Another Simple Transistor-Only Lumped-Distributed Tunable Low-Pass Filter

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ABSTRACT

The idea and theory of the double distributed RC line ($\overline{\text{CRNC}}$) is reminded in the context of transistor-only selective circuits. A new low-pass active transistor-only filter is introduced. Compared to existing filters, it has a different technique of its parameter tuning, and contains a substrate-driven MOSFET operating as the $\overline{\text{RC}}$ element.

1. INTRODUCTION

Transistor-only filters were introduced by J. Khoury, Y. Tsividis and M. Banu in [1]. They used an enhancement MOS transistor as a tunable uniform distributed RC line (U$\overline{\text{RC}}$). In strong inversion, when $V_{GD} = V_{GS} > V_T$ the MOSFET channel resistance is uniform and can be tuned by V_{GS}. The thin oxide and the depletion layer capacitances are distributed along both sides of the channel, forming a double U$\overline{\text{RC}}$. Such a double line we name as $\overline{\text{CRNC}}$. It may be used as a simple small signal model of the distributed MOSFET [4], shown in Fig. 1. Parameters of the

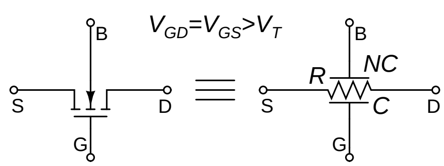

Fig. 1. $\overline{\text{CRNC}}$ as a MOSFET small signal model.

model are as follows:

$$R = \left\{ K' \frac{W}{L} (V_{GS} - V_T) \right\}^{-1} \quad (1a)$$

$$C = C_{ox} = C'_{ox} W L \quad (1b)$$

$$N = \frac{C_b}{C_{ox}} = b = \frac{\gamma}{2\sqrt{V_{SB} + \phi_B}} \quad (1c)$$

where: K' is the transconductance parameter, W, L are the channel width and length, V_{GS}, V_{SB} are the gate–source and the source–substrate bias voltages, V_T is the threshold voltage, C_{ox}, C_b are capacitances of the thin oxide and the depletion layer, C'_{ox} is the capacitance of the thin oxide per unit area, γ is the body effect coefficient, ϕ_B is the build-in potential of the strongly inverted channel.

Distributed RC elements unite resistances and capacitances in the same area, thus they are flexible and more efficient than their lumped counterparts. For example, the basic U$\overline{\text{RC}}$ has three layers and three nodes, so it may operate in three configurations as a passive LP, HP or all-pass filter. The $\overline{\text{CRNC}}$ has four nodes and may operate in 21 different 2-port configurations. In conjunction with lumped resistances or capacitances, $\overline{\text{RC}}$ elements may form notch filters, and together with amplifiers they may be used to build several structures of active filters.

Compared to classical $\overline{\text{RC}}$ filters, transistor-only filters discovered by Y. Tsividis have another important advantage: the tunability. A MOSFET as the distributed RC line has a tunable time constant, dependent on the voltage V_{GS}:

$$\tau = RC = \frac{C'_{ox} L^2}{K'(V_{GS} - V_T)} \quad (2)$$

Compared to classical $\overline{\text{RC}}$ elements, the MOS transistor have to be properly biased in its environment, so that $V_{GD} = V_{GS} > V_T$. Sometimes it is a serious problem, not easy to solve.

There are several structures of low-pass, high-pass and even notch transistor-only filters [1]–[4], [7]–[13]. In the next section we will take a closer look at probably simplest active LP filters ever exist.

2. ACTIVE $\overline{\text{RC}}$ AND $\overline{\text{MOS}}$ LP FILTERS

The U$\overline{\text{RC}}$ element may operate as a passive low-pass network when its capacitive node is grounded, as in Fig. 2(a). The open-circuit transfer function is then equal to:

$$K(s) = \frac{v_2}{v_1} = \frac{1}{\cosh\theta} \qquad \theta = \sqrt{s\tau} \quad (3)$$

In Fig. 2(b) an active LP filter proposed by Wyn-

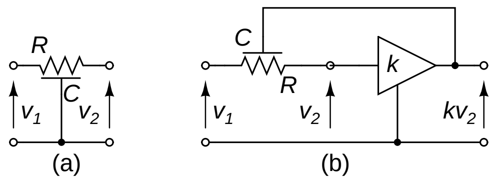

Fig. 2. (a) U$\overline{\mathrm{RC}}$ (b) Wyndrum's A$\overline{\mathrm{RC}}$ LP filter

drum [11] is shown. It is impressively simple and may provide sharp cutoff characteristics, where the cutoff frequency is set by the $\overline{\mathrm{RC}}$ time constant τ and the peak, near the band-edge, is adjusted by the voltage gain $k < 0.92$. For higher values of k there is an oscillatory response. It is easy to show that the transfer function of the filter is as follows:

$$K(s) = \frac{1}{k(1 - \cosh\theta) + \cosh\theta} \tag{4}$$

Based on this simple A$\overline{\mathrm{RC}}$ filter, Tsividis realized a transistor-only version [2], shown in Fig. 3. Transistor M_1 is operating as a distributed $\overline{\mathrm{RC}}$ element. Transistors M_2, M_3, M_4 form a source follower, which plays the role of the amplifier and provides DC bias and signal to the gate of M_1.

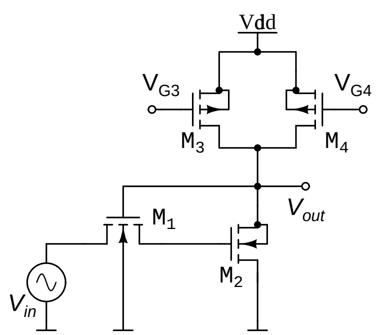

Fig. 3. Tsividis' VHF $\overline{\mathrm{MOS}}$ LP filter

Taking into account a double U$\overline{\mathrm{RC}}$ as a more adequate small signal model of the MOSFET, we realize that an A$\overline{\mathrm{CRNC}}$ LP filter shown in Fig. 4(a) is a true prototype of the Tsividis' filter.

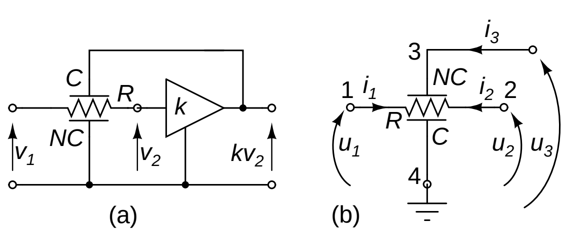

Fig. 4. (a) A$\overline{\mathrm{CRNC}}$ LP filter, (b) 3-port $\overline{\mathrm{CRNC}}$

With a little effort, using some methods from classical theory of distributed RC circuits, we may find an admittance or an impedance matrix of the 3-port circuit shown in Fig. 4(b). The impedance matrix is:

$$Z = \frac{R}{\theta^2}\begin{bmatrix} N + \theta\coth\theta & N + \theta\,\mathrm{csch}\,\theta & M \\ N + \theta\,\mathrm{csch}\,\theta & N + \theta\coth\theta & M \\ M & M & \frac{M^2}{N} \end{bmatrix} \tag{5}$$

where: $M = N + 1$, $\theta = \sqrt{sM\tau}$, $\tau = RC$.

Now it is not difficult to show that the transfer function of the A$\overline{\mathrm{CRNC}}$ filter has a form:

$$K(s) = \frac{1}{k\frac{1}{M}(1 - \cosh\theta) + \cosh\theta} \tag{6}$$

It is very similar to the transfer function (4) of the A$\overline{\mathrm{RC}}$ filter The only difference is in the coefficients k and k/M. If we want the A$\overline{\mathrm{CRNC}}$ filter to have the same frequency response as Wyndrum's A$\overline{\mathrm{RC}}$ filter, the amplifier gain should be:

$$k = Mk' \tag{7}$$

where: k' is the gain of amplifier in the A$\overline{\mathrm{RC}}$ filter.

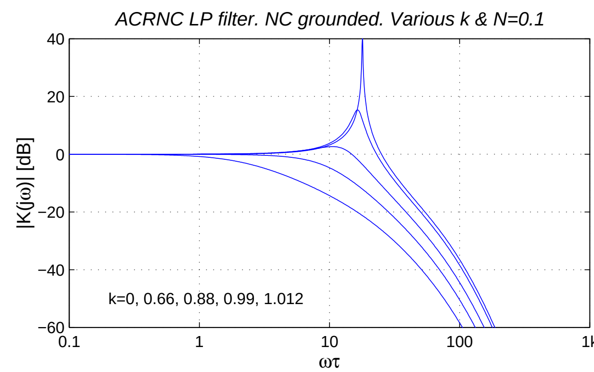

Fig. 5. Magnitude of the A$\overline{\mathrm{CRNC}}$ LP filter

In Fig. 5 frequency responses of the A$\overline{\mathrm{CRNC}}$ LP filter for $N = 0.1$ and different values of k are shown. The frequency axis is normalized. Notice, that to obtain the highest peak near the band-edge, like for $k' = 0.92$ in Wyndrum's filter, we have to set the gain to the value of $k = 0.92 \cdot 1.1 = 1.012$.

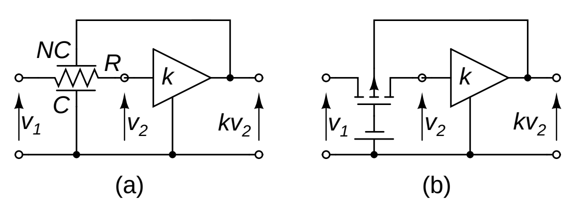

Fig. 6. (a) A$\overline{\mathrm{CRNC}}$ LP filter with swapped $\overline{\mathrm{CRNC}}$ capacitances (b) and its transistor-only version

If we realize that the $\overline{\mathrm{CRNC}}$ has two capacitive nodes — what will be when we change them? A new circuit with swapped capacitances of the $\overline{\mathrm{CRNC}}$ is shown in Fig. 6(a). It is also not difficult to show that its transfer function is equal to:

$$K(s) = \frac{1}{k\frac{N}{M}(1 - \cosh\theta) + \cosh\theta} \tag{8}$$

And again we can see, that to obtain exactly the same characteristics as in Fig. 5, the amplifier gain should be set to:

$$k = Mk'/N = (1 + 1/N)k' \tag{9}$$

where: k' is the gain of amplifier in the $\mathrm{A\overline{RC}}$ filter. If $N = 0.1$, then we obtain the sharpest characteristic for $k = 0.92 \cdot 1.1/0.1 = 10.12$. Notice that if $N < 1$, then in the new filter, the gain $k > 1$ to obtain the same characteristics as for Wyndrum's filter.

3. A NEW TRANSISTOR-ONLY FILTER

The $\overline{\mathrm{CRNC}}$ is a simple small signal model of the MOSFET, when $V_{GD} = V_{GS} > V_T$, with parameters as in (1). The transistor-only realization of the $\mathrm{A\overline{CRNC}}$ LP filter with swapped capacitances is shown in Fig. 6(b).

In the *n-well* CMOS technology, the transistor should be a p-channel device. Then always, its drain and source potential have to be smaller than the potential of its well. An amplifier should be properly designed to provide a correct bias to the well. Its output DC level always have to be bigger than the input level. This is a limitation, but it is not so difficult to realize such an amplifire. The gain of the amplifier may be adjusted by an external voltage or current. For a flat frequency response in the Wyndrum's filter the gain $k < 0.8$. From (9) and (1), we may find the appropriate gain of our filter:

$$k < 0.8 \cdot (1 + 1/b) \tag{10}$$

The value of b is a function of V_{BS} and is shown in Fig. 7, for a standard $0.8\,\mu$m technology from AMS. If the input DC level of the filter is 0 V, then the output DC level of the amplifier is equal to V_{BS}. For example, if $V_{BS} = 1$ V, then $b = 0.17$ and from (10) the gain $k < 0.8 \cdot (1 + 6.88) = 5.5$.

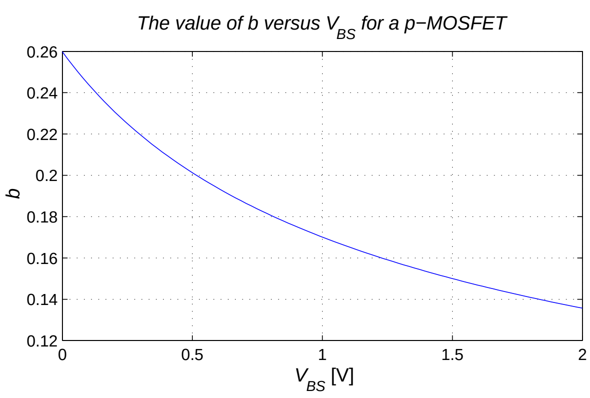

Fig. 7. The value of b for a p-MOSFET

Once the output DC level and the gain is set, we may tune the time constant and thus the characteristic frequency of the filter, by the gate voltage of the distributed transistor $\overline{\mathrm{CRNC}}$.

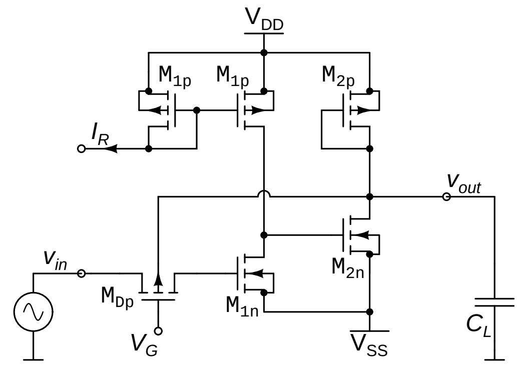

Fig. 8. A new transistor-only LP filter

An example CMOS implementation of the new filter is shown in Fig. 8. The transistor M_{Dp} plays here the role of a $\overline{\mathrm{CRNC}}$. Transistors M_{1n}, M_{1p} form a first common source stage with a current mirror as a load. M_{2n} form a second stage with M_{2p} as a load. A *diode* connection of the M_{2p} guarantee relatively small output resistance. The current I_R adjusts the output DC level and the gain. V_G directly, or through a follower may be used to control the time constant.

Compared to the first transistor-only low-pass filter from Fig. 3, the tuning of the cutoff frequency change neither the gain nor the output DC level.

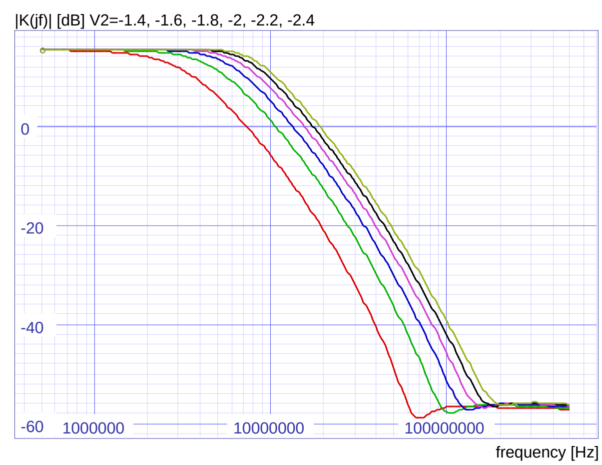

Fig. 9. Frequency responses of the new filter

In Fig. 9 characteristics of the filter for $V_G = -2.4, -2.2, -2.0, -1.8, -1.6$ and -1.4 are shown. The analysis has been made with the *Spice OPUS*, using Bsim3v3 models from *Austria Mikro Systeme*. Transistors dimensions W/L were: M_{Dp} $2\,\mu$m/$32\,\mu$m, M_{1n} $4\,\mu$m/$2\,\mu$m, M_{1p} $6\,\mu$m/$2\,\mu$m, M_{2n} $2\,\mu$m/$1\,\mu$m, M_{2p} $32\,\mu$m/$1\,\mu$m. The current I_R was $160\,\mu$A. The long transistor M_{Dp} was simulated as 20 cascaded shorter channels, without junction and overlap capacitances at intermediate nodes [5]. Supply voltages were symmetrical ± 2.5 V, and the load capacitance $C_L = 2$ pF. The output resistance of the amplifier was then $R_1 \approx 2.7\,\mathrm{k}\Omega$ and the gain $k \approx 5.6$ V/V.

In the design procedure, very helpful may be a more precise small signal model, shown in Fig. 10. It is far more difficult to analyze, but quite easy with a help of *Mathematica* or *Maple*. Using the impedance matrix (5) one may find the transmittance $K(s) = v_3/v_1$ and the influence of parasitic lumped capacitances.

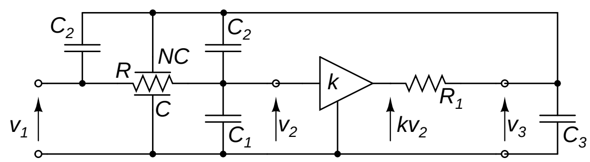

Fig. 10. A small signal model of the new LP filter

Capacitances C_2 are the drain and source junction capacitances of the distributed MOSFET, C_1 is the source (or drain) overlap capacitance plus the input capacitance of the amplifier. C_3 is the junction capacitance of the well in parallel with the load capacitance.

Very important and necessary is to take into consideration the output resistance of the amplifier. In conjunction with the distributed RC line it results in the notch shape of frequency response.

4. CONCLUSION

The idea of a new transistor-only low-pass filter has been introduced. A simple CMOS implementation of the filter has been proposed. It has a substrate-driven p-MOSFET operating as a double $\overline{\mathrm{RC}}$ line in a feedback loop of the CMOS amplifier. The gate voltage of p-MOSFET may be used to adjust a cutoff frequency of the filter. The shape of the frequency response depends on the amplifier gain. The frequency tuning does not change the shape of the frequency response.

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