A LOW-VOLTAGE, LOW-POWER CONTROLLABLE CURRENT AMPLIFIER FOR HEARING INSTRUMENTS

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A controllable current amplifier with a control range of more than 60dB for application in a novel, completely integratable hearing instrument is presented. It operates on power supply voltages of 1V .. 1.3V. Low current consumption is aimed at. The maximum value is 93µA.

Introduction: A controllable current amplifier has been designed for a new, completely integratable hearing instrument, the block diagram of which is given in Fig.1.

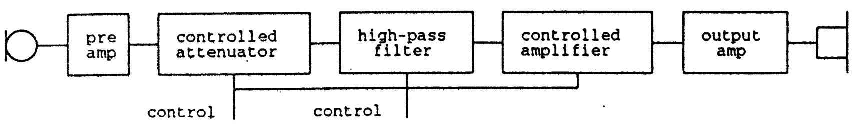

Fig.1 Block diagram of the hearing instrument

Many users of hearing instruments need the ability to improve speech intelligibility in environments with much low frequency noise (e.g. cars). This can be done with the controllable high-pass filter as presented in [1]. To make this filter integratable, it has to operate at a very low current level (signal level $25nA_{peak}$). As a consequence, the signal-to-noise ratio is limited. In order to obtain a sufficiently large dynamic range, a controllable attenuator [2] and a controllable amplifier keep the signal level in the filter at the largest possible value, independent of sound volume. In this letter, this controllable current amplifier is presented. From the defined signal levels at the input and the output it follows that current gain has to be controllable between 0dB and 60dB. The circuit has to operate at a very low supply voltage of 1V .. 1.3V. In line with usual specifications, the minimal required signal-to-noise ratio has been chosen 50dB and the harmonic distortion must be less than 5%. Further the amplifier is optimized with regard to power consumption.

Basic configuration: The basic configuration is the controllable current mirror shown in Fig.2a. In this circuit the influence of the base currents is reduced by means of an auxiliary amplifier. The circuit is of the class of indirect feedback amplifiers [3], the principle of which is given in Fig.2b. The inputs of the amplifier stages are placed in parallel. The output of the first stage is used for feedback, while the output of the

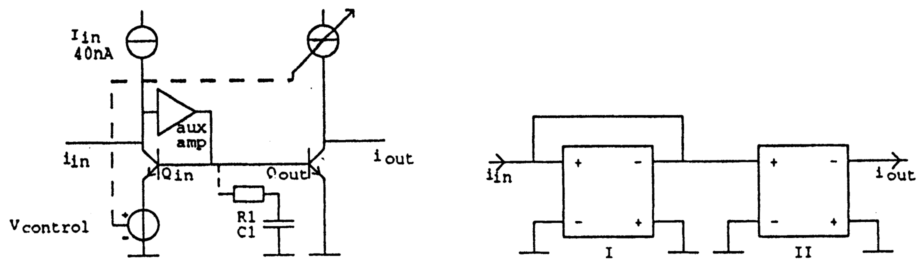

Fig.2 a) Controllable current mirror b) Indirect feedback

second stage is used for driving the load. When the stages are identical, the current gain is -1. The advantages of this configuration are obvious: feedback can be applied without the need for sensing the current through the load. Moreover, in the controllable current mirror, the current gain can easily be made controllable by means of the voltage source $V_{control}$. When base currents are neglected, the current gain is given by

$$a_i = i_{out}/i_{in} = exp(V_{control}/V_T) \qquad (1)$$

where V_T is the thermal voltage. Gain varies exponentially with the control voltage, hence a gain control in dB can be made easily: at room temperature the gain changes 20dB per 60mV. $V_{control}$ must be proportional to the absolute temperature (PTAT), which can easily be realized. The bias current of Q_{in} is chosen somewhat higher than the signal amplitude to avoid clipping. A value of 40nA has been chosen. Because the bias current only needs to be slightly larger than the signal amplitude, the circuit offers very good power efficiency. When the control voltage is increased, the DC current through Q_{out} increases exponentially so an output bias source which is controlled by $V_{control}$ is necessary.

Noise properties: Because of the auxiliary amplifier, base currents are negligible and the only relevant noise sources are the two collector shot noise currents of the transistors. When the noise source of Q_{out} is transformed to the input [4], the equivalent input noise current spectrum $S(i_{n,eq})$ is given by:

$$S(i_{n,eq}) = 2q(1+1/a_i)\cdot I_{in} \qquad A^2/Hz \qquad (2)$$

Thus it becomes clear that the dynamic range of the circuit hardly depends on the adjusted gain. This is an important property in this application. In practice, with a signal bandwidth of 10kHz, a signal-to-noise ratio of 57dB can be obtained.

The auxiliary amplifier: The auxiliary amplifier has to enlarge the loop gain to such an extent that the base currents are negligibly small compared to the collector current of Q_{in}. The circuit is given in Fig.3.

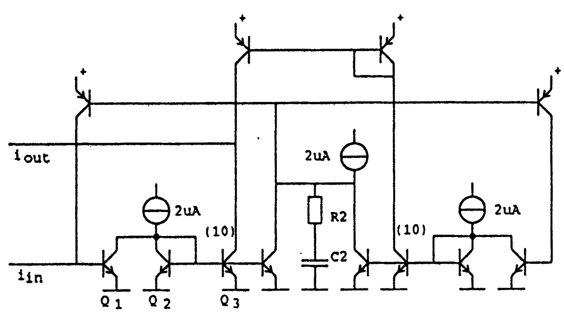

Fig.3 Circuit of the auxiliary amplifier

This is a variant of 'The Alternatively Biased Differential Pair' [5]. The amplifier consists of two stages. The first stage, Q_1, is a CE-stage and the second stage, Q_2/Q_3, is an amplifying current mirror. The circuit is implemented symmetrically because then the input bias currents can be generated by means of a common-mode loop. Because of the load of the amplifier with a PNP current mirror the common-mode loop has hardly any influence on the signal path. The only condition is that it has to be stable, which is provided for by pole-zero cancellation (R_2/C_2) [3]. Now in the signal loop of Fig.2, three poles occur (Fig.4a).

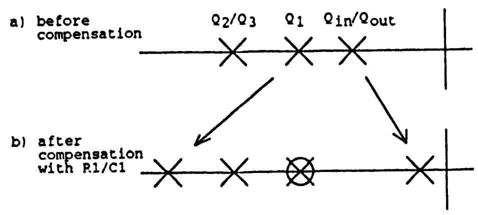

Fig.4 Pole positions in the signal loop

Because the two poles of the auxiliary amplifier are far apart, a compensation with a small, integratable capacitor is sufficient to obtain a stable loop. By using pole-zero cancellation again $(R_1/C_1$ in Fig.2), the pole contributed by Q_{in}/Q_{out} is shifted to lower frequencies while the pole that originates with Q_1 is apparantly shifted towards a much higher frequency (Fig.4).
As gain is adjusted at increasingly higher values, the pole at the lowest frequency shifts towards higher frequencies and loop gain decreases, both because of the decreasing value of $r_{pi}(Q_{out})$. As a result, the positions of the closed loop poles hardly change, so the bandwidth remains the same.
The noise contribution of the auxiliary amplifier can be made small compared to the noise calculated in eq. (2) by taking care that $I_b(Q_1) << I_c(Q_{in})$. In this case the base current shot noise of Q_1 is negligibly small compared to the collector shot noise of Q_{in} and eq.(2) remains valid.

Biasing of the controllable current mirror: Because the DC collector current of Q_{out} varies with gain adjustment, a variable output bias current source that exactly tracks the gain control has to be designed. This source is realized with a second current mirror which is also controlled by the source $V_{control}$ (Fig.5). This current mirror has been extended with an additional amplifier as well. This amplifier can be much simpler because it is not a part of the signal path. As the impedance at the emitter of Q_{in} is relatively high, no high demands are made upon the voltage source. The circuit was tested with a 30kΩ resistor which was biased with a controllable current. The noise contribution of the voltage source is usually negligible because it appears in the circuit as a common-mode effect.

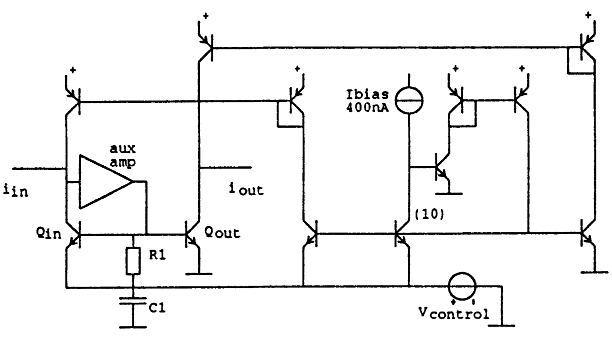

Fig.5 Biasing of the controllable current mirror

Realization: The circuit has been realized in a Philips BICMOS process in a semi-custom version. Of course, when the hearing instrument is integrated on one single chip, a full custom redesign will be made to save chip area. The values of the resistances and capacitances are: $R_1=19k\Omega$, $C_1=120pF$, $R_2=8k\Omega$, $C_2=300pF$. Fig.6 shows the frequency behaviour of the circuit. The bandwidth is approximately 150kHz. The irregularity around circa 15kHz is caused by some overshoot in the common-mode loop of the auxiliary amplifier. This effect can be overcome by using a larger compensation capacitor C_2, but this is not necessary. Moreover, a large capacitor is undesirable.

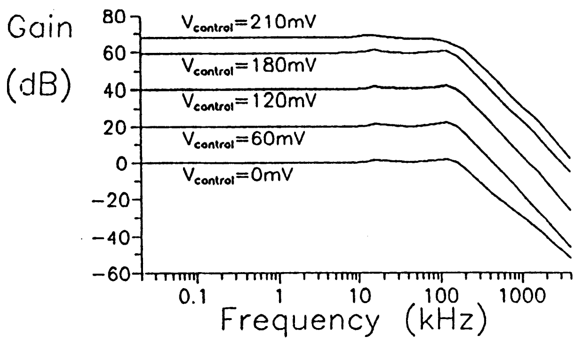

Fig.6 Current gain versus frequency

Conclusion: The proposed circuit is very simple but nevertheless provides an extremely large control range of more than 60dB, while current consumption remains very low. The signal-to-noise ratio is 57dB. THD increases with gain but remains less than 0.9%. Current consumption varies between 29μA and 93μA.

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