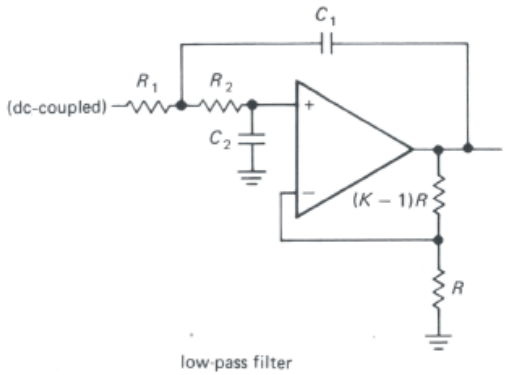
high-pass filter

Design of VCVS Filter Stages

TABLE 5.2. VCVS LOW-PASS FILTERS

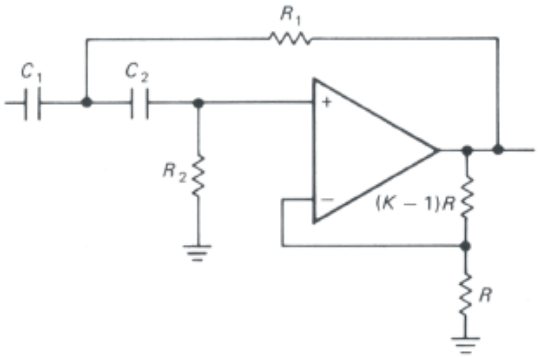
Poles	Butter-worth K	Bessel		Chebyshev (0.5dB)		Chebyshev (2.0dB)	
		f_n	K	f_n	K	f_n	K
2	1.586	1.272	1.268	1.231	1.842	0.907	2.114
4	1.152	1.432	1.084	0.597	1.582	0.471	1.924
	2.235	1.606	1.759	1.031	2.660	0.964	2.782
6	1.068	1.607	1.040	0.396	1.537	0.316	1.891
	1.586	1.692	1.364	0.768	2.448	0.730	2.648
	2.483	1.908	2.023	1.011	2.846	0.983	2.904
8	1.038	1.781	1.024	0.297	1.522	0.238	1.879
	1.337	1.835	1.213	0.599	2.379	0.572	2.605
	1.889	1.956	1.593	0.861	2.711	0.842	2.821
	2.610	2.192	2.184	1.006	2.913	0.990	2.946

VCVS Low-Pass filter design



low-pass filter

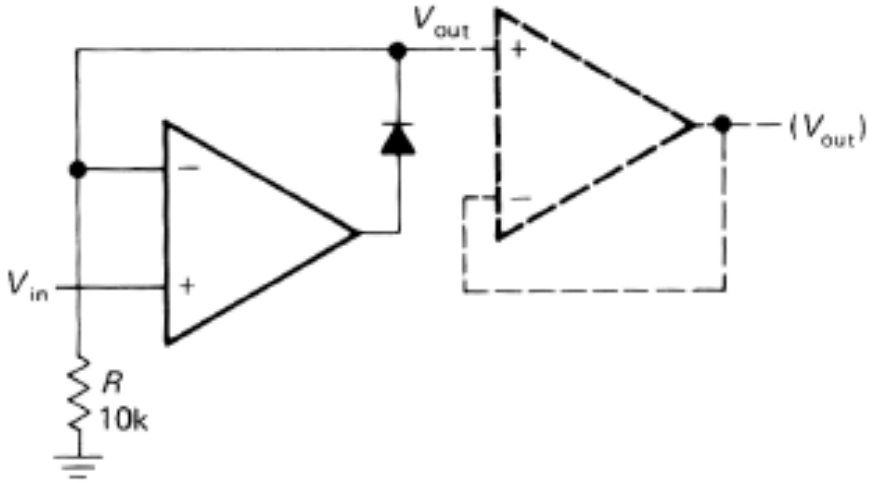
VCVS High-Pass filter design

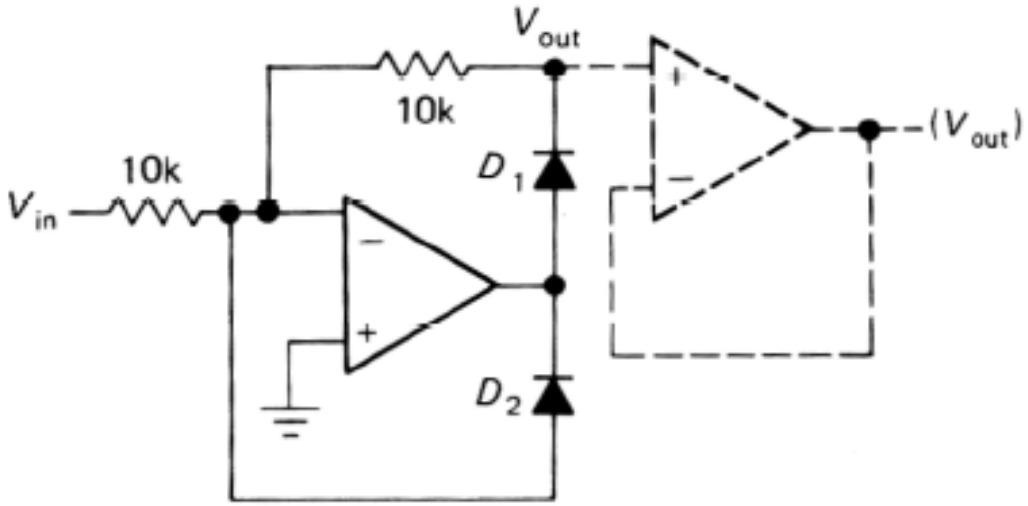


high-pass filter

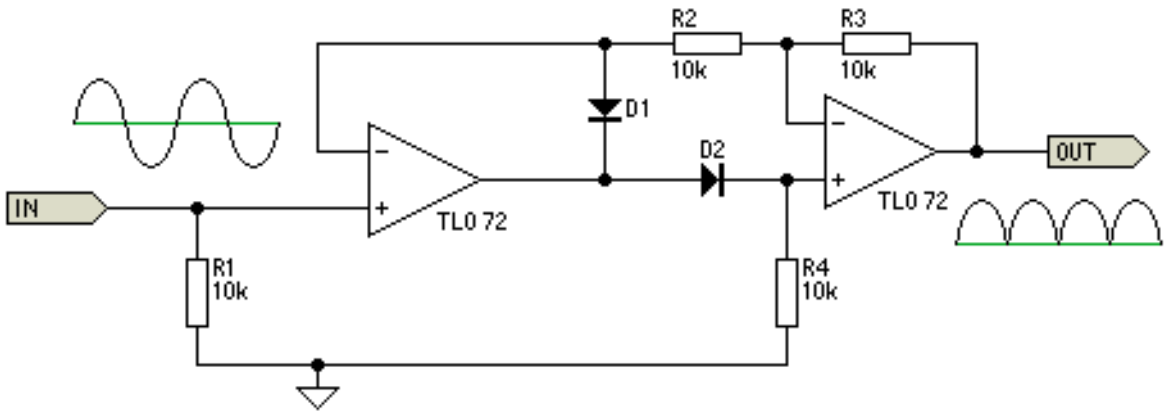
Amplitude Detection

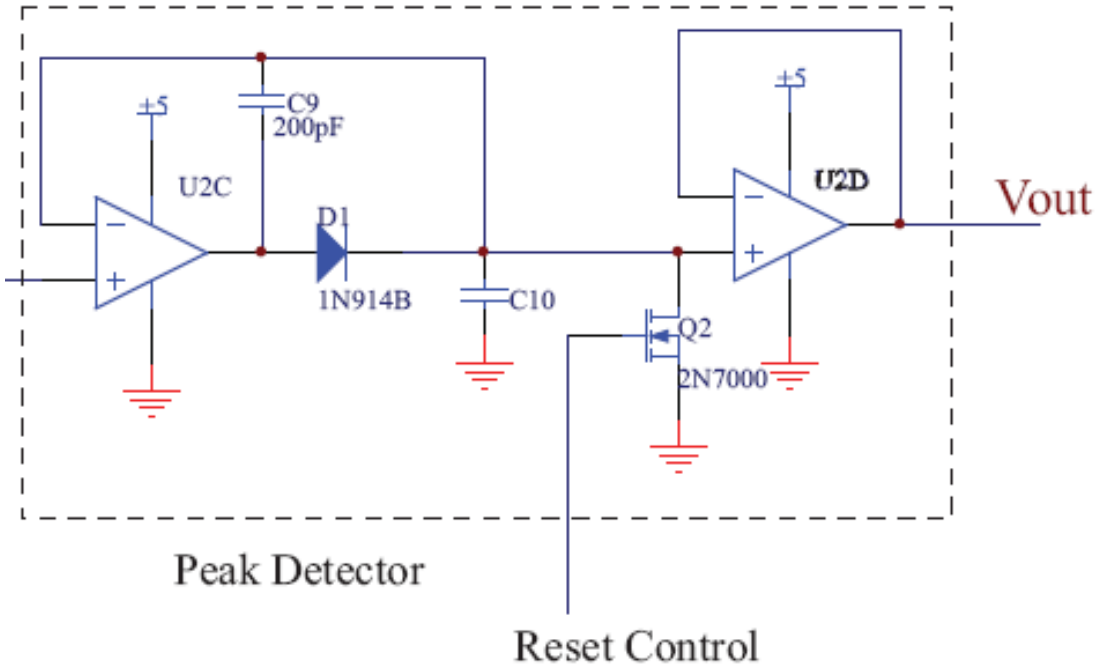
Precision Rectifiers



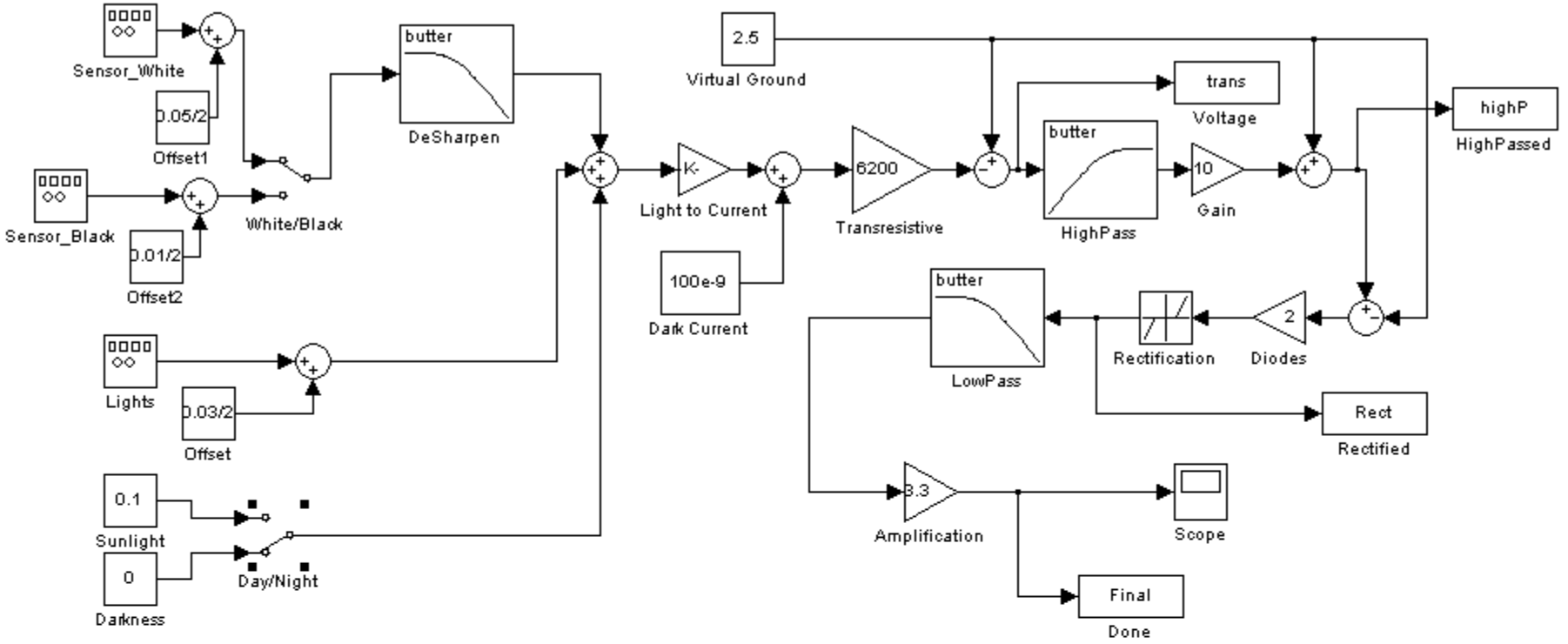


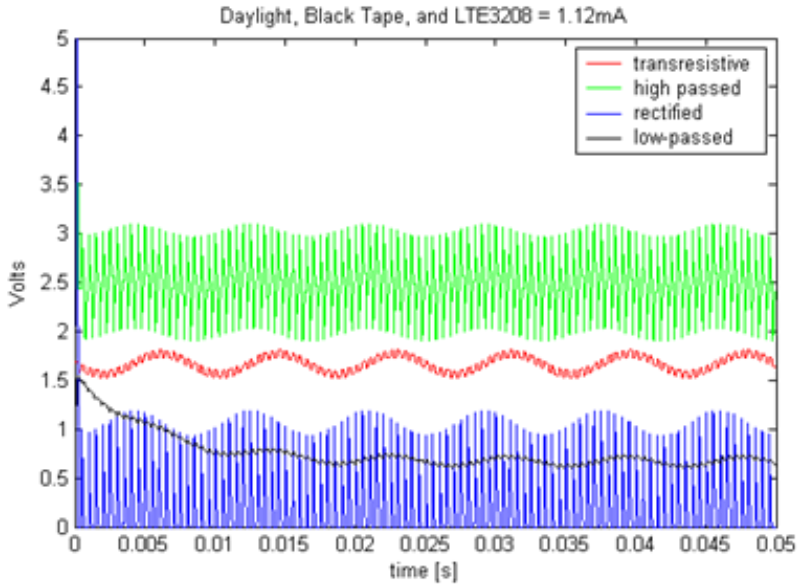
Peak Detector

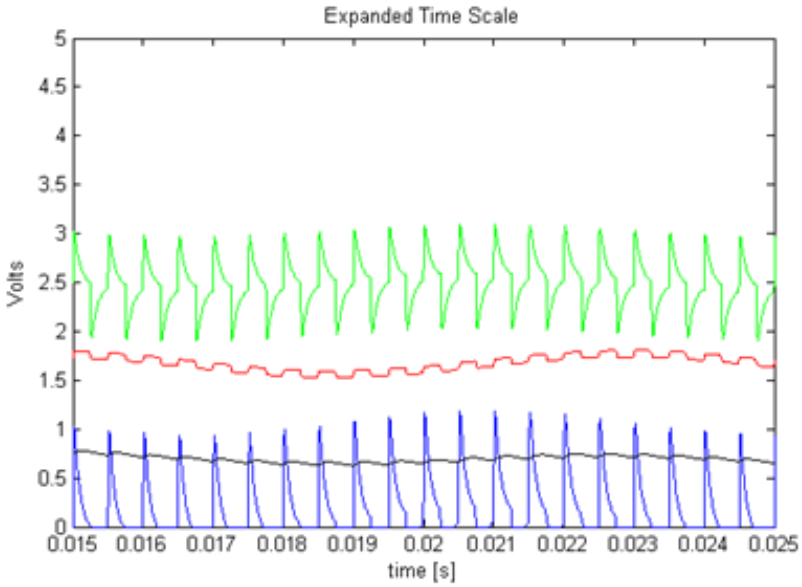


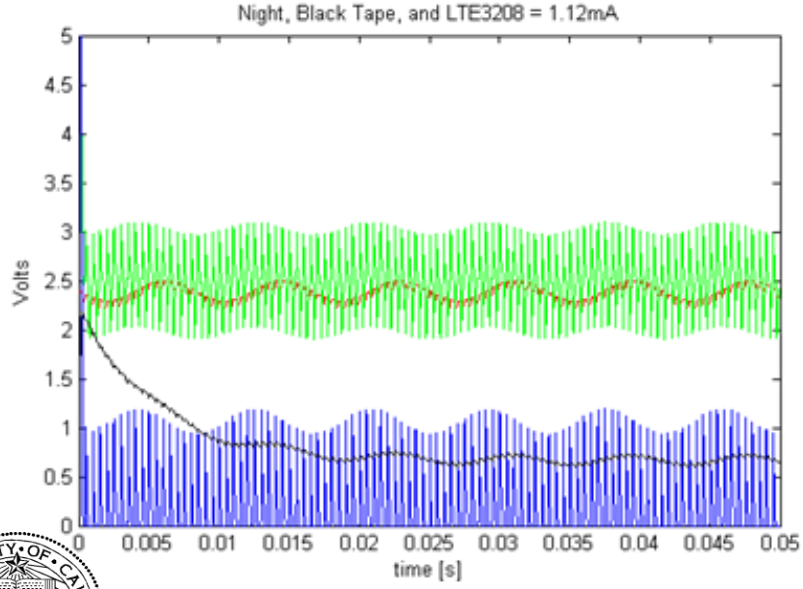


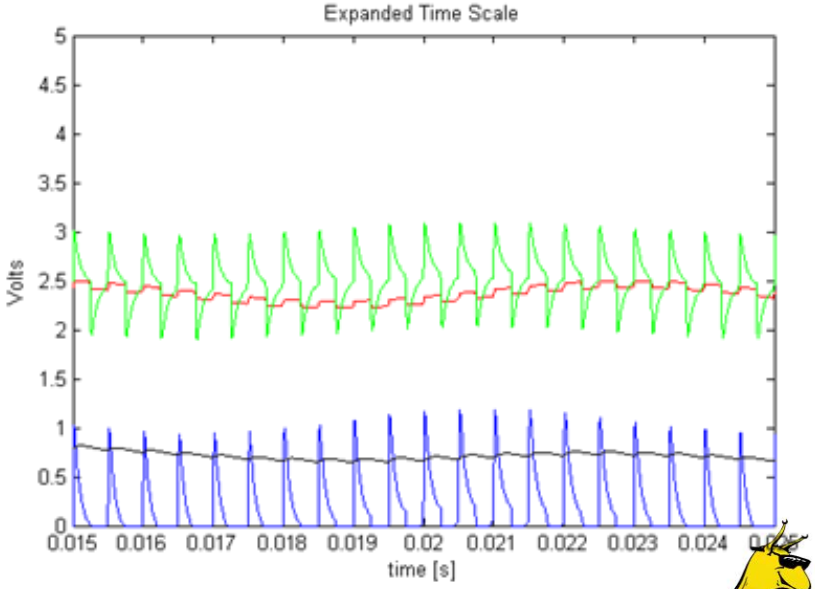
Filtering Problem




Daylight, Black Tape, and LTE3208 = 1.12mA
transresistive
high passed
rectified
low-passed
Volts
time [s]


Expanded Time Scale
Volts
time [s]


Night, Black Tape, and LTE3208 = 1.12mA
Volts
time [s]


Expanded Time Scale
Volts
time [s]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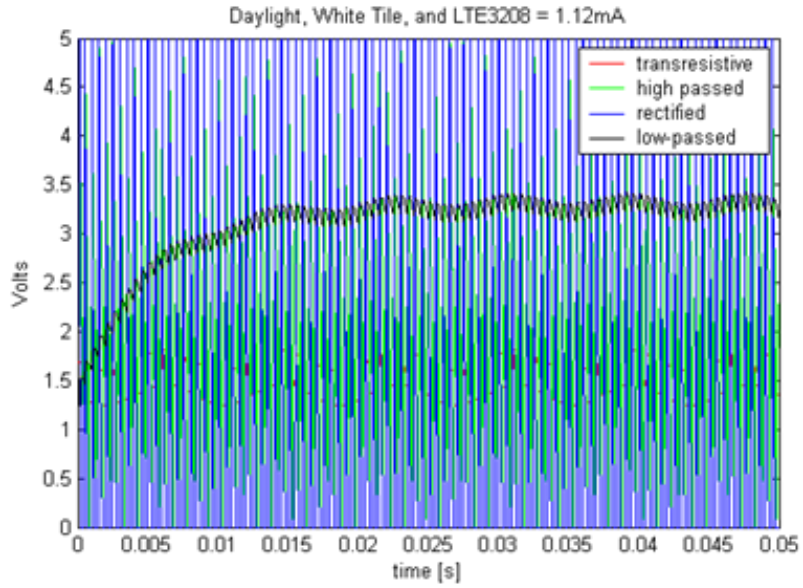
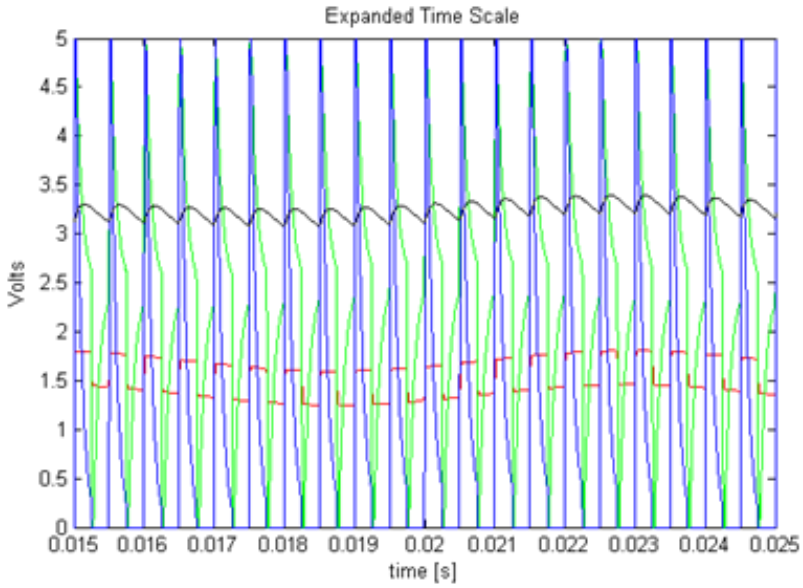
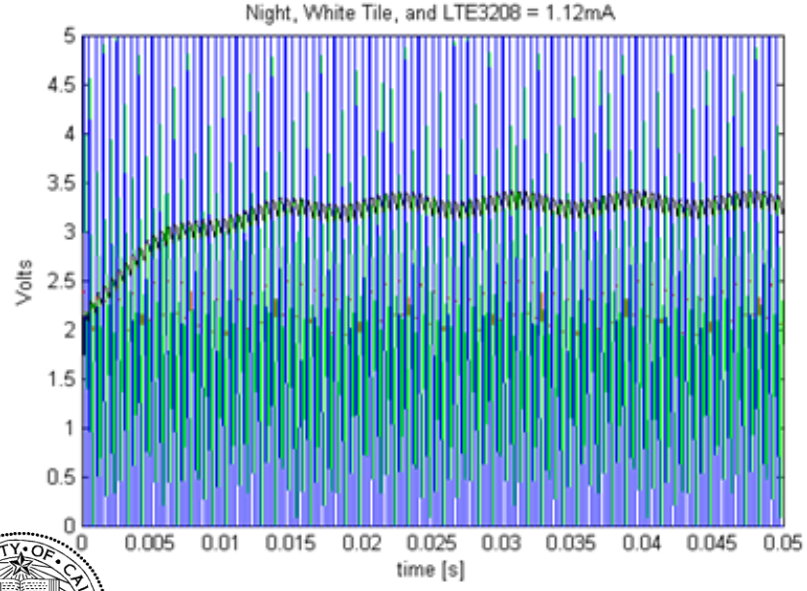
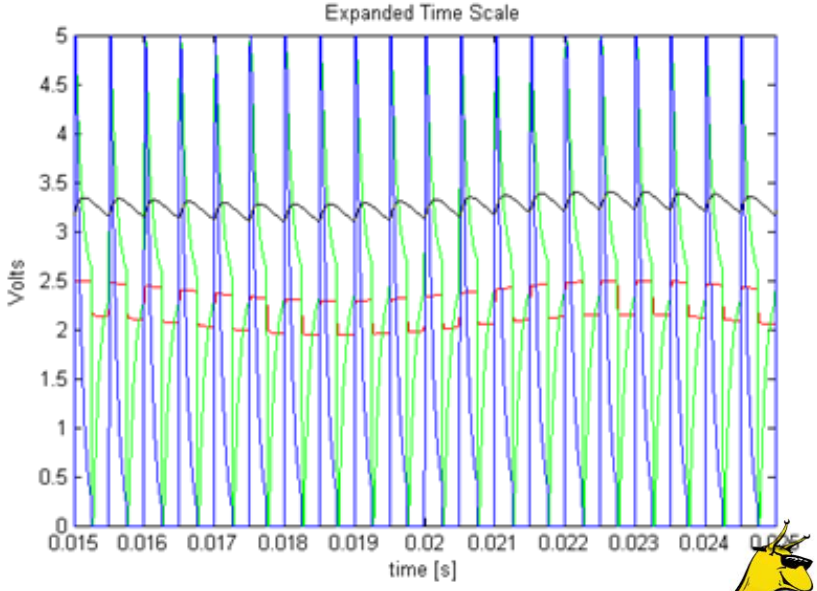

Daylight, White Tile, and LTE3208 = 1.12mA
transresistive
high passed
rectified
low-passed
Volts
time [s]


Expanded Time Scale
Volts
time [s]


Night, White Tile, and LTE3208 = 1.12mA
Volts
time [s]


Expanded Time Scale
Volts
time [s]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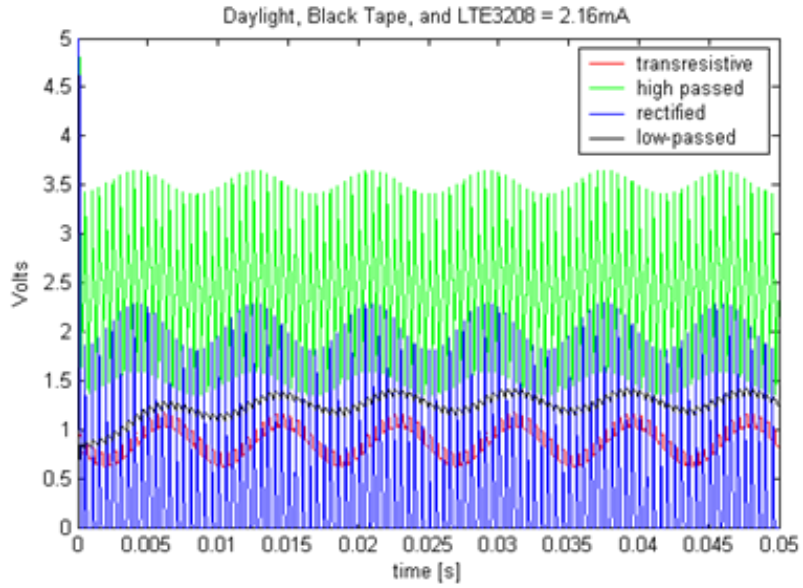
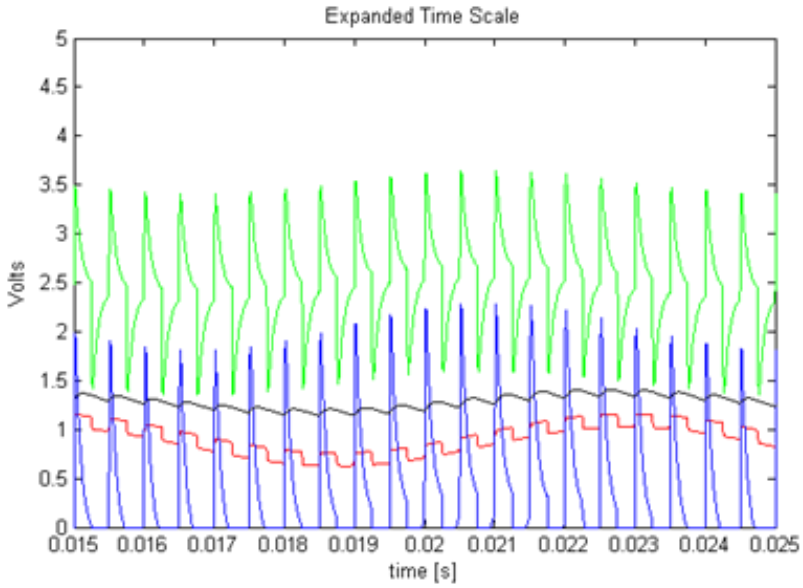
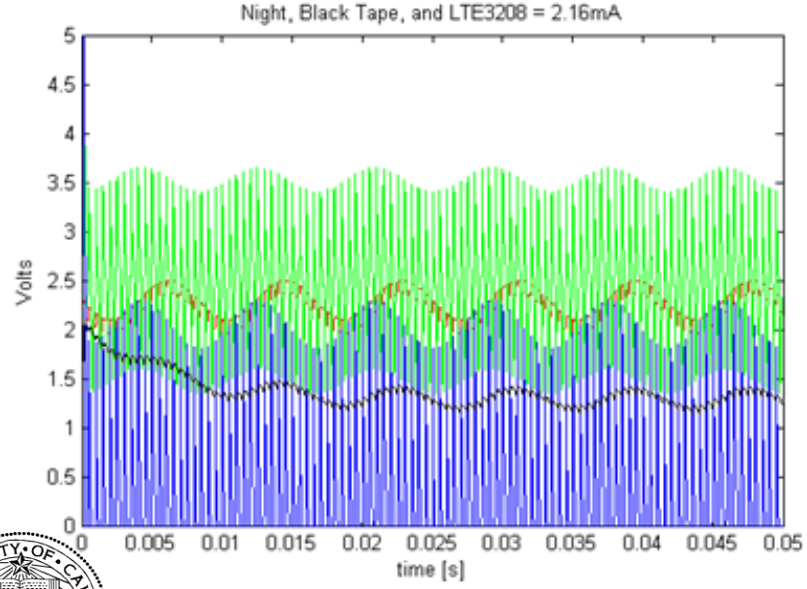
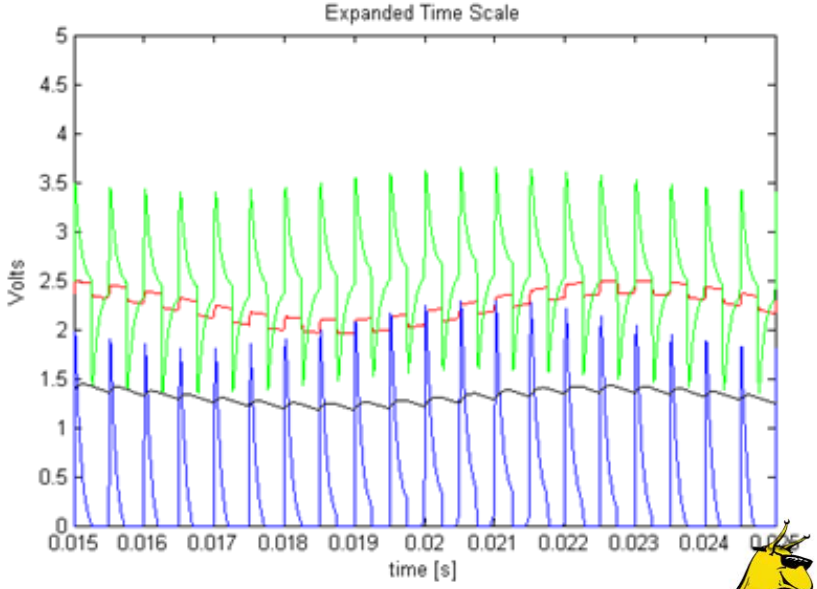
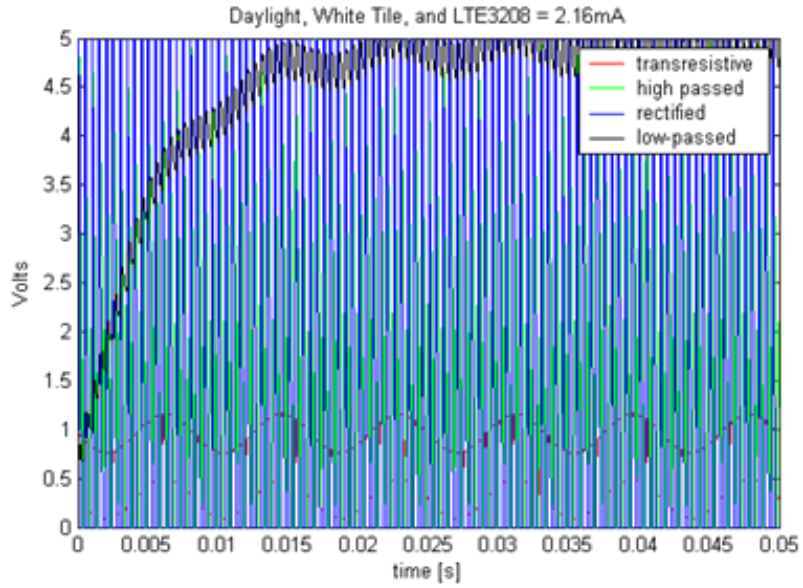

Daylight, Black Tape, and LTE3208 = 2.16mA
transresistive
high passed
rectified
low-passed
Volts
time [s]


Expanded Time Scale
Volts
time [s]


Night, Black Tape, and LTE3208 = 2.16mA
Volts
time [s]


Expanded Time Scale
Volts
time [s]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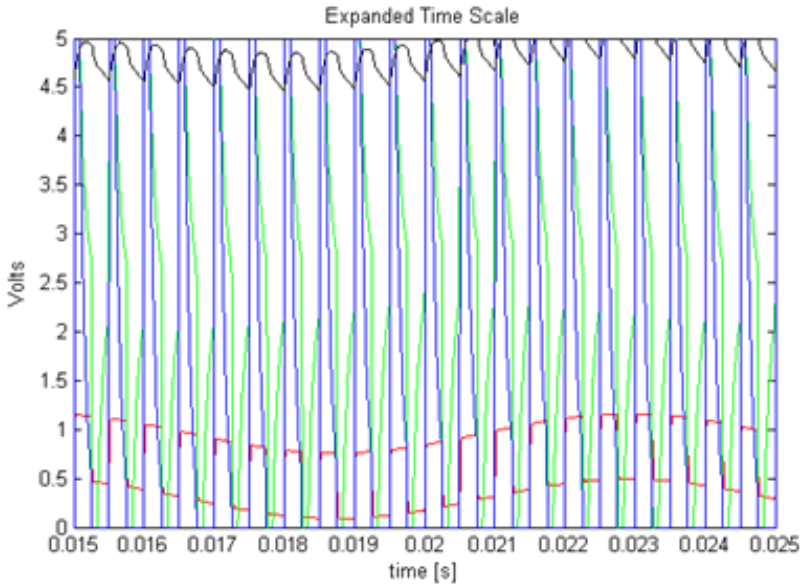
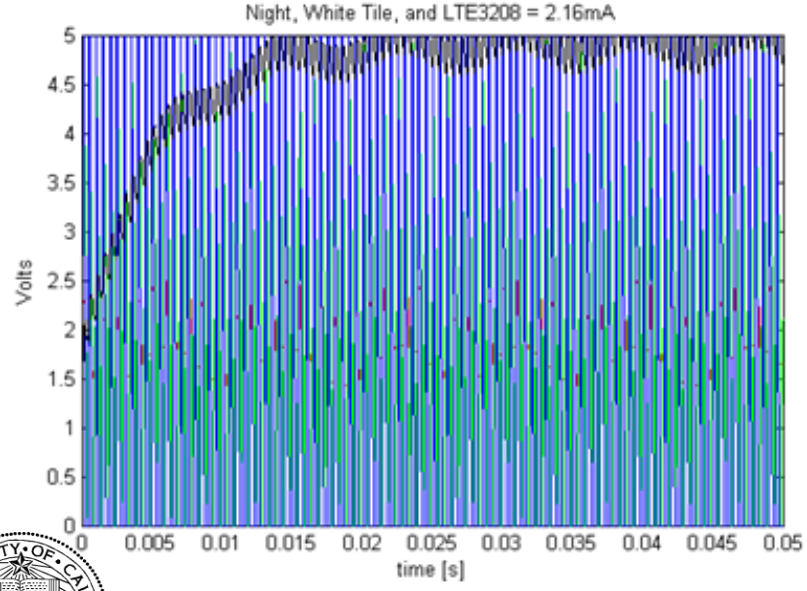
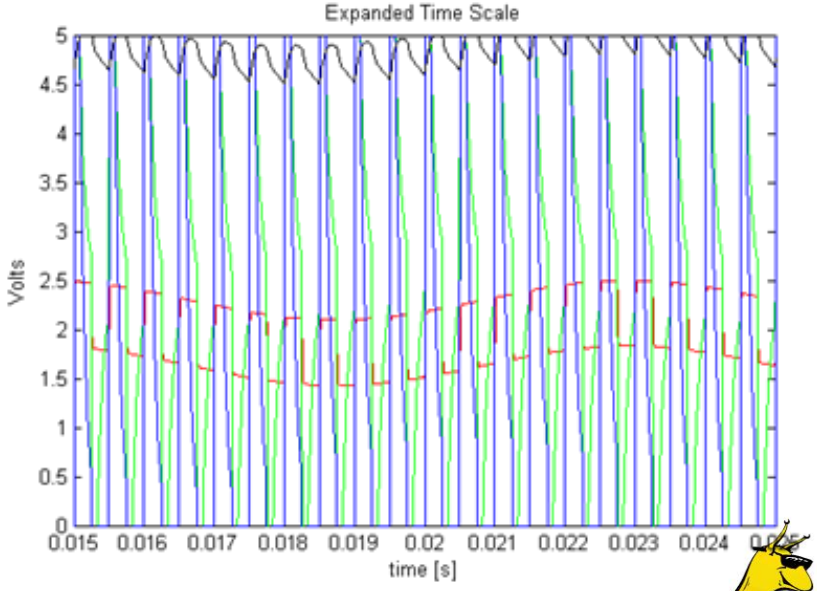
Volts
time [s]


Expanded Time Scale
Volts
time [s]


Night, White Tile, and LTE3208 = 2.16mA
Volts
time [s]


Expanded Time Scale
Volts
time [s]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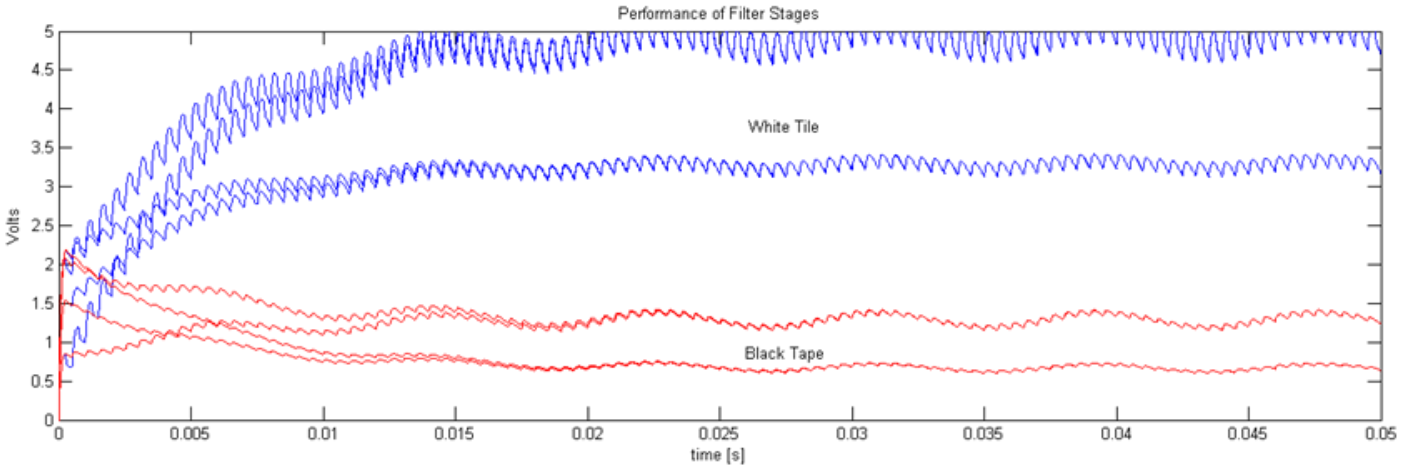
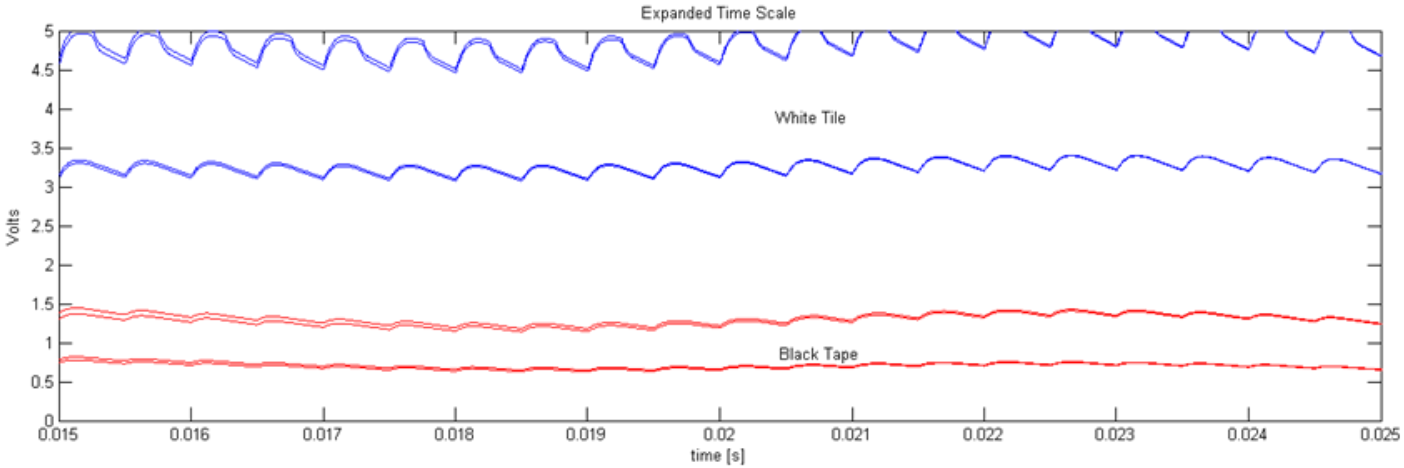
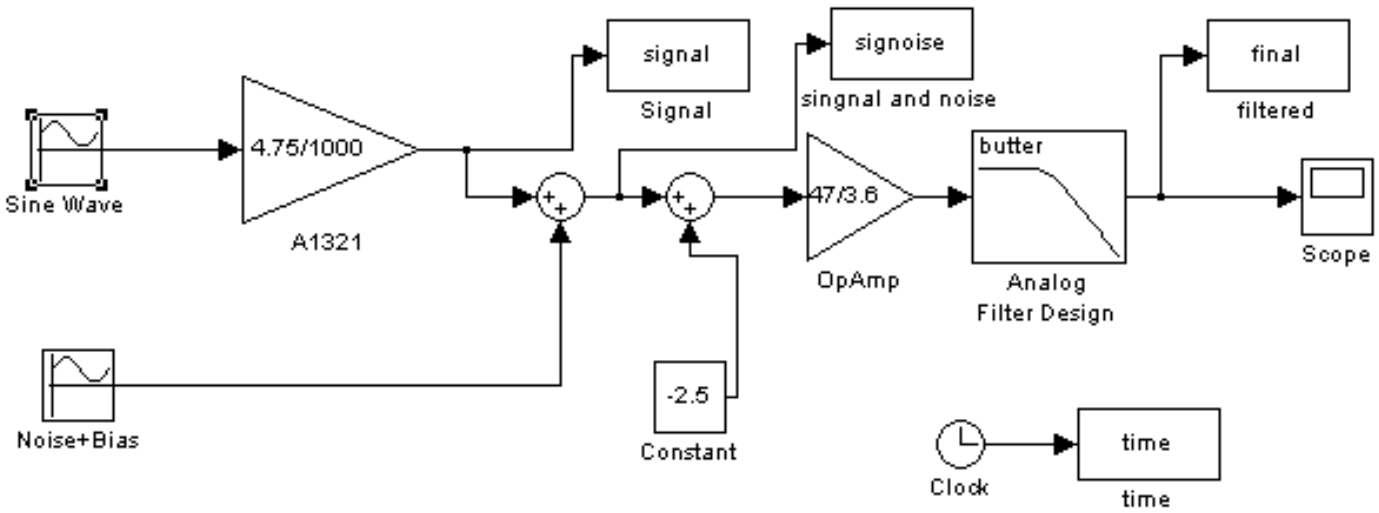
Final Filtered Signal

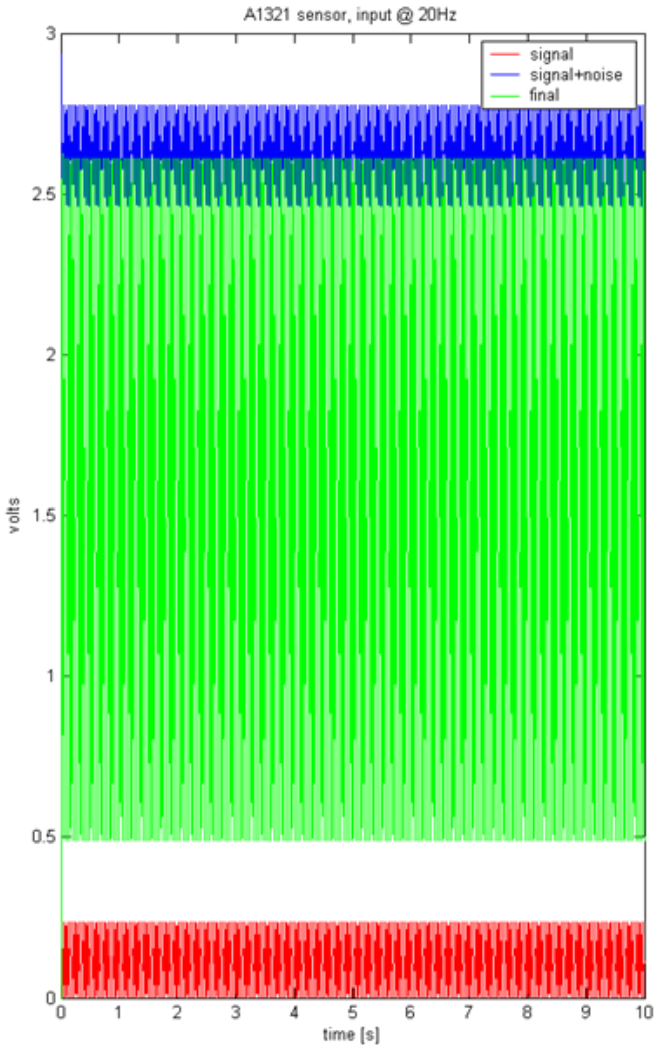


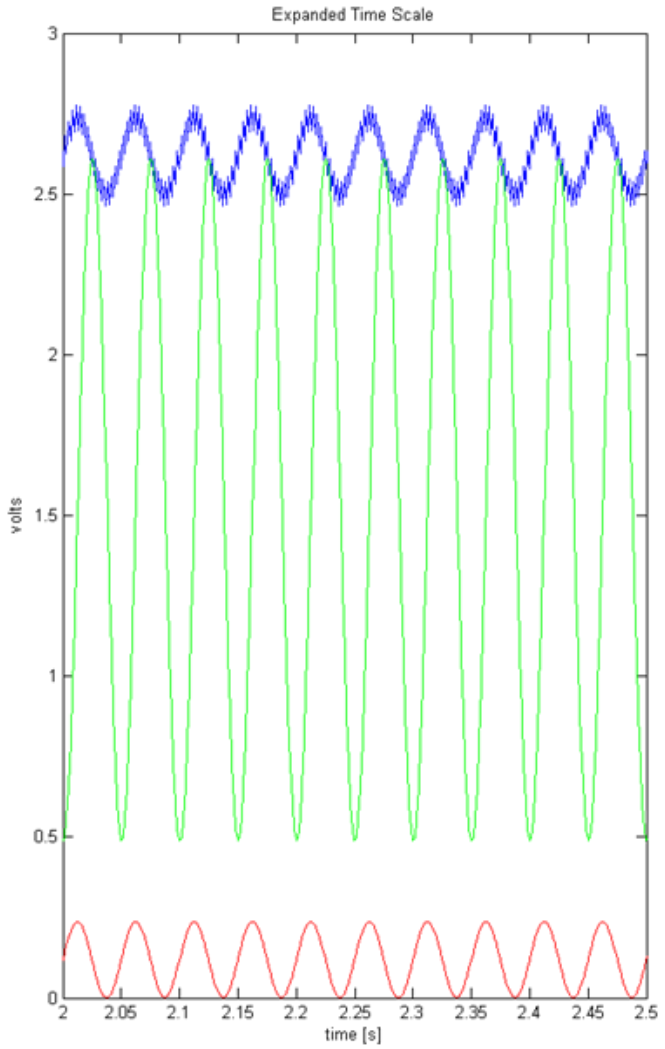


Filter Problem Solved



Final Filtered Signal





Digital Techniques

- Digital Filtering
- ADC input filtering
- Digital input filtering
- Phase coherent sampling
- Hysteresis bounds

Moving Average Filter (1.3)

Moving Average Filter (2.3)

$$Y_i = (X_i + X_{i-1}) / 2$$

$$Y_i = \left(\sum_{j=0}^{j=N-1} X_{i-j} \right) / N$$

Moving Average Filter (3.3)

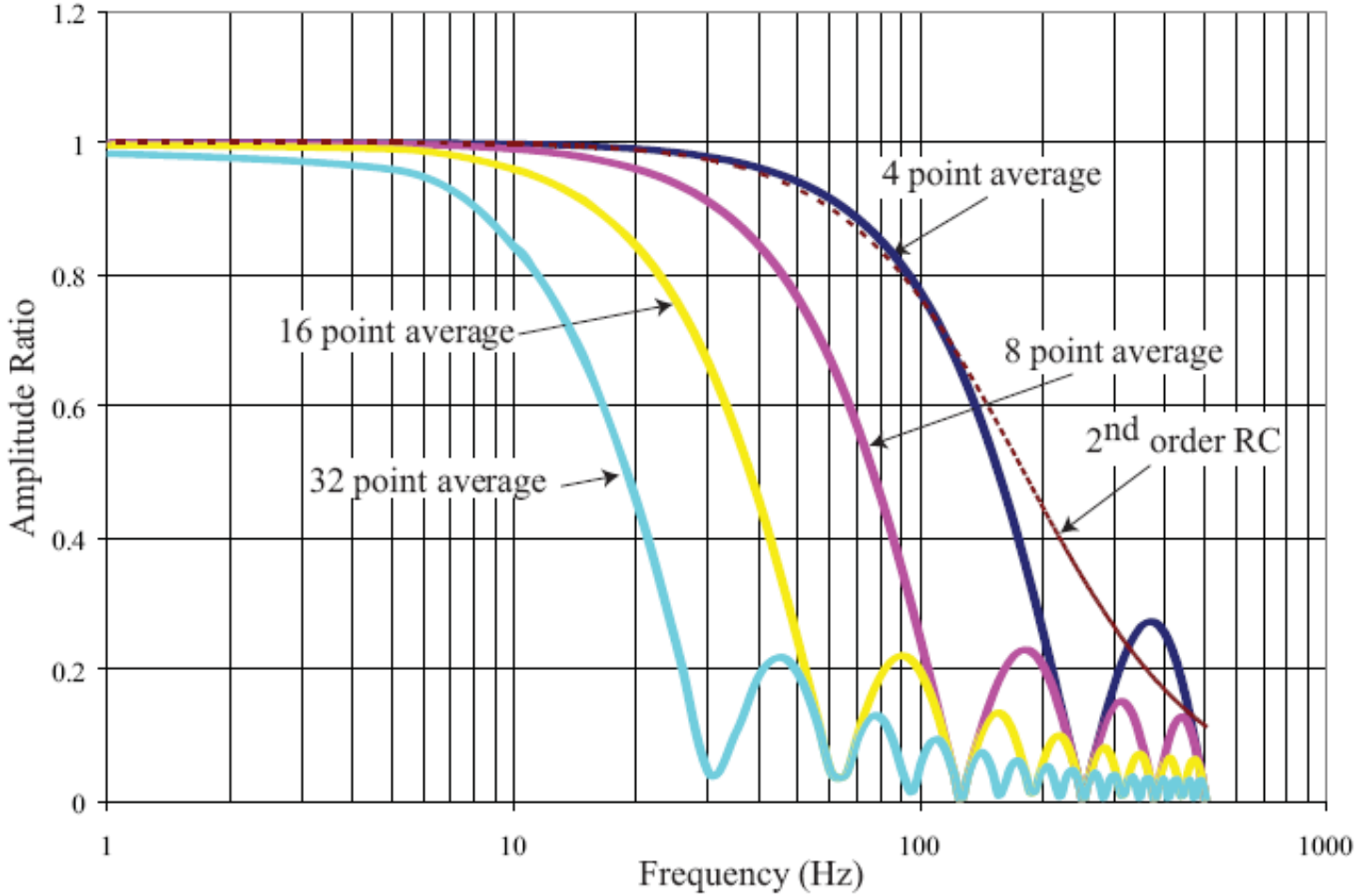
$$Y_{10} = (X_{10}+X_9+X_8+X_7+X_6+X_5+X_4+X_3)/8$$

$$Y_{11} = (X_{11}+X_{10}+X_9+X_8+X_7+X_6+X_5+X_4)/8$$

$$SUM_{11} = SUM_{10} - X_3 + X_{11}$$

$$Y_{11} = SUM_{11}/8$$

$$H(F_{fs}) = \frac{\sin(\pi F_{fs} M)}{M \sin(\pi F_{fs})}$$



FIR and IIR filtering

$$Y_i = \sum_{j=0}^{j=N-1} X_{i-j} * H_{i-j}$$

$$Y_i = \sum_{j=0}^{j=N-1} X_{i-j} * H_{i-j} + \sum_{j=1}^{j=M-1} Y_{i-j} * G_{i-j}$$

Analog or Digital Inputs

Synchronous Measurements

Other techniques

- 3 or 5 in a row
- Best 3 out of 5 etc.
- Moving average with hysteresis