

HIGH-TUNING RANGE FERROFLUID-BASED SOLENOID INDUCTOR FOR WIRELESS LOCAL AREA NETWORK (WLAN) APPLICATIONS

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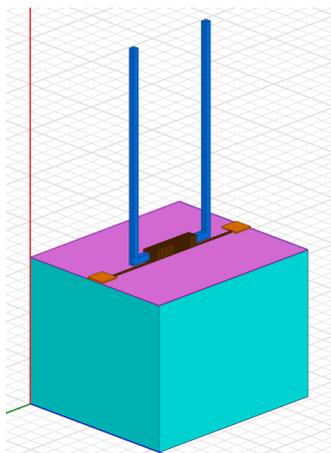
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Graphical abstract



Abstract

In this work, a high-tuning range ferrofluid-based liquid solenoid inductor is proposed. This project utilized the light hydrocarbon-based ferrofluids (EMG 901 660mT type) with magnetic permeability of 5.4. The liquid is injected into the channel of the designed solenoid inductor to improve the tuning range and quality factor of the device. This is achieved by several tuning methods; by changing the number of turns, the thickness and width of copper coils, the cross-sectional area of ferrofluid across the channel and the self-resonance frequency (SRF). The proposed tuning solenoid inductor is simulated using a 3D full-wave electromagnetic field tool, ANSYS HFSS. The simulation is done by injecting the ferrofluid liquid into the channel by a step of 20% until it reached 100%. The inductance values are set to be tuned at a frequency of 2.45 GHz. The simulation results show the inductance values can be tuned from 4.5 nH to 15.2 nH with a maximum quality factor of 25. On the other hand, for tuning capability, the inductor is capable to be tuned with high tuning range of up to more than 200%.

Keywords: Solenoid inductor, ferrofluid, liquid inductor, tuning range, quality factor

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1.0 INTRODUCTION

In recent years, wireless local area network (WLAN) applications have become a major topic of interest to the researchers around the world. The researches on the wireless integration systems are critical, especially on the use of passive components such as an inductor. Inductor as one of the crucial components in the wireless system now comes in a form of MEMS devices as it provides better performance i.e. better quality factor compared to conventional inductors [1, 2, 3].

For WLAN, the system has to operate in a frequency range of 2.4 to 2.5 GHz [4, 5]. This requirement makes it difficult for a passive

component such as inductor to operate because at high frequencies, inductor tends to produce more losses due to skin effect, proximity effect and dielectric losses. The interest towards improving the MEMS inductor has led to the studies of reconfigurable circuits by employing numerous mechanical and electrical tuning techniques for making the inductor a tunable device [1]. Unfortunately, these methods achieved only to a certain discrete values of inductance which is not realizable for MEMS inductors functional purpose [1]. Hence, in this paper, based on MEMS technology, the ferrofluid liquid is proposed and applied into the channel of solenoid inductor to achieve a high-tuning range with a good quality factor.

The light hydrocarbon-based ferrofluids (EMG 901 660mT type) is chosen due to its high magnetic permeability of 5.4, five times higher than Salted water (CaCl_2) and Galinstan (GaInSn) where the permeability for both elements are 1 and 1.257 respectively [1, 2]. By injecting the ferrofluid-based liquid to the channel of solenoid inductors, the quality factor of the inductor is improved. This is caused by the high magnetic permeability in ferrofluid-based which increased the magnetic ferrite-core and hence increase the quality factor of the solenoid inductor. The solenoid type inductor is selected for the design work because of their strong mutual coupling which resulted in twice inductance values than spiral type and smaller external magnetic field in terms of induced electromagnetic interference. In conclusion, a simulation of solenoid inductor is done by using a ferrofluid-based liquid in order to obtain high tuning range and high quality factor. A 3-D full-wave electromagnetic fields tool, ANSYS HFSS is used to simulate the solenoid inductor.

2.0 METHODOLOGY

In this work, tuning methods are used to analyze the variation of inductance values at a center frequency of 2.45 GHz for WLAN CMOS low noise amplifier (LNA) applications [4, 5]. These tuning methods are; by changing the number of turns, the thickness, width and length of copper coils, the cross-sectional area of ferrofluid across the channel and self-resonance frequency (SRF). All the tuning methods are correlated with each other as these can be proved by applying the classical expression of solenoid inductance as in (1). According to (1), the inductance values are estimated to vary by modifying the number of turns, cross-sectional area of copper coils and permeability of the liquid elements (here, ferrofluid) inside the channel [1].

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

where μ_0 and μ_r represent vacuum permeability and relative permeability respectively, n is the number of turns of copper coils and w_c , t_c and l_c are width, thickness and length of copper coils, respectively [1], [6].

The classical expression of solenoid inductance is not reliable for modeling high frequency inductors. This is due to the dominant of the eddy current losses and insertion of the core in which created a complexity of solving the equations [6, 7]. Other difficulties factor is that the demagnetizing field is built-up inside the magnetic core. This forced the magnetic field to overcome the effect by obtaining the same magnetization and hence caused the relative permeability to reduce significantly [7]. However, with the advancement of the simulation tool nowadays, this problem can be solved by i.e. the 3D finite element electromagnetic field

environment, ANSYS HFSS. This HFSS tool is practically used to help accumulate the inductance values and quality factor at high frequencies [8].

By using the HFSS and based on (1), the proposed work here is selected with a number of turns of 35. This value is chosen by considering the effects of the inductance values and the quality factor. It is also sufficient to avoid the self-resonance frequency (SRF) to be shifted towards lower than a frequency of 2.45 GHz. In addition, this number also representing the trade off between the tuning capability and SRF. Higher number of turns provides higher tuning range, but at the same time causes the SRF to shift toward lower frequencies due to high distributed capacitance, floating capacitance and stray capacitance around the coils. Higher number of turns also responsible for the build-up of the winding resistance in the copper coils causing the quality factor to reduce significantly [9]. This relation can be observed by referring to the quality factor as in (2), where the ratio of quality factor is represented by the imaginary part of admittance and real part of admittance [2].

$$Q = \frac{\text{Im}(Y_{11})}{\text{Re}(Y_{11})} = \frac{\omega L}{R_s} \quad (2)$$

where ω , L and R_s are radian frequency, inductance value and inductor series resistance respectively. In other words, the number of turns of solenoid inductor is properly selected to ensure the trade-off between the inductance value and inductor's series resistance. As a result, the resistance effect remains unnoticeable.

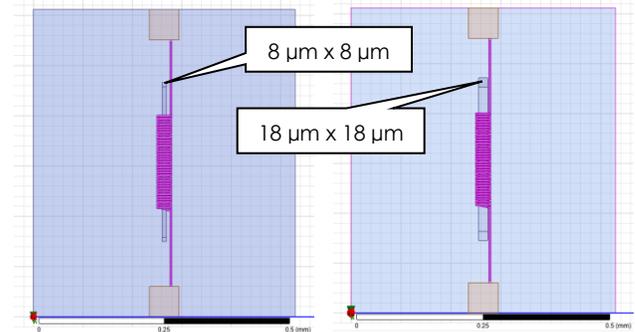


Figure 1 Comparison for difference cross-sectional area of the ferrofluid-based across the channel

The tuning capability of the solenoid inductor is analyzed by injecting the ferrofluid into the channel by a step of 20%, 40%, 60%, 80% and lastly 100%. This procedure can be achieved by using HFSS simulation. The simulation is set by assigning the channel with ferrofluid material, for example 20% is set by assigning the channel with the ferrofluid liquid from number of turns of 1 to 7 while the rest of the channel is assigned as vacuum (number of turns 8 to 35). For real experimental setup, this procedure can be done by using a micro-syringe for injecting the

ferrofluid and micro-pump for controlling the amount of ferrofluid for each step at a particular number of turns.

The percentage of the injected ferrofluid is directly responding to the cross-sectional area of the ferrofluid liquid where it alters the tuning capability of the inductor. This behavior can be observed by referring to Figure 1. The comparison of the difference cross-sectional area of the ferrofluid-based across the channel reflected to the variation of inductance values and quality factor. Figure 1(a) and (b) shows the cross-sectional area of the ferrofluid liquid of $8 \mu\text{m} \times 8 \mu\text{m}$ and $18 \mu\text{m} \times 18 \mu\text{m}$ respectively, having an inductance values of 6.6 nH and 15.2 nH and quality factor of 13 and 25 at a frequency of 2.45 GHz, respectively. This result shows that the inductance values and quality factor will increase correspondingly to the increase of cross-sectional area of the micro-tube of the channel. The initial value of inductance for both cross-sectional areas is the same which is 4.5 nH. This is because both of the designed are in a state of vacuum (empty channel) where there is no interference of the core magnetic field inside the channel. In this work, the ferrofluid cross-sectional is set to $18 \mu\text{m} \times 18 \mu\text{m}$ for tuning range enhancement.

According to (1), the inductance value varies with the cross-sectional area or so called the width, thickness and length of the copper coils, respectively. The width, thickness and length of copper coils are crucial for specifying the acceptable diameter of the whole design because all unnecessary losses such as winding resistance and parasitic capacitance will have to be taken into account especially when the inductor is operating at high frequencies. The length of copper coils usually related to the number of turns which in this case reduced the quality factor if the length is not thoroughly considered. The solenoid inductor is designed with a selected of $30 \mu\text{m} \times 30 \mu\text{m} \times 186 \mu\text{m}$. This diameter is chosen after considering the effect of the DC resistance of the windings which influence the quality factor [9].

3.0 RESULTS AND DISCUSSION

3.1 Design Simulation Setup

Figure 2 shows the 3D view of the proposed design. The solenoid inductor is simulated in ANSYS HFSS where it is designed in such a way that the ferrofluid flows through the channel with a step of 20% until it reached 100%. The results are recorded for a range of inductance values and quality factor from 0% (empty channel), 20%, 40%, 60%, 80% and 100% (full-

injected channel). The tuning range is then calculated after the results of the inductance value for full-injected channel is obtained.

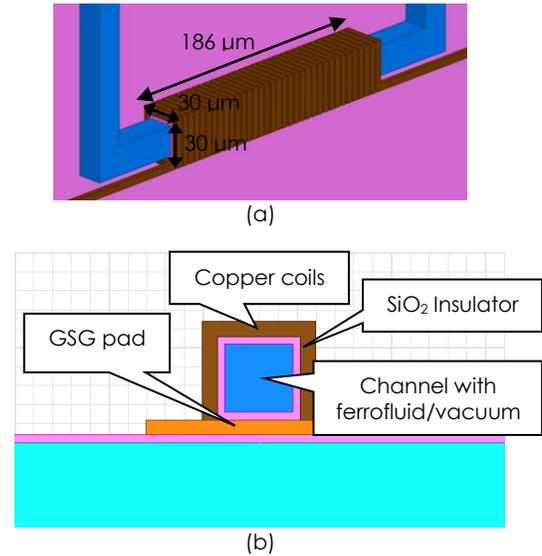


Figure 2 Close view (a) and front view (b) of the ferrofluid solenoid inductor

3.2 Simulation Results

The variation of the inductance values and quality factor are observed by recording the changed of the inductance values and quality factor with the applied ferrofluid in the channel.

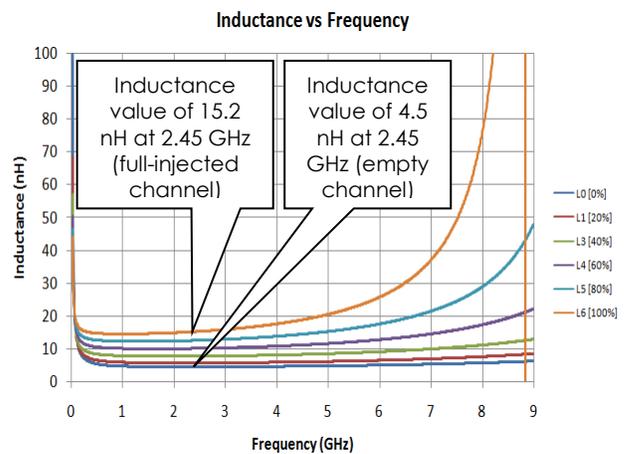


Figure 3 Inductance values with a difference levels of injected ferrofluid

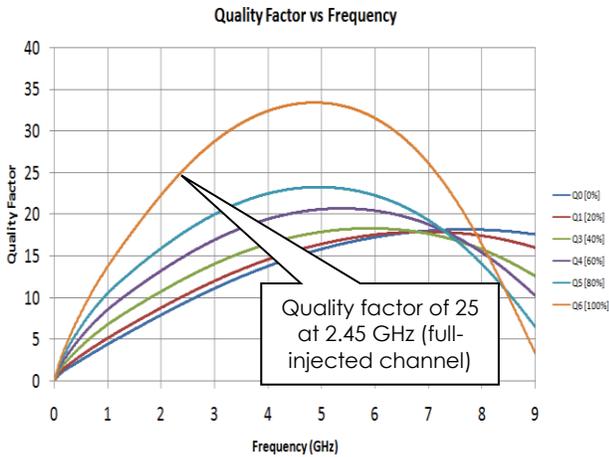


Figure 4 Quality factor with a difference level of injected ferrofluid

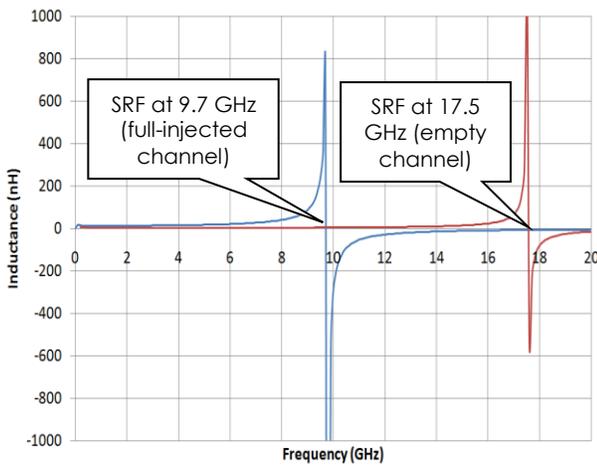


Figure 5 Empty channel SRF and full-injected channel SRF

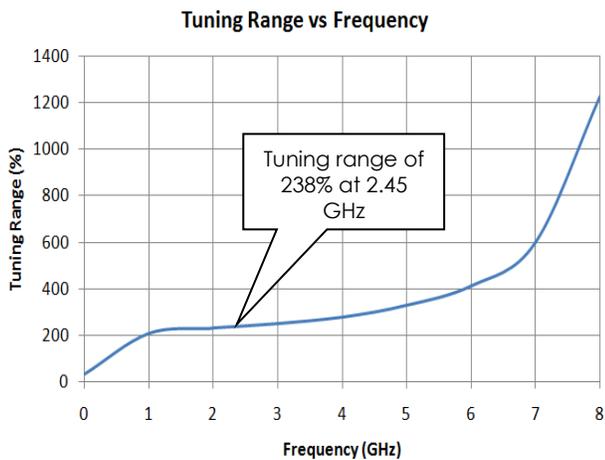


Figure 6 Tuning Range

In Figure 3, the EM simulation result shows the inductance values are tuned from minimum to maximum values of 4.5 nH to 15.2 nH for 0% (empty channel) and 100% (full-injected channel) at a frequency of 2.45 GHz, respectively. The summary of Figure 3 is described in Table 1. The result shows the inductance values are increasing proportional to the increase in the amount of the injected liquid. On the other hand, the inductance values will remain constant for a range of frequencies before it rapidly increased when it reached the SRF value. From observation, an inductance value shows a trend to increase when the inductor is operates near SRF. Therefore, the difference of inductance values is due to the change of SRF from high frequency (empty channel) to lower frequency (fully-injected channel). The changes of SRF are caused by the increasing number of parasitic capacitance, distributed capacitance, floating capacitance and stray capacitance. Meanwhile, in Figure 4, the result shows the quality factor of the solenoid inductor is gradually increased by increasing the volume of ferrofluid that flows inside the channel. The graph shows the quality factor of 25 at 2.45 GHz with 100% of the full-injected channel. The quality factor reached at its highest peak at 5 GHz with quality factor of 34 before it starts to degrade. The quality factor is decreasing to the point where the value is reducing to 0 when it reached SRF. This behaviour can be seen in both Figure 4 and Figure 5 where the quality factor of the inductor is reached 0 values when frequency is at 9.7 GHz (SRF) for fully-injected channel and 17.5 GHz (SRF) empty channel. The ranges of frequencies available for this typical solenoid inductor are between 1 GHz to 6 GHz. In Figure 5, The SRF shift from 17.5 GHz (empty channel) to 9.7 GHz (full-injected channel). The result effectively reduces the frequency reliability of the solenoid inductor from 1 GHz to 14 GHz to 1 GHz to 6 GHz. In Figure 6, the graph demonstrates a high tuning range of 238% at a frequency of 2.45 GHz. The result of tuning range is obtained by accumulating the percentage difference of the inductance values before (empty channel) and after (full-injected channel) the injection of the ferrofluid liquid (values shown in Table 1).

Table 1 Inductance values with difference levels of ferrofluid injection

Ferrofluid injection (%)	Inductance Values (nH)
0	4.5
20	5.6
40	7.7
60	10.1
80	12.5
100	15.2

3.3 Comparison with State of The Art

Table 2 shows the comparison with other works. The tuning range of this work is considered to be the highest above all other works. At frequency range of 2.4 GHz to 2.5 GHz, the performance parameters are comparable with previous works, i.e. with ref no. [8], where the quality factor achieved are 25 and 9.7 with SRF of 9 GHz and 7 GHz respectively.

Table 2 Performance comparison with previous works

Ref No.	L (nH)	Freq. (GHz)	Q-Factor	SRF (GHz)	Tuning Range (%)
This work	4.5-15.2	2.45	25	9	238
[3]	188	0.06	23	0.35	16
[6]	5.5-6.8	2	35	-	15
[8]	1.95	2.4	9.7	7	-

4.0 CONCLUSION

The aim of this work was to achieve a high tuning range with a good quality factor at a frequency of 2.45 GHz for WLAN CMOS LNA applications. For that purpose, the EMG 901 660mT type ferrofluid was used in this work to improve the tuning capability and the quality factor of the device. The ferrofluid possess high magnetic permeability of 5.4 as compared to Salted water (CaCl₂) and Galinstan (GalSn) where both had less effective permeability of 1 and 1.257 respectively.

The design was simulated using 3D finite element electromagnetic field ANSYS HFSS. The proposed design was conducted by injecting the ferrofluid liquid into the channel with a step of 20% until it reached 100%. The values of inductance vary from 4.5 nH to 15.2 nH for 0% (empty channel) and 100% (full-injected channel) with quality factor of 25 at a frequency of 2.45 GHz. Besides, the results demonstrate a successful high tuning range of up to 238% at a frequency of 2.45 GHz.

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