Compact CMOS Constant-g_m Rail-to-Rail Input Stage with g_m-Control by an Electronic Zener Diode

Ron Hogervorst, John P. Tero, and Johan H. Huijsing

***Abstract*—A family of compact CMOS rail-to-rail input stages with constant-g_m is presented. To attain a constant-g_m over the whole common-mode input range, an electronic zener diode is inserted between the tails of the complementary input pairs. This zener keeps the sum of the gate-source voltages of the input pairs, and therefore the g_m of the rail-to-rail input stage, constant. Two possible implementations of the zener have been realized and inserted in a rail-to-rail input stage. These input stages are implemented in two two-stage compact amplifiers. Both amplifiers have been realized in a 1 μm BiCMOS process. They have a unity-gain frequency of 2-MHz, for a capacitive load of 20 pF.**

I. Introduction

OPERATIONAL amplifiers intended for use in low-voltage low-power mixed-mode systems have to be power efficient and compact. Often, particularly in voltage follower applications, these op-amps require an input stage with a rail-to-rail common-mode (CM) input range [1]–[3]. To achieve this, the input stage can be made of an N-channel and P-channel differential pair in parallel. A drawback of such an input stage is that its transconductance (g_m) varies with a factor of two over the CM input range, which impedes a power-optimal frequency compensation of the op-amp [2]. In order to obtain a power-efficient frequency compensation, the g_m of the input stage has to be regulated at a constant value.

In weak-inversion, the g_m of an MOS transistor is proportional to its drain current. Hence, a constant g_m can be obtained by keeping the sum of the tail currents constant. To achieve this, a current switch can be used [1]–[3]. In relatively high slew-rate applications, the input stage of an op-amp is often biased in strong inversion instead of weak inversion. If the rail-to-rail input stage with g_m-control by one current switch is biased in strong inversion, its g_m will vary approximately 41% over the CM input range [3]. This variation still blocks a power-efficient frequency compensation of the op-amp. Several solutions have been presented to make the transconductance of a rail-to-rail input stage constant [3]–[6]. They are all more or less based on the g_m-control principle that is used for a rail-to-rail input stage biased in weak inversion, i.e., the g_m of the rail-to-rail input stage is regulated by adapting the tail currents of the complementary input pairs. The difference is that in strong inversion not the sum of tail currents but the sum of the square roots of the tail currents is regulated at a constant value. A drawback of this method is that it leads to complex designs. In addition, the control circuits introduce additional current paths between the supply rails, which raises the dissipation of the input stage.

This paper presents a novel method to control the g_m of a rail-to-rail input stage which operates in strong inversion [7], [8]. The core of the method is a zener diode which is inserted between the tails of the complementary input stages. This zener keeps the sum of the gate-source voltages of the input pairs, and therefore the g_m of the rail-to-rail input stage, at a constant value. The main advantage of this g_m-control technique over existing technology is that it results in very compact input stages. In addition, the zener does not increase the dissipation of the input stage, because it does not introduce additional current paths between the supply rails.

Two possible implementations of the input stage with a zener diode have been designed. The transconductance of the first input stage is controlled by two complementary diodes. The g_m of this input varies approximately 28% over the CM input range. The second input stage uses a more accurate implementation of the zener diode. The g_m of this input stage varies only 8% over the CM input range. The input stages have been inserted in two two-stage compact op-amps, which have been realized in the CMOS part of a 1 μm BiCMOS process. Both op-amps have a unity-gain frequency of 2 MHz, while driving a load of 20 pF. The op-amps measure only 0.06 mm^2, which makes them very suitable as a VLSI building block.

II. Constant-g_m Rail-to-Rail Input Stage

Fig. 1 shows the basic principle of the constant g_m rail-to-rail input stage. The circuit consists of a complementary input stage, M_{11}–M_{13}. The g_m-control is implemented by means of an ideal zener, Z, which keeps the sum of the gate-source voltages of the input transistors, and therefore the g_m of the input stage, constant.

In order to obtain a constant g_m, the zener is given a zener voltage of

$$V_{\mathrm{ref}} = -V_{TP} + V_{TN} + 2KV_{\mathrm{gs,ref}}$$
$$\text{with } V_{\mathrm{gs,ref}} = \sqrt{\frac{1}{K}I_{\mathrm{ref}}} \qquad (1)$$

where V_{TN} and V_{TP} are the threshold voltages of a P-channel and an N-channel transistor, respectively. $V_{\mathrm{gs,ref}}$ is the effective gate-source voltage of an input transistor biased at $4I_{ref}$, i.e., a gate-source voltage, V_{gs}, minus a threshold voltage, V_T. The subscripts P and N refer to a P-channel and an N-channel transistor, respectively. The factor K is the transconductance parameter of the input transistors which is

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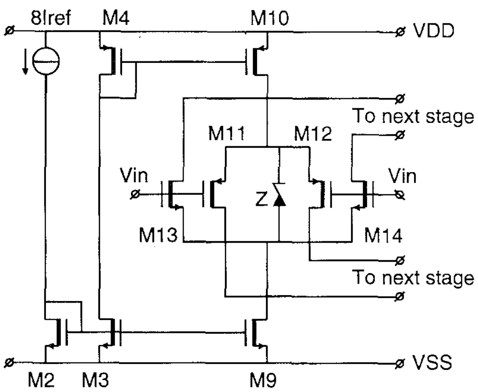

Fig. 1. Rail-to-rail input stage. The zener diode regulates the g_m at a constant value.

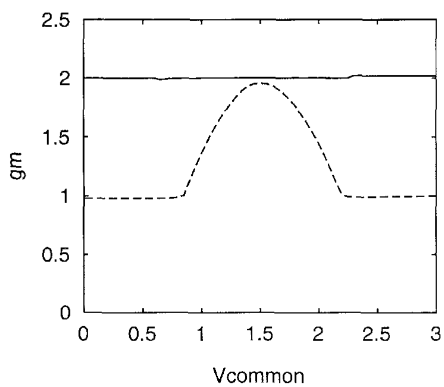

Fig. 2. Normalized g_m versus the common-mode input range for the rail-to-rail input stage with zener diode: – – – – – rail-to-rail input stage without g_m-control, —rail-to-rail input stage with g_m-control.

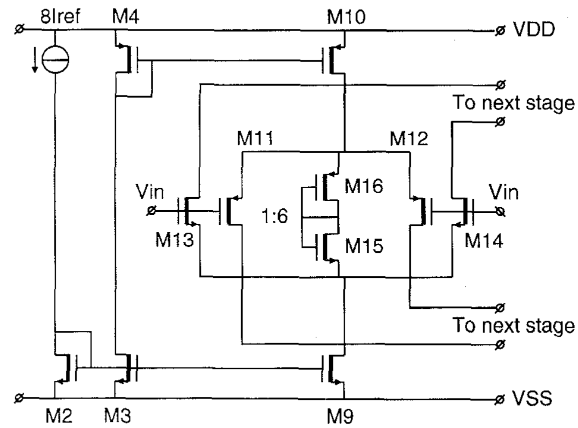

Fig. 3. Rail-to-rail input stage. The g_m is regulated by means of two complementary diodes.

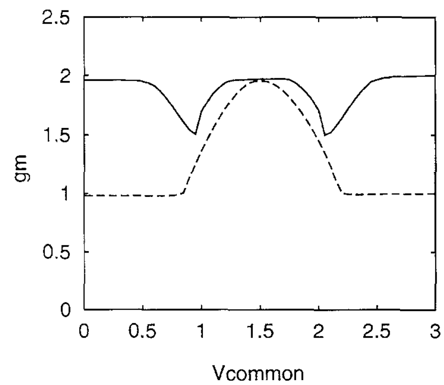

Fig. 4. Normalized g_m versus the common-mode input range for the rail-to-rail input stage with two complementary diodes: – – – – – rail-to-rail input stage without g_m-control, —rail-to-rail input stage with g_m-control.

given by

$$K = \frac{1}{2}\mu C_{\rm ox}\frac{W}{L} = \frac{1}{2}\mu_P C_{\rm ox}\left(\frac{W}{L}\right)_P = \frac{1}{2}\mu_N C_{\rm ox}\left(\frac{W}{L}\right)_N \tag{2}$$

where μ is the mobility of the charge carriers, and $C_{\rm ox}$ is the normalized oxide capacitance. The mobility of an N-type transistor is approximately three times larger than the mobility of a P-type transistor. This difference can be largely compensated by choosing the W over L ratio of the P-channel input transistors a factor μ_N/μ_P larger than the W over L ratio of the N-channel input transistors. Of course, the factor μ_N/μ_P depends on process variations. In the used process, this ratio deviates 15% from its nominal value, which entails a variation of the g_m of approximately 7.5% over the whole CM input voltage range.

The principles of the rail-to-rail input stage with zener diode can be best understood by dividing the CM input range into three parts. In the lower part of the CM input range only the P-channel input pair is active. In this case, the voltage between the tails of the complementary input pairs is smaller than the zener voltage. As a result, the current through the zener is zero, and thus the tail current of the P-channel input pair is equal to $8I_{\rm ref}$. In the intermediate part of the CM input range, the P-channel as well as the N-channel input pair operates. In this situation, the zener makes the sum of the gate-source voltages of the input transistors equal to the zener voltage, which is given by (1). As a consequence, the zener absorbs $6I_{\rm ref}$ from both the tail current sources. The result is that the tail currents of both the complementary input stages equal $2I_{\rm ref}$. In the upper part of the CM input range, only the N-channel input pair is active. In this case, the voltage between the tails of the input pairs is smaller than the zener voltage. Consequently, the current through the zener is zero, and thus the tail current of the N-channel input pair has a value of $8I_{\rm ref}$.

From the above, it can be calculated that the g_m of the input stage with an ideal zener diode equals

$$g_{m,r-r} = 2KV_{\rm gs,ref} = 2\sqrt{KI_{\rm ref}}. \tag{3}$$

Fig. 2 depicts the g_m of the input stage with ideal zener versus the CM input voltage. This picture clearly shows that the g_m is constant over the entire CM input range.

Two possible transistor implementations of the zener have been designed. The first one is shown in Fig. 3. It consists of only two complementary diodes, M_{15}–M_{16}, which result in a very compact input stage. It is also very power efficient because the zener does not introduce additional current paths between the supply rails.

TABLE I

SPECIFICATIONS OF THE AMPLIFIERS, $V_{\text{supply}} = 3$ V, $R_{\text{load}} = 10\ \Omega$, $C_{\text{load}} = 10$ pF, $T_A = 27°$C. OP-AMP1 REFERS TO THE OP-AMP WITH A g_m-CONTROL BY TWO COMPLEMENTARY DIODES. OP-AMP2 REFERS TO THE OP-AMP WITH A g_m-CONTROL BY AN ELECTRONIC ZENER DIODE

Parameter	opamp1	opamp2	unit
Die area	0.06	0.06	mm^2
Supply voltage range	2.7 to 6	2.7 to 6	V
Quiescent current	210	215	µA
Peak output current	7.5	7.5	mA
Common-mode input voltage range	V_{SS}-.5 to V_{DD}+.8	V_{SS}-.5 to V_{DD}+.8	V
Output voltage swing	V_{SS}+.1 to V_{DD}-.1	V_{SS}+.1 to V_{DD}-.1	V
Offset voltage	3	3	mV
CMRR			dB
V_{common}:			
from V_{SS}-0.5V to V_{SS}+.6	80	80	
from V_{SS}+0.6V to V_{SS}+1.1V	43	43	
from V_{SS}+1.1V to V_{DD}-1.1V	74	74	
from V_{DD}-1.1V to V_{DD}-0.5V	43	43	
from V_{DD}-0.5V to V_{DD}+.8V	70	70	
Open-loop gain	83	85	dB
Unity-gain frequency	1.7	1.9	MHz
Unity-gain phase margin	76	80	°
Slew-rate	8	8	V/µs
Settling-time (1%, Vstep=1V)	0.3	0.3	µs

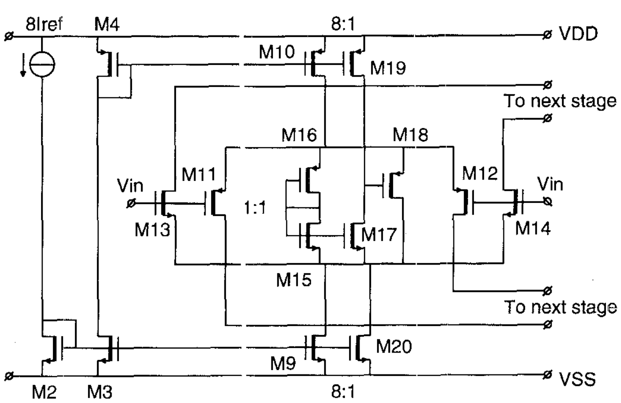

Fig. 5. Rail-to-rail input stage. The g_m is regulated by means of an electronic zener diode.

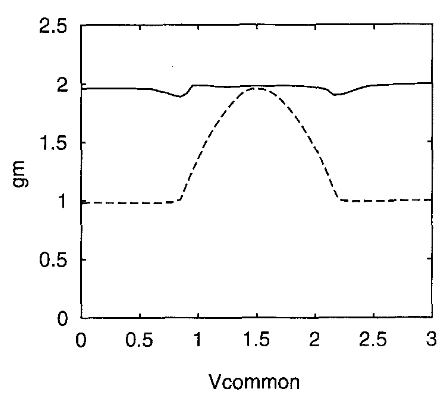

Fig. 6. Normalized g_m versus the common-mode input range for the rail-to-rail input stage with electronic zener diode: – – – – – rail-to-rail input stage without g_m-control, —rail-to-rail input stage with g_m-control.

In order to obtain a zener voltage according to (1), the W over L ratios of the two diodes have to be chosen six times larger than those of the input transistors. By doing so, the input stage with two diodes behaves similar to the input stage with an ideal zener diode. In the intermediate part of the CM input range, the two diodes absorb a current of $6I_{\text{ref}}$. As a result, the tail-currents of the input pairs have the desired value of $2I_{\text{ref}}$ in this part of the CM input range. In the outer parts of the CM input range, the tail current of the actual active input pair is equal to $8I_{\text{ref}}$, because in those cases the current through the two diodes is zero. The total g_m of the complementary input stage with two diodes is equal to that of the input stage with an ideal zener diode, which is given by (3).

Fig. 4 shows the normalized transconductance versus the CM input voltage. This figure displays that the g_m of this input stage varies about 28% over the CM input range. This variation occurs because the current through the two diodes, and therefore the voltage across the diodes, changes when the input voltage travels across the CM input range.

Fig. 5 shows a second, and more accurate, implementation of the complementary input stage with a zener diode. The electronic zener is implemented by means of the transistors M_{15}–M_{20}. Again, two complementary diode-connected transistors, M_{15}–M_{16}, determine the zener voltage. To obtain a

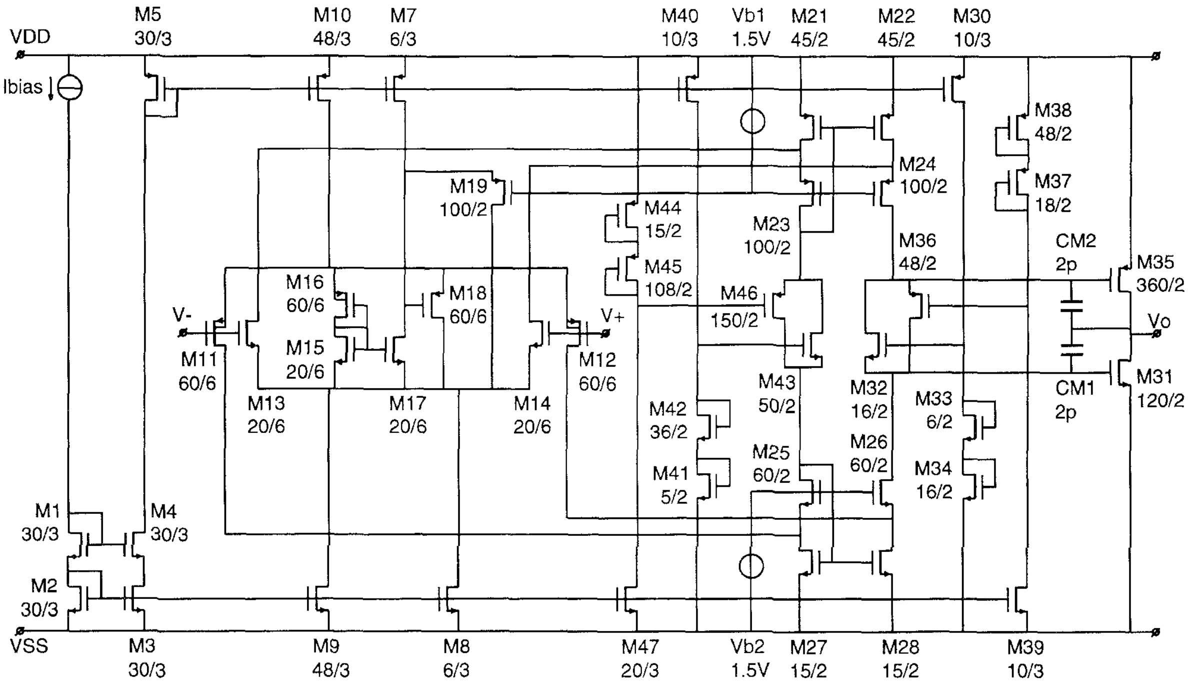

Fig. 7. Realization of the compact operational amplifier. The g_m-control is implemented by means of an electronic zener diode.

zener voltage according to (1), the W over L ratio of the diodes have to be equal to the W over L ratio of the input transistors, and M_{19} has to be eight times smaller than M_{10}. The control transistor M_{18} removes a part of the tail currents, such that the current through M_{17} is equal to the constant current of M_{19}. Because M_{15} and M_{17} have the same W over L ratios, the current through the diode connected transistor is constant, too. As a result, the voltage across the two complementary diodes, and therefore the sum of the gate-source voltages of the input transistors, will be constant. Transistor M_{20} drains away the current of M_{19}. Although M_{19} and M_{20} introduce an additional current path between the supply rails, it hardly increases the dissipation of the input stage.

Fig. 6 shows the normalized g_m versus the CM input voltage. From this figure it can be concluded that the g_m varies only 8% over the entire CM input voltage range. This variation of the g_m is smaller compared to that of the input stage with two complementary diodes, because the electronic zener diode has more internal gain.

The input stages as discussed above are applicable in applications that operate up to a couple of tens of MHz's. At higher frequencies, often minimum channel length input devices are used, in order to obtain a sufficient system bandwidth. As a result, these input devices suffer from velocity saturation, which deteriorates the performance of the g_m-control. Note that this is also the case for existing constant-g_m control circuits.

To conclude, the g_m of a rail-to-rail input stage operating in strong inversion can be made constant by inserting a zener diode between the tails. This results in more compact and more power-efficient input stages, in comparison to existing constant-g_m rail-to-rail input stages.

III. Overall Design and Measurements

The input stage with electronic zener has been inserted in the op-amp as shown in Fig. 7. The op-amp consists of a rail-to-rail output stage with class-AB control, M_{31}–M_{38}, a summing circuit, M_{21}–M_{28}, and a rail-to-rail input stage, M_{11}–M_{14}. A floating current source, M_{41}–M_{47}, biases the summing circuit. The amplifier is compensated using two Miller capacitors, C_{M1} and C_{M2}. A more elaborated discussion of the op-amp topology can be found in [9]. The op-amp uses the electronic zener diode, M_{16}–M_{18}, to control the g_m. The transistor M_{19} limits the drain voltage of M_7. If the drain voltage of M_7 exceeds a certain value, determined by V_{b1}, M_{19} starts to conduct and passes the current of M_7 to the tail of the N-channel input pair. If M_{19} would not be present, the drain voltage of M_7 would be approximately equal to the positive supply rail, when the CM input voltage is near one of the supply rails. As a result, M_8 will increase the tail current of the N-channel input pair with 12% in the upper part of the CM input range. This would entail an undesired additional 6% variation of the transconductance.

The op-amp has been realized in the CMOS part of a 1 μm BiCMOS process. The N-channel and the P-channel devices have a threshold voltage of 0.8 V and −0.8 V, respectively. The micrograph of the op-amp is shown in Fig. 8. It occupies a die area of only 0.06 mm^2, which makes it suitable as a VLSI library cell. Fig. 9 shows the measured Bodeplot of the op-amp with g_m-control by an electronic zener diode. The op-amp has a unity-gain frequency of 1.9 MHz and a phase-margin of 80°, for a load of 20 pF. Fig. 10 shows the large-signal step response for the op-amp connected as a voltage follower. If a 1-V step is applied to this configuration, the op-amp has a 1%

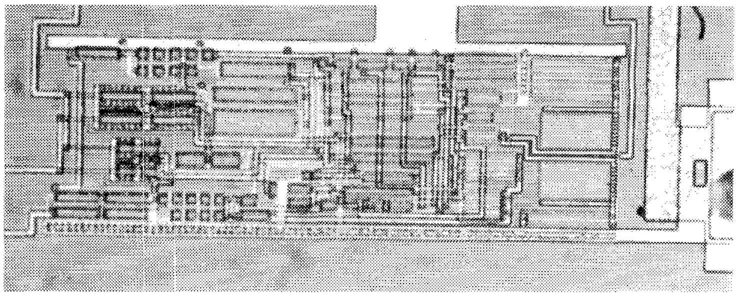

Fig. 8. Micrograph of the amplifier of the compact operational amplifier. The g_m-control is implemented by means of an electronic zener diode.

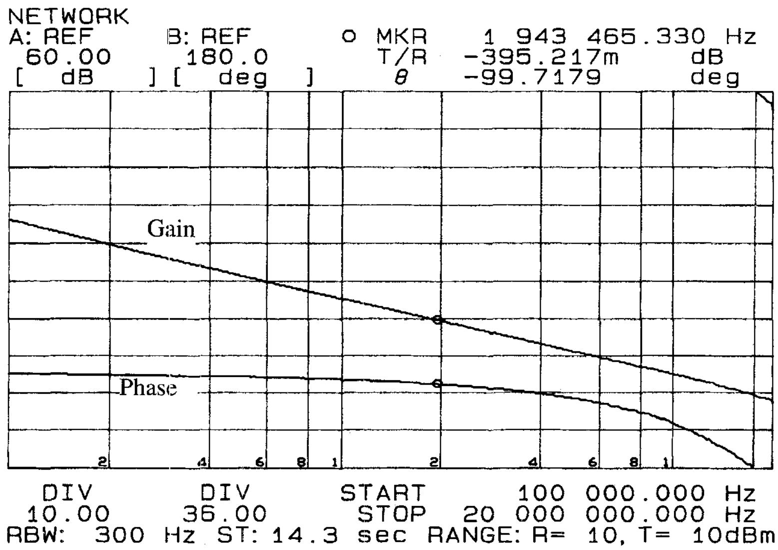

Fig. 9. Bodeplot of the compact operational amplifier. The g_m-control is implemented by means of an electronic zener diode.

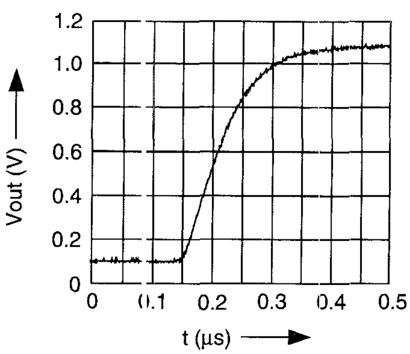

Fig. 10. Step response of the compact operational amplifier ($V_{\text{step}} = 1$ V). The g_m-control is implemented by means of an electronic zener diode.

settling-time of 0.3 μs, when driving a load of 20 pF parallel to 10 kΩ.

Using the same op-amp topology as discussed above, a second op-amp has been realized. In this op-amp, the g_m-control by an electronic zener diode is replaced by two complementary diodes. The results of this op-amp very much resemble those of the op-amp with electronic zener diode, and are therefore not discussed in detail.

A detailed list of specifications of both op-amps is shown in Table I. The minimum supply voltage is 2.7 V. At this supply voltage, the op-amps dissipate only 0.6 mW. The maximum supply voltage is 6 V, which is determined by the process. The random offset is about 3 mV. The offset of the P-channel and N-channel input pair tend to be different, which degrades the common mode rejection ratio (CMRR) of these type of input stages [8]. The input stages as presented in this paper have CMRR figures which are comparable to that of existing rail-to-rail input stages.

IV. Conclusion

A class of compact CMOS rail-to-rail input stages with constant-g_m have been presented. To obtain a constant-g_m over the whole CM input range, a zener diode is inserted between the tails of the complementary input pairs. This zener diode keeps the sum of the gate-source voltages of the input pairs, and therefore the g_m of the input stage, constant. The main advantage of this g_m-control over existing technology is that the zener can be very compact. In addition, the constant-g_m rail-to-rail input stage is very power-efficient because the zener does not introduce any additional current paths between the supply rails.

Two possible implementations of the input stage with zener diode have been realized. The g_m of the first input stage is controlled by two diodes. The g_m of this input stage varies approximately 28% over the CM input range. The second input stage uses a more accurate implementation of the zener diode. The g_m of this input stage varies only 8% over the CM input range. The input stages have been inserted in a compact two-stage op-amp. These op-amps have been realized in the CMOS part of a 1 μm BiCMOS process. The op-amps measure only 0.06 mm^2, which makes them very suitable as VLSI library cells.

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