A Novel Electrically Tunable RF Inductor With Ultra-Low Power Consumption

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***Abstract*—In this study, we propose for the first time an electrically and continuously tunable RF inductor using grounded metal oxide semiconductor (MOS) transistor as a control device. By adjusting the output resistance of the grounded MOSFET, the ground-return current can lead to a significant variation in series inductance. This proposed inductor structure was implemented in a standard CMOS process and characterized up to 30 GHz, which demonstrates maximum inductance variations of 32% and 58% at 5.8 and 18 GHz, respectively. The dc power consumption of the proposed design is kept within 50 μW over the entire tuning range.**

***Index Terms*—Eddy current, inductor, metal oxide semiconductor field effect transistor (MOSFET), radio frequency (RF), silicon, tunable.**

I. Introduction

WITH the increasing demand of low-cost, low-noise, and low-power wireless communication systems, on-chip inductors play an extremely significant role in the design of radio frequency (RF) front-end circuitry. RF inductors have been widely used in matching networks, LC tanks, passive filters, transformers, etc, and have recently been introduced as tuning elements for RF applications. Variation in inductance of the tunable RF inductors allow for adjusting the impedance matching as well as the frequency selection to optimize the circuit performance. In recent years, several tunable inductors using micro-electromechanical systems (MEMS) technology have been presented [1]–[3]. These passive components can achieve high quality factors and self-resonance frequencies, but their applications are restricted by insufficient tuning range and high mask count. The tunable magnetic RF inductor based on a planar solenoid with a ferromagnetic core was developed to increase the tuning range [4]. However, the limited quality factor and dc power consumption are two major issues. Another way to realize the variable inductance is to employ an active inductor [5], [6]. Although the relatively higher tuning range and quality factor can be achieved, it still consumes considerable dc power and has a high noise level.

In this letter, we demonstrate for the first time an electrically and continuously tunable RF inductor based on an inductor with a variable-impedance ground connection. With the utilization of MOS transistor with grounded source, drain, and bulk as a variable resistor, the dc power consumption can be dramatically reduced. To verify the proposed structure, the inductors, MOS transistors, and corresponding de-embedding dummies were fabricated using a standard CMOS technology and characterized up to 30 GHz.

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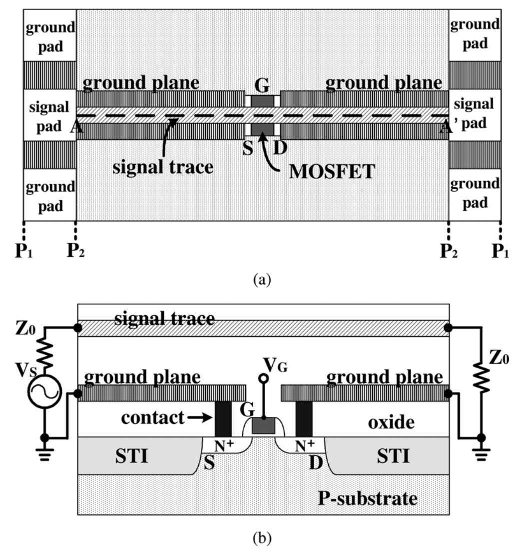


Fig. 1. Illustration of the proposed electrically tunable RF inductor. (a) Top view. (b) A-A′ cross section view (not in scale).

II. Theory and Design

The proposed tunable RF inductor consists of a microstrip signal trace and two finite-width ground planes interconnected with a NMOS transistor. As illustrated in Fig. 1, the source, drain, and bulk of the NMOS transistor are tied to ground potential while the gate electrode is connected to the tuning voltage. The grounded MOSFET acts as a voltage-controlled variable resistance element to adjust the ground-return current, thereby changing the total magnetic flux and inductance between signal and ground conductors. This inductor with imperfect ground can be treated as it is on a lossy substrate. For electrically conductive substrates, the time-varying magnetic fields penetrating into the substrates result in frequency-dependent eddy currents. As the frequency goes higher, these currents induced in the substrate, which are in the opposite direction to the excitation current, can substantially decrease the series inductance. The per-unit-length series inductance of a microstrip line on an electrically conductive substrate can be calculated based on the complex image theory [7], [8].

Fig. 2 demonstrates the frequency-dependent series inductance of a 6 μm-wide microstrip line on various substrates. Simulation shows that the series inductance decreases as the substrate conductivity becomes lower. It indicates that the series

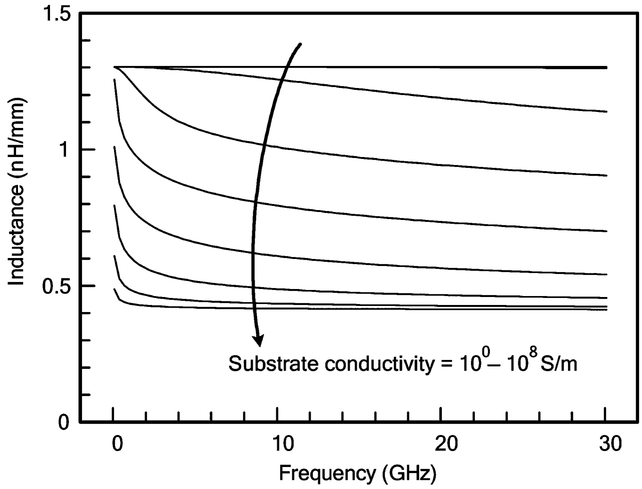


Fig. 2. Simulated series inductance of a microstrip line as functions of operation frequency and substrate conductivity. The line width $=6\ \mu$m, oxide thickness $= 5.6\ \mu$m, and substrate height $= 500\ \mu$m.

inductance of a signal trace can be changed using different substrate conductivities. Consequently, in this study, we attempt to place a MOS transistor in the ground plane to control the equivalent substrate conductivity, thereby, varying the series inductance of the RF inductor.

III. Results and Discussion

To validate the proposed inductor structure, the inductor and corresponding de-embedding structures were fabricated using a standard CMOS process. As referred to Fig. 1, the line length, width, and thickness of the inductor are 200 μm, 6 μm, and 0.8 μm, respectively. The width of the ground plane equals to that of the signal trace and therefore no additional chip area is required. The NMOSFET with the dimensions of channel length $(L_g) = 0.12\ \mu$m and channel width $(W_g) = 8\ \mu\text{m} \times 64$ fingers was inserted between the ground conductors. On-wafer dc and RF measurements from 0.1 to 30 GHz were accomplished with an HP 4142B Modular dc Source/Monitor and an HP 8510C Vector Network Analyzer (VNA), respectively. Before starting the S-parameter measurements, the microwave measurement system was calibrated using the line-reflect-reflect-match (LRRM) calibration procedure with a ceramic impedance standard substrate (ISS). The two-port S-parameters of the devices under test (DUTs) were measured at plane P_1. After subtracting the parasitic effects of probe pads by using the open-short de-embedding method [9], the reference plane was shifted to the plane P_2 and the intrinsic device characteristics can be obtained.

Fig. 3 shows the measured dc characteristics of the fabricated NMOSFET under various bias conditions. The output resistance decreases from about 20 MΩ to 4 Ω with the increasing gate bias. Low-power operation $(< 50\ \mu\text{W})$ thus can be achieved since the MOSFET provides a continuously variable resistance, even with zero drain-to-source voltage. Because of the wide range of output resistance, one MOS transistor with proper gate dimensions would be sufficient to adjust the ground-return current. Fig. 4 shows the inductance and quality factor as functions of operation frequency and tuning voltage for the proposed tunable RF inductor. Here the port 2 of the inductor was short-circuited to calculate the effective one-port inductance and quality factor. When the tuning voltage is zero, the ground is nearly floating and the tunable inductor behaves like an inductor with no ground shield (NGS). As the tuning voltage increases, the equivalent ground impedance goes down and eddy current flows. So now it acts more like an inductor with solid ground shield (SGS). Basically, the RF characteristics of the proposed tunable inductor can be changed between the two boundaries (NGS and SGS inductors), except for some parasitic effects at high frequencies. The maximum inductance variations of 32% and 58% at 5.8 and 18 GHz are observed, and the maximum quality factor of 6.44 at 6.4 GHz is also achieved. High inductance and quality factor can be achieved by increasing line length and metal thickness, respectively. Fig. 5 shows that the characteristic impedance (Z_C) of this design extracted using (1) can be substantially changed, especially at microwave frequencies [10]

$$Z_C = \pm Z_0 \sqrt{\frac{(1+S_{11})^2 - (S_{21})^2}{(1-S_{11})^2 - (S_{21})^2}}. \tag{1}$$

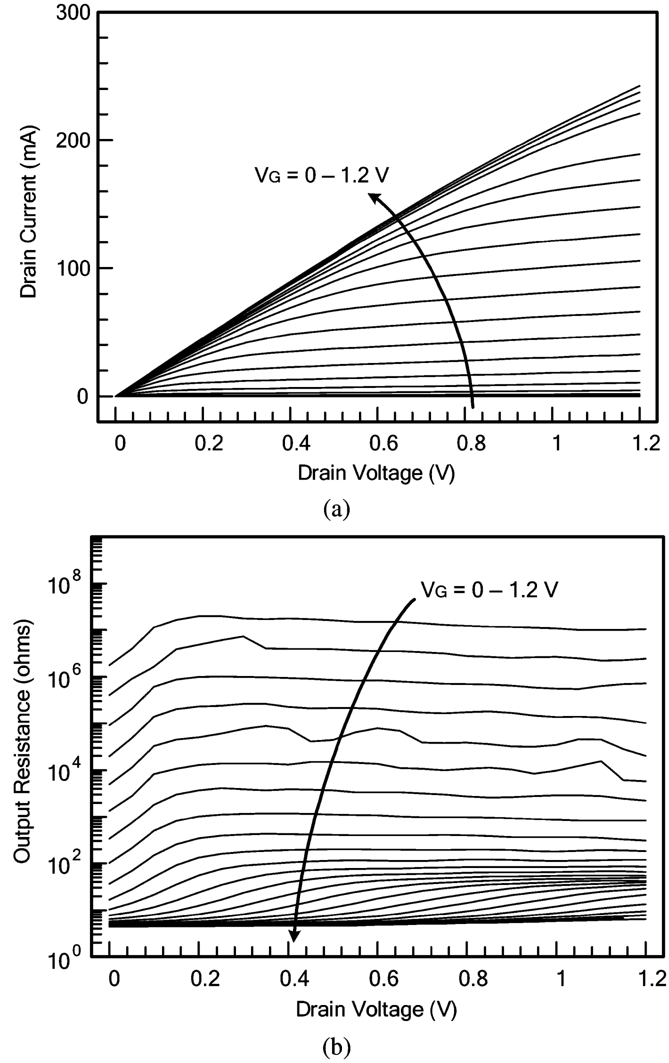
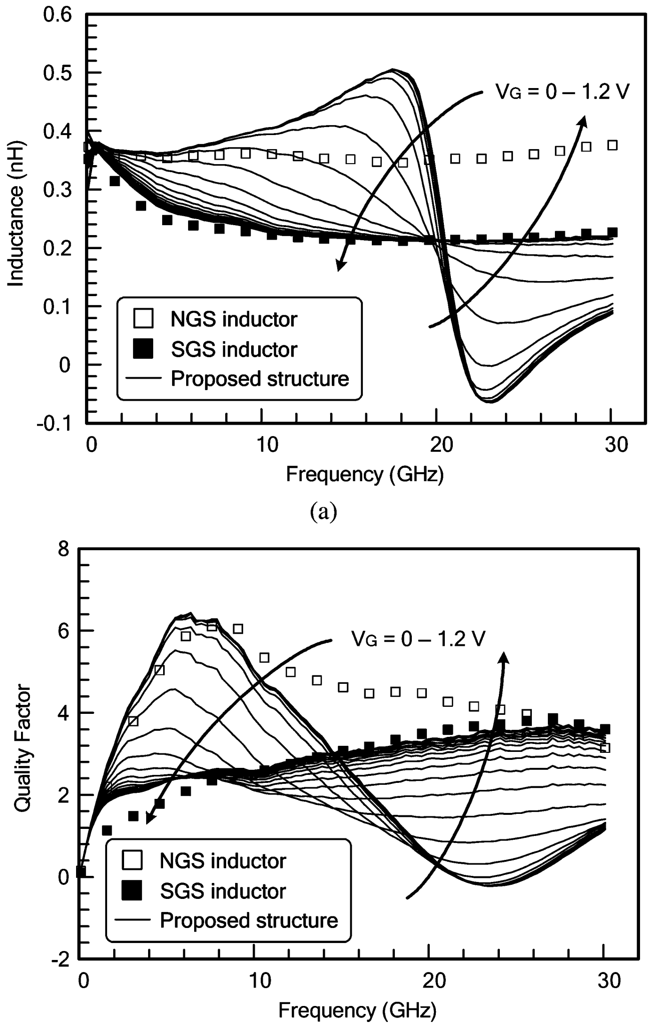


Fig. 3. (a) I_D–V_D curves and (b) output resistance with 50 mV steps obtained from the NMOSFET. The dimensions of channel length $= 0.12\ \mu$m and channel width $= 8\ \mu\text{m} \times 64$ fingers.



(b)

Fig. 4. (a) One-port inductance and (b) quality factor versus frequency for proposed tunable RF inductor at different (gate) tuning voltages. Results from the inductors with no ground shield (NGS) and solid ground shield (SGS) are also shown for comparison.

It should be noted that Z_0 is the impedance of the VNA. This finding would be very helpful for RF engineers to adjust the impedance matching and optimize the circuit performance.

IV. Conclusion

In this letter, an electrically and continuously tunable RF inductor has been presented and verified. This proposed structure uses a MOS transistor to realize the inductance tuning and impedance matching under extremely low-power operation. Measurement results taken over a frequency range from 0.1 to 30 GHz show maximum inductance variations of 32% and 58% at 5.8 GHz and 18 GHz, and a maximum quality factor of 6.44 at 6.4 GHz, respectively. Results also indicate that the proposed tunable inductor is area-efficient and can be used for on-chip optimization.

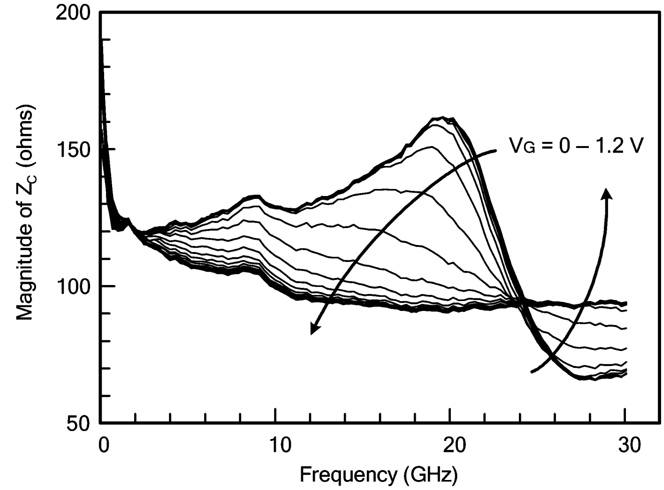


Fig. 5. Characteristic impedance (Z_C) versus frequency for proposed tunable RF inductor at different (gate) tuning voltages.

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