A Novel Switched-Turn Continuously-Tunable Liquid RF MEMS Solenoid Inductor

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***Abstract*— this paper presents a continuously-variable MEMS solenoid inductor operating up to 20 GHz. In this novel idea, a channel is provided to bypass the turns by injection of a conductive liquid (Galinstan). Corresponding to the level of injection, the reduction in number of the turns varies the inductance value. The proposed Solenoid inductor is simulated with HFSS in Silicon substrate with Copper-type coil and injected conductive liquid. The EM simulation results show a maximum quality factor of 20 at 14 GHz and a tuning ratio of 1:5 at 16 GHz frequency. The minimum and maximum inductance values are 0.63 and 3.16 nH at 16 GHz which demonstrates a tuning range equal with 400%.**

Keywords— RF MEMS; tunable inductor; liquid inductor; solenoid; quality factor; tuning range; inductance; liquid-based

I. INTRODUCTION

The growing market of wireless multi-band systems demands for high-quality highly-linear variable RF MEMS components. RF MEMS components including MEMS inductor have wide range of applications in RF transceivers such as VCO [1, 2] , LNA [3, 4], DC-DC converters [5-7], matching networks, multi-band filters, multi-band RF circuits and RF power amplifiers in radio transmitters. MEMS inductors unlike the MMIC inductors benefits from high quality factor which improve the noise figure in low-noise amplifiers and phase noise in oscillators, and also capability for tuning.

In the previous works, there are several methods to make inductors tunable by changing the number of turns [8, 9]. Here, this paper proposes a solenoid inductor which can continuously be tuned. The inductance varies by changing of the number of the turns in the solenoid inductor while a conductive liquid flows through the channel in contact with the segments of the coil; hence, it bypasses some turns.

The main research issue for integrated tunable passive inductors is high tuning ratio with continuous variation state [10]. The challenge is to achieve a high quality (>50) inductor with an adequate tuning ratio (>10) operating in a broad frequency ranges (1-60GHz) until 2015 [11].

In [10, 12], inductance variability was proposed based on changing number of turns in spiral inductor. The novelty in this work which makes this work new technique is injecting conductive liquid (Galinstan and salted water) between the spiral turns and cause to bypass some of the turns. This work achieve 107% tuning range in 1.6 GHz frequency, the peak of quality factor was 12.

In [13], tunable inductors based on transformer mutual action with on-chip micromachined vertical switches and an actuation gap of a few micrometers was developed. In this work, silver was used as the metal to implement the coil. Six masks were used for fabrication. The inductor can work in 1-10 GHz. The tuning range is calculated as 47% at 6 GHZ with a high Q factor around 20-45.

This paper presents a novel idea to implement a continuously tunable RF MEMS solenoid inductor. The technique is based on changing number of turns by injecting a conductive liquid such as Galinstan in the channel which bypasses the segments. When the conductive liquid is injected through the channel, the liquid start to flow continuously and then, it makes the adjacent turns bypassed. The solenoid inductor benefits from silicon substrate and copper metal. GaInSn, called Galinstan is a non-toxic conductive liquid alloy with electrical conductivity of 3.46×10^{6} S/m and relative permeability of 1.257×10^{-6} N.A^{-2} [14].

The solenoid inductor proposed in this paper has 40 turns and 20µm × 20µm × 200µm size. Using the MEMS process, the channel is implemented along with the solenoid coil to have the liquid flow inside. The advantage of this work is continuously tunability with simple process for fabrication since only four mask is required for lithography, and also very high tuning range and adequate quality factor in high frequencies.

II. PRINCIPLES FOR TUNABLE MEMS SELONOID INDUCTOR

The concept and theory of inductor design including inductance and quality factor equations has arisen different tuning techniques. Equation (1) represents a simplified inductance calculation for a solenoid inductor:

$$L = \frac{\mu_0 \times \mu_r \times n^2 \times w_c \times t_c}{l_c} \quad (1)$$

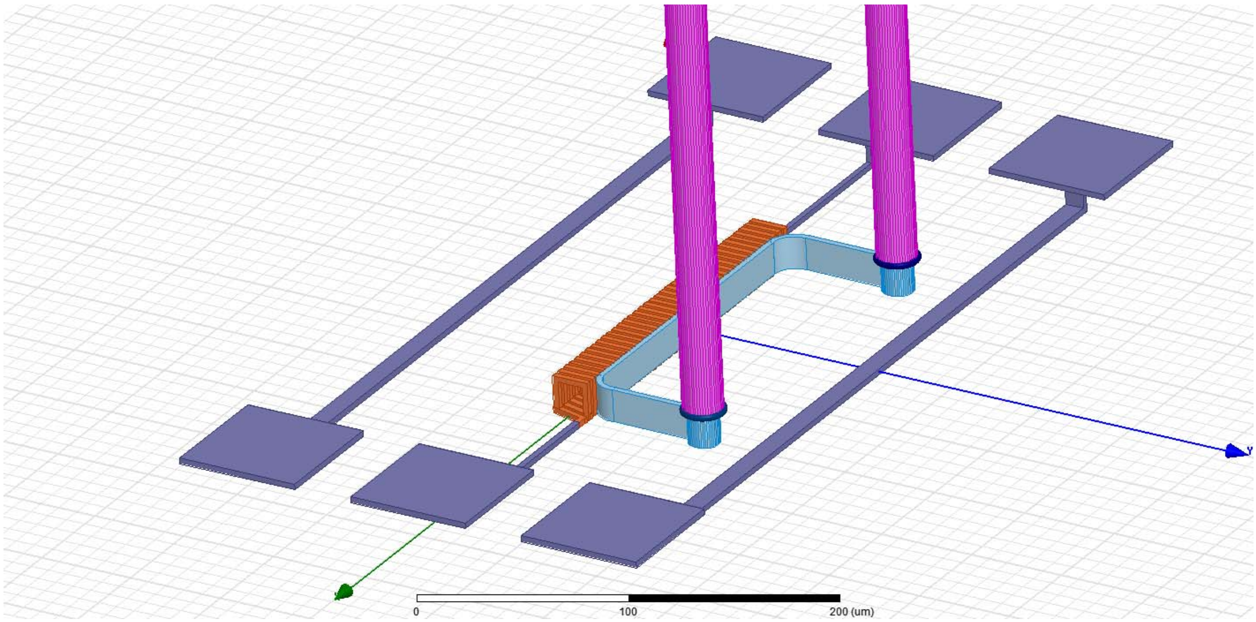

Fig. 1. 3D simulation in HFSS shows channel inside the solenoid inductor how connected to the micropipe, also the pads for measurment is around the inductor. The dielectrics are hidden for illustration purpose.

where μ_0 and μ_r are vacuum permeability and relative permeability, respectively; n indicates number of turns and w_c, t_c and l_c represent the width, thickness and length of the coil [15].

According to inductance equation, the inductance is directly proportional with square number of turns; therefore, different values of inductance can be achieved with changing number of turns. The tuning method in this paper is based on the identical theory. By injection of the Galinstan as the conductive liquid through the channel which is implemented to bypass the segments of the coil, the number of turns is allowed to change from 40 to 2 turns, continuously; hence, the inductance varies. Since the inductance is squarely proportional with number of turns, the tuning range is very high in compared with the methods using other parameters of inductance equation.

The quality factor can simply be found from the ratio of the equivalent reactance and its series resistance:

$$Q = \frac{\omega L}{R} = \frac{\omega \mu_0 \mu_r n^2 w_c t_c w_m t_m}{2\rho (w_c + t_c) n^2 p} \quad (2)$$

where w_m, t_m, ρ and p are metal width, metal thickness, metal resistivity and turns pitch, respectively. As can be observed, number of turns does not have any effect on the quality factor. This means that by changing of the number of turns, the quality factor maintains constant; this is true when lossless switches are used to bypass the turns with zero insertion loss. Here, Galinstan is employed as the conductive liquid to switched turns which its conductivity is at least ten times lower than the copper. In this case, we expect more decrease in quality factor once more turns are bypassed.

According to (2), it is expected that quality factor increases by frequency increase, ω. However, the decrease of the skin depth with the increase in frequency results in reduced conductor cross-section and increased resistance, R. The skin effect rises from the eddy current; this reduces the effective cross sectional area of the segments and hence, increases the series resistance. Unlike the spiral inductors, the direction of flux in solenoid-type inductor is parallel with the substrate which leads to lower substrate loss and skin effect [16]. Because of this reason, Solenoid inductor indicates higher quality factor than spiral ones.

Figure 1 shows a 3D model structure of the proposed inductor. In this figure, the solenoid inductor with a channel along with the coil is illustrated. Micropipes shown in this figure are connected to both ends of the channel for liquid flow from micropipe through the channel. The micropipes is connected to the main tank and a micropump pumps the liquid from the tank to the pipe and then, to the channel. The channel is located in contact with the coil so that the conductive liquid can cause a short between adjacent turns.

III. Design and Fabrication

Figure 2 illustrates the process steps for fabrication of the proposed inductor. In this process, four masks are used. Silicon wafer is selected as the main substrate. The steps are as follow: (*a*) First, silicon oxide film is deposited with phosphorous doping as the sacrificial layer. This causes a distance between the coil and the substrate to improve the quality factor; and then, Au is evaporated as seed layer with 1 μm thickness; (*b*, *c*) a positive photoresist is used for copper electroplating with 3 μm height; (*d*, *e*) using a positive photoresist for copper electroplating , via is created with 14 μm height. On the top of the via, a seed layer of gold is electroplated with thickness of 1 μm without any photoresist. (*f*, *g*) The bridge is made by electroplating copper on the gold with last photoresist mask for 3 μm height; (*h*) the last step for making the air-bridge is to remove the photoresist with acetone. (*i*) to make the channel, SiO_2 is deposited with 22-μm height, and then (*j*) PDMS is deposited on the top with 4 μm height. (*k*) Using fourth mask, the channel pattern is formed on PDMS for dry etching of SiO_2. (*l*) SF6 gas is injected to remove SiO_2 and to create an empty channel; (*m*) the last step is to cover the channel with PDMS to avoid any liquid leakage for later injection. Using these steps, the channel along with the solenoid inductor and in contact with its segments is created. Figure 3 shows a prospective view of steps *l*. Using a micro pump, the Galinstan is injected into the channel and start to flow. A 3D view of the proposed work is given in figure 3 for better understanding. work presents the theory and simulation results.

IV. Simulation Result

The inductor is simulated in HFSS once the channel of the core is empty (air or vacuum) and then, a step-by-step liquid (Galinstan) injection through the channel is carried out; in this case, the variation of the inductance and the quality factor for different levels of injection is recorded.

Figures 4 and 5 shows the plots for the inductance variation and its corresponding quality factor, respectively, for different level of injections (0% to 100% by step of 11.2%). The EM simulation results shows a minimum and maximum inductance value of 0.63 and 3.16 nH in 16 GHz for 0% (empty channel) and 100% (fully-injected channel) levels, respectively. As can be seen in figure 6, the tuning range can be calculated as 400 % in 16 GHz. The maximum quality factor is achieved by 20 at 14 GHz.

As discussed earlier, the quality factor decreases more while more turns are bypassed. This happens because of lossy conductive liquid. The worst quality factor happens when the channel is fully injected by Galinstan; this forms the longest bypass pattern which is the most lossy one.

In addition; the quality factor increases with frequency until a critical frequency in which the skin effect become effective in the series resistance and hence, the quality factor.

V. Conclusion

A novel liquid-based switched-turn variable inductor was proposed and simulated in HFSS. The variable inductor benefits from a continuous tuning state. A tuning range of 0.63−3.16nH was achieved at 16 GHz with a maximum quality factor of 20. The advantage of this work is to achieve high Q factor, wide continuous tuning range with simple process for implementation. The tuning ratio is 5:1 at 16 GHz which is higher than previous works [12, 13, 17, 18]. This inductor operates in a frequency range of 3-20 GHz with a Q of over 5 at its worst case.

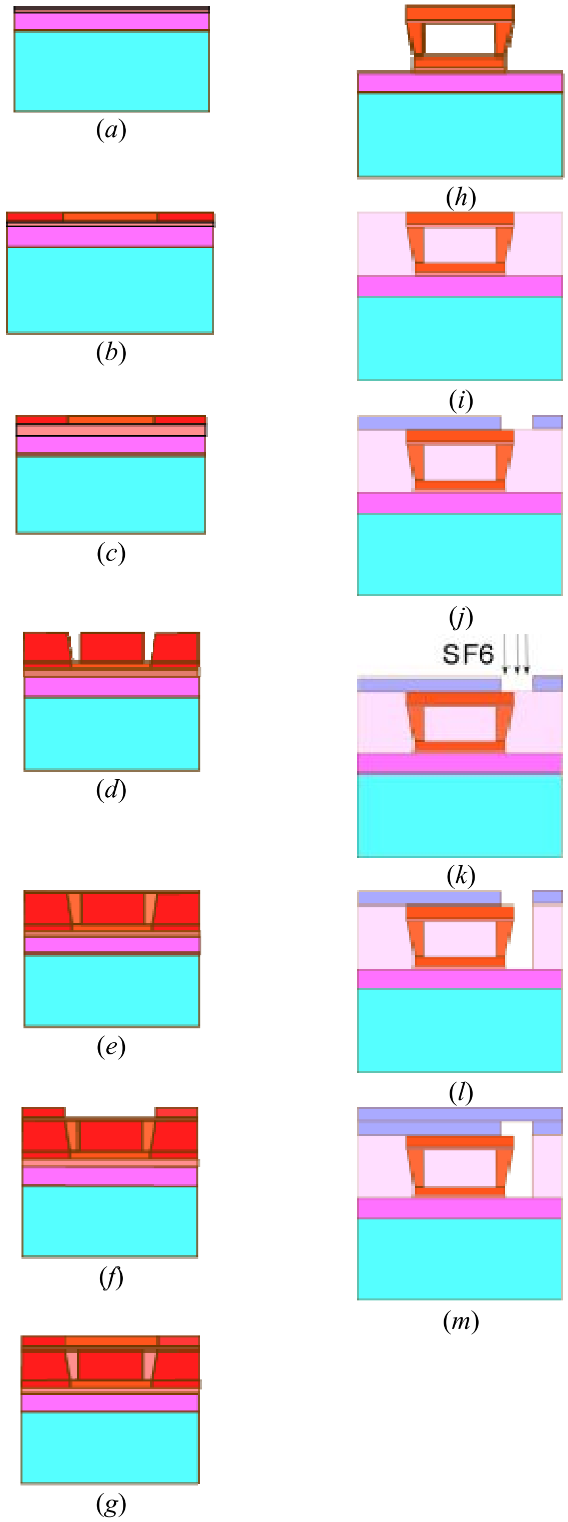

Fig. 2. MEMS process (*a*) Silicon dioxide and gold as seed layer deposition (*b*) photolithography for electroplating base mold using first mask , (*c*) copper electroplating, (*d*) photoresist based on second mask, (*e*) copper electroplating as via, (*f*) photoresist third mask, (*g*) copper electroplating make bridge, (*h*) remove the photoresist with acetone, (*i*) deposit SiO2 , (*j*) deposit PDMS, (*k*) fourth mask for make the holes, (*l*) inject SF6 gas from the holes, (*m*) channel beside the solenoid inductor.

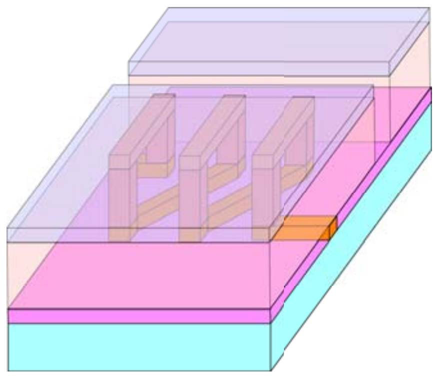

Fig. 3. 3D model of fabrication process shows step (*l*) with 3D view

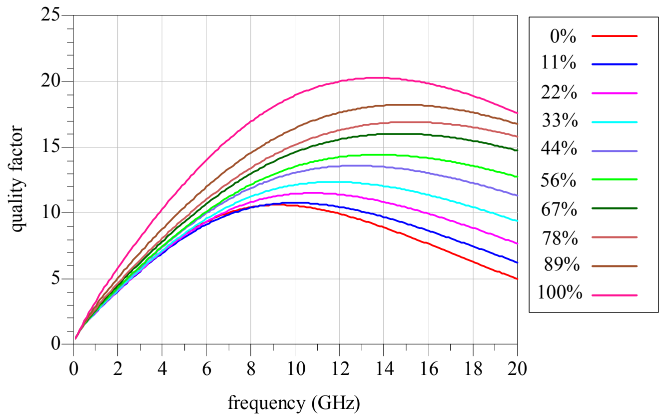

Fig. 5. EM simulated Quality factor with different levels of Galinstan injected into the channel.

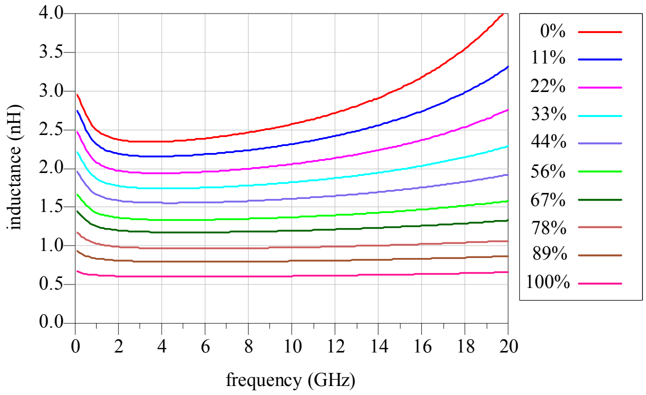

Fig. 4. EM simulated Inductance with different levels of Galinstan injected into the channel

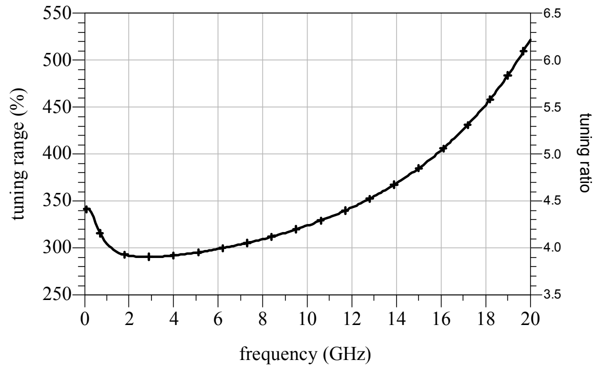

Fig. 6. Tuning range

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