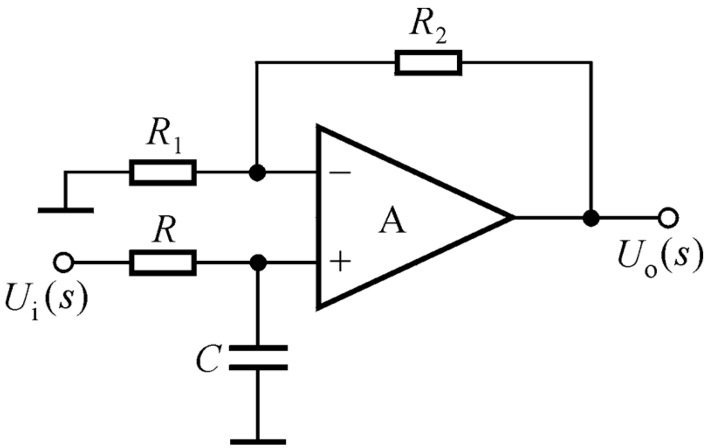
二、低通滤波电路 (*Active Low-Pass Filter*)

1. 一阶低通滤波电路



$$A_u(s) = \frac{U_o(s)}{U_i(s)} = \left(1 + \frac{R_2}{R_1}\right)\frac{1}{1 + sRC}$$

$$\dot{A}_u = \dot{A}_{up}\frac{1}{1 + \mathrm{j}\dfrac{f}{f_0}}$$

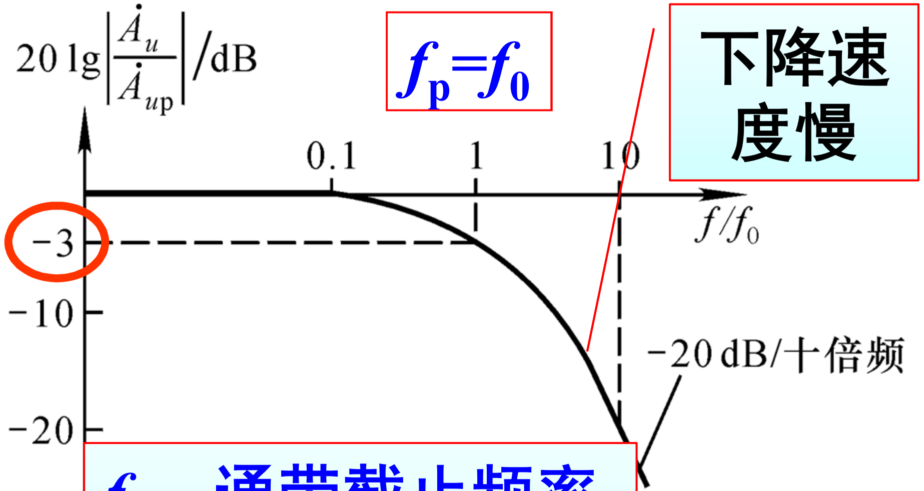
$$\boxed{s = \mathrm{j}\omega = \mathrm{j}2\pi f \qquad f_0 = \frac{1}{2\pi RC}}$$

通带电压放大倍数 $\boxed{\dot{A}_{up} = \dot{A}_u\big|_{f=0}}$

分析方法：虚短、虚断

$$U_+(s) = \frac{\dfrac{1}{sC}}{R + \dfrac{1}{sC}}U_i(s) = \frac{1}{1 + sRC}U_i(s)$$

$$U_o(s) = \left(1 + \frac{R_2}{R_1}\right)U_+(s)$$



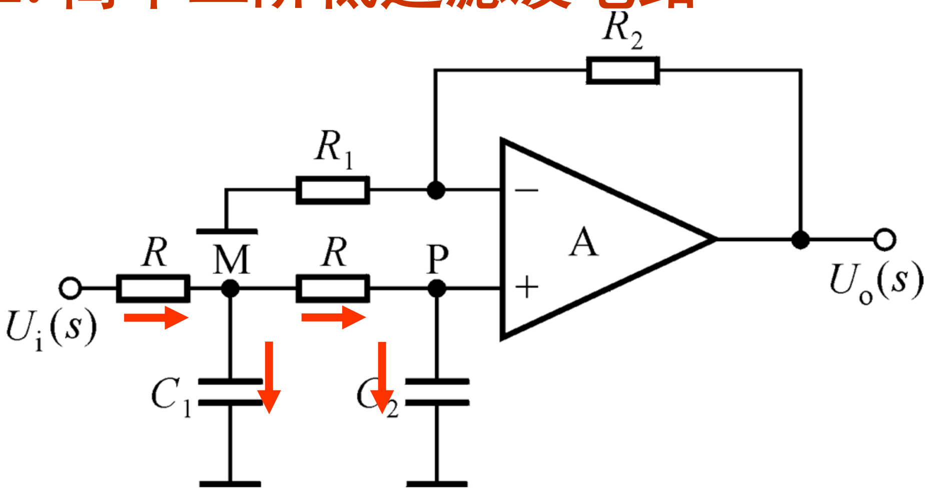
$f_p = f_0$

下降速度慢

f_p：通带截止频率

f_0：特征频率

2. 简单二阶低通滤波电路



设C_1=C_2=C

$$\boxed{A_{up} = 1 + \frac{R_2}{R_1}}$$

$$\boxed{f_0 = \frac{1}{2\pi RC}}$$

$$U_o(s) = (1 + \frac{R_2}{R_1})U_+(s)$$

$$U_+(s) = \frac{1}{1 + sRC}U_M(s)$$

$$U_M(s) = \frac{\frac{1}{sC} // (R + \frac{1}{sC})}{R + \frac{1}{sC} // (R + \frac{1}{sC})}U_i(s)$$

$$A_u(s) = A_{up} \cdot \frac{1}{1 + 3\frac{s}{\omega_0} + (\frac{s}{\omega_0})^2}$$

$$\dot{A}_u = \dot{A}_{up}\frac{1}{1 + \mathrm{j}3\frac{f}{f_0} - (\frac{f}{f_0})^2}$$

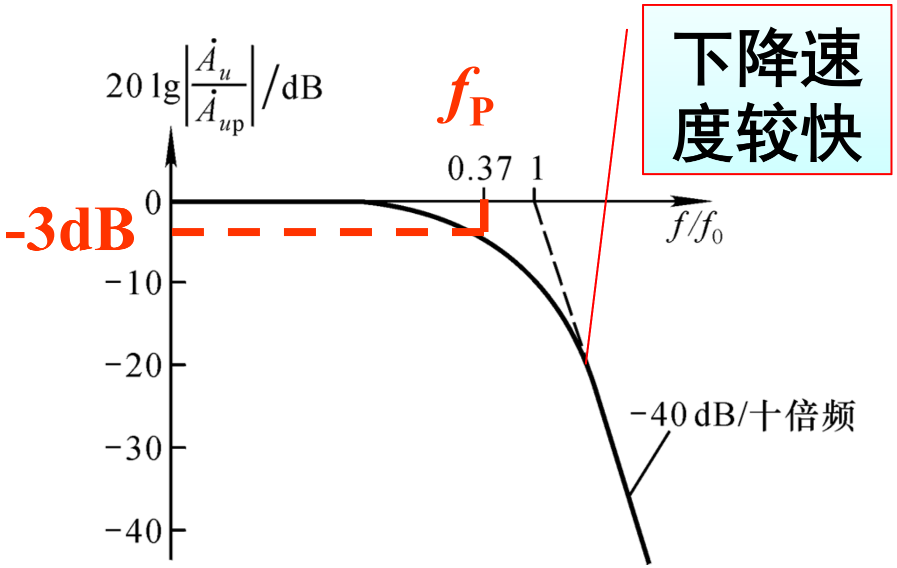
$$\dot{A}_u = \dot{A}_{up}\frac{1}{1+\mathrm{j}3\frac{f}{f_0}-(\frac{f}{f_0})^2}$$

令 $|\dot{A}_u| = \frac{\dot{A}_{up}}{\sqrt{2}}$ 求得 $f_p \approx 0.37 f_0$

$$|\dot{A}_u|_{f=f_0} = \left|\frac{\dot{A}_{up}}{3}\right| = |Q\dot{A}_{up}|$$

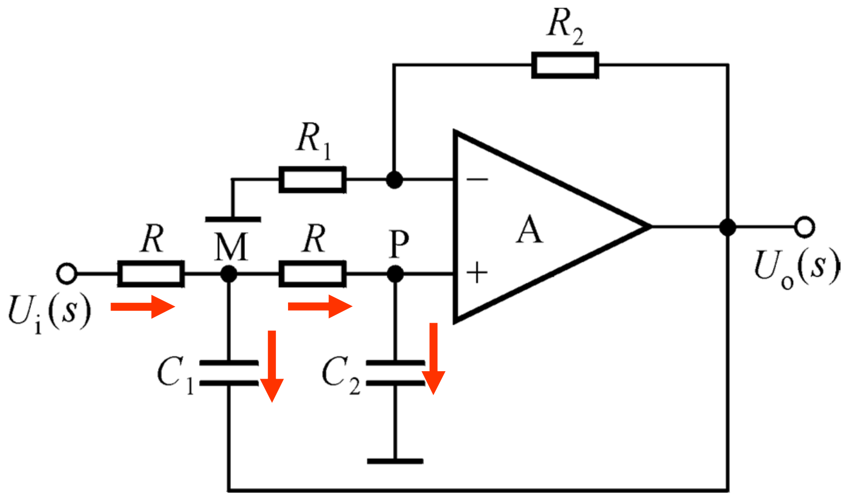
$$Q = \frac{1}{3}$$

Q为品质因数，又称为截止特性系数



为使$f_p \approx f_0$, 使滤波特性更加理想，需要提高f_0点的增益

3. 压控电压源(VCVS)二阶低通滤波电路(*Sallen-Key Low Pass Filter*)



设$C_1=C_2=C$

引入正反馈 增大f_0点的增益

$$A_{up}=1+\frac{R_2}{R_1}\qquad \boxed{f_0=\frac{1}{2\pi RC}}$$

$$U_o(s)=(1+\frac{R_2}{R_1})U_+(s)$$

$$A_u(s)=A_{up}\cdot\frac{1}{1+(3-A_{up})\frac{s}{\omega_0}+(\frac{s}{\omega_0})^2}$$

$$U_+(s)=\frac{1}{1+sRC}U_M(s)$$

考虑电路的稳定性，$A_{up}<3$

$$\frac{U_i(s)-U_M(s)}{R}=\frac{U_M(s)-U_O(s)}{\frac{1}{sC}}+\frac{U_M(s)-U_+(s)}{R}$$

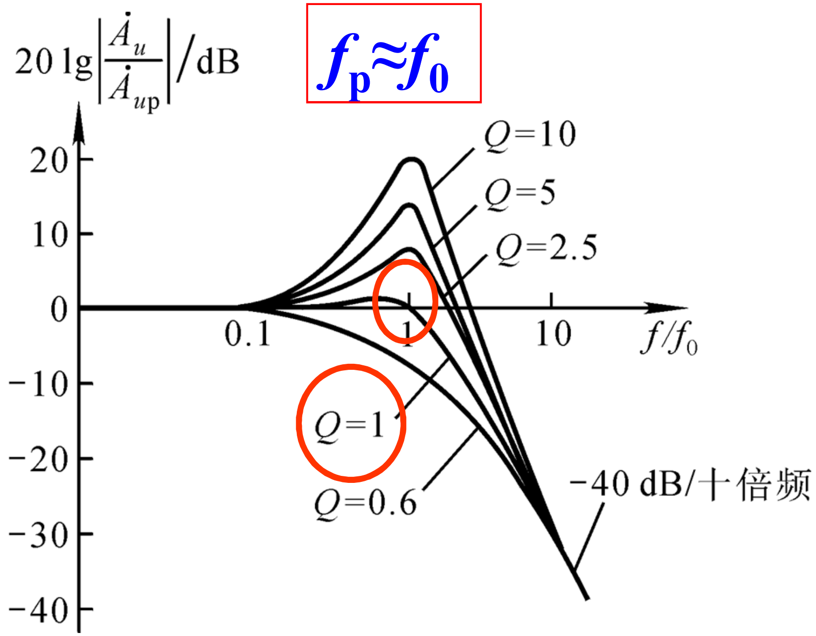
$$\dot{A}_u = \frac{\dot{A}_{up}}{1 + \mathrm{j}(3 - \dot{A}_{up})\dfrac{f}{f_0} - (\dfrac{f}{f_0})^2}$$

$$|\dot{A}_u|_{f=f_0} = \left|\frac{\dot{A}_{up}}{3 - \dot{A}_{up}}\right| = |Q\dot{A}_{up}|$$

$$Q = \left|\frac{1}{3 - \dot{A}_{up}}\right|$$

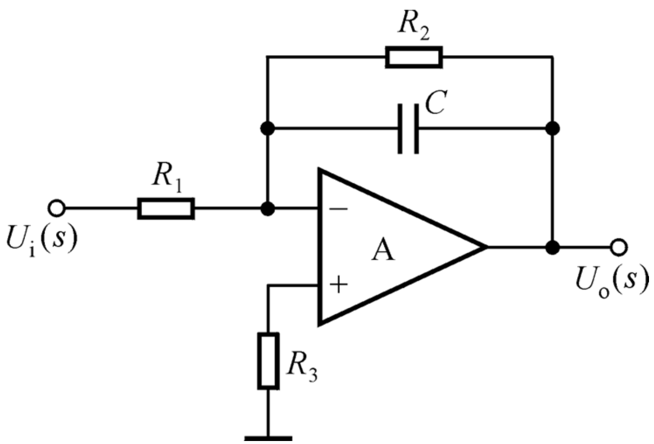
调节A_{up}即可调节f_0点的增益

$f_p \approx f_0$



4. 反相输入低通滤波电路

（1）反相输入一阶低通滤波电路

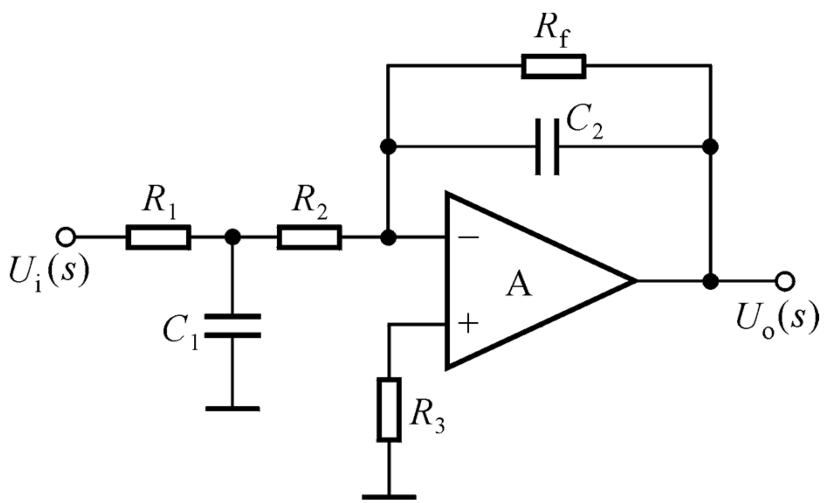


$$A_{up} = -\frac{R_2}{R_1}$$

$$\boxed{f_P = f_0 = \frac{1}{2\pi R_2 C}}$$

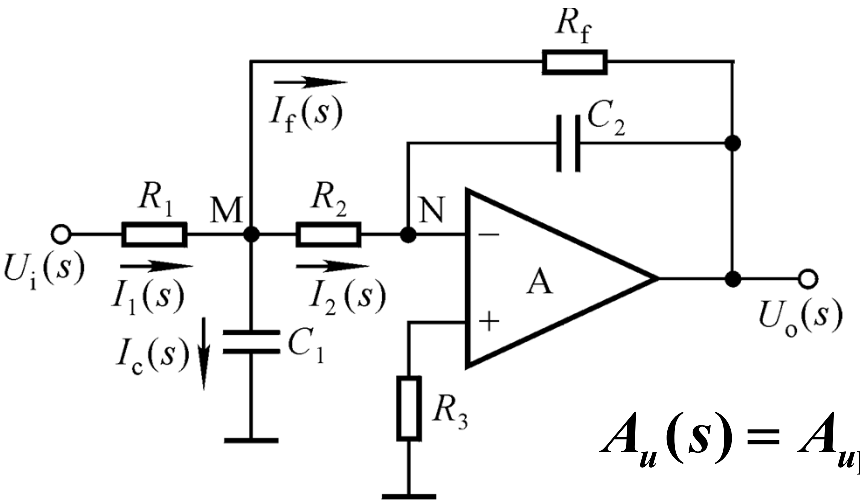
$$A_u(s) = A_{up} \cdot \frac{1}{1 + sR_2C}$$

（2）反相输入简单二阶低通滤波电路



4. 反相输入低通滤波电路

（3）无限增益多路反馈（MFB）二阶低通滤波电路



$$A_{up} = -\frac{R_f}{R_1}$$

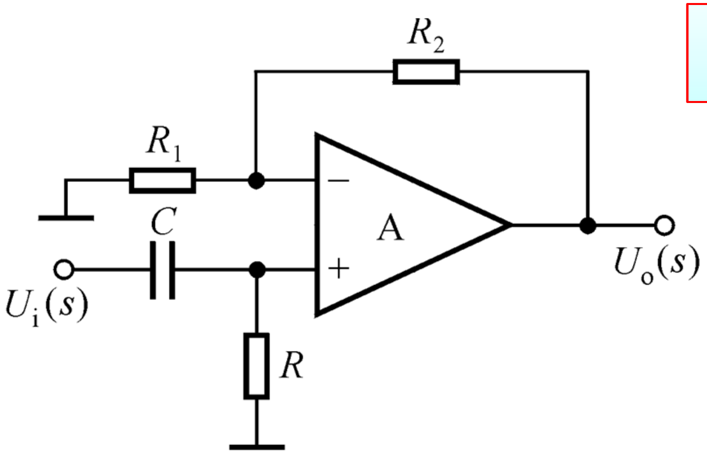
$$f_P = f_0 = \frac{1}{2\pi\sqrt{C_1 C_2 R_2 R_f}}$$

$$A_u(s) = A_{up} \cdot \frac{1}{1 + (\frac{1}{R_1} + \frac{1}{R_2} + \frac{1}{R_f})\frac{1}{C_1}\frac{s}{\omega_0} + (\frac{s}{\omega_0})^2}$$

$$Q = (R_1 // R_2 // R_f)\sqrt{\frac{C_1}{R_2 R_f C_2}}$$

特点： 不会因A_{up}过大而产生自激振荡，Q值受多个因素影响

三、高通滤波电路(*Active High-Pass Filter*)



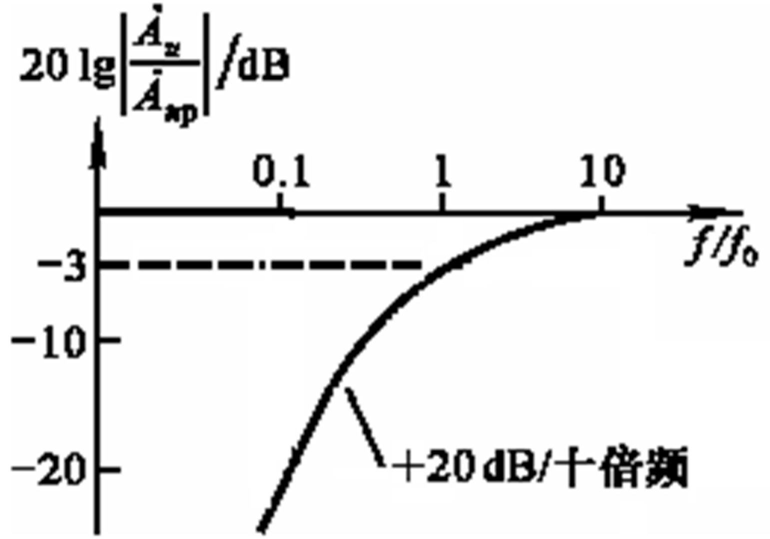
一阶高通滤波电路

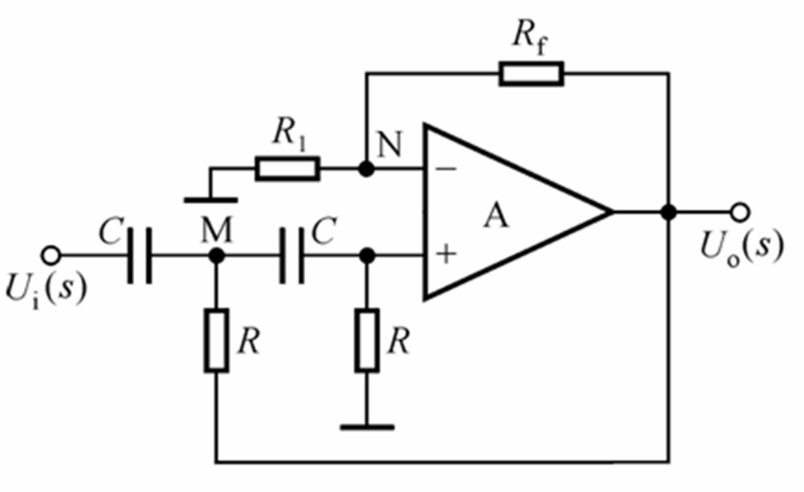
电路形式和传递函数与低通的对偶

$$\dot{A}_u = \dot{A}_{up}\frac{\mathrm{j}\dfrac{f}{f_0}}{1+\mathrm{j}\dfrac{f}{f_0}}$$

$$\dot{A}_{up} = \dot{A}_u\big|_{f=\infty} = 1+\frac{R_2}{R_1}$$

$$\boxed{f_0 = \frac{1}{2\pi RC}}$$



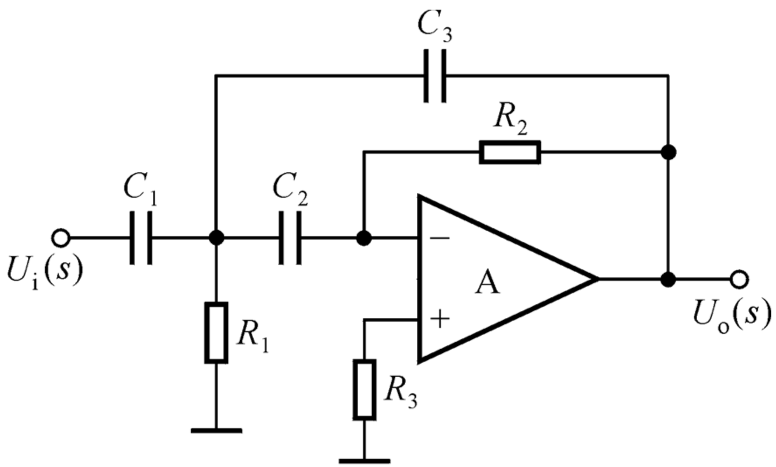


二阶VCVS高通滤波电路

$$\dot{A}_{up} = \dot{A}_u|_{f=\infty} = 1+\frac{R_f}{R_1} \qquad \boxed{f_0 = \frac{1}{2\pi RC}}$$

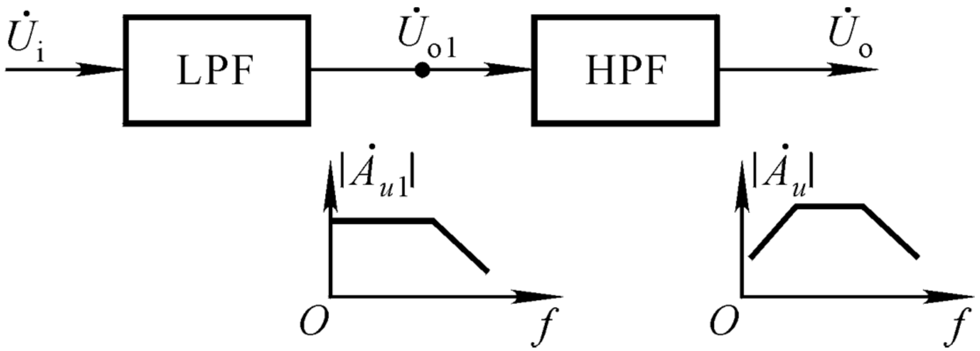
$$A_u(s) = A_{up}\cdot\frac{(\frac{s}{\omega_0})^2}{1+(3-A_{up})\frac{s}{\omega_0}+(\frac{s}{\omega_0})^2}$$

$$Q = \left|\frac{1}{3-\dot{A}_{up}}\right|$$

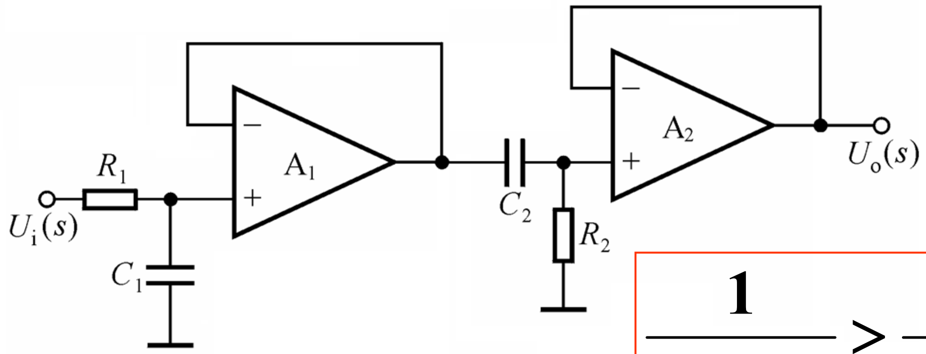


二阶MFB高通滤波电路

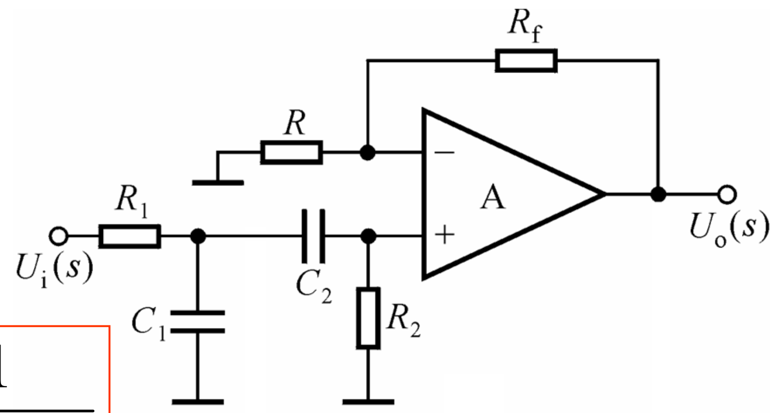
四、带通滤波电路(*Active Band-Pass Filter*)



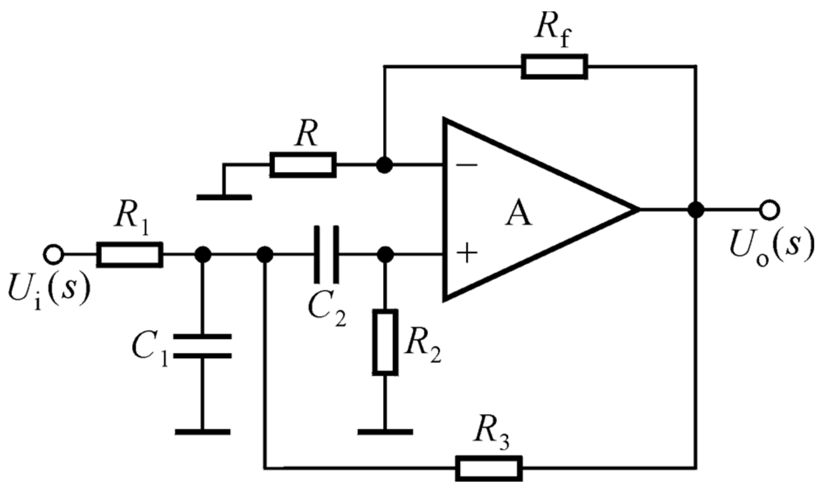
要求$f_{pL}>f_{pH}$



$$\frac{1}{2\pi R_1C_1}>\frac{1}{2\pi R_2C_2}$$



简单带通滤波电路



压控电压源二阶带通滤波电路

设$C_1=C_2=C$，$R_1=R_3=R$，$R_2=2R$

$$\dot{A}_{uf}=\frac{\dot{U}_o}{\dot{U}_+}=1+\frac{R_f}{R}$$

$$\boxed{f_0=\frac{1}{2\pi RC}}$$

$$A_u(s)=A_{uf}\cdot\frac{\dfrac{s}{\omega_0}}{1+(3-A_{uf})\dfrac{s}{\omega_0}+(\dfrac{s}{\omega_0})^2}$$

$$\dot{A}_u=\dot{A}_{uf}\cdot\frac{\mathrm{j}\dfrac{f}{f_0}}{1+\mathrm{j}(3-\dot{A}_{uf})\dfrac{f}{f_0}-(\dfrac{f}{f_0})^2}$$

$$\dot{A}_{up}=|\dot{A}_u|_{f=f_0}$$

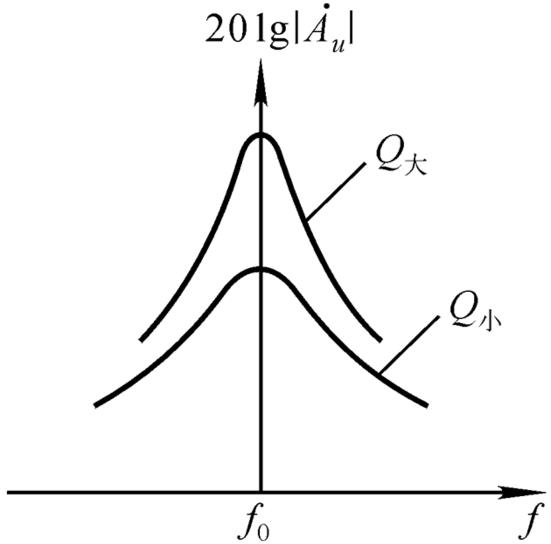
$$=\left|\frac{\dot{A}_{uf}}{3-\dot{A}_{uf}}\right|=|Q\dot{A}_{uf}|$$

$$\boxed{Q=\left|\frac{1}{3-\dot{A}_{uf}}\right|}$$

$$\dot{A}_u = \dot{A}_{uf} \cdot \frac{\mathrm{j}\dfrac{f}{f_0}}{1 + \mathrm{j}(3 - \dot{A}_{uf})\dfrac{f}{f_0} - \left(\dfrac{f}{f_0}\right)^2} = \dot{A}_{uf} \frac{1}{\left(\dfrac{f_0}{f} - \dfrac{f}{f_0}\right) + \mathrm{j}\dfrac{1}{Q}}$$

令 $|\dot{A}_u| = \dfrac{\dot{A}_{up}}{\sqrt{2}}$ 求得f_{p1}和f_{p2}

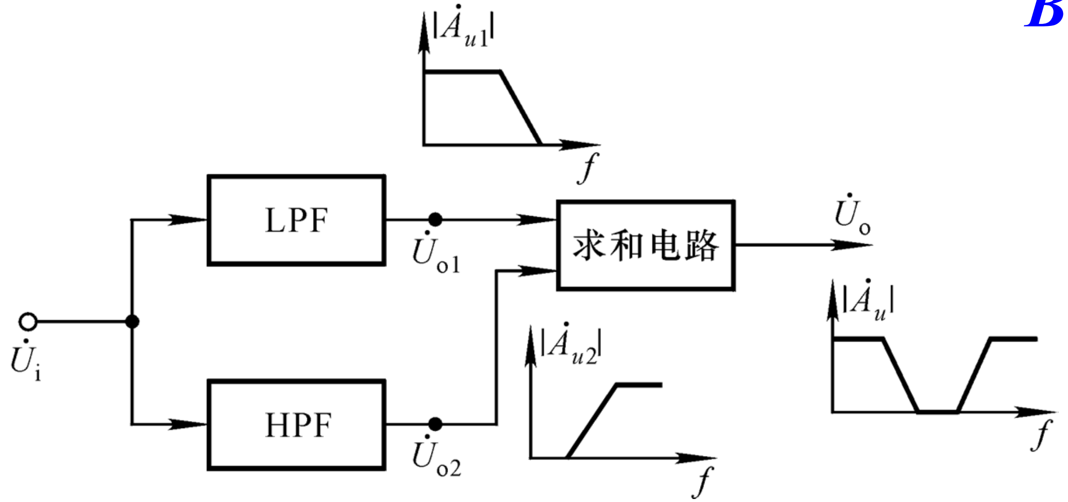
带宽 $\boxed{f_{bw} = f_{p1} - f_{p2} = \dfrac{f_0}{Q}}$



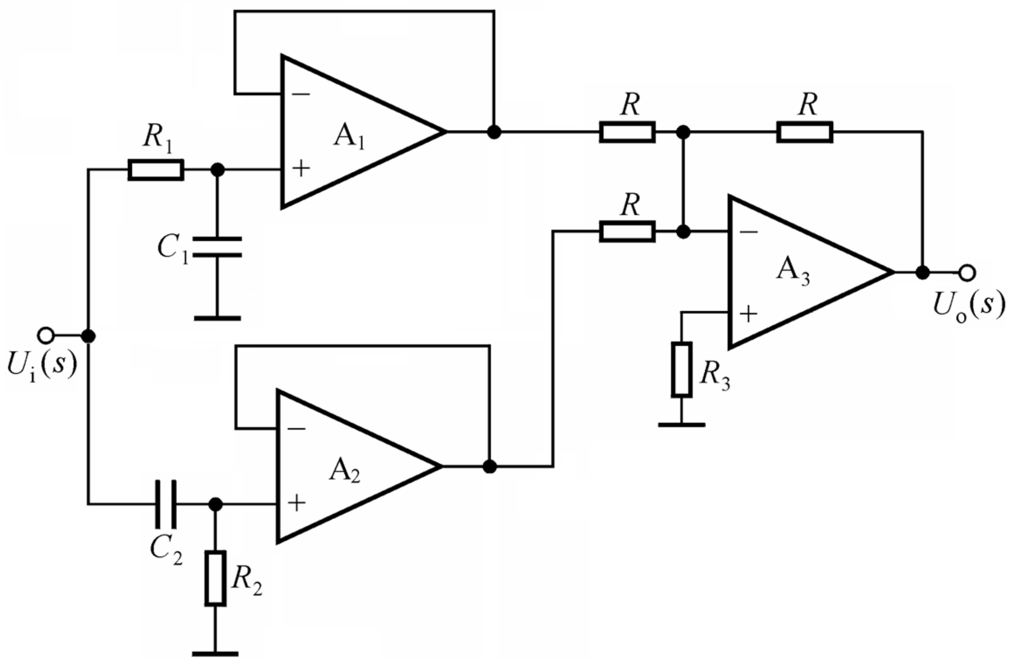
Q 反映了带通滤波器对频率的选择特性。

Q越大，f_{bw}越窄，对单一频率的选择性越好，且$|A_{up}|$越大。

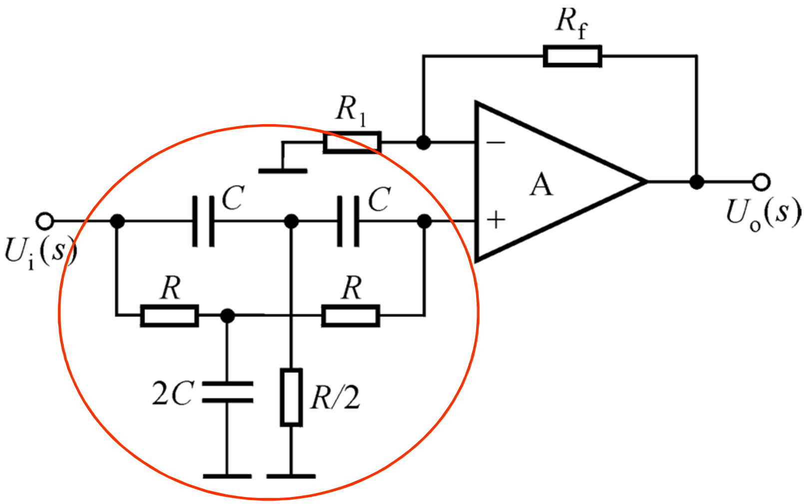
五、带阻滤波电路(*Band-Elimination Filter, Notch Filter, Band-Stop Filter*)



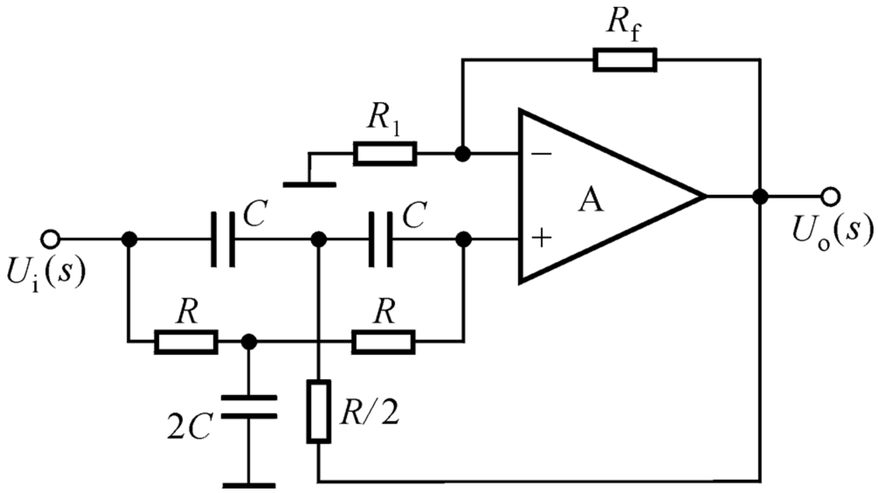
要求$f_{pL}<f_{pH}$



$$\frac{1}{2\pi R_1 C_1} < \frac{1}{2\pi R_2 C_2}$$



双T网络



常用带阻滤波器

$$\boxed{\dot{A}_{up}\big|_{f=0,\infty} = 1 + \frac{R_f}{R_1}}$$

$$f_0 = \frac{1}{2\pi RC}$$

$$A_u(s) = A_{up} \cdot \frac{1 + (\frac{s}{\omega_0})^2}{1 + 2(2 - A_{up})\frac{s}{\omega_0} + (\frac{s}{\omega_0})^2}$$

$$\dot{A}_u = \dot{A}_{up} \frac{1 - (\frac{f}{f_0})^2}{1 - (\frac{f}{f_0})^2 + \mathrm{j}2(2 - \dot{A}_{up})\frac{f}{f_0}}$$

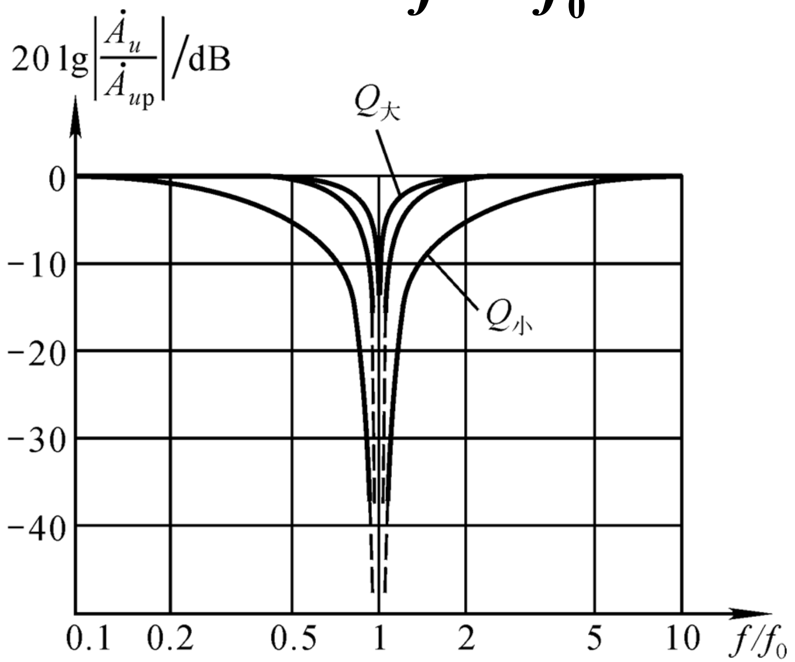
$$\dot{A}_u = \dot{A}_{up} \frac{1-(\frac{f}{f_0})^2}{1-(\frac{f}{f_0})^2 + \mathrm{j}2(2-\dot{A}_{up})\frac{f}{f_0}} = \dot{A}_{up}\frac{1}{1+\mathrm{j}\frac{1}{Q}\cdot\frac{1}{\frac{f_0}{f}-\frac{f}{f_0}}}$$

$1/Q$

$$\dot{A}_u\,|_{f=f_0} = 0 \qquad Q = \left|\frac{1}{2(2-\dot{A}_{up})}\right|$$

令 $|\dot{A}_u| = \frac{\dot{A}_{up}}{\sqrt{2}}$ 求得 f_{p1} 和 f_{P2}

阻带宽度 $\boxed{BW = f_{p1} - f_{p2} = \frac{f_0}{Q}}$



***Q* 反映了带阻滤波器对频率的选择特性**

滤波电路总结

	A_{up}	$A_u(s)$	$\dot{A}_u$	f_0	f_p	Q
一阶 LPF	$1+\frac{R_f}{R_1}$	$\dot{A}_{up}\frac{1}{1+\frac{s}{\omega_0}}$	$\dot{A}_{up}\frac{1}{1+j\frac{f}{f_0}}$	$\frac{1}{2\pi RC}$	f_0	
简单二阶 LPF	$1+\frac{R_f}{R_1}$	$\dot{A}_{up}\frac{1}{1+3\frac{s}{\omega_0}+(\frac{s}{\omega_0})^2}$	$\dot{A}_{up}\frac{1}{1+j3\frac{f}{f_0}-(\frac{f}{f_0})^2}$	$\frac{1}{2\pi RC}$	$0.37f_0$	$\frac{1}{3}$
VCVS 二阶 LPF	$1+\frac{R_f}{R_1}$	$\frac{\dot{A}_{up}}{1+(3-\dot{A}_{up})\frac{s}{\omega_0}+(\frac{s}{\omega_0})^2}$	$\frac{\dot{A}_{up}}{1+j(3-\dot{A}_{up})\frac{f}{f_0}-(\frac{f}{f_0})^2}$	$\frac{1}{2\pi RC}$	f_0	$\frac{1}{3-\dot{A}_{up}}$

	$A_{up(f)}$	$A_u(s)$	A_u	f_0	$f_{p(bw)}$	Q
一阶 HPF	$1+\frac{R_f}{R_1}$	$\dot{A}_{up}\frac{\frac{s}{\omega_0}}{1+\frac{s}{\omega_0}}$	$\dot{A}_{up}\cdot\frac{j\frac{f}{f_0}}{1+j\frac{f}{f_0}}$	$\frac{1}{2\pi RC}$	f_0	
VCVS 二阶 HPF	$1+\frac{R_f}{R_1}$	$\frac{\dot{A}_{up}\cdot(\frac{s}{\omega_0})^2}{1+(3-\dot{A}_{up})\frac{s}{\omega_0}+(\frac{s}{\omega_0})^2}$	$\frac{\dot{A}_{up}\cdot-(\frac{f}{f_0})^2}{1+j(3-\dot{A}_{up})\frac{f}{f_0}-(\frac{f}{f_0})^2}$	$\frac{1}{2\pi RC}$	f_0	$\frac{1}{3-\dot{A}_{up}}$
VCVS 二阶 BPF	$1+\frac{R_f}{R_1}$	$\frac{\dot{A}_{uf}\cdot\frac{s}{\omega_0}}{1+(3-\dot{A}_{uf})\frac{s}{\omega_0}+(\frac{s}{\omega_0})^2}$	$\frac{\dot{A}_{uf}\cdot j\frac{f}{f_0}}{1+j(3-\dot{A}_{uf})\frac{f}{f_0}-(\frac{f}{f_0})^2}$	$\frac{1}{2\pi RC}$	$f_{bw}=\frac{f_0}{Q}$	$\frac{1}{3-\dot{A}_{uf}}$
VCVS 二阶 BEF	$1+\frac{R_f}{R_1}$	$A_{up}\cdot\frac{1+(\frac{s}{\omega_0})^2}{1+2(2-A_{up})\frac{s}{\omega_0}+(\frac{s}{\omega_0})^2}$	$\dot{A}_{up}\frac{1-(\frac{f}{f_0})^2}{1-(\frac{f}{f_0})^2+j2(2-\dot{A}_{up})\frac{f}{f_0}}$	$\frac{1}{2\pi RC}$	$BW=\frac{f_0}{Q}$	$\frac{1}{2-2\dot{A}_{up}}$

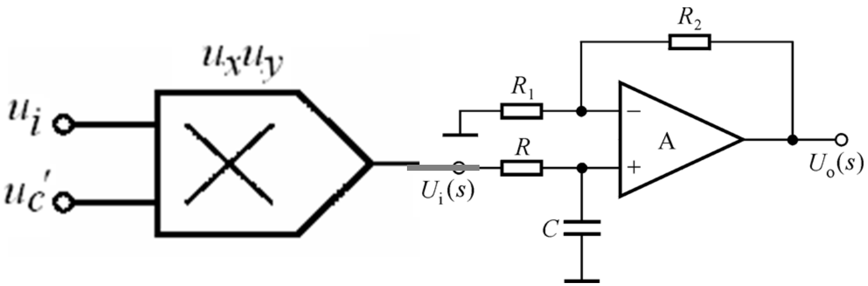
思考题

- 频率趋于零，电压放大倍数趋于通带放大倍数的滤波器有哪几种？
- 频率趋于无穷大，电压放大倍数趋于通带放大倍数的滤波器有哪几种？
- 频率趋于零，电压放大倍数趋于零的滤波器有哪几种？
- 频率趋于无穷大，电压放大倍数趋于零的滤波器有哪几种？
- 哪些二阶滤波器的A_{up}等于A_{uf}，哪些不相等？
- 二阶滤波器带宽与Q值有何关系？
- 用Multisim波特图仪观察滤波器幅频和相频特性。

课外兴趣题5

5. 解调电路:

设输入信号u_i为课外兴趣题4调幅电路的输出信号，同步信号为$u_c{'}$=sin[(2π×1M)t]。求u_o



$$\boxed{\frac{1}{2\pi RC}=2\text{kHz}}$$

第七章要求

知识掌握要求

• 掌握集成运放线性工作区的特点;

• 会用‘虚短’‘虚断’方法分析比例、求和、加减、积分、微分、基本对数和指数、用模拟乘法器组成的除法和开方等各种运算电路的输出电压与输入电压的关系;

• 掌握比例、求和、加减运算电路的特点，掌握其性能指标的分析方法：R_i, R_o, 共模输入电压U_{IC}

•正确理解通带电压放大倍数A_{up}、通带截止频率f_p的含义; 正确理解一阶LPF、HPF和二阶LPF、HPF、BPF的电路组成及工作原理，能够根据需要合理选择电路。

第七章基本电路、基本分析方法总结

电路总结（请自己将电路特点列表对比细化）：

比例、求和、加减、积分、微分、基本对数和指数、用模拟乘法器组成的除法和开方等各种运算电路，一阶LPF、HPF，二阶压控电压源LPF、HPF，简单二阶BPF、BEF电路。

方法总结:

- 虚短、虚断+节点电流法：该方法主要用于分析运放同相端、反相端以及其它中间节点电流；
- 虚短、虚断+叠加原理：该方法主要用于分析有多个输入的线性运算电路如比例、求和、加减、积分、微分电路（乘法、除法、平方、立方、平方根电路不能用）；
- 传递函数分析法：如利用$Zc=1/sC$来分析积分、微分电路输出电压的表达式，再利用拉普拉斯反变换求解输出电压的时域表达式。

第七章常见题型

（1）判断电路是否为运算电路和属于哪种基本运算电路。

（2）运算电路的分析计算。

（3）根据需求选择运算电路。

（4）有源滤波器的识别及电路分析。

（5）工作在线性区的集成运放的其它应用电路的分析。