Wide tunable CMOS active inductor

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A tunable CMOS active inductor is presented. The circuit uses a cross-coupled pair of transistors providing positive feedback for enhanced quality factor. The circuit is biased with a controllable current source varying the feedback and tuning the inductor. The proposed inductor is designed and simulated in a 90 nm digital CMOS process. It shows a wide-frequency range inductive impedance and a very high resonance frequency. By cascading two inductors, a wideband filter/amplifier is designed to characterise the inductor performance.

Introduction: CMOS active inductors have attracted much attention in RF/microwave circuit design because of their high quality factor (Q), wide tunability, large inductance value and small chip area [1–5]. The input impedance of these inductors resembles the transfer function of a bandpass filter (BPF). This resemblance gave us an idea to tune the parameters of these active inductors to achieve a high Q and wide tuning range and, in turn, to extend their applications to the design of fully-active RF circuits. In our approach, the active inductor's parameters, the self-resonant frequency ω_0 and the Q-factor, are controlled by a single DC current source. In this Letter, we describe the characteristics of the proposed active inductor and its novel application for realising a wideband BPF and a wideband amplifier.

Tunable active inductor: The well-known cascode active inductor circuit is shown in Fig. 1*a* [1]. The proposed modified circuit for enhanced Q-factor and wide-frequency range inductive impedance is shown in Fig. 1*b*. Here, transistors M1 and M2 are connected in a cross-coupled manner, providing positive feedback to create inductive impedance from capacitive components. The currents in all transistors are defined by one control current I. Indeed, if current I is the drain current of transistors M1 and M3, then the drain current of transistors M2 and M4 is defined as a function of gate–source voltage V_{GS2} of transistor M2, which is calculated by subtracting gate–source voltage V_{GS3} of transistor M3 from voltage V_D. To avoid the triode operation of transistor M3, V_D should be greater than the sum of V_{GS2} and V_{GS3} ($V_{GS2}+V_{GS3}$). If each transistor is modelled by the transconductance g_m and the gate–source capacitance C_{gs} only, then neglecting the output conductance g_{ds} and the gate–drain capacitance C_{gd}, one finds that the input impedance is expressed as:

$$Z_{in} \simeq \frac{(C_{gs3}+C_{gs4})s}{C_{gs1}(C_{gs3}+C_{gs4})s^2 + C_{gs1}g_{m3}s + g_{m1}(g_{m3}-g_{m4})} \qquad (1)$$

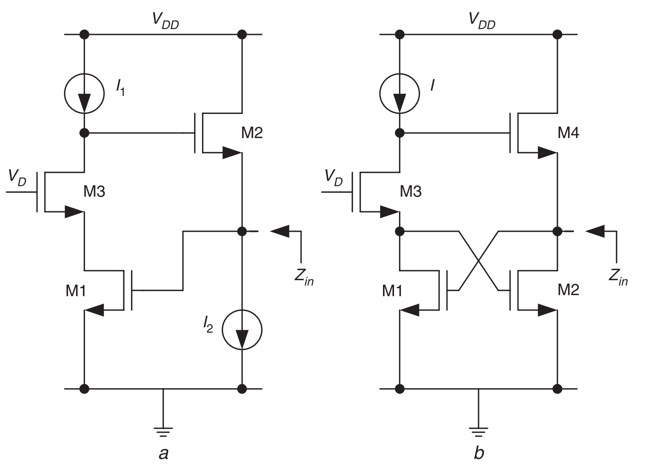

Fig. 1 *Cascode active inductor and proposed active inductor*
a Cascode active inductor
b Proposed active inductor

Indeed, Z_{in} resembles the transfer function of a second-order BPF. The parameters, ω_0 and Q can be derived as:

$$\omega_0^2 = \frac{g_{m1}(g_{m3}-g_{m4})}{C_{gs1}(C_{gs3}+C_{gs4})} \quad Q = \frac{\omega_0(C_{gs3}+C_{gs4})}{g_{m3}} \qquad (2)$$

In terms of current and device parameters, ω_0 and Q can be rewritten as:

$$\omega_0^2 = A\sqrt{I}(\sqrt{I}-B) \quad Q = D\sqrt{1-\frac{B}{\sqrt{I}}} \qquad (3)$$

where

$$A = \frac{4(K_3+K_4)\sqrt{K_1}}{\sqrt{K_3}C_{gs1}(C_{gs3}+C_{gs4})};\ B = \frac{K_4\sqrt{K_3}(V_D-2V_T)}{K_3+K_4};$$
$$D = \frac{1}{2}\sqrt{\frac{C_{gs3}+C_{gs4}}{C_{gs1}}}\sqrt{\frac{K_3+K_4}{K_3}}\sqrt{\frac{K_1}{K_3}} \qquad (4)$$

We assume that $K_i = 1/2\,\mu C_{ox}W/L$ ($i = 1$, 2, 3 and 4) and $I_i = K_i(V_{GSi}-V_T)^2$ (devices described by the quadratic law, where W/L is the aspect ratio of the devices, V_T is the transistor threshold voltage and μC_{ox} is the process constant). If V_D is chosen close to $2V_T$, then B is small and ω_0 becomes proportional to the square root of I ($\sqrt{I}$) and Q is nearly constant. Hence, the analysis shows that Q and ω_0 of the proposed inductor can be defined by one variable (one DC current) only, which leads to a simple tuning.

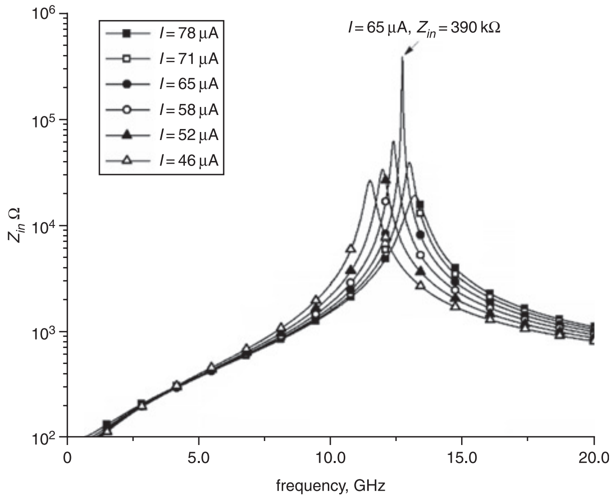

Fig. 2 *Frequency characteristics of input impedance Z_{in}*

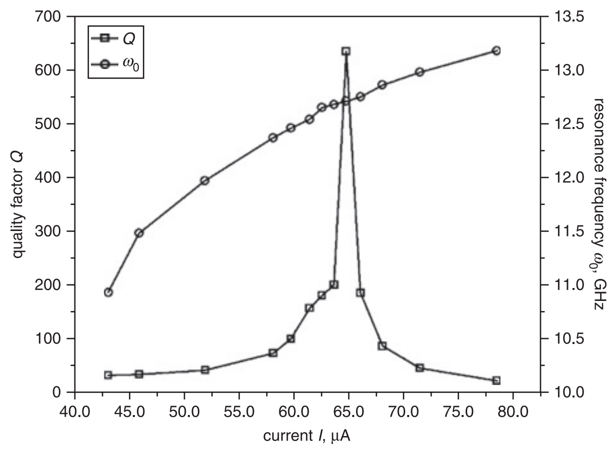

Fig. 3 *Tuning characteristics (ω_0 and Q) over current I*

Design realisation and simulation: The proposed active inductor is designed and simulated in STMicroelectronics 90 nm digital CMOS using the Cadence SpectreRF simulator. Transistors M1 ($W = 2.3\ \mu$m), M2 ($W = 5\ \mu$m), M3 ($W = 3.4\ \mu$m) and M4 ($W = 1.5\ \mu$m) have the length (L) of 100 nm (0.1 μm). Fig. 2 shows the frequency characteristic of the input impedance of the active inductor at different values of tuning current I. Note that the inductive impedance extends from a few megahertz to 12.5 GHz. Fig. 3 shows Q and ω_0 of the active inductor against current I. Indeed, ω_0 is proportional to $\sqrt{I}$. At $I \simeq 65\ \mu$A, it shows a very high Q of 635 (this may be a numerical problem), which is beyond any practical applications. However, the Q

shows an acceptable variation when I is chosen below 60 μA. The proposed circuit is a further modification of that given in [6]. Instead of using a pair of NMOS and PMOS transistors [6], we are using a cross-coupled NMOS transistor pair to realise the positive feedback. This allows us to use a smaller NMOS device and broaden the operating frequency range of the inductive impedance. The positive feedback generates negative resistance, which reduces the inductor loss and, in turn, increases the Q factor.

Bandpass filter/amplifier: In a novel design approach, two active inductors are connected back-to-back through a coupling capacitor C_c (=50 fF) resulting in a wideband active BPF or amplifier, as shown in Fig. 4. The independent tuning of these inductors (using currents I_1 and I_2) allows one to obtain a circuit with amplitude response similar to that of two coupled resonators with Chebyshev filter characteristics. In an alternative approach, by controlling only V_D, one can tune the resonant peak of the BPF and turn the filter into an amplifier. The frequency responses of the proposed BPF/amplifier, terminated with 1 kΩ resistor at both ends (R_S at source and R_L at load), are shown in Fig. 5. Note that, for voltage $V_D = 0.8$ V, the circuit in Fig. 4 shows the characteristics of an amplifier with −3 dB bandwidth of around 3 GHz and for $V_D = 0.9$ V, it exhibits the characteristic of a filter with −3 dB bandwidth of 8 GHz and 0.7 dB ripple.

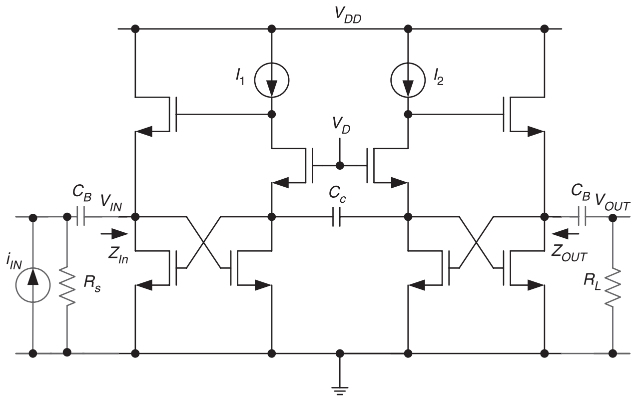

Fig. 4 *Proposed wideband filter/amplifier with cascaded active inductors*

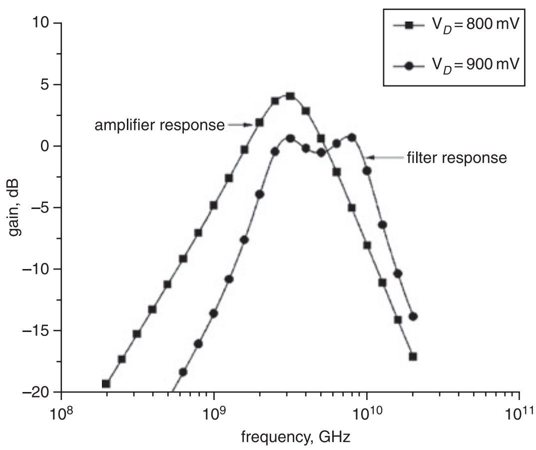

Fig. 5 *Frequency characteristics of wideband filter/amplifier*

Conclusions: We propose an active inductor exploiting the controllable positive feedback to enhance Q-factor and extend the inductive impedance over 12.5 GHz. The proposed circuit topology in realising positive feedback simplifies the design by allowing one to tune and bias the entire inductor simultaneously. We have also shown that back-to-back connection of two such inductors results in a circuit topology that behaves as a wideband filter or a wideband amplifier.

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