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A Design of Ferrofluid-Based Fine-Tunable Solenoid MEMS Inductor Using Wire Bonding Technique for Ultra-High Frequency Applications

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Abstract: *In this paper, a ferrofluid-based fine-tunable solenoid MEMS inductor using a wire bonding technique is proposed. The proposed tunable solenoid inductor is fabricated and measured at 400 MHz. In this work, the light hydrocarbon-based ferrofluid EMG 901 660 mT with a magnetic permeability of 5.4 is utilized in the design to achieve fine-tuning inductance. In addition to that, the wire bonding technique is applied to form a wire-wounded of solenoid shape by bonded diagonally at the edge of the metal pad, crossing it over the top of a micro-tube. The micro-tube acts as a channel for tunability. The simulation results obtained from HFSS show that, at 400 MHz, the quality factor increases from 10 to 12 with inductance values tuning from 7.48 nH to 9.06 nH for empty channel and fully injected channel, respectively. However, the measured results of the fabricated inductor revealed that, at 400 MHz, the quality factor gradually decreases from 6.79 to 5.49 with inductance values tuning from 21.40 nH to 22.40 nH for empty channel and fully injected channel, respectively. Thus, a tuning range of 21% and 4.67% are successfully achieved for both simulation and measured results, respectively. In conclusion, the design of ferrofluid-based fine-tuning solenoid MEMS inductor is proven to be workable for ultra-high frequency applications.*

Keywords: *MEMS inductor, ferrofluid, fine-tuning, bond wire, and quality factor*

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I. Introduction

Recently, integrated passive devices such as inductors, capacitors, and varactors are studied by researchers for the purpose of improving the performance of radio frequency integrated circuits (RFIC). For instance, an integrated inductor plays an important role in RFIC i.e. power amplifier, low noise amplifier (LNA), filters, and voltage-controlled oscillator (VCO) [1]. Conventionally, planar monolithic microwave integrated circuits (MMIC) inductor was mostly used as an integrated passive device due to its low power consumption, small in size and low manufacturing cost. However, due to high parasitic capacitance and eddy-current loss inherent in a substrate, the performance of the inductor was greatly affected by that and thus, reduced the quality factor of the inductor significantly. This behavior was studied by [2] [3] [4], where a high substrate loss appeared in a bulk silicon substrate. To encounter those problems, microelectronic mechanical systems (MEMS) technology is introduced to the RFIC applications for better inductor performances [5].

MEMS technology is one of the methods to improve the quality factor of the inductors. Several techniques using MEMS design approach can be implemented such as; removing the substrate under the coil or increasing the distance between the substrate and inductor coil; increasing the thickness and width of the conductor metal; the use of high resistivity substrate; and the use of high conductivity material of the inductors. All of these methods will eventually help to improve and reduce the effect of substrate loss inherent in a substrate. There are few studies that have been presented by previous researchers in order to improve the performances of the inductor. Such studies are; maximizing the width of conductor [6][7]; shrinking the size of inner turns of the metal coil [8][9]; increasing the distance between segments of winding [10] [11]; embedding the inductor on the substrate wafer [12]; and back-grinding the substrate wafer [13].

A high performances tunable inductor can also be achieved with a MEMS design approach. The unique of the MEMS inductor design is that tuning can easily be achieved by changing the magnetic permeability of the inductor core. One of the most popular methods to achieve inductance tuning is by using liquid-based properties. This method can be achieved by allowing a magnetic fluid element to flow through the inductor core. This will cause the permeability of the inductor to change and induce inductance tuning. Such recorded studies from previous researchers using liquid-based approaches are; the design of ferrofluid-based variable solenoid inductor with micro-pipe [14]; the design of MEMS variable solenoid micro-fluidic inductor with galinstan-based [15]; the design of stretchable inductor with metal liquid galinstan [16]; the design of ferrofluid-based variable planar inductor with actuation coil [17]; and the design of on-chip liquid micro-variable inductor [18].

In this paper, a wire bonding technique using ferrofluid-based as an inductance tuning is implemented in the MEMS inductor design. The main objective of this work is to achieve high quality factor with a fine-tuning inductance. This inductor is fabricated and measured at 400 MHz as a proof-of-concept work. A wire bonding technique is implemented in the design as a method to reduce the ohmic loss in a metal coil as well as to improve the quality factor of the inductor. The solenoid shape is chosen for this design due to its low current distribution especially at a metal edge of coils [19]. The ferrofluid-based is selected for inductance tuning due to its high magnetic permeability of 5.4 as compared to galinstan-based (GaInSn) and salted water ($CaCI_2$ solved in water); which both are having a magnetic permeability of 1.257 and 2.41, respectively [15][20]. Thus, Section II, Section III and Section IV will be discussing on the device description, fabrication process and results of the fabricated tunable MEMS inductor at 400 MHz, respectively. Frequency of 400 MHz was chosen as a proof of concept work due to the limitation of the inductor size which our tool can fabricate. To summarize, Section V will be concluding the objective of this research thoroughly.

II. Methodology

In this work, the integrated solenoid MEMS inductor is presented, as seen in Fig. 1(a). The inductor model is designed by using awire bonding technique. This technique is utilizing the gold bond wire as one of the components to create a solenoid coil. The bond wire is implemented in such a way that the bond wire is bonded diagonally at the edge of metal lines which formed a semi-circle shape on top metal lines; where bond wire is acting as the upper half of the solenoid coil while metal lines (here, aluminum) is acting as the bottom half of the solenoid coil. The close-up illustration of this model is seen in Fig. 1(b). The micro-tube is then placed in between metal lines and bond wire in order to create a channel for liquid (here, ferrofluid) to flow into the inductor core. Fig. 2 illustrated the dimension of the micro-tube. The dimension of metal lines, bond wire, and micro-tube are depicted in Table 1.

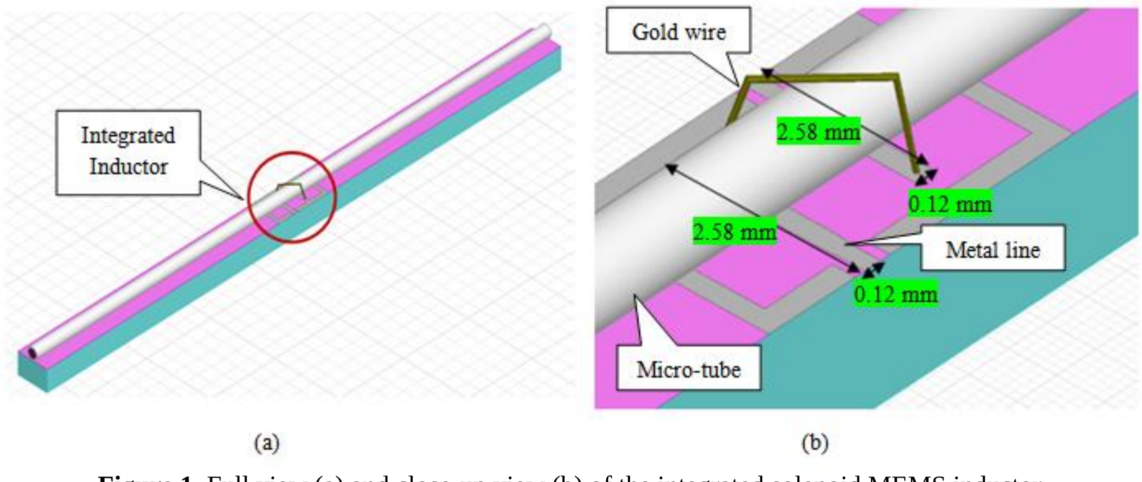

Figure 1. Full view (a) and close-up view (b) of the integrated solenoid MEMS inductor

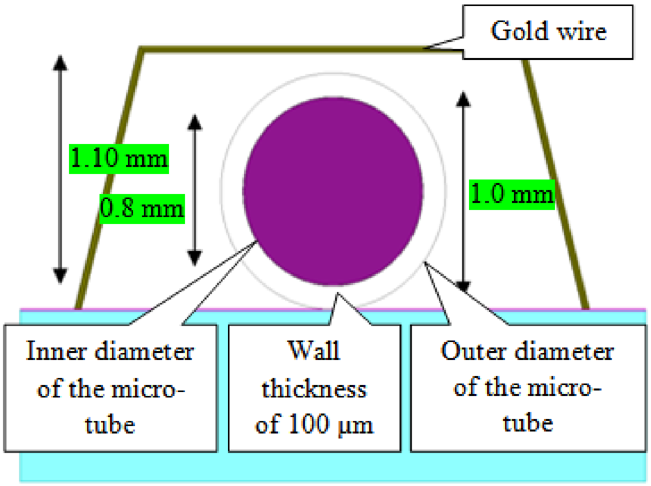

Figure 2. The dimension of the micro-tube

Table 1. The dimension of the inductor

Dimension of the inductor			
Inductor size *(W×L)*	0.74 mm × 2.38 mm		
Metal line *(W×L)*	2.58 mm × 0.12 mm		
Micro-tube	Inner diameter	Outer diameter	Wall thickness
	0.8 mm	1.0 mm	100 µm
Gold wire	Diameter	Height	
	30 µm	1.10 mm	

The magnetic ferrofluid is used to vary the permeability of the inductor core. The ferrofluid is injected through one end of the micro-tube with micro-syringe in order to change the permeability from air core to ferrofluid core. By referring to Eq. 1, the inductance (L_s) is directly proportional to the permeability of the core (μ_r).

$$L_S = (\mu_o . \mu_r . N^2 . w_c . t_c)/l_c (1)$$

where N, μ_o, μ_r, w_c, t_c, and l_c are referring to the number of turns, vacuum permeability, core permeability, width of metal lines, metal line thickness and length of inductor, respectively.

The inductance is observed based on the percentage of ferrofluid been injected to the inductor core. Thus, the higher the percentage of ferrofluid in the inductor core, the higher the tuning of the inductance. For this device, only one turn of winding is used.

III. Fabrication process

In this work, the design is started with a wafer dicing. The dimension of the wafer substrate is fixed according to the size and length of the inductor and micro-tube, respectively. In this design, the size of the substrate is 20 mm × 76.2 mm (*W*×*L*). A silicon on insulator (SOI) is used in the design to reduce substrate loss in the substrate wafer. Here, silicon dioxide (SiO_2) is utilized to increase the distance between the solenoid coil and the substrate.

After that, the process continues with a sample cleaning. The sample is cleaned using acetone-methanol-isopropanol (AMI) method where it is prepared by immersing the SOI sample in the acetone for five minutes, followed by the ultrasonic cleaner. This procedure is then repeated for both methanol and isopropanol.

The process then continues with metal deposition where, aluminum powder is deposited with a thickness of 1 micron, as seen in Fig. 3. The auto RF sputter coater was used in this process for metal deposition.

Figure 3. Aluminum metal deposited on SOI sample

After the metal deposition is completed, an annealing treatment is performed on the sample to improve the roughness of the aluminum surface layer. This is due to the uneven surface caused during the metal deposition process.

Follow by annealing treatment is the laser patterning process. This process is performed to create metal lines on the sample. In this work, the laser patterning is done by creating metal lines as the bottom half of the solenoid coil. Fig. 4 shows the sample is patterned using laser micromachining; both metal line 1 and metal line 2 are patterned with a dimension of 2.58 mm × 0.12 mm.

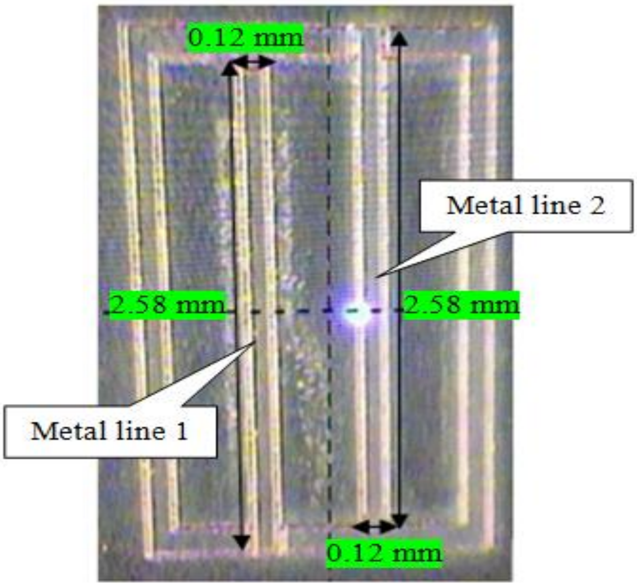

Figure 4. Laser patterning process using laser micromachining

The process then continues with a plasma cleaning. The surface of metal lines needs to be cleaned first in order to remove unwanted organic material on the surface especially before wire bonding process. In addition, it also improves the adhesion of the surface metal by changing the surface properties from hydrophobic to hydrophilic. This sample undergoes plasma cleaning treatment using oxygen for two minutes.

Finally, the gold bond wire is bonded diagonally at the edge of the first metal line and the second metal line. The ball technique is used as an interconnection between the bond wire and underlying of the aluminum pad. In this design, the bond wire will act as the top half of the solenoid coil. Fig. 5 shows the gold wire bonding at the edge of the first metal line to second metal line; the length of the gold wire from metal line 1 to metal line 2 is 1.58 mm while the size of the micro-tube is 1.0 mm (outer diameter). Flow chart of the fabrication process can be referred to in Fig. 6.

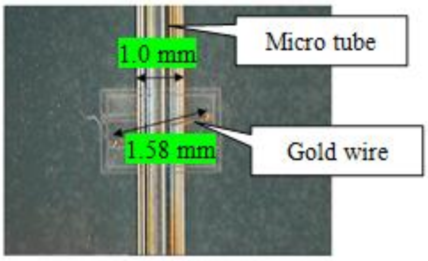

Figure 5. Gold wire bonding at the edge of the first metal line to second metal line

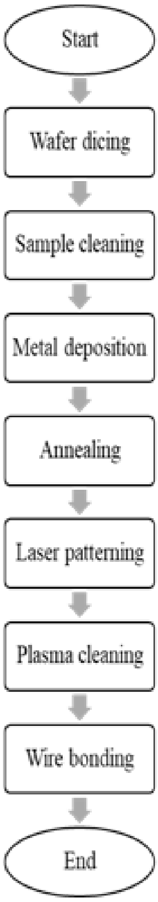

Figure 6. Flow chart of the fabrication process

IV. Results And Discussion

In this work, the light hydrocarbon-based ferrofluid EMG 901 660 mT is injected to the inductor core from 0% (empty channel) to 100% (fully injected channel). The results are recorded for quality factor performance, inductance values and tuning range for both EM simulation and measurement results.

Simulation Results

In Fig. 7, the graph shows that the quality factor observed at 400 MHz is gradually increased from 10 (empty channel) to 12 (fully injected channel), respectively. As for the inductance, in Fig. 8, the inductance is tuned from 7.48 nH (empty channel) to 9.06 nH (fully injected channel), respectively. Thus, the simulation observed that the tuning range of 21% was successfully achieved, as seen in Fig. 9.

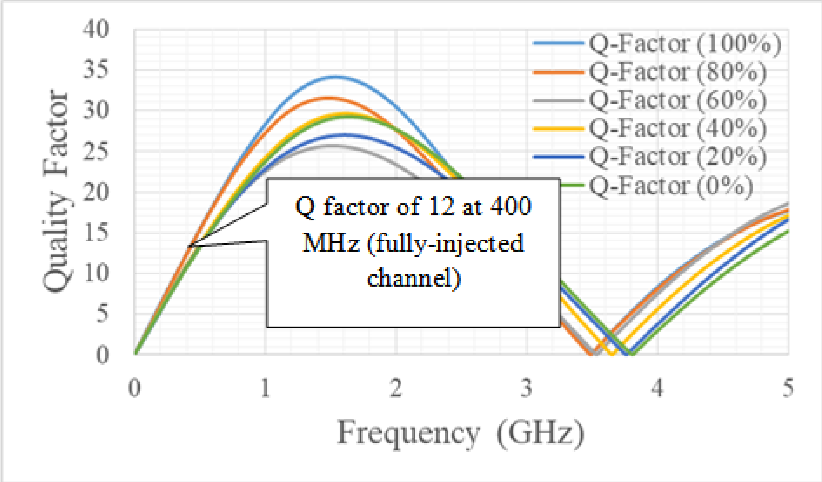

Figure 7. Simulated quality factor from 0% (empty channel) to 100% (fully injected channel) at 400 MHz

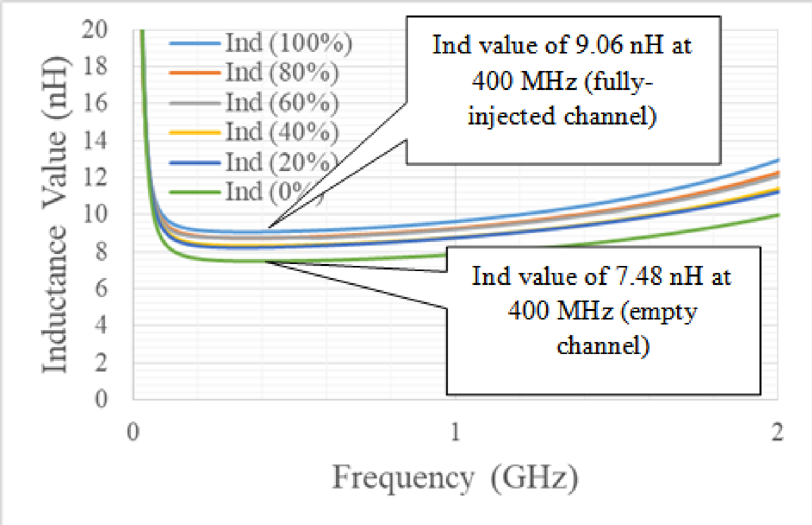

Figure 8. Simulated inductance values from 0% (empty channel) to 100% (fully injected channel) at 400 MHz

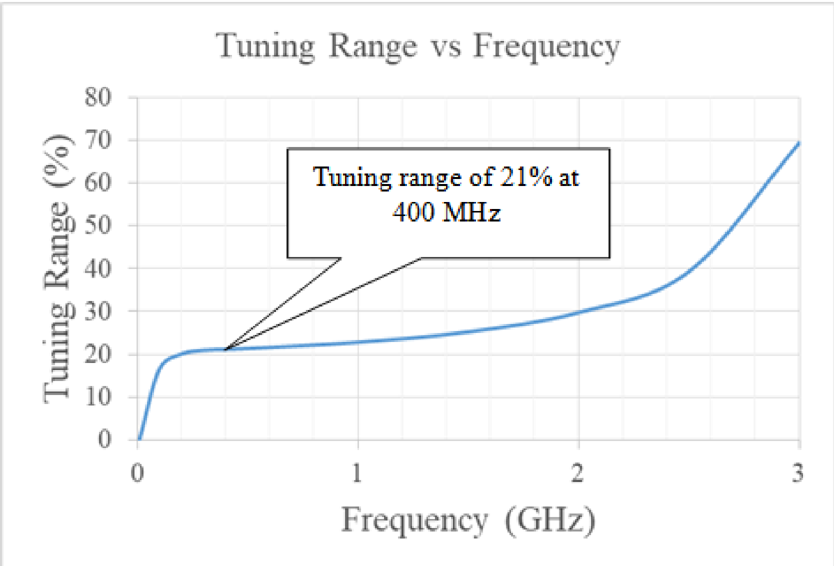

Figure 9. Simulated tuning range at 400 MHz

Measurement Results

For measurement results, only 0% and 100% injected channels were recorded. This is due to measurement tool limitation to take the reading during the liquid injection. In Fig. 10, the graph shows that the quality factor observed at 400 MHz is decreased from 6.79 (empty channel) to 5.49 (fully injected channel), respectively. As for inductance, in Fig. 11, the inductance is tuned from 21.40 nH (empty channel) to 22.40 nH (fully injected channel), respectively. Thus, the measured inductor observed that the tuning range of 4.67% was successfully achieved, as shown in Fig. 12.

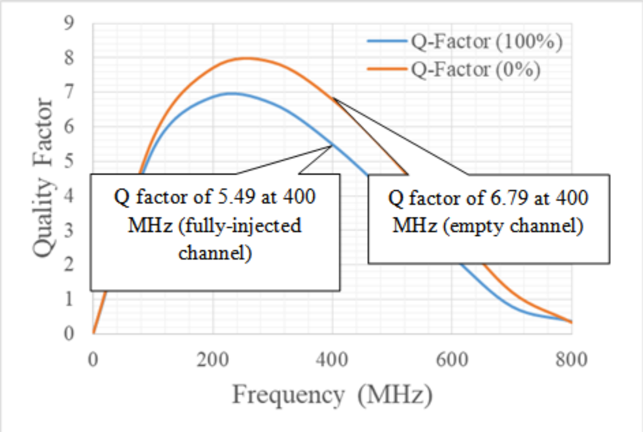

Figure 10. Measured quality factor from 0% (empty channel) to 100% (fully injected channel) at 400 MHz

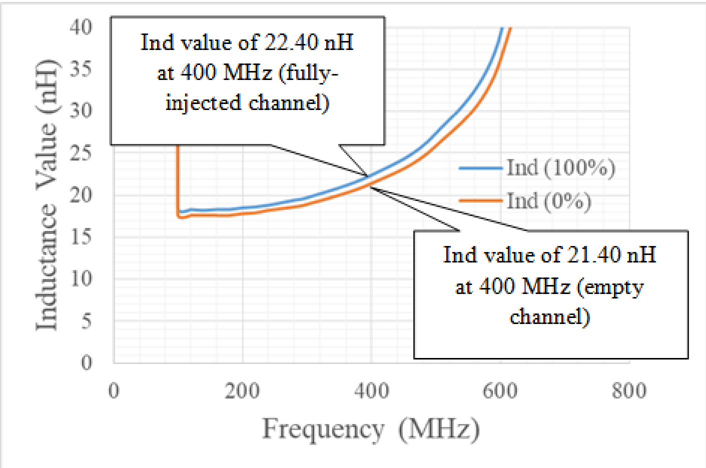

Figure 11. Simulated inductance values from 0% (empty channel) to 100% (fully injected channel) at 400 MHz

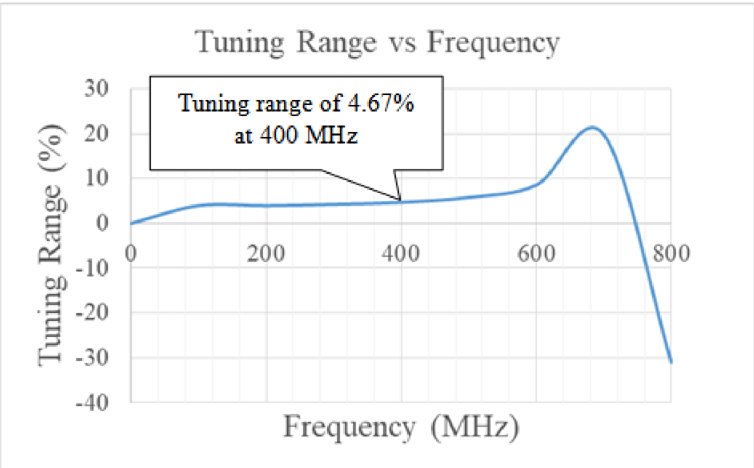

Figure 12. Simulated tuning range at 400 MHz

V. Discussion

There are few issues that contribute to poor performances on the measured inductor. One of the factors is due to weakening magnetic ferrofluid applied to the inductor core (lower than 5.4). This problem had led the quality factor to be decreased from 6.79 to 5.49 at 400 MHz. Furthermore, the laser etching process had caused contaminated (unwanted) materials (SiO_2 and Si) to firmly attach on the surface of metal traces. Thus, metal (Si) contamination during laser etching has changed the inductor trace properties that lead to different values on inductance recorded between the simulated and measured inductor. Another factor was due to the bond wire issue where the gold bond wire was interdiffused with a contaminant surface of metal traces caused by the contaminated materials of SiO_2 and Si. Then, the non-stick surface bond pad had an effect on the inductance of the device thus causing the changed in inductance values. To conclude, Table 2 depicted the comparison of the performance between simulated and measured inductor for the quality factors, inductance values and tuning ranges, respectively.

Table 2: Performances comparison between simulated and measured inductor

Ferro injection (%)	Simulation results			Measured results		
	Q factor	L (nH)	Tuning range (%)	Q factor	L (nH)	Tuning range (%)
0	10	7.48	21	6.79	21.4	4.67
100	12	9.06		5.49	22.4	

VI. Conclusion

In this paper, a ferrofluid-based fine-tunable solenoid MEMS inductor using a wire bonding technique was proposed. This paper introduced a technique of wire bonding in the MEMS inductor design in order to achieve high quality factor with a fine-tuning inductance. A ferrofluid-based was implemented as a medium to vary the permeability of the inductor thus causing a change in inductance values. The result obtained for EM simulation shows that the quality factor was gradually increased from 10 (empty channel) to 12 (fully injected channel) at 400 MHz, respectively. Meanwhile, the inductance was tuned from 7.48 nH (empty channel) to 9.06 nH (fully injected channel), respectively. Thus, a tuning range of 21% was successfully achieved. For the measured inductor, the result obtained shows that, the quality factor was decreased from 6.79 (empty channel) to 5.49 (fully injected channel) at 400 MHz, respectively. As for the inductance, the graph shows that the inductance was tuned from 21.40 nH (empty channel) to 22.40 nH (fully injected channel), respectively. Thus, a tuning range of 4.67% was successfully achieved. In conclusion, the design of ferrofluid-based fine-tuning solenoid MEMS inductor was proven to be workable for ultra-high frequency applications.

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