Tanh cascode cell amplifier – an arbitrary transfer characteristics amplifier

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An arbitrary transfer characteristic (TC) amplifier, called the tanh cascode cell (TCC) amplifier, is reported. This novel amplifier is capable of synthesising an arbitrary TC including the ideal rectifier transfer characteristic, which is highly desirable for analogue circuits such as power amplifiers, low-noise amplifiers, mixers, op-amps, instrumentation amplifiers etc. The flexible transfer characteristic, wide dynamic range and high linearity capability of the TCC amplifier are demonstrated with a 16-cell MOSFET prototype.

Introduction: Over the past six decades electronic transistors have evolved from generation to generation [1]; however, the basic shape of their transfer characteristic (TC) remains similar to that shown in Fig. 1. It is well known that the minute details (including derivatives) of the TC shape of a transistor are of paramount importance to the linearity/distortion of an amplifier. To date a few amplifier TC manipulation techniques are known to designers, such as the derivative superposition [2], the multi-tanh technique [3], and others [4–7]. The derivative superposition method [2, 4–6] is a single-ended topology but the dynamic range performance appears to be limited by the inherent nonlinearities of the devices. Multi-tanh techniques [3, 7] are based on differential pair topologies making them unattractive for power-efficient applications such as class A or B linear power amplifiers.

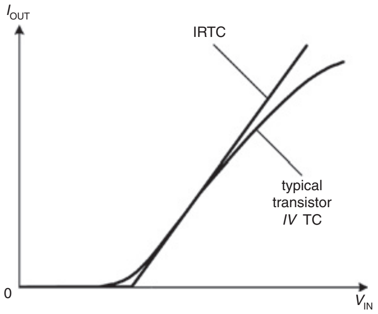

Fig. 1 *Typical transistor IV TC IRTC*

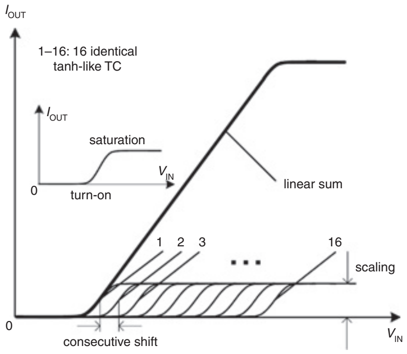

Fig. 2 *Synthesis concepts with 16 basis cells*

In this Letter, we introduce the tanh cascode amplifier, which is capable of achieving arbitrary TCs, including the ideal rectifier transfer characteristic (IRTC). The goal is to provide an analogue circuit synthesis technique that offers circuit designers more freedom to engineer various amplifiers TC to their needs. The Letter focuses conceptually on how to attain specific TCs with the tahn cascode cell (TCC) amplifier but not the specific applications that would benefit from such capability.

TCC amplifier: Fig. 2 shows the synthesis concepts of a TCC amplifier with 16 single-ended basis cells. Each basis cell is engineered to exhibit a tanh-like *IV* TC with turn-on and saturation features as shown in Fig. 2. With appropriate offset (shifting) and magnitude (scaling) arrangement, virtually any single-ended TC can be synthesised with a sufficient number of basis cells. For instance, in Fig. 2*a* practical IRTC can be synthesised by a total of 16 basis cells with, in this case, equal scaling and equal shifting.

In this Letter the TCC, as shown in Fig. 3*a*, is based on MOSFET transistors but it can be readily applicable to other members of the FET or BJT family. The TCC shown in Fig. 3*a* appears strikingly similar to a conventional cascode amplifier, but the operation of the TCC is fundamentally different. Unlike the conventional cascode amplifier, node *N* of the TCC is deliberately reduced to a small value. Consequently, as the gate voltage of M_1 increases beyond its threshold voltage, the voltage at node *N* quickly reduces such that M_1 enters into deep triode region operation. This quickly saturates the cell current (I_{OUT}). As a result the shape of the TCC TC exhibits a tanh-like shape.

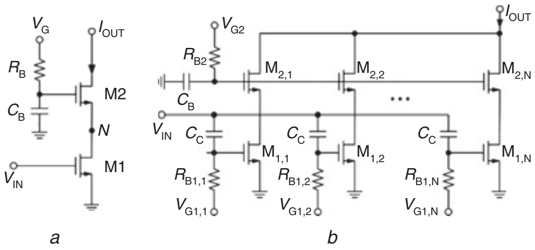

Fig. 3 *MOSFET implementation of arbitrary TC amplifier*

a Tanh cascode cell
b *N*-cell TCC amplifier

Notice that if the voltage headroom at node *N* is slightly raised, the tanh-like feature is still preserved and the magnitude is increased. Therefore scaling of the basis TC can be controlled by the voltage V_{G2}, in addition to absolute/relative sizing of the transistors. On the other hand, the shifting of the basis TC is achieved via biasing at the gate of M_1, control of the threshold voltage/body bias or by other physical means. Owing to the tanh-like TC we therefore coined this cell the TCC.

Fig. 3*b* delineates the overall arbitrary *IV* TC amplifier constructed from a multiplicity of *N* TCCs with flexible shifting and/or scaling. The maximum number of TCCs is limited only by the gate oxide breakdown voltage for a typical MOSFET device. Therefore, the MOSFET TCC amplifier in Fig. 3*b* offers surprisingly wide dynamic range, which is only restricted to gate oxide breakdown voltage. This feature is indeed novel when compared to conventional amplifiers where the dynamic range is limited by its (fixed) TC nonlinearities. The benefits of cascode-like topology of the TCC amplifier include fruitful alleviation of drain voltage stress [8], better output–input isolation as well as larger output impedance, all of which are appreciated by analogue amplifier designers. Furthermore, absolute and relative device sizing (between M_1 and M_2) can also be exercised to improve bandwidth, minimise hot carrier degradation and further fortify amplifier ruggedness, without jeopardising dynamic range (or linearity) as consequential modifications made to the overall TC can be simply rectified by adjustment of the basis cell shifting and/or scaling. The small peak efficient penalty due to consumption of a small voltage headroom at node *N* of the TCC can be more than offset by the improved linearity and increased dynamic drain–source voltage for the common gate device (M_2 in Fig. 3*a*) owing to its constant gate voltage. Moreover this drawback can be further offset by increased V_{DD} applicable to the cascode topology [8] for power amplifiers.

Experimental results for 16-cell demonstrator: To demonstrate the innovative concepts of the TCC amplifier, a 16-cell ($N = 16$) TCC amplifier was designed and manufactured with 1.1 µm discrete MOSFET transistors. The schematic of this TCC amplifier is shown in Fig. 3*b* (with $N = 16$). For this amplifier, each tanh cascode basis cell has the same scaling and manipulation of the *IV* TC is achieved only through proper shifting. Nevertheless, the arbitrary *IV* TC capability is demonstrated by showing three different linearity characteristics: an increasing TC transconductance (*gm*), flat TC *gm* (IRTC) and a decreasing TC *gm* in Fig. 4. By comparing the IRTC from the prototype with the *IV* TC of a conventional linear MOSFET cascode (same size for M_1 and M_2) amplifier, significant dynamic range advantage of the prototype is also observed.

For highly linear single-ended class-A amplifiers it is well known that an IRTC is needed. In Fig. 5 the measured harmonic distortions are compared for a 2 MHz input signal of the experimental TCC amplifier configured for IRTC (biased for class-A operation) with that of a conventional linear cascode amplifier (also biased for class-A) of the same size. Measured results in Fig. 5 clearly demonstrate that the TCC amplifier (when operated as class-A with IRTC) has a minimum of 20 dB advantage for all harmonics when compared to a conventional linear cascode amplifier with ample headroom. Also interesting is the non-classical slope for all harmonic distortions (second (HD2), third (HD3), fourth (HD4) and fifth (HD5)). Since the linearity of the conventional linear cascode amplifier is dominated by the common source device, of which the *IV* TC resembles that of a normal MOSFET, it is comfortable to infer that similar harmonic distortion advantageous figures can be expected when compared with a normal class-A MOSFET transistor amplifier.

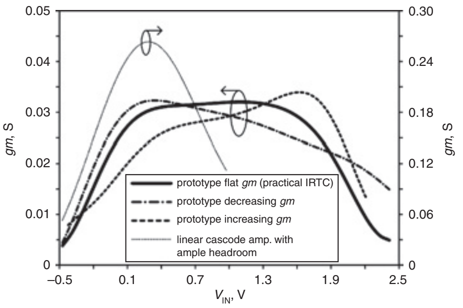

Fig. 4 *Measured transconductance (gm) of TCC and conventional linear cascode with ample headroom*

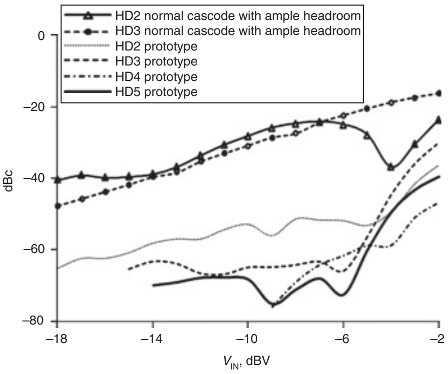

Fig. 5 *Measured harmonic distortions of 16-cell TCC amplifier (class-A with IRTC) and linear cascode amplifier with ample headroom*

Conclusions: An arbitrary TC amplifier called the TCC amplifier is presented. The TC of the TCC amplifier is controlled by voltage biasing, device sizing and other physical means at the device or amplifier levels. The arbitrary *IV* TC concepts are also demonstrated by several different *IV* TC transconductances as well as its highly linear performance when configured as an IRTC amplifier biased for class-A operation.

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