SYSTEMATIC ANALYSIS, SYNTHESIS AND REALIZATION OF MONOLITHIC MICROWAVE ACTIVE INDUCTORS.

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ABSTRACT

A unified analysis of monolithic microwave active inductors based on an amplifier-feedback topological description is introduced. Active inductors are classified based on the gain and feedback elements constituent to their design. Small signal, large signal and noise behavior are considered in the generic case. An illustrative example of the synthesis procedure for, as well as the measured results of a novel topology are presented.

INTRODUCTION

The realization of monolithically integrated narrow-band microwave filters is of paramount importance to system designers. A promising approach to solving this problem employs active inductors as has been widely reported [3-10].

We have developed a unified analysis of active inductors, for small-signal, noise as well as large-signal behaviour.

The synthesis of active inductors based on this analysis methodology is discussed. The synthesis procedure is then used to realize in GaAs a novel active inductor topology, which has been characterized at X-band.

GENERAL INDUCTOR DESCRIPTION

We have shown that, for all active microwave inductors reported in the literature, a unified theory can be formulated. To that end, we introduce an inverting transconductance amplifier with capacitive input and apply positive feedback as shown in Figure 1. The imaginary part of the input impedance of the output port of the amplifier is likely to be positive.

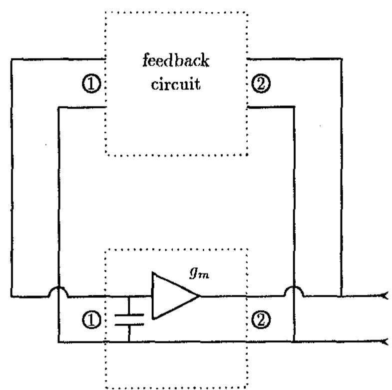

Figure 1: General active inductor concept.

The active inductor can best be described in terms of admittance matrices. The admittance matrix of

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the amplifier and feedback circuit are given by:

$$Y_a = \begin{bmatrix} y_{11,a} & y_{12,a} \\ y_{21,a} & y_{22,a} \end{bmatrix}, Y_f = \begin{bmatrix} y_{11,f} & y_{12,f} \\ y_{21,f} & y_{22,f} \end{bmatrix} \quad (1)$$

Parallel connection of these matrices leads to the admittance matrix $Y_t = Y_a + Y_f$.
The input impedance as seen from port 2, with port one left open, is equal to

$$Z_{in} = \frac{y_{11,t}}{y_{11,t}y_{22,t} - y_{12,t}y_{21,t}} \quad (2)$$

$= j\omega L$, for an ideal active inductor. The difficulty in designing active inductors is then to find suitable amplifier and feedback topologies to realize Y_a and Y_f.

CLASSIFICATION AND EXAMPLES

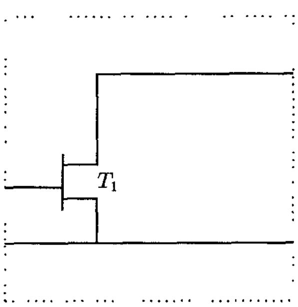

Figure 2: Adams' amplifier

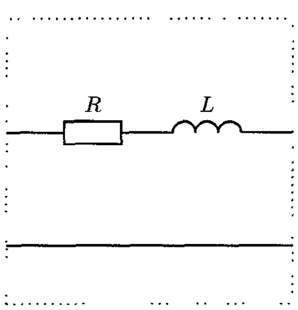

Figure 3: Adams' feedback

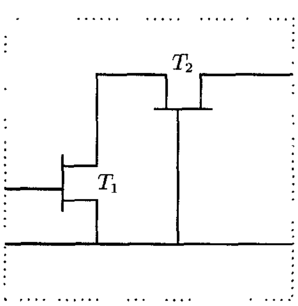

Figure 4: Hara's amplifier

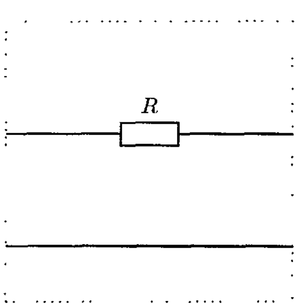

Figure 5: Hara's feedback

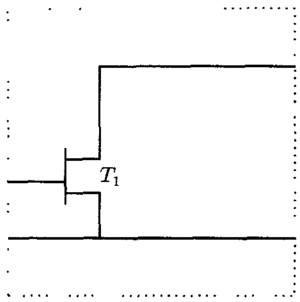

Figure 6: Zhang's amplifier

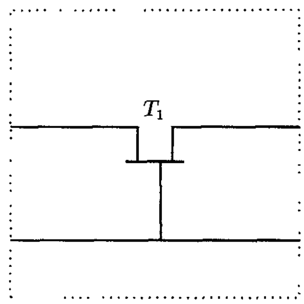

Figure 7: Zhang's feedback

The first active inductor we investigate combines the simplest amplifier, a common-source amplifier, with the simplest non-inverting feedback network, a low-quality inductor. This active inductor is equivalent to that published by Adams [2]. One step more complicated is the use of a cascoded common-source amplifier, described by Hara [6]. With this topology, resistive feedback is sufficient. Zhang [10] replaced the resistor of our first example with a common-gate amplifier, as in Figure 7. If we were to replace the feedback amplifier with a long-tailed pair, the gyrator described by Chien [4] results.
In calculating the large-signal behaviour, we must determine signal levels throughout the circuit. The maximum levels of these signals determine the large-signal behaviour. Please note that large-signal behaviour can be worse in resonant structures due to the transformation ratio of the resonator.
Measurement aspects concerning large-signal behaviour will be presented.

NOISE ANALYSIS

For passive inductors, noise and large-signal behaviour are generally not problematic. The introduction of active devices, however, adds a significant amount of noise. The noise analysis of active inductors is therefore important. The noise of an active inductor can be represented by a noise current source across its two terminals.
To analyse the noise behaviour, we extend the Y-

matrices with their current noise sources. They are present in parallel to port 1 and 2 of both the amplifier and the feedback. The noise current sources of the amplifier will be correlated, as will be these sources associated with the feedback. There will be no correlation between the noise current sources of the amplifier and the feedback.

We now reduce the two-port network to a one-port. This means that the noise equivalent will reduce to a single noise current source. It's value is computed as the correlated sum of the noise currents at port two and the transformed noise currents at port one, where the transformation is equal to:

$$\mathrm{i}^2 = \mathrm{i}^1 * y_{21,t}/y_{11,t}. \tag{3}$$

Note that the theoretical minimum noise current is related to the value of the reactance and is equal to the thermal noise current of a resistance with the value of the reactance [1].

Based on this observation, we introduce a figure of merit, the inductor noise factor, that normalizes the active inductor noise current with respect to the resulting reactance. That is:

$$\text{L-NF}(f) = \frac{i_{n,\text{active inductor}}}{i_{n,\text{passive reactance}}} \tag{4}$$

This figure-of-merit seems to favour designs with a minimal number of transistors.

SYNTHESIS ASPECTS

The active inductor is taken to be a two-port, there is thus no need to ground one of the terminals of the inductor. If no internally grounded nodes are present, the impedance seen from both ports will be the same. In the case of internal grounded nodes, this is no longer true. In practice, active inductors are built using real FET's. They have parasitics to ground so that grounded internal nodes are present. Active inductor realizations will thus almost never have an impedance that is the same seen from both ports. These parasitics may affect the impedance drastically, resulting in a circuit that shows inductive behaviour at only one port or, even worse, no inductive port at all.

If such an inductor is used as a one-port, it pays to look carefully to the choice of grounded terminal. Consider a given amplifier with frequency dependent admittance parameters Y_a as in (1). Specify the desired input impedance as $Z_{in} = R+jX$. For a parallel feedback impedance Z_f, as in Figure 3, the admittance parameters are given by

$$Y_f = \begin{bmatrix} Z_f^{-1} & -Z_f^{-1} \\ -Z_f^{-1} & Z_f^{-1} \end{bmatrix} \tag{5}$$

Combining (1), (2) and (5), we find for Z_f

$$Z_f = \frac{1 - Z_{in}(y_{11,a} + y_{12,a} + y_{21,a} + y_{22,a})}{Z_{in}(y_{11,a}y_{22,a} - y_{12,a}y_{21,a}) - y_{11,a}}. \tag{6}$$

This impedance must then be approximated using an appropriate classical synthesis method. We note that Z_f may not be realizable over a broad frequency range.

NOVEL TOPOLOGY

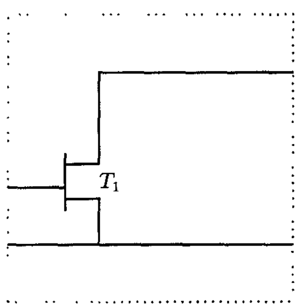

Figure 8: Amplifier of novel inductor

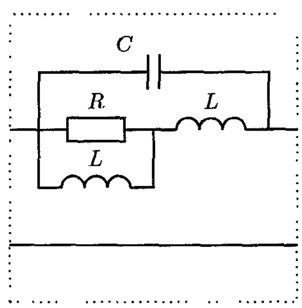

Figure 9: Feedback of novel inductor

Based upon the equations of the previous paragraph we have synthesized an active inductor with a common-source amplifier and a passive higher-order feedback network. Amplifier and feedback circuit are shown in Figure 8 and 9.

The final measurements shown in figure 10 illustrate the improved flatness of the real part with respect to frequency as well as the high Q of the active inductor.

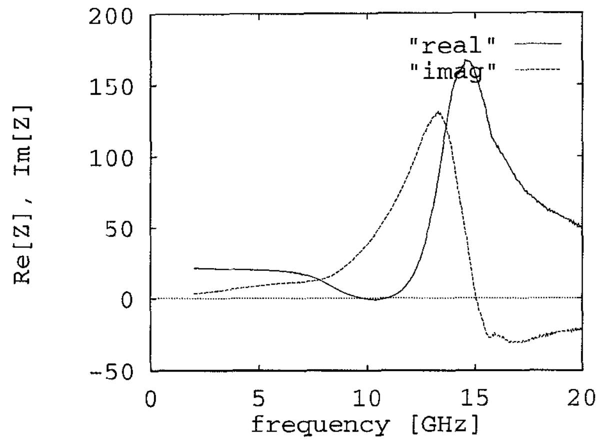

Figure 10: Measured results for the novel active inductor

CONCLUSION

In this paper we have introduced the first unified approach to the design and analysis of microwave active inductors. This approach splits the active inductor in two, a gain block and a feedback network. The parts have been separately analyzed and conclusions drawn as to their influence on noise and large-signal behaviour. Based on this approach a novel active inductor with low noise and broad-band behaviour has been synthesized and subsequently realized in a commercial 0.5 μm GaAs MESFET process technology. Measurements have established the superlative X-band performance of these inductors.

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