DESIGN AND IMPLEMENTATION OF LIQUID-BASED FINE-TUNABLE SOLENOID MEMS INDUCTOR

AHMAD HAFIZ BIN MOHAMAD RAZY

UNIVERSITI SAINS MALAYSIA

2018

DESIGN AND IMPLEMENTATION OF LIQUID-BASED FINE-TUNABLE SOLENOID MEMS INDUCTOR

by

AHMAD HAFIZ BIN MOHAMAD RAZY

Thesis submitted in fulfilment of the

requirements for the degree of

Master of Science

April 2018

ACKNOWLEDGMENT

First and foremost I would like to pay a heartfelt tribute to some of the parties who had let me gain a knowledge and experience during my postgraduate research project implementation. There are individuals who assisted and helped me, directly or indirectly during my research projects designation. I would like to take this opportunity to show my deepest gratitude to all of them.

First of all, I would like to thank Dr Mohd Tafir Bin Mustaffa for guiding me to accomplish my postgraduate research project. I am grateful to my supervisor for his encouragement, permission and approval during my project designation. Special thanks to Assoc. Prof. Dr Asrulnizam Bin Abd Manaf for his hospitality extended to me. He gave me a lot of guidance and willing to share his experience with me.

Next, I would like to express my deepest gratitude to my guidance, Dr Farshad and Dr Fatemeh. They encourages me and provides me many opinions during project designation and implementation. My gratitude also goes to the staff from CEDEC for the technical supports on the network analyzer provided.

Last but not least, my thanks go to my family members who offered me unlimited moral support. Without them, I can never complete my research project successfully. A word also goes to those who inevitably forgot to mention. I am no less grateful to them and I hope that they will forgive my oversight.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

LIST OF ABBREVIATIONS

RFIC	Radio Frequency Integrated Circuit
RF	Radio Frequency
IC	Integrated Circuits
Si	Silicon
MEMS	Microelectronic Mechanical Systems
MMIC	Monolithic Microwave Integrated Circuits
UHF	Ultra-High Frequency
VCO	Voltage-Controlled Oscillator
LNA	Low-Noise Amplifier
IEEE	Institute of Electrical and Electronics Engineers
PCB	Printed Circuit Board
SOI	Silicon on Insulator
CMOS	Complementary Metal-Oxide-Semiconductor
3D	3-Dimensional
SiO_2	Silicon Dioxide
SRF	Self-Resonance Frequency
PDMS	Polydimethylsiloxane
ABS	Acrylonitrile Butadiene Styrene
WLAN	Wireless Local Area Network
GSG	Ground Source Ground
RCA	Radio Corporation of America
AMI	Acetone-Methanol-Isopropanol
DC	Direct Current

CAD	Computer-Added Design
EFO	Electronic-Flame-Off
VNA	Vector Network Analyzer
SMA	SubMiniature version A
SOLT	Short-Open-Load-Thru

REKA BENTUK DAN PELAKSANAAN BERASASKAN BENDALIR BOLEH LARAS-HALUS PENGARUH MEMS SOLENOID

ABSTRAK

Peranti pasif seperti pengaruh litar bersepadu memainkan peranan penting dalam litar frekuensi radio. Walau bagaimanapun, prestasi kualiti faktor bagi pengaruh jenis ini dihadkan atas pengaruh substrat yang tinggi. Oleh itu, dalam tesis ini, bendalir boleh laras-halus pengaruh sistem mikroelektronik mekanikal solenoid dibentangkan untuk aplikasi frekuensi ultra tinggi. Bendalir Ferro berasaskan hidrokarbon ringan digunakan dalam reka bentuk untuk mencapai penalaan halus bagi nilai pengaruh. Tiub mikro bertindak sebagai saluran untuk penalaan. Tambahan daripada itu, teknik 'wire bonding' digunakan bagi tujuan mengurangkan rintangan siri, kehilangan substrat, dan kehilangan resonan kendiri. Wayar emas digunakan bagi mengikat bahagian pinggir dua pad logam. Ikatan dilakukan secara diagonal dengan menyeberangi bahagian atas tiub mikro. Pengaruh direka bentuk menggunakan ANSYS HFSS dan bacaan pengukuran ditetapkan pada frekuensi 400 MHz bagi tujuan pembuktian konsep. Pada frekuensi 400 MHz, keputusan simulasi menunjukkan kualiti faktor meningkat dari 10 hingga 12 manakala nilai pengaruh berubah dari 7.48 nH hingga 9.06 nH bagi saluran tiub kosong dan saluran tiub yang telah disuntik dengan bendalir Ferro. Keputusan menunjukkan julat penalaan sebanyak 21% berjaya dicapai. Namun demikian, keputusan bagi bacaan pengukuran pengaruh menunjukkan, pada frekuensi 400 MHz, nilai kualiti faktor secara perlahan menurun dari 6.79 kepada 5.49 dengan nilai pengaruh meningkat dari 21.40 nH kepada 22.40 nH bagi saluran tiub kosong dan saluran tiub yang telah disuntik dengan bendalir Ferro. Keputusan ini telah memberikan bacaan julat penalaan sebanyak 4.67%. Kesimpulannya, reka bentuk berasaskan bendalir boleh laras-halus pengaruh sistem mikroelektronik mekanikal solenoid berjaya dicapai untuk aplikasi frekuensi ultra tinggi.

DESIGN AND IMPLEMENTATION OF LIQUID-BASED FINE-TUNABLE SOLENOID MEMS INDUCTOR

ABSTRACT

Passive devices such as on-chip inductors play an important role in radio frequency circuits. However, these types of inductor lacked in terms of quality factor performance due to high substrate parasitic. Thus, in this thesis, liquid-based fine-tunable solenoid microelectronic mechanical systems inductor with high quality factor is presented for ultra-high frequency applications. The light hydrocarbon-based ferrofluid is utilised in the design to achieve a fine-tuning inductance. A micro-tube acts as a channel for tunability. In addition to that, wire bonding technique is applied to reduce series resistance, substrate loss, and self-resonance loss. A gold wire is bonded diagonally at the edge of metal pad by crossing it over the top of the micro-tube. The designed inductor was simulated using ANSYS HFSS and measured at a frequency of 400 MHz for proof-of-concept work. At 400 MHz, simulation results show that 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. Thus, tuning range of 21% is successfully achieved. The measured results however, reveals 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, giving a tuning range of 4.67%. In conclusion, the design of liquid-based fine-tunable solenoid microelectronic mechanical systems inductor is proven workable for ultra-high frequency applications.

CHAPTER ONE

INTRODUCTION

1.1 Introduction of Research

For years, integrated passive devices become a major topic in radio frequency integrated circuit (RFIC) applications. Integrated passive device such as inductor play a key role in radio frequency (RF) circuits. However, the miniaturization of the inductor along with integrated circuits (IC) are hard to realize (Gijs, 2008). Beside of having difficulties to reduce its size, the performance of integrated inductor such as quality factor is hard to achieve especially at GHz frequency. This is due to ohmic loss and eddy-current loss in a metal traces and substrate. Aside from that, a high substrate loss also appears in a bulk silicon (Si) substrate (Niknejad and Meyer, 2001). Therefore, studies have come out with a solution where a high frequency devices can be realized by applying microelectronic mechanical systems (MEMS) technologies into the inductor (Zhang *et al.*, 2010).

MEMS can be applied to the geometries of the inductor as an approach to improve quality factor. The quality factor performance can be improved through several techniques such as; maximizing the width of the conductor (Weon *et al.*, 2005); shrinking the size of inner turns (Lopez-Villegas, Samitier and Cane, 1998); distance the gap between segments of winding (Passos, 2013); embedding the inductor on the wafer (Sun and Miao, 2005), and back grinding the substrate (Han *et al.*, 2013). Besides, another best way to approach MEMS technology is by making the inductor tunable (Banitorfian *et al.*, 2013). One of the techniques that can be realized is by

changing the magnetic permeability of inductor core with a magnetic fluid i.e. ferrofluid (Banitorfian, 2016). A tunable MEMS inductor has a capability to tune a range of inductance values depending on the number of turns of the winding coils. Another interesting approach on MEMS inductor is by having Si wafer as the substrate of the device. This approach will completely open-up to a new discovery on the RFIC applications. Figure 1.1 show one example of the MEMS inductor (Yu *et al.*, 2014).

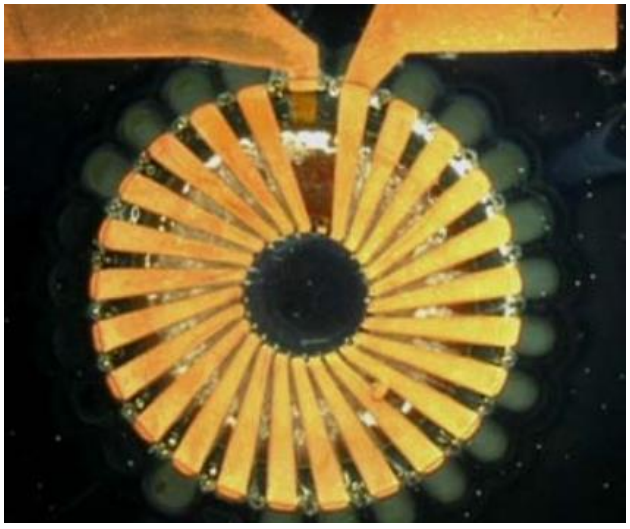

Figure 1.1: Silicon-embedded toroidal MEMS inductor (Yu *et al.*, 2014)

The MEMS inductor can be categorised into several types. These types of inductor are; solenoid, spiral, square, hexagonal, octagonal, toroidal, and meander. The best way to utilise inductance tuning is to use solenoid shape. This is due to less edge and corner effects on the solenoid type compared to others. The edge of metal conductor contributes more current distribution crowded on that area which increase the series resistance of the inductor (Banitorfian *et al*., 2014). In addition, the solenoid type has an advantage on low substrate loss effect. This is due to only the bottom part of the solenoid is in direct contact with the substrate. Thus, a high quality factor can

easily be achieved with the solenoid shapes. Figure 1.2 show an example of the solenoid MEMS inductor (Seok *et al.*, 2001).

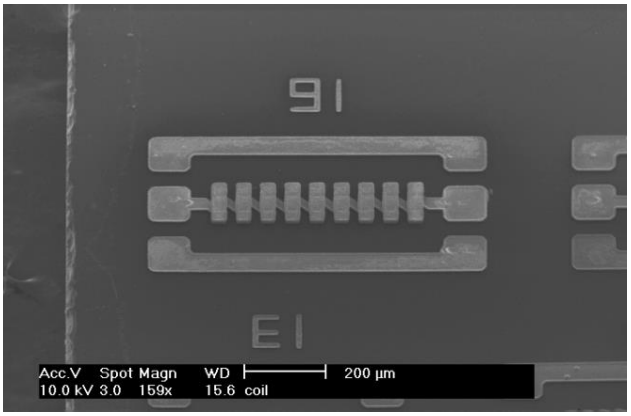

Figure 1.2: Solenoid MEMS inductor (Seok *et al.*, 2001)

1.2 Problem Statement

The demands on low-cost fabrication with high-performance on-chip RFIC applications are strongly needed today. Conventionally, on-chip monolithic microwave integrated circuits (MMIC) inductor are integrated with a standard silicon substrate and aluminium as a metal interconnects (Zaki, 2006). This low-cost on-chip inductor exhibit poor quality factor due to the substrate parasitic and ohmic losses in aluminium traces. Moreover, the MMIC inductor cannot be made tunable. For that matter, several solutions have been made to increase the quality factor of the devices and at the same time to make it tunable. Therefore, the MEMS inductor is utilised in this work for achieving high-performance integrated inductor.

In previous work, several methods were implemented to improve quality factor. Most of the inductor designed by previous researchers were said to achieve a

good quality factor performance. However, most of them do not have a tuning capability. Such examples can be seen in (Chomnawang and Lee, 2001), (Weon *et al.*, 2005), and (Pólik and Kuczmann, 2010), where quality factors observed are more than 30 but do not have tuning capability. Following these work, inductors with tuning capability were introduced to add values to the high quality factor performance of the inductor (Banitorfian *et al.*, 2015) and (Banitorfian *et al.*, 2016). Unfortunately, the proposed designs are not dedicated for 2.4 GHz range of application, where wireless communication devices such as routers or mobile phones normally operate.

In work (Banitorfian *et al.*, 2015) and (Banitorfian *et al.*, 2016), the operating frequencies were recorded at 4 GHz and 0.15 GHz. As observed, this operating frequencies were way off the proposed design of 2.4 GHz. The problem of tuning the operating frequency to 2.4 GHz was due to the size constraint of the inductor. For example, (Banitorfian *et al.*, 2016) was only recorded as proof-of-concept work due to smaller inductor design was not achievable. This resulted has led (Banitorfian *et al.*, 2016) work to only capable operating at frequency of 0.15 GHz. However, in work (Banitorfian *et al.*, 2015), the design was recorded as a simulation inductor which a high frequency of 4 GHz can easily be achieved. Thus, to ensure the inductor can be fabricated, operating frequency is need be limited to 400 MHz as a proof-of-concept, considering that low operating frequency of less than 500 MHz can only be achieved with inductor size of more than 1 mm.