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On the Optimization of Enhanced Cascode

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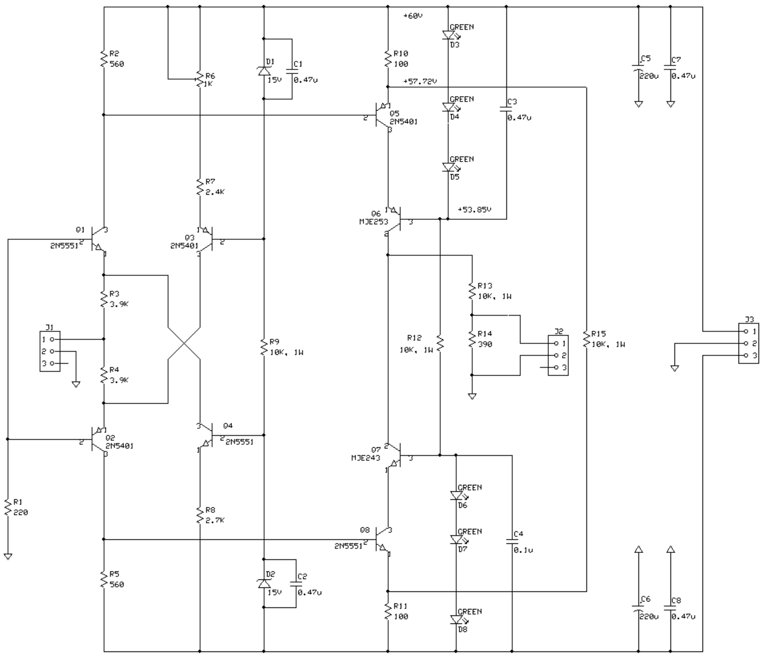
ABSTRACT

Twenty years ago enhanced cascode and other circuit topologies based on the same design principles were presented to audio amplifier designers. The circuit was supposed to be incorporated in transconductance gain stages and current sources. Enhanced cascode was used in some commercial products but have not received wide adoption. It was speculated that enhanced cascode has reduced phase margin and at times higher distortion being compared to conventional cascode. Enhanced cascode is analyzed on the basis of distortion and frequency response. It is shown how to make the most of enhanced cascode. Optimized novel circuit topology is presented.

1. INTRODUCTION

Conventional audio (power) amplifier consists of input stage, voltage amplification stage, current amplification (power) stage and feedback network. The input stage is a transconductance amplifier; loaded on frequency compensation network. The second is an inverting transconductance amplifier, loaded on the input impedance of the output stage. The third stage is a noninverting one providing power and current required by the load. There are several approaches to reduce amplifier distortion – to maximize the loop gain of the amplifier and to minimize distortion in forward path. The unity loop gain frequency can hardly be made above 5 MHz for power amplifier and this set the limit to loop gain in audio band. There are many approaches to make the loop gain higher – formation of the pole-zero pair in forward path frequency response, nested frequency compensation, additional positive feedback loop inside the main loop (error correction topologies).

The main origin of nonlinearity in transistor is the nonlinear transfer function – dependence of the output current from the input voltage. The transfer function can be linearized by the local feedback or some form of error correction. After this secondary effects like nonlinearity of transistor output impedance will prevail especially with large output voltage swing. The popular solution is a cascode, composed of a transconductance (common emitter) stage loaded with a current follower (common-base stage). Common-base stage acts as a low-impedance load for the input common-emitter stage and breaks the unwanted feedback (reverse transmission) between output and input nodes. The nonlinearity associated with common-base stage output impedance is greatly reduced but still exists in cascode configuration.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R6
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D1
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C1
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R10
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C5
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C7
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+57.72V
GREEN
D4
C3
0.47u
Q5
2N5401
GREEN
D5
R7
2.4K
Q6
MJE253
+53.85V
Q1
2N5551
Q3
2N5401
R13
10K, 1W
R3
3.9K
J1
R9
10K, 1W
R12
10K, 1W
R14
390
J2
R15
10K, 1W
J3
R4
3.9K
Q2
2N5401
Q4
2N5551
Q7
MJE243
GREEN
D6
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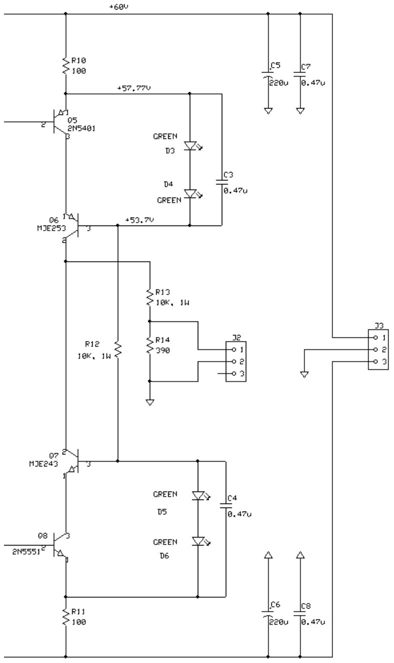
(a)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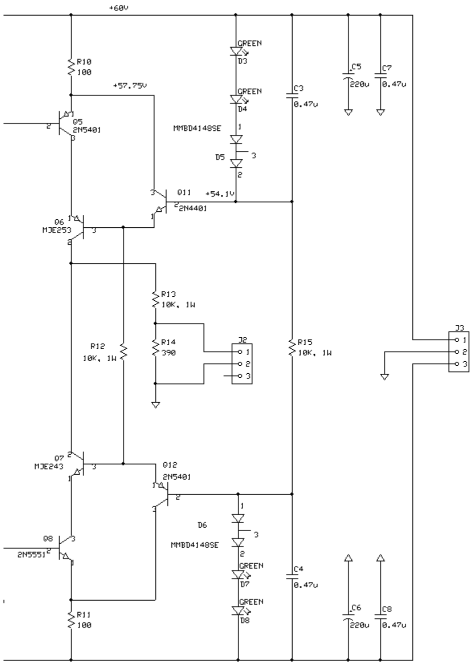
(b)



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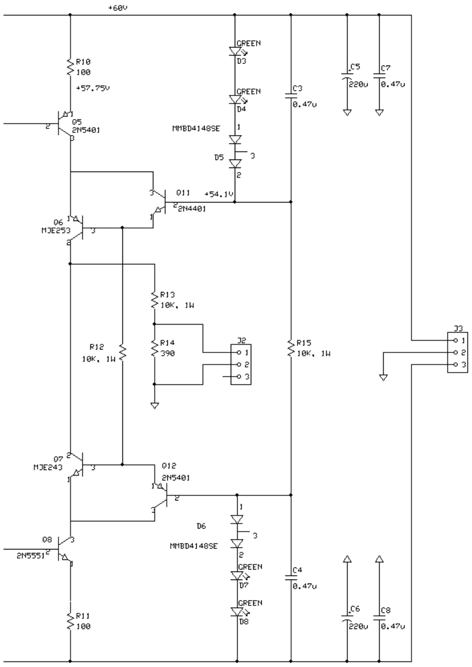


(d)

Fig. 1. Test circuit with four output stage variants. (a) Complete circuit with complementary cascode output stage. (b) Enhanced cascode. (c) Enhanced cascode with additional common base stage. (d) Optimized cascode.

Twenty years ago so-called 'enhanced cascode [1]', which allows additional distortion reduction in comparison with conventional cascode was analyzed in great detail. While this particular circuit arrangement with junction field-effect transistors [2] and bipolar junction transistors [3] was known prior to cited publication [1], the name 'enhanced cascode' will be retained throughout as an appreciation of Prof. Hawksford efforts to make the principle popular in audio community.

2. MEASUREMENTS

Tests and measurements were performed with very similar circuits that were used for validation of the technique [1]. Test circuits were constructed with full accordance with original schematics [1] and measured in detail. A special care was taken to maintain the same quiescent operating points in consequently modified test circuits. These circuits are presented in Fig. 1.

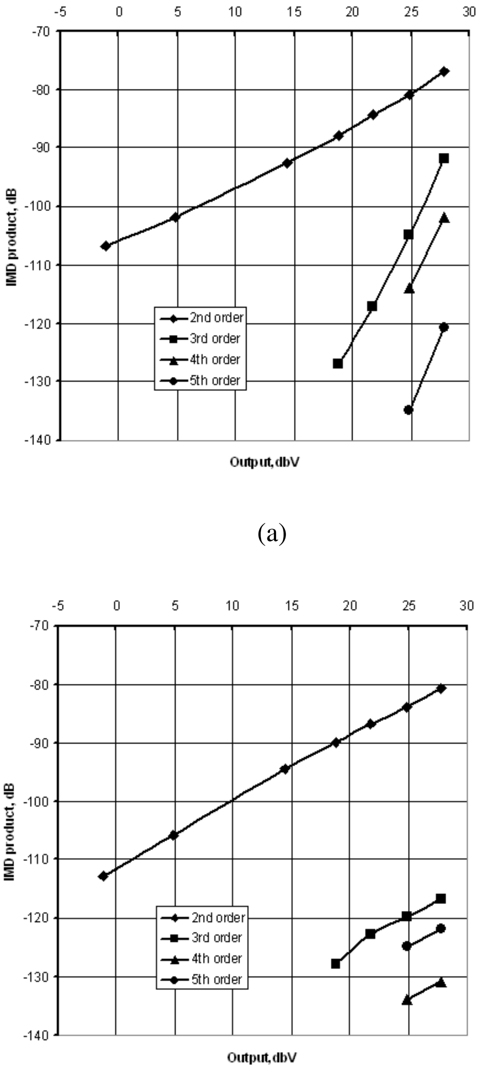
Distortion of test circuits was measured with ITU-R (CCIF) method. The test signal is a pair of equal amplitude tones spaced 1 kHz apart - 29.5 kHz and 30.5 kHz. Reference test signals near 30 kHz allow stressing nonlinearities in junction capacitances. Test signals and distortion components were in the passband of the test circuits and spectrum analyzer. The following distortion products were measured: 1 kHz, 28,5 kHz, 2 kHz, 27.5 kHz, 3 kHz, and 26.5 kHz. These products were above the noise floor.

Asymmetrical nonlinearities produce low frequency difference-frequency components, while symmetrical nonlinearities produce components near the input-signal frequencies. There are simple relations between intermodulation distortion and harmonic distortion [4].

The distortion products, measured at the output of conventional cascode are plotted in Fig. 2(a) for a voltage output from 0 dBV to 28 dBV (reference 1V rms) at 10 kΩ load. The distortion products for the enhanced cascode are plotted in Fig. 2(b) for the same conditions. Overall, a 20 dB improvement in high-order distortion products is achieved. There is small reduction (within 6dB) of difference-frequency tone (at 1 kHz), as the second order product is caused by inequality between circuit parameters of upper and lower half.

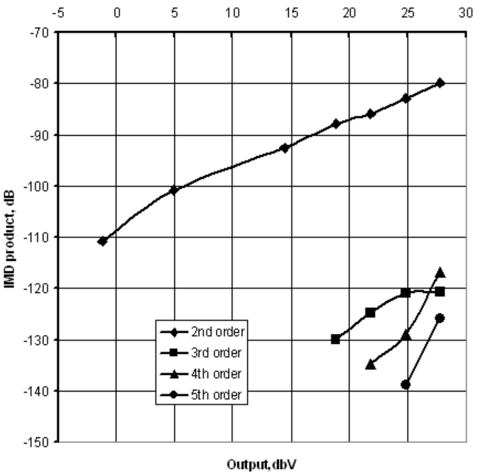
Frequency response and phase response measured at the outputs of conventional and enhanced cascode are presented in Fig. 3(a) and Fig. 3(b). Enhanced cascode allows 20 dB improvement in –3 dB bandwidth, but has substantially higher phase shift at high frequencies (above 8 MHz for test circuits, marked by circle in Fig. 3(b)).

It was mentioned [5] than this unwanted phase shift could be caused by forward transmission of the signal from emitter of common emitter stage to the load via



(a)

(b)



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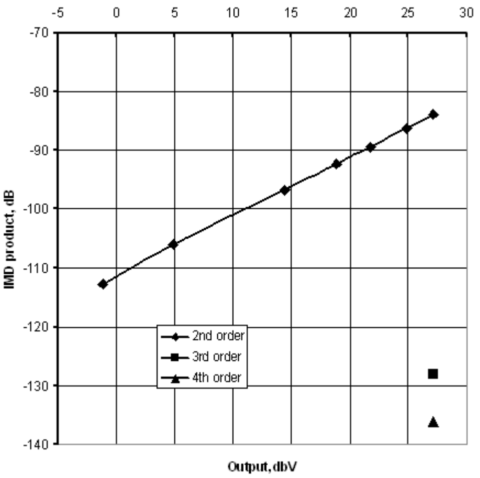


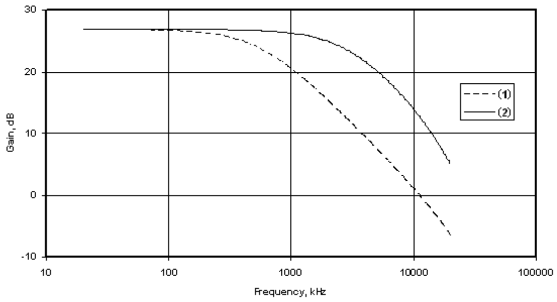
(d)

Fig. 2. CCIF distortion of the test circuits with different output stages (reference 29.5 kHz/30.5 kHz test tone pair). (a) Complementary conventional cascode. (b) Enhanced cascode. (c) Enhanced cascode with additional common base stage. (d) Optimized cascode

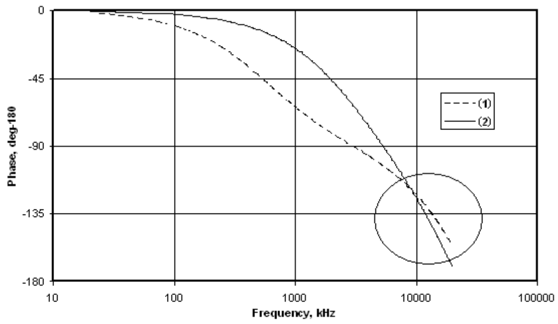
the collector-base capacitance of common-base stage. To check the validity of this idea the current follower (additional common base stage) was inserted in base network of each cascode common-base stages Fig. 1(c). The extra transistor breaks the forward transmission path, but allows addition of base current to collector current of cascode common base stage.

The distortion products, measured at the output of this cascode are plotted in Fig. 2(c). The distortion plot is slightly differed in shape from enhanced cascode, being again 20 dB less than conventional cascode. It corroborates that the main distortion reduction mechanism in enhanced cascode is the establishing of a correct return path of base current of common-base stage. Distortion reduction associated with the bootstrapping of collector-base capacitance of common emitter stage is negligible, at least in tested circuits.

At the same time, inclusion of additional current followers gives no effect to the frequency and phase response of the test circuit (Fig. 3(a) and Fig. 3(b)).



(a)



(b)

Figure 3 Frequency (a) and phase (b) response for different output stages. Dotted trace (1) corresponds to conventional complementary cascode. Solid trace (2) corresponds to enhanced cascode and enhanced cascode with additional common base stage.

3. DISCUSSION

The nodal equations can be written for frequency response analysis of the enhanced cascode. The resulted equation after four by four matrix transformation is rather complicated and doesn't allow physical interpretation. So we will consider significant terms and discard unimportant.

Let us address to the simplest transconductance stage with current feedback provided by emitter (source) resistor (Table 1(a), low frequency simplified.) The active device here is represented with simplest π model. Only input impedance and voltage controlled current source (VCCS) are taken into account. The VCCS current flows through *R3* and *R2*. The voltage drop across emitter resistor *R2* subtracted from the input voltage, thus allow less current through *R1*. The equivalent input resistance of the stage is: $R11=(1+g_m R2)R1$ (Table 1(b)).

Now let us have a look on the simplified small signal model of enhanced cascode (Table 1(c).) Here *C1* represents collector – base capacitance of common base stage. The fundamental difference with conventional stage is the existence of two current paths. The high frequency VCCS current is shorted through *C1*, while low frequency flows through *R3* and *R2*, as shown in Table 1(c) with rounded rectangle traces. As emitter resistor *R2* is not in the high frequency current path anymore, it would be no reduction of the voltage drop across *R1* at higher frequencies, and the input impedance of the cascode would be equal to the input impedance of conventional cascode without emitter degeneration resistor (see Table 1(d).) Combined with high output impedance of the preceding stage this is the reason of additional phase lag. Note that the equivalent circuit (Table 1(d)) doesn't contain *C1* in the output network – this is an origin of distortion reduction. Instead, nonlinear *C1* appears in the input network, and that can give a substantial contribution in overall distortion with high source impedance.

When capacitive load of enhanced cascode is taken into account (Table 1(e)), only fraction of VCCS current will flow through *C1,* being proportional to *C1* and *C2* ratio. For the enhanced cascode the input impedance at low frequency can be written as $R1+g_m R2R1$ and at high frequency as $R1+$ $+g_m R1R2C2(C1+C1)$ (Table 1(f)).

Two basic principles of enhanced cascode are [1]:

- Adequately high current feebdback resistor (emitter resistor) to disassociate collector-emitter impedance of the common base stage from the output impedance of enhanced cascode
- Addition of base current of the common base stage to its collector current to disassociate collector-base capacitance of the common base stage from the output impedance of enhanced cascode

These principles give numerous possibilities for generating new circuits. One of the examples – optimized cascode is presented in Fig. 1(d). Emitter resistor is substituted with the output impedance of the common emitter stage (Q5 and Q8), while the return of common base stage base current is organized by additional common base stage (Q11 and Q12) [6]. The distortion products for the optimized cascode are plotted in Fig. 2(d.) Additional 12 dB of reduction in high-order distortion products is achieved. This cascode does not require low source impedance and proposed common base stage can be used in parallel (folded) cascode as well, as shown in Fig.4.

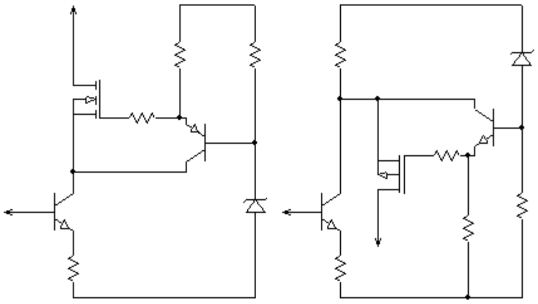
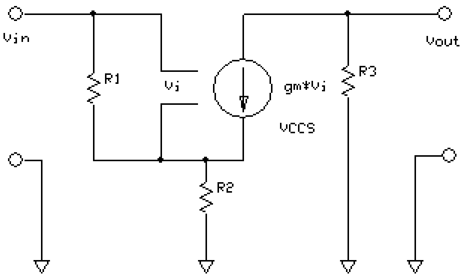


Fig. 4. Series and parallel (folded) cascode with optimized common gate stage.

Table 1. Small-signal equivalent circuits of transconductance gain stage with current feedback



(a)

Transistor represented with voltage controlled current source with transconductance g_m and input resistance *R1* (for bipolar junction transistor $g_m = I_c/26mV$, $R1=\beta / g_m$), *R2* is the current feedback shunt (emitter resistor) and *R3* is the load.

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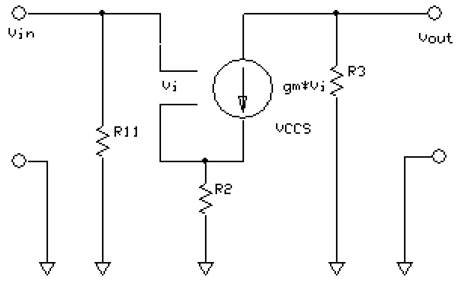
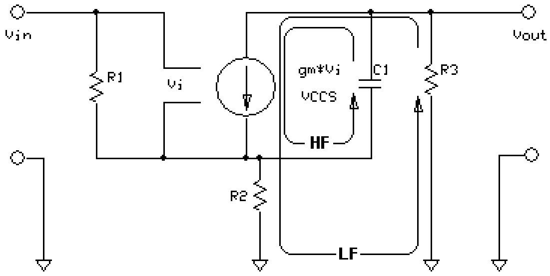


(b)

$R11=R1(1+g_m R2)$



(c)

Enhanced cascode gain stage, *C1* represents collector – base capacitance of common base stage. (Observe different paths for low frequency and high frequency currents.)

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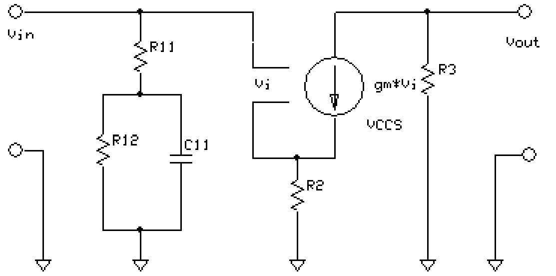
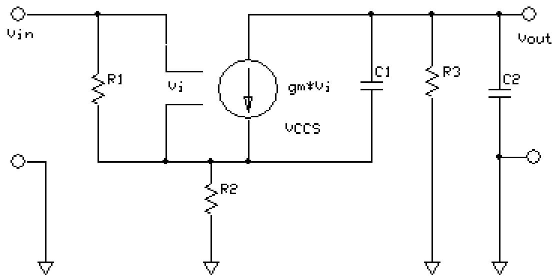


(d)

$R11=R1$, $R12=g_m R1R2$, $C11=C1/2$



(e)

Enhanced cascode gain stage with capacitive load *C2*.

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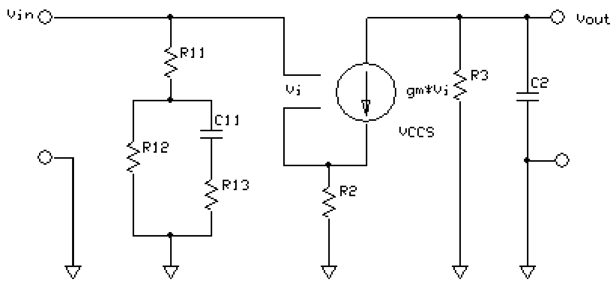

(f)

$R11=R1$, $R12=g_m R1R2$, $R13=g_m R1R2C2/C1$

4. CONCLUSION

In this paper consideration is given to voltage amplification stages suitable for the second stage of the audio amplifier. In comparison to conventional cascode enhanced cascode allows substantial reduction of high-order distortion products. Low impedance signal source (emitter follower) is required for correct operation of enhanced cascode. Presented optimized cascode allows additional 12dB reduction of high-order distortion products and diminishes requirement to preceding stage output impedance.

5. ACKNOWLEDGEMENTS

The author is grateful to Walter Jung, who brought Ref. [6] to the author's knowledge.

6. REFERENCES

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