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CMOS RF Bandpass Filter Design using a Compensated Active Inductor

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***Abstract**: A novel tuning technique which improves the performances of an RF CMOS band-pass filter based on simulated inductors is presented. Gain enhancement techniques are applied to reduce the inductor losses by using a novel negative resistance topology. The proposed method is sufficiently general to be applied to other active filters topologies based on active inductors as well and is intended to be used for CMOS multi-standard filters design.*

***Keywords:** MOS simulated inductors, active RF multi-standard filters, frequency and Q-factor tuning, negative resistance.*

I. Introduction

The growing market of wireless communications is a significant reason that motivates the study of new low-cost and highly integrated architectures.

Radio frequency (RF) filters are essential components of any RF wireless transceiver and are used to attenuate undesired out of band signals. RF filters typically use passive inductors; however, on-chip passive inductors are notorious for their low quality factor and the large amount of chip area they consume [1], [2]. As a result, RF filters are usually implemented off-chip, a process which adds extra cost and manufacturing time to the design cycle. Indeed, spiral inductors are a critical issue in RF-design, their large on-chip area and weak quality factor being the main constraints for highly integrated products.

Active inductors drastically reduce the required chip area while improving the quality factor and potentially performance of the emulated inductor. Additionally, both the frequency and selectivity (bandwidth) of the active filter can be tuned by simply changing the amount of current channeled by the transistors. This tunable nature makes active filters especially suitable for multi-standard systems.

There are numerous topologies proposed and analyzed in literature for active inductors in CMOS technology in a frequency range up to a few GHz [3-4]. A reference paper for simulated inductors is [3] where a model for microwave applications is proposed.

This paper describes an architecture for a tunable active bandpass filter using the gyrator principle to transform a capacitive impedance into an inductive one. Q-Enhancement is accomplished by using a negative resistance coupled to active inductor. The technique presented here has a greater effect on the available tuning range. The theory behind the filter and tuning enhancements will be described first, followed by simulation results demonstrating the performance improvements.

II. Active inductor topology

Inductor is now becoming a highly attractive choice for CMOS wireless communication systems. Its interesting and unique advantages over spiral inductors include the following factors:

- Occupying smaller die area,
- High quality factor,
- Tunable inductance,
- And the possibility of achieving higher inductance with high resonance frequency.

Applications of the active inductor include Wilkinson power divider [5], phase shifter [6], filter [7], [8], oscillator [8], and current-mode phase-locked loop [9].

The concept of an active inductor is based on a well-known gyrator theory [10]. It is a two-port network that can be realized by connecting two transconductors in negative feedback, Fig.1. Gm_1 and Gm_2 are the transconductances of transconductors 1 and 2, respectively, and C is the load capacitance at node 1. The transconductor in the forward path has a positive transconductance while the transconductor in the feedback path has a negative transconductance.

The input admittance looking into port 2 of the gyrator-C network is given by:

$$Y_{in} = \frac{I_{in}}{V_2} = \frac{1}{s\left(\frac{C}{g_{m1}g_{m2}}\right)} \tag{1}$$

Equation (1) indicates that port 2 of the gyrator-C network acts as a single-ended lossless inductor with its inductance given by:

$$L = \frac{C}{g_{m1}g_{m2}} \tag{2}$$

Hence, gyrator-C networks can be used to synthesize inductors. These synthesized inductors are called active inductors. This active inductor is directly proportional to the load capacitance C and inversely proportional to the product of the transconductances of the transconductors of the gyrator.

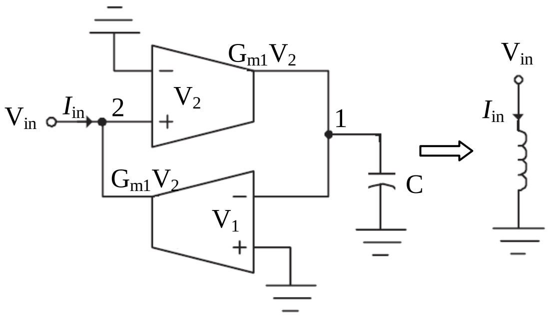
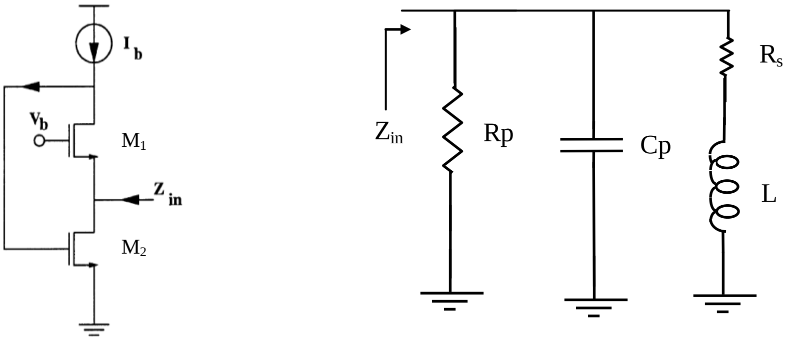


Figure 1: Schematics of active inductor using a gyrator topology

Several active inductors have been proposed in the literature. All structures aim at keeping the number of transistors as small as possible due to their noise effect and parasitic resistances which degrade the quality factor of the active inductor.

The inductor choosen in the filter structure contains two transistors and one current source, as shown in Fig. 3. Its main advantage consists in the ease of frequency tuning possibility, allowing the possibility to work in the GHz range.

The inductor presented in Fig. 3.a is obtained based on the gyrator theory, where the load capacitor is represented by the parasitic capacitor C_{gs2}. Due to the presence of parasitic capacitor C_{gs1}, the circuit will have a self–resonance frequency, determined by the effective value of the inductor and parasitic capacitor C_{gs1}. The quality factor for this circuit is limited by the series resistance Rs, which is determined by the finite output resistances of transistors, especially that of M_1. An equivalent small signal circuit is shown in Fig. 3.b.



-a- -b-

Figure 2: a- Active inductor architecture used in this work
b- It's equivalent resonator circuit

an approximate expression for input admittance Yin(s)=1/Zin(s) can be expressed as:

$$Y_{in}(s) = sC_{gs1} + g_{ds2} + \frac{g_{m1}g_{m2}}{g_{ds2} + sC_{gs2}} \tag{3}$$

As expected, the input admittance shows that it is equivalent to an RLC network, as shown in Fig. 3.b.
The element values can be determined as follows.

$$L = \frac{C_{gs2}}{g_{m1} g_{m2}} \tag{4}$$

$$R_S = \frac{g_{ds1}}{g_{m1} g_{m2}} \tag{5}$$

$$R_p = \frac{1}{g_{ds2}} \tag{6}$$

$$C_p = C_{gs1} \tag{7}$$

In most cases, due to the presence of the parasitic capacitor Cgs1, the active inductor is seen as a bandpass filter with its resonant frequency.
Neglecting the transistor output resistance, the relations for the resonant frequency and quality factor are given respectively by:

$$\omega_0 = \frac{1}{\sqrt{LC_p}} = \sqrt{\frac{g_{m1} g_{m2}}{C_{gs1} C_{gs2}}} = \sqrt{\omega_{t1} \omega_{t2}} \tag{8}$$

$$Q = \frac{R_p}{\sqrt{L / C_p}} = \sqrt{\frac{g_{m2} C_{gs1}}{g_{m1} C_{gs2}}} = \frac{\omega_{t1}}{\omega_{t2}} \tag{9}$$

Where ω_{t1} and ω_{t2} are the transit (unity-gain) frequencies of M_1 and M_2 respectively. Thus, for a high-frequency active filter, both transistors need to be biased for a high unity-gain frequency. However, if M_1 has a high unity-gain frequency, (9) shows that this will also degrade the selectivity of the filter.
This problem can be circumvented by using a negative resistance circuit to compensate loss in inductance and increase the Q of the filter.
In the following we discuss topologies of negative resistance.

III. The proposed negative resistance circuit

The negative resistance can be built by bipolar and FET devices. In the case of FET device, there are two kinds of topology: the one using a passive feedback and one using an active feedback. In the case of passive feedback, common-gate with inductance feedback and drain output as well as common source with capacitance feedback and gate output are commonly used. Each method has its own working frequency and resistance value [11].

In [12] the negative resistance circuit is using an active feedback. Among three topologies studied, a Common Drain- Common Gate (CD-CG) structure has been proposed and represented in Fig. 3 as well, proving to be a promising solution in compensating loss of CMOS active inductor.
Further details regarding this principle are presented in [12].

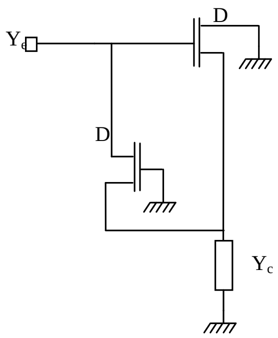


Figure 3: CD-CG negative resistance circuit

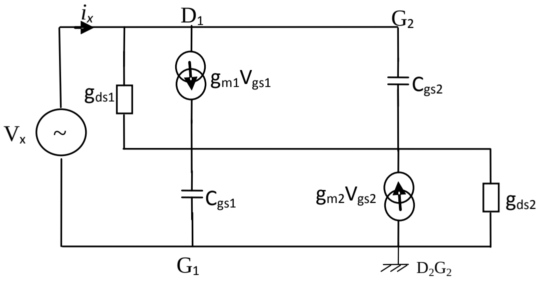


Figure 4: Small signal equivalent circuit of the negative resistance

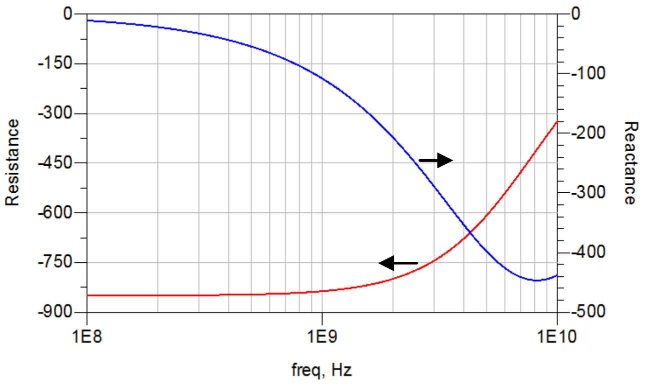


Figure 5: Simulated resistance and reactance of the negative resistance circuit.

IV. Design of bandpass filter using compensated active inductor

A. Circuit principle

The block diagram of the RF bandpass filter based on the active inductor is shown in Fig. 6. It's associated in parallel with a negative conductance and a variable capacitor (varactor). This allows the adjustment of respectively the filter bandwidth and the center frequency. It is obvious that the order of the filter can't allow the same response as commercial SAW filters. However we have to combine several cells coupled to have higher levels of responses [13].

The input buffer realized by M_{in}, converts the input voltage V_{in} to a current that is applied to the active inductor [14]. This is the most effective way to change the gain of the filter. For measurement requirement, an output buffer composed of a common-drain transistor M_{out} and a current source I_B is added [15]. The output buffer is used to drive the resistive loads. Besides, it prevents the load resistors and capacitors from reducing the resonant frequency and quality factor of the filter. The output buffer provides an adequate driving current and matching output impedance to the load. The output buffer must also have a large bandwidth so that its impact on the performance of the filter is minimum. Source-follower configurations are typically used in realization of the output buffer due to their low and tunable output impedance and large bandwidth.

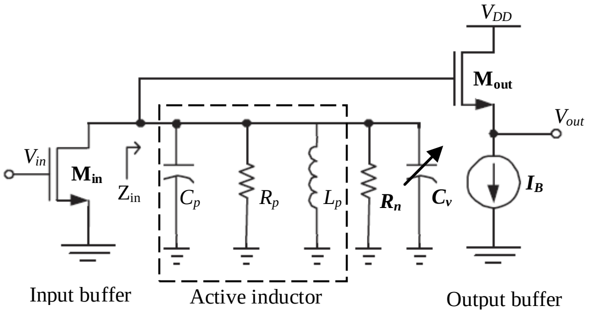


Figure 6: Block diagram of the Bandpass filter based on compensated active inductor

B. Simulation results

This work was simulated using AMS 0.35-µm process parameters with 2.3V power supply. All transistors have the minimum channel length of 0.35-µm. Through a S-parameter simulation the transfer function is shown in Fig. 7. The measured centre frequency f_0 is 6.2 GHz without C_v. The measured Q is 124.4.

The f_0 tuning (using C_v) and Q tuning (using R_n) curves are shown in Figs. 8 and 9, respectively. The performance of the filter is summarized in Table I.

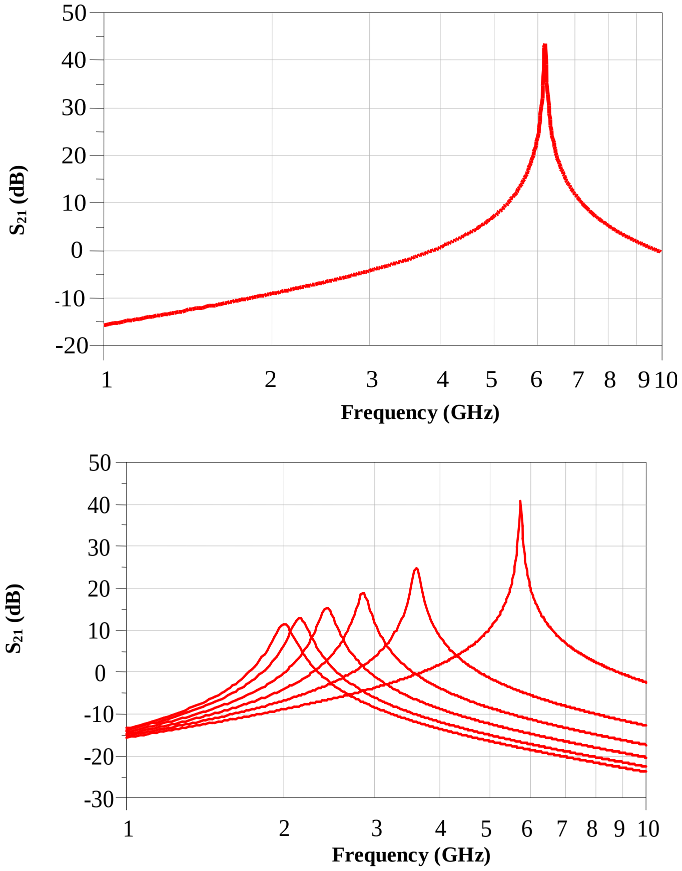


Figure 8: Center frequency tuning of the bandpass filter in the range 2–5.7 GHz

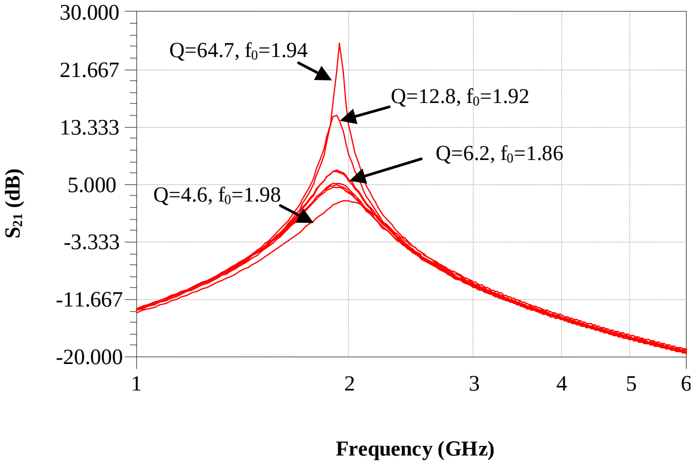


Figure 9: Quality factor (Q) tuning of the bandpass filter by R_n.

Technology (μm)	**0.35**
Filter Order	**2**
ω_0 Tuning Range (GHz)	**1.9 ~ 6**
Quality factor (Q)	**> 60**

Table1: Characteistics Of The RF Bandpass Filter Based On Active Inductor

V. Conclusions

In this paper a novel negative resistance network topology is shown to provide loss compensation on all-transistor active inductor.

The second order bandpass filter based on this active inductor has been proposed. Q-enhancement is accomplished by varying value of negative resistance coupled to the resonator. Tuning range of resonant frequency is demonstrated by varying varactor C_v.

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