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DESIGN AND ANALYSIS OF MEMS INDUCTORS AND FILTERS FOR 1GHz APPLICATION

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Abstract - This paper investigates the use of spiral and meander inductors designed using MEMS (Micro-Electro-Mechanical-System) technology in passive filter circuit. To obtain better Quality factor the width, spacing, number of turns and thickness of the inductor coil are appropriately selected after studying their interdependencies and ease in fabrication. The substrate losses of the inductor were reduced as it is suspended above the substrate thereby improving the Quality factor of the inductors. HFSS Design tool is used to design and measure the substrate losses of the inductors and plot its scattering performance parameters. Two planar meander inductors connected in series was fabricated using surface and bulk micromachining techniques and optical lithography. Lastly 3 pole passive filters designs in MEMS using spiral inductor and meander inductor designs and interdigited capacitor is proposed for applications in transreceiver system having a cut off frequency of 1GHz.

Key words — RF Filter, Self Resonance Frequency (SRF), Planar Inductor, Spiral Inductor, Meander Inductor, MEMS Filter.

I. INTRODUCTION

During the past decade communication technology has grown up particularly in portable and low-cost consumer applications [1]. Off chip passive components like inductors occupy a large area as well as cause inpedance mis match and hence interference in communication systems [2]. So processes to develop on-chip efficient passive components particularly at radio-frequency (RF) has become an attraction nowadays, passives like inductors, resistors, capacitors, varactors etc. as performing and cost limiting components [3]. Inductor is a critical component mainly used in oscillators, filters and other tuned circuits. Filter circuits are mostly found using passive components mounted as off chip components for low-frequency applications, but as the frequency increases, the characteristics of the passive devices are modified substantially by the parasitics involved and evolved [4]. Numerous methods for modeling inductors a key component particularly in higher frequency applications using semiconductor technologies popular silicon wafer base has been reported in past several years [5]–[12]. Most of these models involve loads of computational technique, curve fitting or empirical formulae and may not be accurate as well as scalable over a wide range of layout designs. For inductor design, an optimized physical model is required. Planar technology demonstrate difficulties in physical modelling at high-frequencies in the form of losses caused by eddy currents and substrate loss typically in case of silicon as substrate [13]. This paper discusses a low cost solution employing MEMS technology exploring the different types of inductors and providing useful information about its fabrication and optimization in RF applications. Literature survey shows there are several types of MEMS inductors like circular, octagonal, square and meander types that were implemented and some of their performances compared [14]. The circular-type inductor has a high quality factor and low insertion loss due to its low resistance and capacitive loss but due to the limitations in mask preparation during fabrication it is avoided. Mostly rectangular/square MEMS inductors are chosen by processes as they restrict angles to right angles but again are difficult to fabricate and accumulate charges at the edges thereby giving rise to losses. Meander inductors although occupy the largest area among all the inductor shapes for a given inductance value but are simplest to fabricate and also save some lithographic steps in fabrication [15-17]. Optimizing physical parameters of inductor topology such as metal width, spacing between turns, thickness of inductor coil, etc. can minimize the inductor area without affecting the inductor value.

With this terminology spiral and meander inductor designs were made using HFSS (High Frequency Structural Software) tool and variations in their value, Q factor and Self Resonant Frequency with variations in structural topography was determined. Finally filter designs using them and interdigited capacitors is simulated. Though active signal filters compatible with CMOS technology have an advantage that its gain can be adjusted but passive filters demonstrates flexibility in tuning and also have an advantage that it does not need any additional power supply [18].

II. SPIRAL INDUCTOR DESIGN AND ANALYSIS

To determine the effects of variations in dimensions of the inductor coil on different parameters like Q-Factor, SRF and inductance value, a six turn spiral inductor of Aluminium metal (shown in Fig. 1) was designed in HFSS with thicknesses of different layers as shown in Table I. Aluminium with its fair conductivity, low cost and known fabrication processes has been a reliable choice in recently developed MEMS cantilevers [19] and hence was used here. The metal width of the inductor was varied from 20 µm to 30µm and spacing between the coils was kept at 15µm keeping in view the challenges that can be faced during fabrication processes and mask preparation. The inductor designs with different combinations of these physical parameters were simulated to determine its effect on inductor SRF and Quality Factor.

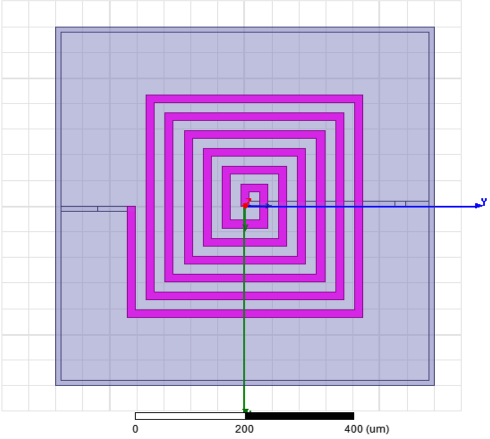

Fig.1. Spiral Inductor in HFSS

TABLE I - SPIRAL INDUCTOR DIMENSIONS

Layer Number from bottom to top	Layer Name	Material	Thickness (µm)
1	Substrate	Si	30
2	Oxide Layer	SiO2	0.5
3	Underpass	Al	1.7
4	Suspension/ Pillars	Al	2
5	Inductor turns	Al	2

II.A. Varying Conductor Width

Simulations of inductor coils for applications related to RF domain were carried out and it was observed that increasing the width of the conductors helps to reduce skin and DC loss but beyond a certain point, eddy current loss dominates and Q and SRF of the coil decreases (shown in Table II).

TABLE II - EFFECT OF INDUCTOR WIDTH ON QUALITY FACTOR AND SRF

Sr. No.	Spacing between turns (µm)	Width of coil (µm)	Number of Turns	Inductance (nH)	Q - factor	SRF (GHz)
1	15	20	6	6.37	5.87	5
2	15	25	6	3.6	7.2	5.8
3	15	30	5	4.4	5.8	5.6

II.B. Varying Oxide Thickness

It is known that inductors suspended above the substrate has a better Q-factor than planar inductors but simulations in HFSS led to the inference that depositing an additional thick dielectric layer above the substrate increases isolation between the inductor coil and substrate reducing the substrate losses and thus increasing the quality factor of the coil (shown in Table III).

TABLE III

EFFECT OF OXIDE THICKNESS ON QUALITY FACTOR AND SRF

Sr. No.	Spacing between turns (µm)	Width of coil (µm)	Number of Turns	Tox (µm)	Inductance (nH)	Q - factor	SRF (GHz)
1	15	20	6	0.2	0.9	3.2	Above 10
2	15	20	6	0.5	5.4	6.6	6.2

II.C. Varying Metal Thickness

Results as shown in Table IV indicates that decrease in the conductor's cross-sectional area at higher frequencies keeping all the other physical parameters of the coil constant, leads to higher charge accumulations and hence increased current density at the surface which causes more energy dissipation in the form of heat. Thicker metal cross sectional area gives more outer surface for current conduction, leading to fewer losses and hence Q increases but they are difficult to fabricate using prevalent micromachining techniques of MEMS. However, increase in metal thickness after some time gives rise to the resistive losses in the conductor thereby reducing Q and SRF of the coil.

TABLE IV

EFFECT OF METAL THICKNESS ON Q AND SRF FOR L = 0.75nH

	Aluminium Metal Thickness				
	3µm	**3.5µm**	**5µm**	**6µm**	**7µm**
Q	18.3949	19.441	19.5186	16.0957	15.3374
SRF	18.1823	18.3992	18.2218	18.7648	19.319

Using the dimensions given in Table I and optimized values obtained from Table II and Table III, spiral inductor is designed in HFSS and simulated. The thickness of the metal inductor is kept at 0.5µm overlooking the losses due to skin effect keeping in mind the ease in fabricating the device using optical lithography as depositing thick uniform metal layer using surface or bulk micromachining is difficult and can be done using electroplating. The frequency sweep of the spiral inductor was done and variation in inductance value and Quality factor observed (shown in Fig. 2 and Fig. 3). Simulation results gave a peak Q-factor of 6.7 at 2.4GHz while the SRF was obtained at 6.4GHz.

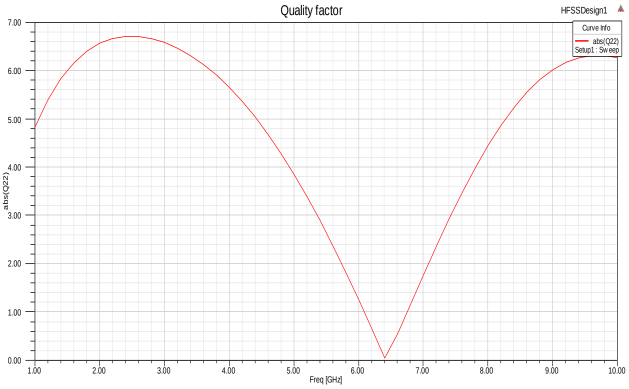

Fig.2. Quality Factor vs. Frequency curve having peak Q = 6.7

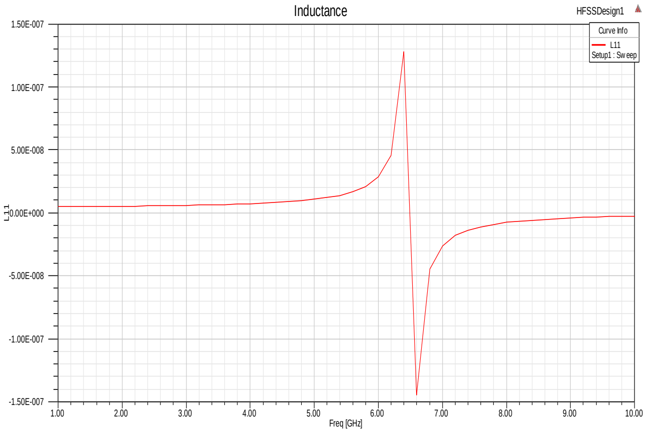

Fig.3. Inductance vs. Frequency curve having SRF at 6.4GHz

III. MEANDER INDUCTOR DESIGN, FABRICATION AND ANALYSIS

In comparison with other inductor types, meander line inductor gives smaller inductances in larger areas which in turn increases metal resistance thereby deteriotating Q-Factor. But meander inductors are simpler in structure and hence easy to fabricate using conventional lithographic steps giving robust reliable structures. A suspended meander inductor is designed and analyzed in HFSS with 4.5 turns, suspended using 11 pillars to provide appropriate support to the coil keeping in view the performance and the structural robustness of the design. The dimensions of the meander inductor designed as shown in Fig.4 are given in Table V.

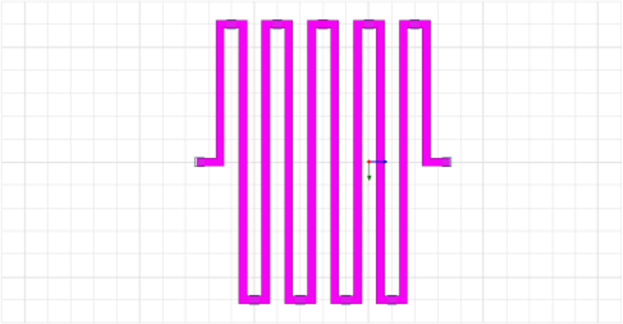

Fig.4. Meander line inductor implemented on HFSS

TABLE V

DIMENSIONS OF MEANDER INDUCTOR

Physical Parameters	**Value**
Number of inductor turns	4.5
Width of inductor	35µm
Length of one inductor straight segment	1200µm
Spacing between inductor turns	65µm
Thickness of bottom dielectric SiO_2 above substrate	0.25µm
Length and Width of Al pillars	40µm

The frequency sweep of the meander inductor gives a peak Q-factor of 3.35 at 2.5GHz while the SRF was obtained at 6GHz. (shown in Fig. 5 and Fig. 6)

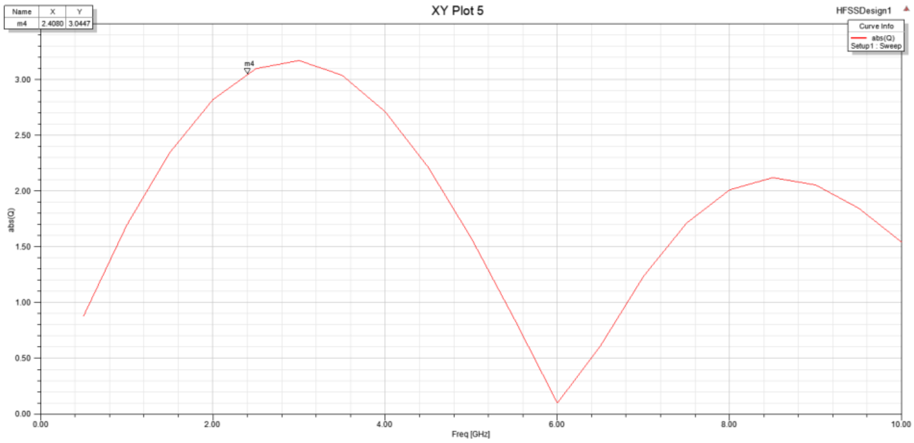

Fig.5. Quality Factor vs. Frequency curve having peak Q = 3.4

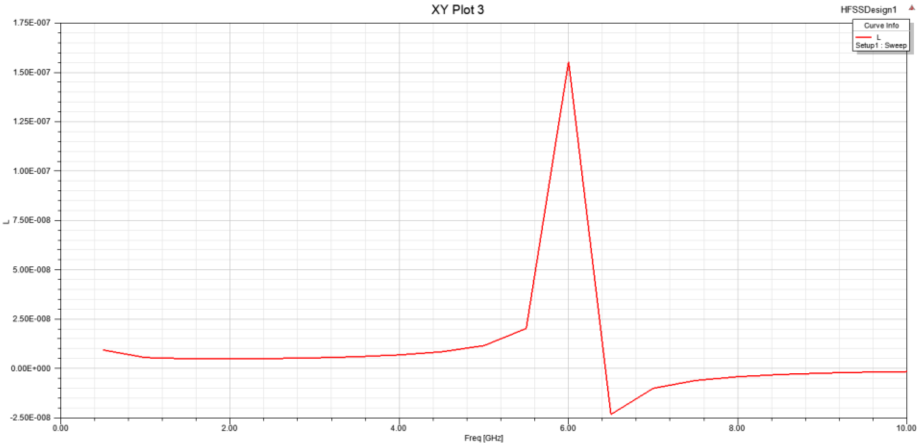

Fig.6. Inductance vs. Frequency curve showing SRF at 6GHz

A 5 turn meander inductor cascaded in series with interconnects and measuring pads was fabricated as shown in Fig. 7. A 320 micron silicon wafer was used as substrate with around 400nm thick silicon dioxide layer deposited over it as dielectric using Plasma Enhanced Chemical Vapour Deposition (PECVD). Silicon dioxide provided isolation between the top inductor metal layer of 140nm thickness deposited by thermal deposition process and optical lithography and the silicon substrate. Validating the dimensions of meander inductor using SEM imaging technique, the inductance value of fabricated inductor was calculated to be around 7nH [20].

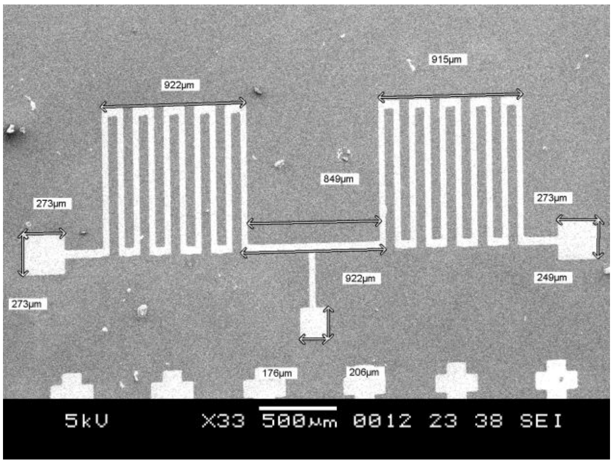

Fig.7. SEM image of the Series Meander Inductors.

IV. FILTER DESIGNS AND ANALYSIS

Inductors were used as passing element while capacitor as grounding element and a 3 component passive low pass filter was designed and simulated. The dimensions of the components involved in the design were scaled up for possible easy fabrication using 3D printers. The metal selection was also changed to silver having similar characteristics as aluminium but more reliable and widely used in printing and PCB technology.

4.5 turn spiral and meander inductors were initially designed and later optimized to obtain the desired frequency response of low pass filter for target cut off frequency of 1GHz. This shift of inductor value in the filter circuit can be attributed to the combined effect of lumped components and micro strip transmission line metal resistivity. The change in the length of the micro strip line consequently demands change in the component values and were kept large to facilitate fabrication using 3D printing technology. Thus in the process, the moderate tolerance in the changes of component value and hence its dimensions were adopted. Table VI shows the dimensions of the filter circuits implemented using 4 turn inductors and 28 teeth interdigited capacitors. The circuit and the response curve obtained by simulating the filters are shown in Fig. 8 and Fig. 9. The cut off frequency of the meander inductor filter is 1.1 GHz and that of spiral inductor filter is 1.2GHz (shown in Fig. 8 and Fig. 9).

TABLE VI

DIMENSIONS OF THE FILTER CIRCUIT

Layer Name	Material	Thickness (µm)
Substrate Thickness	Si	250
Inductor and capacitor teeths width	Ag	130
Spacing between inductor coil	Air	170
Thickness of inductor and capacitor	Ag	130
Inductor turns	Ag	4
Suspension Height of inductor	Air	30

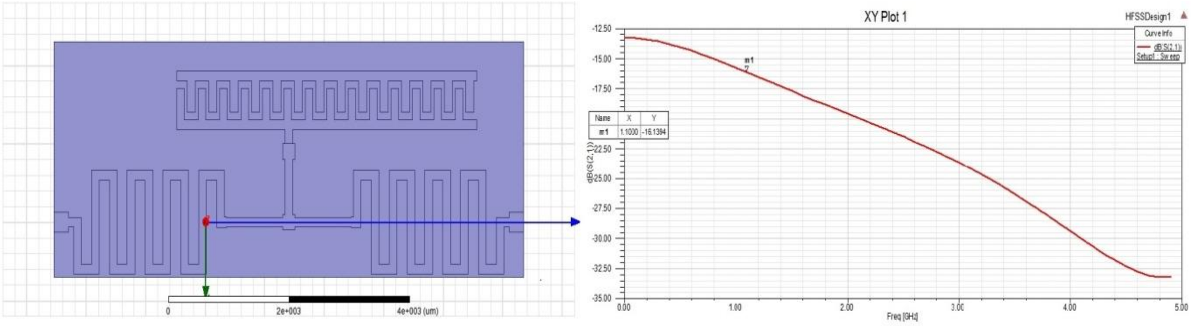

Fig. 8 Meander Inductor Filter circuit and graph showing frequency Vs S_{21}

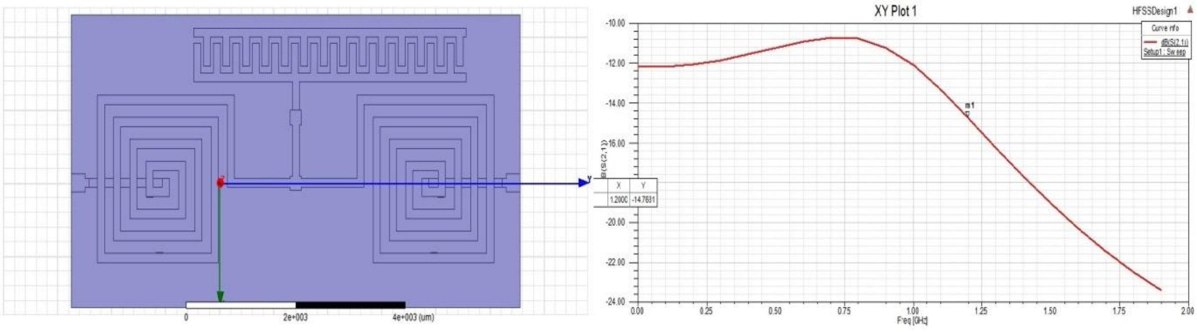

Fig. 9 Spiral Inductor Filter circuit and graph showing frequency Vs S_{21}

V. CONCLUSION

In this paper, the lumped components are optimally designed to achieve a low pass response with 3dB frequency at 1GHz. The three pole filters designed showed attenuation in stopband of more than 10dB/division indicating better roll off rate in case of spiral inductor filter than meander inductor filter validating design of higher Q inductors for filters with spiral inductors. The proposed interdigited capacitor, meander inductor combination saves at least one lithograpy step in the fabrication process over the conventional parallel plate capacitor manufacturing in which intermediate dielectric layer is required to be deposited and patterned and then used as grounding element. High end 3D printing facility is proposed to be used to fabricate the simple designs of inductor and capacitor and also the filter circuit. The MIM capacitor with high K dielectrics can be designed to check for any variations in the filter response and area which was approximately same as in case of both spiral and meander inductor filters.

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