Active Inductor and Capacitor for DCS receiver band (1.71GHz – 1.785GHz) using multi-MESFET Negative Resistance Circuit

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Abstract: **Traditional spiral inductors are usually large, bulky, and difficult to model, hence active inductors look very attractive particularly because of their tuning capability. The basic idea of this design is to realize an active inductor and capacitor that could be used to substitute the spiral inductors and lumped capacitors in Monolithic Microwave Integrated Circuit (MMIC) active filters. The resulting negative resistance serves to compensate the pass-band insertion loss. The benefits of reduced cost, small size and weight justify the effort to develop fully integrated Radio Frequency (RF) and Microwave systems using MMIC technology. In line with this interest, this work will lay a key foundation on which the step toward full integration can be made. For proof of concept, a 5GHz active capacitor using single MESFET negative resistance was designed, simulated and fabricated by GEC F20 Foundry. The test and measurement was done using HP8510 Network Analyzer. The simulated and measured results compared well. Following on this concept, an active inductor for dcs receiver band (1.71GHz – 1.785GHz) using multi-MESFET negative resistance circuit was designed and simulated. The results obtained show constant inductor and negative resistance values within the desired frequency band.**

Introduction: It is appropriate to describe negative resistance as a source of electrical energy as against a positive resistance which absorbs (sinks) electrical energy. The Tunnel diode, Gunn and IMPATT diodes and few other two terminal devices can exhibit negative resistance at RF frequencies when biased appropriately. Application of d.c. bias to a bipolar or field-effect transistor, however, requires a suitable series or parallel feedback to induce negative resistance. The frequency range over which the negative resistance is present in the diodes is determined by the physical mechanisms in the device as well as the feedback topology chosen for the circuit. All negative resistance devices are one-port networks. The basic structure consists of a transistor, such as a MESFET, and a simple reactance feedback element Z as shown in Figure 1 [1].
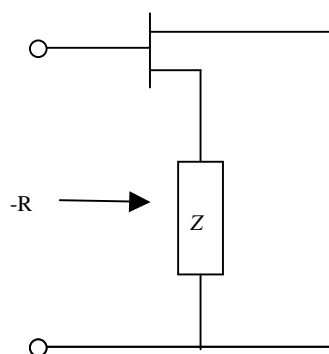

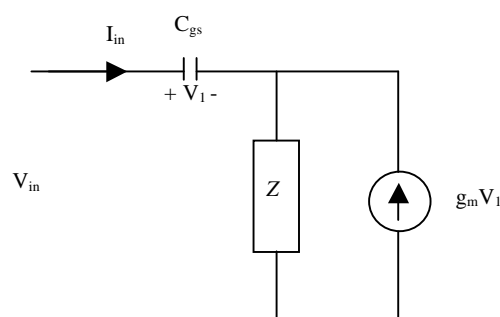**Figure 1**. *Basic Negative Resistance circuit*

Figure 2. *Model of Figure 1.*

If the MESFET is modelled by its input capacitor C_{gs}, and related current generator as shown in

Figure 2, the input impedance seen at the circuit terminal can be calculated as

$$Z_{in} = Z + Z_{gs} + g_m Z_{gs} Z \qquad (1)$$

As the equation shows, the term which can produce negative resistance is $g_m Z_{gs} Z$ where $Z_{gs} = \frac{-j}{\omega C_{gs}}$. It therefore follows that the element Z must be a capacitor, which results in a negative resistance value of

$$R_{in} = \frac{-g_m}{\omega^2 C_{gs}} \qquad (2)$$

It is also possible to use an inductor as the feedback element, but in a different circuit configuration, as shown in Figure 3 [2], in which two similar MESFETs are used.

Here, the analysis of the circuit in Figure 3, given in equation (3), shows that the term which produces the negative resistance is $g_m Z_{gs}^2$

$$Z_{in} = 2Z_{gs} + g_m Z_{gs}^2 + Z_L \qquad (3)$$

$$+2g_m Z_{gs} Z_L + g_m^2 Z_{gs}^2 Z_L \qquad \text{where}$$

$$Z_{gs} = \frac{1}{j\omega C_{gs}} \quad \text{and} \quad Z_L = j\omega L$$

In each configuration, the circuit input impedance is a frequency-dependent negative resistance in series with a reactance.
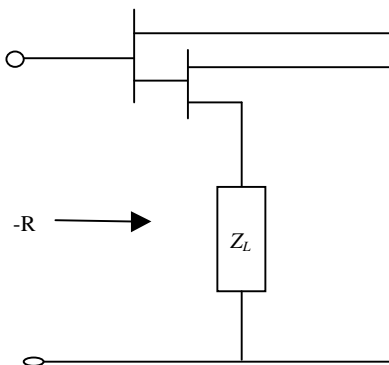

Figure 3. *Another configuration of Negative Resistance circuit*

Active Capacitor using single-MESFET Negative Resistance Circuit

The complexity or simplicity of the negative resistance circuit largely depends on the bias circuitry. The design is based upon the serial feedback of a single MESFET, using self-bias arrangement to enable the use of a single bias source. The corresponding circuit is shown in Figure 4 while the chosen dc bias operating point is shown in Figure 5, for the four-finger $75\mu m$ gate width (4x75) MESFET operating at

$$I_{ds} = \frac{I_{dss}}{2} = 25mA \text{ for } V_d = 2.5V$$

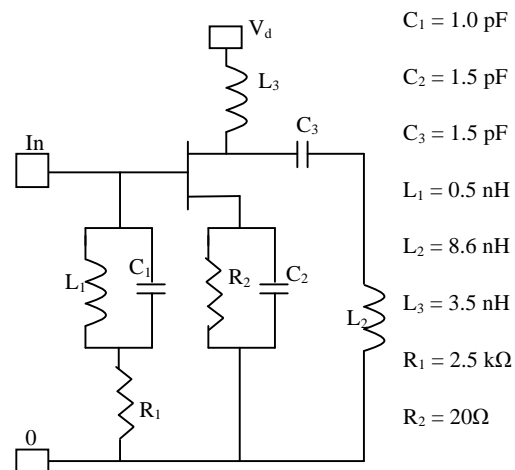|	
V_d = 2.5 V	
C_1 = 1.0 pF	
C_2 = 1.5 pF	
C_3 = 1.5 pF	
L_1 = 0.5 nH	
L_2 = 8.6 nH	
L_3 = 3.5 nH	
R_1 = 2.5 kΩ	
R_2 = 20Ω	

Figure 4. *Schematic of the 1-MESFET active capacitor with negative resistance*

The bias circuit uses a source resistor R_2 which sets the dc operating point of the negative resistance circuit, provides automatic transient protection and also decreases the effect of variations of the drain current I_{ds} with respect to temperature and I_{dss}. The source bypass capacitor C_2 also serves as the capacitive serial feedback component. The resistor R_2 sets the gate bias voltage, V_g.

Analysis of the Active Capacitance/Negative Resistance Circuit

The small-signal model of the negative resistance circuit of Figure 4 is shown in Figure 6. The analysis of the circuit is as follows:

$$I_{in} = I_1 + I_2 \qquad (4)$$

where I_{in} is the input current, I_1 the gate bias current, and I_2 the current flowing into the active device.
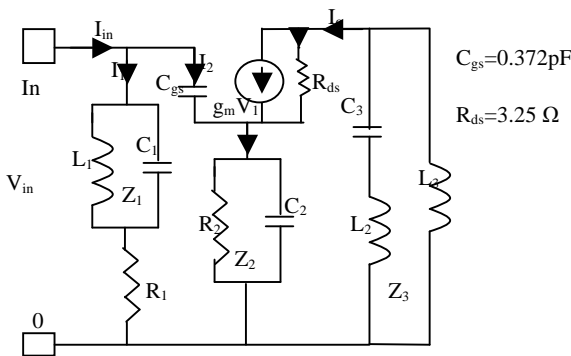
Figure 6. *Small-signal model of Figure 4*

In the figure: $C_{gs}=0.372\text{pF}$, $R_{ds}=3.25\ \Omega$

$$I_1 = \frac{V_{in}}{Z_1 + R_1} \qquad (5)$$

$$V_1 = I_2 Z_{gs} = \left(I_{in} - \frac{V_{in}}{Z_1 + R_1}\right) Z_{gs} \qquad (6)$$

where V_1 is the gate-source bias voltage (V_{gs}), which is set by the resistor R_2.

$$V_2 = (I_2 + I_o)Z_2$$

$$= V_{in} - \left(I_{in} - \frac{V_{in}}{Z_1 + R_1}\right) Z_{gs} \qquad (7)$$

Here V_2 is the voltage across the self-biasing circuit Z_2, which is formed by the resistor R_2 which sets the dc operating point, and the source bypass capacitor C_2, while I_o is the drain current (I_d).

$$I_o = g_m V_1 + \frac{V_2 + I_o Z_3}{R_{ds}} = \frac{g_m V_1 R_{ds} + V_2}{R_{ds} + Z_3} \qquad (8)$$

$$V_2 = \frac{Z_2\left[(I_{in}(Z_1 + R_1) - V_{in})(R_{ds} - Z_3 + g_m X_{gs} R_{ds})\right]}{(Z_1 + R_1)(R_{ds} - Z_3 - Z_2)}$$

$$= V_{in} - \left(I_{in} - \frac{V_{in}}{Z_1 + R_1}\right) X_{gs} \qquad (9)$$

The input impedance of the negative resistance circuit (a negative resistance in series with a reactance), Z_{in}, therefore becomes

$$Z_{in} = \frac{V_{in}}{I_{in}}$$

$$= \frac{Z_2(Z_1 + R_1)\left[(R_{ds} - Z_3 + g_m X_{gs} R_{ds}) + X_{gs}(Z_1 + R_1)(R_{ds} - Z_3 - Z_2)\right]}{(Z_1 + R_1 + X_{gs})(R_{ds} - Z_3 - Z_2) + Z_2(R_{ds} - Z_3 + g_m X_{gs} R_{ds})} \qquad (10)$$

where

$$Z_1 = \frac{j\omega L_1}{1 - \omega^2 L_1 C_1} \equiv jX_1 \qquad (11)$$

$$Z_2 = \frac{R_2 - j\omega C_2 R_2^2}{1 + \omega^2 C_2^2 R_2^2} \equiv R - jX_2 \qquad (12)$$

$$Z_3 = \frac{j\omega C_3(L_3 - \omega^2 L_2 L_3 C_3)}{C_3(1 - \omega^2 C_3(L_2 + L_3))} \equiv jX_3 \qquad (13)$$

Using the MATLAB software, the real and imaginary parts of the calculated input impedance Z_{in} (equation 10), are plotted against frequency as shown in figures 7(a) and 7(b) respectively.
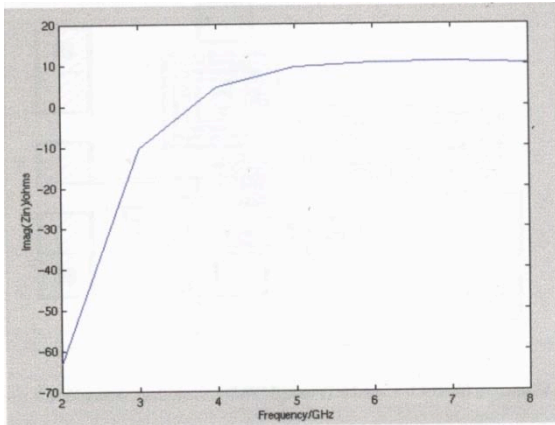
Figure 7(a): *Calculate Real(Z_{in}) response of the MMIC Negative Resistance for*
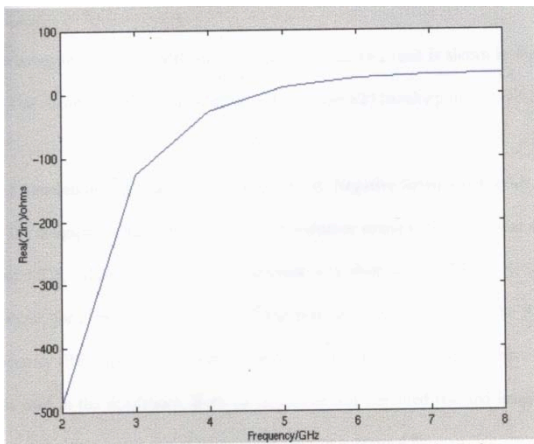

Figure 7(b): *Calculate Imag(Z_{in}) response of the MMIC Negative Resistance for* $V_d = 2.5V, I_{ds} = \frac{I_{dss}}{2} = 25mA$

The layout of the final MMIC of this negative resistance/active capacitance circuit is shown in figure 8. This circuit was fabricated using the GEC- Marconi F20 foundry process.

Simulation and measurement of the MMIC Negative Resistance/Active Capacitance Circuit.

The design and simulation of the negative resistance/active capacitance circuit in figure 4 was done using MDS, while the test and measurement was done using HP8510 Network Analyzer, for drain voltage (V_d) at 2.5V and drain current (I_d) at $25\,mA$. The Radio Frequency models of the circuit components and the interconnectors have also been used in the simulations. Both the simulation and measured real and imaginary parts of the input

impedance of the circuit are shown in figure 9. Inspection of figures 7 and 9 show that the measured performance of the negative resistance circuit compares well with the calculated results than it does with the simulated. This is due to the discrepancy between the measured S-parameter data and the S-parameter data of the library models of the GEC MESFETs which caused severe shift in frequency of the simulated result This problem was overlooked at this stage of the research because here the priority was to obtain a flat frequency response and a reasonable value (few ohms) of negative resistance that is sufficient to compensate the passband insertion loss of a distributed filter [3]. However, within the frequency band of interest (4GHz – 5GHz), the calculated, the simulated and the measured results produced a flat negative resistance of about -30Ω.
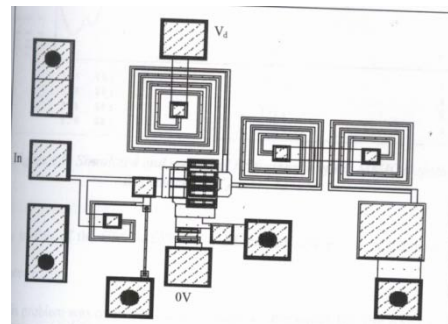

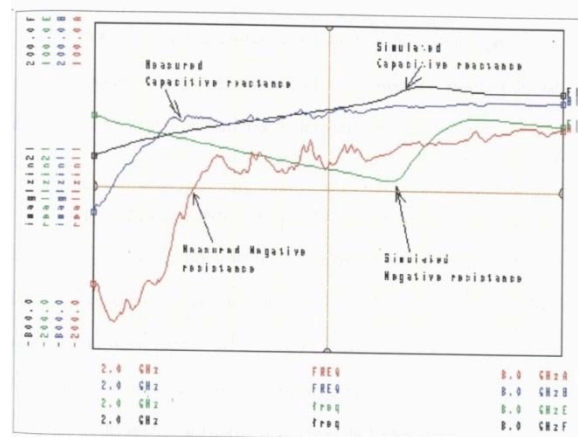**Figure 8:** *Negative Resistance layout (1.02mmx0.95mm) generated using CadenceMMIC*

Figure 9: *Simulated and measured performance of the MMIC Negative Resistance for* $V_d = 2.5V, I_d = 25mA$

$Z_{in} = -R + jX$

$V_s = 2.0$ V

$C_1 = 19$ pF

$C_2 = 15$ pF

$L_1 = 4.5$ nH

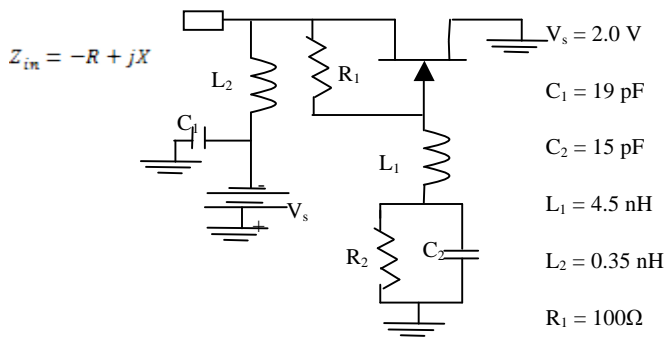$L_2 = 0.35$ nH

$R_1 = 100\Omega$

Figure 10: Schematic of the Active Inductor using a single MESFET Negative Resistance circuit

Active Inductor using a single-MESFET Negative Resistance circuit

An active inductor in a filter structure can have a negative loss factor, that is gain, whereas the capacitors remain passive and lossy. Here, we have chosen even more simpler circuit arrangement to enable the use of a
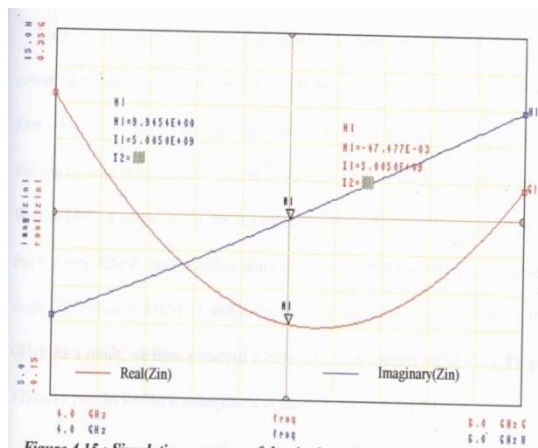

Figure 11: Simulation response of the single-MESFET Active Inductor with Negative Resistance

single bias source. The schematic of the common-drain circuit is shown in figure 10, with a single source bias voltage [4]. The resistor R_I sets the source-gate voltage V_{gs}, C_I is the source bias capacitor, while L_I and C_2 are the gate bias inductor and capacitor respectively.

For the source voltage of $V_s = -2.2V,$ and current $I = 85mA$, the simulated result is shown in figure

11. It is important that constant negative resistance and inductor values be obtained within the frequency band of interest. This circuit is to form the resonator inductor of a pass-band filter operating at a centre frequency of 5GHz, with a 2% fractional bandwidth (BW = 100 MHz) [5]. Figure 15 shows a flat negative resistance of -0.047Ω between 4.8 GHz and 5.4 GHz, and a linear inductive reactance between 4 GHz and 6 GHz.

Active Inductor for DCS Receiver band (1.71GHz – 1.785GHz) using multi-MESFET Negative Resistance circuit

The two previous negative resistance/active reactance circuits have been used mainly for proof-of-concept demonstration for applications in: (a) distributed filter and (b) MMIC active filter. Now we design a circuit to realize an active inductor with negative resistance that can be used in applications such as in the mobile communication frequency band. We also prefer a simple circuit, but our experience in the course of this work suggests that it is a very difficult task to realize active inductance with negative resistance using a single GEC-Marconi MESFET within the DCS 1800 receiver band (1.71GHz – 1.785GHz). As a result, we have employed a common-source cascade MESFETs T1 and T2) and a parallel feedback arrangement as shown in figure 16 [6]. A common-gate MESFET (T3) is used in the feedback circuit instead of a resistor. As in the last circuit, there is no measured result as it is an integral part of a MMIC active filter, but its simulated response is shown in figure 17, from where constant inductor and negative resistance values can be seen within the desired frequency band (1.5GHz – 2.0GHz).The potential usefulness of the active inductor is employed in the design of fully integrated filters.

Conclusion: The main objective in this work was to investigate the concept of active capacitor and inductor with negative resistance. We designed

and fabricated a negative resistance circuit capable of producing appreciable amount of negative resistance over a wide frequency band. Although the measured performance of the first negative resistance circuit showed some discrepancies with the simulated performance using foundry models, it compares very well with the calculated results. However, in all the three cases of calculated, the simulated, and the measured, satisfactory negative resistance values were realized for the desired range of frequencies. The advantages of using negative resistance elements are that they are comparably easy to construct, they require no external pump source, only dc bias; they have relatively wide bandwidth, and they are capable of working at high frequencies. The disadvantages are that they have relatively high noise figures, and they are potentially unstable. The solution to this problem is being studied as part of further work to this project.
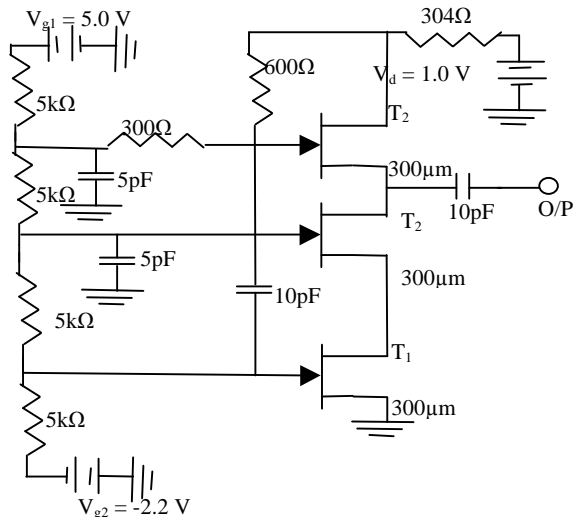

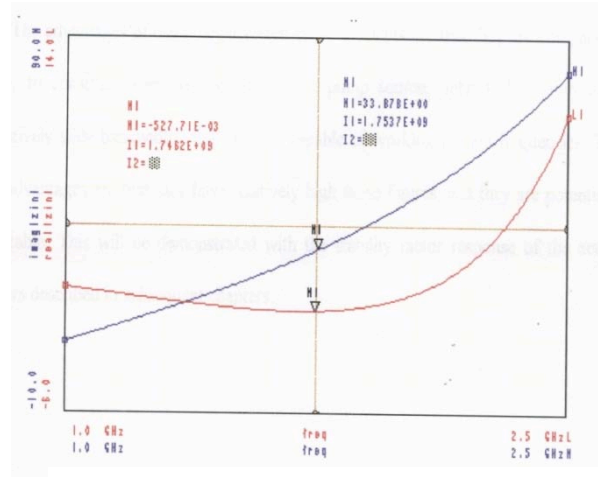**Figure 13: Simulated real and imaginary parts of the input impedance response of the multi-FET Active Inductor for dcs receiver band**

Figure 12: Schematic of the multi-MESFET Active Inductor with Negative Resistance for dcs receiver

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