

Filtros Ativos

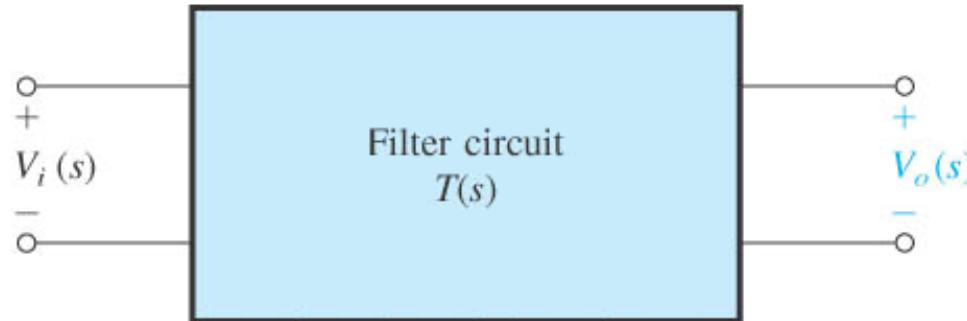
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Millman&Grabel; Microeletronica Vol 2 – 2.^a Edição

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Função de Transferência



$$T(s) = \frac{A(s)}{B(s)} \quad s = \sigma + j\omega \quad T(j\omega) = |T(j\omega)| e^{j\angle T(j\omega)}$$

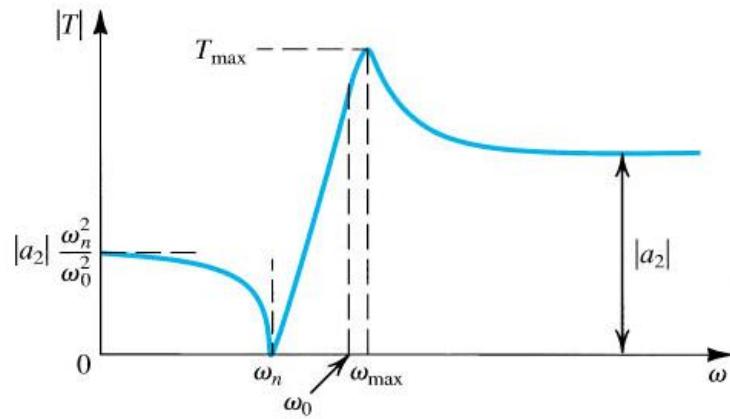
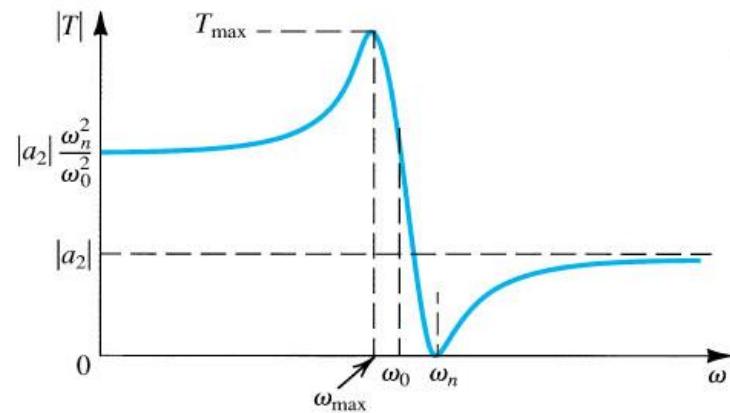
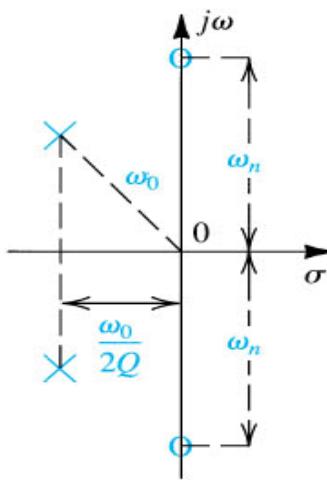
- ✓ Zeros de $T(s) \rightarrow$ são os zeros de $A(s)$
- ✓ Pólos de $T(s) \rightarrow$ são os zeros de $B(s)$

Exemplo: Função de Transferência de 2º Ordem...

$$T(s) = a_2 \frac{s^2 + \omega_n^2}{s^2 + s\frac{\omega_0}{Q} + \omega_0^2}$$

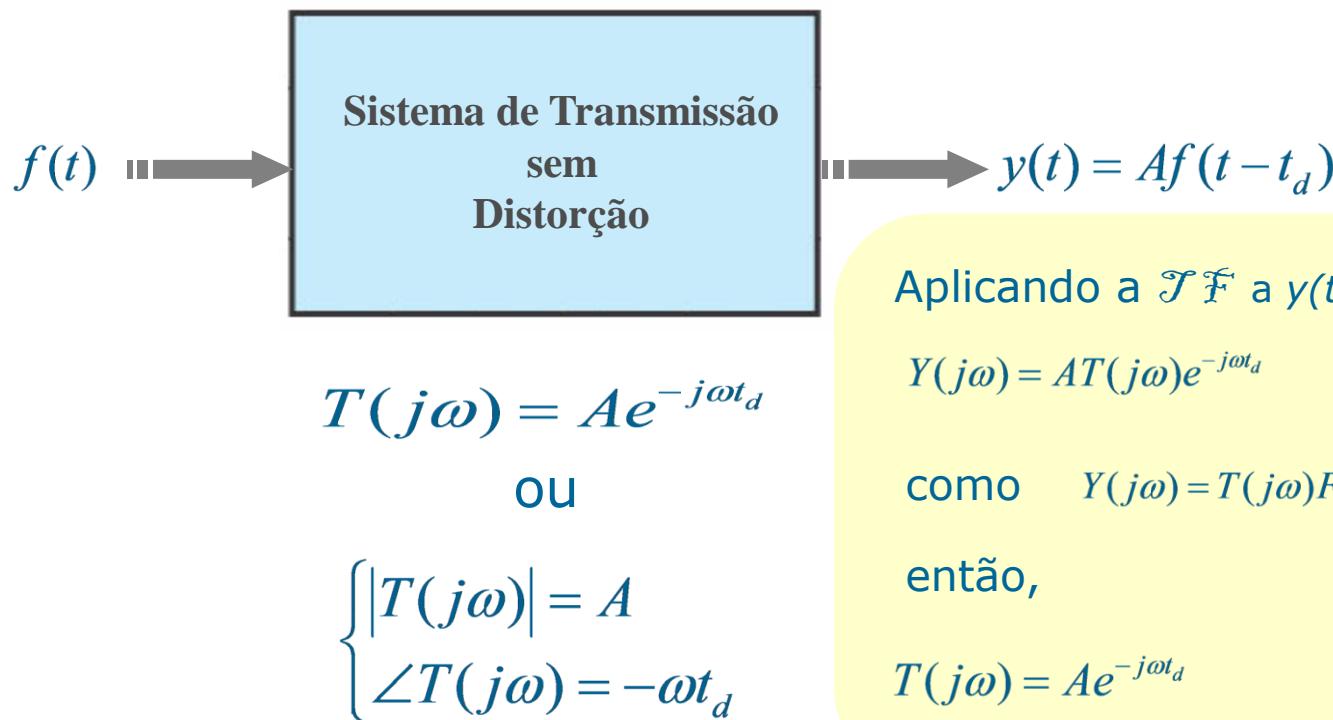
$$\text{DC gain} = a_2 \frac{\omega_n^2}{\omega_0^2}$$

$$\text{High-frequency gain} = a_2$$



Transmissão sem Distorção

Para transmissão sem distorção de um sinal através de um sistema, é requerido que a forma exata do sinal de entrada seja reproduzida na saída do sistema.



Aplicando a \mathcal{TF} a $y(t)$, temos:

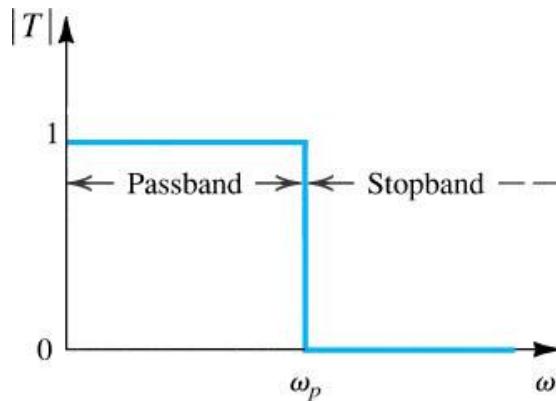
$$Y(j\omega) = AT(j\omega)e^{-j\omega t_d}$$

como $Y(j\omega) = T(j\omega)F(j\omega)$

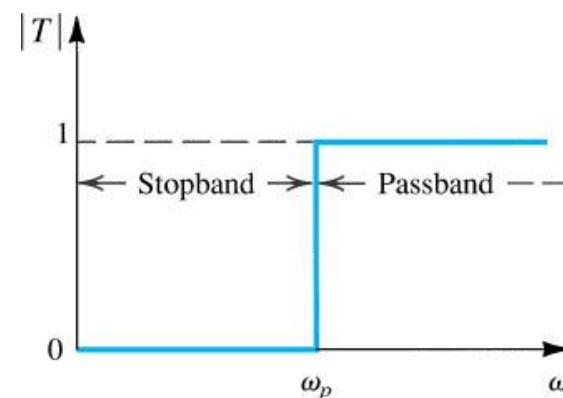
então,

$$T(j\omega) = Ae^{-j\omega t_d}$$

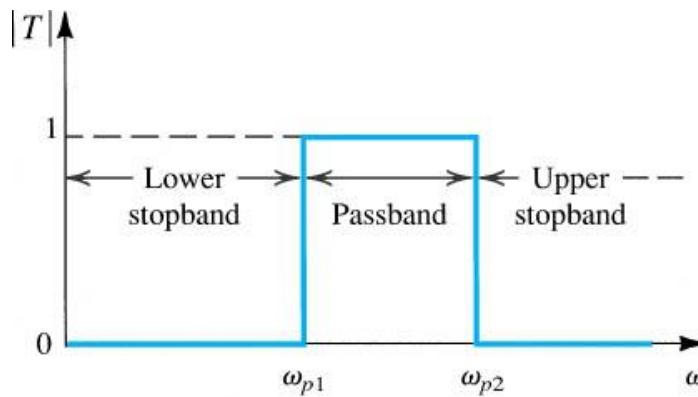
Filtros Ideais



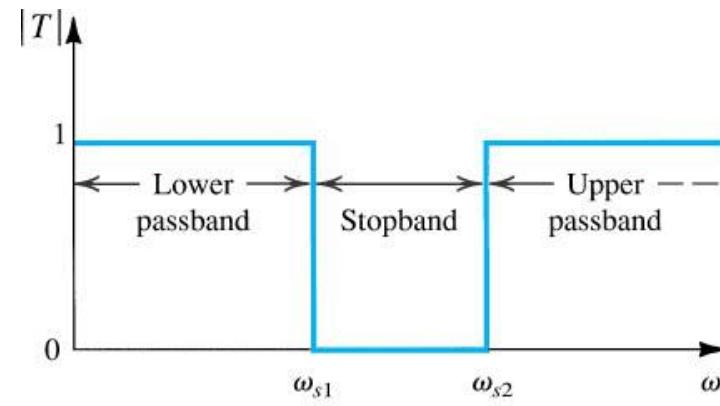
(a) Low-pass (LP)



(b) High-pass (HP)

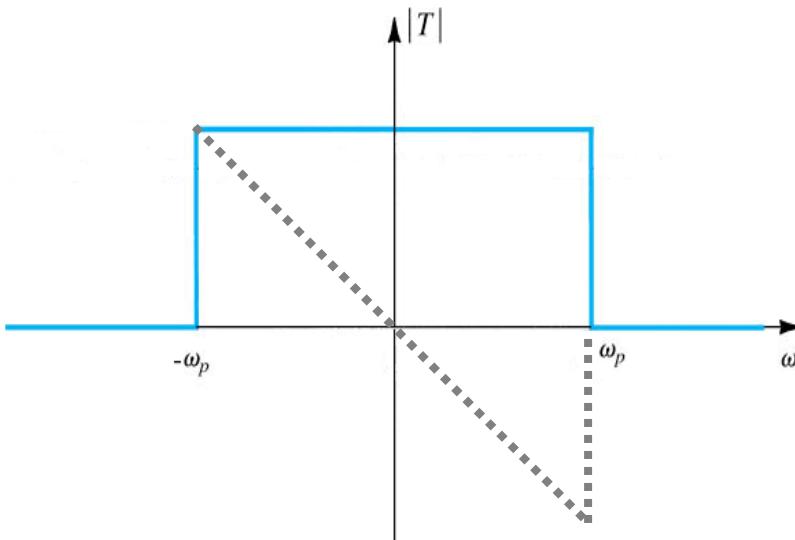


(c) Bandpass (BP)



(d) Bandstop (BS)

Filtro Passa Baixo Ideal...

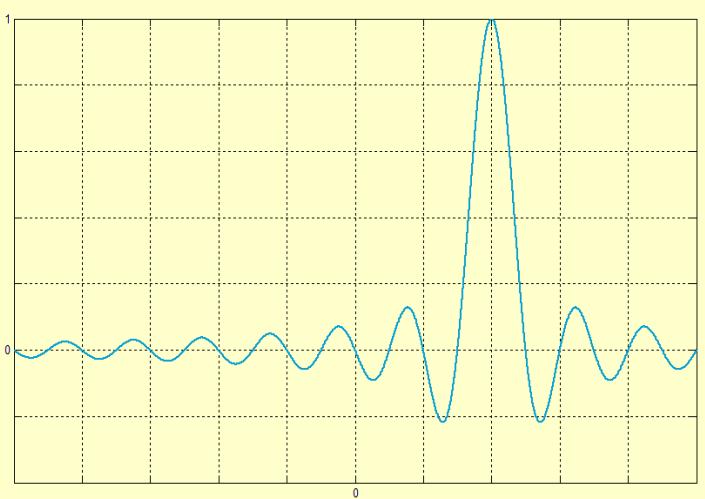


$$H_{PB}(j\omega) = \begin{cases} Ae^{-j\omega t_d} & |\omega| < \omega_p \\ 0 & \text{c.c.} \end{cases}$$

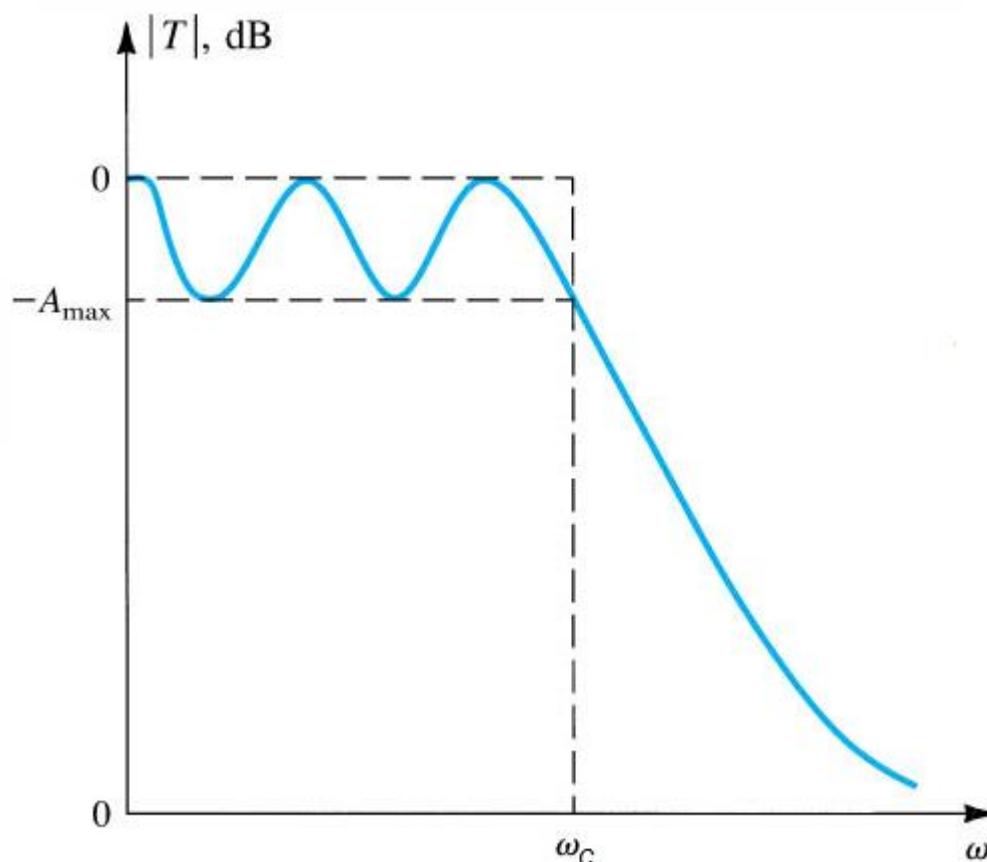
Aplicando a \mathcal{F}^{-1} , temos:

$$h_{PB}(t) = \frac{1}{2\pi} \int_{-\infty}^{+\infty} H_{PB}(j\omega) e^{j\omega t} d\omega$$

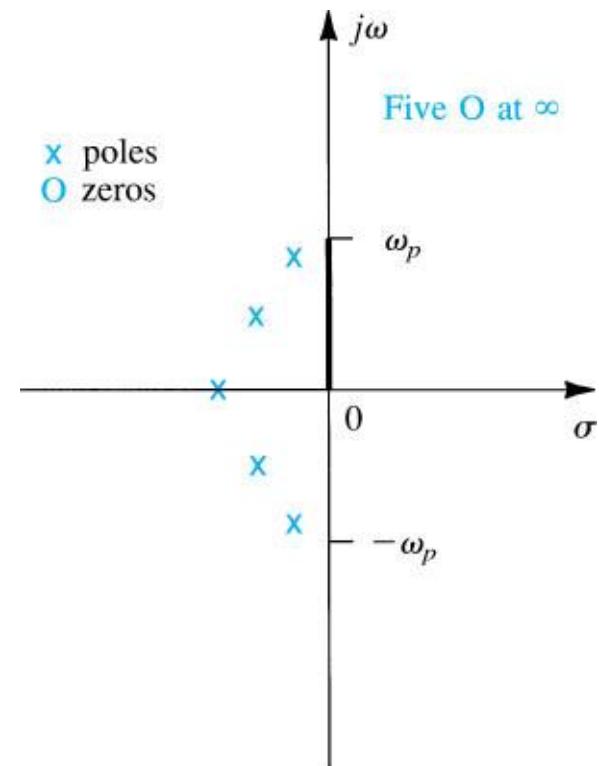
$$h_{PB}(t) = \frac{A\omega_p}{\pi} \frac{\sin \omega_p(t-t_d)}{\omega_p(t-t_d)}$$



Exemplo: Filtro Passa Baixo Real

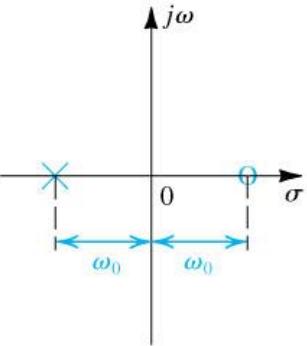
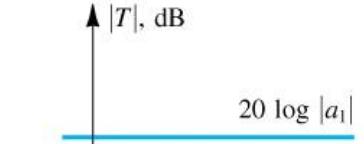
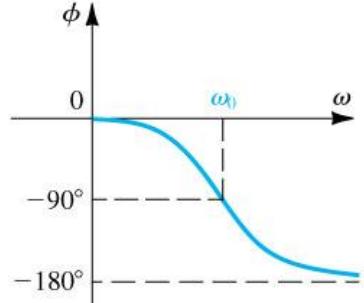
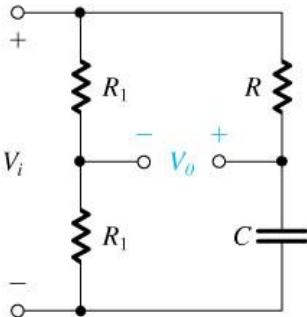
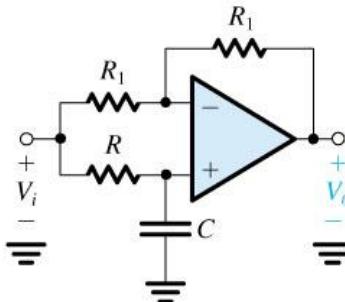


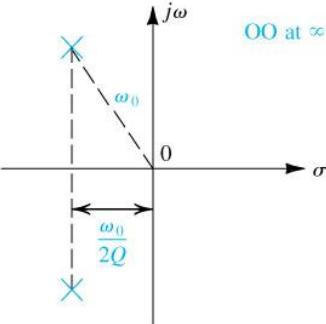
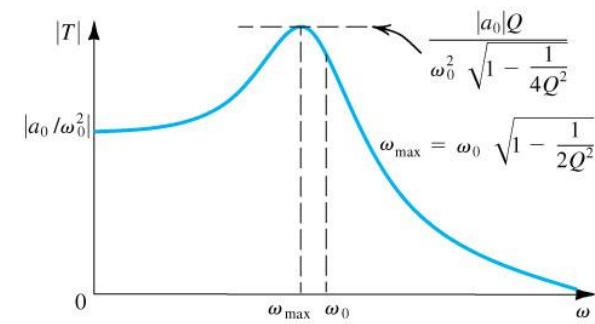
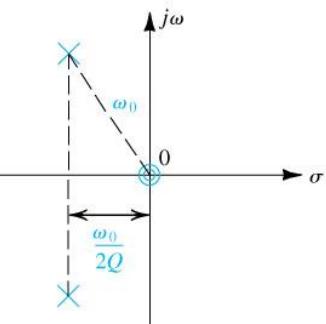
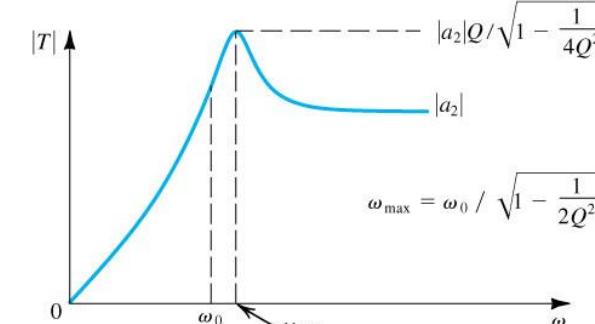
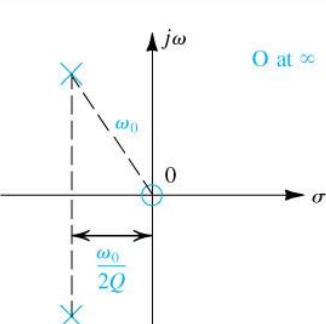
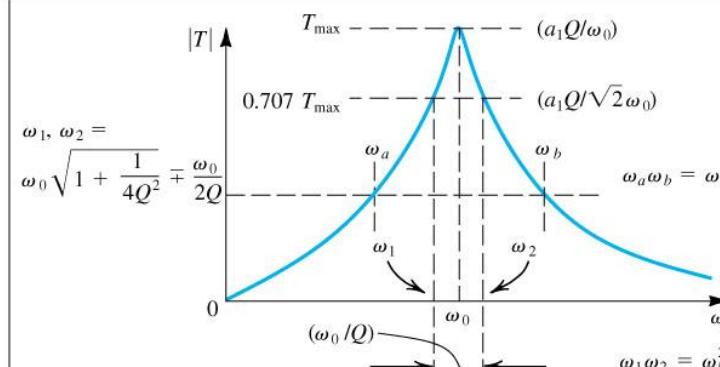
(a)



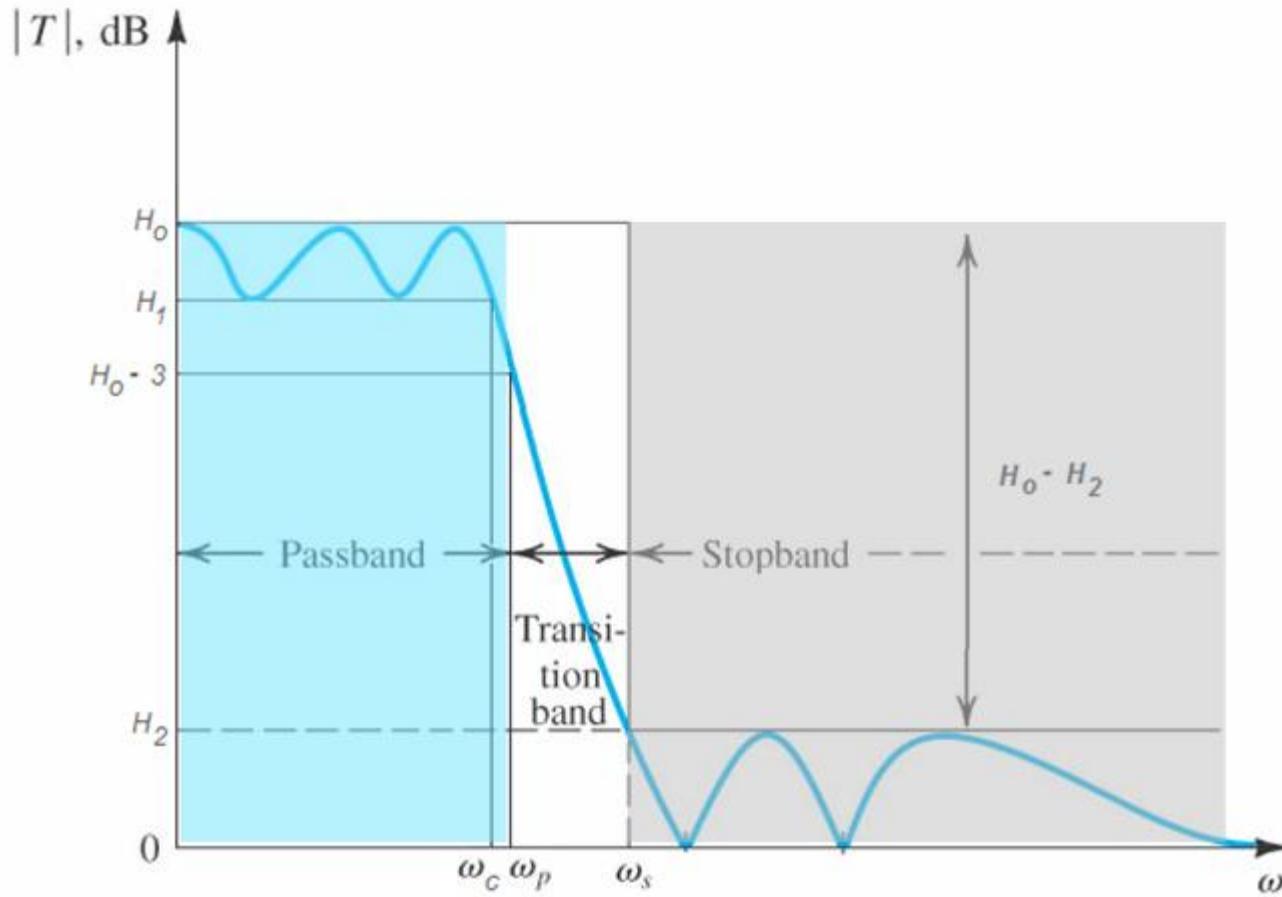
(b)

| Filter Type and $T(s)$ | s -Plane Singularities | Bode Plot for $ T $ | Passive Realization | Op Amp-RC Realization |
|---|--------------------------|---------------------|---|---|
| (a) Low pass (LP) $T(s) = \frac{a_0}{s + \omega_0}$ | | | $CR = \frac{1}{\omega_0}$ DC gain = 1 | $CR_2 = \frac{1}{\omega_0}$ DC gain = $-\frac{R_2}{R_1}$ |
| (b) High pass (HP) $T(s) = \frac{a_1 s}{s + \omega_0}$ | | | $CR = \frac{1}{\omega_0}$ High-frequency gain = 1 | $CR_1 = \frac{1}{\omega_0}$ High-frequency gain = $-\frac{R_2}{R_1}$ |
| (c) General $T(s) = \frac{a_1 s + a_0}{s + \omega_0}$ | | | $(C_1 + C_2)(R_1 // R_2) = \frac{1}{\omega_0}$ $C_1 R_1 = \frac{a_1}{a_0}$ DC gain = $\frac{R_2}{R_1 + R_2}$ HF gain = $\frac{C_1}{C_1 + C_2}$ | $C_2 R_2 = \frac{1}{\omega_0}$ $C_1 R_1 = \frac{a_1}{a_0}$ DC gain = $-\frac{R_2}{R_1}$ HF gain = $-\frac{C_1}{C_2}$ |

| $T(s)$ | Singularities | $ T $ and ϕ | Passive Realization | Op Amp-RC Realization |
|---|---|--|---|---|
| All pass (AP) $T(s) = -a_1 \frac{s - \omega_0}{s + \omega_0}$ $a_1 > 0$ |  <p>$j\omega$</p> <p>σ</p> <p>ω_0</p> |  <p>T , dB</p> <p>$20 \log a_1$</p>  <p>ϕ</p> <p>ω</p> <p>0°</p> <p>-90°</p> <p>-180°</p> |  <p>V_i</p> <p>V_o</p> <p>R_1</p> <p>R</p> <p>C</p> <p>$CR = 1/\omega_0$</p> <p>Flat gain (a_1) = 0.5</p> |  <p>V_i</p> <p>V_o</p> <p>R_1</p> <p>R</p> <p>C</p> <p>R_1</p> <p>$CR = 1/\omega_0$</p> <p>Flat gain (a_1) = 1</p> |

| Filter Type and $T(s)$ | s-Plane Singularities | $ T $ |
|---|--|---|
| (a) Low pass (LP) $T(s) = \frac{a_0}{s^2 + s\frac{\omega_0}{Q} + \omega_0^2}$ DC gain = $\frac{a_0}{\omega_0^2}$ |  |  |
| (b) High pass (HP) $T(s) = \frac{a_2 s^2}{s^2 + s\frac{\omega_0}{Q} + \omega_0^2}$ High-frequency gain = a_2 |  |  |
| (c) Bandpass (BP) $T(s) = \frac{a_1 s}{s^2 + s\frac{\omega_0}{Q} + \omega_0^2}$ Center-frequency gain = $\frac{a_1 Q}{\omega_0}$ |  |  |

Especificação de Filtros: Passa Baixo...



Modelos de Filtros

Metas ou requerimento para um filtro prático:

- Ganho constante na banda passante (r_1)
- Resposta de fase linear na banda passante (r_2)
- Máxima rejeição fora da banda passante (r_3)

A simultaneidade destas metas não pode ser alcançada por um único tipo de filtro que seja fisicamente realizável.

Modelos

- i. Filtro de Butterworth → maximiza a meta (r_1)
- ii. Filtro de Chebyshev → maximiza a meta (r_3)
- iii. Filtro de Bessel → maximiza a meta (r_2)
- iv. Filtro Elíptico → maximiza a meta (r_3)

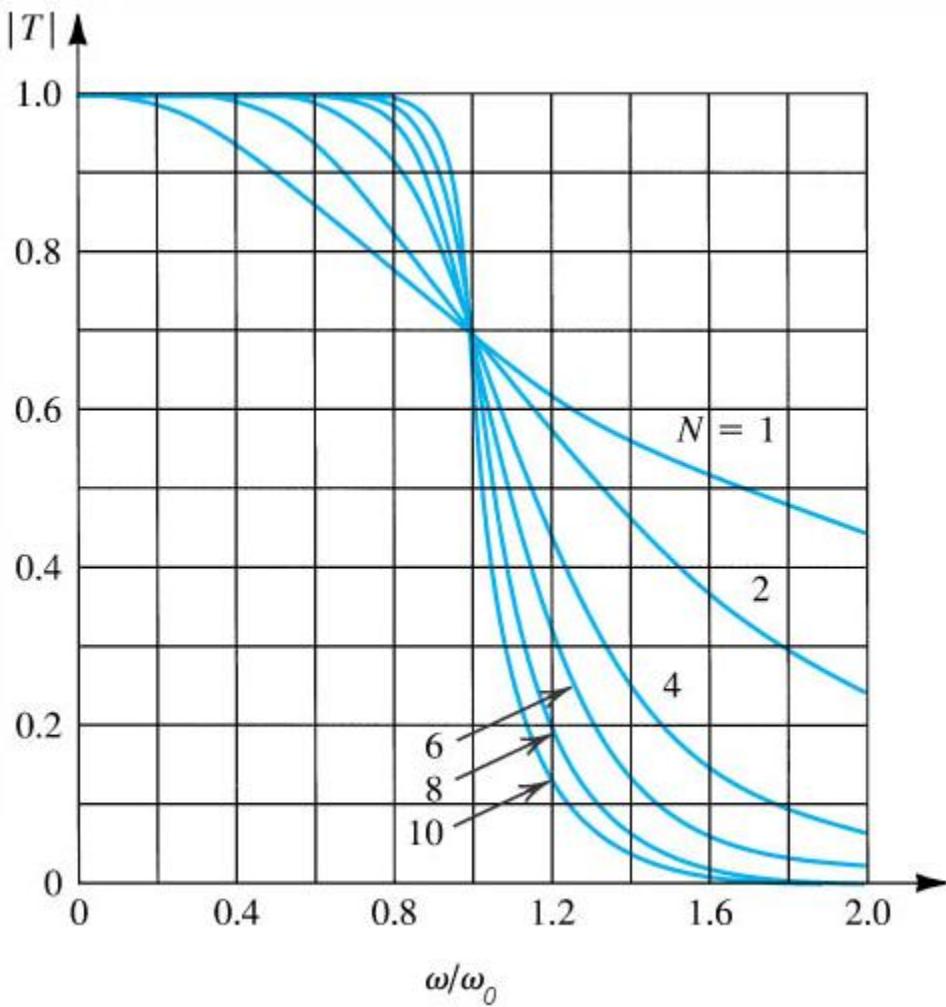
Filtros de Butterworth

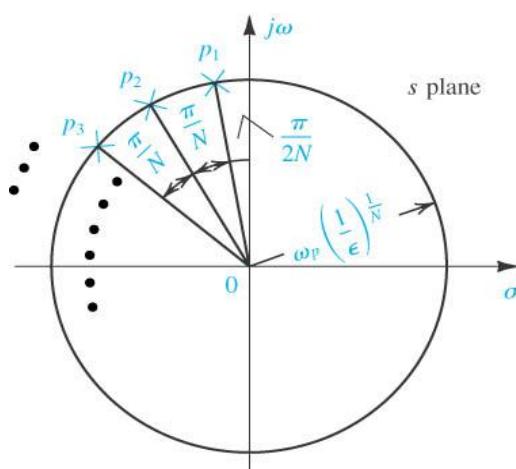
$$H(s) = \frac{H_0}{B(s)}$$

$B(s)$ é um polinômio de Butterworth com amplitude dada por:

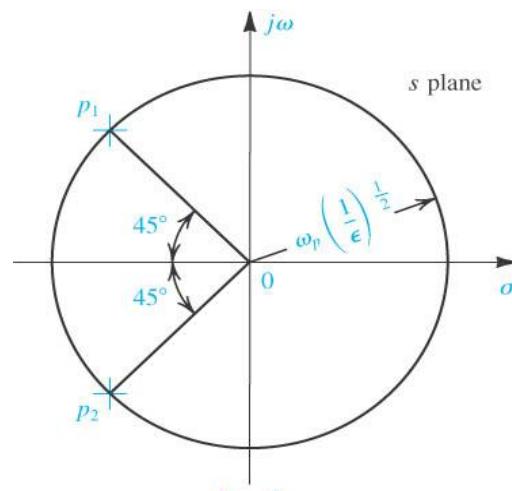
$$|B(s)|_{s=j\omega}$$

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

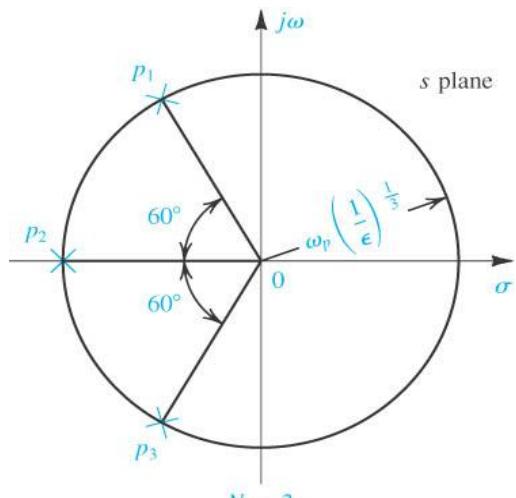




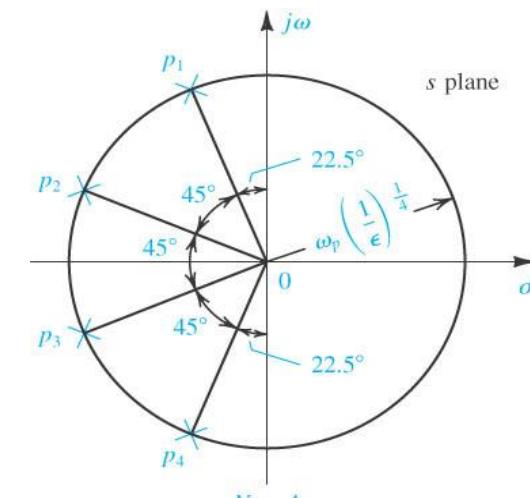
(a)



(b)



(c)



(d)

| N | Fatores de Polinômios $B_N(s)$ Normalizados |
|----------|--|
| 1 | $s + 1$ |
| 2 | $s^2 + 1.414s + 1$ |
| 3 | $(s+1)(s^2 + s + 1)$ |
| 4 | $(s^2 + 0.765s + 1)(s^2 + 1.848s + 1)$ |
| 5 | $(s + 1)(s^2 + 0.618s + 1)(s^2 + 1.618s + 1)$ |
| 6 | $(s^2 + 0.518s + 1)(s^2 + 1.414s + 1)(s^2 + 1.932s + 1)$ |
| 7 | $(s + 1)(s^2 + 0.445s + 1)(s^2 + 1.247s + 1)(s^2 + 1.802s + 1)$ |
| 8 | $(s^2 + 0.390s + 1)(s^2 + 1.111s + 1)(s^2 + 1.663s + 1)(s^2 + 1.962s + 1)$ |

Exemplo:

Determine a ordem de um filtro de Butterworth passa baixo que proporcione uma atenuação de 40dB para $\omega/\omega_0=2$.

$$\left| \frac{H(j\omega)}{H_0} \right|^2 = \frac{1}{1 + (\omega/\omega_0)^{2N}}$$

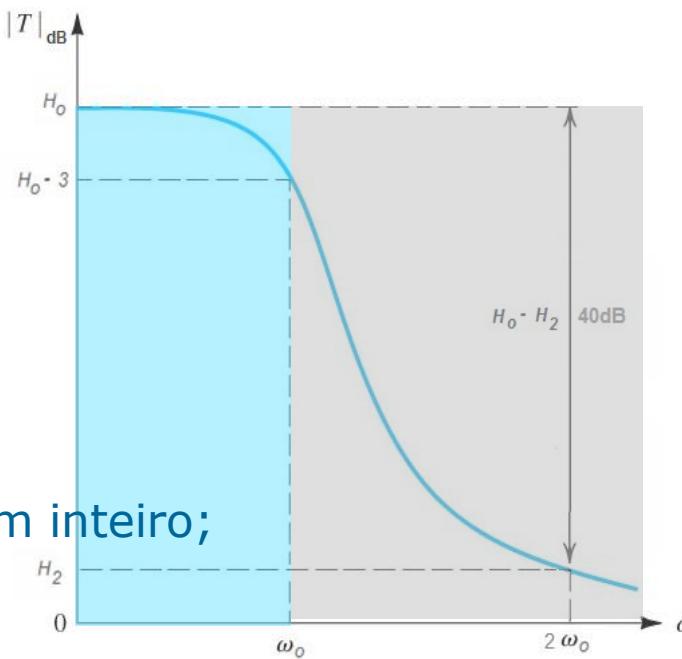
Para uma atenuação de 40 dB. $[|H_0 - H(j\omega)|]_{dB} = [40]_{dB} \rightarrow |H_0/H(j\omega)| = 10^2 \Big|_{\omega=2\omega_0}$

$$\left(\frac{1}{10^2} \right)^2 = \frac{1}{1 + 2^{2N}}$$

$$2N = \frac{\log(10^4 - 1)}{\log 2} \rightarrow N = 6,64$$

Como a ordem do filtro deve ser um inteiro;

$$N = 7$$



Filtros de Chebyshev

O filtro Chebyshev é uma aproximação só com pólos. A função de transferência do filtro é dada por:

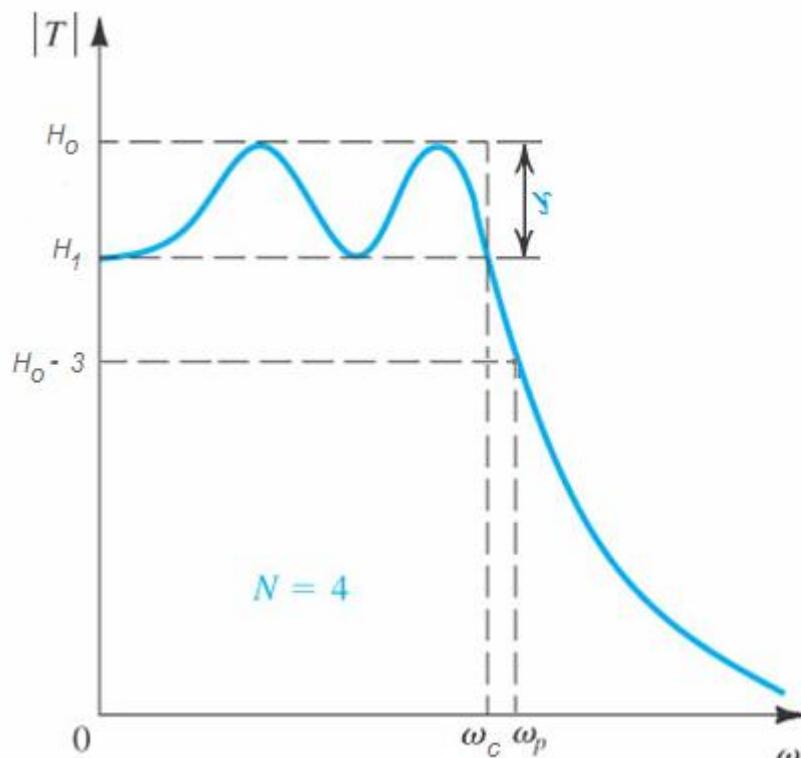
$$H^2(j\omega) = \frac{H_0^2}{1 + \varepsilon^2 C_n^2(\omega/\omega_c)}$$

$$C_n\left(\frac{\omega}{\omega_c}\right) = \begin{cases} \cos\left(n \cdot \arccos \frac{\omega}{\omega_c}\right) & 0 \leq \frac{\omega}{\omega_c} \leq 1 \\ \cosh\left(n \cdot \arccos h \frac{\omega}{\omega_c}\right) & \frac{\omega}{\omega_c} > 1 \end{cases}$$

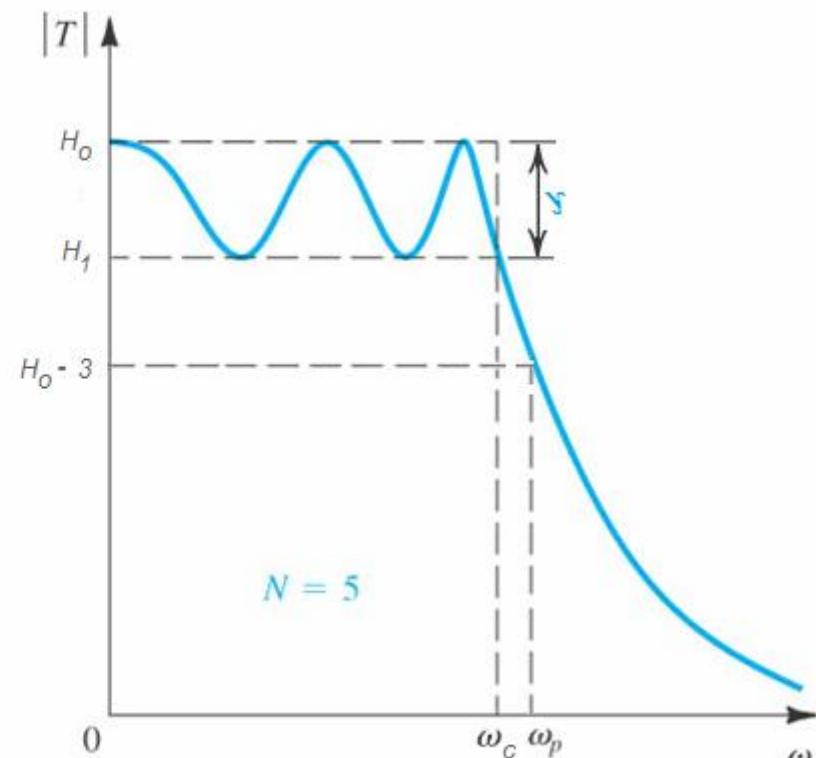
O parâmetro ε relaciona-se com a ondulação da banda passante γ em decibels e é dado por:

$$\varepsilon^2 = 10^{\gamma/10} - 1$$

Exemplo: Filtro de Chebyshev Passa Baixo



(a)



(b)

$$\omega_p = \omega_c \cosh\left(\frac{1}{n} \arccos h \frac{1}{\varepsilon}\right)$$

| N | Fatores de Polinômios Normalizados |
|--|--|
| Ondulação de 0,5 dB ($\varepsilon = 0.3493$) | |
| 1 | $s + 2.863$ |
| 2 | $s^2 + 1.425s + 1.516$ |
| 3 | $(s + 0.626)(s^2 + 0.626s + 1.142)$ |
| 4 | $(s^2 + 0.351s + 1.064)(s^2 + 0.845s + 0.356)$ |
| 5 | $(s + 0.362)(s^2 + 0.224s + 1.036)(s^2 + 0.586s + 0.477)$ |
| 6 | $(s^2 + 0.1554s + 1.024)(s^2 + 0.4142s + 0.5475)(s^2 + 0.5796s + 0.157)$ |
| 7 | $(s + 0.2562)(s^2 + 0.1014s + 1.015)(s^2 + 0.3194s + 0.6657)(s^2 + 0.4616s + 0.2539)$ |
| 8 | $(s^2 + 0.0872s + 1.012)(s^2 + 0.2484s + 0.7413)(s^2 + 0.3718s + 0.3872)(s^2 + 0.4386s + 0.08805)$ |
| Ondulação de 1.0 dB ($\varepsilon = 0.5089$) | |
| 1 | $s + 1.965$ |
| 2 | $s^2 + 1.098s + 1.103$ |
| 3 | $(s + 0.494)(s^2 + 0.494s + 0.994)$ |
| 4 | $(s^2 + 0.279s + 0.987)(s^2 + 0.674s + 0.279)$ |
| 5 | $(s + 0.289)(s^2 + 0.179s + 0.988)(s^2 + 0.468s + 0.429)$ |
| 6 | $(s^2 + 0.1244s + 0.9907)(s^2 + 0.3398s + 0.5577)(s^2 + 0.4642s + 0.1247)$ |
| 7 | $(s + 0.2054)(s^2 + 0.0914s + 0.9927)(s^2 + 0.2562s + 0.6535)(s^2 + 0.3702s + 0.2304)$ |
| 8 | $(s^2 + 0.07s + 0.9942)(s^2 + 0.1994s + 0.7236)(s^2 + 0.2994s + 0.3408)(s^2 + 0.3518s + 0.00702)$ |

Exemplo:

Determine a ordem de um filtro de Chebyshev passa baixo com ondulação de 1dB, que proporcione uma atenuação de 40dB para $\omega/\omega_c=2$. Determine a largura de banda do filtro.

$$\frac{H^2(j\omega)}{H_0^2} = \frac{1}{1 + \varepsilon^2 C_n^2(\omega/\omega_c)}$$

Para uma atenuação de 40 dB, $|H(j\omega)/H_0|=0,01$

$$(0,01)^2 = \frac{1}{1 + (0,5089)^2 C_n^2(2)} \rightarrow C_n(2) = 196,5$$

$$196,5 = \cosh(n \arccos h(2)) \rightarrow n = 4,536$$

Como a ordem do filtro deve ser um inteiro, então $n = 5$

$$\omega_p = \omega_c \cosh\left(\frac{1}{5} \arccos h \frac{1}{0,5089}\right) \rightarrow \omega_p = 1,034\omega_c$$

Funções de Transferência Biquadráticas

A Função de Transferência de um filtro Butterworth e Chebyshev baseia-se na função biquadrática e pode ser escrita sob a forma.

$$T(s) = \frac{k}{s^2 + (\omega_0/Q)s + \omega_0^2}$$

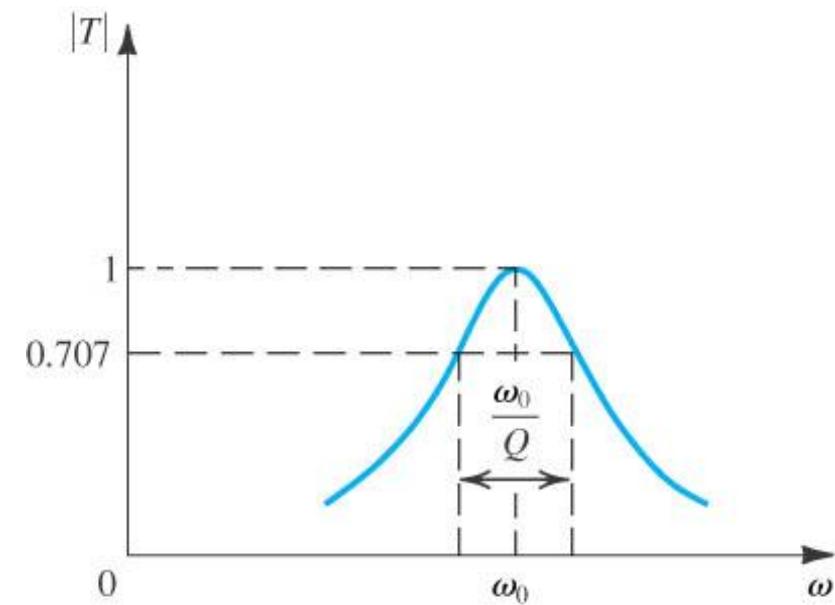
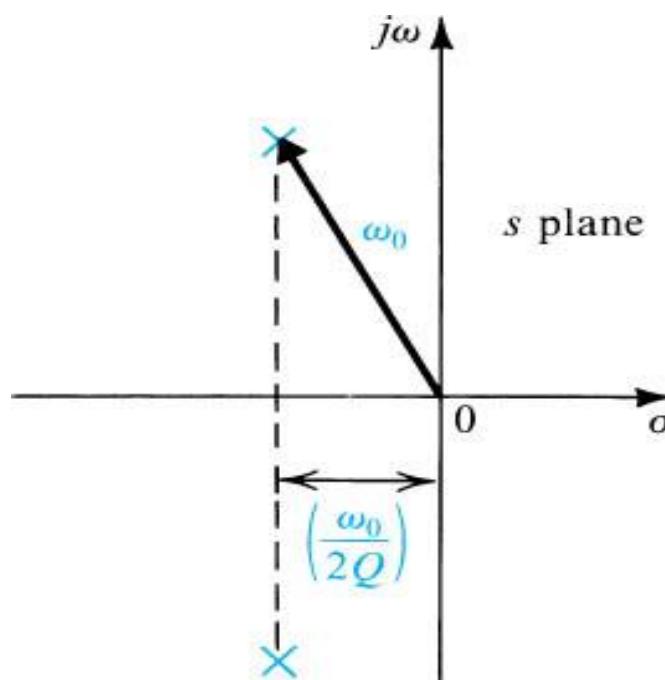
ou

$$H(s) = \frac{H_0}{(s^2/\omega_0^2) + (1/Q)(s/\omega_0) + 1} \quad \text{onde} \quad H_0 = K/\omega_0^2$$

$Q \rightarrow$ fator de qualidade

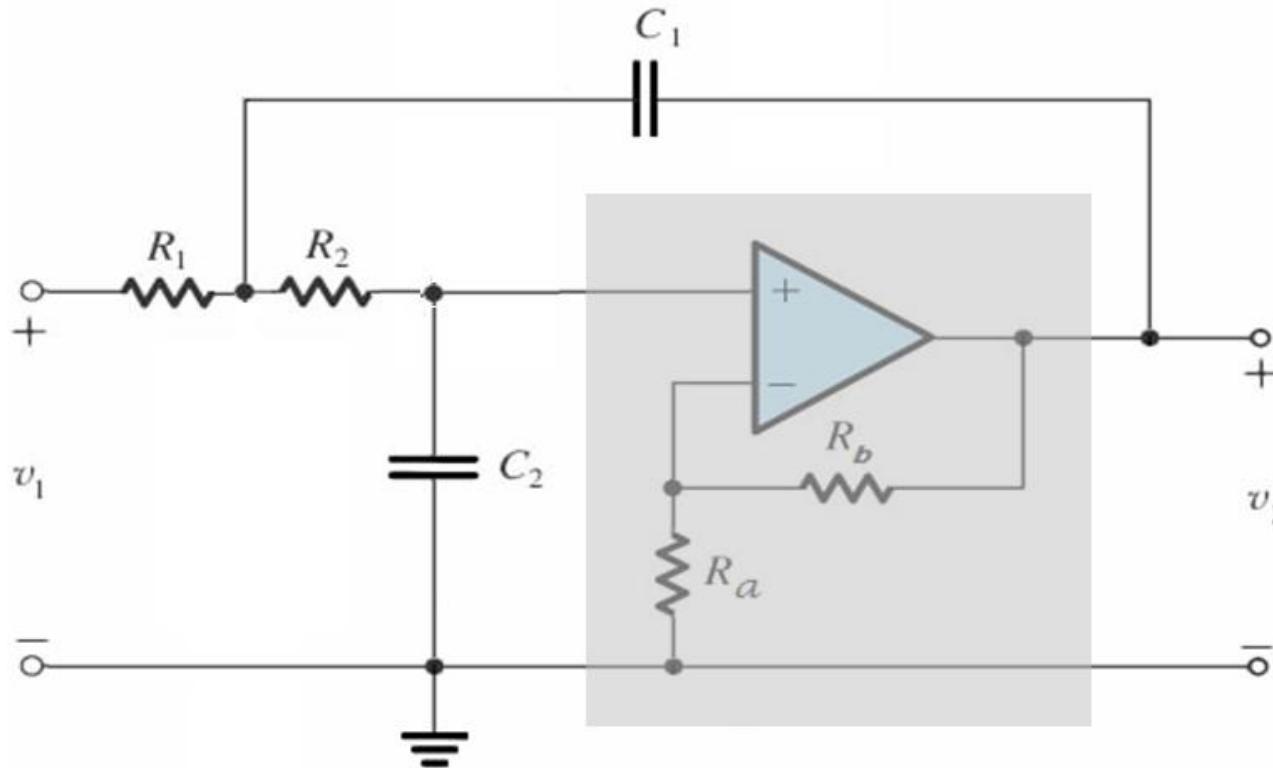
$\xi = 1/2Q \rightarrow$ fator de amortecimento

Definição dos parâmetros ω_0 e Q



Seções Biquadráticas com Amplificadores Operacionais

Círculo de Sallen e Key com amplificador não inversor.



Para simplificar o projeto, faz-se $C_1 = C_2$ e $R_1 = R_2$.

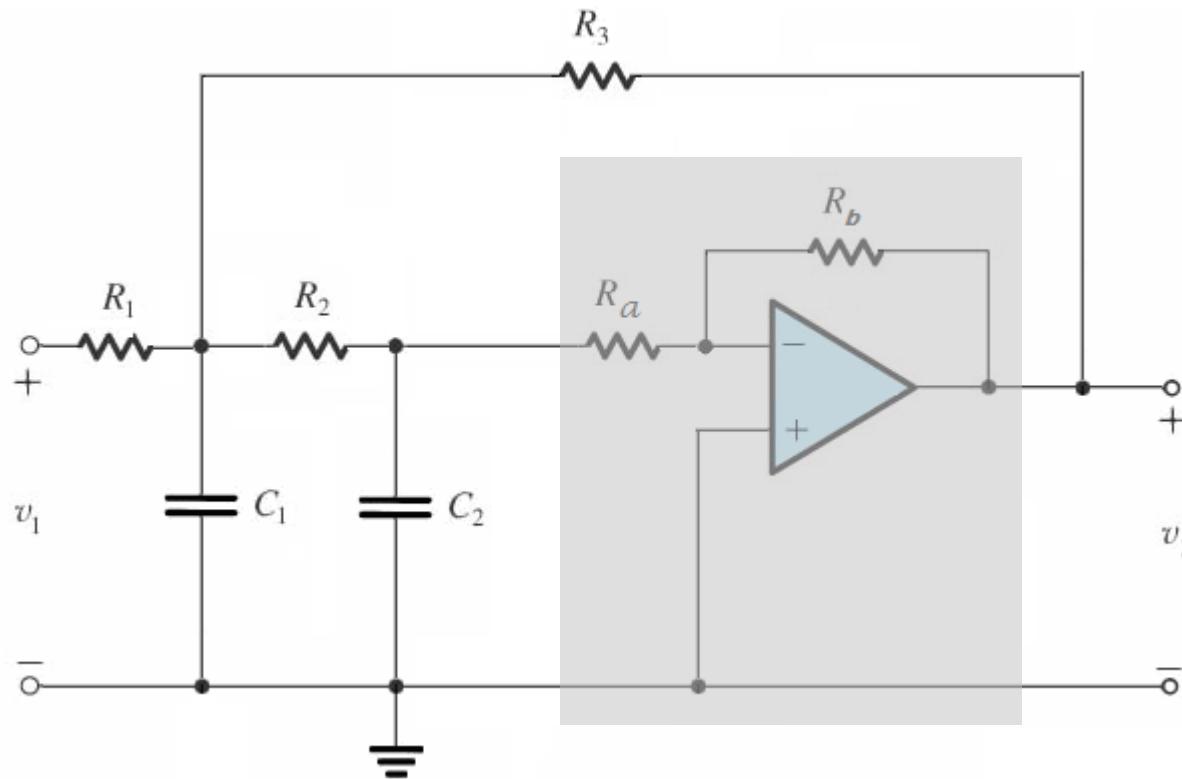
$$H(s) = \frac{A_v}{R^2 C^2 s^2 + R C s (3 - A_v) + 1}$$

$$Q = \frac{1}{3 - A_v}$$

$$\omega_0 = \frac{1}{R C}$$

Seções Biquadráticas com Amplificadores Operacionais

Círcuito de Sallen e Key com amplificador inversor



Exemplo:

Projete um filtro passa baixo com ondulação não superior a 1dB desde DC até 1KHz e que proporcione uma atenuação mínima de 40dB 2KHz.

Do exemplo anterior foi mostrado que nesse caso o filtro deve ser de ordem 5. Então a partir da tabela para os polinômios de Chebyshev, temos:

Como $H(s) = H_0/B(s)$ tem três factores, usa-se um filtro de três secções. Estas secções são

$$H_1(s) = \frac{H'_{01}}{s + 0,289}$$

$$H_2(s) = \frac{H'_{02}}{s^2 + 0,179s + 0,988}$$

$$H_3(s) = \frac{H'_{03}}{s^2 + 0,468s + 0,429}$$

Cada função dada anteriormente está normada com a frequência angular de corte $\omega_c = 1$ rad/s. A frequência de corte desejada é $f_c = 1$ kHz ou $\omega_c = 2\pi \times 10^3$ rad/s. As funções não-normadas são

$$H_1(s) = \frac{H_{01}}{(s/0,289\omega_c) + 1}$$

$$H(s) = \frac{H_0}{(s^2/\omega_0^2) + (1/Q)(s/\omega_0) + 1}$$

$$H_2(s) = \frac{H_{02}}{(s^2/0,988\omega_c^2) + 0,179s/0,988\omega_c + 1}$$

$$H_3(s) = \frac{H_{03}}{(s^2/0,429\omega_c^2) + (0,468s/0,429\omega_c) + 1}$$

Tanto H_2 como H_3 podem ser realizadas por secções passa-baixo de Sallen e Key com $R_1 = R_2$ e $C_1 = C_2$. A comparação de H_2 e H_3 com as ...

$$\omega_{02} = \sqrt{0,988\omega_C^2} = 0,994\omega_C = 0,994 \times 2\pi \times 10^3 \text{ rad/s}$$

$$\frac{1}{Q_2} = \frac{0,179}{\sqrt{0,988}} \quad \text{e} \quad Q_2 = 5,55$$

$$\omega_{03} = \sqrt{0,429\omega_C^2} = 0,655\omega_C = 0,655 \times 2\pi \times 10^3 \text{ rad/s}$$

$$\frac{1}{Q_3} = \frac{0,468}{\sqrt{0,429}} \quad \text{e} \quad Q_3 = 1,4$$

$$H(s) = \frac{A_V}{R^2C^2s^2 + RCs(3 - A_V) + 1}$$

$$Q = \frac{1}{3 - A_V} \quad \omega_0 = \frac{1}{RC}$$

em todas as secções. Escolha-se $C = 0,05 \mu\text{F}$. Então será

$$R_2 = \frac{1}{\omega_{02}C} = \frac{1}{0,994 \times 2\pi \times 10^3 \times 0,05 \times 10^{-6}} = 3,20 \text{ k}\Omega$$

$$R_3 = \frac{1}{\omega_{03}C} = \frac{1}{0,655 \times 2\pi \times 10^3 \times 0,05 \times 10^{-6}} = 4,86 \text{ k}\Omega$$

calcula-se $A_V = 3 - 1/Q$. Por isso, obtém-se

$$A_{V2} = 3 - \frac{1}{5,55} = 2,82 \quad A_{V3} = 3 - \frac{1}{1,4} = 2,285$$

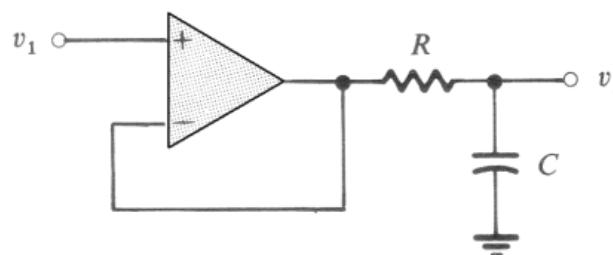
Como $A_v \gg 1$ num ampop comercial, será $A_V = 1 + R_b/R_a$. Para minimizar o número de valores óhmicos de resistências e a extensão dos parâmetros dos componentes (relação entre a maior e a menor resistência), escolhe-se $R_a = 4,86 \text{ k}\Omega$ para ambas as secções. Então

$$R_{b2} = (A_{V2} - 1)R_{a2} = (2,82 - 1)4,86 = 8,84 \text{ k}\Omega$$

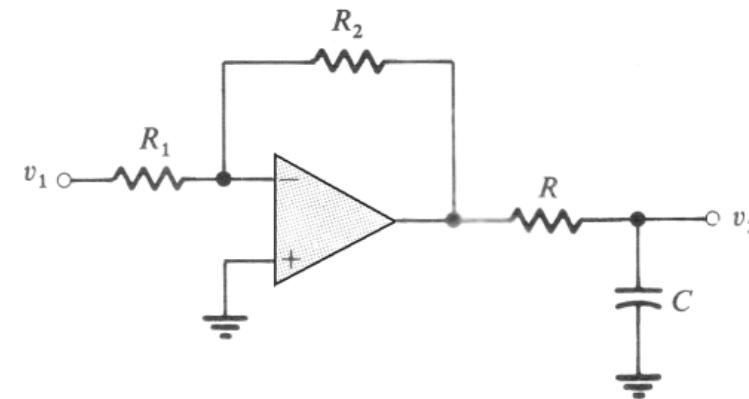
$$R_{b3} = (A_{V3} - 1)R_{a3} = (2,285 - 1)4,86 = 6,4 \text{ k}\Omega$$

A restante secção, $H_1(s)$, contém um polo real em $s = -0,289\omega_c = 0,289 \times 2\pi \times 10^3 \text{ rad/s}$. O simples seguidor de tensão que excita um circuito RC como mostra a Fig. tem uma função de transferência

$$\frac{V_2}{V_1} = \frac{1}{RCs + 1}$$



a)



b)

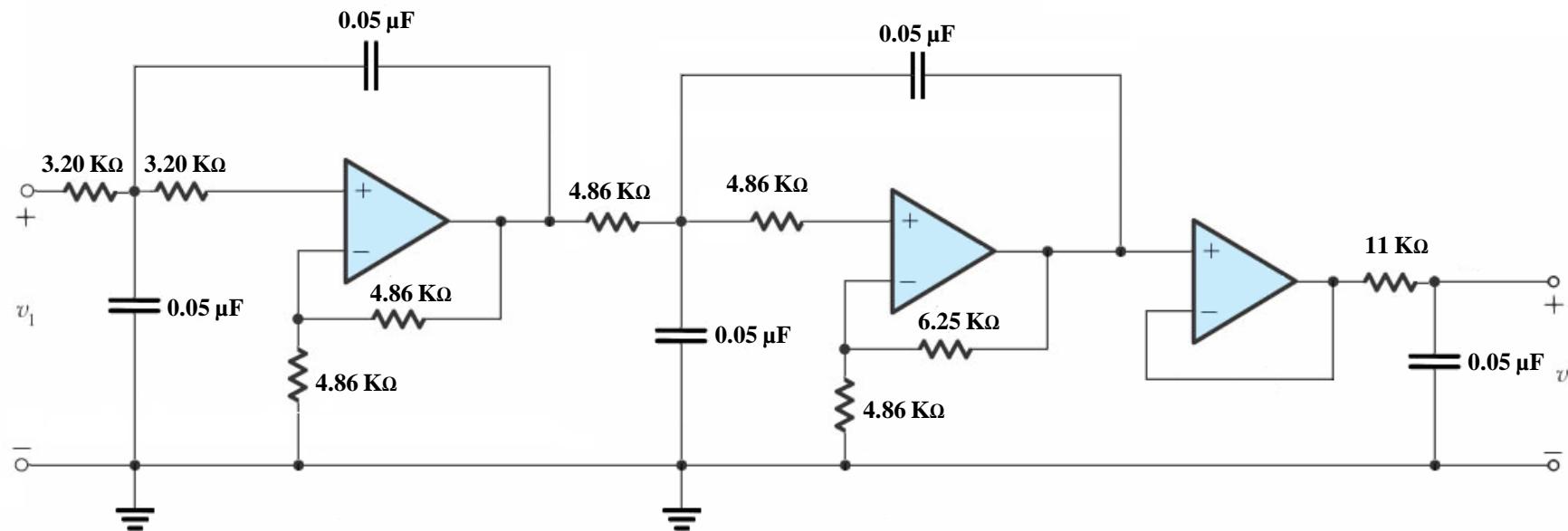
que se utiliza para realizar o polo real de $H_1(s)$. A comparação das funções de transferência fornece

$$RC = \frac{1}{0,289\omega_C}$$

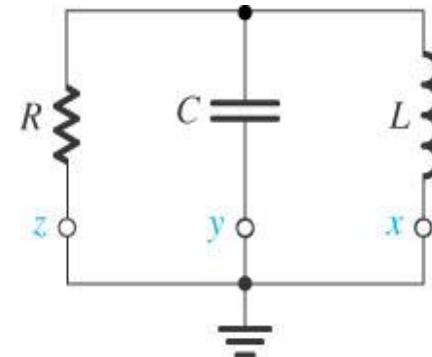
A escolha de $C = 0,05 \mu F$ origina

$$R = \frac{1}{0,289} \times 2\pi \times 10^3 \times 0,05 \times 10^{-6} = 11,0 \text{ k}\Omega$$

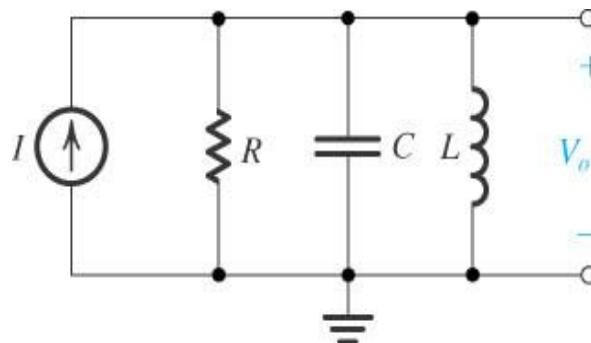
Circuito Completo



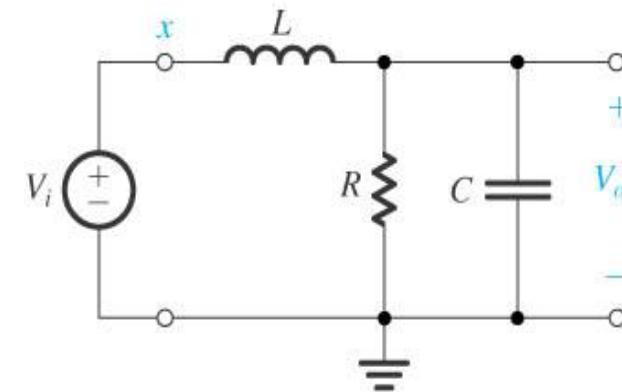
Ressonador RLC de Segunda Ordem



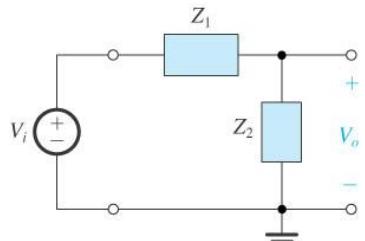
(a)



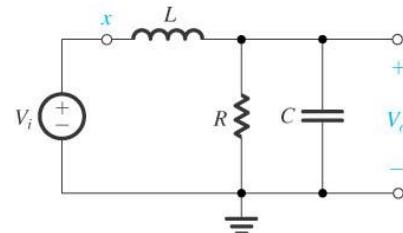
(b)



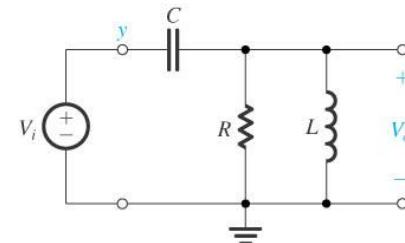
(c)



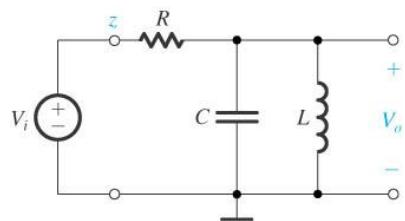
(a) General structure



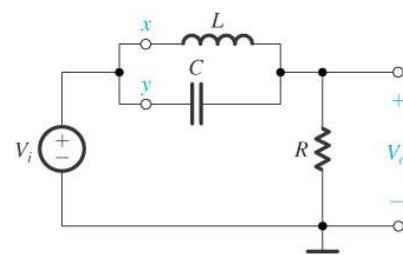
(b) LP



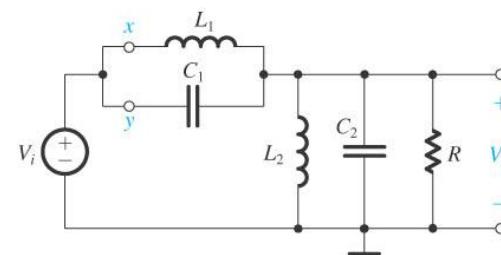
(c) HP



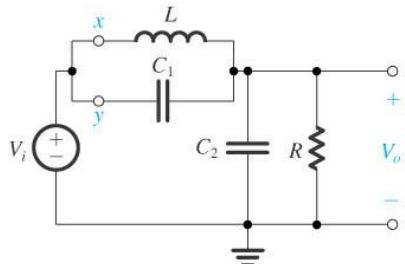
(d) BP



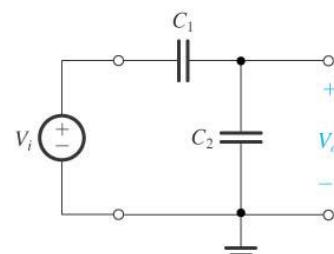
(e) Notch at ω_0



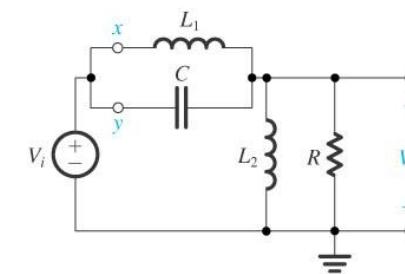
(f) General notch



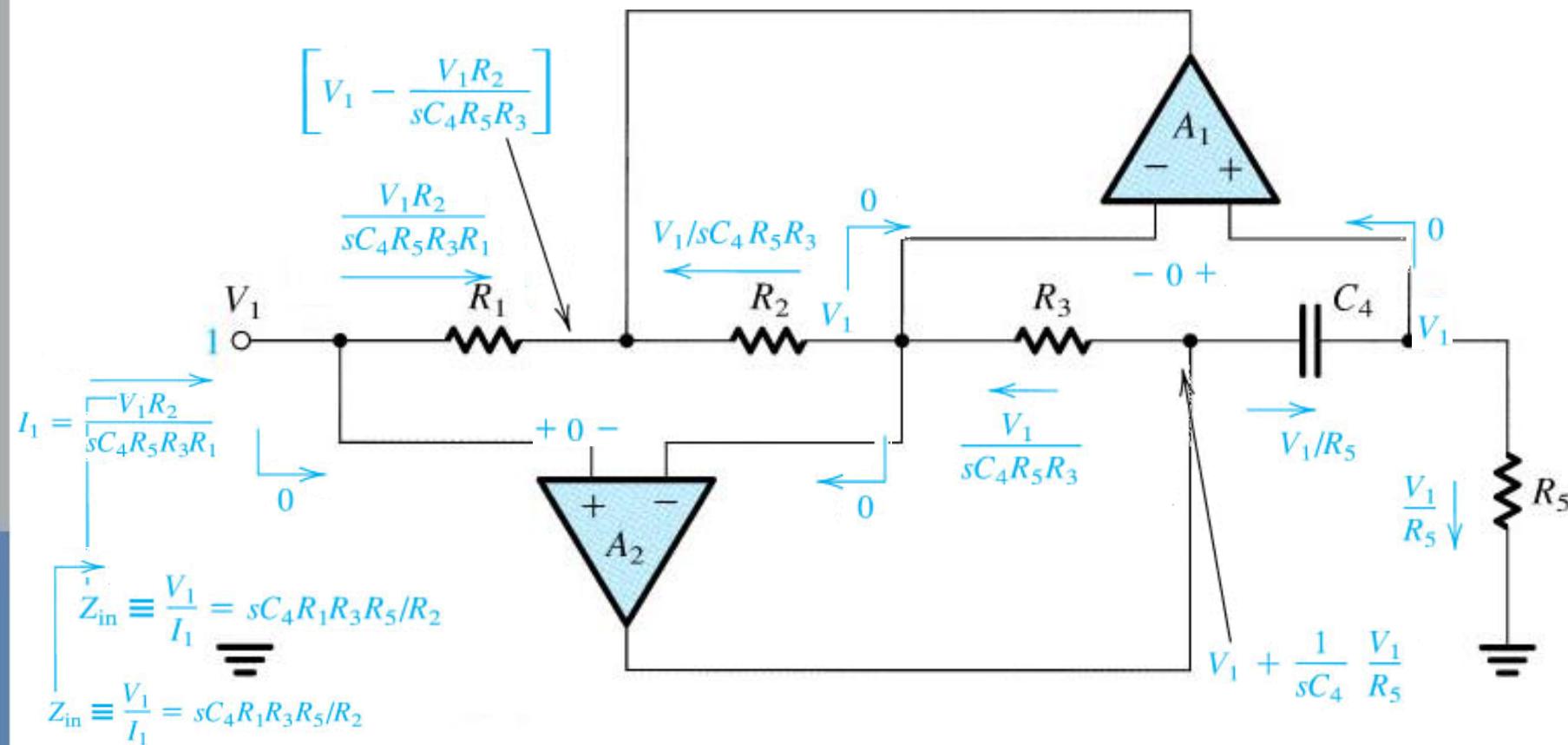
(g) LPN ($\omega_n > \omega_0$)

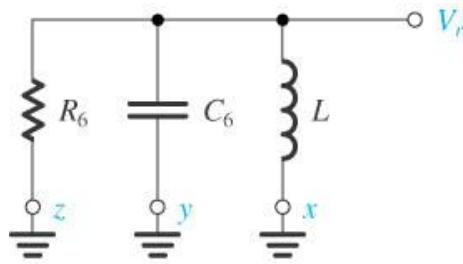


(h) LPN as $s \rightarrow \infty$

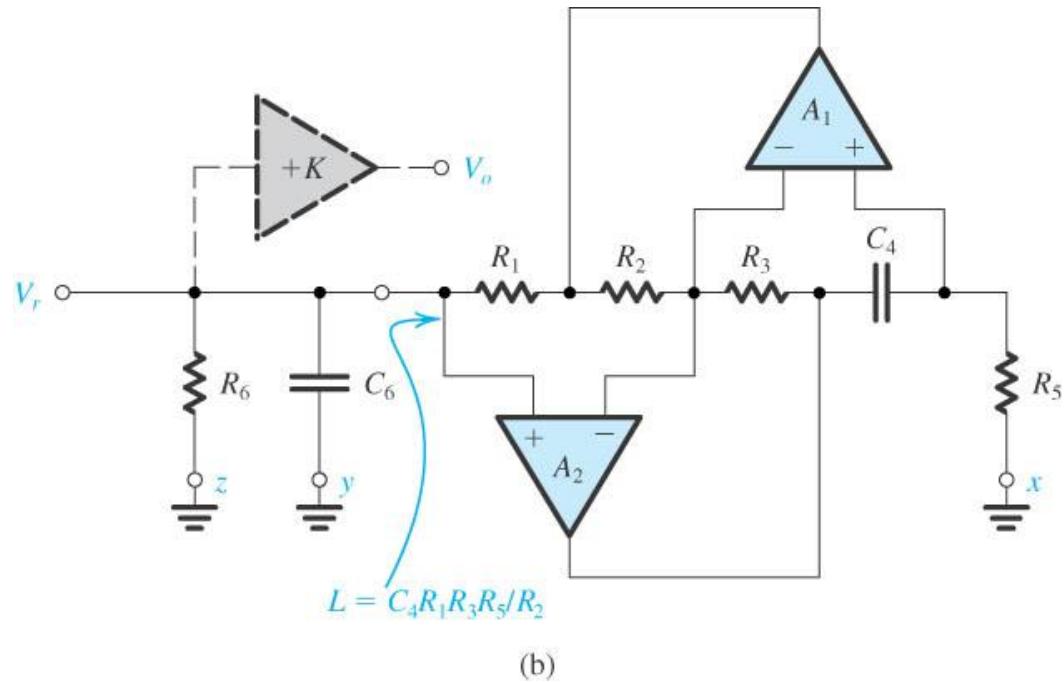


(i) HPN ($\omega_n < \omega_0$)

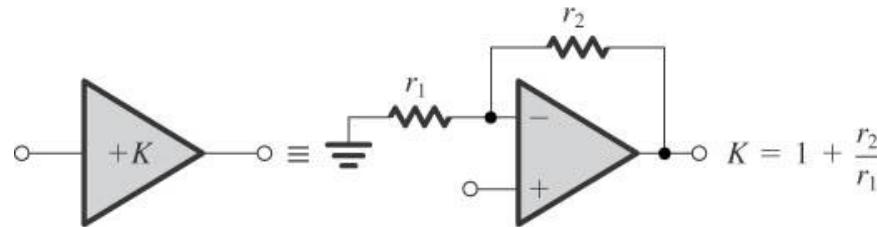




(a)



(b)



(c)

Figure 12.21 (a) An LCR resonator. (b) An op amp–RC resonator obtained by replacing the inductor L in the LCR resonator of (a) with a simulated inductance realized by the Antoniou circuit of Fig. 12.20(a). (c) Implementation of the buffer amplifier K .

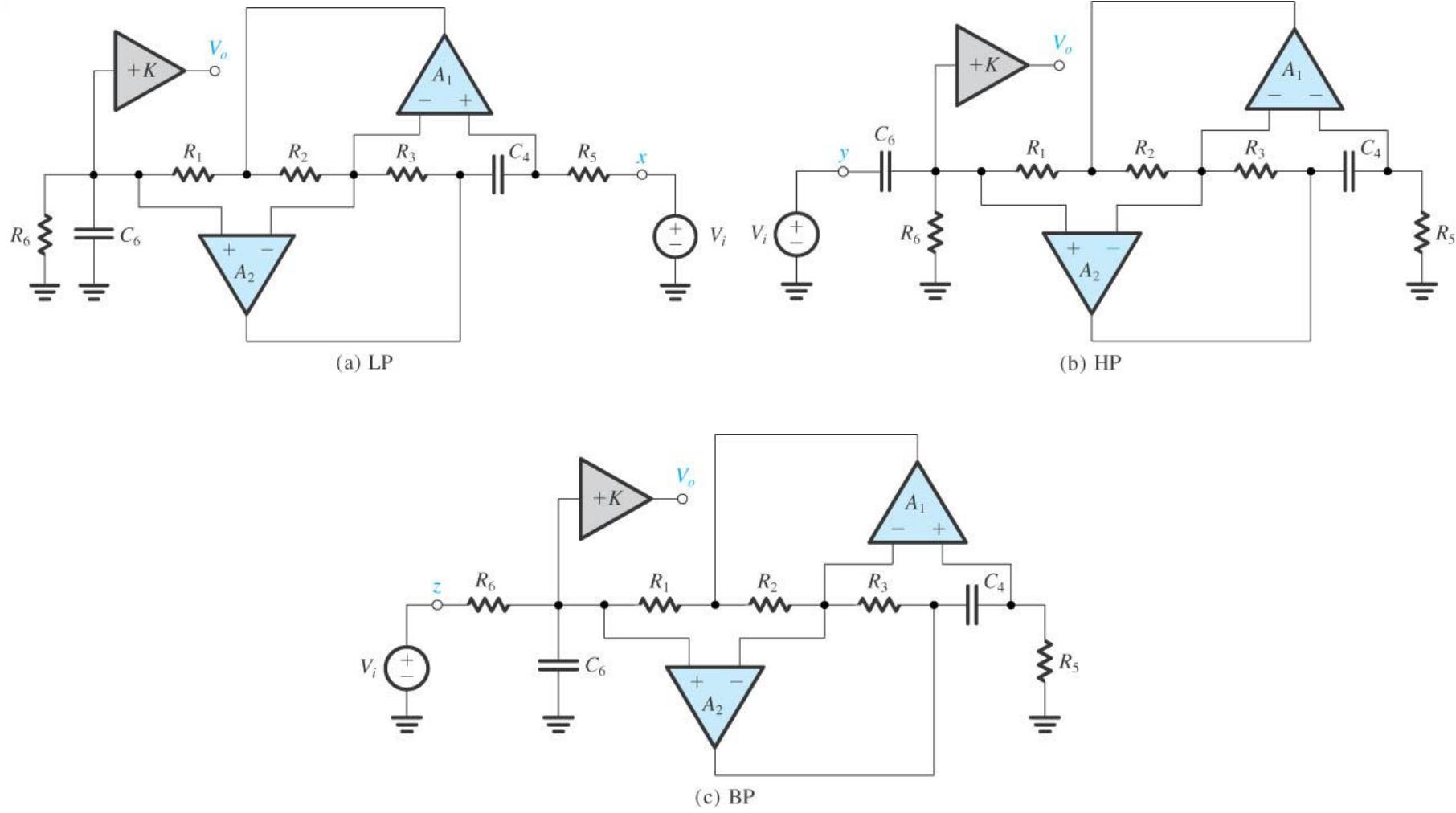
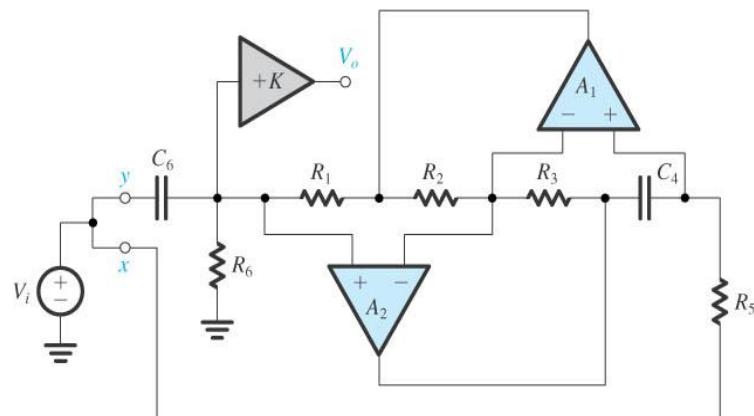
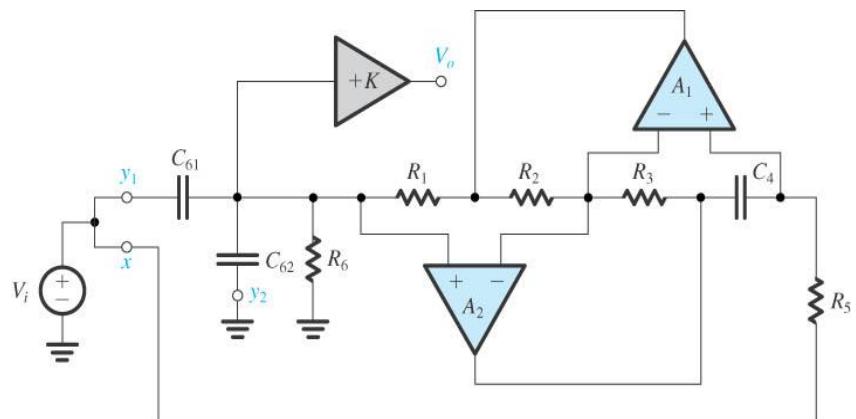


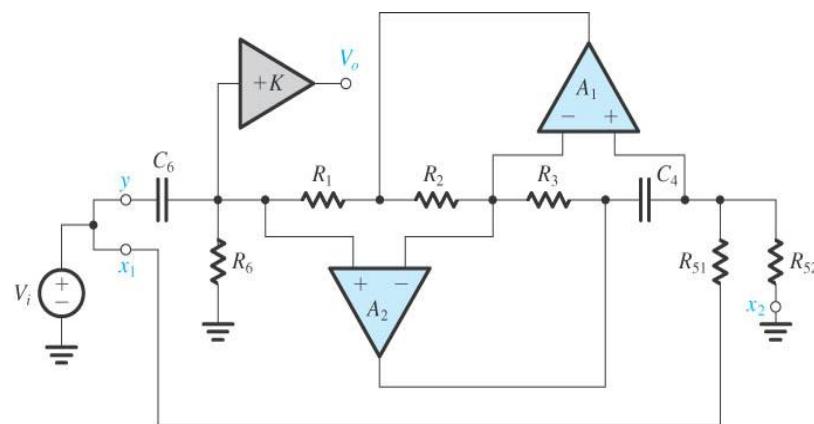
Figure 12.22 Realizations for the various second-order filter functions using the op amp–RC resonator of Fig. 12.21(b): **(a)** LP, **(b)** HP, **(c)** BP,



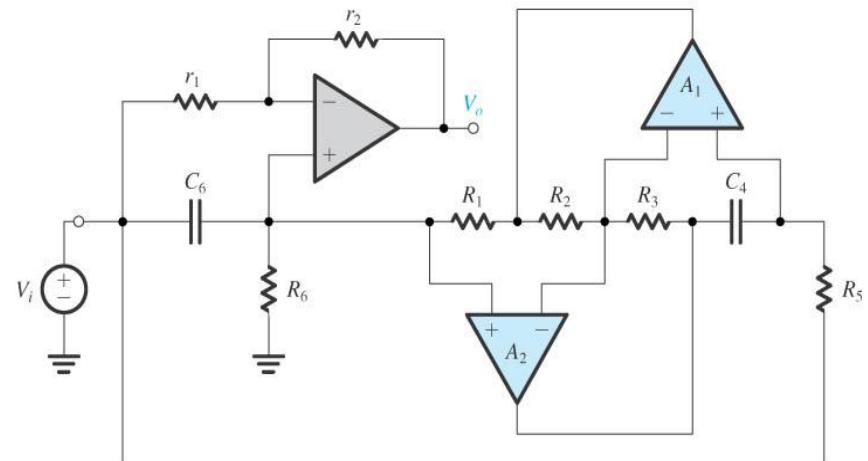
(d) Notch at ω_0



(e) LPN, $\omega_n \geq \omega_0$



(f) HPN, $\omega_n \leq \omega_0$



(g) All-pass

Figure 12.22 (Continued) (d) notch at ω_0 , (e) LPN, $\omega_n \geq \omega_0$, (f) HPN, $\omega_n \leq \omega_0$, and (g) all pass. The circuits are based on the LCR circuits in Fig. 12.18. Design equations are given in Table 12.1.

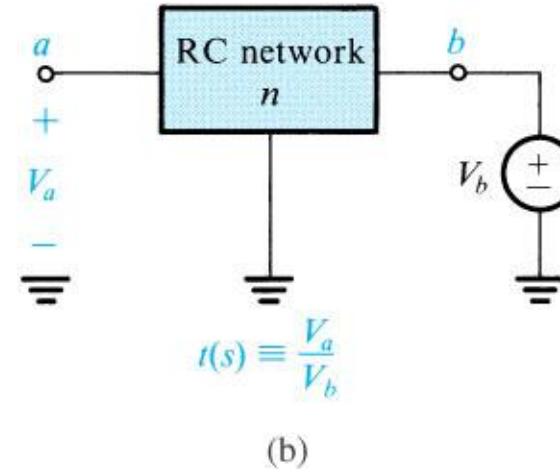
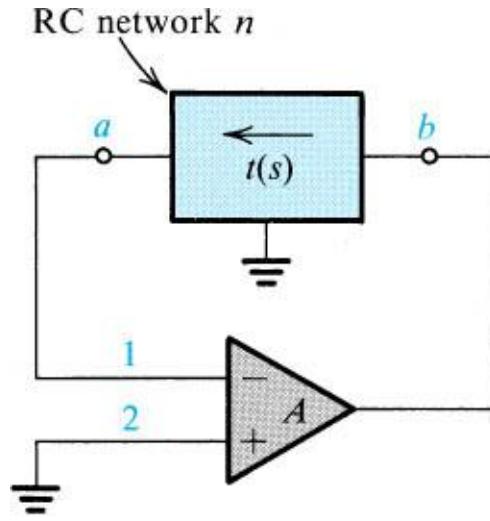
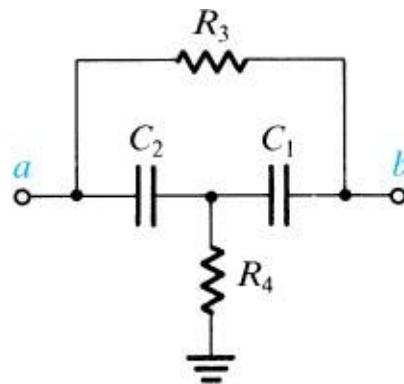
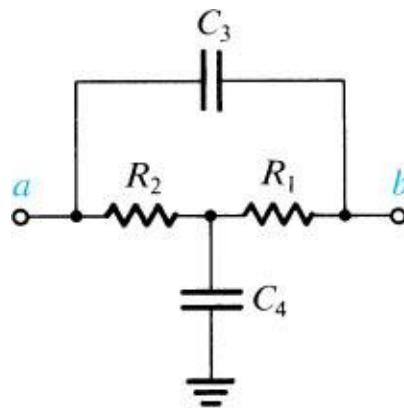


Figure 12.27 (a) Feedback loop obtained by placing a two-port RC network n in the feedback path of an op amp. (b) Definition of the open-circuit transfer function $t(s)$ of the RC network.



$$t(s) = \frac{s^2 + s\left(\frac{1}{C_1} + \frac{1}{C_2}\right)\frac{1}{R_3} + \frac{1}{C_1 C_2 R_3 R_4}}{s^2 + s\left(\frac{1}{C_1 R_3} + \frac{1}{C_2 R_3} + \frac{1}{C_1 R_4}\right) + \frac{1}{C_1 C_2 R_3 R_4}}$$

(a)



$$t(s) = \frac{s^2 + s\left(\frac{1}{R_1} + \frac{1}{R_2}\right)\frac{1}{C_4} + \frac{1}{C_3 C_4 R_1 R_2}}{s^2 + s\left(\frac{1}{C_4 R_1} + \frac{1}{C_4 R_2} + \frac{1}{C_3 R_2}\right) + \frac{1}{C_3 C_4 R_1 R_2}}$$

(b)

Figure 12.28 Two RC networks (called bridged-T networks) that can have complex transmission zeros. The transfer functions given are from b to a , with a open-circuited.

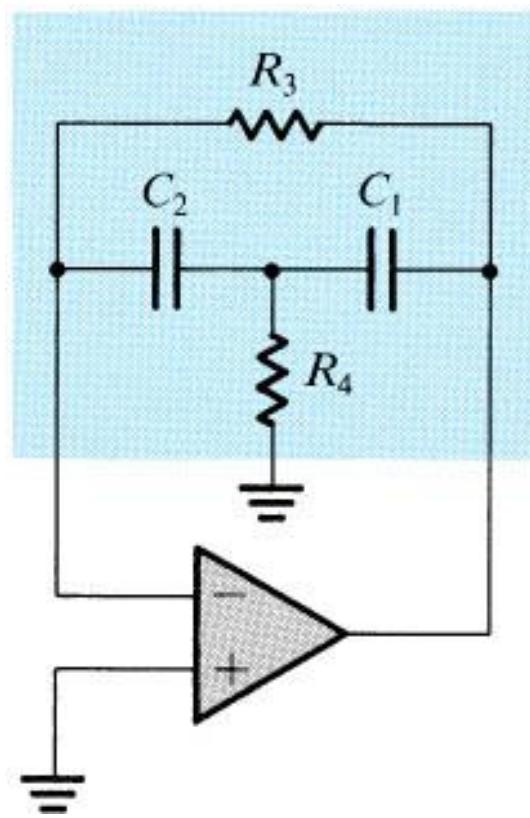
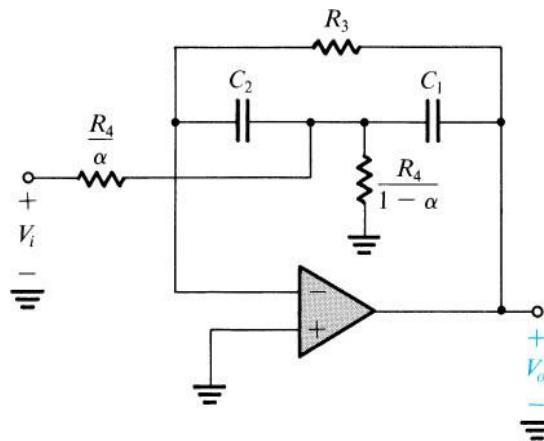
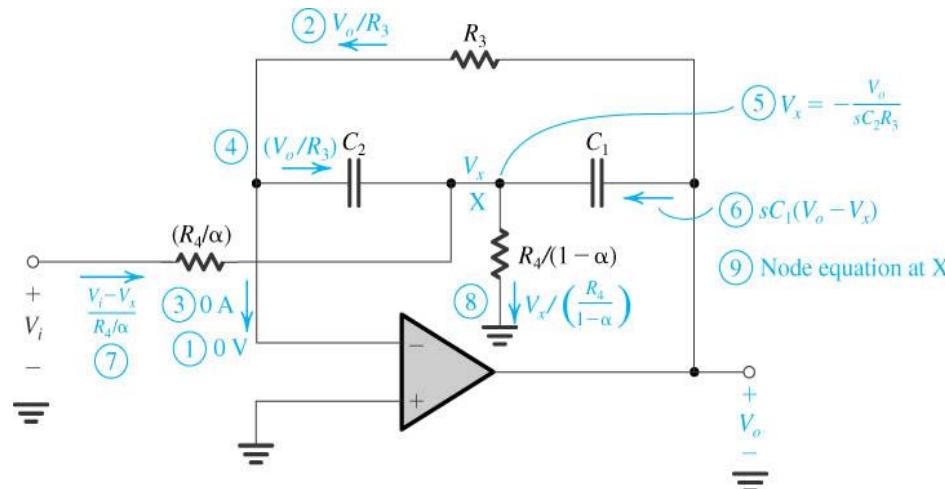


Figure 12.29 An active-filter feedback loop generated using the bridged-T network of Fig. 12.28(a).

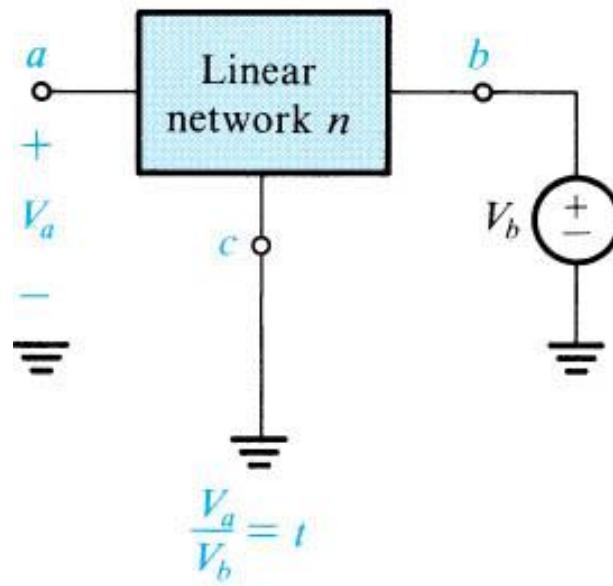


(a)

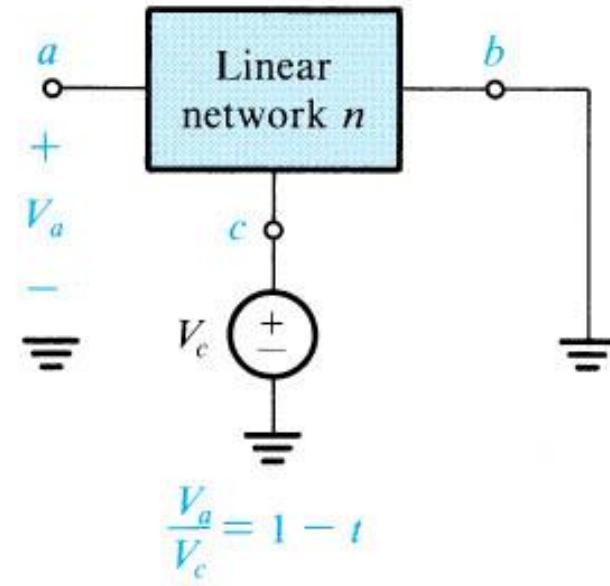


(b)

Figure 12.30 (a) The feedback loop of Fig. 12.29 with the input signal injected through part of resistance R_4 . This circuit realizes the bandpass function. (b) Analysis of the circuit in (a) to determine its voltage transfer function $T(s)$ with the order of the analysis steps indicated by the circled numbers.

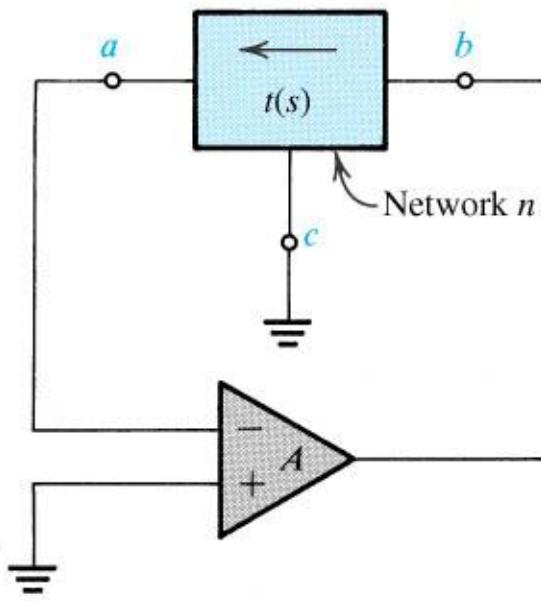


(a)

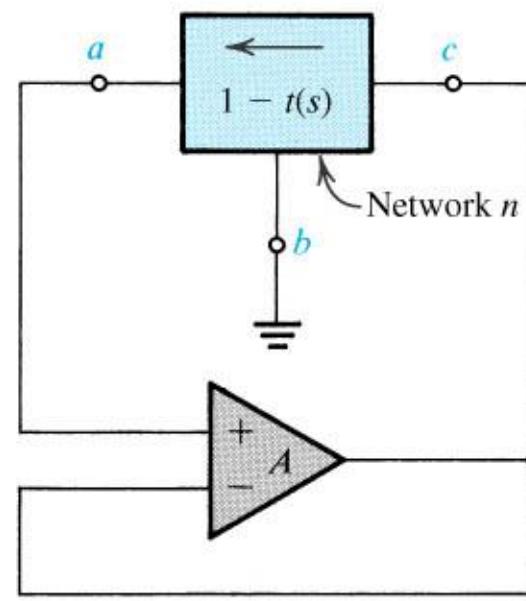


(b)

Figure 12.31 Interchanging input and ground results in the complement of the transfer function.

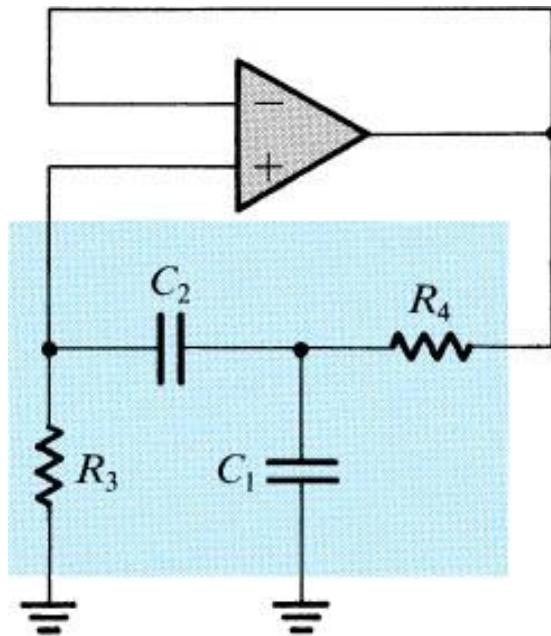


(a)

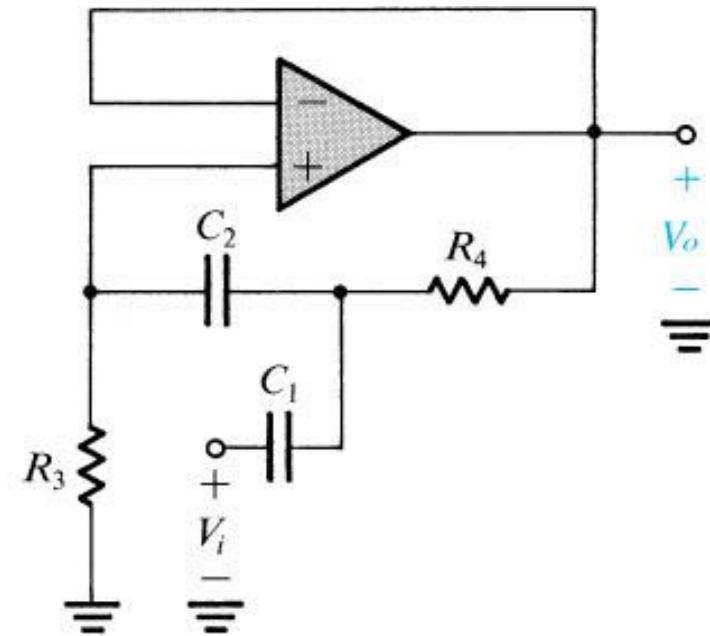


(b)

Figure 12.32 Application of the complementary transformation to the feedback loop in (a) results in the equivalent loop (same poles) shown in (b).

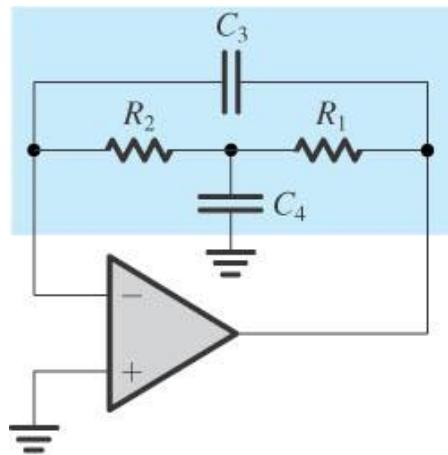


(a)

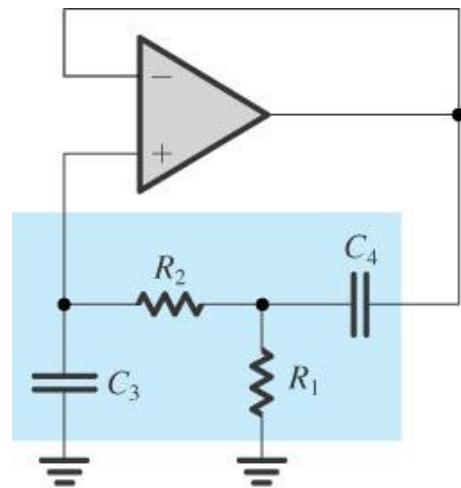


(b)

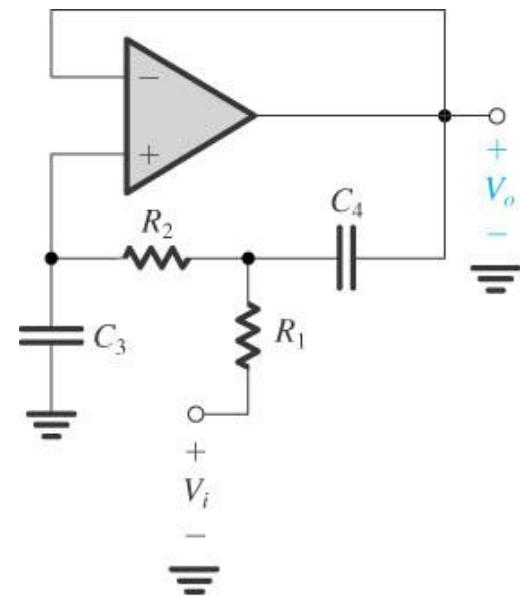
Figure 12.33 (a) Feedback loop obtained by applying the complementary transformation to the loop in Fig. 12.29. (b) Injecting the input signal through C_1 realizes the high-pass function. This is one of the Sallen-and-Key family of circuits.



(a)

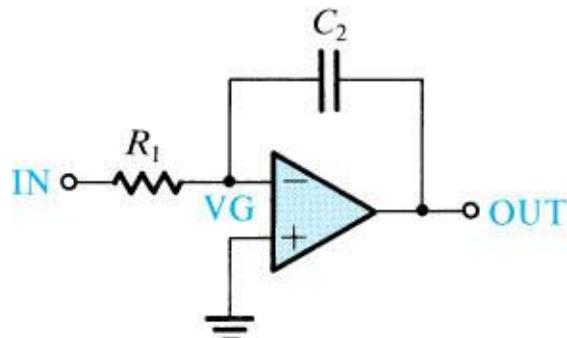


(b)

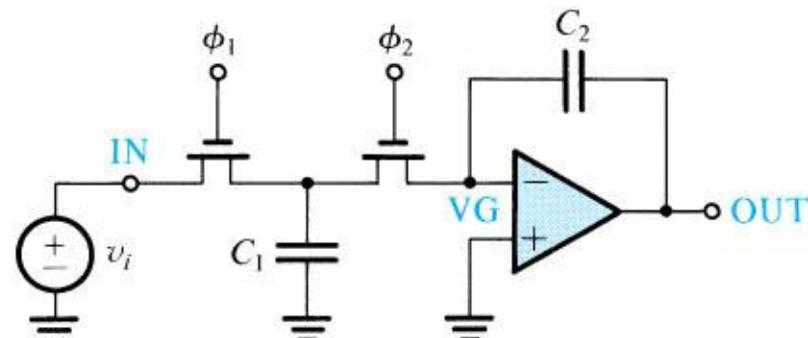


(c)

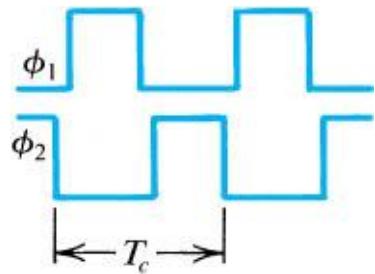
Figure 12.34 (a) Feedback loop obtained by placing the bridged-T network of Fig. 12.28(b) in the negative-feedback path of an op amp. (b) Equivalent feedback loop generated by applying the complementary transformation to the loop in (a). (c) A low-pass filter obtained by injecting V_i through R_1 into the loop in (b).



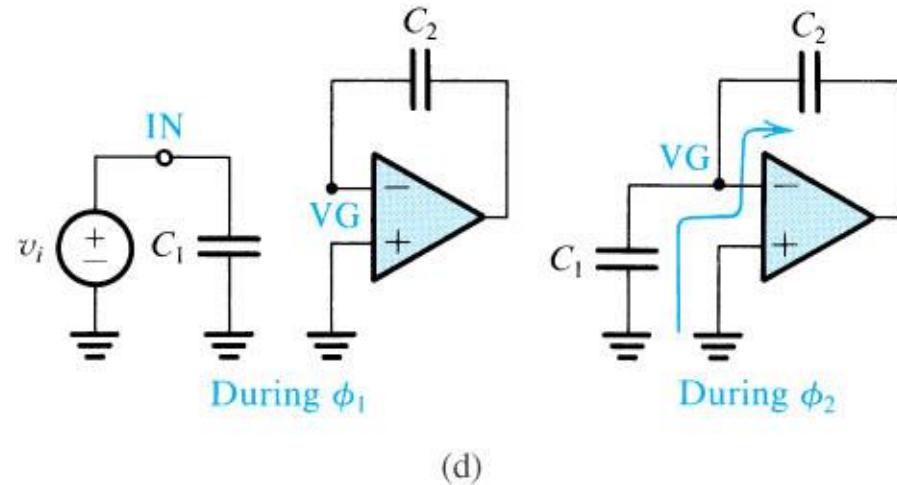
(a)



(b)

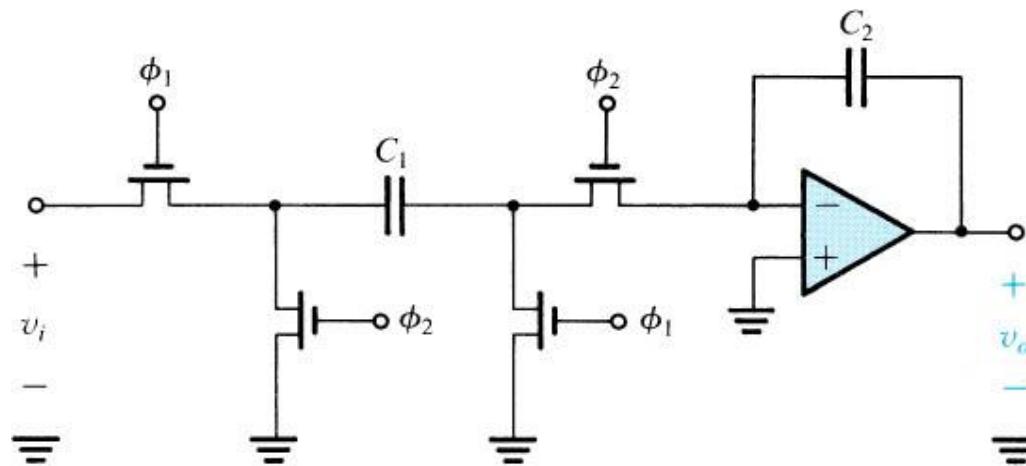


(c)

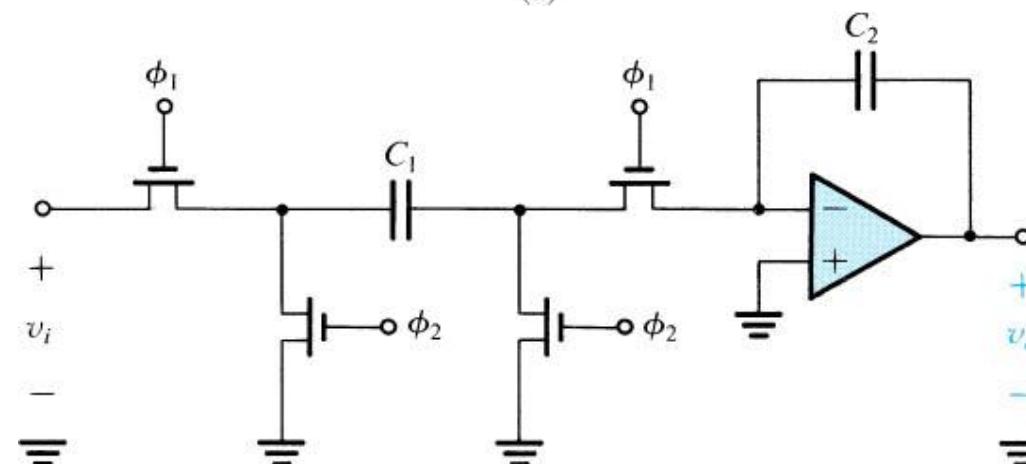


(d)

Figure 12.35 Basic principle of the switched-capacitor filter technique. **(a)** Active-RC integrator. **(b)** Switched-capacitor integrator. **(c)** Two-phase clock (nonoverlapping). **(d)** During ϕ_1 , C_1 charges up to the current value of v_i and then, during ϕ_2 , discharges into C_2 .

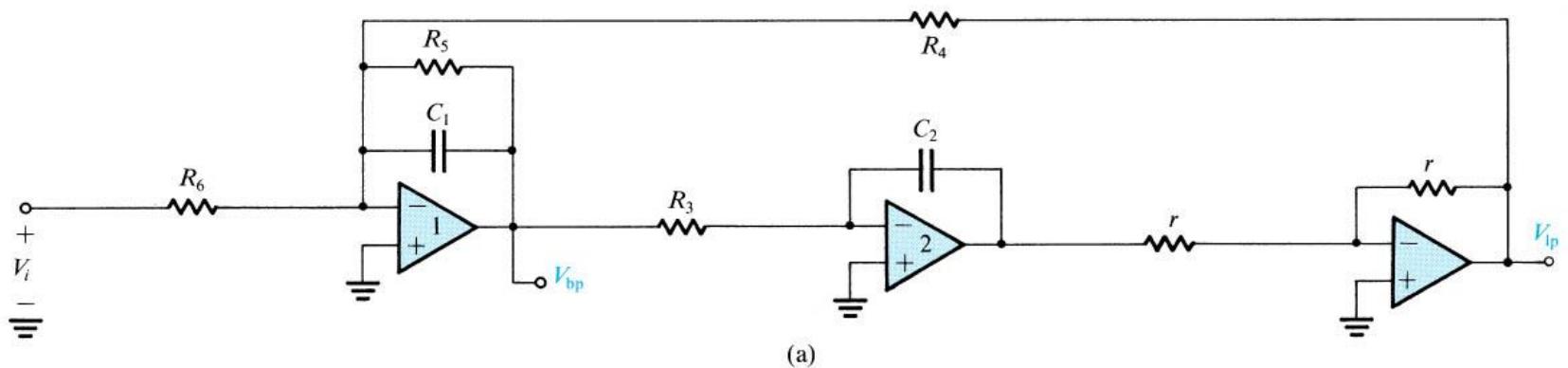


(a)

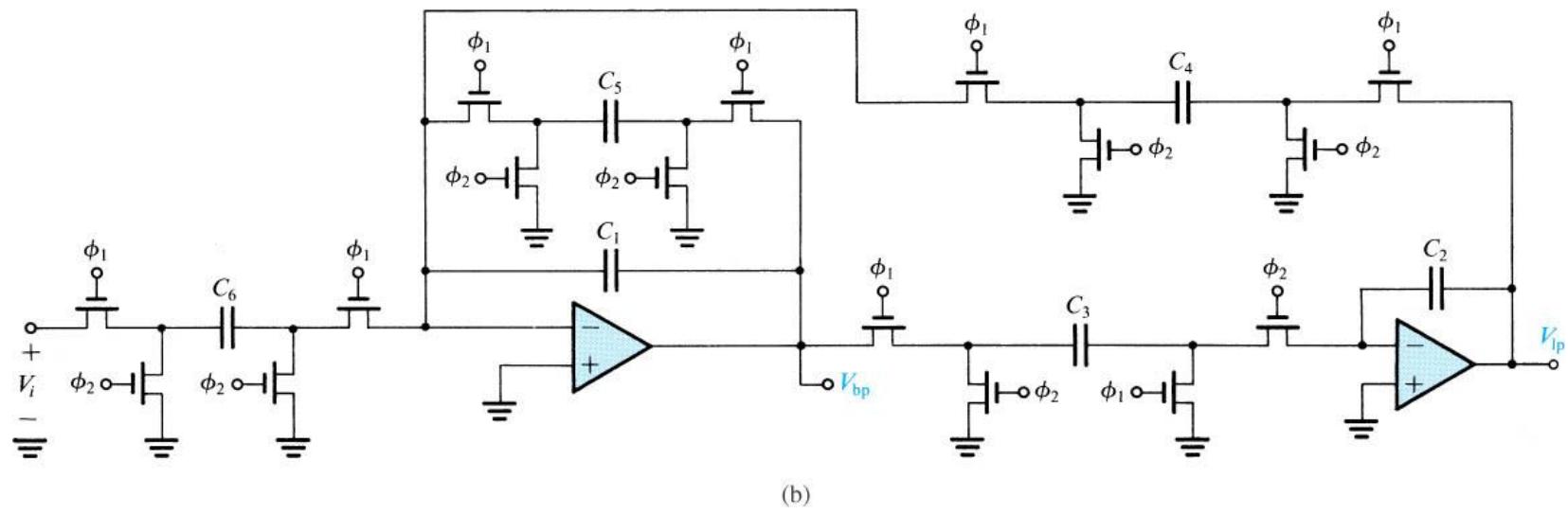


(b)

Figure 12.36 A pair of complementary stray-insensitive switched-capacitor integrators. **(a)** Noninverting switched-capacitor integrator. **(b)** Inverting switched-capacitor integrator.

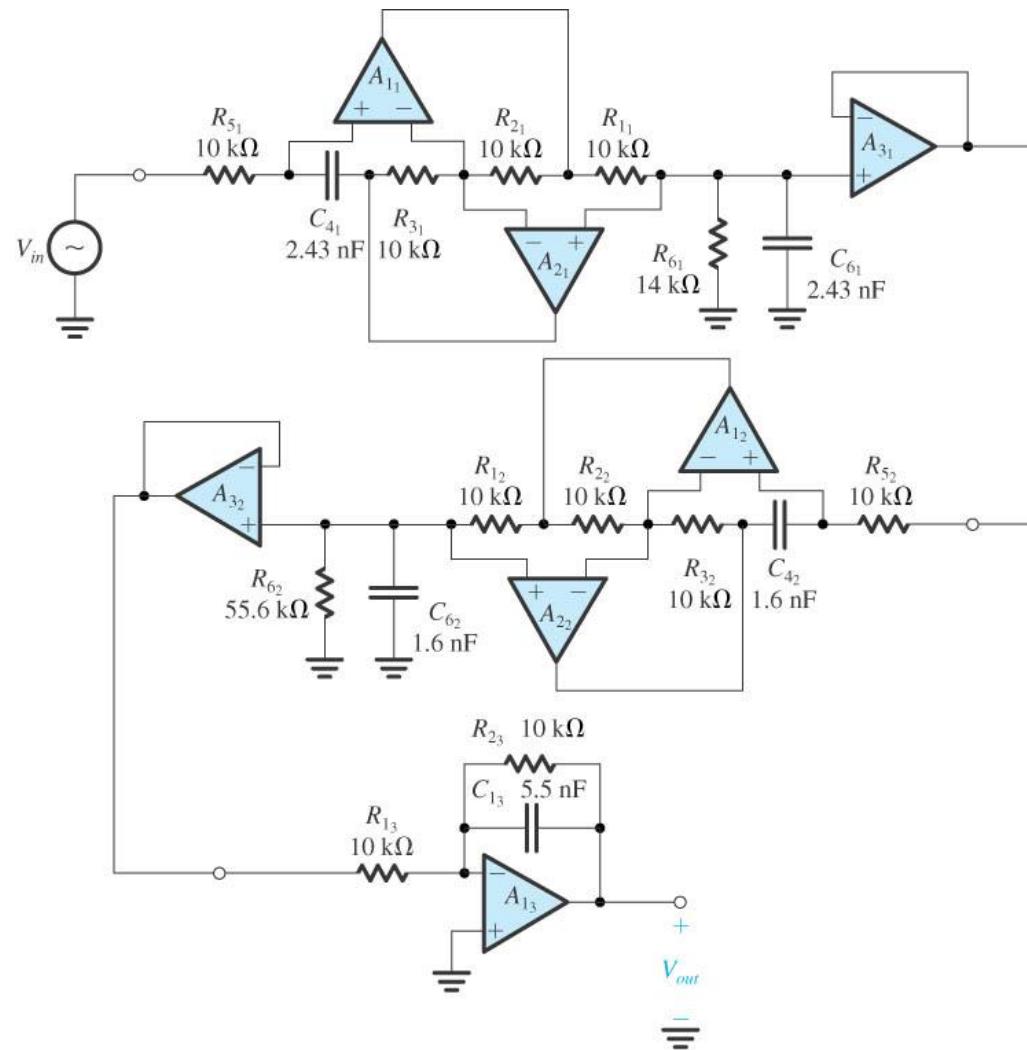


(a)



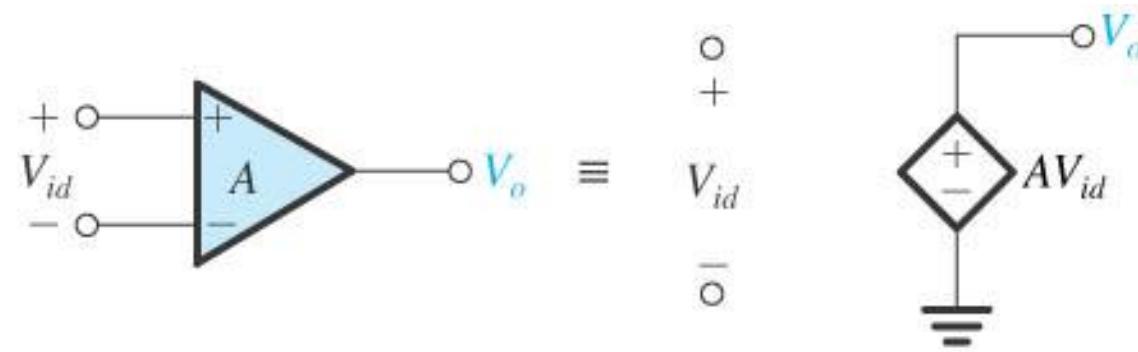
(b)

Figure 12.37 (a) A two-integrator-loop active-RC biquad and (b) its switched-capacitor counterpart.



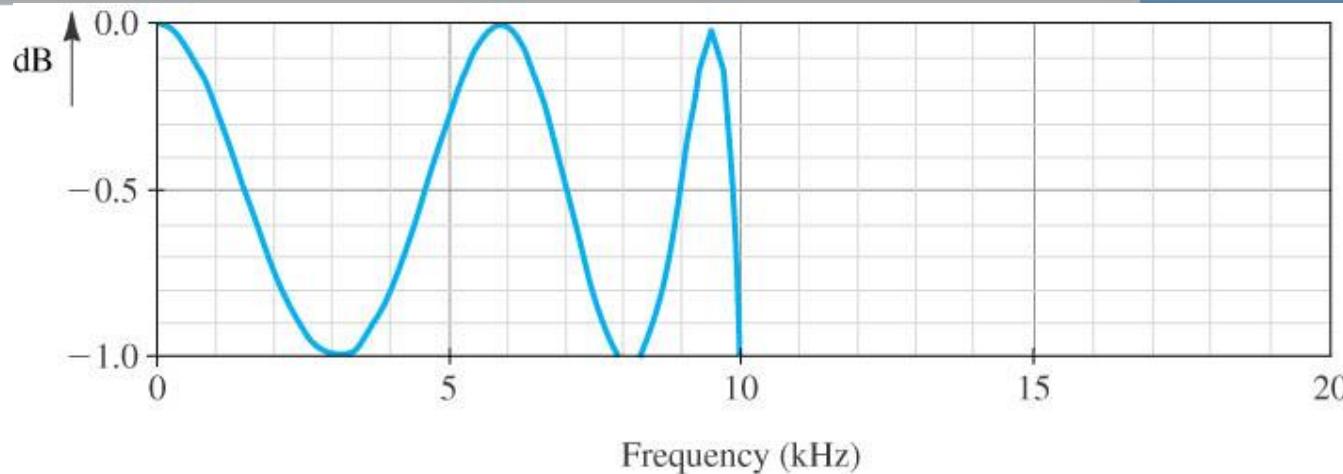
(a)

Figure 12.49 Circuits for Example 12.5. (a) Fifth-order Chebyshev filter circuit implemented as a cascade of two second-order simulated LCR resonator circuits and a single first-order op amp-RC circuit.

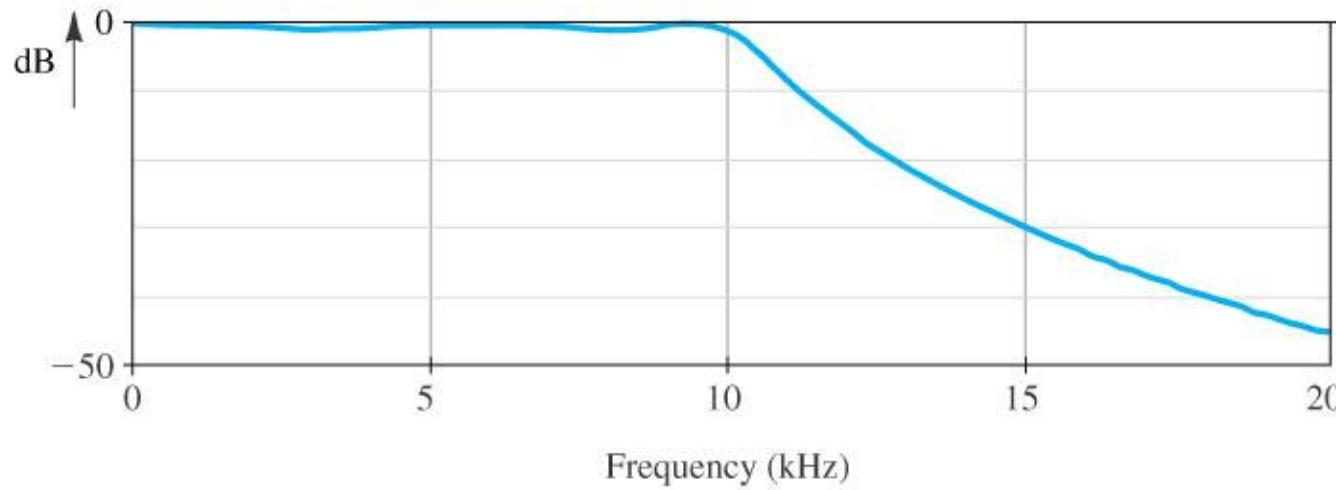


(b)

Figure 12.49 (Continued) (b) VCVS representation of an ideal op amp with gain A .

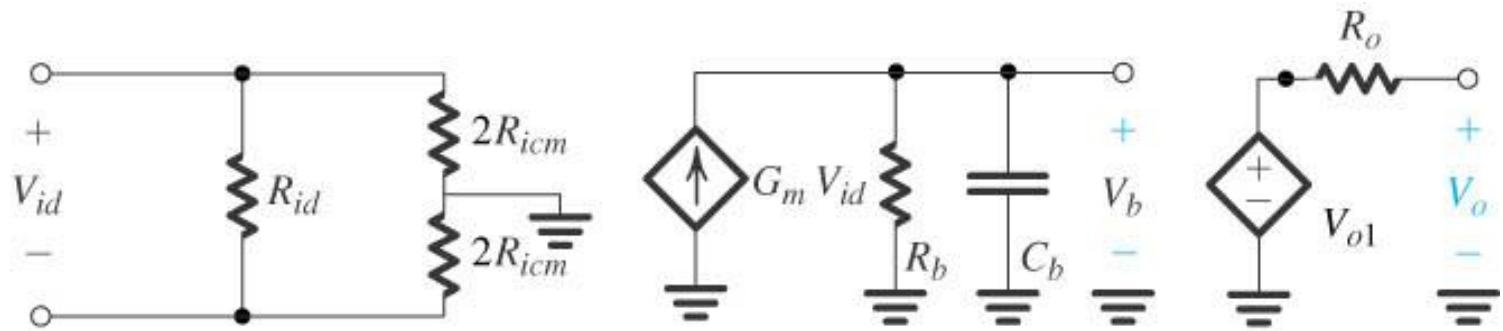


(a)



(b)

Figure 12.50 Magnitude response of the fifth-order lowpass filter circuit shown in Fig. 12.49: (a) an expanded view of the passband region; (b) a view of both the passband and stopband regions.



$$A_0 = G_m R_1 \quad \omega_b = 1/R_b C_b$$

Figure 12.51 One-pole equivalent circuit macromodel of an op amp operated within its linear region.

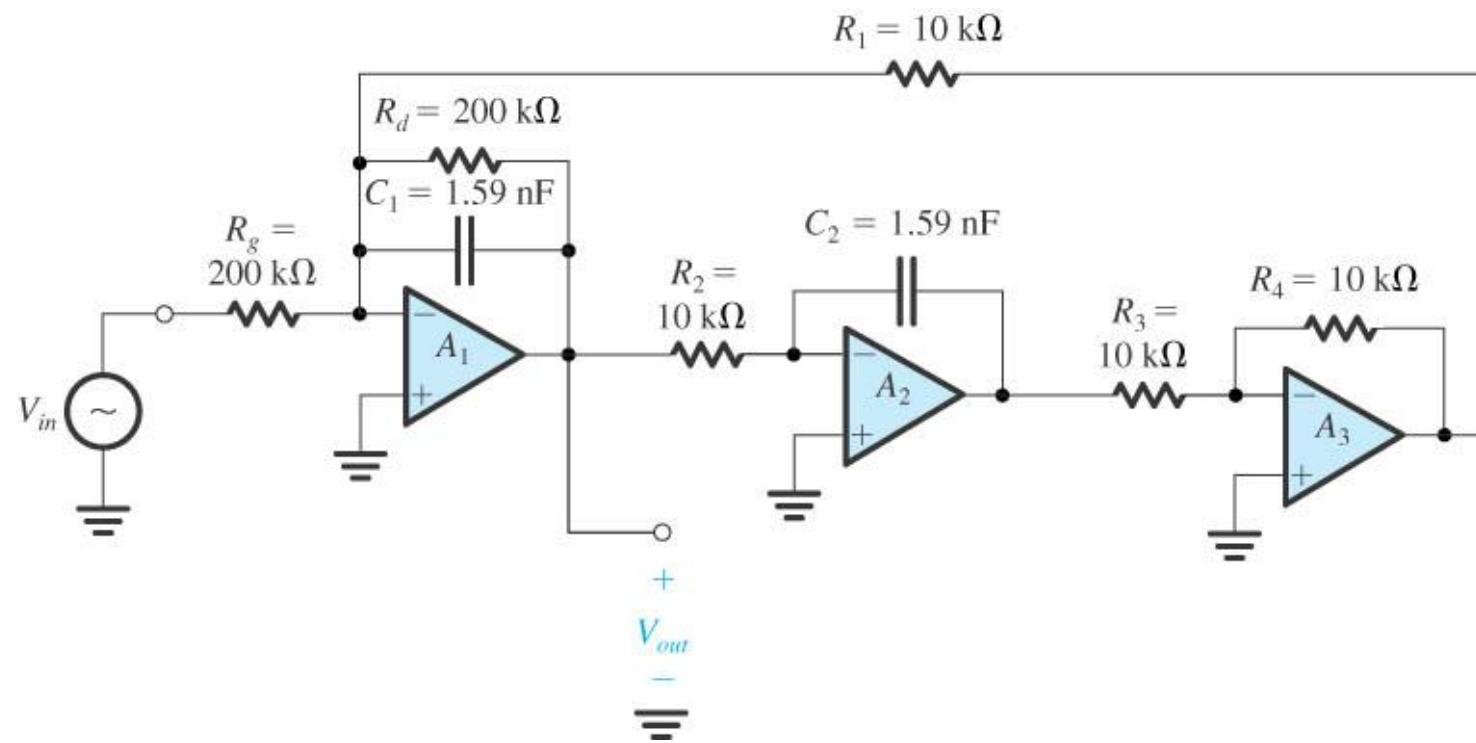


Figure 12.52 Circuit for Example 11.6. Second-order bandpass filter implemented with a Tow–Thomas biquad circuit having $f_0 = 10\text{ kHz}$, $Q = 20$, and unity center-frequency gain.

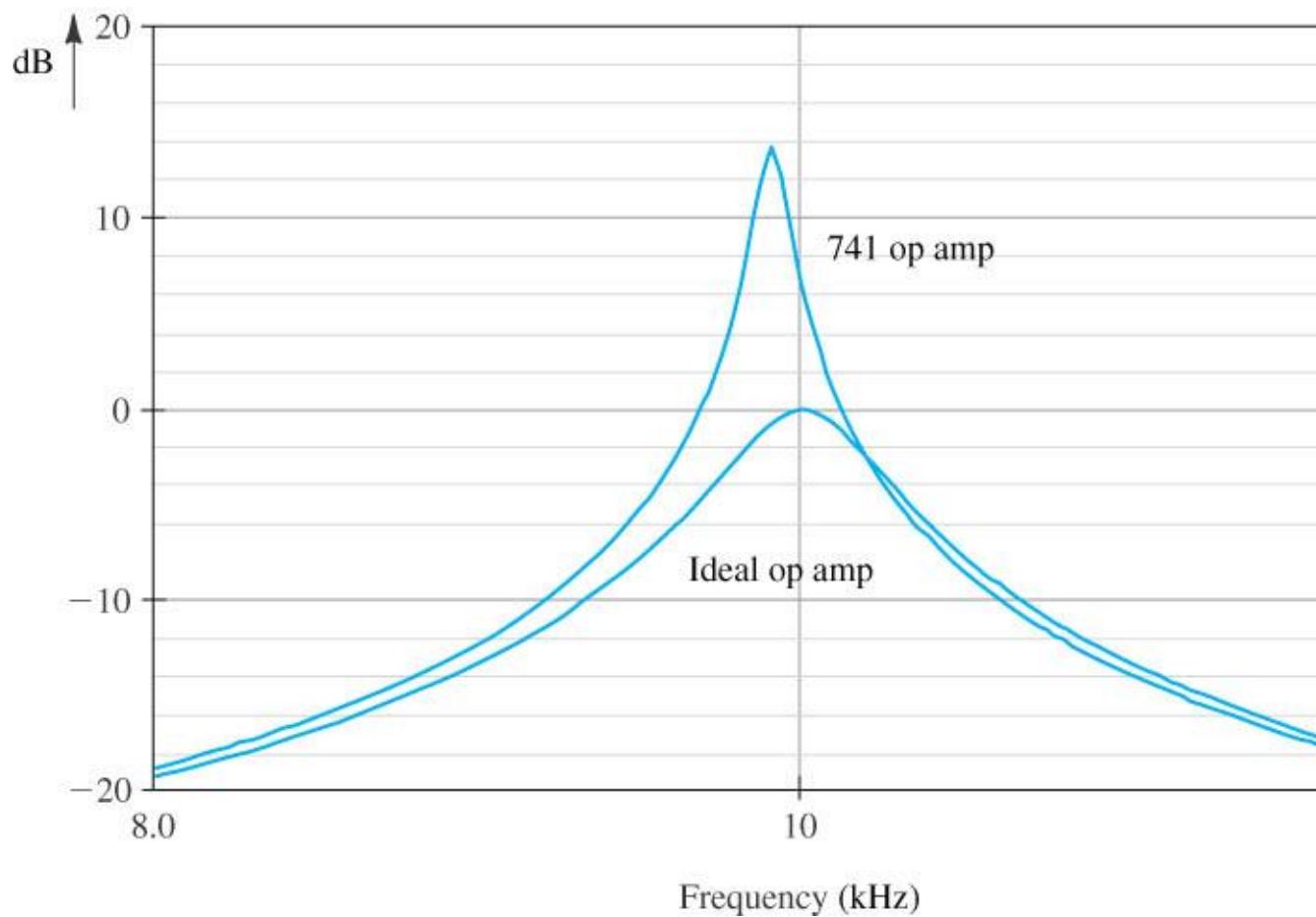
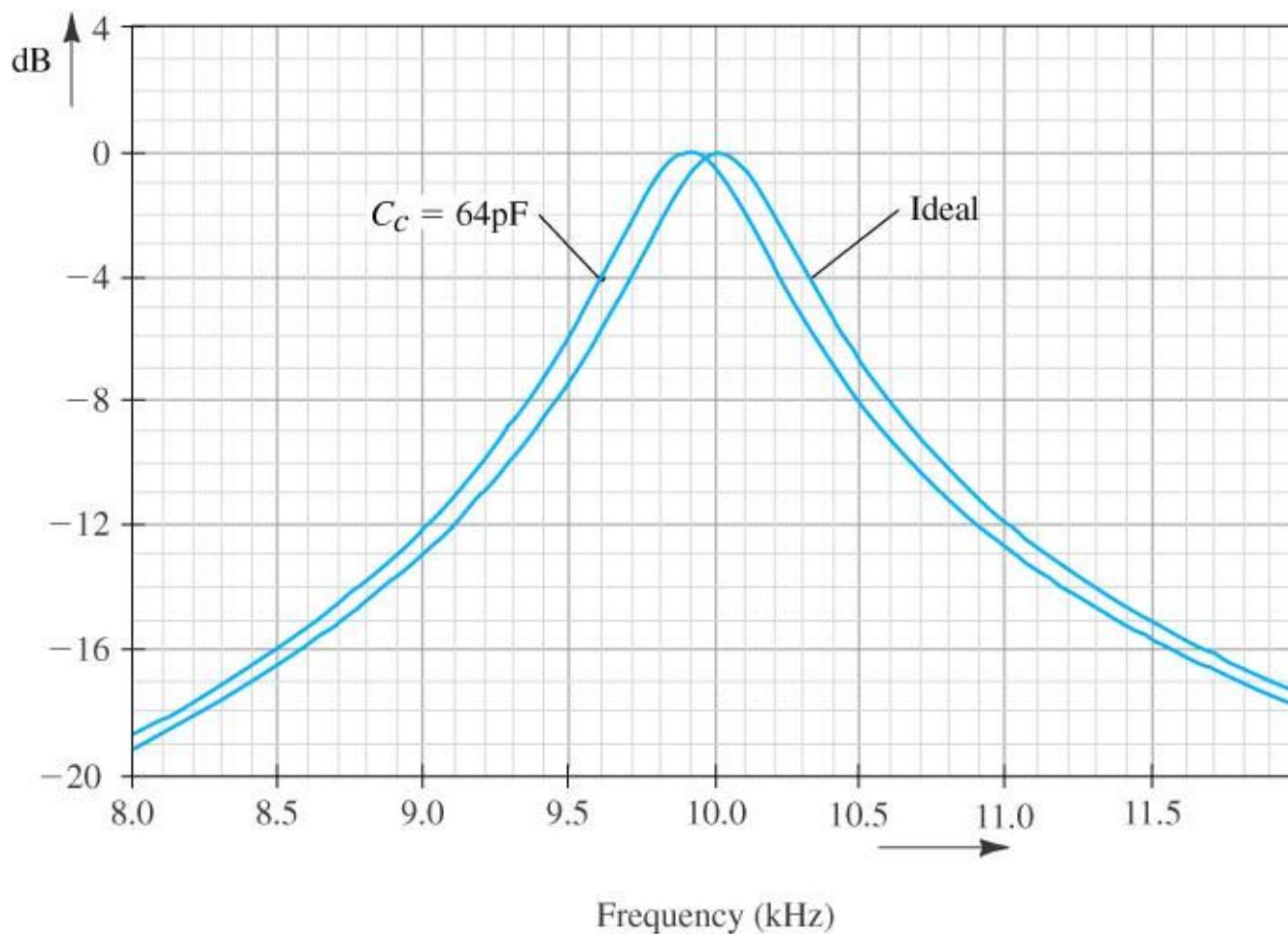


Figure 12.53 Comparing the magnitude response of the Tow–Thomas biquad circuit (shown in Fig. 12.52) constructed with 741-type op amps, with the ideal magnitude response. These results illustrate the effect of the finite dc gain and bandwidth of the 741 op amp on the frequency response of the Tow–Thomas biquad circuit.

Figure 12.54 (a) Magnitude response of the Tow–Thomas biquad circuit with different values of compensation capacitance. For comparison, the ideal response is also shown.



(b)

Figure 12.54 (Continued) (b) Comparing the magnitude response of the Tow–Thomas biquad circuit using a 64-pF compensation capacitor and the ideal response.