

Cascode-based voltage-amplifier stage

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Abstract. Voltage-amplifier stages are the basic components of commonly used high gain amplifiers the bias and other parameters of whose are set by the external negative feedback. The typical device that uses the voltage-amplifier stage is the operational amplifier. Similar constructions can also be created on the basis of discrete transistors. From the circuit designer's point of view, the voltage-amplifier stage defines the crucial parameters of the whole unit - the amplification factor, dominant pole of its transfer function and the slew rate. In this paper the proposal on construction of the voltage-amplifier stage based on discrete transistors is described. When connected between the input differential amplifier and the output stage, it allows creating of cheap amplifier for HiFi applications with considerable performance.

1 Introduction

The typical structure of an operational amplifier is depicted in Fig. 1. It consists of three basic parts – the differential input front-end, voltage-amplifier stage and the output circuit that increases the output current delivery capability.

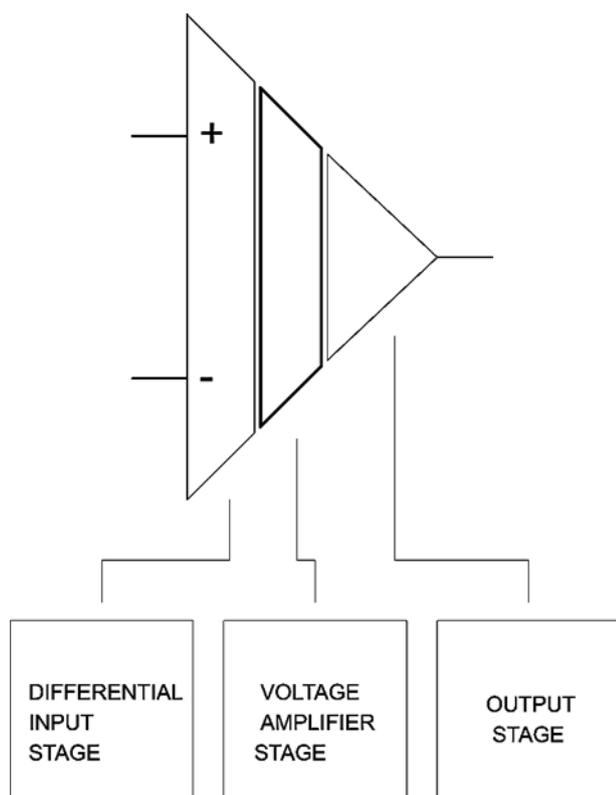


Fig. 1. Stages of a conventional operational amplifier.

Not only in power amplifiers, the voltage-amplifier stages are considered as one of the most critical parts, since they not only provide considerable gain but also must give the full output voltage swing [1]. Typical constructions of the voltage-amplifier stage are depicted in Fig. 2.

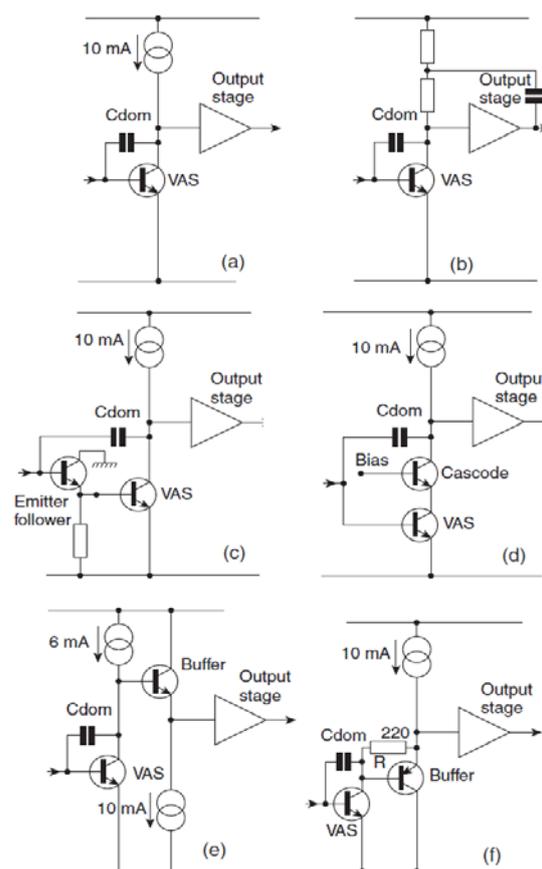


Fig. 2. Typical approaches to the construction of the conventional voltage-amplifier stages (see text).

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According to [1], the approaches depicted in figure 2 can briefly be described as follows. The approach (a) represents a typical solution with a current source load to the transistor's collector. Similar results can also be obtained by the approach (b) that is based on collector load bootstrapping. The emitter follower applied in the approach (c) allows increasing of the transistor's beta, resulting in higher local negative feedback. The feedback increase can also be performed by means of a cascode, as depicted in Fig. 2d. This solution also allows increasing of the power supply voltage as the voltage spreads across the transistors. The approach (e) consists in buffering the transistor's collector from the output stage. Another form of buffering is introduced by the approach (f).

The following goals are pursued by all of the above mentioned approaches: There is a need for high voltage amplification factors together with local negative feedback that allows linearization of the stage. Additional linearization is provided by means of the global negative feedback that defines operating parameters of the circuit. Due to the high amplification factor, the Miller's effect at the capacity between the transistor's collector and base acts as the dominant capacity (C_{dom}) to define the dominant pole of the transfer function of the whole amplifier.

In the past, several enhancements of the voltage-amplifier stage construction have been introduced. An example of such improvement is presented in the figure 3.

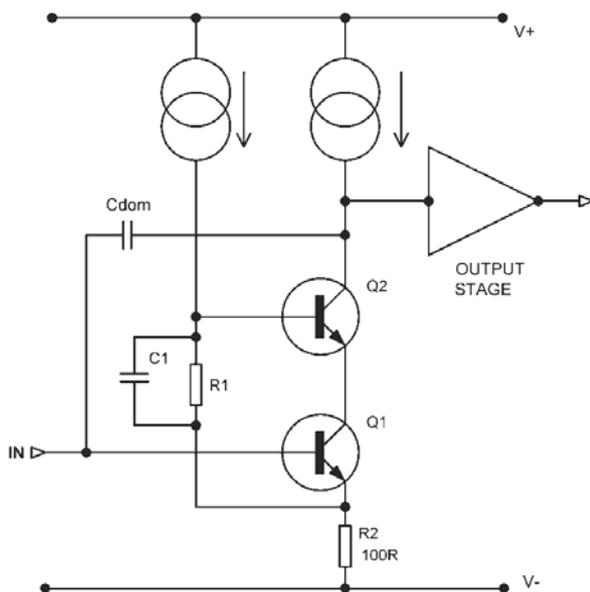


Fig. 3. Hawksford's variation of the cascoded voltage amplifier stage.

The Hawksford's solution [2] depicted in figure 3 consists in bootstrapping of the cascode transistor Q2 from the emitter of the transistor Q1 which leads to reduction of variations of the V_{CE} voltage across the transistor Q1. Many more approaches to the construction of the voltage-amplifier stage can be found in the appropriate literature [3], [4], [5].

2 Alternative approach

The authors of this paper decided to apply an alternative approach. The circuit diagram of their cascode is depicted in the figure 4. The basis of the circuit is derived from the relevant circuit diagram disclosed in [6]. It is a common-emitter common-base cascode.

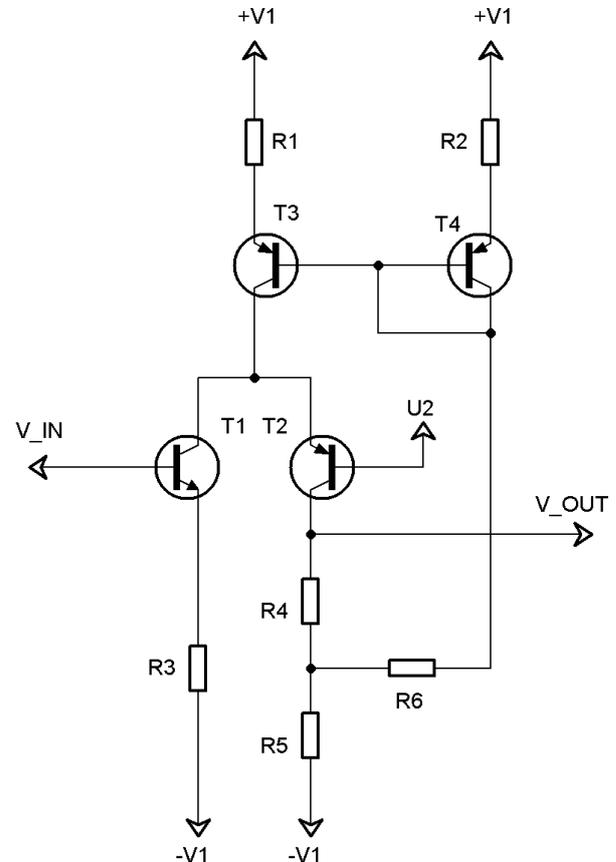


Fig. 4. The voltage-amplifier stage proposed by the authors of this paper.

The cascode depicted in the figure 4 consists of the transistors T1 and T2. While the base of the transistor T2 is connected to a fixed voltage V_2 , the base of the transistor T1 is biased by the voltage V_{IN} . The circuit's driving signal is also superimposed to this voltage. Both transistors are fed from the collector of the transistor T3 which represents a current source in this structure. The quiescent current of the cascode is defined by means of the current mirror composed of the transistors T3 and T4 and it is influenced by the negative feedback bounded between the resistors R4 and R5. Since symmetrical power supply $\pm V_1$ is expected, the target output voltage bias V_{OUT} is expected to lie near 0 V. In order to achieve large signal amplitudes, the front end's output voltage is expected to lie close to the value of $-V$ while the fixed bias V_2 of the transistor T2 is expected to lie close to the value of $+V$.

When compared to the stages described above, the hereby presented design employs large local negative feedback which eliminates its harmonic distortion and helps to stabilize the circuit's bias, even when the global negative feedback must also be applied. While the voltage

amplification factor is quite low, the circuit shows excellent performance at high frequencies.

3 Simulation

The hereby described voltage-amplifier stage has been implemented in an audio frequency preamplifier. The design of the circuit was processed with the aid of simulation software Multisim, which is based on SPICE algorithms and libraries. Several simulation outputs are provided within this chapter.

3.1 Creating the basis

The basis of the circuit depicted in the figure 4 has been inserted into the simulation software. The following points have been assumed:

- The circuit is based on BC550/BC560 low-cost low-noise transistors.
- The quiescent currents of the transistor T1 and T2 are both approximately 1 mA.
- The power supply voltage is ± 24 V.
- The front-end stage's bias is -20 V.
- The T2 bias is $+20$ V.

The values of the appropriate resistors can be defined by means of the following procedure:

The emitter current of the transistor T1 should be approximately 1 mA. Therefore:

$$R_3 = \frac{V_{IN} - V_{BE_T1} - V^-}{I_{E_T1}} \approx 3.3 \text{ k}\Omega \quad (1)$$

Where:

$V_{IN} = -20$ V (input bias voltage),

$V_{BE_T1} = 0.65$ V (BE voltage of T1),

$V^- = -24$ V (negative power supply voltage),

$I_{E_T1} = 1$ mA (emitter current of T1).

Because the required output voltage is 0 V, the voltage across the resistors R4 and R5 should be one half of the total power supply voltage, i.e. 24 V. When the feedback current through the resistor R6 is neglected, the following assumption can be made:

$$(R_4 + R_5) = \frac{0 - V^-}{I_{E_T2}} \approx 24 \text{ k}\Omega \quad (2)$$

Where:

$I_{E_T2} = 1$ mA (emitter current of T2).

The following points must be taken into consideration:

- Also the collector current of the transistor T4 flows through the resistor R5.
- The ratio between R5 and R4 defines the strength of the local negative feedback.

According to the above mentioned, the feedback current through the resistor R6 must be chosen before the values of R4 and R5 are assigned. Supposing the transistors R3 and R4 have the same current gain β , the ratio between their collector currents is as follows:

$$\frac{I_{C_T3}}{I_{C_T4}} = \frac{R_2}{R_1} \quad (3)$$

Moreover the following assumption should be fulfilled:

$$I_{C_T3} = I_{C_T1} + I_{C_T2} \approx 2 \text{ mA} \quad (4)$$

Considering the voltage drop at the resistor R1 should not be higher than 1 V, so the peak-to-peak signal voltage was not limited, it seems reasonable to choose $R_1 = 470 \Omega$. As the feedback current should be lower in order to decrease the circuit's power consumption, the following value of R2 has been chosen: $R_2 = 2.2 \text{ k}\Omega$. Now, according to (3), the estimated collector current of the transistor T4 should be approximately 430 μ A. Compared to I_{C_T2} , this current cannot be neglected. Therefore the equation (2) must be transformed into the following form:

$$(0 - V^-) = R_4 I_{C_T2} + R_5 (I_{C_T2} + I_{C_T4}) \quad (5)$$

Considering the conventional resistor values, the following combination fits well: $R_4 = 15 \text{ k}\Omega$, $R_5 = 5.6 \text{ k}\Omega$, $R_6 = 82 \text{ k}\Omega$.

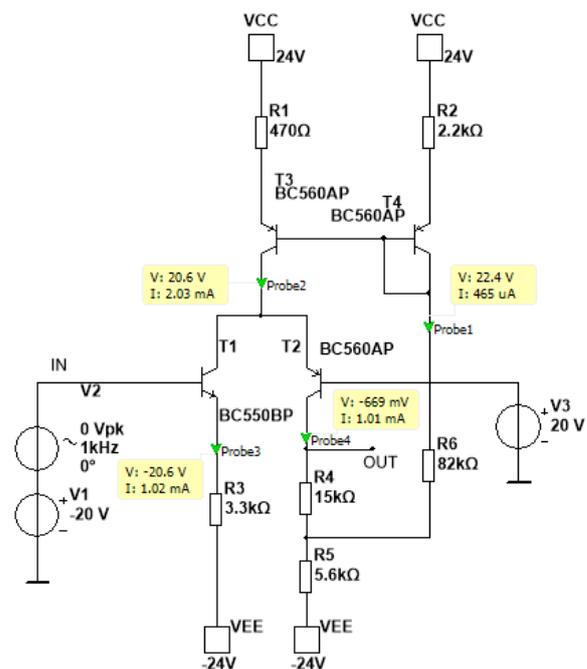


Fig. 5. Simulation diagram of the basis of the proposed voltage-amplifier stage.

The diagram of the simulated circuit is depicted in the figure 5 together with the probes showing voltages and currents in the relevant nodes. The input bias is given by the voltage source V1 while the bias of the transistor T2 is given by the voltage source V3. The voltage source V2 represents the driving signal of the circuit.

The performance of the basic circuit depicted in the figure 5 is as follows: the AC gain is 13.5 dB, the -3 dB bandwidth is 5 MHz and the total harmonic distortion is lower than 0.015 % for the output magnitude of 1 V at the frequency of 1 kHz. It is worth mentioning that the overall performance of the whole amplifier will be improved by the global negative feedback.

3.2 Gain increasing

Usually, the gain of 13.5 dB would not be satisfying in real application. There are two ways to increase the AC gain of the simulated circuit:

1. Decreasing of the local negative feedback established by the current mirror T3/T4.
2. Decreasing of the local negative feedback established by the resistor R3.

There are several technical reasons to choose the second option:

- The simple way to decrease the local negative feedback established by the resistor R3 is to bridge it by a serial combination of another resistor and a capacitor.
- The adjustments of the negative feedback introduced by the current mirror can further be made in order to improve the overall transfer function of the whole amplifier and/or to modify its slew rate.

In the figure 6 the simulation diagram of the circuit with the increased gain is depicted. The resistor $R7 = 1\text{ k}\Omega$ and the capacitor $C1 = 47\text{ }\mu\text{F}$ have been added in order to increase the AC gain of the circuit to 26 dB in the range from 4.5 Hz to 4.5 MHz (-3 dB). For the output magnitude of 1 V the total harmonic distortion is approximately 0.05 %.

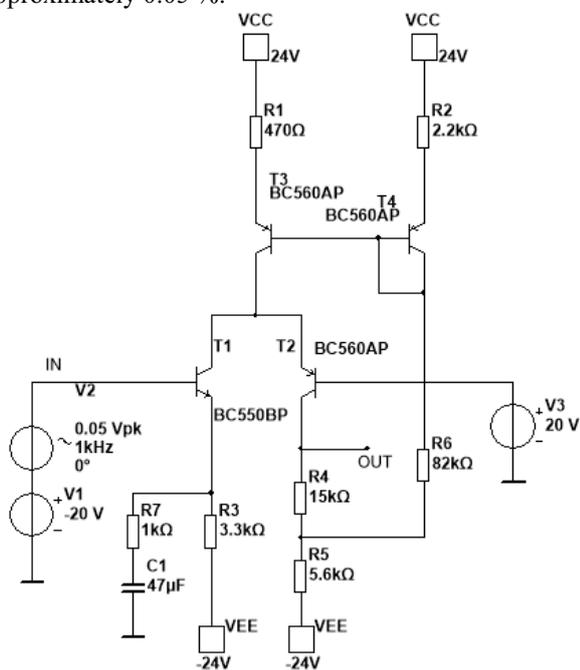


Fig. 6. Simulation diagram of the basis of the proposed voltage-amplifier stage with increased gain.

3.3 Temperature stability

The temperature drift of the output DC voltage for the circuit depicted in the figure 6 is approximately $-11\text{ mV}/^\circ\text{C}$. The temperature dependence of collector currents of the transistors T1 and T2 is depicted in the figure 7, provided the input bias is not temperature-dependent. However, this condition is rarely fulfilled in practice. The front end and back end circuits of the voltage-amplifier stage are temperature-dependent as well. Therefore this issue must be solved in the framework

of the whole amplifier. For illustration, in the figure 7 there is a simulation result of temperature dependencies of collector currents of the transistors T1 and T2 if the stage's front end employs a current mirror at its output, which is quite usual for the input differential amplifiers (see below).

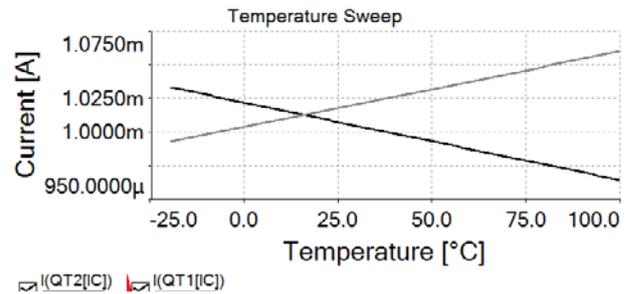


Fig. 7. Temperature dependence of T1 and T2 collector currents provided the input voltage bias is not temperature-dependent.

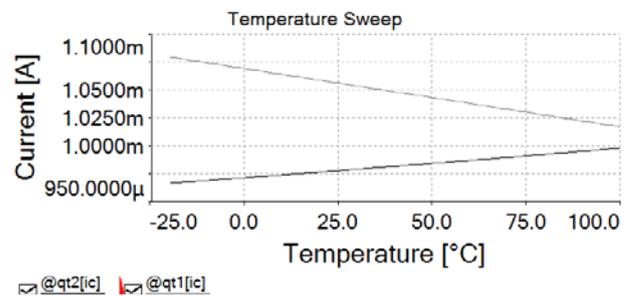


Fig. 8. Temperature dependence of T1 and T2 collector currents provided the input voltage bias is obtained from a simple current mirror.

3.4 Creating a whole

The designs of the differential input stage as well as of the output voltage follower are not the subjects of this paper. However, in practice, the voltage-amplifier stage cannot operate alone. In order to check how this stage affects the behaviour of the whole amplifier, the structure of which is depicted in the figure 1, the circuit depicted in the figure 9 has been simulated. It consists of ideal input differential stage the gain of which is 20 dB and the output bias voltage of which is -20 V , the hereby described voltage-amplifier stage and the output stage the voltage gain of which is as high as 0 dB. The internal gain of this circuit is expected to be as high as 46 dB but the set of resistors R7, R8 sets the total value to the level of 20 dB.

First of all, the open-loop transfer function of the whole circuit must be known in order to determine the stability of the circuit when the feedback loop is closed. Because the DC feedback is still necessary to process this simulation, the inverting input of the differential unit is blocked by the capacity as high as 1F. This ensures the feedback loop will not affect the transfer function at the operating frequencies. According to the simulation, the circuit would not be stable with the closed feedback loop.

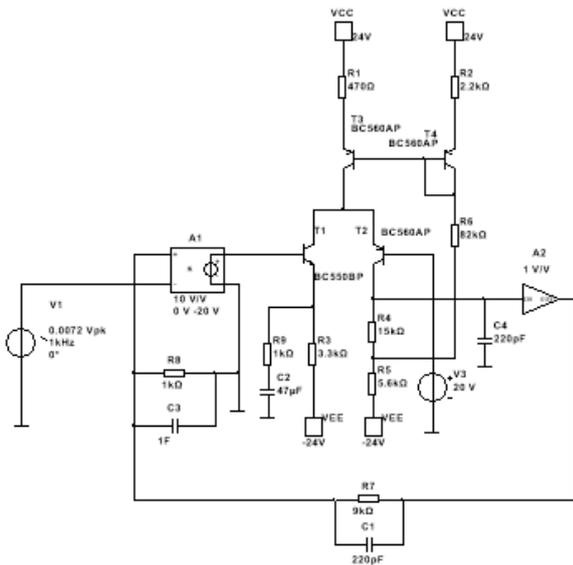


Fig. 10. A test bench for the hereby described voltage-amplifier stage.

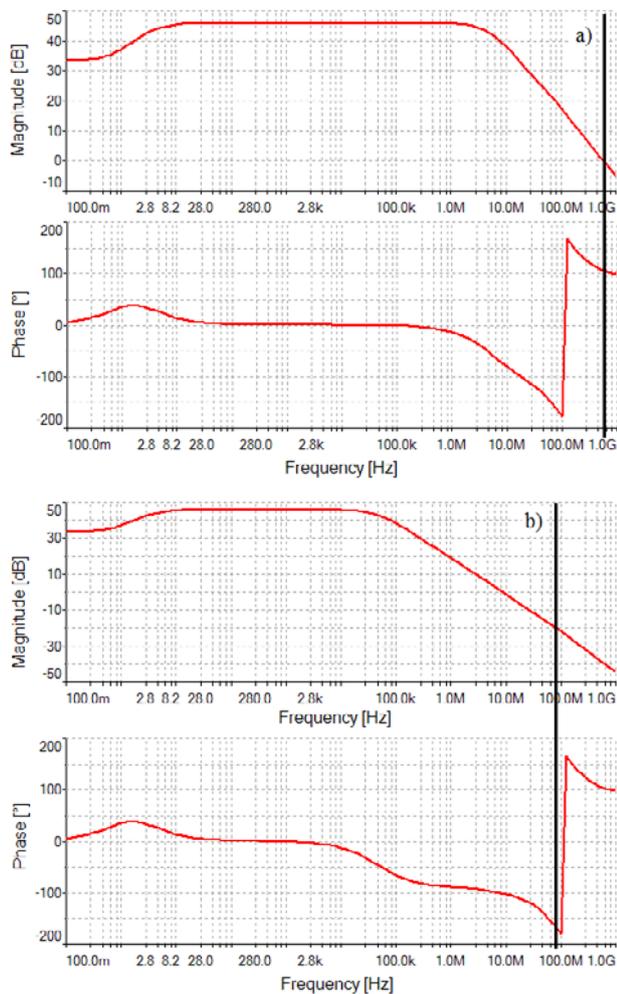


Fig. 10. Transfer function of the circuit depicted in Fig. 9 with opened feedback loop: a) without dominant pole, b) with dominant pole.

In order to fulfil the Nyquist’s stability criterion, the capacitor C4 was added into the circuit depicted in the Figure 9. It implements the dominant pole of the circuit’s transfer function. In the Figure 8b it can be seen how the transfer function is affected.

Now the circuit is expected to be stable with the closed feedback loop and the capacitor C3 (1 F) can be disconnected in order to let the feedback loop operate. Within this configuration, the simulated parameters of the circuit are as follows:

- The gain is 19.5 ± 0.5 dB for frequencies from 1 Hz to 40 kHz.
- The phase shift within the frequency range from 20 Hz to 20 kHz is lower than $\pm 15^\circ$.
- The total harmonic distortion at the frequency of 1 kHz and the output magnitude of 1 V is as low as 0.0025 %.

4 Implementation

The hereby described voltage-amplifier stage was implemented in several designs of audio-frequency amplifiers, such as universal amplifier for an equaliser or a preamplifier for MM phono cartridge. It was observed that it operated according to expectations. The application examples is depicted below.

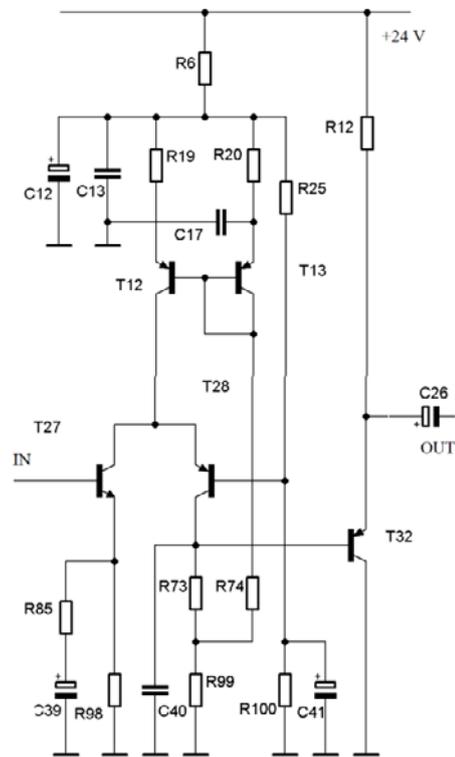


Fig. 11. Application example of the cascade-based voltage-amplifier stage. This connection has been used in an MM phono preamp with non-symmetrical power supply voltage of 24 V.

5 Conclusions

This paper provides an example of design of a voltage-amplifier stage assembled of discrete transistors. The authors provide comparison of their solution together with the usually applied solutions as well as simulations on their stage's behaviour. Obviously, this topic is too large to be fully described within a framework of a single paper. The hereby described voltage-amplifier stage has been implemented in several amplifier circuits and it can be stated that it operated as expected. However, once the stage is a part of a complex circuit obtained with one global feedback loop, it is not easy to specify how much does it causes that the whole circuit is not strictly ideal. Therefore we provided simulations showing what behaviour of the whole circuit can be expected once the hereby proposed voltage-amplifier stage is employed together with other components that show strictly ideal behaviour.

The most likely objection against this approach is probably the following one: why would anyone assemble the audio frequency amplifier using lots of discrete devices when there are suitable operational amplifiers obtainable at the market. Of course, this is true. There are, however, also arguments against this objection: The typical operational amplifiers target to as high internal amplification factor as possible. This has lots of positive effects, but there are also the negative ones – the dominant pole of the transfer function lies at low frequencies, the complex structure of the operational amplifier embodies considerable phase shifts etc. On the other hand, sensitive designer can, using discrete devices, produce any operational amplifier he likes, even that one with quite low amplification factor, but having the dominant pole of the transfer function at considerably high frequency. Moreover, when the price of a single transistor can be as low as 0.025 €, who would resist the temptation?

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References

1. Douglas Self, *Audio Power Amplifier Design Handbook* (Focal Press, 2009). ISBN: 978-0-240-52162-6
2. M. Hawksford, *Reduction of transistor slope impedance dependent distortion in large-signal amplifiers*, JAES 36 (4) (April 1988)
3. P.P. Gray , R.G. Meyer, *Analysis and Design of Analog Integrated Circuits* (Wiley, 1984),
4. J. Hefley, *High fidelity, low feedback, 200W* (Electronics & Wireless World, June 1992)
5. G. Stochino, *Ultra-fast amplifier* (Electronics & Wireless World, October 1996)
6. P. Neumann, J. Uhler, *Electrical circuits and functional units [Elektrické obvody a funkční bloky]* (Prague, CVUT, 2005), ISBN 80-01-03281-7