

A simple charge sensitive preamplifier for experiments with a small number of detector channels

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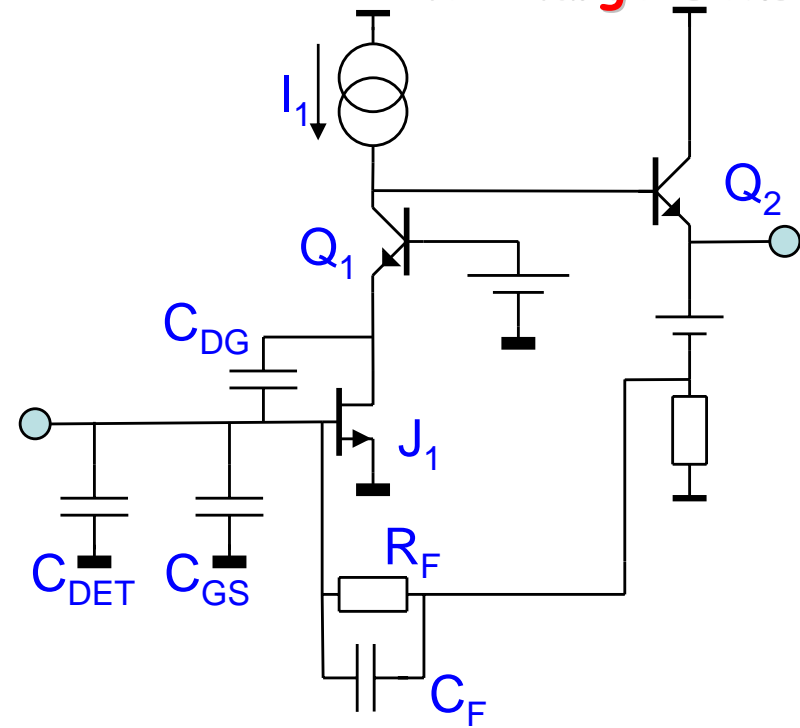
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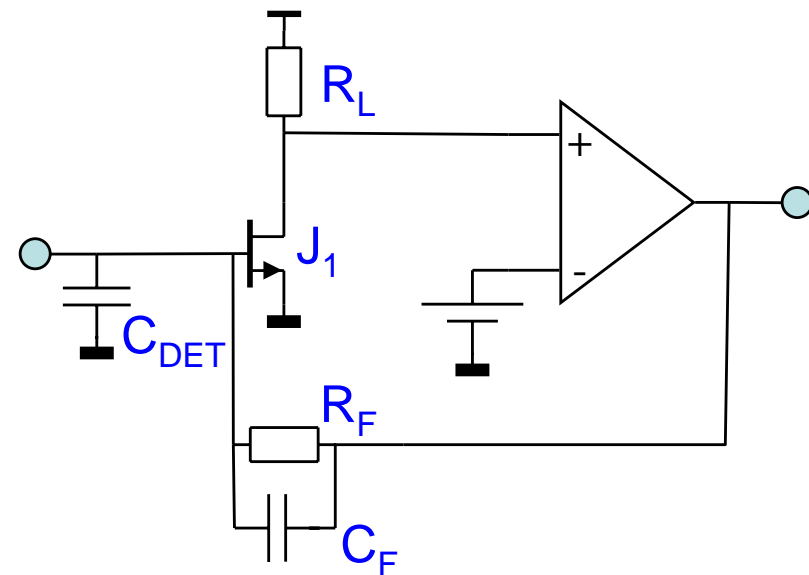
ABSTRACT

We present a Charge Sensitive Preamplifiers, CSP, based on a very simple design. It is indicated for applications where a small number of detector channels do not need a monolithic solution. The CSP consists of an input transistor and an Operational Amplifier in the second stage. The circuits do not make use of a cascode connection to load the input transistor, to minimize both the number of active devices needed and the supply voltage, with a consequence reduction of power dissipation. Thank to the circuit design, very simple mathematical rules are needed to optimized the dynamic performances and stability.

The Charge Sensitive Preamplifier, CSP: the classical design



A CSP based on the use of transistors only as active devices is often used in both discrete and monolithic implementations.

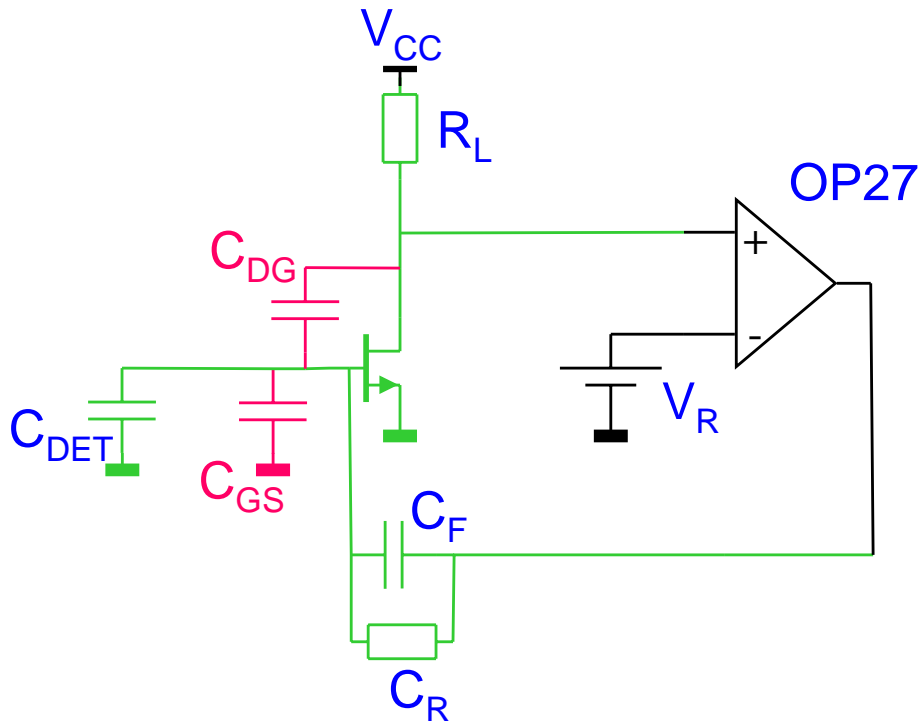


A CSP implemented with discrete devices is very simple if use is made of an Operational Amplifier, OA, as active device.

This way the input transistor J_1 is chosen for the optimization of the S/N, while the OA allows for obtaining a large open loop gain and drives the output load.

One of the very important items that concerns the design of these 2 and any other stuff is the frequency stability.

CSP with Operational Amplifier: classical



When using discrete devices the design is simplified if an OA is exploited. The remark for this adoption is the stability.

If we neglect for a while the output impedance of the OA the inverse of the return path, β , (green/pink path in the figure) around the OA itself is:

$$\frac{1}{\beta} \approx \frac{C_F + C_{DET} + C_{GS} + (1 + g_m R_L) C_{DG}}{C_F} \frac{1}{g_m R_L}$$

For large values of the product $g_m R_L$, that allows to maintain limited the input referred noise of the OA, we have:

$$\frac{1}{\beta} \xrightarrow{g_m R_L \gg 1} \frac{C_{DG}}{C_F}$$

Sometimes this value may be small, and the preamplifier may break into oscillation.

CSP dynamic performances of the classical configuration

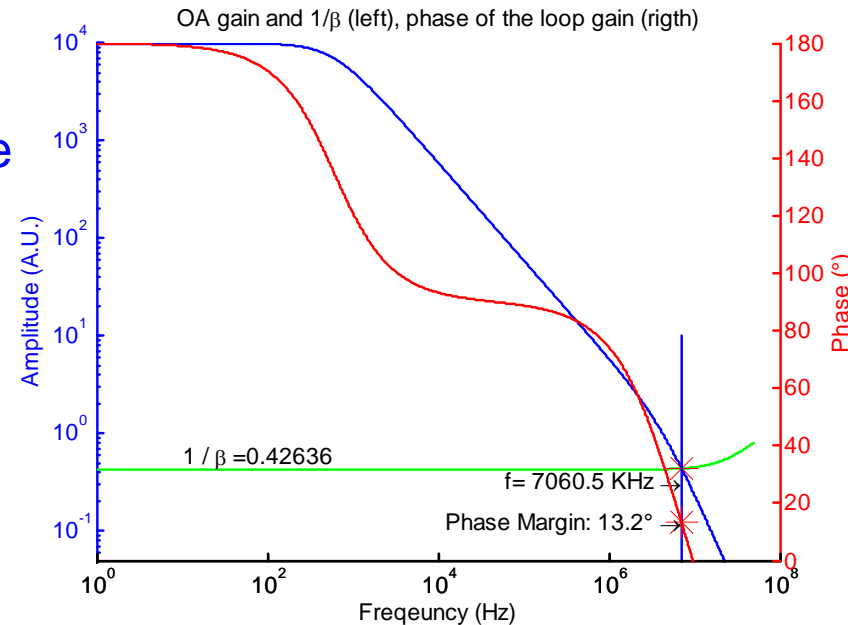
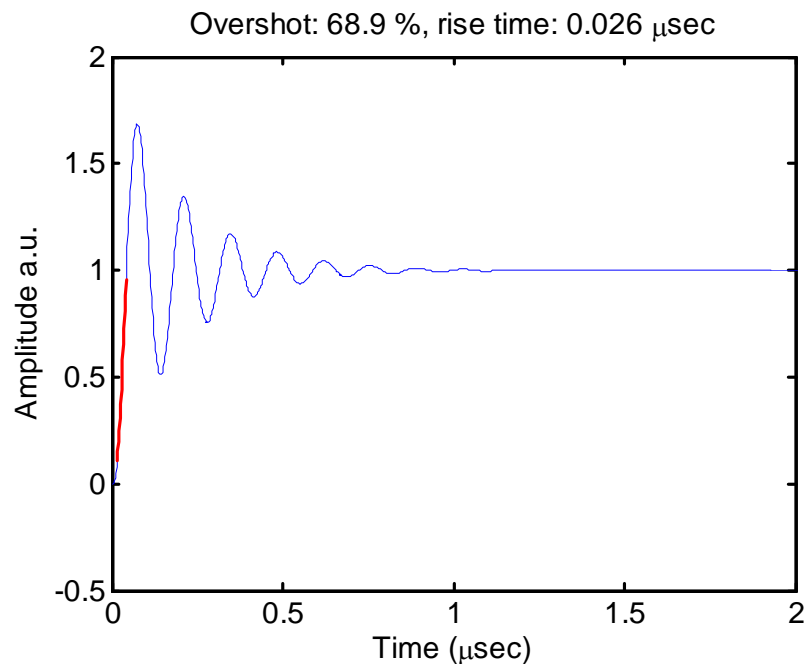
Let's consider a situation, maybe unreal, but interesting for what concern the study of the stability:



$$\begin{aligned}C_F &= 500 \text{ pF} \\ C_{DET} &= 30 \text{ pF} \\ R_L &= 1400 \Omega\end{aligned}$$

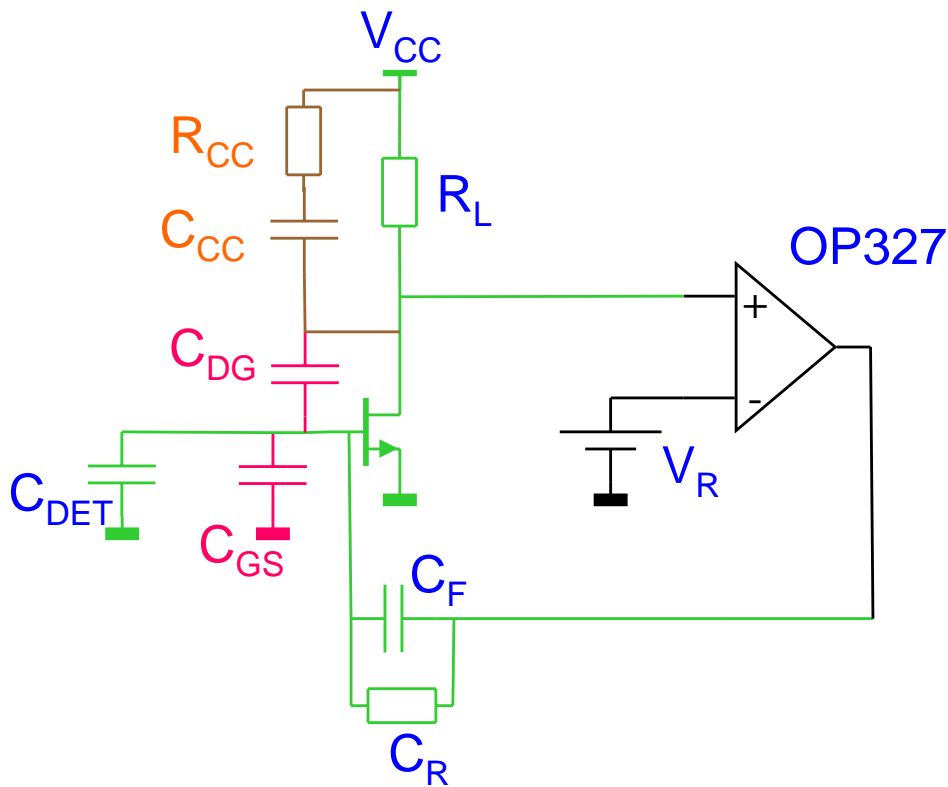
$$\begin{aligned}C_{GS} &= 350 \text{ pF} \\ C_{DG} &= 210 \text{ pF} \\ g_m &= 0.15 \text{ A/V}\end{aligned}$$

The comparison of the OA and $1/\beta$ and the phase of their product gives rise to a very small phase margin:



As a consequence, the response to an input impulse of the preamplifier has a very long settling time.

CSP compensation for the classical configuration



Adding C_{cc} and R_{cc} allows to obtain, at frequencies large enough, the gain lowered to about $g_m R_{cc}$, from $g_m R_L$.

At large frequencies:

$$\frac{1}{\beta} \approx \frac{C_F + C_{DET} + (1 + g_m R_{cc}) C_{GS}}{C_F} \frac{1}{g_m R_{cc}}$$

$g_m R_{cc}$ should be small, of the order of 1 or less, if we would like the closed loop gain to have enough phase margin.

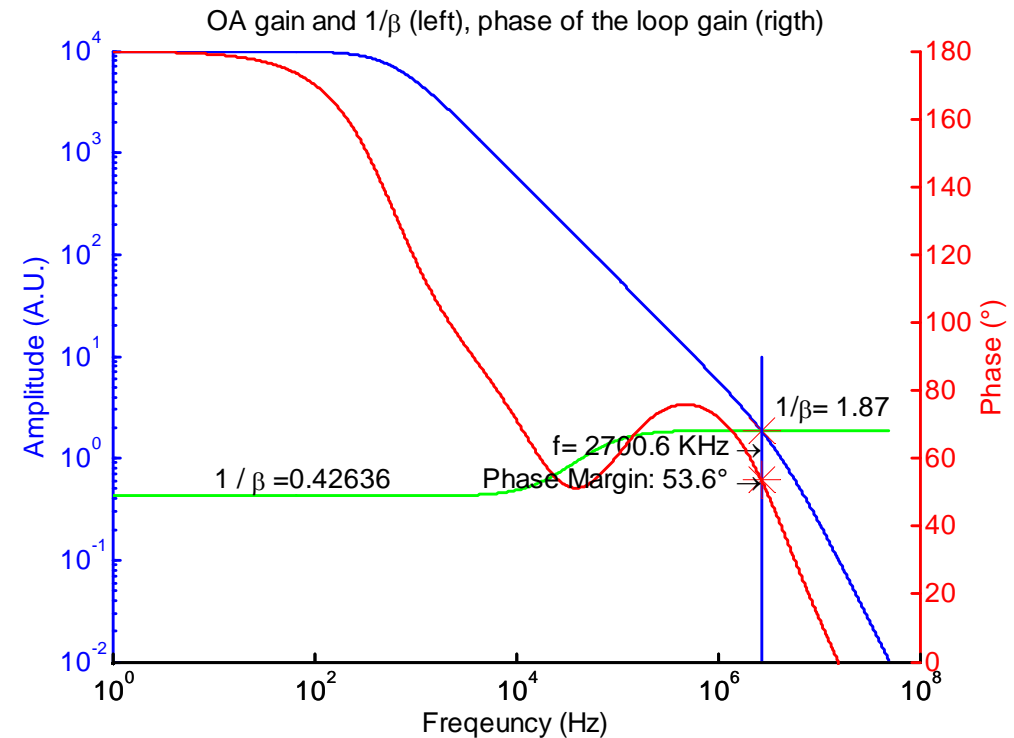
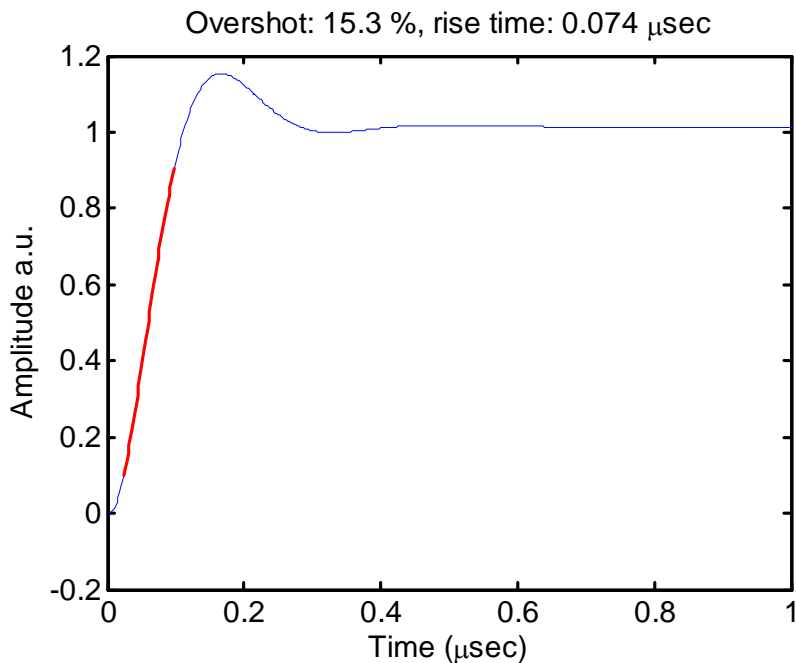
Since R_{cc} is much smaller than R_L at large frequencies the input noise of the OA is reflected at the input with a smaller attenuating factor.

Effects of compensation on the classical configuration

The effect of compensation improves the return path gain at high frequencies. As a consequence, the phase margin improves.

In the example shown $R_{cc} = 10 \Omega$, while $C_{cc} = 200 \text{ nF}$.

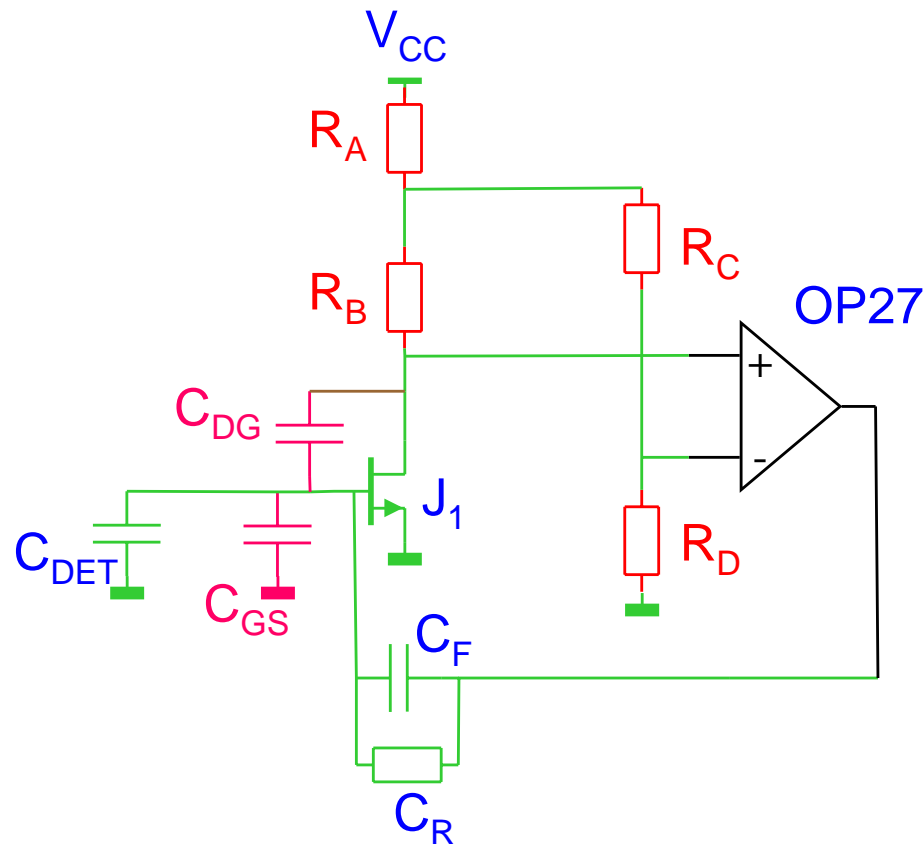
The input reflected noise of the OA at large frequencies is only 1.5 V/V in this example.



The phase margin increase reflects in a impulse response that has a much shorter settling time.

CSP with Operational Amplifier: a further suggested method

The aim of the suggested method was to make independent the Miller effect due to C_{DG} and the gain, from the detector requirements. To do this we have exploited both inputs of the OA and made the gain of the transistor partially common mode at the OA inputs:



We added 3 resistors to accommodate the drain of J_1 .

The equivalent resistor that loads J_1 is now:

$$R_{Miller} = R_B + R_A \parallel (R_C + R_D)$$

At the OA input we obtain instead:

$$\begin{aligned} V_+ - V_- &= - \left[R_B + \frac{R_A R_C}{R_A + R_C + R_D} \right] g_m V_i = -R_{Eq} g_m V_i \\ &= - \left[R_{Miller} - \frac{R_A R_D}{R_A + R_C + R_D} \right] g_m V_i \end{aligned}$$

So we have that $R_{Eq} < R_{Miller}$.

Considering the condition that at DC $V_+ \approx V_-$ we obtain 2 eqs that allows to set V_{DS} and I_{DS} . After having selected the other 2 parameters R_{Miller} and R_{Eq} 4 eqs are obtained to find the 4 resistors R_A, \dots, R_D, \dots

CSP with Operational Amplifier: a further suggested method, cont 1

$$R_A = \frac{V_{cc} (R_{Miller} - R_{Eq})}{(R_{Miller} - R_{Eq}) I_D + V_{DS}}$$

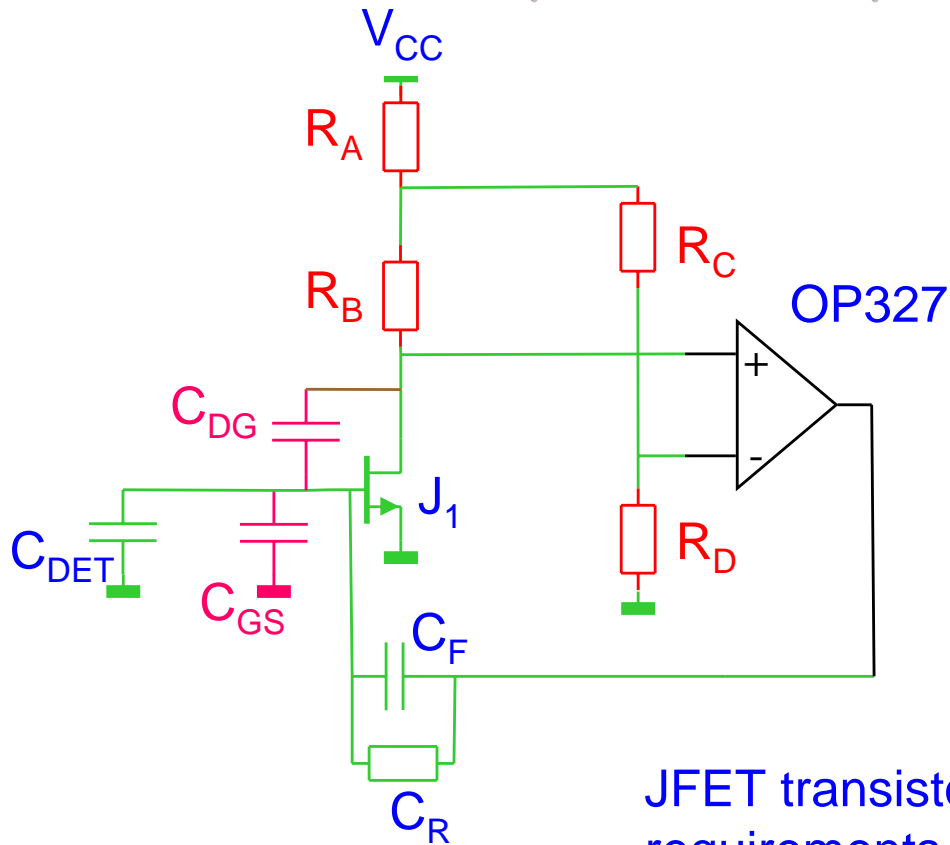
The roots of the 4 eqs that forms a linear system gives the value of the 4 resistors as a function of the static and dynamic parameters.

$$R_B = \frac{R_{Eq} V_{DS}}{(R_{Miller} - R_{Eq}) I_D + V_{DS}}$$

$$R_C = \frac{V_{cc} (R_{Miller} - R_{Eq}) I_D R_{Eq}}{(V_{cc} - V_{DS} - R_{Miller} I_D) ((R_{Miller} - R_{Eq}) I_D + V_{DS})}$$

$$R_D = \frac{V_{cc} (R_{Eq} - R_{Miller})}{R_{Miller} I_D + V_{DS} - V_{cc}}$$

CSP with Operational Amplifier: a further suggested method, cont 2



The inverse of the return path (green/red path) is:

$$\frac{1}{\beta} \approx \frac{C_F + C_{DET} + C_{GS} + (1 + g_m R_{Miller}) C_{DG}}{C_F} \frac{1}{g_m R_{Eq}}$$

When $g_m R_{Miller} \gg 1$ $1/\beta$ reduces to:

$$\frac{1}{\beta} \xrightarrow{g_m R_{Miller} \gg 1} \frac{C_{DG}}{C_F} \frac{R_{Miller}}{R_{Eq}}$$

JFET transistor and C_F can be chosen to satisfy the detector requirements. R_{Miller} and R_{Eq} are set to satisfy the stability condition of the network.

The input reflected noise of the OA is inversely proportional to $g_m R_{Eq}$. R_{Eq} can be asked the further requirements to maintain limited the OA noise reflected to the input.

The last consideration concerns the input parallel noise of OA.....

CSP with Operational Amplifier: a further suggested method, cont 3

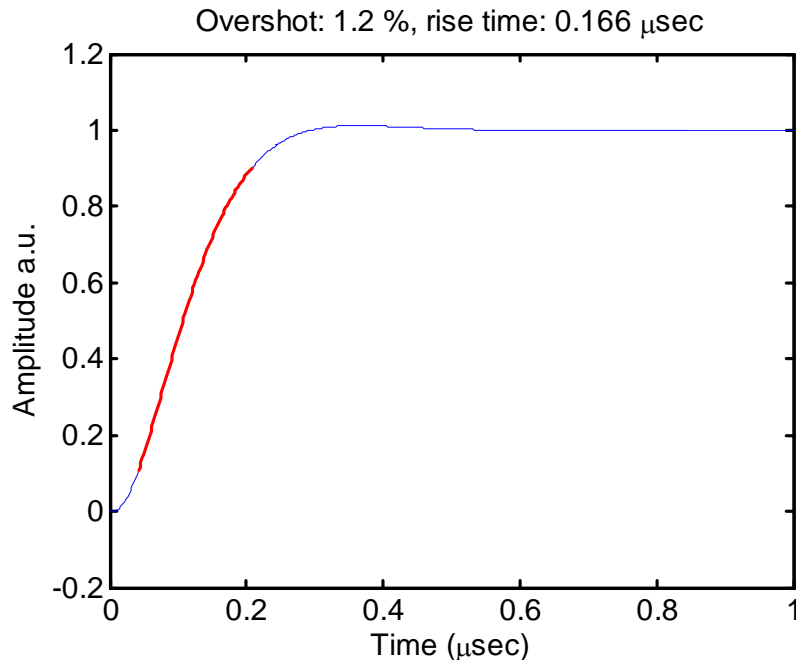
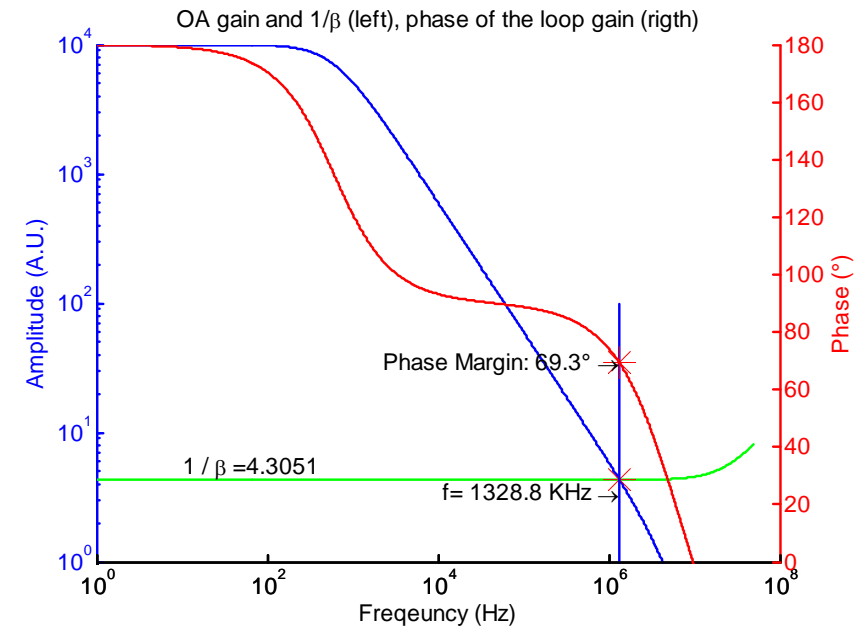
The effect at the input of the OA parallel noise is given by:

$$\begin{aligned}\overline{e_{iOA}^2} &= \frac{1}{g_m^2} \left\{ \overline{i_+^2} + \frac{1}{R_{Eq}^2} \left(\frac{R_C R_D}{(R_A + R_C + R_D)} \right)^2 \overline{i_-^2} \right\} \\ &\approx \frac{\overline{i_+^2}}{(g_m R_{Eq})^2} \left\{ R_{Eq}^2 + \left(\frac{R_C R_D}{(R_A + R_C + R_D)} \right)^2 \right\} \\ &= R_{No}^2 \overline{i_+^2}\end{aligned}$$

CSP with Operational Amplifier: a further suggested method, cont 4

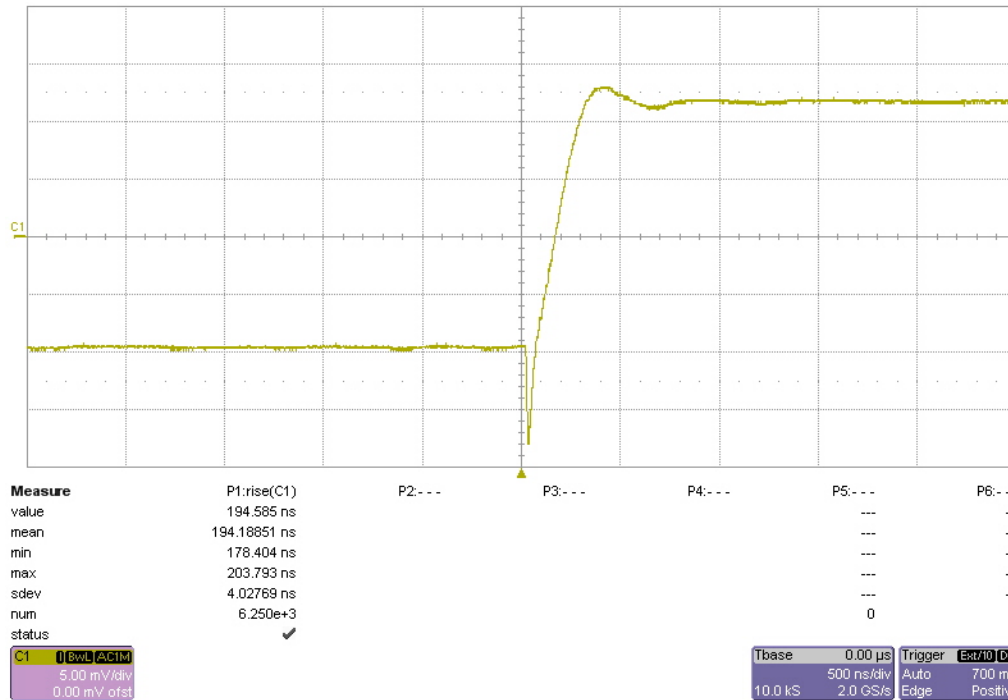
Following the same example above we have set $R_{\text{Miller}}=1 \text{ k}\Omega$ and $R_{\text{Eq}}=100 \Omega$. As a consequence $1/\beta$ resulted 4.3 and the phase margin 70° ($R_A=1200 \Omega$, $R_B=40 \Omega$, $R_C=300 \Omega$ and $R_D=4500 \Omega$, $V_{\text{CC}}=10 \text{ V}$, $V_{\text{DS}}=3 \text{ V}$ and $I_{\text{DS}}=5 \text{ mA}$).

At all frequencies the input reflected series noise of OA has an attenuation of 15 V/V, and the noise reflected resistor R_{No} for parallel noise is about 17Ω .



With a so large phase margin the overshoot of the signal is almost negligible. Setting R_{Eq} to 200Ω the phase margin lowers to 54° and the overshoot rises to 15 %, with a rise time of about 90 ns. This way the noise reflected to the input has an attenuation of 30 V/V and R_{No} is 15Ω .

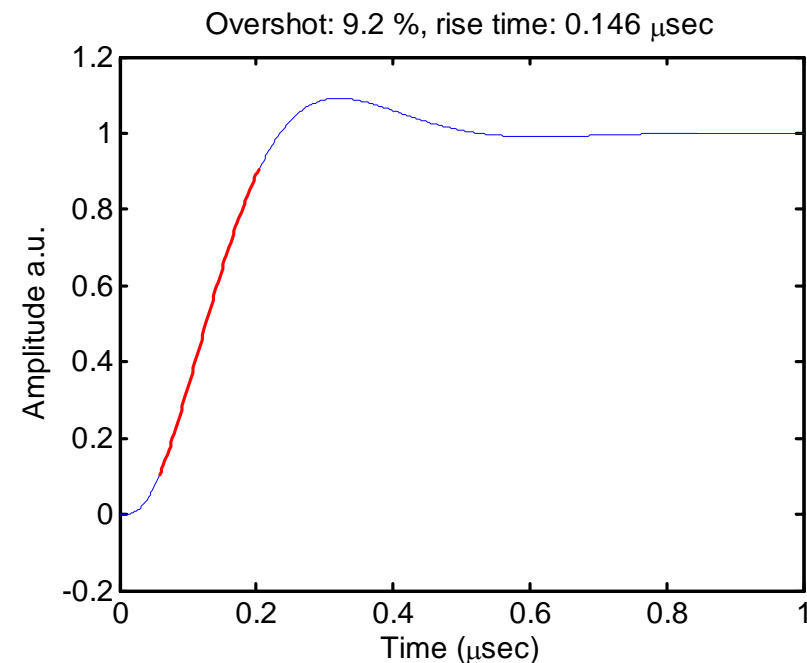
CSP with Operational Amplifier: a further suggested method, cont 5



The actual response of the preamplifier is shown here. We can see that the overshoot is slightly larger than 5 %.

This effect comes about if we consider that the OA output impedance is not negligible and lower the phase margin. The OP27, when loaded with about 1 K Ω , has an output impedance of about 50 Ω .

Including the effect of the OA output impedance in our model we are able to take into account also for this effect.



Conclusions

A method is suggested for the frequency compensation of a charge sensitive preamplifier based on the use of an OA as second stage in the feedback loop.

The method allows to have degrees of freedom in setting the return path gain by only selecting the value of 4 resistors.