GigaHertz 2003 Symposium, Linköping, Sweden, November 4-5, 2003, http://www.ep.liu.se/ecp/008/

TUNED ACTIVE INDUCTOR AND SWITCHED BANDPASS AMPLIFIER IN CMOS TECHNOLOGY

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ABSTRACT

A tunable differential active inductor and a switched bandpass amplifier in CMOS technology are presented. The active inductor is implemented in a 0,25 μm CMOS technology at a supply voltage of 2,5 V. The measured lower end of the inductance tuning range is 3,2 nH with a estimated resonant frequency of 5,6 GHz and a current consumption of 13 mA. The inductance value can be tuned up to 23 nH with a measured resonant frequency of 1,9 GHz and a current consumption of 1,9 mA. The switched differential bandpass amplifier is implemented in a 0,18 μm CMOS technology at a supply voltage of 1,8 V. By activating the first or the second active inductor, the measured bandpass frequeny can be switched between 100 MHz and 770 MHz. A modified switching concept of the active inductors can provide an amplifier with a bandpass frequency that can be switched between 125 MHZ and 875 MHz in 125 MHz steps. Simulations indicate that the maximum gain is 16 dB for all 7 operation modes of the circuit.

INTRODUCTION

Today's wireless communication standards are using a variety of carrier frequencies. To save cost and to improve functionality, it is desirable that transceiver integrated circuits or modules can be used with many different standards. Amplifiers and filters with a tunable bandpass frequency f_{BP} are required, if parallel signal paths for each standard shall be circumvented. Moreover, very broadband receivers, i.e. cable modems, are becoming more and more popular. For linearity reasons and their broad bandwidth, they consume a lot of power. More narrow band receivers with a tunable bandpass frequency f_{BP} could offer power consumption reduction.

Conventional tuning of bandpass or resonant LC-circuits is done by changing the capacitance C. But as the resonant frequency f_{res} is proportional to the reciprocal of the square root of C, large f_{res} tuning range requires even larger C tuning range. A varactor offers only very limited C tuning range. Switched capacitors offer more tuning range, but the upper resonant frequency $f_{res,max}$ decreases with increasing f_{res} tuning range because of the increasing parasitic capacitance. Active inductors and G_m-C circuits are elements to provide a "virtual" inductance. In such circuits, the resonant frequency f_{res} is proportional to the transconductance value G_m. With a tuned or switched G_m -value, a large tuning range for the bandpass frequency $f_{BP} = f_{res}$ can be implemented. Whereas G_m-C circuits are common in the lower MHz frequency range, this work shows the implementation and application of active inductors in the several hundred MHz- and in the GHz-range.

ACTIVE INDUCTOR

The active inductor uses a gyrator topology consisting of two differential amplifiers [1,2]. The schematic is given in fig. 1. The equivalent circuit, the input impedance Z_{IN} and the inductance value L are given in fig. 2. The transconductance $G_{m1,2}$ of the differential amplifiers and thus the inductance value L are controlled by steering the bias current I_{Lref}. The currents I_{Q1ref} and I_{Q2ref} control the output conductance $G_{1,2}$ of the differential amplifiers via negative-G_m-cells. Thus, the quality factor of the inductor is also tunable.

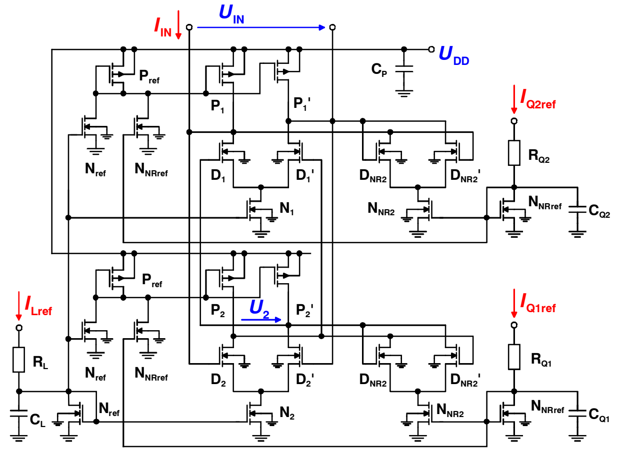
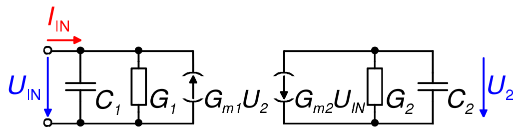


Figure 1: Schematic of the active inductor.



$$Z_{IN} = \frac{U_{IN}}{I_{IN}} = \frac{G_2 + sC_2}{[G_{m1}G_{m2} + G_1G_2] + s[G_1C_2 + G_2C_1] + s^2C_1C_2}$$

$$L = \frac{C_2}{G_{m1}G_{m2}}$$

Figure 2: Small-signal, differential-mode equivalent circuit of the active inductor (top). Input impedance Z_{IN} and inductance L (bott.).

The S-parameter measurements were done using a one-port differential measurement setup with a conventional network analyser and a 180-degree hybrid and matched differential signal paths. Figure 3 shows the comparison of the simulated and measured differential reflection coefficient Γ_{IN} of the active inductor for different settings of bias currents in Smith chart plots. Table 1 summarizes the results. It can be seen that the inductance L can be adjusted in a wide range by changing the bias current I_{Lref} and that the quality factor can be adjusted by changing the currents I_{Q1ref} and I_{Q2ref}. A disadvantage of the tuning concept is the dependence of the linearity of the active inductor on the bias currents.

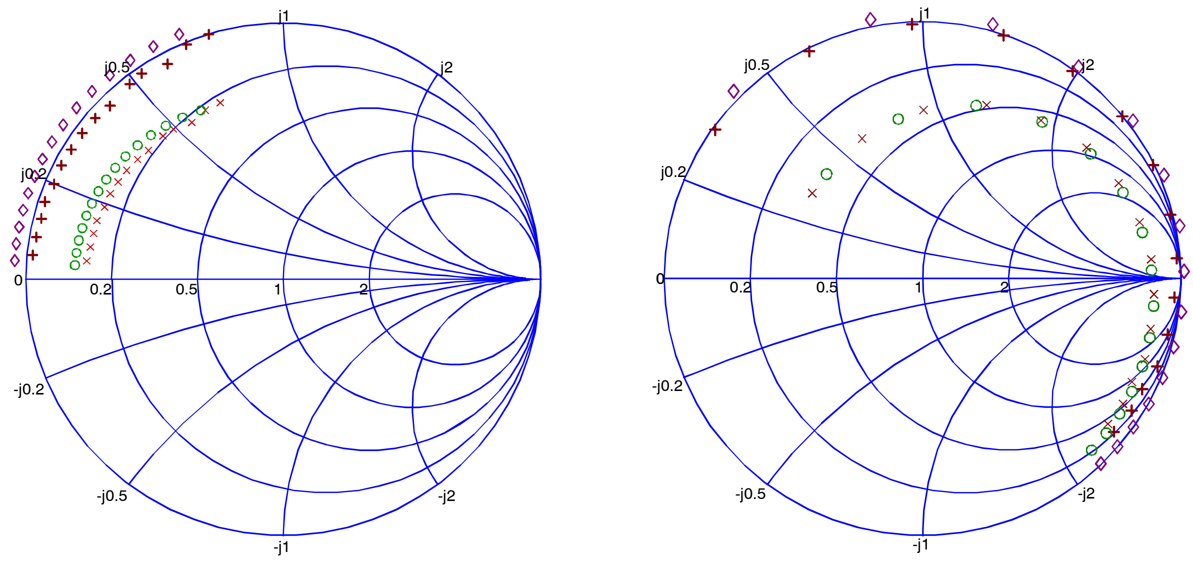


Figure 3: Measured and simulated differential reflection coefficient Γ_{IN} for small inductance bias (left Smith chart) and large inductance bias (right Smith chart). Frequency sweep from 200 MHz to 3 GHz in 200 MHz steps. Smith chart center equals 100 Ω. Symbol definition and bias conditions see table1.

Smith Chart		**← left**		**right →**	
Symbol measurement		×	+	×	+
Symbol simulation		○	◇	○	◇
Current I_{Lref}	**[μA]**	**800**		**100**	
Current I_{Q1ref}	[μA]	0	0	0	10,7
Current I_{Q2ref}	[μA]	0	200	0	11,7
Current consumption I_{DC}	**[mA]**	**12,8**		**1,89**	
Power consumption P_{DC}	**[mW]**	**32,0**		**4,73**	
Inductance L	**[nH]**	**3,2**		**23**	
Resonant frequency f_0	**[GHz]**	**5,6 *)**		**1,9**	

Table 1: Symbol definition and bias conditions for figure 3. Measurement results for the active inductor for U_{DD} = 2,5 V.
*) estimated from simulation.

BANDPASS AMPLIFIER

The circuit concept is given in fig. 4. A differential common-gate amplifier acts as transconductor G_{mV} and provides the input impedance $R_{IN} = 1/ G_{mV}$. The tuned load of the amplifier consists of a RLC parallel resonator. The resistor R_L sets the voltage gain V_U of the amplifier at resonance to $V_U = G_{mV} \cdot R_L$. Two differential active inductors provide the inductance values $L_1 = C/G_{mL1}^2$ and $L_2 = C/G_{mL2}^2$. The bias voltages $U_{Bias\ L/Q1/Q2}$ for the active inductors are generated by the currents $I_{L/Q1/Q2\ ref}$. They are applied to either the first or the second active inductor by on-chip switching circuitry. The switch is controlled by the voltage $U_{control}$. As a result, the bandpass frequency can be switched between $f_{BP1} = G_{mL1}/(2\pi C)$ and $f_{BP2} = G_{mL2}/(2\pi C)$. The bandwidth is given by $B = 1/(2\pi R_L C)$ for both modes of operation. The on-off switching of two active inductors is preferred to tuning the bias of a single active inductor due to linearity reasons. The linearity of active inductors are bias dependant and best at maximum bias current.

The capacitance C is the sum of parasitic and intentional capacitors. The capacitance C should have the same value at all three output nodes of the active inductors to provide for equal voltage swings and therefore maximum large signal performance. To improve linearity further, MOSFET-source degeneration is used in the differential amplifiers of the active inductors [3].

To avoid excessive loading of the amplifier by the $50\ \Omega$ measurement equipment at the output, the resistor R_L (~ 500 Ω) is realized as a voltage divider and only a fraction of the output voltage U_{OUT} is applied to the measurement equipment.

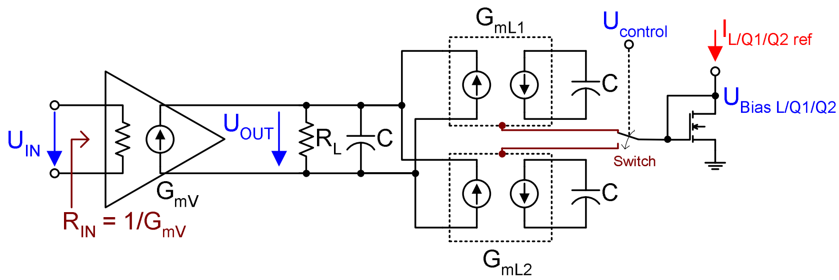


Figure 4: Bandpass amplifier principal schematic.

The S-Parameter measurements were done by using a two-port differential measurement setup with a conventional network analyser and two 180-degree hybrids and matched differential signal paths. Table 2 summarizes the measurement and simulation results. Figure 5 shows the voltage gain of the amplifier for the two modes of operation. The voltage gain is calculated from the measured S-parameters and corrected by the loss of the output voltage divider.

From the noise figure simulation results can be seen that the main drawback of using active inductors is the rather high noise figure. This is due to the fact that the emulated "inductive" current is generated by active devices that contribute noise. This is a basic characteristic of active inductors and G_m-C-circuits and cannot be changed. The large-signal performance is satisfactory and can be enhanced by linearization techniques, but at the expense of increased current consumption.

activated active inductor		1	2
bandpass frequency *)	f_{BP}	96 MHz	770 MHz
input impedance @ f_{BP} *)	Z_{IN}	(78 - j 1)Ω	(84 - j 7)Ω
voltage gain *)	V_U	13 dB	17 dB
3-dB bandwidth *)	B	153 MHz	120 MHz
current consumption *)	I_{DC}	8 mA	46 mA
Noise figure **)	NF	9 dB	16 dB
input voltage rms value @ 1 dB compression **)	$U_{IN,1dB}$	127 mV	83 mV

Table 2: Switched bandpass amplifier measurement and simulation results for first and second active inductor activated for U_{DD} = 1.8 V.
*) measurement result
**) simulation result

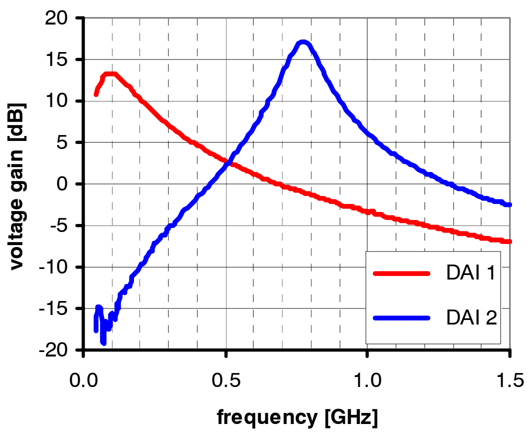


Figure 5: Bandpass amplifier voltage gain.

MODIFIED BANDPASS AMPLIFIER

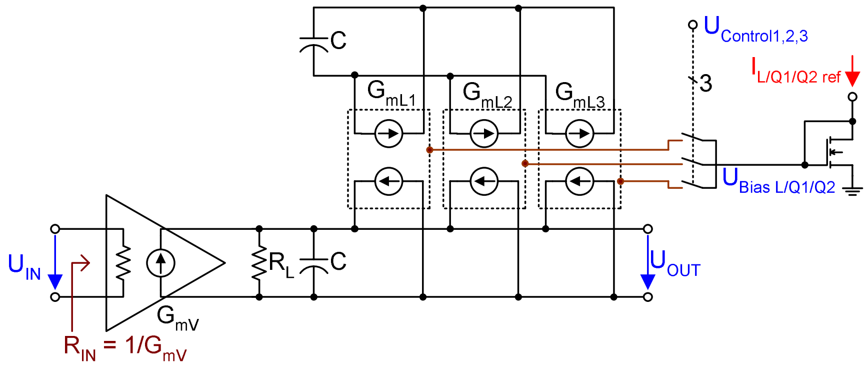


Figure 6: Modified bandpass amplifier principal schematic

The modified bandpass amplifier uses three active inductor cells (fig. 6). All three cells are connected at their differential inputs and outputs. Each individual inductor cell can be switched on and off by the control voltages $U_{Control1,2,3}$. The active inductor transconductances are designed as follows: $G_{mL3} = 2\,G_{mL2} = 4\,G_{mL1}$. With this concept, the bandpass frequency can be chosen to $f_{BPn} = n{\cdot}G_{mL1}/(2\pi C)$, n = 1…7. Figure 7 shows the simulated voltage gain for the seven modes of operation.

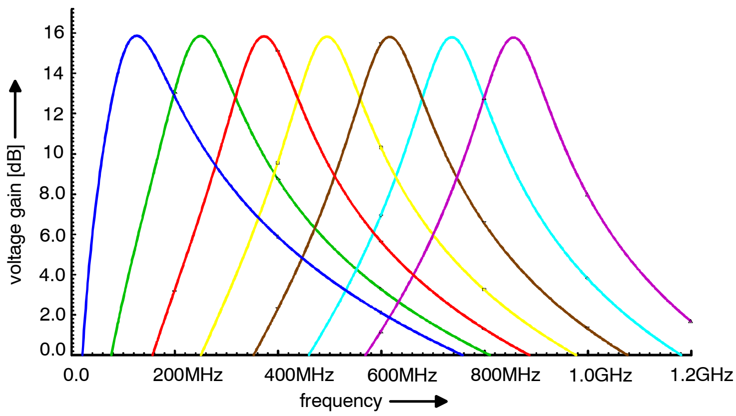


Figure 7: Modified bandpass amplifier voltage gain for the seven different modes of operation

CONCLUSION

The presented 0,25 μm CMOS active inductor features over 10:1 tuning range of the inductance value and up to 5 GHz operation. The presented 0,18 μm CMOS switched bandpass amplifier demonstrates that switching the resonant frequency over a 8:1 range is possible by applying active inductors. With the switching concept, large signal performance can be kept constant over frequency. A disadvantage of active inductors is their poor noise performance. Therefore, they can be hardly used in low noise amplifiers. The increasing current consumption for lower inductance values also restricts the application of active inductors in power amplifiers. But for medium signal levels, active inductors can offer an interesting alternative to conventional circuits. In particular, they are advantageous if the bandpass frequency of a system has to be changed or reconfigured over a broad range.

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