Stability: Capacitance on Inverting Input

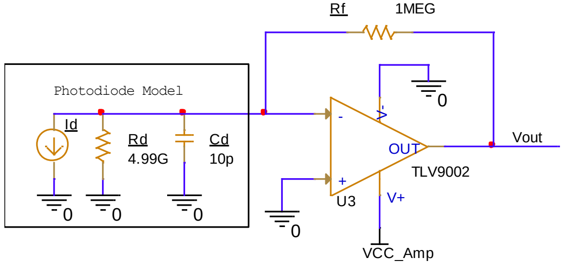
TI Precision Labs – Op Amps

Prepared by Art Kay

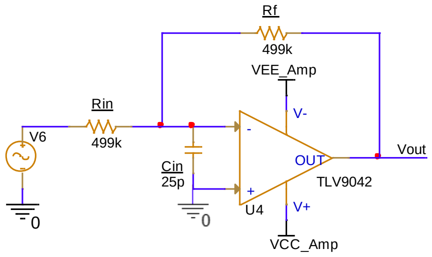
Presented by Brittany Hertneky

Amplifiers with capacitance on inverting input

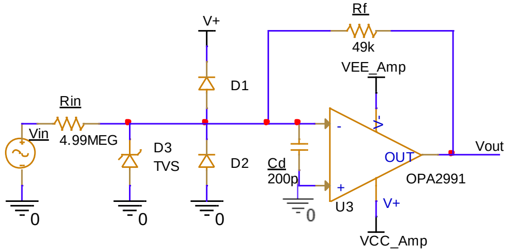
Transimpedance amplifiers



Large value resistors for low-power circuits



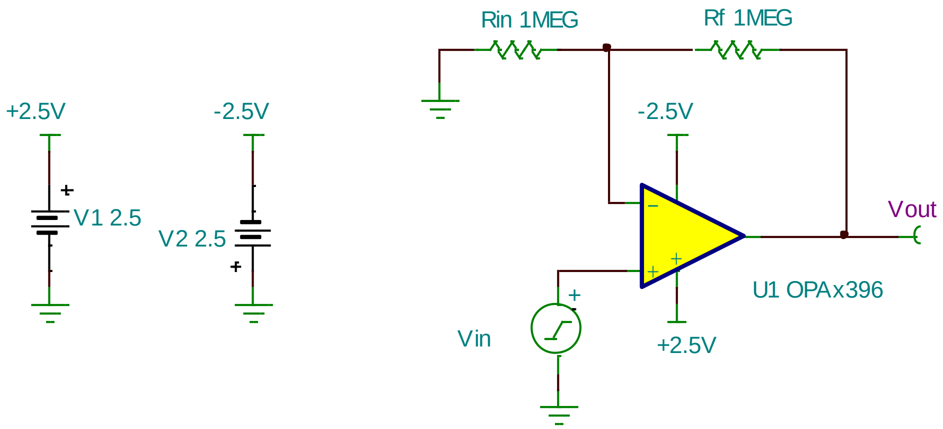
Transient suppression

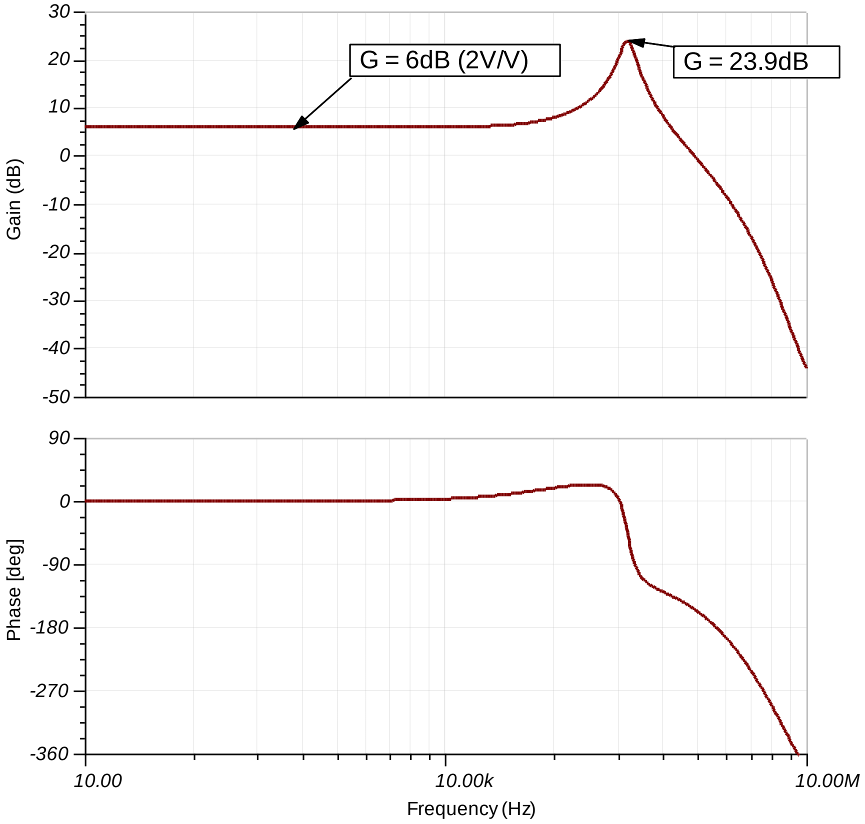


- Capacitance on inverting input interacts with feedback to cause stability problems
- Let’s discuss how to solve this issue

TEXAS INSTRUMENTS

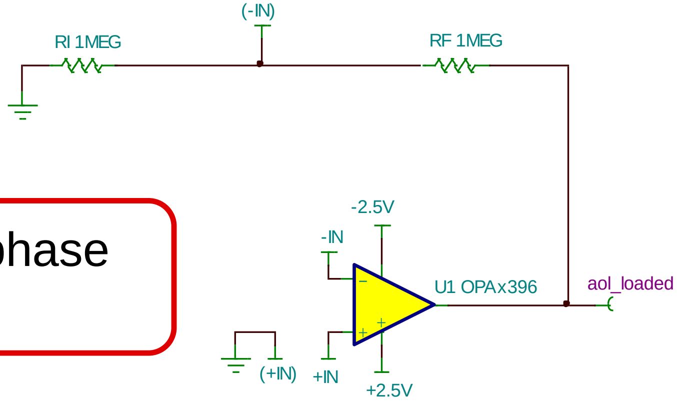
Amplifier with large feedback resistors

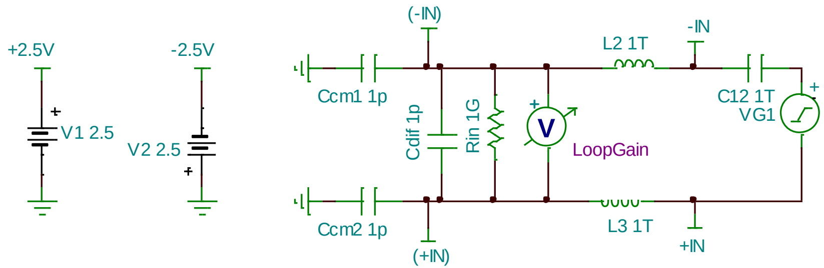


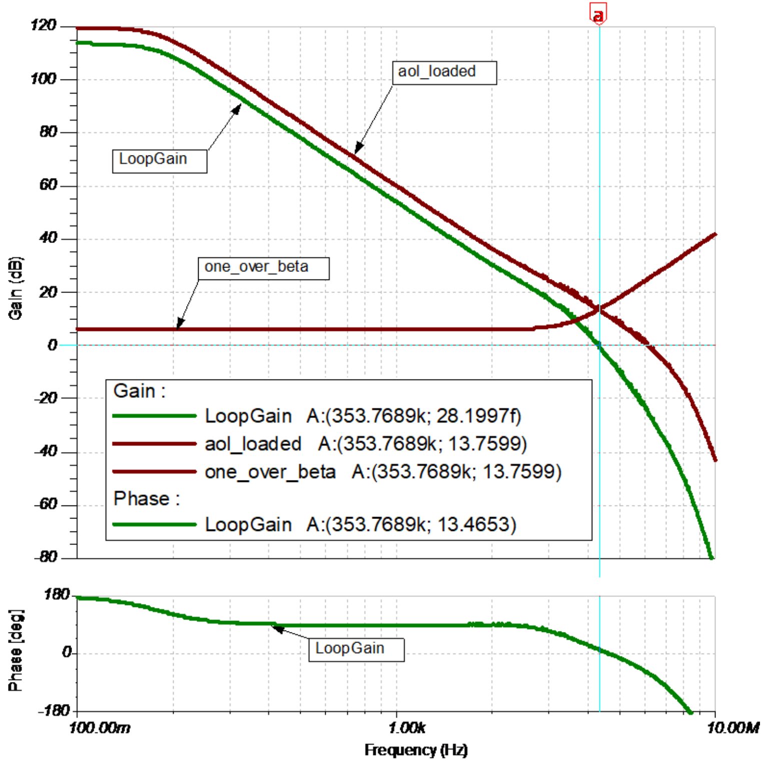


Open loop stability test

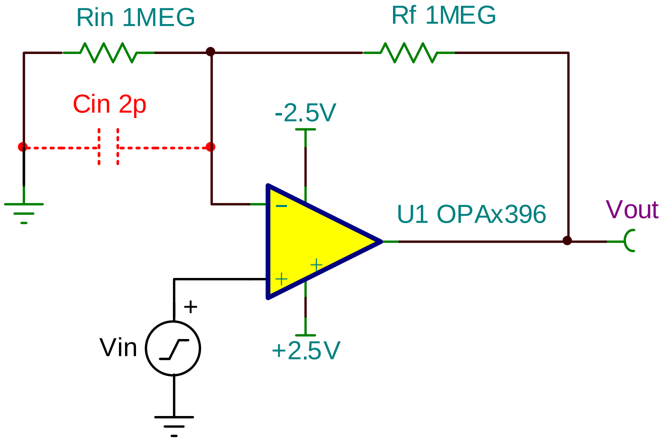
- 14º of phase margin

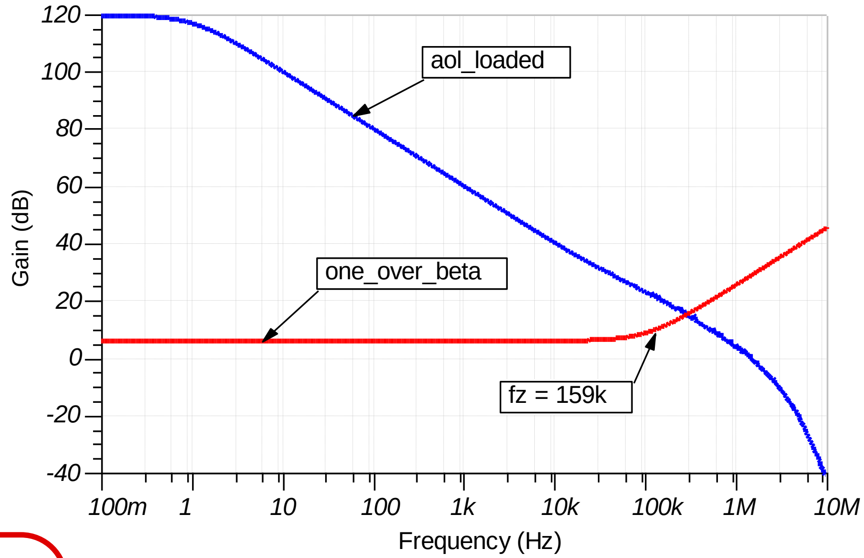






Why 1/β increases at high frequency



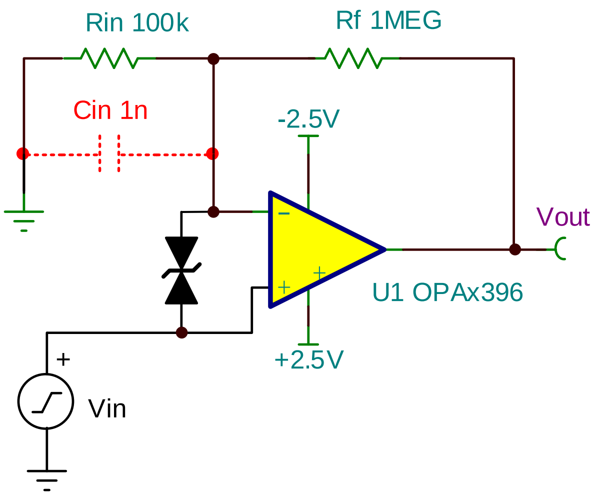


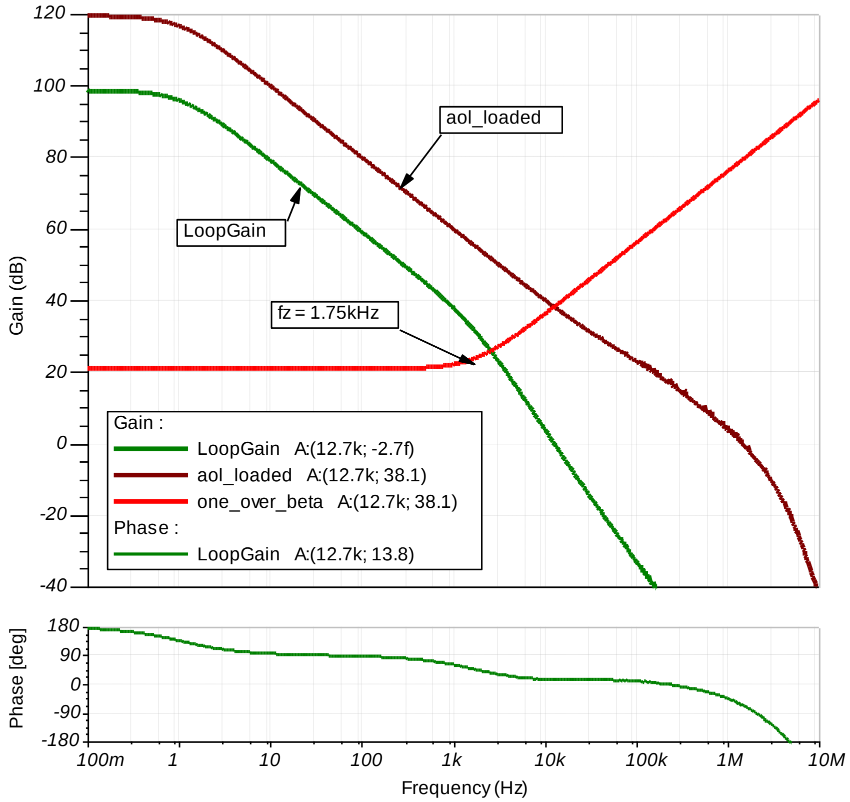
$$G = \frac{Z_f}{Z_{in}} + 1, \quad Z_{in} = R_{in}||X_{cin}, \quad X_{cin} = \frac{1}{2\pi f C_{in}}$$

$$f_z = \frac{R_{in} + R_f}{2\pi C_{in} R_{in} R_f} = \frac{1M\Omega + 1M\Omega}{2\pi(2pF)(1M\Omega)(1M\Omega)} = 159kHz$$

$$\uparrow G = \frac{Z_f}{Z_{in}\downarrow} + 1, \text{at high f}$$

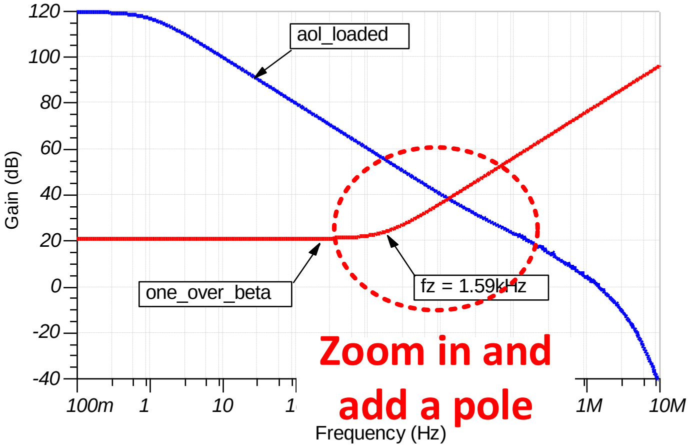
Some components add significant capacitance





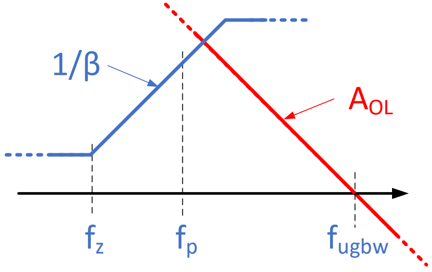
Sometimes external components included in the design add substantial capacitance. The TVS in this example adds 1nF of capacitance across Rin.

Add a pole to cancel the zero

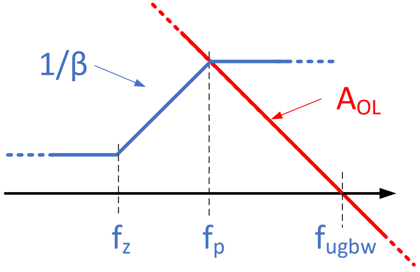


- The position of the pole will determine stability.
- The pole frequency must be lower than the intersection of 1/β and A_{OL}

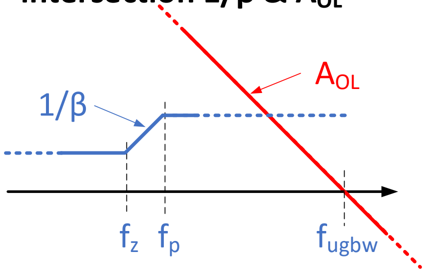
1. Unstable!
Pole near after 1/β intersects A_{OL}



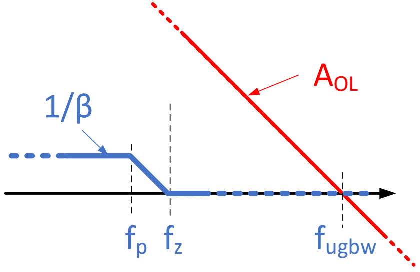
2. Stable (minimal)
Pole at intersection 1/β & A_{OL}



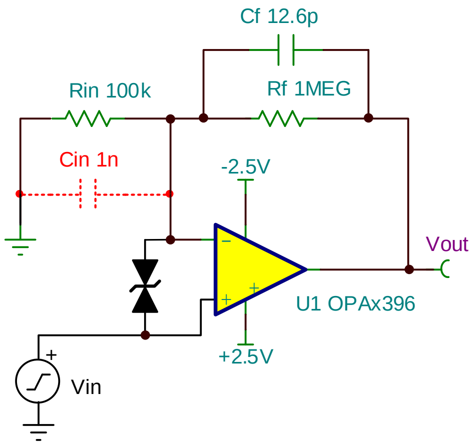
3. Stable
Pole before intersection 1/β & A_{OL}



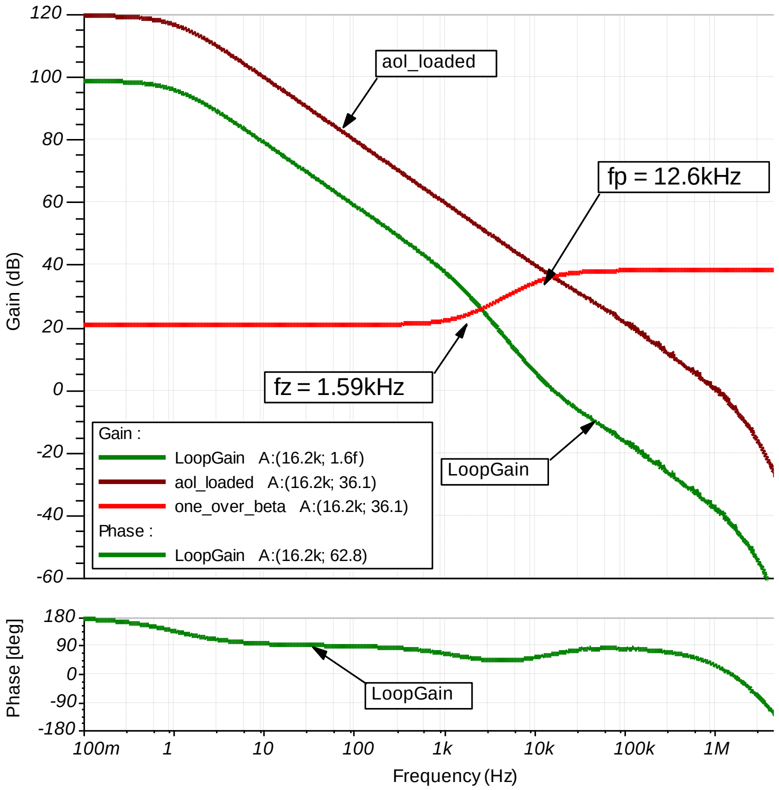
4. Stable
Pole before zero



Minimum capacitance to stabilize amp



$$G = \frac{Z_f}{Z_{in}} + 1$$

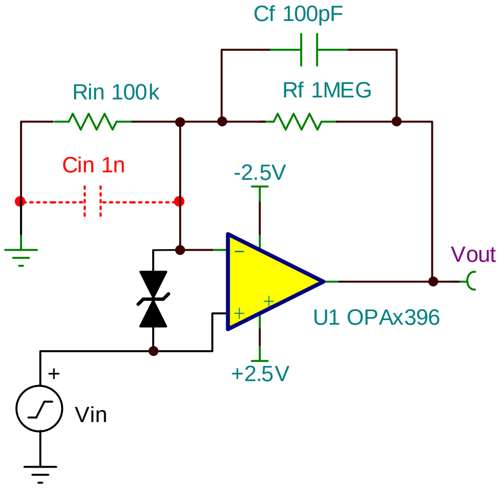


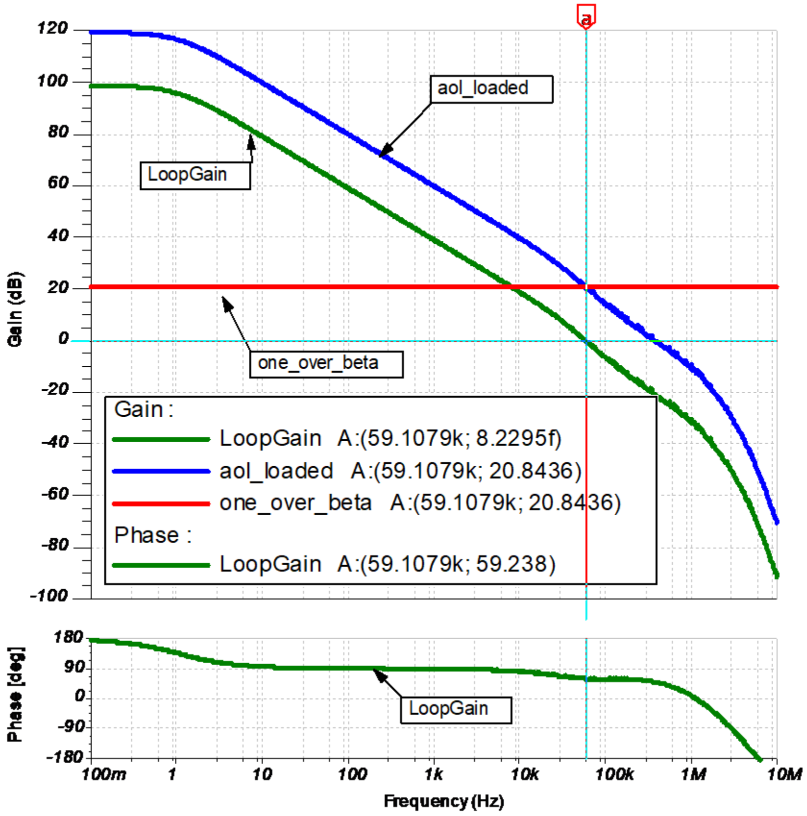
Minimum feedback capacitor:

$$C_{f(min)} = \sqrt{\frac{C_{in}}{2\pi R_f f_{ugbw}}} = \sqrt{\frac{1nF}{2\pi(1M\Omega)(1MHz)}} = 12.6pF$$

$$f_p = \frac{1}{2\pi C_f R_f} = \frac{1}{2\pi(12.6pF)(1MHz)} = 12.6kHz$$

Solving stability issues from input capacitance



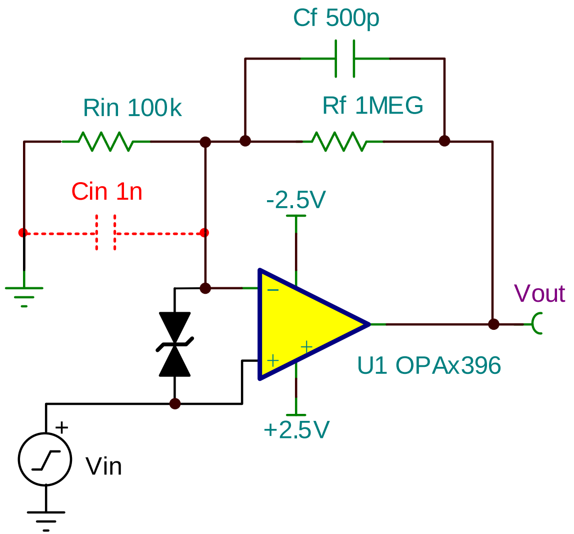


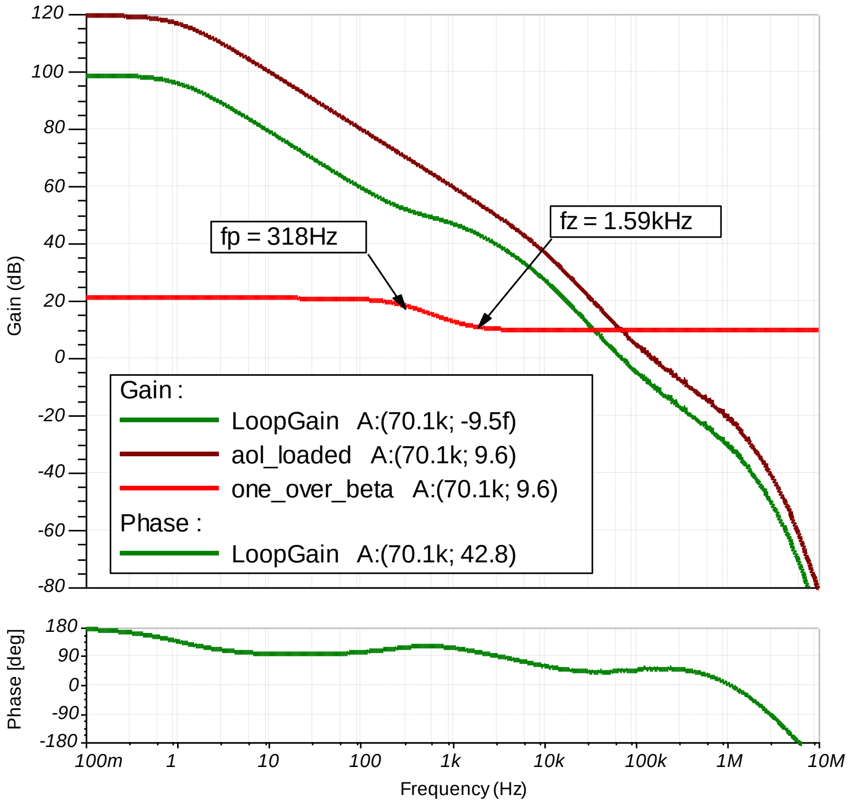
Adding a capacitance in the feedback cancels the zero caused by C_{in}.

Choose: $R_f \times C_f = R_{in} \times C_{in}$

$$C_f = \frac{R_{in}C_{in}}{R_f} = \frac{(100k\Omega)(1nF)}{(1M\Omega)} = 100pF$$

Maximum feedback capacitance





$C_{f(min)}$ = 13.2pF, $C_{f(fp = fz)}$ = 100pF
Choosing $C_f > C_{f(fp = fz)}$ reduces bandwidth and noise

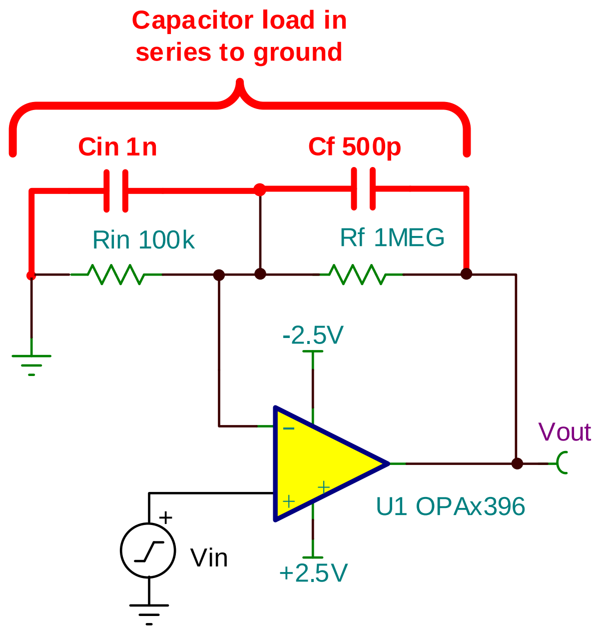
$$f_p(500pF) = \frac{1}{2\pi R_f C_f} = 318Hz$$

Feedback capacitor as an output load

Remember: $C_{total} = \frac{1}{\frac{1}{C_1}+\frac{1}{C_2}+\cdots+\frac{1}{C_N}}$

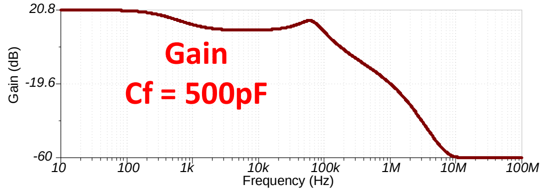
$$C_{total} = \frac{1}{\frac{1}{1nF}+\frac{1}{500pF}} = 333pF$$

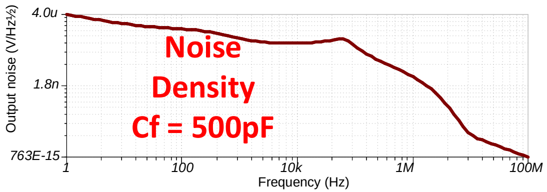
- Capacitors in series add like parallel resistors
- Total capacitance is less than the smallest capacitor
- For small C_{in}, C_f can be very large and C_{total} is still small.

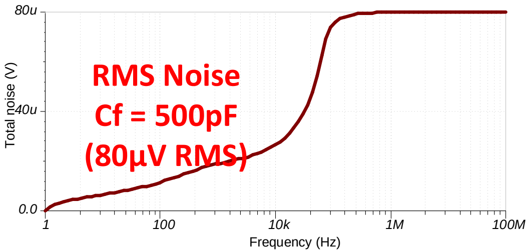


AC and noise response for minimum capacitance

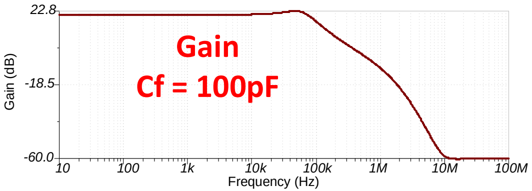
fp < fz

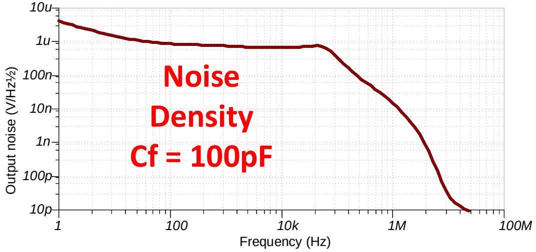


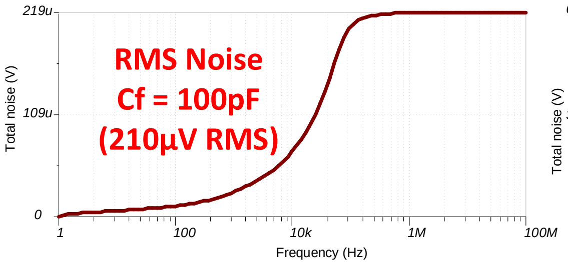




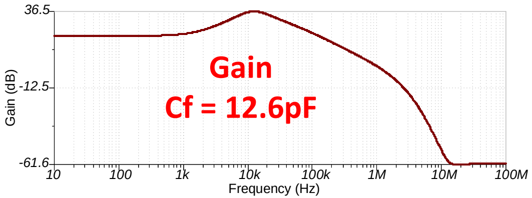
Rf x Cf = Rin x Cin

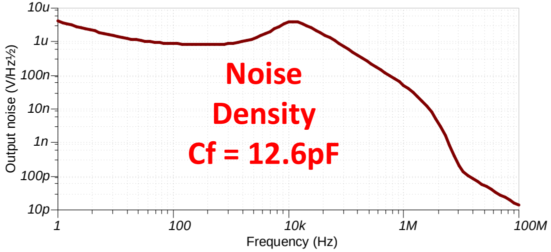


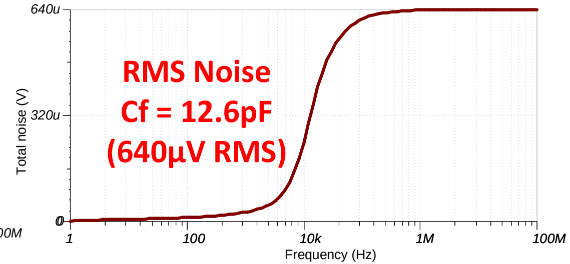




Minimum Cf

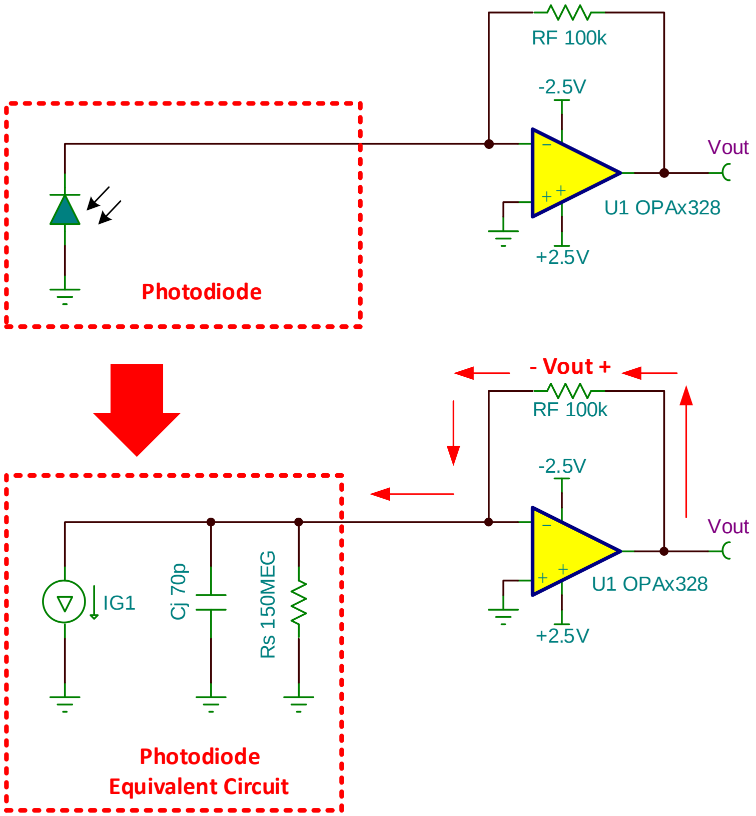




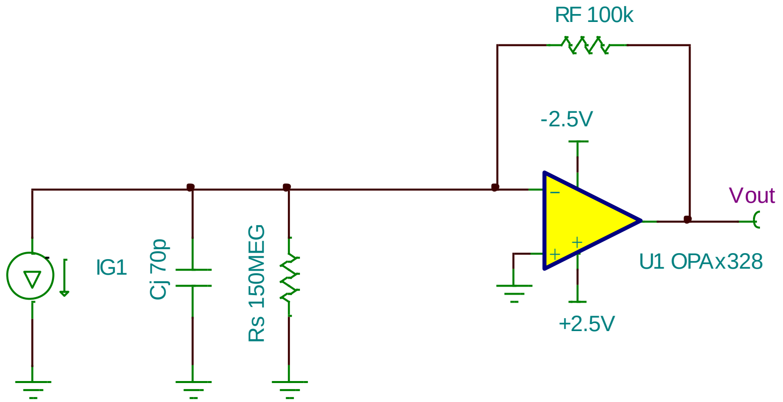


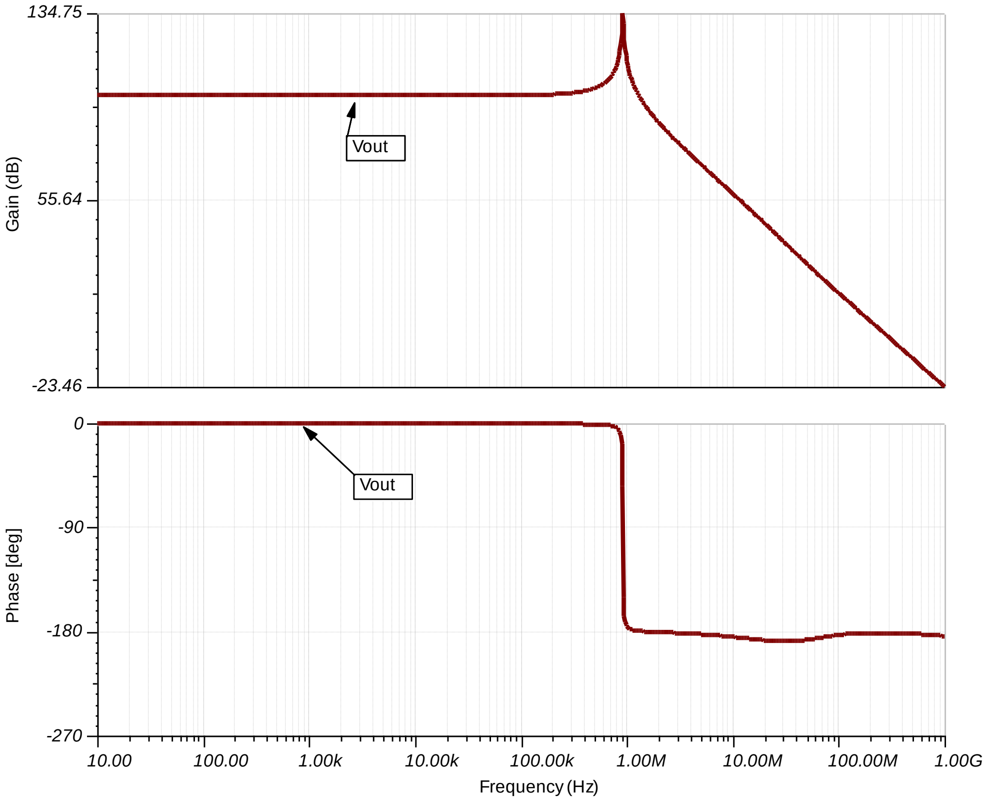
Another example: Transimpedance amp

- A transimpedance amplifier converts an input current to an output voltage
- Commonly used to convert photodiode current to voltage
- Photodiodes have significant capacitance that can cause instability in this application.
- The parasitic resistance of the photodiode is quite high



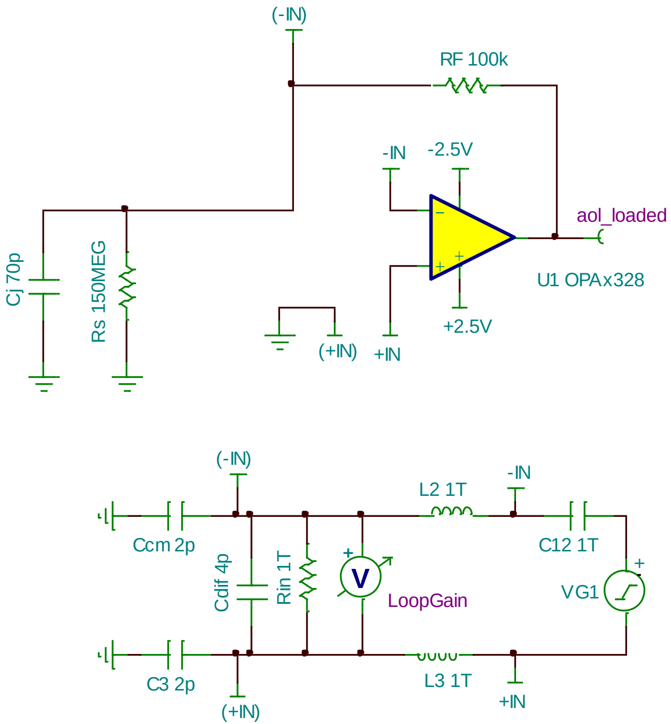
AC response of transimpedance example

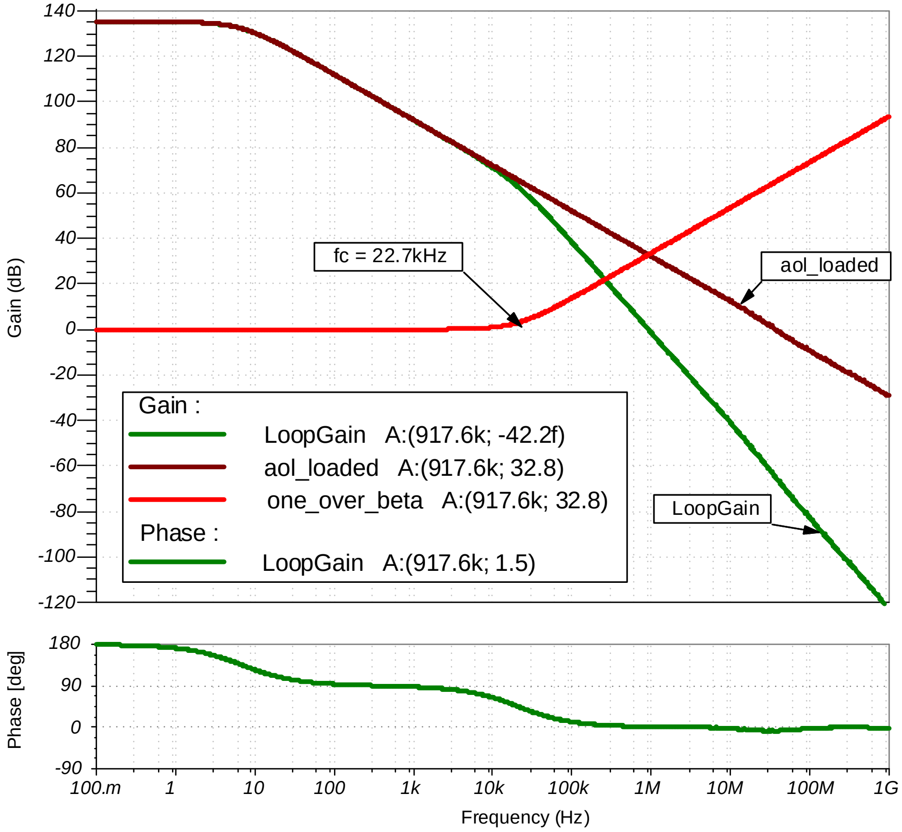




TEXAS INSTRUMENTS

Open loop stability test for transimpedance amp





Stabilizing transimpedance with minimum C_f

Feedback capacitor for amplifier

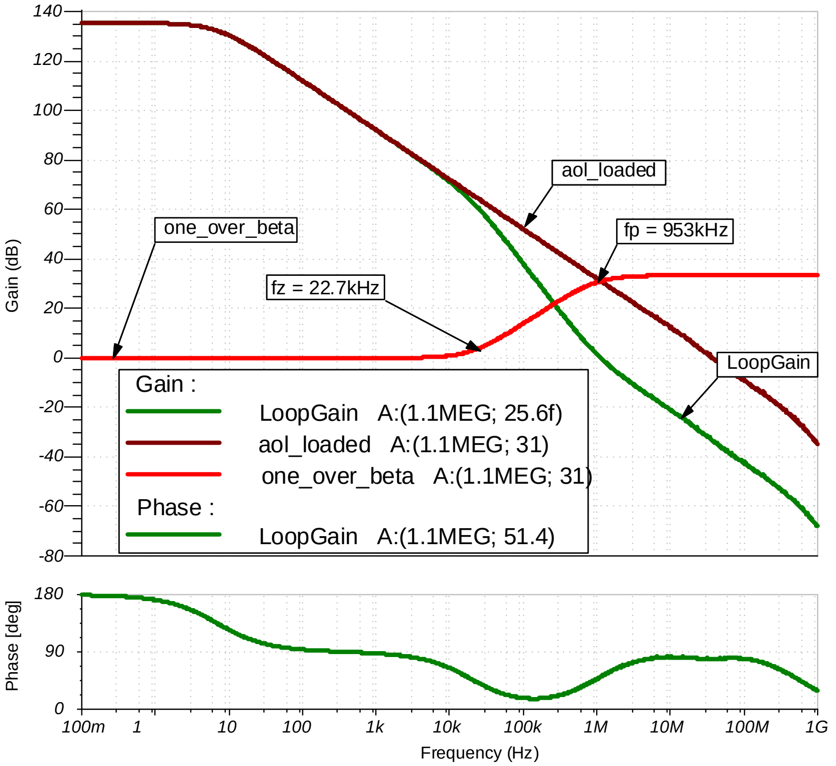
$$C_{f(min)} = \sqrt{\frac{C_{in}}{2\pi R_f f_{ugbw}}} = \sqrt{\frac{70pF}{2\pi(100k)(40MHz)}} = 1.67pF$$

Poles and zeros

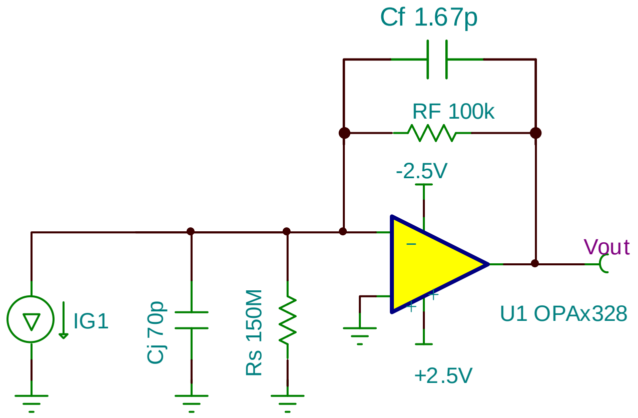
$$f_z = \frac{R_s + R_f}{2\pi C_{in} R_s R_f} = \frac{150M\Omega + 100k\Omega}{2\pi(70pF)(150M\Omega)(100k\Omega)} = 22.7kHz$$

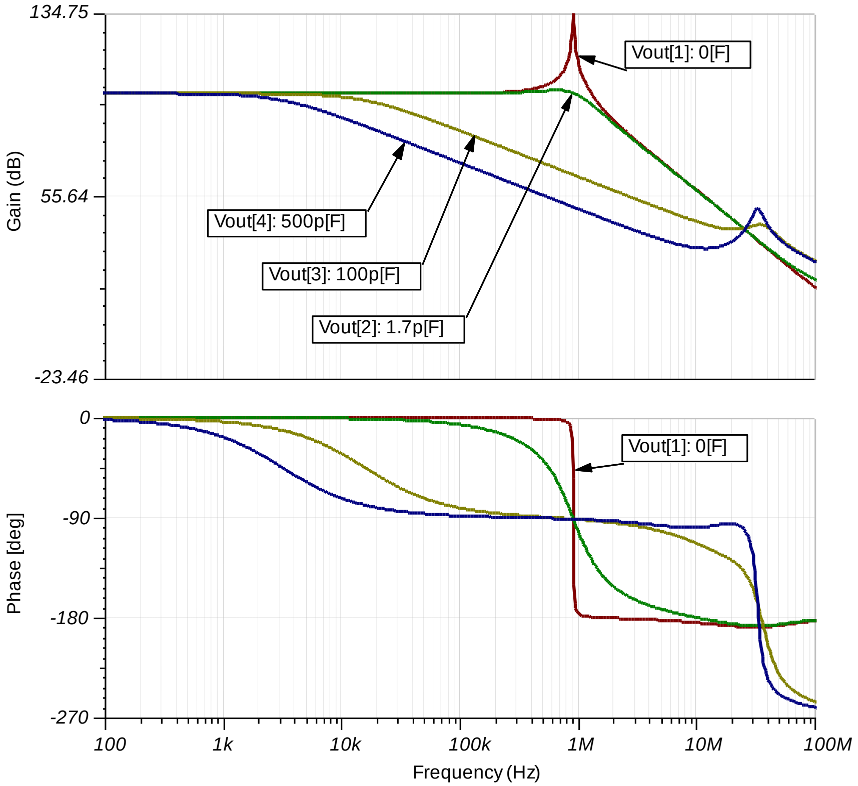
For $R_s \gg R_f, f_z \approx \frac{1}{2\pi C_{in} R_f} = 22.7pF$

$$f_p = \frac{1}{2\pi C_f R_f} = \frac{1}{2\pi(1.67pF)(100k\Omega)} = 953kHz$$



Transimpedance AC response





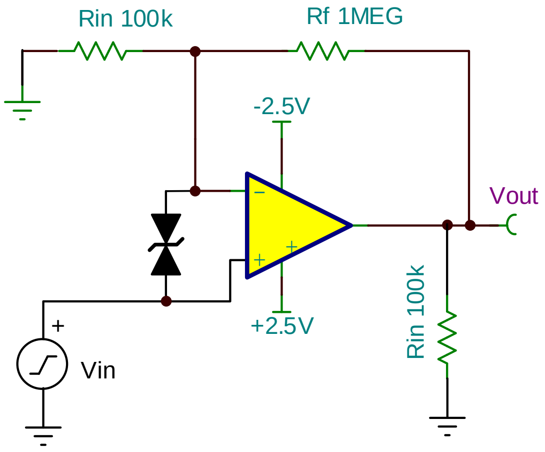
Closed loop transimpedance bandwidth relates to feedback capacitator

$$f_{BW} = \frac{1}{2\pi R_f C_F}$$

Thanks for your time!
Please try the quiz.

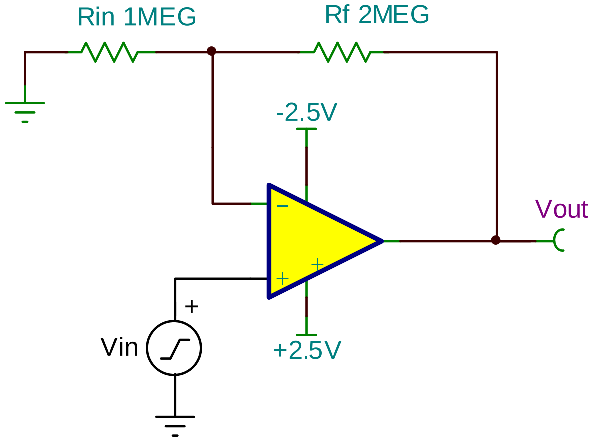
Questions: Capacitance on inverting input

1. What is the most likely reason the circuit below is unstable?
   a. Capacitance at the output adds a pole in A_{OL}
   b. Capacitance on the inverting input adds a zero in 1/β
   c. Capacitance on the inverting output adds a pole in 1/β
   d. Capacitance on the inverting adds a zero in loop gain



Questions: Capacitance on inverting input

2. For the transimpedance circuit below, how can stability be improved?
   a. Reduce resistance of Rf and Rin proportionately while keeping gain constant
   b. Choose a photodiode with a lower junction capacitor
   c. Add a feedback capacitor
   d. Improve the PCB layout so that the parasitic capacitance on the inverting input is minimized
   e. All of the above



Thanks for your time!

Derivations: Pole and zero for noninverting amp

"Feedback impedances"

$$Z_{in}=\frac{\frac{1}{s\cdot C_{in}}\cdot R_{in}}{R_{in}+\frac{1}{s\cdot C_{in}}}\qquad Z_f=\frac{\frac{1}{s\cdot C_f}\cdot R_f}{R_{out}+\frac{1}{s\cdot C_f}}$$

"Geneal Gain equation"

$$G=\frac{Z_f}{Z_{in}}+1$$

"Substitute impedances into gain"

$$G=\frac{\frac{\frac{1}{s\cdot C_f}\cdot R_f}{R_f+\frac{1}{s\cdot C_f}}}{\frac{\frac{1}{s\cdot C_{in}}\cdot R_{in}}{R_{in}+\frac{1}{s\cdot C_{in}}}}+1$$

"simplify for standard trransfer function"

$$\frac{\frac{\frac{1}{s\cdot C_f}\cdot R_f}{R_f+\frac{1}{s\cdot C_f}}}{\frac{\frac{1}{s\cdot C_{in}}\cdot R_{in}}{R_{in}+\frac{1}{s\cdot C_{in}}}}+1\xrightarrow{simplify}\frac{(C_{in}+C_f)\cdot R_f\cdot R_{in}\cdot s+R_{in}+R_f}{R_{in}\cdot(C_f\cdot R_f\cdot s+1)}$$

"find the pole"

$$R_{in}\cdot(C_f\cdot R_f\cdot s+1)=0\xrightarrow{solve,s}-\frac{1}{C_f\cdot R_f}$$

"pole frequency"

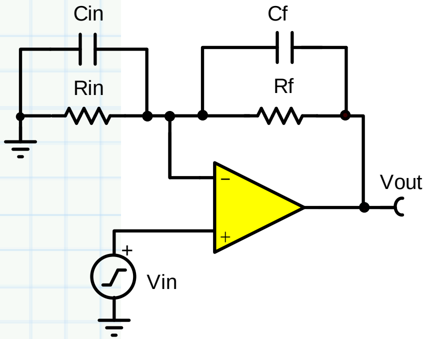
$$f_p=\frac{1}{2\cdot\pi\cdot C_f\cdot R_f}$$

"find the zero"

$$(C_{in}+C_f)\cdot R_f\cdot R_{in}\cdot s+R_{in}+R_f=0\xrightarrow{solve,s}\frac{-R_{in}-R_f}{(C_{in}+C_f)\cdot R_f\cdot R_{in}}$$

"zero frequency"

$$f_z=\frac{R_{in}+R_f}{2\cdot\pi\,(C_{in}+C_f)\cdot R_f\cdot R_{in}}$$



This shows the derivation of poles and zeros for a noninverting (and inverting) op amp.

Derivations: Pole and zero when Rin*Cin = Rf*Cf

General pole frequency

$$f_p = \frac{1}{2 \cdot \pi \cdot C_f \cdot R_f}$$

General zero frequency

$$f_z = \frac{R_{in} + R_f}{2 \cdot \pi \left(C_{in} + C_f\right) \cdot R_f \cdot R_{in}}$$

This shows the derivation for Cf that will set the pole and zero equal. This is a good general choice for stability.

substitute gain relationship for Rin*Cin = Rf*Cf
into general equation

$$G = \frac{R_f}{R_{in}} + 1 \qquad C_f = C_{in} \cdot \frac{R_{in}}{R_f}$$

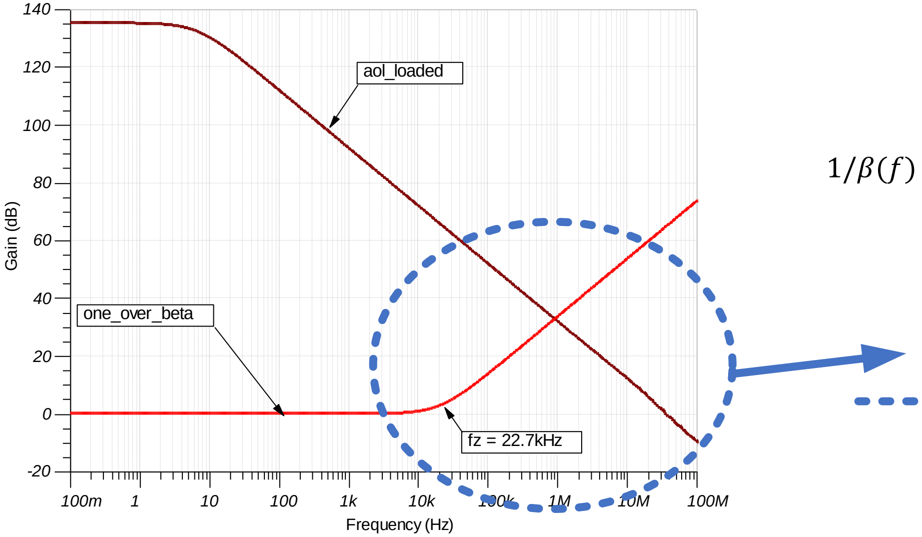
$$\frac{R_{in} + R_f}{\left(C_{in} + C_f\right) \cdot R_f \cdot R_{in}} \xrightarrow{substitute, G = \frac{R_f}{R_{in}} + 1, C_f = C_{in} \cdot \frac{R_{in}}{R_f}} \frac{1}{C_{in} \cdot R_{in}}$$

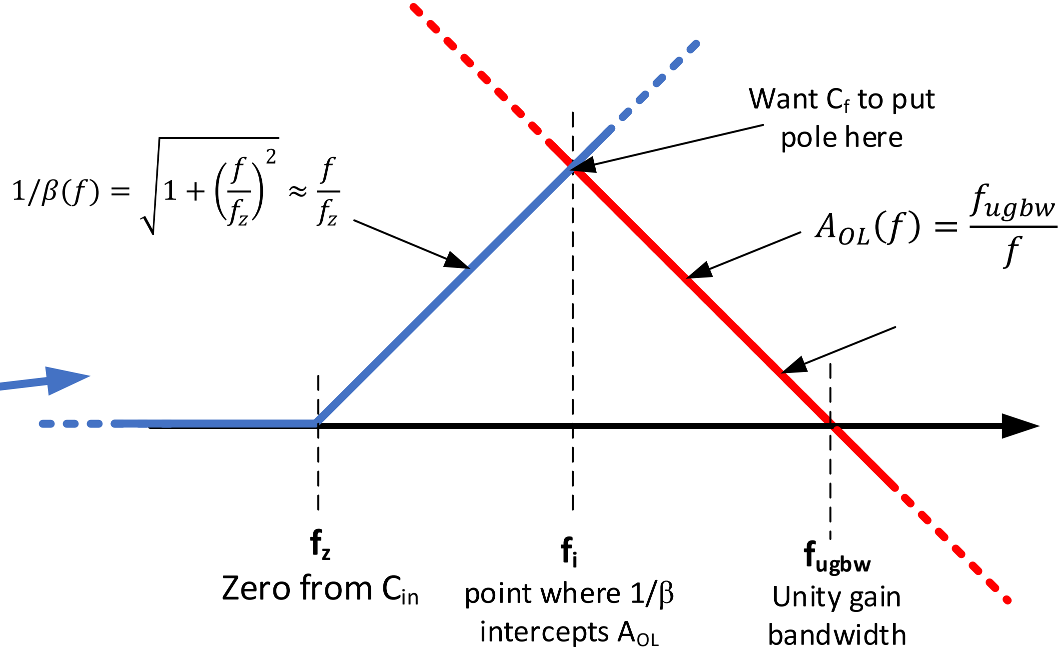
$$f_z = \frac{1}{2\ \pi \cdot C_{in} \cdot R_{in}} \qquad f_p = \frac{1}{2 \cdot \pi \cdot C_f \cdot R_f}$$

Note from above that when Rin*Cin = Rf*Cf, then fz = fp

Use $C_f = C_{in} \cdot \frac{R_{in}}{R_f}$ to find Cf for good stability

Derivations: Minimum Cf for stability: part 1





Equations on next slide relate to this figure

Derivations: Minimum Cf for stability: part 2

Closed loop gain or 1/β is the DC gain multiplied by the zero response

$$1/\beta\,(f) = G_{dc}\sqrt{1+\left(\frac{f}{f_z}\right)^2} \approx G_{dc}\left(\frac{f}{f_z}\right)$$

Open loop gain near the unity gain bandwidth:

$$A_{OL}(f) \approx \frac{f_{ugbw}}{f}$$

Find the point where Aol and 1/β intersect

$$G_{dc}\left(\frac{f}{f_z}\right) = \frac{f_{ugbw}}{f}$$

$$f_i = \sqrt{\frac{f_{ugbw} f_z}{G_{dc}}}$$

Substitute $f_z = \frac{R_{in}+R_f}{2\pi C_{in} R_f R_{in}}$ into f_i

$$f_i = \sqrt{\frac{f_{ugbw}(R_{in}+R_f)}{2\pi C_{in} R_f R_{in} G_{dc}}}$$

Set pole $f_p = \frac{1}{2\pi R_f C_f}$ to intercept of A_{OL} and 1/β

$$\frac{1}{2\pi R_f C_f} = \sqrt{\frac{f_{ugbw}(R_{in}+R_f)}{2\pi C_{in} R_f R_{in} G_{dc}}}$$

Substitute $G_{dc} = \frac{R_f}{R_{in}} + 1$ and solve for Cf

$$C_f = \sqrt{\frac{C_{in}}{2\pi f_{ugbw} R_f}}$$

General eq for inverting non-inverting, and transimpedance