BOOTSTRAPPING TECHNIQUES TO IMPROVE THE BANDWIDTH OF TRANSIMPEDANCE AMPLIFIERS

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1. Abstract

Transimpedance amplifiers using voltage feedback operational amplifiers are widely used for current to voltage conversion in applications when a moderate/high bandwidth and a high sensitivity are required, such as photodiodes, photomultipliers, electron multipliers and capacitive sensors. The conventional circuit presents a virtual earth to the input and at low frequencies, the input capacitance is usually not a significant concern. However, at high frequencies and especially for high sensitivity circuits, the total input capacitance can severely limit the available bandwidth from the circuit [1,6]. The input capacitance in effect constitutes part of the feedback network of the op-amp and hence reduces the available loop gain at high frequencies. In some cases a high input capacitance can cause the circuit to have a lightly damped or unstable dynamic response. Lag compensation by simply adding feedback capacitance is generally used to guarantee stability, however this approach does not permit the full gain-bandwidth characteristic of the op-amp to be fully exploited.

Active techniques for reducing the input capacitance, for instance bootstrapping, have been previously reported [2,3] and over the last ten years several papers have described successful examples of transimpedance circuits using bootstrapping [5]. The basic bootstrapping principle is to use an additional buffer amplifier to actively charge and discharge to input capacitance as required. By doing so the effective source capacitance is reduced, enabling the overall bandwidth of the circuit to be increased.

This paper presents a brief overview of the technique and introduces for the first time the four possible bootstrap configurations (series or shunt bootstrapping loops, with either floating or grounded sources) applied to the basic transimpedance circuit. Previous published techniques have employed the series technique, for example in the case of a photodiode bootstrapped by the source of the input FET [4,7]. The shunt configuration has not been reported as in this paper. This work presents new analysis and practical results that demonstrate the shunt bootstrap configuration on a transimpedance circuit. A doubling of bandwidth over the standard transimpedance circuit has been realised using the same type of op-amp for both the amplifying and bootstrap elements of the circuit.

2. Background

The standard transimpedance amplifier (Fig. 1) comprises an op-amp of gain $A(s)$ with feedback resistor, R_f and feedback capacitor, C_f. The signal source is represented by a current generator, i in parallel with a capacitance, C_s, and resistance, R_s. The capacitance, C_s represents both the source capacitance and the input capacitance of the op-amp. Negative feedback causes the op amp to 'look' at it's input terminals and swing it's output around so that the external feedback network brings the input differential to zero. The output voltage needed to do this is the voltage across the feedback resistor, R_f, this being set by the input current, the majority of which flows through R_f. The advantage of this circuit is that the inverting input is a virtual ground, thus the circuit presents almost zero load impedance to the current source.
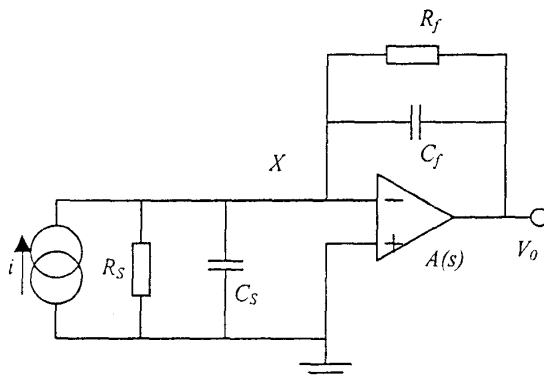
An expression for the transimpedance gain of the circuit can be readily derived if the following assumptions are made:

Fig. 1   The op amp based transimpedance amplifier

i   The amplifier is assumed to have infinite input impedance.
ii   The source resistance, R_s is considered infinite.

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iii   The open-loop response of the amplifier, $A(s)$ is approximated by a transfer function with a single dominant pole at a frequency ω_a and dc gain of A_o, i.e:

$$A(s) = \frac{A_o}{1 + \dfrac{s}{\omega_a}} \tag{1}$$

Then by summing current at node 'X' the transimpedance gain of the circuit can be shown to be:

$$v_o = \frac{-iR_f}{\dfrac{s^2(C_s + C_f)R_f}{A_o\omega_a} + s\left(C_f R_f + \dfrac{1}{A_o\omega_a} + \dfrac{(C_s + C_f)R_f}{A_o}\right) + \dfrac{1}{A_o} + 1} \tag{2}$$

Using *(2)* the transimpedance frequency response of the circuit can be plotted. The specification for an LF353N op-amp, 1MΩ feedback resistor and source capacitance of 100pF were used in *(2)* to produce the frequency responses shown below in Fig. 2. To show the effect of feedback capacitance on the frequency response of the circuit two responses are shown. Plot *(a)* shows the frequency response with no feedback capacitance and *(b)* shows the frequency response with a feedback capacitance of 2.8pF. With no feedback capacitance the response has a resonant peak as a direct consequence of the source capacitance. This peak indicates that the response is likely to have a lightly damped or unstable dynamic response. It can be seen that it is possible to obtain a critically damped frequency response by introducing feedback capacitance (lag compensation). However it is evident that this approach does not permit the full gain-bandwidth characteristic of the op-amp to be fully exploited.
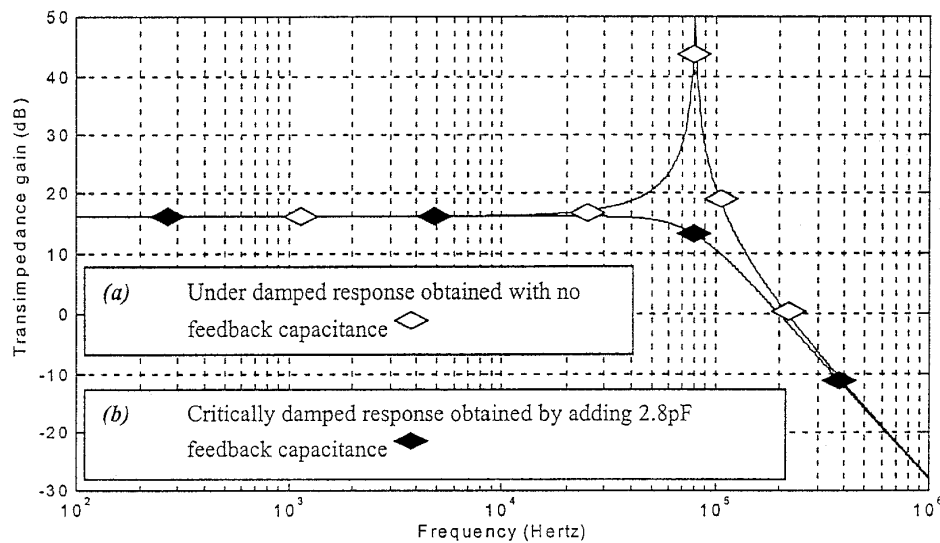

Fig. 2   Frequency response of the op-amp based transimpedance amplifier showing how the addition of feedback capacitance can lead to a critically damped response.

An effective reduction in source capacitance results in less feedback capacitance being required to obtain a critically damped response. This allows a more efficient use of the op-amp gain-bandwidth characteristic leading to an increase in bandwidth. It has been suggested [2,5] that by bootstrapping the source capacitance at the preamplifier stage, the ac voltage drop across the input capacitance can be kept to a minimum - thus maximising bandwidth. This work has largely been aimed at the transistor level of design where bootstrap signals may be available from internal amplifier nodes. Clearly another possible solution is to bootstrap the source capacitance with an additional amplifier block, with the same aim of keeping the ac voltage drop across the input capacitance zero.

3.   The Shunt and Series Bootstrap circuits

The four possible configurations are described in the following section.

3.1   The Shunt Bootstrap Circuit

This circuit has an additional buffer / voltage amplifier in parallel with the main transimpedance amplifier to allow the generation of a suitable 'forcing voltage' to keep the ac voltage drop across the input capacitance virtually zero. The two possible configurations for this circuit are shown below in Fig. 3 and Fig. 4.
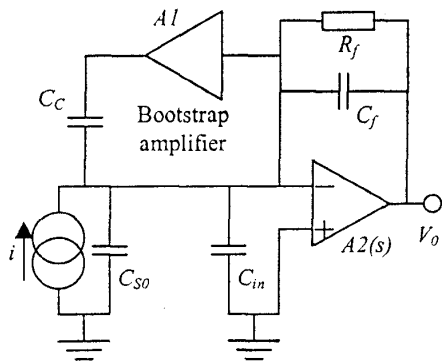
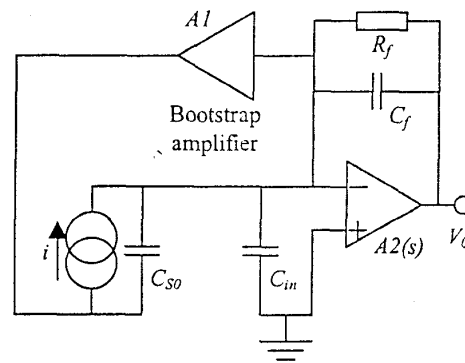Fig. 3 Grounded source / shunt bootstrap

Fig. 4 Floating source / shunt bootstrap

In Fig. 3, the source is connected to ground. The capacitance associated with the source is shown in parallel as C_{S0}. This source is connected to a transfer resistance circuit that comprises an amplifier of gain $A2(s)$ with feedback components R_f and C_f in parallel. The output of the bootstrapping amplifier $A1$ is fed back via a coupling capacitor C_c, to keep the ac voltage drop across the source capacitance, C_{S0} virtually zero. Fig. 4 shows the floating source configuration which, assuming appropriate bias conditions, can be connected directly to the source.

3.2   The Series Bootstrap Circuit

This circuit has an additional buffer amplifier in series with the main transimpedance amplifier for the generation of a suitable 'forcing voltage'. Again the two possible configurations are shown below in Fig. 5 and Fig. 6.
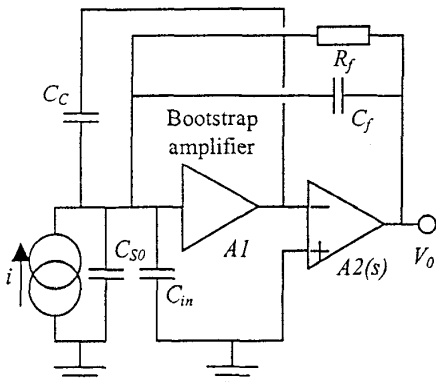

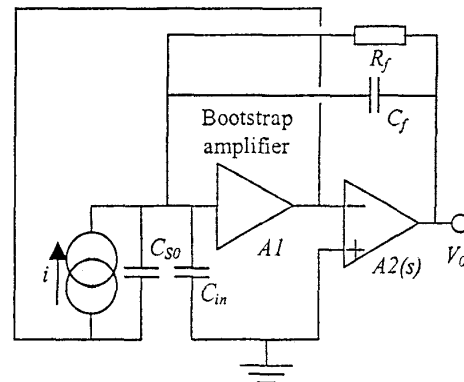Fig. 5 Grounded source / series bootstrap

Fig. 6 Floating source / series bootstrap

Fig. 5 shows a simplified diagram of the grounded source circuit. The source is connected to a transfer resistance circuit that comprises amplifiers $A2$ and $A1$ with feedback components R_f and C_f in parallel. The amplifier $A1$ is a buffer / voltage amplifier connected directly in series with $A2$. The output from $A1$ is fed back via a coupling capacitor C_c, to keep the ac voltage drop across the capacitance, C_{S0} virtually zero. The floating source configuration is shown in Fig. 6. The floating source configuration can be readily configured at transistor level using the source connection of the input FET [7] as shown in Fig. 7, opposite.
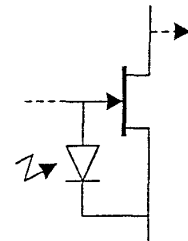

Fig. 7

4.   The Shunt Bootstrap Circuit

4.1   Development of a model to predict the transimpedance frequency response of the Shunt Bootstrap Circuit

The small signal transfer functions of the previous circuits can be readily derived if a few basic simplifications are made. For example, in the case of the floating source / shunt circuit (Fig. 4):

i.   Take C_s as the total input capacitance at the source node to ground (note, $C_s = C_{in}$ for Fig. 4).

ii.   Take C_a as the total capacitance associated with the bootstrap connection (note, $C_a = C_{S0}$ for Fig.4).

iii.   Assume the source resistance is infinite.

iv.   Take $A1$ to be a unity gain buffer configured with the same type of op-amp as $A2$. A single pole model, *(1)*, can be used to provide a first order description of the op-amp response. Note, the gain-bandwidth produce of the op-amp, $\omega_0 = \omega_a A_0$.

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Giving the following relationship for the transimpedance gain of the circuit:

$$v_o = \frac{-iR_f}{\dfrac{s^2(C_s + C_f + C_a)R_f}{\omega_o} + \dfrac{s(C_s + C_f + C_a)R_f\omega_a}{\omega_o} + sC_fR_f - \dfrac{s(s + \omega_a)C_aR_f}{s + (\omega_o + \omega_a)} + \dfrac{s}{\omega_o} + \dfrac{\omega_a}{\omega_o} + 1} \tag{3}$$

The mathematical models of *(2)* and *(3)* were used in Fig. 8 to compare the frequency responses of the shunt circuit and the standard transimpedance amplifier. In both models the specification for an LF353N op amp and a 1MΩ feedback resistor were used. A source capacitance of 80pF (the typical capacitance possessed by a large area photodiode) was used in both cases and an op-amp input / stray capacitance to ground of 20pF assumed. Sufficient feedback capacitance was added in both models to obtain a critically damped response. A feedback capacitance of 1.4pF was required in the shunt model *(3)* compared to 2.8pF in the standard model *(2)*, showing the reduction in feedback capacitance, as predicted. The increase in bandwidth exhibited by the shunt circuit can be attributed to this reduction in feedback capacitance. This indicates the effect of bootstrapping in effectively reducing the source capacitance as less feedback capacitance is required to obtain a critically damped response. Frequency responses for a range of op-amps and bootstrap circuits have been plotted and these have been extensively compared to SPICE simulations with very good accord.
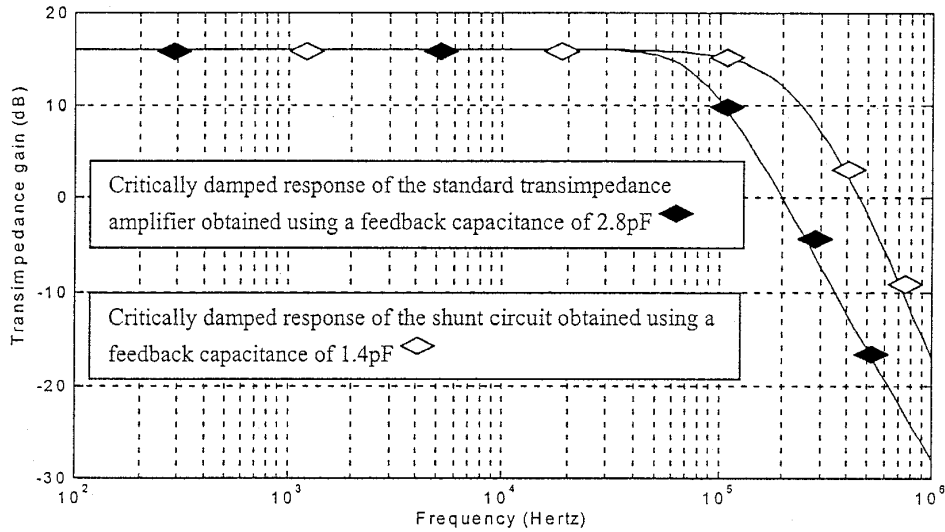

Fig. 8   Theoretical frequency responses of the shunt circuit and standard transimpedance amplifier

4.2.   Practical transimpedance frequency response of the shunt circuit

The bootstrap principle was applied to a photodiode pre-amplifier circuit in order to assess whether the shunt circuit could indeed achieve an increase in bandwidth over the standard circuit while maintaining an adequate stability margin. The circuit diagram is shown in Fig. 9 and is very similar to Fig. 4, but with the inclusion of an a.c. coupled bootstrap path. The frequency response of this circuit was compared to that of the standard circuit. To obtain the standard circuit, this circuit was modified by removing the Bootstrap element completely from the circuit, with the rest of the circuit remaining the same. To allow an alignment between theory and practice an LF353N op amp, 1MΩ feedback resistor and a photodiode (Part Number 0SD15-5T, C_{So} ≈ 80pF) signal source were selected. In the shunt circuit, the only feedback capacitance used was the parasitic capacitance possessed by the layout and feedback resistor.
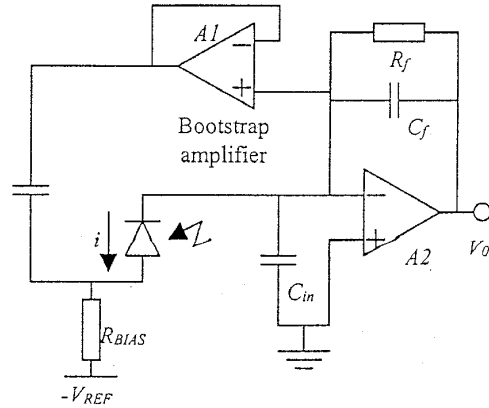

Fig.9 Simplified schematic of the shunt bootstrap photodiode preamplifier

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The shunt circuit was driven by a square wave and the output waveform observed to assess the level of damping. From the resulting waveform shown in Fig. 10 the damping ratio, ξ can be estimated to be 1, i.e. critically damped. The standard circuit was also subjected to a square wave input and feedback capacitance added until a critically damped output was achieved, i.e. such that no ringing was experienced. A 1.8pF capacitor was required, in addition to the parasitic feedback capacitance and the resulting output waveform is shown in Fig. 11.
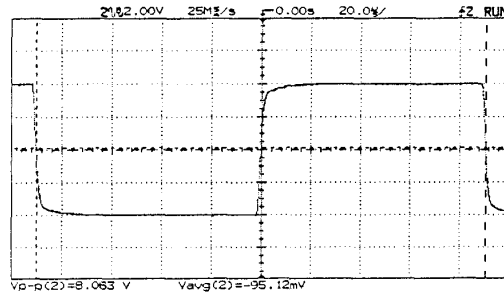

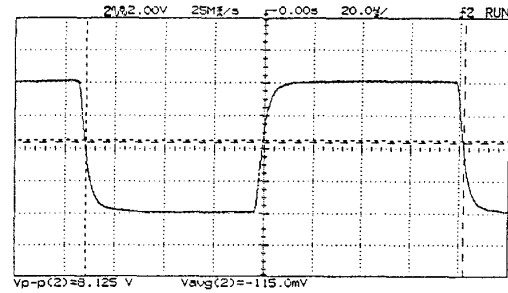Fig. 10 Step response of the shunt circuit

Fig. 11 Step response of the standard circuit

The critically damped transimpedance frequency responses using these values of feedback capacitance are shown in Fig. 12. It can be seen that the shunt circuit has twice the bandwidth of the standard circuit. To obtain the response in Fig. 12 the shunt circuit only required the parasitic feedback capacitance, whereas the standard circuit required an extra 1.8pF in addition to the parasitics. Both circuits appear to have the same level of damping so the stability margins of both circuits can be considered to be the same. In order to obtain a critically damped response the shunt circuit required a smaller value of feedback capacitance, indicating that bootstrapping had effectively reduced the source capacitance. The increase in bandwidth can be attributed to the decrease in feedback capacitor required to produce a critically damped response.
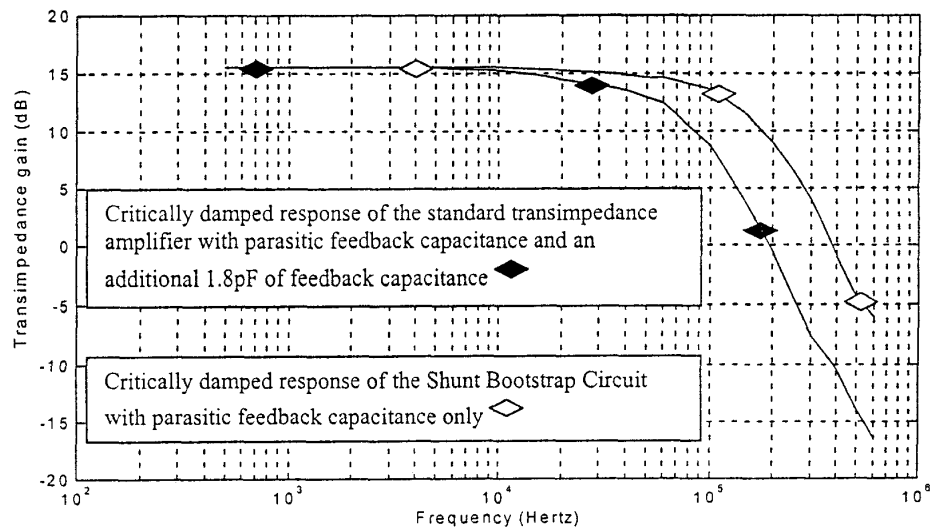

Fig. 12 Practical frequency responses of the shunt circuit and standard transimpedance amplifier

5. Conclusions

This paper has presented a brief overview of four basic bootstrap configurations for the standard transimpedance amplifier, namely series and shunt for either floating or grounded sources. Examples of the series configuration have been previously reported with examples of designs at both transistor and op-amp level.

This paper has presented a simple example of a new shunt bootstrap amplifier based on two operational amplifiers of the same type and shows that the techniques can be used to realise a faster response than is possible with a single amplifier alone. The bootstrap method may provide a viable design option for applications with high gain (i.e. high R_f) and requiring a wide bandwidth (where the bandwidth is limited by the parasitic effects of the input capacitance).

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6.   References

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