# A New Approach to Designing Active MMIC Tuning Elements Using Second-Generation Current Conveyors

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***Abstract*— A new method for designing active monolithic microwave integrated circuit (MMIC) tuning elements is proposed. It will be shown that by using a cascade of GaAs FET's, one can closely model a second-generation current conveyor (CCII−) at microwave frequencies and thus synthesize many types of microwave circuit elements, including positive and negative active capacitors and inductors, and gyrators. As a result of this discovery, current conveyor synthesis techniques can now be directly applied to microwave circuit design.**

## I. INTRODUCTION

ACTIVE tunable MMIC circuit elements have two distinct advantages over their passive counterparts: 1) they can achieve higher $Q$'s and 2) they can be made electronically tunable so that it is possible to tune out uncertainties in circuit models. In recent years, a number of papers have been published on how to use GaAs field effect transistors (FET's) to generate active inductors [1]–[7]. Most of these topologies have been arrived at by trial and error. Although a systematic approach for developing all possible positive and negative inductors has been proposed by Khoury [1], [2], this technique does not provide any insight into the design of other active microwave elements such as active tunable negative and positive capacitors, microwave gyrators, and tunable microwave impedance transformers. Secondly, many of the MMIC active inductors described in the literature have inductance values that are a direct function of $g_m$, which may require the user to have to change the operating point of the GaAs FET's in order to tune the active inductor, resulting in restrictions on the circuit element tuning range and allowable input drive power.

The following sections will describe a new technique for using MESFET's to carry out active network synthesis using a building block called the current conveyor [8]–[10]. Current conveyors have been used extensively at lower frequencies, but due to the low transconductance and large gate-source capacitance of the GaAs MESFET's, they cannot be approximated accurately using individual GaAs FET's. It will be shown that by using *cascaded* MESFET's, one can approximate the behavior of an ideal negative second-generation current conveyor (CCII−) at microwave frequencies, and thus one can apply current conveyor design techniques to generate a new class of MMIC circuits with a higher level of functionality. Circuit simulations will be used to demonstrate performance using a detailed circuit model of the TriQuint Semiconductor HA2 MESFET derived from measured S-Parameters.

## II. MICROWAVE CURRENT CONVEYOR DESIGN

A negative second generation current conveyor (CCII−) is a three-port circuit element characterized by the following set of hybrid circuit parameters as described by Sedra [8], [10]:

$$\begin{pmatrix} i_1 \\ i_2 \\ v_3 \end{pmatrix} = \begin{pmatrix} 0 & 0 & 0 \\ 0 & -1 & 0 \\ 1 & 0 & 0 \end{pmatrix} \begin{pmatrix} v_1 \\ i_3 \\ v_2 \end{pmatrix} \equiv \begin{pmatrix} h_{11} & h_{12} & h_{13} \\ h_{21} & h_{22} & h_{23} \\ h_{31} & h_{32} & h_{33} \end{pmatrix} \begin{pmatrix} v_1 \\ i_3 \\ v_2 \end{pmatrix}. \tag{1}$$

The current at ports 2 and 3 are equal in magnitude and 180° out of phase. The voltage at port 1 follows the voltage at port 2, but the current flow from port 1 to port 2 is zero.

We now consider a GaAs MESFET as a candidate for use as a current conveyor by assigning the gate, drain, and source to ports 1, 2, and 3 of (1), respectively. If we assume that the device is modeled with an input capacitance $c_{gs}$, a drain source resistance of $r_{ds}$, and a transconductance $g_m$, some algebra yields the following hybrid parameters in the Laplace transform domain:

$$\begin{pmatrix} h_{11} & h_{12} & h_{13} \\ h_{21} & h_{22} & h_{23} \\ h_{31} & h_{32} & h_{33} \end{pmatrix} = \frac{1}{\Delta} \begin{pmatrix} \frac{c_{gs}s}{r_{ds}} & -c_{gs}s & \frac{-c_{gs}s}{r_{ds}} \\ \frac{-c_{gs}s}{r_{ds}} & -g_m - \frac{1}{r_{ds}} & \frac{c_{gs}s}{r_{ds}} \\ g_m + c_{gs}s & 1 & \frac{1}{r_{ds}} \end{pmatrix} \tag{2}$$

where

$$\Delta = \frac{1}{r_{ds}} + g_m + c_{gs}s$$

and

$$s = j\omega + \sigma$$

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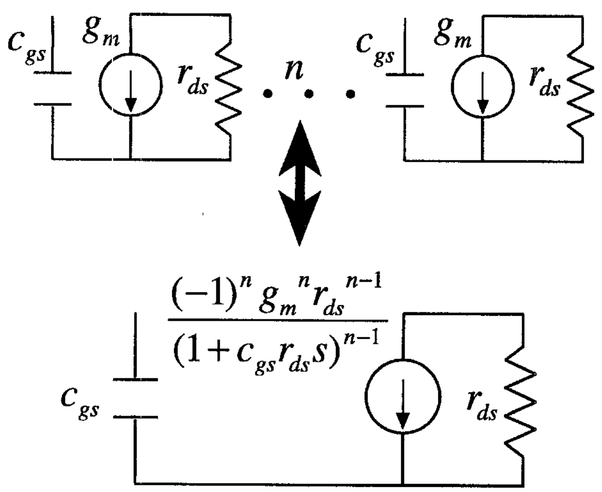


Fig. 1. Equivalent circuit for common source cascaded MESFET's.

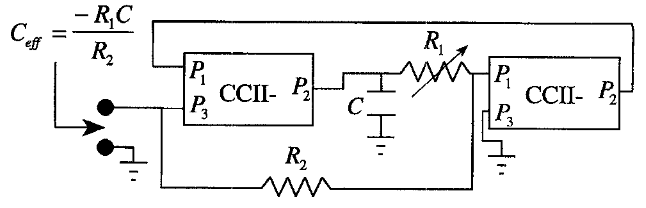


Fig. 2. Equivalent circuit for an electronically tunable negative capacitor.

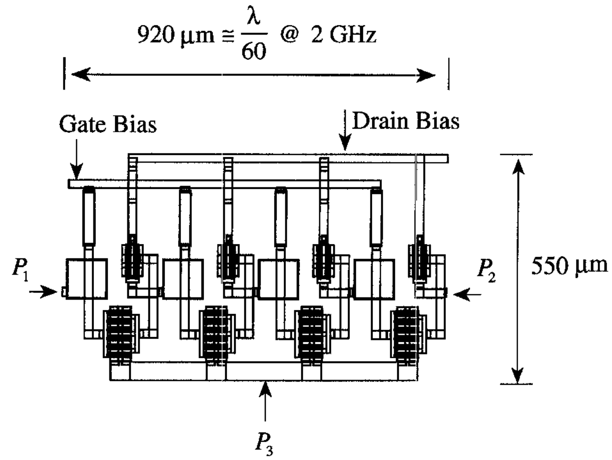


Fig. 3. Microwave CCII− layout using TriQuint 600-$\mu$m MESFET's.

By inspection of (2), it is clear that if $g_m \gg |c_{gs}s|$ and $g_m \gg 1/r_{ds}$, this matrix formulation will converge to the numerical values in (1) *except* $h_{32}$, which approaches $1/g_m$. For typical MESFET's used in MMIC circuits with $g_m$'s on the order of 5–80 mS, $h_{32}$ can have values of 12.5–200 Ω. This value is large enough to prevent the single MESFET from functioning as an adequate current conveyor at microwave frequencies. One possible solution is to increase the periphery of the MESFET; however, one would have to obtain a $g_m$ of 2000 mS to obtain a value of 0.5 Ω for $h_{32}$. This is impractical in the context of a MMIC circuit. It would appear as though the MESFET is not a very good current conveyor.

We now consider a string of $n$ MESFET's in cascade. By comparing the Y-Parameters of an individual MESFET with the Y-Parameters of a cascade of $n$ FET's connected in a common source configuration. We can derive a simple equivalent model for a cascade of devices as illustrated in Fig. 1. Noting the equivalence, we can write the hybrid matrix for a cascade of $n$ MESFET's by replacing $g_m$ in (2) with

$$g_{m_{eff}} = \frac{(-1)^{n+1} g_m^n r_{ds}^{n-1}}{(1 + c_{gs} r_{ds} s)^{n-1}}. \tag{3}$$

This modification will allow (2) to converge to the ideal hybrid parameters in (1) when $g_{m_{eff}} \gg |c_{gs}s|$, $g_{m_{eff}} \gg 1/r_{ds}$, and $1/g_{m_{eff}} \approx 0$. Since $g_{m_{eff}}$ is a function of $n$, we have control over its value without modifying the individual device parameters. It will be shown that $g_{m_{eff}}$ can easily be made large enough to obtain good current conveyor performance in the low microwave frequency band.

## III. Design Example and Simulation

As an example of the application of this technique, we will look at the design of a tunable negative capacitor. Other elements such as positive tunable inductors, capacitor, and gyrators can be built just as easily using the same approach illustrated here [11]. The negative capacitor has potential benefits in active broadband matching applications, as suggested by Moazzam *et al.* [12]. In contrast to the negative capacitor designs proposed by Moazzam *et al.* [12] and Sussman-Fort [13], the following circuit is tunable, requires no spiral inductors, and can be made to synthesize very large values of negative capacitance. The circuitry used (see Fig. 2) is that of a negative impedance converter (NIC) as outlined in [14] implemented with CCII− building blocks. The equivalent negative capacitance value for this circuit is given by

$$C_{eff} = \frac{-R_1 C}{R_2}. \tag{4}$$

This value can be changed using a variable resistor which can be implemented in a GaAs MMIC chip using a MESFET with $v_{ds} = 0$.

Each of the ideal CCII− in Fig. 2 is replaced with a set of cascaded GaAs FET's. Equation (2) with $g_m \to g_{m_{eff}}$ can be used to estimate the performance of the current conveyor at a given frequency by comparing the resulting hybrid parameters with those in (1).

In this example, a current conveyor designed using four cascaded 600 $\mu$m GaAs FET's from TriQuint Semiconductor Corporation's HA2 process [15] will be used. This current conveyor design includes bias resistors, active loads, lossy capacitors, and microstrip lines as illustrated in Fig. 3. Some off-chip bias circuitry is required. TriQuint's HA2 process 600-$\mu$m GaAs FET's have an $f_T = 18$ GHz, $g_m \approx 38$ mS, $c_{gs} \approx 0.38$ pF, and $r_{ds} \approx 340\,\Omega$ at $I_{DS} = 24$ ma. The number of devices and associated gate periphery were selected such that $|h_{32}| < 1\,\Omega$. In general, the required value of $h_{32}$ is dependent on the specific design that the current conveyors will be used in. For example, for synthesizing smaller negative

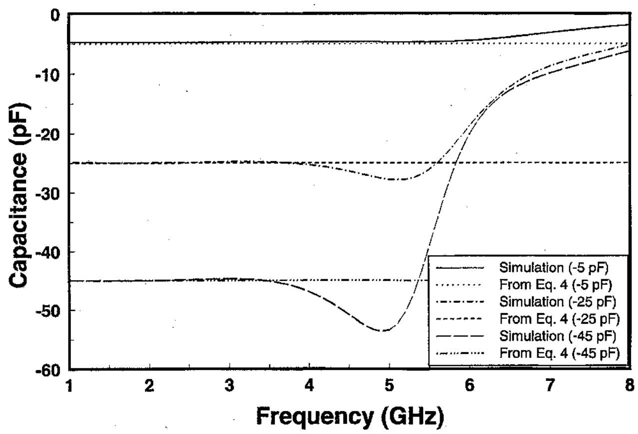


Fig. 4. MMIC tunable negative capacitor: capacitance values.

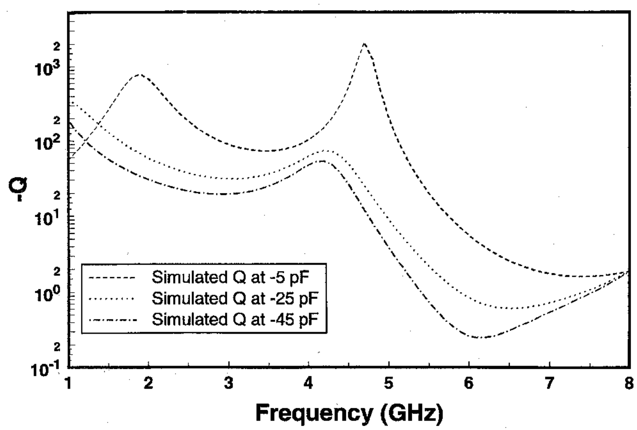


Fig. 5. MMIC tunable negative capacitor: $Q$ values.

capacitance values (i.e., $-1$ to $-5$ pF), one can accept larger values of $h_{32}$ and reduce the required dc power consumption of the circuitry considerably. The simulation results shown in Figs. 4 and 5 are the resulting negative capacitance and quality factor obtained using the layout in Fig. 3 as a CCII− building block. This simulation takes into account the complete device models derived from measured S-Parameters, as well as all parasitic effects and coupling within each current conveyor. It can be seen that there is excellent agreement between the simple prediction of (4) and detailed simulation capacitance value for frequencies below 4 GHz. The simulated quality factor ($Q$) is shown in Fig. 5. A parallel resistor was included to make the circuit's effective parallel resistance positive at all frequencies. As with all active microwave circuits, stability is an important design consideration [16]–[18] that must be carefully addressed. We have found through simulations that higher values of $g_{m_{eff}}$ improve the circuit $Q$, bandwidth performance, and range of tuning. One must trade off these benefits with the increased power consumption that typically is required to obtain larger values of $g_{m_{eff}}$.

## IV. Conclusion

It has been shown that although the individual GaAs FET is a poor current conveyor, a cascade of FET's can be used to make a very good current conveyor at microwave frequencies much less than $f_T$ of the devices. Performance is determined by the $g_{m_{eff}}$ of the cascaded FET's and the $f_T$ of the individual devices. The demonstrated technique should open the door for the synthesis of a new class of electronically tunable microwave circuits with a higher level of functionality and better performance than currently available. This is an exciting prospect.

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