MINIATURIZED BROADSIDE-COUPLED SPLIT RING RESONATOR FILTER FOR COMPACT WIRELESS APPLICATIONS

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MINIATURIZED BROADSIDE-COUPLED SPLIT RING RESONATOR FILTER WITH CAPACITIVE LOADING

by

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LIST OF ABBREVIATIONS

AC	Alternate current
BC-SRR	Broadside-coupled split ring resonator
CSRR	Complementary split ring resonator
DC	Direct current
EC-SRR	Edge-coupled split ring resonator
ESR	Equivalent series resistance
FBW	Fractional bandwidth
HDI	High density interconnect
LF	Low frequency
LHM	Left-handed material
PCB	Printed circuit board
SAW	Surface acoustic wave
SMA	SubMiniature version A
SRR	Split ring resonator
TEM	Transverse electromagnetic
UUT	Unit under test
VCO	Voltage controlled oscillator
VHF	Very high frequency
VNA	Vector Network Analyzer
VSWR	Voltage standing wave ratio

LIST OF SYMBOLS

C	Capacitance
ε_r	Relative permittivity
ε_{re}	Effective relative permittivity
f_0	Resonant frequency
k	Coupling coefficient
L	Inductance
Q	Quality factor
Q_0	Unloaded quality factor
Q_{ex}	External quality factor
Q_L	Loaded quality factor
R	Resistance
Z_C	Characteristic impedance

PENAPIS PENYALUN GELANG BELAH SISI LEBAR TERGANDING BERSAIZ KECIL MENGGUNAKAN PEMUATAN PEMUAT

ABSTRAK

Teknologi gelombang mikro masa kini mempunyai fokus dalam pengecilan penyalun. Pengecilan penyalun adalah penting untuk reka bentuk litar frekuensi tinggi dalam saiz yang kecil. Sejenis teknik baru penapis gelang belah sisi lebar terganding bersaiz kecil dikaji dengan meningkatkan tahap kemuatan penyalun dengan menggunakan pemuat di atas setiap bulatan berasingan untuk mengurangkan frekuensi penyalun. Penapis gelang belah sisi lebar kecil dengan frekuensi 1 GHz direalisasikan dan pengecilan sebanyak 27.17 % dicapai dengan menggunakan pemuat bernilai 0.7 pF, berbanding dengan penapis yang tidak dibeban dengan pemuat. Penapis ini juga menunjukkan prestasi penularan jalur lurus sempit sebanyak 1.65 % pecahan lebar jalur dan penolakan atas frekuensi sehingga $5.1f_0$. Cara baru untuk merangsang penyalun juga diselidik dengan teknik talian penghantaran maju dengan menyertakan interaksi substrat berlapis-lapis. Sebanyak sepuluh sampel penapis gelang belah penyalun sisi lebar kecil terganding dengan pemuat difabrikasikan, diukur dan dianalisiskan dari segi perubahan dan menunjukkan prestasi tentukur sebanyak 0.52 % berbanding dengan rekaan awal. Satu sampel diuji dari segi suhu sejuk dan panas dan menunjukkan ia mempunyai pemalar haba yang baik dan perubahan sebanyak 0.6 MHz. Akhirnya, kebolehlaksanaan penapis penyalun gelang patah sisi lebar terganding bersaiz kecil dibincangkan serta pertimbangan untuk pelaksanaan dicadangkan dan dibentangkan.

MINIATURIZED BROADSIDE-COUPLED SPLIT RING RESONATOR FILTER USING CAPACITIVE LOADING

ABSTRACT

The current microwave technology state of the art has been focused on the miniaturization of resonator. The importance of resonator miniaturization is based on the need to implement high frequency circuits in a compact form factor. A novel version of broadside-coupled split ring resonator (BC-SRR) is explored in this thesis by using a method of enhancing the resonators' capacitance by loading a surface mount capacitor on each individual rings that leads to reduction of resonant frequencies. A miniaturized BC-SRR filter with center frequency of 1 GHz is realized and achieved a miniaturization of 27.17 % by using 0.7 pF surface mount capacitors as compared to a filter that does not use a capacitor. The filter also exhibits a narrowband passband transmission response of 1.65 % fractional band width and excellent upper stopband rejection up to $5.1f_0$. A novel method to excite the resonator is explored by using advanced transmission line design technique that incorporates multi-layer interaction. Ten samples of capacitor-loaded BC-SRR filter is developed, measured and analyzed in terms of variation and shows excellent tolerance performance with 0.52 % frequency offset from initial design. A single sample is subjected to extreme cold and hot temperatures and show excellent thermal coefficient property with as much as 0.6 MHz passband response shift at both temperature extremes. Finally, the feasibility of using capacitors to further miniaturize broadside-coupled split ring resonator (BC-SRR) filter is discussed and recommendations of implementation is proposed and presented.

CHAPTER ONE

INTRODUCTION

1.1 Motivation

The demand for highly sophisticated and advanced electronic products has pushed the boundaries of several engineering disciplines to miniaturize components to be ever smaller. This is including the discipline of microwave and radio frequency engineering that has spent decades in the art of microwave resonator miniaturization. Traditionally, microwave filters have been employed for filtering of unwanted frequencies but are prohibitively too large. The advancement of Surface Acoustic Wave (SAW) filters that is based on piezoelectric principles are proven to be effective miniaturized filters but are expensive in large scale implementations. The findings of this study will continue to further achieve that goal of realizing smaller microstrip resonators for wireless radio frequencies components and applications. As cost becomes a critical element that determines the manufacturability and feasibility of a product, more compact microstrip resonator elements that contribute to a desired feature in a product reaches a step forward towards feasible realization. Thus, a method to miniaturize microstrip resonator filters may be arrived at.

1.2 Problem Statement

The need to obtain a higher degree of miniaturization has received plenty of attention in the past few decades due to rapid development of microwave and telecommunications industry. Pioneering microwave technology such as waveguides and dielectric resonator filters are too heavy and bulky for most applications [1]. As technology advances, the demand for mobile communications systems presents a considerable challenge to design RF filters that both meet the performance and level of miniaturization. This is especially true to Ultra High Frequency (UHF), L-band (1-2 GHz) and S band (2-4 GHz) applications where resonators tend to be large due to long electrical wavelengths [2].

In Low Frequency (LF) up to Very High Frequency (VHF) applications, passive lumped elements such as inductors and capacitors are typically used to form a tuned circuit that are widely used in filters, voltage-controlled oscillators (VCO) and amplifiers. At microwave frequencies and beyond, smaller values of lumped elements are difficult to obtain, which is the reason microstrip resonators and cavities are used in place of lumped elements for such high frequency applications [3].

Over the years, there has been plenty of successful methods explored to reduce the size of microstrip resonators. Among those are hairpin filter [4-6], high permittivity materials [7], ladder microstrip line filter [8-10], meander open-loop resonators [11], slow-wave resonators [12-15], dual-mode resonator filters [16-22], multilayer filters [23-29] and broadside-coupled split ring resonator (BC-SRR) filters [30]. Loaded open-loop resonator has been investigated and shows promise to further miniaturize the resonator by using a surface mount capacitor to reduce resonant frequency [2].

This thesis focuses on a novel method to further reduce the size of Broadside-Coupled Split Ring Resonator with surface mount capacitors. The use of surface mount capacitors to load the capacitive gap of the resonator rings is hypothesized to increase the guided wavelength, thus reducing the resonant frequency and resonator size. A filter is then designed and developed using cascaded loaded BC-SRRs. No existing literature currently presents the design and fabrication method of the resonator as these prior arts did not emphasize on application and manufacturability. Design, fabrication and analysis of BC-SRR filter in a highly applicable scenario is explored at a great depth in this thesis to facilitate use in final assembly products.

1.3 Objectives

The objective of this thesis to study new methods used to enable a higher degree of miniaturization of a capacitor-loaded BC-SRR resonator. The objectives in detail are as follows:

(i) To design a capacitor-loaded broadside-couple split ring resonators by loading the top ring with surface mount capacitors.

(ii) To investigate the performance of a capacitor-loaded BC-SRR structure with enhanced coupling of the top and bottom rings of the resonator, in terms of miniaturization

(iii) To design the filter by incorporating multilayer transmission line techniques that will contribute to miniaturization.

1.4 Scope of Work & Limitations

The primary tools that will be used to deliver the research findings are references to prior arts and literature reviews. This will be used to find relevant arts that are closely related with the topic and relevant knowledge will be leveraged that will help to reach the research objectives. In addition to that, an evaluation CST Studio Student is used to perform simulations that help to give better clarity to the design work that will ultimately lead to realization of the filter. A Keysight E5071C Vector Network Analyzer is used to perform S-Parameter measurements to characterize the filter performance in terms of transmission response and input and output reflections. A SH-642 temperature and humidity chamber is used to measure the filter performance in extreme cold and hot circumstances.

The resonant frequency of the resonators and filters are targeted to be at 1 GHz as a means of simplified reference to existing literature reviews. The range of the frequency response spans from 100 MHz up to 6 GHz to evaluate the filter performance in the lower stopband, passband and upper stopband. The resonant frequency and frequency response span is chosen such as to easily compare the performance with an important literature that uses a similar configuration and frequencies as well [2]. This provides a clear picture of the wideband filter response, which is a critical element in filter designs.

1.5 Research Contribution

The current state of research surrounding microstrip resonator filters revolves around the need for miniaturization using many different techniques explained in Section 1.2. This research is intended to contribute directly to a degree of miniaturization of resonator filters. Hypothetically, the employment of multilayer substrate in resonator implementation utilizes the unused space in a multilayer printed circuit board (PCB) to achieve higher degree of miniaturization. The use of capacitive loading is also expected to further reduce the resonant frequency which translate to a reduction of resonator size. Collectively, these elements will contribute to the industry, academia and applications in terms of providing a method to further reduce the overall size of a resonator filter.

1.6 Thesis Organization

Chapter Two provides the background of the research. Transmission line theory such as microstrip line, embedded microstrip lines and blind via design is explored in depth as these are fundamental pieces that enable broadside-coupled split ring resonators to be practically applied in the field. Filter design and characteristics, namely coupled resonator filter theory, quality factor and unloaded and loaded Q factors are also reviewed. Finally, microstrip resonators are discussed, with regards to open loop resonators and prior studies of broadside-coupled split ring resonators.

Chapter Three proceeds on design methodology of the filter. Early on the chapter, the analysis of a broadside-coupled split ring resonator is performed using simulation software to demonstrate effects of using a surface mount capacitor. PCB stackup used to design and develop the product, including the materials used is also described in detail. Coupling coefficient of the resonators is simulated and tabulated in graphical forms. The chapter ends with design and synthesis of the miniaturized BC-SRR filter.

Results of the filter is discussed in Chapter Four. The final filter product is evaluated and measurement results are compared against simulated results. Variables and controls are explored to pinpoint potential root cause of results deviation from simulation.

Chapter Five concludes the study with discussions on the work done. Suggestions for future research studies are proposed.

CHAPTER TWO

LITERATURE REVIEW

2.1 Introduction

Resonators are commonly used in applications such as filters, oscillators, frequency meters and tuned amplifiers and frequently encountered in radio frequency circuits. Microwave resonators are encountered in similar applications at much higher frequencies where lumped element components are unable to meet the size requirements used in microwave frequency circuits [31]. Resonators can be developed using distributed elements of transmission lines, waveguides and dielectric cavities.

2.2 Transmission Line

They are many planar transmission line structures developed over the years. These are microstrip lines, embedded microstrip lines, striplines, coplanar waveguides and grounded coplanar waveguides [32]. The most common of these, the microstrip line will be described in the following paragraphs. A primer on the less common embedded microstrip line is also explored as this method of transmission line has an important role in broadside-coupled split ring resonator excitation. Types of via and via discontinuity is also discussed as vias serve as interconnects between microstrip and embedded microstrip lines. In this thesis, all transmission line techniques are designed to adhere to a characteristic impedance of 50Ω to accommodate the source and load impedances of a typical radio system and of a vector network analyzer.

2.2.1 Microstrip Line

The structure and geometry of a microstrip line is shown in Figure 2.1. The microstrip line is made up from a conducting strip of width *W* and microstrip thickness *t* and is deposited on top of a substrate with electric permittivity ε_r and substrate thickness *h*. The microstrip line alongside with the substrate is backed by a conducting ground plane.

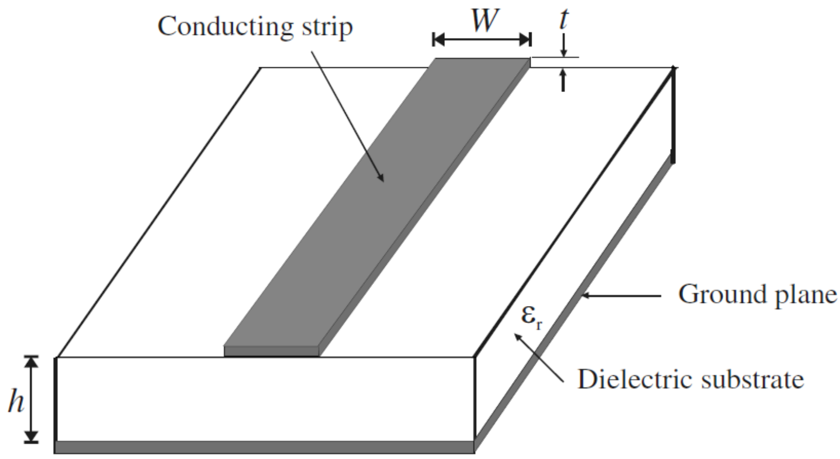

Figure 2.1: Microstrip line structure [33].

The microstrip line is known to be an inhomogeneous transmission line [33]. This is because the fields in the microstrip are contained within two media – the air above conducting strip and dielectric below. The inhomogeneity nature of the microstrip line would mean that it does not support a pure TEM wave. This is due to that a pure TEM has only transverse components and the propagation velocity is a function of the material's permittivity ε and permeability μ. The mode of propagation for a microstrip line is Quasi-TEM in that the longitudinal components of the fields for the dominant mode remain much smaller than the transverse components.

For $W/h \leq 1$, the effective relative permittivity and characteristic impedance are given as [33]:

$$\varepsilon_{re} = \frac{\varepsilon_r + 1}{2} + \frac{\varepsilon_r - 1}{2}\left\{\left(1 + 12\frac{h}{W}\right)^{-0.5} + 0.04\left(1 - \frac{W}{h}\right)^2\right\} \qquad (2.1)$$

$$Z_C = \frac{\eta}{2\pi\sqrt{\varepsilon_r e}}\ln\left(\frac{8h}{W} + 0.25\frac{W}{h}\right) \qquad (2.2)$$

For $W/h \geq 1$, the effective relative permittivity and characteristic impedance of the microstrip line are given as:

$$\varepsilon_{re} = \frac{\varepsilon_r + 1}{2} + \frac{\varepsilon_r - 1}{2}\left(1 + 12\frac{h}{W}\right)^{-0.5} \qquad (2.3)$$

$$Z_C = \frac{\eta}{2\pi\sqrt{\varepsilon_r e}}\ln\left\{\frac{W}{h} + 1.393 + 0.677\ln\left(\frac{W}{h} + 1.444\right)\right\} \qquad (2.4)$$

The effective relative permittivity described here is the relative permittivity of a homogenous medium that includes both the air and dielectric regions of the microstrip line.

The microstrip line is a popular choice of transmitting high frequency signals within a printed circuit board in a guided manner. Microstrip is only applicable with two effective printed circuit board layers as any conductive element between the microstrip line trace and ground plane will cause discontinuity. In most resonator designs, the microstrip line is used to excite the resonators. In this thesis, the microstrip line, while critical for implementation, alone is not adequate to excite the broadside-