Analog Filter Design: A Comprehensive Guide

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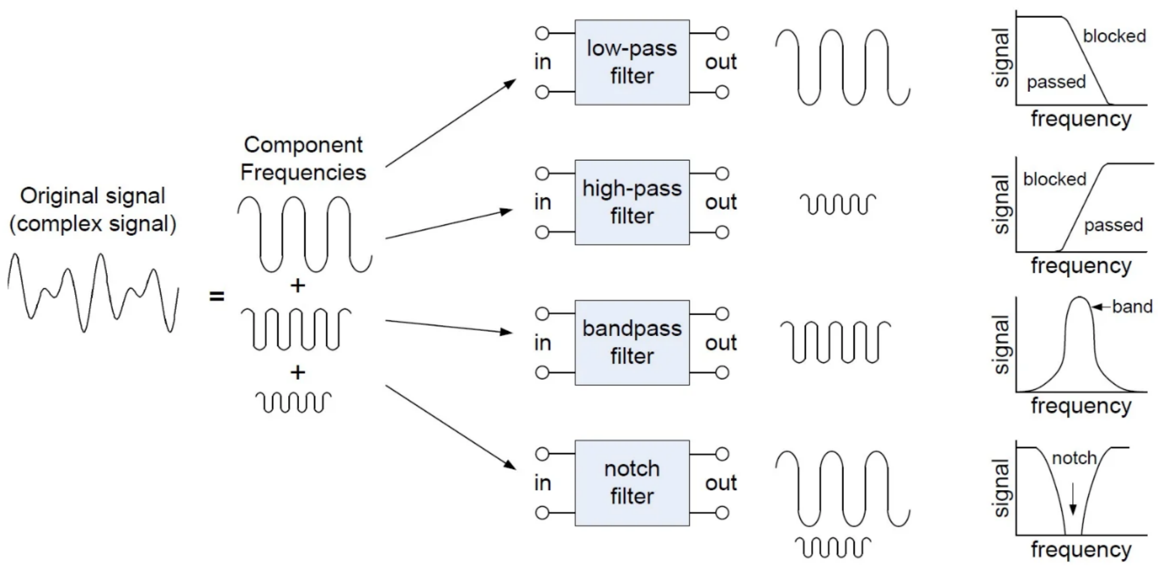
Introduction

Analog filters are essential components in electronic systems, used to selectively pass or attenuate signals based on their frequency content. They find applications in a wide range of fields, including audio processing, communication systems, and instrumentation. This article provides a comprehensive overview of analog filter design, covering key concepts, types, and design considerations.



Fundamental Concepts

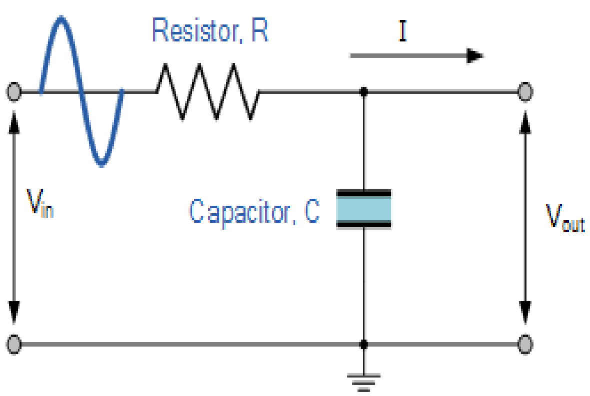
- **Frequency Response:** Describes how a filter responds to signals of different frequencies. It is typically characterized by the filter's gain and phase shift as a function of frequency.
- **Cutoff Frequency:** The frequency at which the filter's gain is reduced by 3 dB (approximately 70.7%) from its maximum value.
- **Passband:** The range of frequencies that a filter allows to pass with minimal attenuation.
- **Stopband:** The range of frequencies that a filter significantly attenuates.
- **Roll-off:** The rate at which the filter's gain decreases in the stopband.

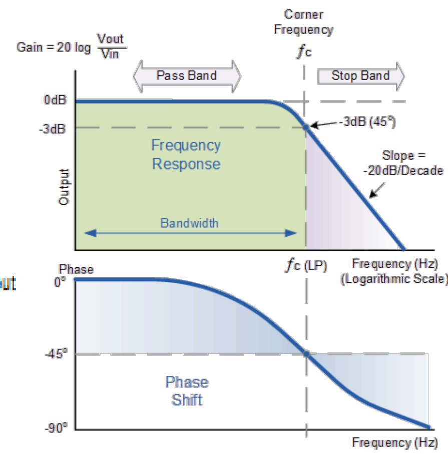
Types of Analog Filters

1. **Low-pass Filter:** Passes low-frequency signals and attenuates high-frequency signals.

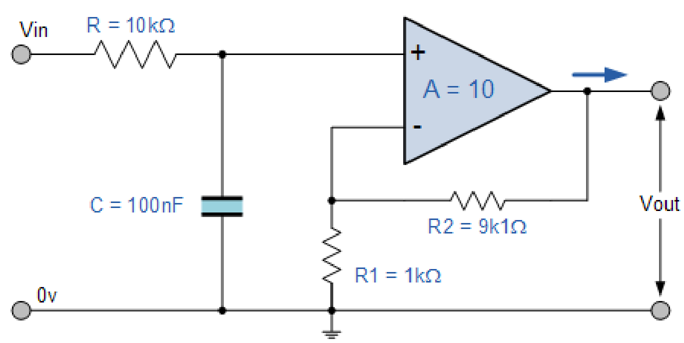
Passive Low Pass Filter

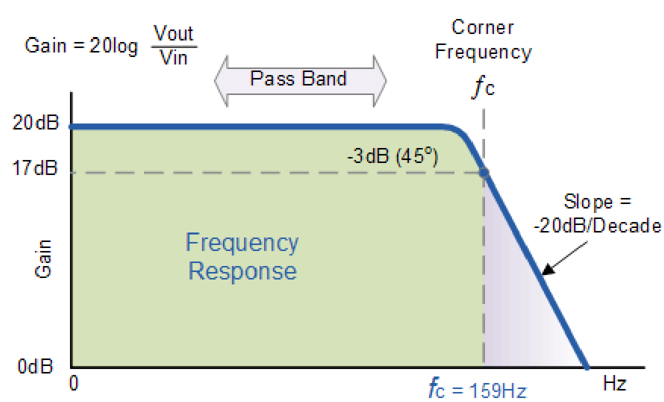
$$fc = \frac{1}{2\pi RC}$$





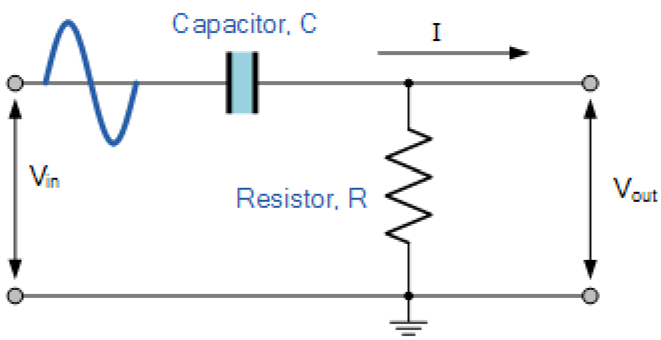
Active Low Pass Filter

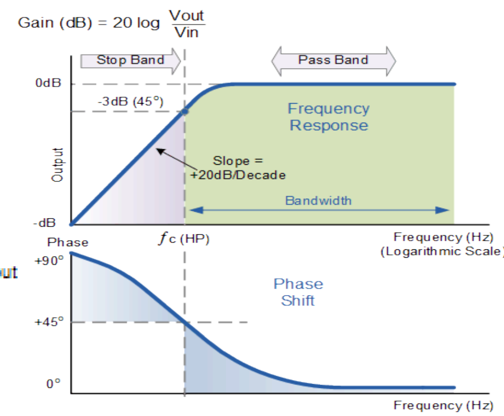




2. **High-pass Filter:** Passes high-frequency signals and attenuates low-frequency signals.

Passive High Pass Filter

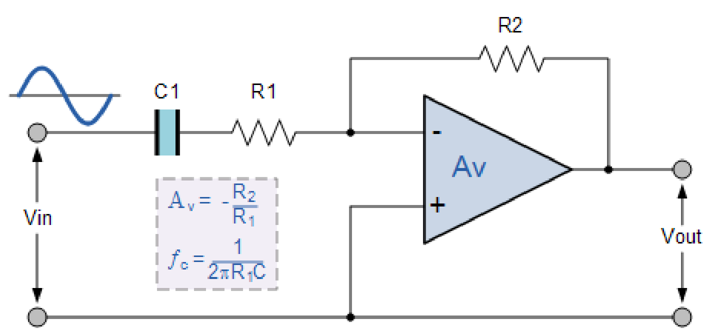


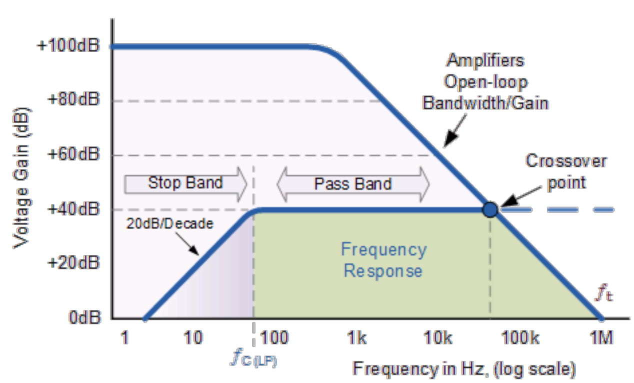


$$fc = \frac{1}{2\pi RC}$$

$$Phase\ Shift\ \phi = arctan\ \frac{1}{2\pi fRC}$$

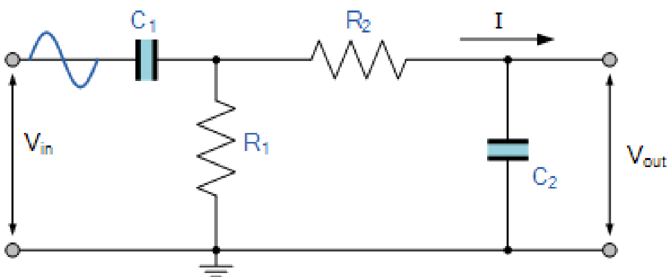
Active High Pass Filter

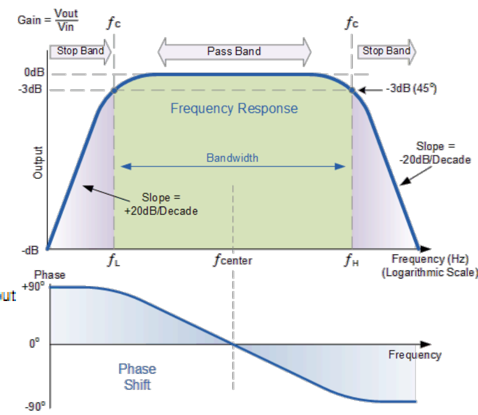




3. **Band-pass Filter:** Passes signals within a specific frequency range and attenuates signals outside that range.

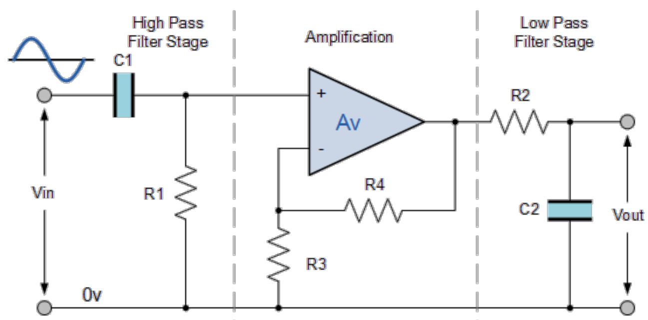
Passive Band Pass Filter

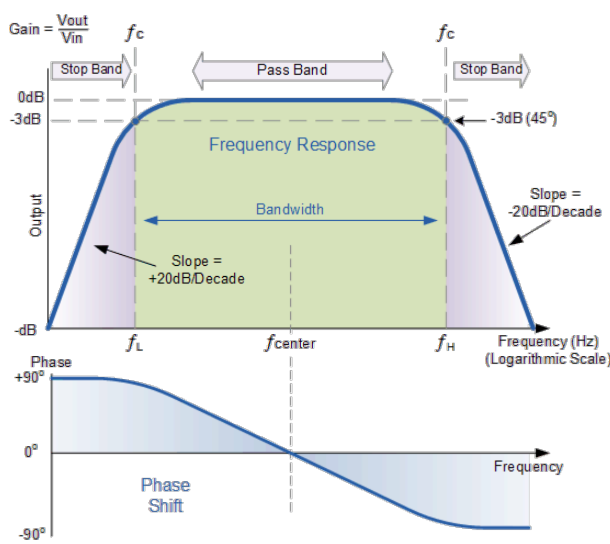




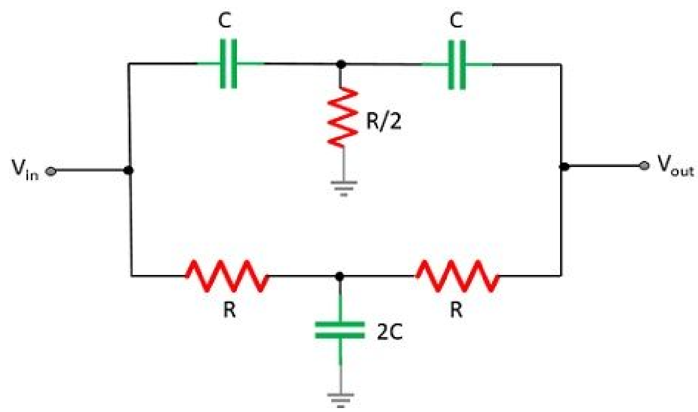
$$fr = \sqrt{f_L \; x \; f_H}$$

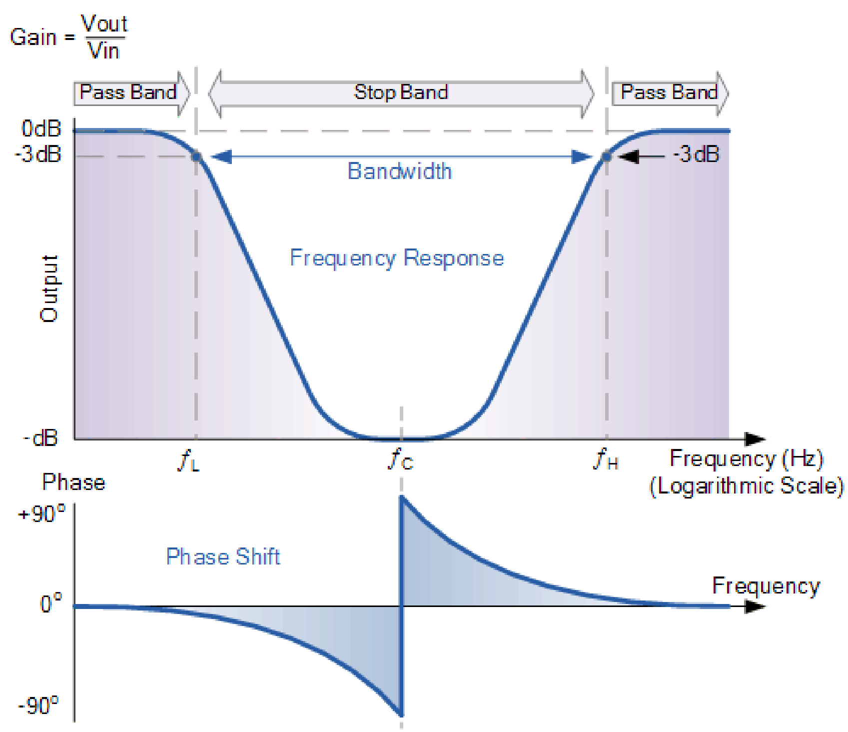
Active Band Pass Filter





4. **Band-stop(Notch) Filter:** Attenuates signals within a specific frequency range and passes signals outside that range.





$$f_C = \sqrt{f_L \times f_H}$$

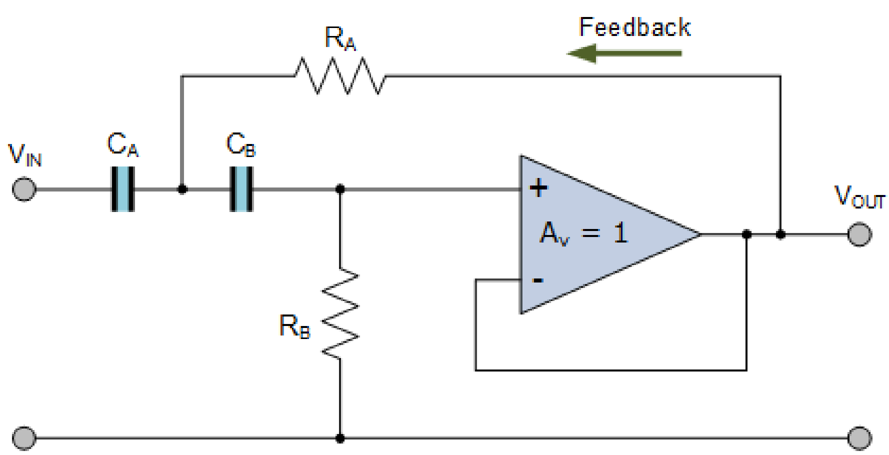
$$f_{BW} = f_H - f_L$$

Design Considerations

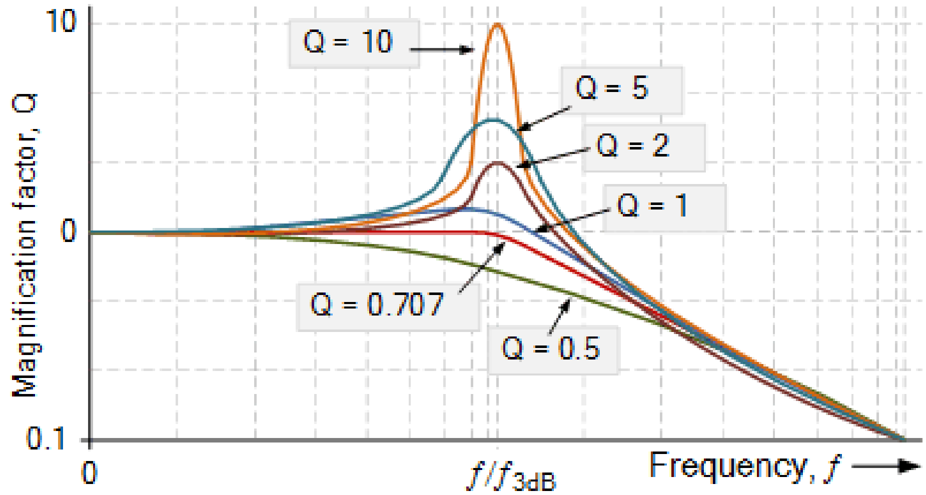
- **Filter Order:** Determines the steepness of the filter's roll-off. Higher-order filters have steeper roll-offs but are more complex to design and implement.
- **Passband Ripple:** The maximum amount of variation in the filter's gain within the passband.
- **Stopband Attenuation:** The minimum amount of attenuation provided by the filter in the stopband.
- **Quality Factor (Q):** A measure of a filter's selectivity. A high Q filter has a narrow bandwidth and a high peak gain.
- **Realizability:** The ability to physically implement a filter using practical components such as resistors, capacitors, and inductors.

Filter Topologies

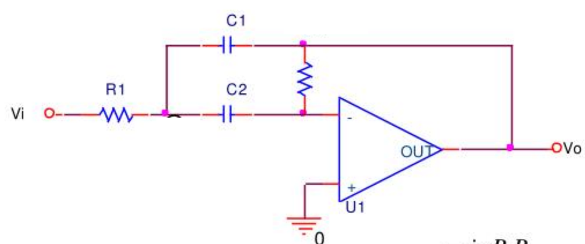
- **Passive Filters:** Use only passive components (resistors, capacitors, and inductors). They are simple to implement but have limitations in terms of gain and impedance matching.
- **Active Filters:** Use active components (op-amps) in combination with passive components. They offer greater flexibility and can provide gain, impedance matching, and isolation. Common topologies include:
  - Sallen-Key

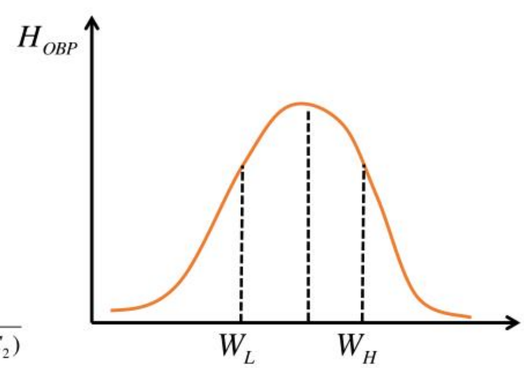


$$f_C = \frac{1}{2\pi\sqrt{R_A R_B C_A C_B}}$$



- Multiple Feedback





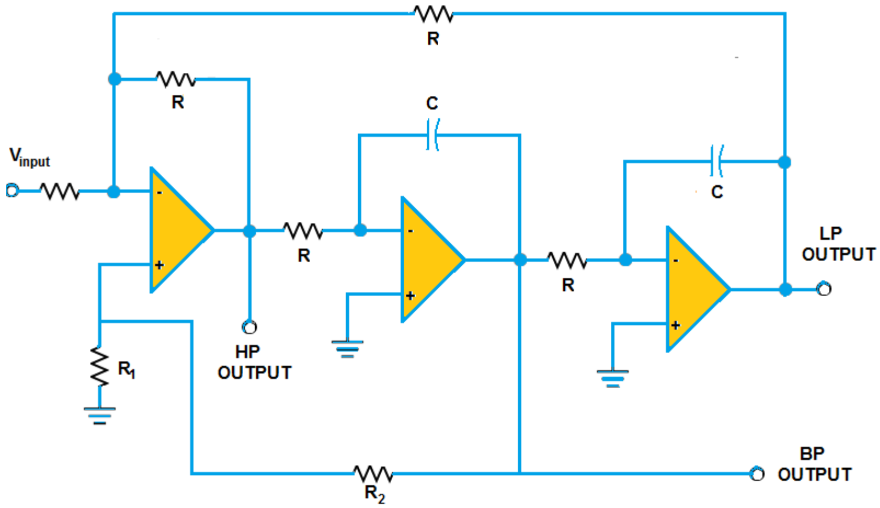
$$H(jw) = \frac{-jwR_1R_2}{1 - w^2R_1R_2C_1C_2 + jwR_1(C_1 + C_2)}$$

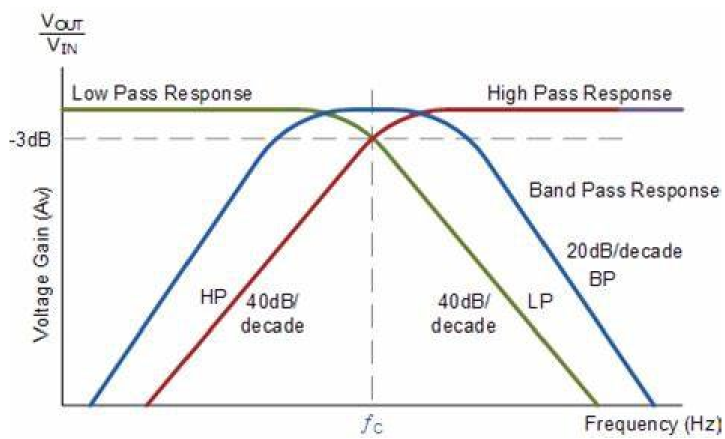
$$w_0 = \frac{1}{\sqrt{R_1R_2C_1C_2}}, Q = \frac{\sqrt{\frac{R_2}{R_1}}}{\sqrt{\frac{C_1}{C_2}} + \sqrt{\frac{C_2}{C_1}}}$$

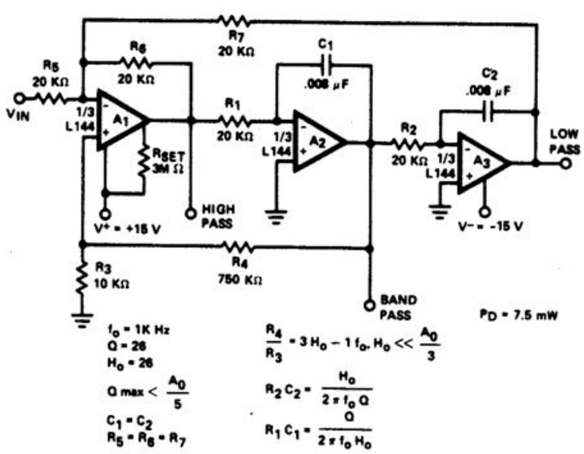
$$\frac{w_0}{w_H - w_L} = \frac{w_0}{BW} = Q$$

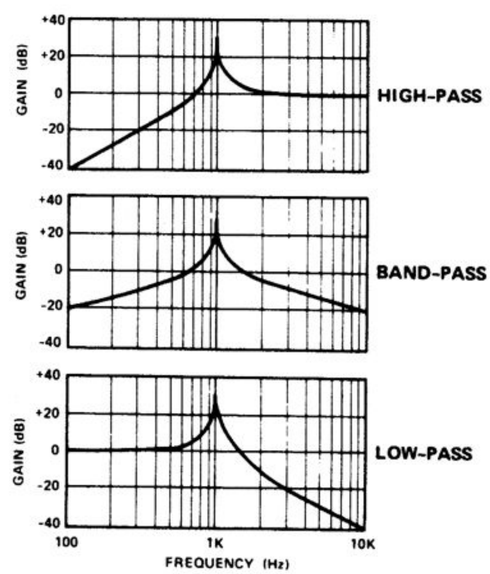
$$H_{OBP} = -\frac{\frac{R_2}{R_1}}{1 + \frac{C_1}{C_2}}$$

- State-variable









Design Techniques

- **Bode Plots:** Graphical representations of a filter's frequency response.
- **Transfer Functions:** Mathematical expressions that describe a filter's input-output relationship.
- **Computer-Aided Design (CAD) Tools:** Software tools that can automate the design process and provide simulations.

Conclusion

Analog filter design is a complex but rewarding field with numerous applications. By understanding the fundamental concepts, types, and design considerations, engineers can create filters that meet the specific requirements of their systems. With the aid of advanced design techniques and CAD tools, it is possible to design filters that are both efficient and high-performing.