Low power, current mode CMOS circuits for synthesis of arbitrary nonlinear functions

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Abstract - *Low voltage CMOS circuits, operating in current mode, that exhibit piecewise transfer characteristics are presented. These circuits can be used for the synthesis of arbitrary piecewise transfer functions. Several circuits were developed. Nonlinear functions were synthesized with several approaches and results were compared using the Monte Carlo simulation of PSPICE software. The best results were obtained with double break point circuits. These circuits can be supplied with less than 1V.*

1 Introduction

Analog nonlinear signal processing is usually at least 1000 times faster than digital signal processing. While the main disadvantage of analog processing is its limited accuracy, it can be used in many applications where speed is more important than accuracy. The concept of piecewise approximations of nonlinear systems is not new [1-3]. Piecewise networks are usually implemented as a resistive network with diodes and it is often assumed that the diodes are ideal [4-6]. Unfortunately such diode-resistor network cannot be implemented in modern CMOS integrated circuits and another solution has to be found. Authors of [7] have proposed usage of the MOS current mirrors to obtain the required one direction (diode like) operations. Slopes of piecewise approximations are not controlled by a resistor value but by the W/L ratios of transistors in current mirrors.

The concept described in [7] used simple current mirrors and was implemented to create trapezoidal fuzzy membership functions. In this publication three different approaches are presented. Section 2 describes usage of current mirrors as nonlinear elements. This concept is similar to the one used in [7], but more general shapes are created. The approach of section 2 has several disadvantages but a major one is that in more complex systems, for large input currents the error cumulates, and often a significantly different shape than the required one is obtained. The concept presented in the Section 3 does not have these disadvantages.

2. Current mirror as nonlinear element with a single break point

A simple current mirror operates as a diode since the output current flows only for positive input current. If this diode is combined with a constant current source then the threshold of the input current can be arbitrarily shifted. Such a combination of a simple current mirror with current source exhibits piecewise transfer characteristics with one break point and can be used for synthesizing arbitrary nonlinear functions. In this case, the slopes of the piecewise approximations are not controlled by a resistor value but by the W/L ratios of transistors in the current mirrors. Another advantage of these circuits is that they operate in current mode, which follows the current trend of analog signal processing circuits.

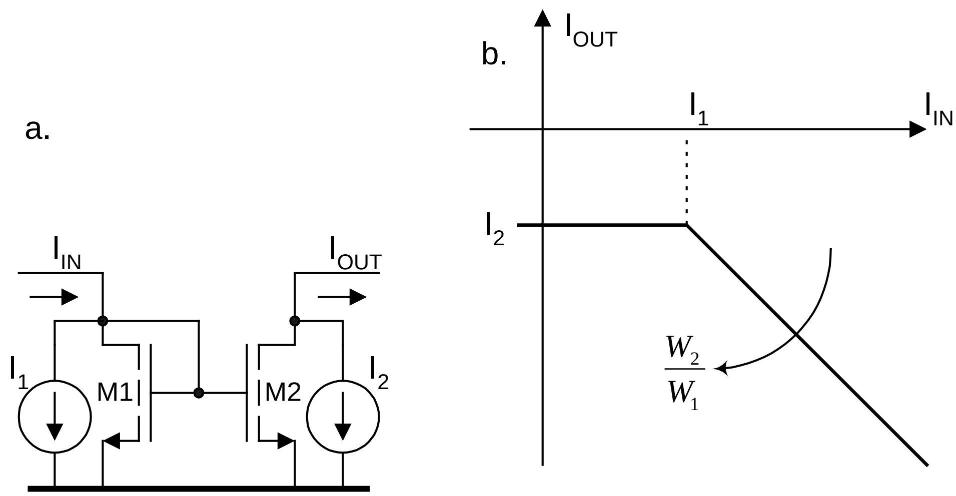

Fig. 1. A biased current mirror composed of two NMOS transistors and two constant current sources (a), and its input-output characteristics (b).

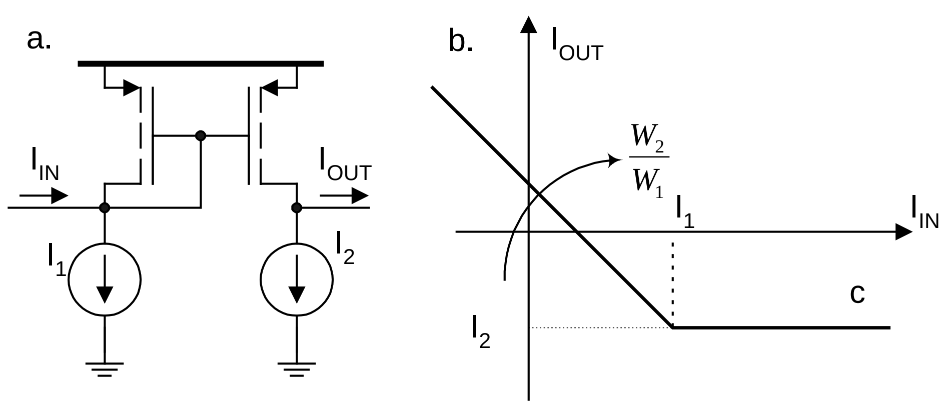

Fig. 2. A biased current mirror composed of two PMOS transistors and two constant current sources (a), and its input-output characteristics (b).

A current mirror with biasing current sources is shown in Fig. 1 (a). The input-output characteristics of such a current mirror is shown in Fig. 1 (b). Note that by changing I_1 and I_2 the transfer characteristics can be moved vertically and horizontally. When a PMOS current mirror is used (Fig. 2), the transfer characteristic has a different character. NMOS and PMOS current mirrors can be combined as shown in Fig. 3 and Fig. 4 resulting in another type of piecewise dc transfer functions. Slopes of the transfer functions shown in Figs. 1 to 4 can be easily adjusted by proper W/L ratios of MOS transistor pairs. For example, assuming the same channel length for the transistors in the current mirror, then as W_2/W_1 (W are channel widths) increases, the slope of the transfer characteristic increases.

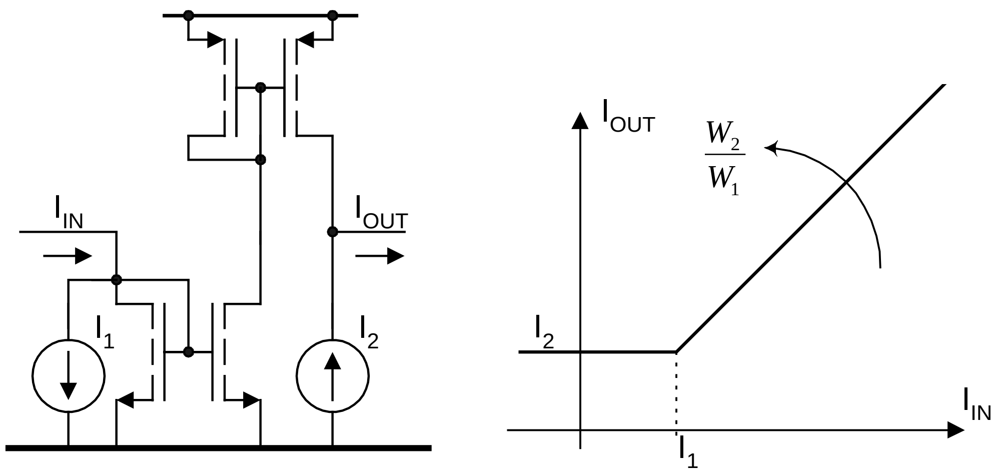

Fig. 3. NMOS-PMOS combination of current mirrors.

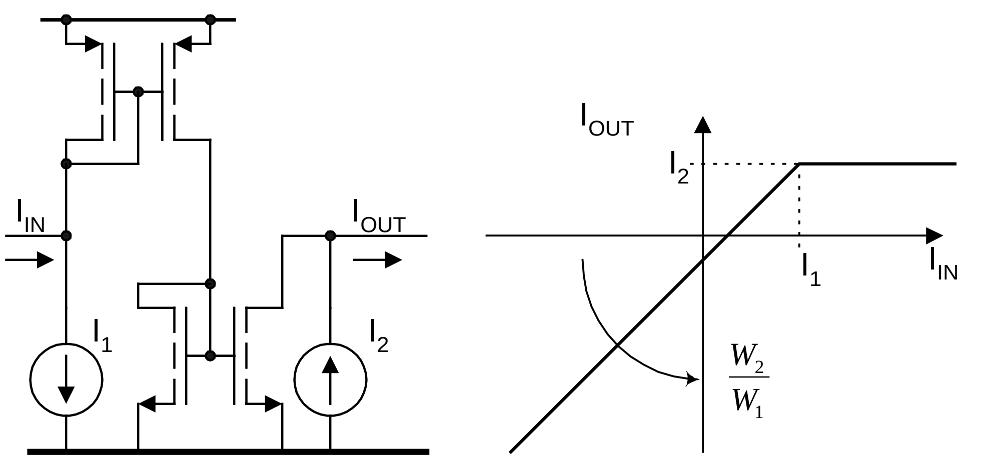

Fig. 4. NMOS-PMOS combination of current mirrors.

The four different transfer characteristic shapes of Figs. 1 to 4 can be combined to synthesize any nonlinear transfer characteristic. For example by connecting four circuits to one common output node the shape of Fig 5 can be synthesized. In this case three circuits of Fig. 1, one circuit of Fig. 3, and a constant current source are used.

Unfortunately such an approach has one significant drawback. In this case, the output current is the result of additions and subtractions of currents from the different stages. Since these are not ideal current mirrors, the small difference in the transfer characteristics of individual current mirrors will result in a relatively large error for large input currents. Note that a relatively small output current is a sum of large positive and negative currents generated by "diode" circuits. This disadvantage is illustrated in the Monte Carlo analysis shown in Fig. 6.

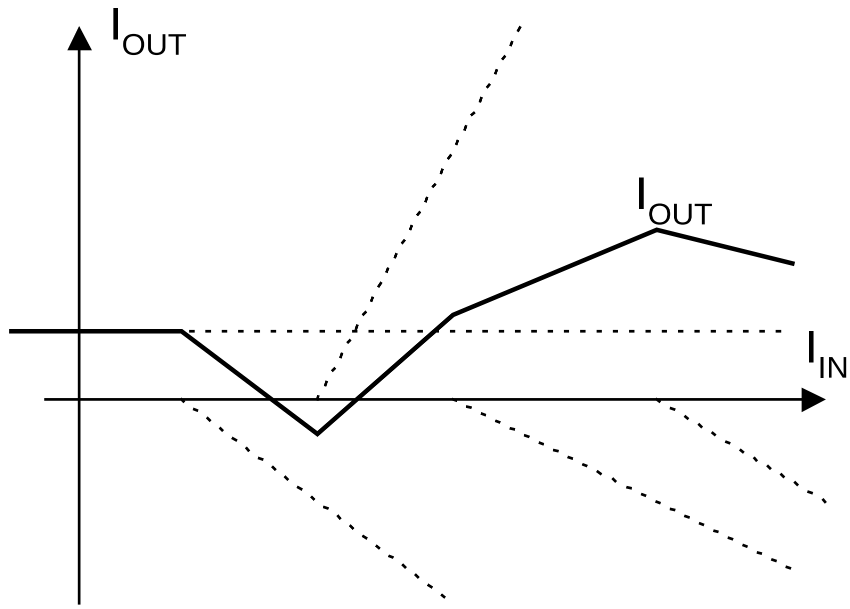

Fig. 5. Theoretical transfer characteristic when connecting four stages in parallel.

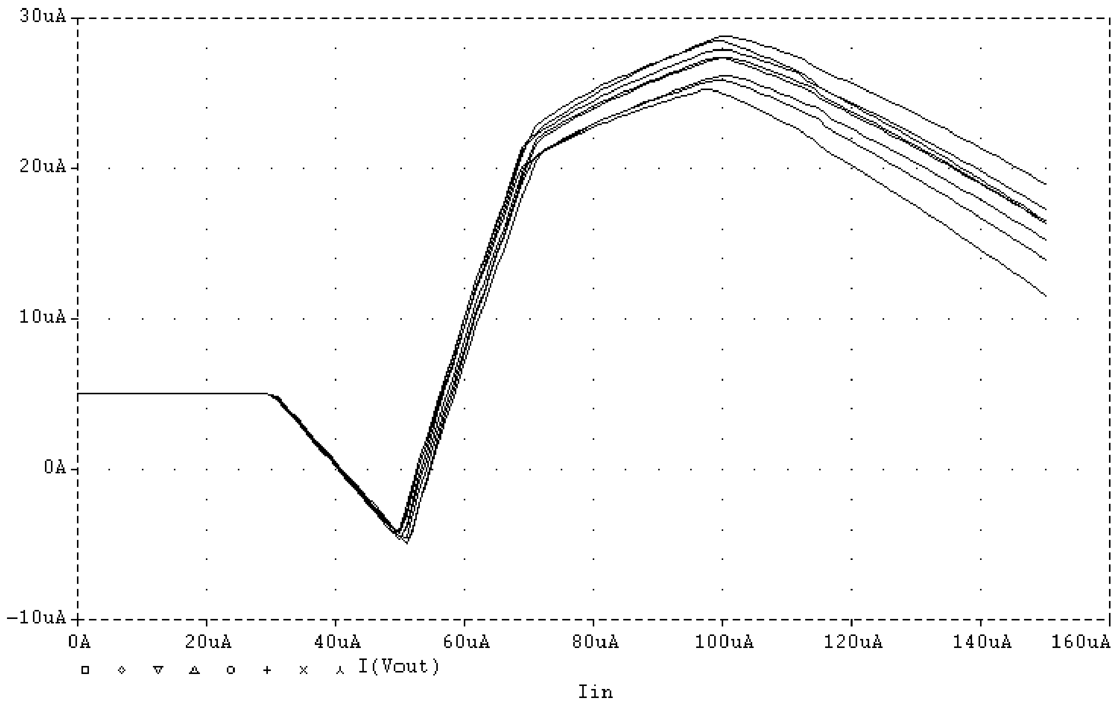

Fig. 6. Monte Carlo analysis using SPICE program of the circuit built of current sources from Figure 1 and 3. In the analysis the following parameter deviations were used: V_{TH}=>±5mV, K_p=>±1%, t_{ox}=>±0.1%, μ=>±1%, L=>±2%, and W=>±2%.

3. Current Mirrors with double break points

Improved nonlinear transfer functions can be synthesized using circuits composed of two MOS current mirrors. One such circuit is shown in Fig. 7. The circuit is composed of two NMOS current mirrors connected in cascade instead of parallel connection. The resulting characteristic has two break points. For small input currents the output is constant and equal to αI_2 , while for large currents the output is zero. The constant α is the ratio of W_4/W_3. Note that this circuit may operate with less than 1V power supply. A similar concept with PMOS transistors and its corresponding characteristics are shown in Fig. 8. By combining circuits of Fig. 7 and 8 any piecewise transfer characteristics can be synthesized.

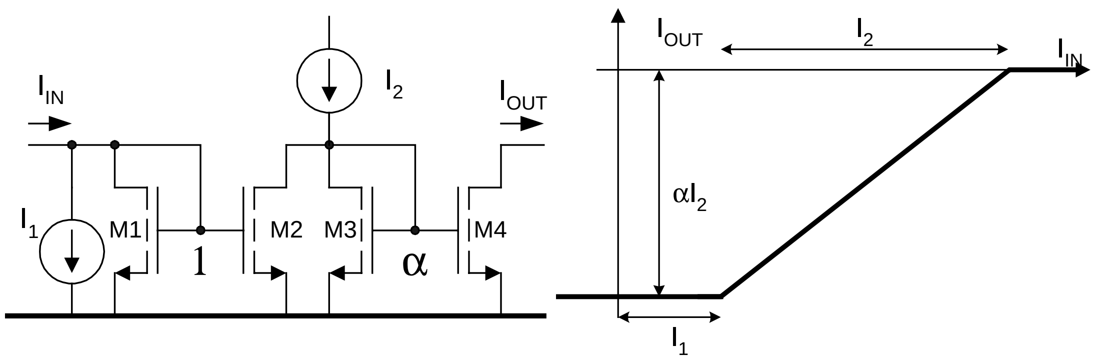

Fig. 7. Double break point circuit with NMOS transistors

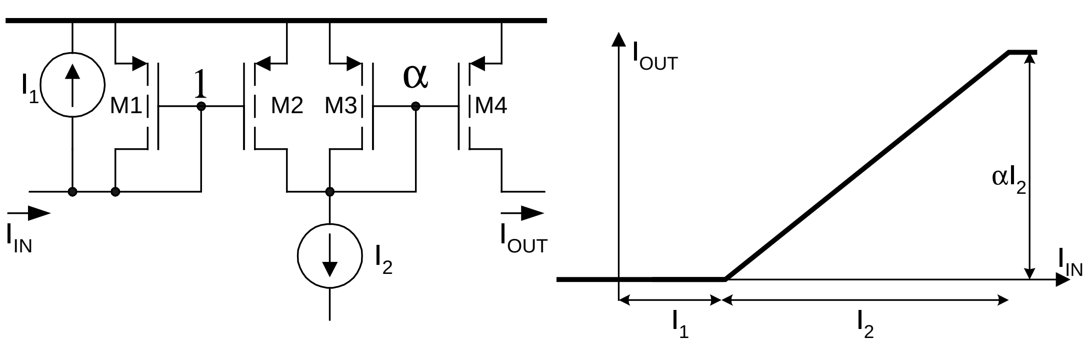

Fig. 8. Double break point circuit with NMOS transistors

Other implementations of the double break point characteristic are shown in Figs. 9 and 10. When the sum of the currents through the first current mirror (I_{D1} and I_{D2}) is less than the current through M3, there is a linear relation between I_{OUT} and I_{IN}. When $I_{D1} + I_{D2} \geq I_{D3}$, the output current levels-off at a value determined by the current I_2 and the W/L ratios of the first current mirror (M1 and M2). In this circuit, the W/L ratio of the current mirror M1 and M2 can be used to change the slope of the transfer characteristic. The addition of the current source I_1 allows for movement of the transfer characteristic along the y-axis. A similar circuit can be implemented using PMOS current sources (see Figure 10).

With two break point circuits any piecewise transfer function can be synthesized as shown in Fig. 11. Actual implementation, using subcircuits of Fig. 9 and 10 is shown in Fig. 12. Results of SPICE simulation for this circuit is shown in Fig. 13.

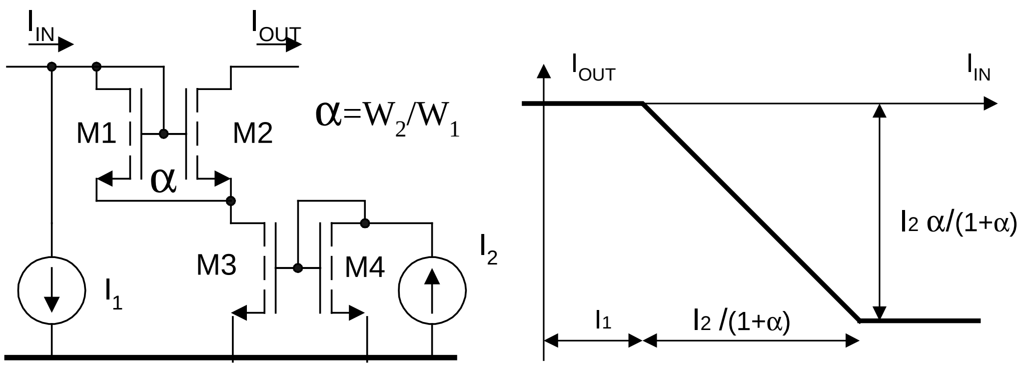

Fig. 9. Improved circuit that uses two NMOS current mirrors and its dc transfer characteristics.

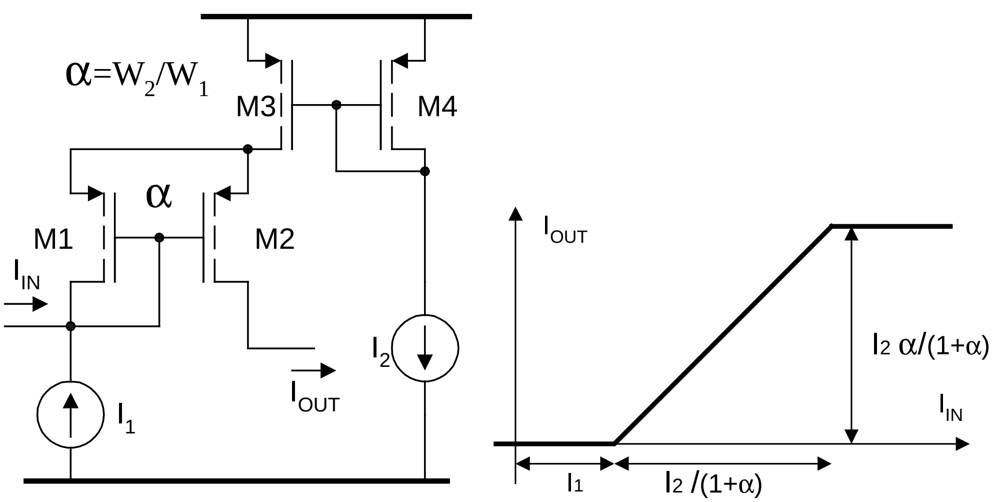

Fig. 10. Improved circuit that uses two PMOS current mirrors and its dc transfer characteristics.

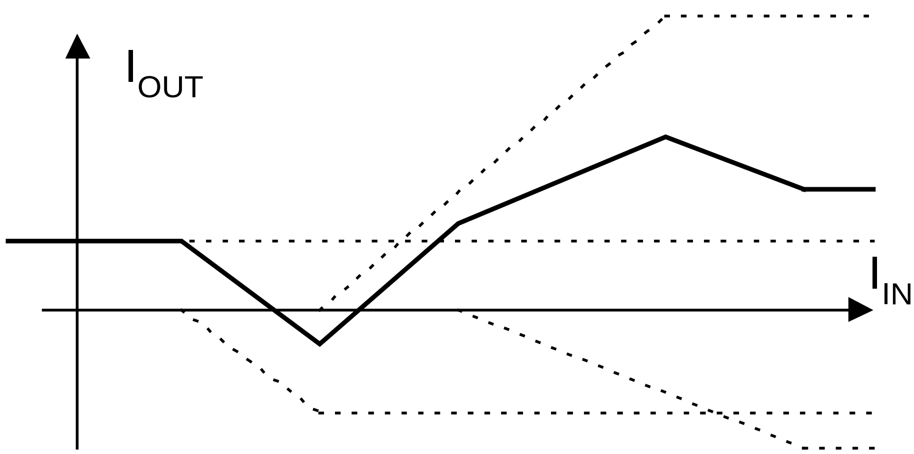

Fig. 11. Example of the same transfer function implemented with improved circuits.

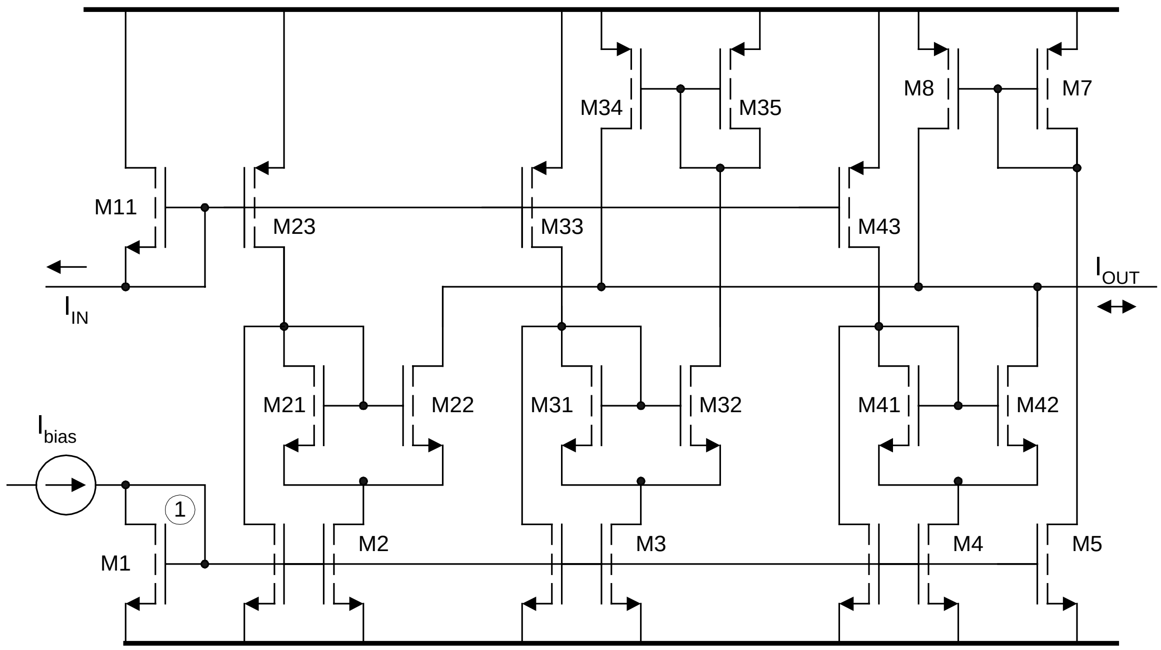

Fig. 12. Circuit implementation of the transfer function from Fig 11.

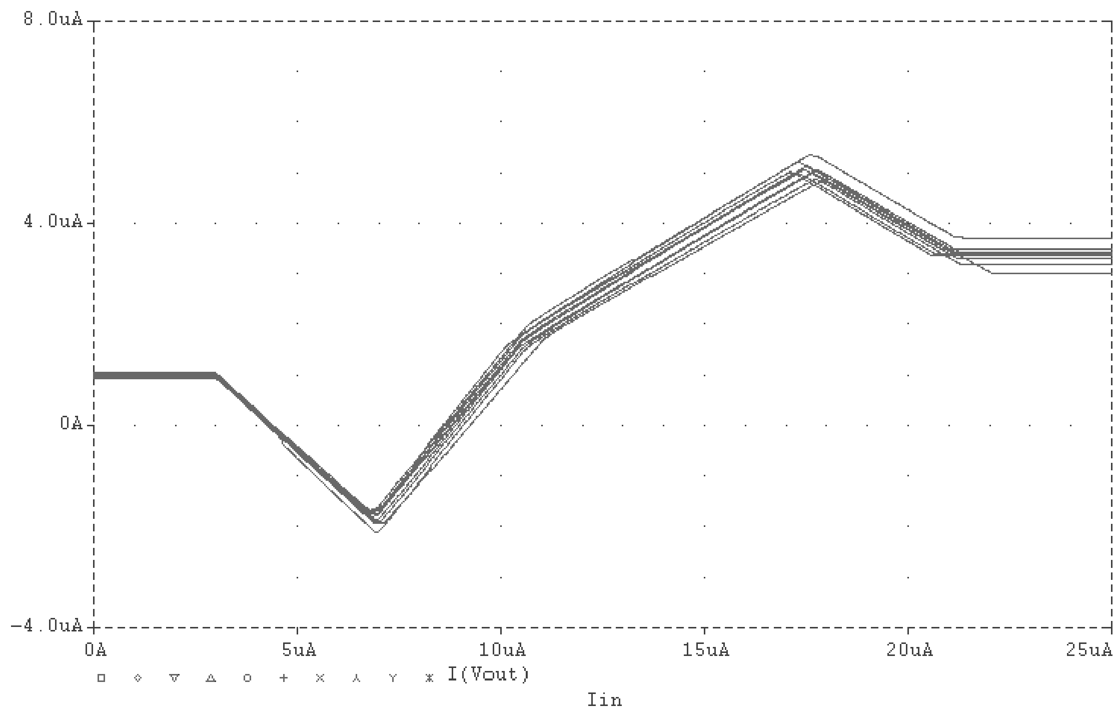

Fig. 13. Monte Carlo analysis using SPICE program of the circuit from Figure 12. In the analysis the following parameter deviations were used: V_{TH}=>±5mV, K_p=>±1%, t_{ox}=>±0.1%, μ=>±1%, L=>±2%, and W=>±2%.

4 Conclusion

Low voltage CMOS circuits, operating in current mode, that exhibit piecewise transfer characteristics were described and simulated with SPICE program. These circuits can be used for the synthesis of arbitrary nonlinear functions. Several different circuits were developed. Nonlinear functions were synthesized and verified using the Monte Carlo simulation of PSPICE software. The best results were obtained with double break point circuits. These circuits can be supplied with less than 1V.

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