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DESIGN AND FABRICATION OF INTEGRATED INDUCTORS WITH POLYMER-FERROMAGNETIC CORE

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ABSTRACT

The wireless communication system is rapidly improving with the integration of several Integrated Circuits (Ics) on a single chip, and the integration of elements such as resistors, transistors and capacitors was overcome without many difficulties, but the integration of high quality inductors at microwave frequencies still remains a big threat in scaling down remote communication devices**.** This is because high inductance inductors require large spacing and usually have smaller operating frequency range**.** Many Techniques has been used to augment the quality factor (Q-Factor) of the inductor, but implemented inductors using these techniques cannot operate over 5 GHz**.** Therefore**,** in this research we are aiming to show the improvement of performance after using a mixture of a polymer (SU8) and Ferromagnetic materials in the trenches of a spiral inductor by design of two types of inductors: one type uses SU8 and the other type uses FM-SU8 core and then compare the results of the these inductors, the fabrication method used is microfabrication processes which includes photolithography of photoresist and SU8, sputtering, lift-off and electroless-plating.

Keywords: *Q-factor, Inductance density, FM-polymer core, aspect ratio, permeability.*

INTRODUCTION

Inductors are indispensable in the transmission of a signal from one location to another. They are used to temporarily store magnetic energy. The storage of magnetic energy is very crucial in the wireless communication for receiving and transmitting any signal in the electrical form. Figure 1.1 shows the schematic of a simple receiver. This receiver is composed of a Low Noise Amplifier (LNA), a Mixer, a Local Oscillator (LO), a Filter and an antenna.

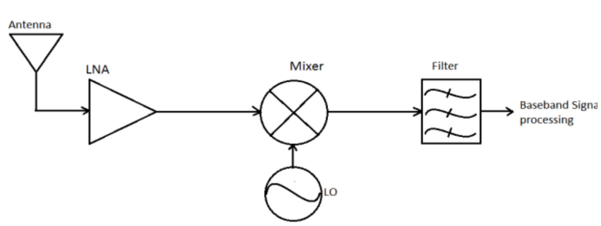

Figure 1.1 A simple RF receiver.

Low noise amplifiers are used to suppress the noise figure (NF) of the succeeding stages. Therefore, one important design factor of an LNA is its gain, which should be as high as possible. By considering[6] the simple LNA-Mixer cascade connection shown in Figure 1.2. The total noise figure (NFtot) of the cascade connection can be expressed as follows:

$$NF_{tot}=NF_{LNA}+\frac{NF_{mix}-1}{G_{LNA}} \quad \textbf{1.1}$$

Where noise figure LNA (NFLNA) and noise Figure mix (NFMix) are the noise figures of the LNA and Mixer respectively. GLNA is the power gain of the LNA.

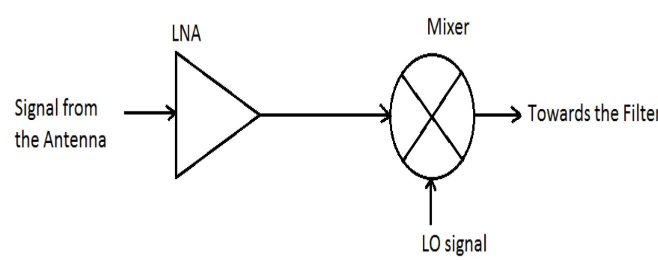

Figure 1.2 Simple cascade connections of LNA and Mixer used in transceivers.

Figure 1.3 shows the circuit representation of a LNA. From Eq. (1.1), we can clearly see that NFtot can be decreased if the gain of the LNA (GLNA) is increased[9]. This power gain of the LNA is proportional to its transconductance (Gm) and its load impedance (ZL): $G_{LNA} \propto G_m Z_L$

The load impedance (Z_L) is basically an inductor (L) which has a parasitic capacitor (C) in parallel and a parasitic resistor (R_s) in series. Its real part R_{load} [11]is related to its equivalent parallel resistor

(Rp) which is proportional to the Q-factor of the inductor as given in Eq. (1.2):

$$R_p = R_s(Q^2+1) \quad 1.2$$

where Q represents the quality factor of the inductor and is expressed below;

$$Q = \frac{\omega_o L_s}{Rs} \quad 1.3$$

From Eq. (1.2), the load impedance is proportional to the square of the quality factor of the inductor. Therefore, the LNA needs a high quality factor inductor in order to have a high gain which is desired for noise suppression of the succeeding stages.

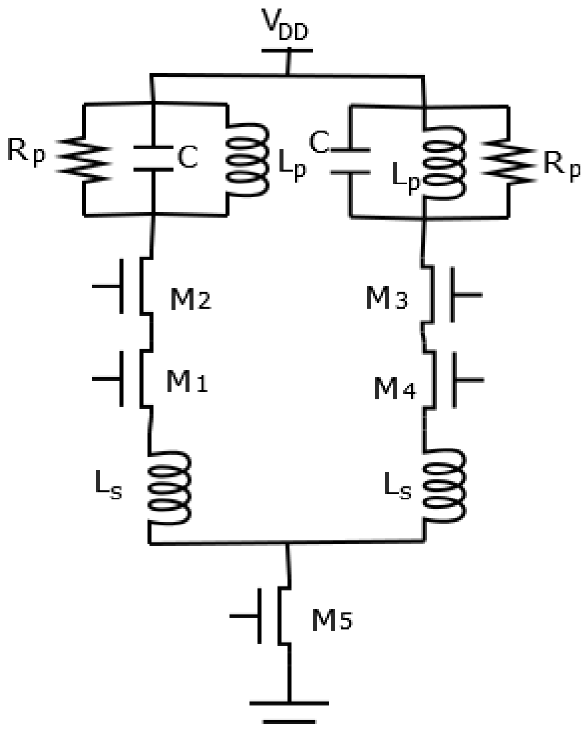

Figure 1.3 Low noise amplifier.

The Voltage-controlled oscillator (VCO) is used as a Local Oscillator (LO). This LO sends a signal at a particular frequency to the mixer which multiplies it with the main signal for up- or down-conversion. The important design factors of a VCO are its phase-noise and power consumption. Figure 1.4 shows a simple VCO configuration.

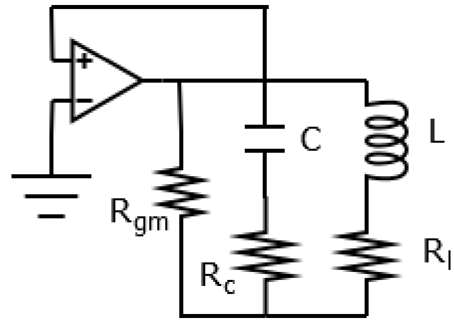

Figure 1.4 A simple Voltage-controlled oscillator.

Design Factor of a simple voltage controlled oscillator

Phase-noise

The phase-noise of a VCO should be as low as possible. The phase-noise of the VCO in Figure 1.4 can be expressed as follows:

$$L(\omega)=(2\pi R_e(A+1)/V^2{}_{amp})x(\frac{\omega_o}{\Delta\omega}) \quad 1.4$$

Where A is a constant, ω_0 is the resonant or central frequency of the RLC network, V_{amp} is the amplitude of oscillation, Re is the effective resistance. This effective resistance can be approximated to the sum of the series resistances of the capacitor and the inductor represented by R_c and R_l, respectively.

$$R_e \approx R_c + R_l \quad 1.5$$

Nevertheless, the series resistance of the inductor is much larger than that of the capacitor. Therefore, the effective resistance from Eq. (1.5) is reduced to the following:

$$R_e \approx R_l \quad 1.6$$

One important way of reducing the phase-noise is decreasing the series resistance of the inductor (Rl) which means increasing the Q-factor of the inductor.

Another crucial factor that engineers have to consider while designing a VCO is its power consumption. The power consumption of a VCO must be as low as possible in order to reduce its cost. It can be represented by the following equation:

$$G_m = R_e(\omega_o C)^2 \approx R_1(\omega_o C)^2 \quad 1.7$$

From Eq. (1.7), the power consumption can be decreased by reducing the series resistance of the inductor. In sum, a high performance oscillator requires a good quality inductor for the reduction of their noise and power consumption.

Inductors are actively used in filter designs. LC filters use typically capacitors and inductors connected in series or shunt, as shown in Figure 1.5. A filter must be able to eliminate the unwanted frequency components and keep the desired ones. In order to achieve such requirements, the lumped elements which are inductors and capacitors must be free from any parasitic component. For instance, if an inductor used in a filter has high values of capacitance or resistance, there will be a bandwidth shift from the desired one or power dissipation in the signal as well as noise production. In order to avoid these issues, all the inductors used in a filter must be free from any parasitic element. Note that the capacitors can have relatively high Q-factors, hence they have reduced parasitic effects. Therefore, high Q-factor inductors are strongly required in the design of filters, especially at microwave frequencies where inductors are prone to parasitics.

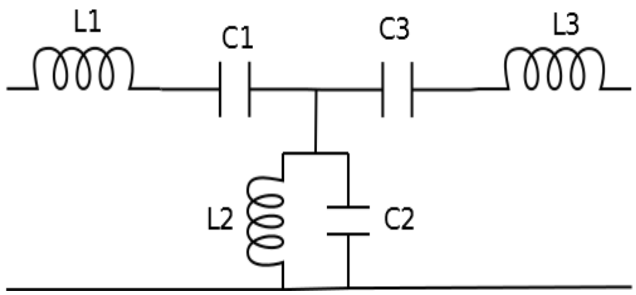

Figure 1.5 RF Bandpass filter.

Literature Review

The idea of integrating inductors dates several decades ago. Spiral inductors are simpler and easier to fabricate and optimize when compared to their solenoidal counterparts. The very first spiral inductors used in general GaAs substrates and were very large in size with only few nano Henrys inductance. In 1984, a group of scientists have modeled a Monolithic microwave intergrated circuits MMIC spiral inductor with high accuracy [1]. It uses a GaAs substrate and has a relatively large size, even though it has a high cutoff frequency. Further, the first computer aided design of a square shape spiral inductor was implemented by K. Araki, H. Ueda and M. Takahashi [2] in 1985. Besides, using a GaAs substrate, this inductor was showing relatively high losses for a 0.2 mm size. Due to their substrate nature and large footprint, the previous inductors could not be integrated in our daily ICs which use silicon substrates in general. Therefore, Attentions have been put into employing silicon substrates for designing spiral inductors. However, the lossy nature of Silicon substrates caused many challenging issues. In 1996, a publication by Yue and others [3] demonstrated the effects of parameters such as substrate resistivity, oxide thickness and metal thickness on the quality factor of the inductor. This paper outlined the Q-factor reduction of low resistivity substrates and thin-layer oxide inductors. Further publications include [4] where the effect of the inductor's physical geometry modifications has been analyzed. Many techniques have been employed by researchers for the sake of producing high quality factor spiral inductors using silicon substrate. In 1998, Yue and Wong produced spiral inductors using different ground shields [5]. Although a Q-factor improvement was observed, the inductance decreases exponentially at frequencies above 2 GHz and the inductor's footprint is large. Xiangming Xu and others have implemented a multiple layer stacked spiral inductor (in 2012) [6]. The results have shown that even thought the quality factor improves with the staking layer, the self resonant frequency is too low with three or more stacking layers. In 2013, J. Zhan and others have used two different FM nanoparticle cores in multilayer spiral inductors [7]. The results show a huge improvement in the inductance density. However, the process is very expensive and the Q-factor is poor beyond 2.5 GHz. Despite myriads of optimizations throughout couple decades ago, the implemented inductors are not still satisfactory in general to overcome the integration issues for high frequency applications. Therefore, an initiative consisting of mixing insulating polymer and FM nanoparticles is a novel idea that can considerably augment the Q-factor of a spiral inductor. This mixture results in a semi-magnetic core that has fairly good permeability and high resistivity, hence the inductance density and self resonant frequency can be high, as expected. In this paper, the aim is to produce integrated passive elements especially inductors with very small sizes in order to shrink the size of our everyday communication devices like cell phones.

MATERIAL AND METHODS

Method and Software Optimization

Our aim of this project is to show the inductance density and the quality factor improvement due to the use of a novel material –which is FM-polymer core in the spiral inductor. The HFSS simulation software was used for simulation and optimization purposes. It is important to always use a simulation software before starting any real fabrication. By sweeping the parameters, it is possible to have optimum results at the desired frequency. Using the HFSS software, a 1 nH and a 5 nH inductors were designed and simulated. These inductors were designed with a glass substrate, a polymer (SU-8) on top of the substrate and a circular spiral copper pattern inside the SU-8 layer. In addition, these inductors were optimized by using parameterization to get the minimum sizes. However, our optimization is limited by the capability of the available facility which allows a minimum width of 10 µm. Therefore, all the sizes must be above that value. The Inductance values and Q-factors of these inductors were plotted with respect to frequency in a rectangular graph. Our frequency of interest is 7.95 GHz. The Q-factor was plotted by using Eq. 2.1[20]. The inductance was determined by taking the imaginary part of the input impedance (Z_{11} or $1/Y_{11}$[21]) and dividing by two pi times the frequency (f) as given in Eq. 2.1. This equation only gives an approximate value of the inductance since it ignores the parasitic capacitance values.

$$L_S = \frac{I_M}{2\pi f}(Z_{11}) \qquad 2.1$$

Later, the 1 nH and 5 nH inductors were re-designed and simulated by replacing the SU-8 with the FM-SU8 core that has a relative permeability assumed to be 10. The inductance value and Q-factor of these new inductors were plotted and compared to the previous results. Lastly, the microfabrication process in the clean room was started, but not terminated in the time frame. However, the simulation results are sufficient to observe the improvement factors.

Fabrication Process

After the software optimization, comes the fabrication process which involves fabrication devices and the clean room. A soft baked glass substrate is used as the basement. Photolithography is then used on the photoresist coated substrate. Next, we deposit a thin copper layer uniformly using Sputtering process. Lift-off is used to vanish away the copper non-located on the spiral pattern. Then, we coat the surface with a thick SU-8 polymer or the SU8-FM mixing core layer by using spin coating. Next, the exposure is started in the photolithography process. After development, the SU-8 on top of the metal pattern is removed. Later, Electroless plating is applied to deposit the copper layer on the spiral metal pattern to level it to the core. A thicker metal layer can be deposited. The overpass is formed after we finish with the two-dimensional fabrication. Lastly, metallization is used to make metal contacts for the real measurement purpose. Figure 2.1 depicts the summarized microfabrication process of the inductors.

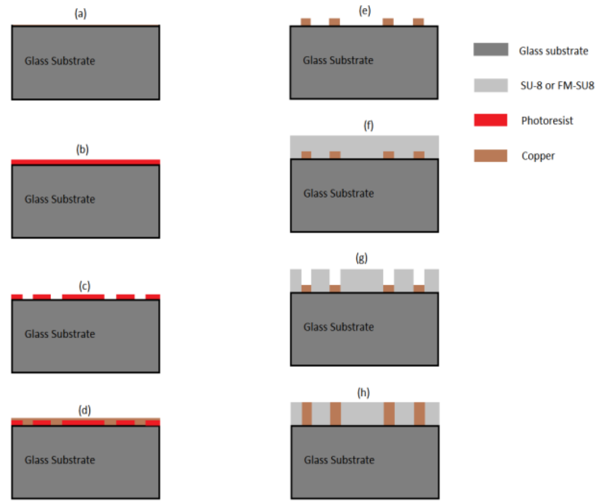

Figure 2.4 Fabrication steps of a spiral inductor using SU8-FM core.

RESULTS AND DISCUSSION

Dial Readings of Mud Samples at Various Concentrations of Additives

In this project, we have assumed the permeability of the FM-SU8 core to be 10. Table 1.1 shows the design parameters for the 1 nH and 5 nH with and without the FM-SU8 core after simulations.

Table 1.1 Design parameters of inductors using SU-8 and SU8-FM cores.

Table 1: Design Parameters of Inductors Using SU-8 and SU-FM Cores

	1 nH with SU8 core	1.6 nH with SU8-FM core	5 nH with SU8 Core	5 nH with SU8-FM core
Internal radius ri (in µm)	25	10	98	48
Metal width Wm (in µm)	10	10	10	10
Metal thickness Tm (in µm)	10	10	10	10
Turn number N	2.97	2.97	2.97	2.97
Spacing between coils S (in µm)	10	10	20	20
Side length of the inductor l	179	148	325	284

(in µm)				

Table 2: Comparison Between Inductors SU-8 and SU8-FM Cores

	1 nH with SU8 core	1.6 nH with SU8-FM core	5 nH with SU8 Core	5 nH with SU8-FM core
Length of the inductor (µm)	178	148	376	284
Q-Factor	34	40	30	41

Comments: we can observe a decrease in the size of the inductors when we use the FMSU8 core in both cases.
The Simulation results are presented in Figure 2.1 (a) and (b).

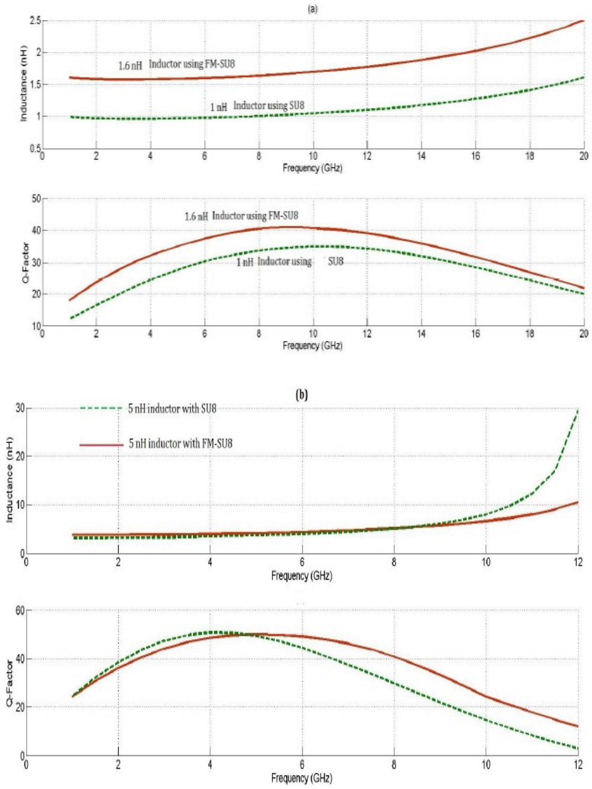

Figure 2.1 Comparison between the inductors using SU-8 and the inductors using FMSU8.
(a) 1.6 nH inductor with FM-SU8 versus 1 nH inductor with SU8 at 7.95 GHz. (b) 5 nH inductor with FM-SU8 versus 5 nH inductor with SU8 at 7.95 GHz. From Figure 2.1, we can say that the Q-factor was improved from 34 to 40 for the 1.6 nH inductor and from 30 to 41 for the 5 nH inductor when we use FM-SU8 core. Table 1.2 summarizes the results
Figure 2.2 represents the progressive picture of the inductor during Fabrication. The de-embedding measurement technique can be used since the measurement probes are relatively large. It consists of measuring the chip with the metal contacts and measuring the metal contacts only then subtracting the measurement values of the metal contacts from that of the chip. Basically, a simple spiral inductor is composed of spiral metal tracks that can be in polygonal or circular shape, a dielectric material (e.g. Silicon dioxide) and a silicon substrate at the bottom. Due to the conductivities or resistivities of the metal and the semiconductors, spiral inductors exhibit losses that are either electrically induced or magnetically induced. Because of these losses, the Q-factors of integrated spiral inductors are poor in general. Later, we have studied different quality improvement techniques that are being used along with their drawbacks. Techniques such as ground shielding and stacking of metal layers are very common. However, they encounter the problem of reduced self resonant frequency which limits the operating frequency range of the inductor. This mixture is an insulating material that exhibits some magnetic properties. Using HFSS software, we have presented the inductance and Q-factor simulation results of two different inductors (1 nH and 5 nH) using SU-8 core with the minimum possible sizes. The frequency of interest was 7.95 GHz..

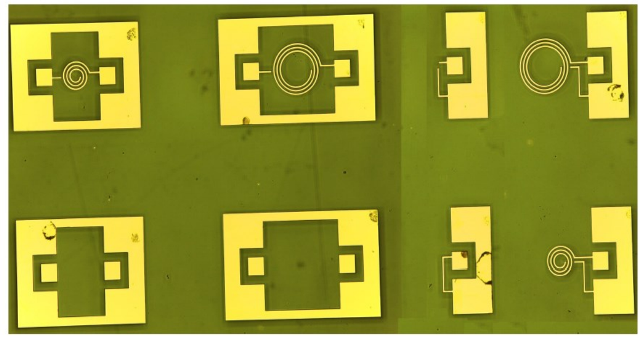

Figure 2.2 Fabricated inductors (in progress) and metal contacts.

Then, we have replaced the SU-8 by the FM-SU8 core and repeated the simulations for the minimum sizes obtained. Taking into account the limitations of the available facilities, we managed to design a 1.6 nH and a 5 nH inductors that use FM-SU8 core that has a permeability of 10. For the 5 nH inductor, we observed a reduction of size of 24%, while the Q-factor was improved by 36%. The size of the 1.6 nH inductor with FM-SU8 is 1.2 times less than that of the 1 nH inductor with SU8; and the quality factor improvement is 20%. We can conclude that the performance of the inductor is improved when we use a mixture of an insulating polymer (SU8) and an FM material in the trench of a spiral inductor.

CONCLUSION

In this study, we have first highlighted the importance of high Q-factor inductors used in on-chip applications. All devices for receiving and transmitting as well as amplification contain inductors. Next, we have presented a descriptive study of integrated spiral inductors using a silicon substrate with different loss mechanism associated with its operation. Lastly, we have proposed a novel method that implies the use of a mixture composed of a polymer (SU-8) and an FM material. Although the fabrication process was not completely finished, the simulation results proved to be sufficient to observe the improvement factor of our new magnetic material. The use of Polymer-Ferromagnetic mixture in future ICs can have significant advantages. The quality factors of different elements like transistors and capacitors can be further improved. At the same time, an important improvement in their sizes can be observed. Therefore, we can improve the performances of devices such as cell phones, computers by keeping their sizes even smaller.

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