Defects Analysis and
A Self-Repairable Strategy for
Tunable RF MEMS Filter

by

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Radio frequency (RF) Micro-Electro-Mechanical Systems (MEMS) is currently a developing field. In order to make RF MEMS devices more applicable and marketable, the reliability and testability of the device are critical.

In this thesis, a testing methodology to be applied onto the RF MEMS devices is proposed. The RF MEMS device under test is the tunable filter with RF MEMS switches.

First, the layout of the tunable MEMS filter is determined. Then electromagnetic simulation is carried out on the filter. Faults are introduced into the layouts of the filters and the frequency output responses of the faulty filter are simulated using the Sonnet EM simulation software. The faults that are simulated are broken structures, parametric variation, stuck-at-on and stuck-at-off for switch faulty condition, and a combination of stuck-at-on and stuck-at-off faults. From the simulation analysis two classifications of the faults are made: one is made according to the effect on the output frequency response, another one is made according to the fault on the filter.

Using this testing methodology, the fault that occurs during fabrication process can be quickly identified from measuring the frequency output response of the tunable filter. With the quick identification of the fault, this fault can be corrected during fabrication process so that less faulty filter will be fabricated. Once the list of faults and their effects is available, the tunable filter can be quickly tested to determine the fault. The limitation of this method is that the change of the filter design will require the repetition of the whole procedure to obtain a whole new list of the fault and effect. Admittedly, only a single fault and the combination of the stuck-at-on fault can be detected from the list, but future work will address this issue.

Knowing the importance of the MEMS switches, a filter with built-in self repair function is proposed. This filter is designed using “redundant structures” method. This is done by redesigning the MEMS switch biasing circuit into separate control biasing circuit. Then each of the resonators is designed separately for the required tuning center frequency by elongating the narrow line segments. Lastly, all three resonators are put together as one filter. The location of
the MEMS switches and switch grounding pads will move according to the narrow line segments. Then this design method is simplified to obtain another similar filter with the built-in self-repair function. This simplified method is easier and requires shorter time to implement the built-in self-repair function on the filter.
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Declaration of Originality

This thesis contains no material which has been accepted for the award of any other degree or diploma in any university, except where due reference is made in the text of the examinable outcome. To the best of my knowledge, this thesis contains no material previously published or written by another person except where due reference made in the text of the thesis. The work that is based on joint research or publications in this thesis fully acknowledges the relative contributions of the respective workers or authors.

Signed ........................................

Ker Chia, Lee

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Chapter 1

1. Introduction

This section introduces the Micro-electro-Mechanical Systems (MEMS), presents the current MEMS technology and discusses the advantages and the challenges in using MEMS devices.

1.1 Micro-Electro-Mechanical Systems

Micro-Electro-Mechanical Systems or MEMS is an integration of mechanical elements, sensor, actuators and electronics circuitry in a package measuring from microns to millimeters in size. The advantages of MEMS include [1]:

- Since MEMS devices can be produced using integrated circuit batch fabrication technology, they can be fabricated in larger number at low cost.
- Due to its small size and volume and being light weight, it is easily deployable.
- Radio Frequency (RF) switches based on MEMS, which is the device under study in this work, has a larger isolation when off and low device insertion loss when on.

MEMS have been used in various fields, such as telecommunication, automobile and measuring instrumentation. For MEMS to appeal to wider applications, the following issues need to be resolved [1]:

- Reliability and testability of MEMS devices, which are addressed in this work.
- Complex MEMS packaging process.
1.2 Current MEMS Technologies

Micro-accelerometer
Micro-accelerometer is generally made up of a poly-silicon beam suspended over the surface of the substrate. When the substrate body is accelerated, the beam will be deflected due to its inertia. The deflection is detected using capacitive sensor which gives voltage output that is proportional to the acceleration. The micro-accelerometer is usually used for vibration monitoring and motion sensing [2]. Figure 1.1 shows the commercially available Analogue Device ADXL 50 accelerometer which senses acceleration in two dimensions.

![Figure 1.1 Analog Device ADXL 50 accelerometer. Image from reference [2].](image)

Optical and Micro-mirror
Optical MEMS mirrors are used to create optical biopsies that provide high-resolution, cross-sectional imaging of tissue [3], which enable the application of several biopsy techniques including the optical coherence tomography, non-linear optical imaging and confocal imaging [4]. Micro-mirrors are also used for projection systems where they form part of the digital light-processing pixel that can be electronically titled to the required angle by applying the biasing voltage [5], as shown in Figure 1.2.

![Figure 1.2 Illustration of 2 landed DMD mirrors. Image from reference [5].](image)
**BioMEMS**

BioMEMS chips are designed for pathogen detection, drug discovery and DNA fingerprinting. With the addition of more separation techniques and on-chip chemistry, BioMEMS can now be applied to protein analysis, immunoassays and point-of-care diagnostics [6, 7]. Figure 1.3 shows Agilent’s “Lab-on-a-chip” BioMEMS which consists of micro-channel which is able to separate DNA fragment sample according to size by the means of molecular sieving. DNA fragments are detected by fluorescence at the detection point with the Agilent 2100 bioanalyzer software.

![Figure 1.3](image)

*Figure 1.3 The ‘core’ of an Agilent lab-on-a-chip cartridge showing the microfluidic channels. The photo on the right is the plastics cover of the core of the chip. Image from reference [7].*

**Micro Actuators**

Pick-and-place robotic micro assembler and manipulator systems which are capable of micron scale assembly have been developed at Zyvex Corporation [8]. The end-effector is the microgripper as shown in Figure 1.4. The tele-operated microgripper is designed for microsurgery [9]. Another micro-actuator, the micropipette has been developed for placing liquids in chemical analysis systems, drug delivery or biofluid sampling applications [10].

![Figure 1.4](image)

*Figure 1.4 Photo of microgripper. Image from reference [8].*
RF MEMS and MEMS switch

The radio frequency and microwave application can refer to as communication radar system, navigation, radio astronomy, sensing, medical instrumentation, automotive, wireless communication and others. The RF MEMS device, such as phase shifter, switch filter banks, antenna, capacitors, inductors, resonators and MEMS switches, offer low loss, high Q factor, high linearity and good power handling.

The device under study in this work, the RF MEMS switch, is becoming the preferred choice for RF switching due to its outstanding performance when compared to the conventional solid state RF switch such as p-i-n diodes or FET transistor. RF MEMS switch has very low insertion loss but high isolation and consumes minimal power in the microwatts rather than the milliwatts that solid state switches require. RF MEMS switch generally consists of a thin metal membrane suspended few micron above two open-circuited conductors. When sufficient actuation voltage is applied to the electrodes beneath the membrane, the membrane is pulled down towards the conductors by electrostatic force, shorting the two conductors [11].

Figure 1.5 RF MEMS switch from Raytheon Systems Company. Image from reference [11].
1.3 Motivation of this work

The testability and reliability of the MEMS devices are crucial for quality control and long term application of the devices. This work addresses the issue of testability and reliability of a tunable RF MEMS filter using RF MEMS switch, which unlike electronics integrated circuit, MEMS switch is based on interaction between electrical and mechanical components of the device.

Blanton et al. first addressed the issue of MEMS reliability and testing in 1997 where attempts were made to map MEMS structural defects and the resulting behaviours with contaminations during the fabrication process [12]. Blanton et al. suggested that the MEMS defects could be categorized according to the faulty behaviour classes. Then, with the available fault classes, the test methodologies could be developed to ensure the reliability of the MEMS devices.

With more understanding of the possible MEMS defects and their effect on the system response, work on a Built-In-Self-Test (BIST) MEMS have started recently. Blanton et al. has developed an algorithm to detect faulty MEMS microaccelerometer on a modularized design, where the sensing elements of the microaccelerometer are divided into standalone segments [13]. By applying certain test pattern (a combination of ON and OFF modules), the modules that are faulty could be detected. In [14], Xiong et al. proposed a Built-In-Self-Repair (BISR) technique that enables the microaccelerometer to switch to redundant module when defect occurs.

Most previous work on MEMS reliability focused on micro-accelerometer and resonators which exhibit the basic elements of MEMS, but proper mapping between possible physical defects with the RF MEMS filter response has been lacking. The defects of the RF MEMS filter could occur on the filter structure or the MEMS switch used for tuning the filter. By analyzing the faulty RF filter output responses, some of these defects can be identified. Hence, with a library of common defects and the resulting defective output, if a defective response is detected right after device fabrication it can be quickly mapped to the defect that causes it. The defects is identified and corrected during normal operation of the device. Admittedly, this technique is only possible for common defects and does not cater for multiple defects but even with this limitation the reliability of RF MEMS filter can be potentially improved.
1.4 Objective of this work

This work addresses the reliability of the tunable RF MEMS filter, where the possible common defects during fabrication and normal operation of the device are analyzed and classified according to the nature of the defects.

The effects of all these defects on the filter response are then analyzed via simulation so that:

1. The impact of each defect can be assessed and thus allowing the designer to optimize the design in certain area which is more susceptible to the defects.
2. In future, the defects can be identified by just analyzing the faulty response, or at least the general location and type of the defect that causes the filter faulty behaviour.
3. A build-in-self-testable and repairable technique can be developed for MEMS switch failure.

After analyzing the possible defects and effects on the RF filter, a Built-In-Self-Repair technique is developed so that the device can ‘repair’ itself in the event of MEMS switch failure.

Although the study carried out in this work is specifically for a tunable three poles Chebyshev bandpass filter, the methodology used in this study can be replicated for other filter devices. This study also demonstrates how the reliability of a RF device can be analyzed and how failure analysis can be used for the development of built-in-self-repair mechanism with some device design changes.
1.5 Thesis Overview

This chapter starts with an introduction to the thesis. It gives a summary of the MEMS technology, the advantages and challenges of MEMS and the motivation for this work.

In Chapter 2, the first part reviews the design and development of the tunable RF MEMS filter. The second part discusses the testing methods of the RF MEMS filter.

The simulation set-up and various tests that were carried out are summarized in Chapter 3. This chapter will include the description of the tunable filter under test, the setting of the test, the software that is being used, the testability of the fault and failure mode in this setting, the combination fault mode that will be tested, and the limitation of this methodology.

Chapter 4 summarizes the results and observations from the simulation, and discusses different faults as well as the effects they have on the filter response. These faults include the fault caused by particulate contamination, geometric variation broken structure, switch stuck-at-on, switch stuck-at-off and a combination of the fault mode.

Chapter 5 presents a Build-In-Self-Repairable filter design which is able to maintain the filter functionality even when the MEMS switch used to tune the filter fails. This is made possible using the “redundant structures” approach. The limitation of this design is also listed.

Chapter 6 concludes the work and discusses further work in this research area.
Chapter 2

2. Literature Review

This chapter reviews the current development of the tunable RF MEMS filter. Then the current test method based on induction fault analysis for MEMS devices is presented and related to the RF MEMS filter.

2.1 Current development of Tunable MEMS Filter

Parameters such as signal-to-noise ratio, selectivity of signal, linearity and insertion loss are optimized when designing a tunable radio frequency filter for the transceiver of multi-channel communication systems. To tune the filter, varactor (tunable capacitor) and MEMS switches, and in some cases p-i-n diodes, can be used.

When different biasing voltage is applied to a varactor, the capacitance of the varactor will change. Examples of varactor used for tuning filter include those by Borwick et al. [15] which has a good quality factor value of more than 100 and by Kraus et al. [16] which includes varactor together with filter fabrication giving a good 35% tuning range with constant fractional bandwidth. For Barium Strontium Titanate (BST) thin film type varactor, changing the biasing voltage of the varactor will alter the value of the dielectric material thereby changing the capacitance. Figure 2.1 shows a BST varactor designed by Nath et al. [17]. The varactor requires biasing voltage between 0 V to 200 V to give good return loss of better than 13 dB over the tuning range. Commercial varactor SMV1763 manufactured by Skyworks Solutions Inc. was used in the tunable filter developed by Zhang and Xue [18], as shown in Figure 2.2. The
varactor capacitance can be tuned from 1.8 to 9 pF over a 5 V bias range. The filter gives an insertion loss of less than 3.4 dB and the return loss of better than 10 dB over the tuning range.

MEMS switches can be used to change RF filter capacitive and inductive behaviour by breaking or extending filter structures. For example, Nordquist et al. [19] fabricated a tunable X-band combline filter where the inner three resonators can be extended using MEMS switches to make the combline longer, as shown in Figure 2.3. This has the effect of increasing the coupling effects of the resonators and thus the frequency response of the filter. In [20], a switched filter bank is designed so that it can be switches to three different fixed center frequencies using a single-pole triple-throw (SP3T) MEMS switch as shown in Figure 2.4. In the tunable filter designed by Entesari et al. [21] shown in Figure 2.5, commercially available MEMS switches from Radant MEMS Inc. were used to switch between capacitor banks.
Figure 2.3 (Left) optical micrograph of completed RF MEMS filter from [19]. Insert: RF MEMS switches. (Right) (a) Insertion loss and (b) return loss.

Figure 2.4 (a) Photograph of the SP3T, (b) The overall layout of the filter from [20].

Figure 2.5 (Left) Layout of the two-pole tunable filter on a 62-mil FR4 substrate (100 mm x 60 mm). (Right) Photograph of the MEMS switch from Radant MEMS inc. mounted to the FR4 substrate [21].
Previous work in the field has generally indicated MEMS switch as the better performing RF tuning method as compared to varactors, p-i-n diodes and FET transistor. While MEMS switch has the advantage of low insertion loss and high isolation, current work on the MEMS switch focuses on improving the switch biasing lines design in further minimize insertion loss, improving the switch linearity and enhancing the lifetime of the switch. There is also an emerging trend where tunable filter is designed with high quality, commercially available external MEMS switches.
2.2 Current Development of Testing Method of MEMS

There is an emerging interest in the issue of MEMS testing methodologies, which is uncommon as unlike electronics integrated circuit, there are diverse MEMS devices based on interaction between different physical domain including electrical, mechanical, optical, thermal, chemical and fluidic. Work carried out in the field so far suggested that the development of cost effective reliability testing techniques for MEMS is an important factor to ensure successful mass-production of the devices.

The development of MEMS testing methodology follows the footprint of its silicon based integrated circuit counterparts [22-26]. These methods generally analyze the defective behaviours of the device and inspect the device under the scanning electron microscope for particulate contamination, broken structures and geometrical error which may lead to the cause of defects.

In an effort to address comb-driven MEMS micro-resonator reliability, Blanton et al. [12, 13, 27-30] extends the testing method introduced by Ohletz for integrated circuit testing [26]. The method, called the “Contamination and Reliability Analysis of Microelectromechanical Layout” or CARAMEL, involves familiarization with the manufacturing process, contamination properties and microstructure layout of the microresonator. With these three inputs, the fabrication process is simulated using a proposed “Contamination-Defect-Fault” or CODEF simulator to predict the resulting shuttle, comb finger and flexure defects. The defective microstructure is then simulated using ABAQUS to investigate their effects on the device response. Figure 2.6 shows the flowchart of the defect analysis process. This work included that some defects cause catastrophic changes in resonator behaviour, others cause subtle or insignificant changes in behaviour but might have some implications on long term reliability, and the impact of some defects cannot be predicted with mechanical simulation alone but require experiment with real defective MEMS. The CARAMEL method is then improved with the addition of electrical simulation using HSPICE in [27-30]. Electrical simulation is incorporated to determine the electrical misbehaviour of the comb-drive micro-resonator that cannot be detected using mechanical simulation only. With the fault model data in hand, when a device fails the source of the defects can be quickly determined and if possible removed by comparing the actual test data with the model data.
Deb and Blanton [31, 32] have also analyzed the failure source in surface-micromachined MEMS device such as micro-resonator and micro-accelerometer. Failures on these devices that are being investigated include sensor finger stiction, particulate contamination, and etch variations. These failures are further classified as anchor defect on flexure beam, shuttle, movable finger, broken beam defect or inter-finger defect.

Courtois et al. [33, 34] investigated the testing methodology for MEMS electro-thermal converter and resonant beam force sensor using the behaviour model and HDL-A language to model the devices and their possible defects. The HDL-A together with input stimulus is input into the mixed-mode multi-level simulator to obtain faulty device graphical interface. The extended fault-based testing to both bulk and surface micromachined systems are done by Mir, Charlot and Courtois [34, 35]. There are two main groups of faults are being considered: faults affecting the MEMS gauge and faults affecting the microstructure that supports the gauge.

Rosing et al. [36-39] proposed a validation methodology which is extended the mixed signal and analogue integrated circuit fault simulation techniques. The method includes behavioural modeling techniques with compatible electrical simulators and data classification for failure mode and effect analysis on MEMS pressure sensor and comb-drive resonator. The layout of the device is described using the lumped level modeling. Then component level modeling is used to
obtain the complete behaviour model of the device which is then used for modeling the fault of the devices. Once the fault model of the device is obtained, they are used for developing design-for-testability or built-in-self-test techniques for the device.

![Flowchart of the proposed test method from Rosing [36].](image)

Apart from test methodology development, work on built-in self-repairable (BISR) techniques for MEMS has begun. Xingguo Xiong et al. in [14, 40] proposed a new microaccelerometer layout that has a built-in self-test (BIST) function which compares a faulty behaviour with simulated data pre-stored on the device. Once defect is detected, the device has a BISR mechanism which enables the microaccelerometer to switch to the redundant module.

In summary, the stages in developing testing method for MEMS devices are as follows.

1. Common of defects in MEMS device are identified.
2. Effects of the defects on the behaviour of MEMS elements are analyzed and classified.
3. Simplified fault model of MEMS elements is developed. Realistic wafer-level tests are done on MEMS components to investigate the incipient failure condition.
4. A test methodology is developed to determine if the device is operating correctly.
5. Some built-in tests for in-service verification of component functional correctness are developed to improve the testability of device.
6. Eventually, with a good built-in-self-testing mode, a built-in self-repairing technique can be developed.

Development of testing method and fault modeling for MEMS devices are made complicated by the multi-domain (electromagnetics, mechanical, thermal and others) nature of MEMS, the infinite possibilities of defects and the need to be familiar with the device fabrication process. However, once the common defects and their corresponding impact on the device response are known when a device fails the source of the defects can be quickly determined. In the following chapters, testing challenges, methodologies and self-repairing strategy for RF MEMS filter will be investigated.
3. Methodology

The work in this thesis focuses on developing fault models for the RF MEMS filter which can be used for identification defects from the filter defective response. From these work, a built-in-self-repairing strategy for the filter is then proposed.

This chapter describes the RF MEMS filter structure under investigation and how software simulation is used to study the common defects and their effects on the filter behaviour.

3.1 RF MEMS Filter under study

Radio Frequency Micro-Electro-Mechanical system or RF MEMS filter is a device that eliminates undesired frequencies from the received signal thus only allowing the desired frequencies to pass through it. RF MEMS filter is fabricated using micro-fabrication technology integrated with MEMS micro-switches which are used for tuning its frequencies.

The RF MEMS filter under investigation is a 3-pole Chebyshev bandpass filter [41] fabricated on a 0.52 mm thick quartz substrate with dielectric constant of 3.78. The microstrip on the filter is made of 0.003 mm thick gold with the conductivity of 40900000 S/m. The design of this filter is based on the half-wavelength hairpin resonator topology with three hairpin resonators connected to two feedlines for the input and output of the signal. The tips of each hairpin resonator can be extended with three narrow line segments with the length of 0.50 mm apart, which can be connected to each other using the RF MEMS switches. Figure 3.1 shows the layout of the RF MEMS filter under investigation.
The hairpin resonators are half wavelength of the required center frequency. The following is the formula for calculating the wavelength of the length value for center frequency of the hairpin resonator.

\[ \lambda = \frac{c}{f_c \sqrt{\varepsilon}} \]  

where \( \lambda \) is the wavelength of the resonator, \( c \) is the speed of light in meter per second, \( f_c \) is the center frequency of the resonator of the filter, \( \varepsilon \) is the effective dielectric constant. The half-wavelength of the resonator’s arm is calculated as 1/2 of the hairpin resonator wavelength.

The turns of the hairpin resonator are wider than the hairpin arms in order to reduce the resistance for the electrons that flow through the microstrip. As shown in Figure 3.2, the 0.05 mm wide narrow line segments at the tips of the hairpin resonator can be connected or disconnected using MEMS switch to alter the electrical length of the half-wavelength hairpin.
resonator. These segments are 0.05 mm apart, in accordance to the RF MEMS switch actuation size so that the switch pad is large enough to connect one narrow line segment to the adjacent narrow line segment. Connecting the narrow line segment at the tip of the hairpin resonator with second line segment will decrease the center frequency of the filter. With all the three narrow line segments connected together, the center frequency of the filter will decrease further.

A 50 ohms signal input feedline/tapline is connected to the first hairpin resonator through a thin line segment that act as an inductor to provide the required external quality factor for the filter. Similarly, a signal output tapline is connected to the last hairpin resonator through another thin line segment. The location of the tapline connected to the hairpin resonator is determined from the value of the external quality factor of the design specification of the filter.

![Diagram of narrow line segments, biasing line, grounding pads, grounding line of the RF MEMS switches that are located at the tip of the resonator.](image)

The following section is a step-by-step demonstration on how this filter is designed, starting from the design theory of a microwave filter.
3.2 Design Concepts for a microwave filter

The design theory of a microwave filter will be discussed, starting from its filter transfer function and its lowpass prototype. For a given filter specification, the design parameters will be explained. The final filter is a 3-pole Chebyshev bandpass filter as from reference [41], consists of hairpin resonators in microstrip structure. The filter is made tunable using Microelectromechanical systems (MEMS) switches. The design consideration for a tunable filter is given.

3.2.1 Filter Transfer Function

Two-port filter network characteristics can be written as an amplitude transfer function given as

\[ |S_{21}(j\Omega)| = \frac{1}{\sqrt{1 + e^2 F_n^2(\Omega)}} \]

where \( e \) is the ripple constant. \( F_n(\Omega) \) is the filtering characteristic function that will be described in the following section. \( \Omega \) is the frequency variable and is equal to 1 radian per second at the cutoff frequency.

The rational function for the linear time-invariant network is defined as follows:

\[ S_{21}(p) = \frac{N(p)}{D(p)} \]

where \( D(p) \) is a Hurwitz polynomial where the roots (or zeros) are located in the left half-plane of the complex plane. The roots of zero of \( N(p) \) may occur anywhere on the entire complex plane. The value of \( p \) which causes the function to become zero is the zero of the function. When the function \( S_{21}(p) \) to become infinite, the values of \( p \) in the denominator \( D(p) \) function are singularities (poles) of the function. When the function of \( S_{21}(p) \) becomes zero, the values of \( p \) in the numerator \( N(p) \) function are the roots of the function.
3.2.2 Chebyshev Response
Chebyshev response is used because it gives better selectivity, better equal-ripple passband and flatter stopband for the bandpass filter response compared to Butterworth response. The amplitude of the transfer function is as follows.

\[|S_{21}(j\Omega)| = \frac{1}{\sqrt{1 - \epsilon^2 F_n^2(\Omega)}}\]  

(4)

where \(\epsilon\) is the ripple constant that gives passband ripple \(L_{AR}\) in dB with

\[\epsilon = \sqrt{10^{\frac{L_{AR}}{10}} - 1}\]  

(5)

\(F_n(\Omega)\) is the first kind of order \(n\) Chebyshev function general formula taken from Rhodes [42] as follows.

\[F_n(\Omega) = \cos(n \cos^{-1} \Omega) \quad |\Omega| \leq 1\]  

(6)

\[F_n(\Omega) = \cosh(n \cosh^{-1} \Omega) \quad |\Omega| \leq 1\]  

(7)

Or use the Rhodes generalized rational transfer function as follows:

\[S_{21}(p) = \frac{\prod_{i=1}^{n} \left[\eta^2 + \sin^2\left(\frac{i\pi}{n}\right)\right]^{\frac{1}{2}}}{\prod_{i=1}^{n} (p + p_i)}\]  

(8)

where

\[p_i = j \cos \left[\sin^{-1} j\eta + \frac{\pi}{2n}(2i - 1)\right]\]  

(9)

\[\eta = \sinh\left(\frac{1}{n} \sin^{-1} \frac{1}{\epsilon}\right)\]  

(10)
3.2.3 Chebyshev Lowpass Prototype Filter

Chebyshev lowpass filter serves as a prototype for designing Chebyshev bandpass filter with frequency and element transformation. Hence, the element values in the Chebyshev lowpass prototype filter have to be calculated first before the design of the Chebyshev bandpass filter. The following Figure 3.3 showing the two forms of an \( n \)-pole lowpass prototypes for \( n \)-pole filter response.

![Diagram of Chebyshev lowpass prototype filters](image)

Figure 3.3 (a) Lowpass prototype filters for all-poles filter with a ladder network structure and (b) its dual.

The Chebyshev lowpass prototype filter transfer function is computed with the passband ripple \( L_{AR} \) and the cutoff frequency of 1. The lowpass prototype element values denoted as ‘\( g \)’ values can be computed using the following formula.

\[
g_0 = 1.0
\]

\[
g_i = \frac{2}{\gamma} \sin \left( \frac{\pi}{2n} \right) \quad \text{for } i = 1, 2, 3, \ldots, n
\]

\[
g_i = \frac{1}{g_{i-1}} \cdot \frac{4 \sin \left( \frac{\pi}{2n} (2i - 1) \right) \sin \left( \frac{\pi}{2n} (2i - 3) \right)}{\gamma^2 + \sin^2 \left( \frac{\pi}{n} (i - 1) \right)} \quad \text{for } i = 2, 3, \ldots, n
\]
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\[ g_{n+1} = \begin{cases} 1.0 & \text{for } n \text{ odd} \\ \coth^{2} \left( \frac{\beta}{4} \right) & \text{for } n \text{ even} \end{cases} \]

(14)

where

\[ \beta = \ln \left[ \cosh \left( \frac{L_{AR}}{17.37} \right) \right] \]

(15)

\[ \gamma = \sinh \left( \frac{\beta}{2n} \right) \]

(16)

where \( n \) is the number of the pole for the filter. The value of \( n \) can be determined by

\[ n \geq \frac{1}{\cosh^{-1} \Omega} \cosh^{-1} \sqrt{\frac{10^{0.1L_{AS}} - 1}{10^{0.1L_{AS}} - 1}} \]

(17)

where \( L_{AS} \) is the minimum stopband attenuation. Using the formula listed below to calculate the passband ripple, the minimum passband return loss is \( L_{R} \).

\[ L_{AR} = -10 \log \left( 1 - 10^{0.1L_{AS}} \right) dB \]

(18)

### 3.2.4 Tunable bandpass filter design

The bandpass filter consists of half-wavelength resonators folded into “U” shape. Due to its folded U-shape structure, it is commonly known as the “hairpin” resonator. This filter design is a tunable filter design. It is tuned using MEMS switches to reach the required center frequencies. The design of this filter includes a quartz material with dielectric constant of 3.78 and the thickness of the quartz is 0.52 mm. The targeted center frequencies are 10.0 GHz, 9.6 GHz and 9.3 GHz.

The device-under-test in this study is a 3-pole Chebyshev hairpin resonators filter design with a fractional bandwidth of 2.0% \((FBW=0.02)\) and a passband ripple of 0.01 dB. The values obtained from a normalized lowpass filter with cutoff frequency of 1 radian per second are \( g_0=1, g_1=0.6292, g_2=0.9703, g_3=0.6292 \) and \( g_4=1 \).
With these normalized values, the bandpass design parameters are then calculated using the following formulae:

\[ Q_{ei} = \frac{g_n g_{i+1}}{FBW} \]  \hspace{1cm} (19)

\[ Q_{eo} = \frac{g_n g_{n+1}}{FBW} \]  \hspace{1cm} (20)

\[ M_{i,i+1} = \frac{FBW}{\sqrt{g_i g_{i+1}}} \quad \text{for } i = 1 \text{ to } n-1 \]  \hspace{1cm} (21)

where \( Q_{ei} \) is the input signal external quality factor, \( Q_{eo} \) is the output signal external quality factor, and \( M_{i,i+1} \) is the coupling coefficient value between the resonators, \( n \) is the number of poles in the filter design, and \( FBW \) is the fractional bandwidth of the passband. Fractional bandwidth \((FBW)\) is calculated using the following equation:

\[ FBW = \frac{f_{2(-3dB)} - f_{1(-3dB)}}{\sqrt{f_{2(-3dB)} f_{1(-3dB)}}} \]  \hspace{1cm} (22)

where \( f_{2(-3dB)} \) is the upper limit of the -3 dB of the passband and \( f_{1(-3dB)} \) is the lower limit of the -3 dB of the passband.

For the given fractional bandwidth and normalized values, the calculated input quality factor \((Q_{ei})\) and output external quality factor \((Q_{eo})\) are both 31.46. The coupling coefficient between the first resonator and the second resonator \((M_{1,2})\) is 0.02560. The coupling coefficient value between the second resonator and the third resonator \((M_{2,3})\) is also 0.02560.

The guided wavelength of the microstrip filter is calculated using the formula (1). The half-length of the resonator is about a quarter length of the guided wavelength \( \lambda \). The width of the hairpin resonator is 0.5 mm, but the folding area has a width of 0.8 mm. The size of the hairpin resonator without the narrow line segment is 4.8 mm in length and 1.5 mm in width.

The three narrow line segments located on the tip of the resonator is for the tuning of the three different center frequencies. The width of the narrow line segments is 0.05 mm. The length of first narrow line segment is 0.50 mm. The length of second and the third narrow line segments
is 0.20 mm. The gap between the two narrow line segments has a size of 0.05 mm. This is needed for the implementation of the MEMS switches for tuning the length of the wavelength in the resonators together with the biasing line for the MEMS switches. The biasing line for the MEMS switches is designed together with the narrow line segments.

As for the biasing circuit for the MEMS switch, the biasing circuit is designed as far as possible from the narrow line segment. The biasing line should not be longer than ¼ of the wavelength of the filter; this is to prevent spurious resonant peaks occurring close to the desired filter’s center frequency.

**External quality factor** $Q_e$

The external quality factor for both the input and output are obtained using the tapline connected to the first resonator and a weak coupling at the output end, as shown in Figure 3.4. The $Q_e$ is calculated by varying the tap position $t$ as shown in the following figure.

![Figure 3.4 (a) Layout of the resonator to compute external quality factor value. $t$ is the tap position of the tapline. This layout will give the frequency response as in (b).](image)

The external quality factor is computed based on the simulated center frequency and the 3 dB bandwidth using the formula

$$Q_e = \frac{f_c}{f_{2(-3dB)} - f_{1(-3dB)}}$$

(23)
where $f_c$ is the center frequency of the passband, $f_{2(-3dB)}$ is the upper limit of the -3 dB of the passband and $f_{1(-3dB)}$ is the lower limit of the -3 dB of the passband. These three frequencies are marked in Figure 3.4(b) as an example. The external quality factors are plotted against the location of tapline on the resonator to obtain the following designed curve in Figure 3.5.

![Figure 3.5 External quality factor value versus tap position on the resonator.](image)

From the above diagram, the required tapping position, $t$ on the resonator is about 0.825 mm for the external quality factor value of 31.45.

**Coupling coefficient between resonators**

Coupling coefficient between two resonators is computed as a function of the spacing, $s$ between the resonators. The two resonators are loosely coupled to the input and output ports, as shown in Figure 3.6. The layout is simulated using the Sonnet EM software to obtain the output frequency response. Two resonant peaks can be obtained and the null between the two peaks should be between -30 dB to -40 dB.

The coupling coefficient values are computed as

$$M = \frac{f_{high}^2 - f_{low}^2}{f_{high}^2 + f_{low}^2}$$

where $f_{high}$ is the frequency of the higher peak and $f_{low}$ is the frequency of the lower peak in Figure 3.6(b). These coupling coefficient values are then plotted against the spacing between the two resonators as shown in the following Figure 3.7.
Figure 3.6  (a) Layout for measuring the coupling coefficient value between two resonators.  S is the spacing between the two resonators.  (b) Output frequency response that is given by the layout of the resonators.

Figure 3.7  Spacing between the resonators versus the coupling coefficient value between the first resonator and the second resonator.

The least-squares second- or third-order polynomial function can be fitted to the data shown in Figure 3.7.  The fitted curve should pass through the data points with very low residual error.  Hence, the $n$-th order polynomial function with a R-squared value of closest to 1 is chosen as the best-fit curve.
The required value of the coupling coefficient is 0.0256. The design specification of the filter requires 0.825 mm spacing between the resonators. This is the same for both the coupling coefficient values of $M_{1,2}$ and $M_{2,3}$.

**Simulation results**

After obtaining the required spacing between the resonators and the location for the tapline on the resonator, three of the resonators are arranged into the required layout together with the input and output taplines. With the shortened on the narrow line segments on the second resonator, the three poles hairpin resonator Chebyshev bandpass filter (Figure 3.1) with fractional bandwidth of 2% and ripple of 0.01 is obtained with the tuning center frequencies of 10.0 GHz, 9.7 GHz and 9.3 GHz as in the following Figure 3.8.

![Figure 3.8 Simulated results for output frequency response of the filter with all the tuning.](image-url)
3.3 MEMS Switch for RF Filter

MEMS switches are used to connect or disconnect the narrow line segment to tune the center frequency of the filter. The MEMS switch used for the filter under study was developed in [43] and is as shown in Figures 3.9 (schematic) and 3.10 (actual photograph). It is a direct contact type switch as opposed to capacitive type. The size of the switch is about 0.5 mm x 0.32 mm with the signal line width of 0.05 mm and thickness of 3 µm. The switch is built on the same substrate as the filter. Its contact bar is made of gold with resistance of about 2 ohms and is connected to the actuation pad through a thin dielectric membrane. The contact bar is held 1.2 µm above the two narrow line segments (labeled S in the Figure 3.9) of the filter. When a biasing voltage of 35 V is applied between the actuation pad and ground plate (labeled G), the pad together with the gold contact bar will be pulled down by electrostatic force, thus connecting the filter’s two narrow line segments. The switch shows isolation of 8 dB and insertion loss of 0.5 dB at 20 GHz. At cold switching, the lifetime of the switch is approximately $10^7$ cycles [44]. After that, wear and erosion occurs at the contact surface and causes the switch to fail. The lifetime of the switch during hot switching is $10^5$ cycles with the conduction of the current of 50mA [44].

The switches on the filter are divided into two sets. Set 1 consists of the switch with odd numbering and Set 2 consists of switch with even numbering as shown in Figure 3.11. When Set 1 switch is turn ON, the center frequency of the filter will be tuned to 9.6 GHz. When both Set 1 and Set 2 are turned ON, the center frequency will be further lowered to 9.3 GHz. The biasing lines of the RF MEMS also affect the filter behaviour because it is fabricated using the same material as the filter. The biasing lines were designed before adjusting the external quality factor values and the coupling coefficient values of the filters. Figure 3.11 shows the biasing lines together with the ground plate for Set 1 switches and Figure 3.12 shows the biasing lines together with the ground plate for Set 2 switches.
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Figure 3.9 Schematic view of the RF MEMS switch from Reference [43].

Figure 3.10 Photograph of the RF MEMS switch under inspection microscope [43].
Figure 3.11 Set 1 switches (red lines are the biasing line and the orange lines are the ground line).

Figure 3.12 Set 2 switches (red lines are the biasing line and the orange lines are the ground line).
3.4 Fault simulation and Modeling

The effect of different possible fault during fabrication and normal operation on the RF MEMS filter behaviour were investigated via simulation using Sonnet Suite Version 11.52 software [45]. From the simulation results, the faulty behaviours are classified according to their causes and their effects. This method of fault study is adopted from the inductive fault analysis approach proposed by Blanton et al. in [13] to study the defect and their effects on the comb-drive MEMS accelerometer. In their work, firstly the layout, the contaminations and fabrication process of the MEMS are input into a simulator to simulate the effects of contamination and fabrication process on the device structure. Then a finite element analysis is carried out to simulate the mechanical performance of the defective structure. Next, electrical simulation for the defective device is simulated using HSPICE. Finally, the misbehaviour classifications are done according to the structural defects, process step classification, probabilities of occurrence and mechanical and electrical misbehaviour of the device. With these data available, it was shown that future defects detection and rectification can be carried out quickly.

Similarly for studying the defects and faulty behaviour of RF MEMS filter in this work, first the possible structural defects such as broken structures and geometrical error due to defective fabrication process are introduced to the filter layout. Then, electromagnetic finite element analysis is performed on the faulty filter structure using Sonnet software for the S-parameter of the filter. Loss of tenability and performance degradation of the filter due to MEMS switch malfunction is also studied in similar manner. Mechanical and electrical analyses on the RF filter were omitted as RF MEMS filter operation is solely electromagnetic in nature. The faulty behaviours of the defective filter are then classified according to the cause of defects and effects on filter performance. This is a novel attempt on applying the inductive fault analysis on RF MEMS filter. Figure 3.13 shows the methodology undertaken by this work.

Through this study of the defects and the resulting faulty behaviour of the filter, it may enable:

1. Quick prediction of the type and location of defects in future by analyzing the behaviour of faulty filter. Rectification process can then take place.
2. Filter design to be improved to be less susceptible to common defects.
3. Development of self-test and self-repairing RF MEMS filter that could identify defects itself and perform in-chip rectifications. This will be demonstrated at a later part of this thesis.
Figure 3.13 Flow chart of the method used in this study.
3.5 RF MEMS Filter Defects

Admittedly, there are infinite possibilities of defects and combination of them. In this work, only the common MEMS defects as analyzed in Blanton et al. [13, 30-32] and MEMS switch failures which is the main cause of failure during normal operation are studied. These defects are discussed below.

3.5.1 Particulate Contamination

During fabrication process, unwanted materials may be introduced to the device to be fabricated. Common contamination includes chemical agents and base materials used and environment particulate. Contamination may cause the disappearance of parts of the structure leading to pitting (hole) on the surface and on a more severe note may lead to complete breakage of structure. Contamination may also add unwanted material that leads to small bridging or bonding of the structures. In this work, particulate contamination defect is simulated as small square pieces of gold particle randomly placed throughout the surface of the filter structure. For breakage, it is treated as structural omission in the filter layout.

3.5.2 Geometrical Variation

Geometrical or parametric variation is the deviation of the length, width and height of the filter structure from intended fabrication specification. The deviation may be caused during masking, electroplating and etching processes. Mask variation occurs when there is variation in the frequency, quality and exposure duration of the light-wave that is applied onto the photo resist mask [46]. Under-etching of the structure happens when the mask is smaller than the required dimension, therefore retaining unwanted parts on the structure. This may lead to complete filter failure if the under-etched area bridges the two separate components on the filter structure. Over-etching occurs when the masked area that is not supposed to be etched is accidentally etched away. This can happen when the photo-resist protection mask is too small or the concentration of the etching solution is too thick.

Geometrical variation at the filter’s narrow line segments affect its behavior mostly due to the segment relatively smaller dimension compared to the rest of the structure. Over or under-etching of the narrow lines may decrease or increase the quarter-wavelength of the hairpin resonator thereby changing the center frequency. In severe cases, over-etching may lead to
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broken structures especially at these lines such as the RF MEMS switch biasing line and the connection between the tapline and the hairpin resonator.

3.5.3 MEMS Switch Stuck-at-ON and Stuck-at-OFF
MEMS switch failure is perhaps the most probable defect which will occur during fabrication and normal operating time [47]. During the wet release stage in the fabrication process, the MEMS switch may get stuck-at-ON due to the strong capillary force that pulls down the contact pad onto the signal lines for the filter [47]. During normal operating times, repeated switching between the ON and OFF state accumulates the charges trapped on the substrate, generating electrostatic force. Over time, these charges are large enough to generate its own electrostatic force to hold the switch at ON state permanently even without any biasing voltage. The MEMS switch may get stuck-at-OFF during fabrication if there is a broken biasing line or incomplete release of the sacrificial layer between the contact bar narrow lines blocking their contact [47].

Switch stuck-at-ON is modeled as a short circuit between the narrow lines segments and the stuck-at-OFF is modeled as open circuit. A combination of multiple stuck-at-ON and stuck-at-OFF switch failures can be modeled in this work. But any combination of more than 3 switch failure is disregarded as the resulting faulty behaviour is indistinguishable. Moreover, once a switch fails usually the device is rendered useless.

3.5.4 Other Defects
Inter-metallic diffusion may occur on the RF MEMS switch as it is fabricated with two types of metal - gold and nickel. When inter-metallic diffusion happens, it increases the resistivity of the switch contact bar. Fortunately, the change in the resistance is insignificant and therefore the inter-metallic diffusion is not taken into consideration in this study.

Under-cutting of silicon substrate during etching is not common for the filter under investigation since the substrate for the filter is made of quartz. Under-cutting may only happen on the actuation pad and the contact bar of the RF MEMS switch. When under-cutting happens, cracks are observed on the actuation pad and on the contact pad. This might lead to the stuck-at-OFF fault on the switch.
3.6 Software and Hardware Used

Sonnet Suit Version 11.52 [45], high-frequency electromagnetic simulation software capable of simulating various layouts, for example, microstrip, printed circuit board, with vias - with any number of layers of metal traces embedded in stratified dielectric material and others. The software can simulate precise RF models for the S, Y and Z parameters for the layout of the microstrip filter structure based on Method-of-Moments EM algorithm. This analysis will take into consideration the parasitic effects, cross-coupling effects, enclosure effects and package resonance effects of the layout of the microstrip filter design. Sonnet Suite can also compute all the cross-talk, loss and self parasitic effects in the microstrip filter structure for the signal integrity of the circuit.

The layout of the microstrip filter structure is simulated using cell size of 0.005 x 0.005 mm\(^2\). The total size of the filter is 13.75 x 16.0 mm\(^2\) with 2750 x 3200 cells. The resistance of the signal input port and signal output port are both 50.0 ohms. The analysis is setup to obtain the output frequency response from 8.5 GHz to 12.0 GHz using adaptive sweep. The box resonances are also examined based on lossless empty cavity. A Dell Optiplex GX620 Pentium 4 with 4GB DDR2 SDRAM operated using Microsoft Window XP Professional is used for the simulation analysis. A typical simulation takes an hour to complete. The estimated memory used for this simulation is 539 MB with a total of subsection of 5371 as shown in Figure 3.14.

![Figure 3.14 Subsections of the filter's layout.](image-url)
Chapter 4

4. Simulation Results

In this chapter, the common MEMS defects discussed previously are simulated and their effects on MEMS filter response are studied. The simulation output of the filter’s S-parameters, specifically the return (S11) and the insertion loss (S21) parameters for frequency, ranges from 8.5 GHz to 11.5 GHz. The faulty behaviours are classified according to the nature of the defects and the effects that they bring about to the filter response.

4.1 Particulate contamination

Only particulate contaminations that potentially change the capacitive value of the main MEMS filter structure are taken into account in this simulation study. Therefore, particles with the size of less than 5µm in diameter are not considered as they were shown to be rather inconsequential due to the relatively small size as compared to the filter structure. In this work, 5µm gold particles are scattered randomly at different parts on the layout of the filter structure to emulate particulate contamination as gold is the most probable contaminations, since the main structure of the filter is fabricated using gold.

4.1.1 Particles away from the filter structure

Particles in the region further than 5µm away from the filter structure, as shown on grey in Figure 4.1 have no significant effect on the response of the filter as well because the particle cannot generate electromagnetic field that is large enough to affect the electromagnetic field
pattern of their main filter structure. This has been verified by randomly placing gold particle in this region, and all simulation results show the filter response is not affected.

Figure 4.1 The region further away from the main structure (grey colour). The particulate contamination in the grey areas will not show any effect on the output frequency response of the filter.

4.1.2 Particulate on the RF MEMS switch biasing lines
From simulation, it is shown that any particulate contamination on the biasing lines and area around them, as shown in grey in Figure 4.2 will not affect the response of the filter.

Figure 4.2 RF MEMS switches biasing lines are in the grey regions.
4.1.3 Particulate on the filter main structure
The main filter structures consist of the taplines, hairpin resonators and narrow line segments at the end of the resonators. The RF MEMS switch and biasing line are not considered here. Particulate contamination may lead to surface protrusion and side protrusion. All the MEMS switches are at the OFF state.

i. Taplines/feedlines
Figure 4.3 shows the layout of the signal input feedline with port 1 and output feedline with port 2. If particle contamination leads to surface protrusion on the edge of the dark grey region on the feedline, it may reduce the return loss from 25.5 dB to as low as 23 dB. If particle contamination occurs on the light grey regions, return loss may be increased to 26 dB. However, if contamination occurs in the white regions, the filter response is not affected. Particle contamination that causes protrusion on the side of the feedlines leads to a decrease in the return loss from 25 dB to 22 dB. If particle contamination appears next to the surface mount connector, it may bounce back the signal from the input/output line, leading to noise and therefore reduce the value of the return loss further.

![Figure 4.3](image)

Figure 4.3 Layout of the (a) input signal feedline with port 1 and (b) output signal feedline with port 2.

ii. Hairpin resonators
Any particle on the resonators that causes surface protrusion has insignificant effect on the frequency response of the filter. However, the particle that caused protrusion on the side of the resonator will lead to a formation of extra parasitic capacitance, affecting the response of the filter. Tables 4.1, 4.2 and 4.3 below detail the effect of contamination at the different resonators.

iii. Narrow line segments
Any particle contamination at the narrow line segments does not affect the response of the filter as long as the contamination does not impede the MEMS switch operation. The details are presented in Table 4.4. The MEMS switch contact pad is located about 1.2 micrometers above the narrow line. If the particulate contamination occurs on the line that is covered by the contact pad, the movement of the contact pad will be impeded, causing the filter to loose its tunability.
Table 4.1 Effect of particulate contamination at the first hairpin resonator.

<table>
<thead>
<tr>
<th>On the first hairpin resonator</th>
<th>S11</th>
<th>S21</th>
<th>Frequency shift</th>
<th>Remark</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tip of the resonator, far from the narrow line segments</td>
<td>11 dB – 15 dB</td>
<td>S21 decreases</td>
<td>Lower frequency</td>
<td>The increase in the length of the half-wavelength resonator leads to the decrease in the center frequency of the resonator.</td>
</tr>
<tr>
<td>The inside of the U-bend of the resonator</td>
<td>23 dB – 24 dB</td>
<td>No significant change</td>
<td>No significant shift</td>
<td>Only a minute change in the bending area.</td>
</tr>
<tr>
<td>The outside of the U-bend of the resonator.</td>
<td>14 dB – 20 dB (from the edge to the center of U)</td>
<td>S21 decreases</td>
<td>Higher frequency</td>
<td>The contamination acts as a capacitance that shifts the center frequency to a higher frequency value.</td>
</tr>
<tr>
<td>The connection between the tapline and the resonator</td>
<td>23 dB – 24 dB</td>
<td>No significant change</td>
<td>No significant shift</td>
<td>Only a minute change in the bending area.</td>
</tr>
<tr>
<td>Tip of the resonator, close to the narrow line segments</td>
<td>26 dB – 28 dB (from narrow line segment to the side of resonator)</td>
<td>No significant change</td>
<td>No significant shift</td>
<td>This actually improves the external quality factor of the input signal into the filter.</td>
</tr>
<tr>
<td>Side of the resonator tip</td>
<td>25 dB – 28 dB</td>
<td>No significant change</td>
<td>No significant shift</td>
<td>This actually improves the external quality factor of the input signal into the filter.</td>
</tr>
</tbody>
</table>

Note: Please refer to Figure 4.4 for the location of the particulate contamination on first hairpin resonator.
### Table 4.2: Effect of particulate contamination at the second hairpin resonator.

<table>
<thead>
<tr>
<th>On Second hairpin resonator</th>
<th>S11</th>
<th>S21</th>
<th>Frequency shift</th>
<th>Remark</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tip of the resonator, far from the narrow line segments</td>
<td>20 dB – 25 dB (from the hairpin edge toward the narrow line segment)</td>
<td>S21 decreases</td>
<td>Lower frequency</td>
<td>The increase in the length of the half-wavelength resonator leads to the decrease in the center frequency of the resonator.</td>
</tr>
<tr>
<td>The inside of the U-bend of the resonator</td>
<td>25 dB – 28 dB</td>
<td>No significant change</td>
<td>No significant shift</td>
<td>Minute change in the bending area. Does not change the overall output frequency response.</td>
</tr>
<tr>
<td>The outside of the U-bend of the resonator.</td>
<td>11 dB – 21 dB</td>
<td>No significant change</td>
<td>Higher frequency</td>
<td>Extra capacitance is introduced onto the bending area, thus shifting the center frequency to a higher frequency.</td>
</tr>
<tr>
<td>Tip of the resonator, close to the narrow line segments</td>
<td>24 dB – 20 dB</td>
<td>No significant change</td>
<td>No significant shift</td>
<td>Similar to the frequency response of the faultless filter. However, the coupling coefficient between the resonators is affected, hence the decrease in the S11 value.</td>
</tr>
<tr>
<td>Tip of the resonator, the side of the resonator</td>
<td>21 dB to 24 dB</td>
<td>No significant change</td>
<td>No significant shift</td>
<td>Similar to the frequency response of the faultless filter. This might have affected the coupling coefficient between the resonators, hence the decrease in the S11 value.</td>
</tr>
</tbody>
</table>
Table 4.3 Effect of particulate contamination at the third hairpin resonator.

<table>
<thead>
<tr>
<th>On the third hairpin resonator</th>
<th>S11</th>
<th>S21</th>
<th>Frequency shift</th>
<th>Remark</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tip of the resonator, far from the narrow line segments</td>
<td>18 dB - 23 dB</td>
<td>S21 decreases</td>
<td>Lower frequency</td>
<td>The increase in the length of the half-wavelength resonator leads to the decrease in the center frequency of the resonator.</td>
</tr>
<tr>
<td>The inside of the U-turn of the resonator</td>
<td>23 dB – 24 dB</td>
<td>No significant change</td>
<td>No significant shift</td>
<td>Minute change in the bending area.</td>
</tr>
<tr>
<td>The outside of the U-turn of the resonator</td>
<td>18 dB - to 21 dB</td>
<td>S21 decreases</td>
<td>Higher frequency</td>
<td>Extra structure acts as a capacitance that shifts the center frequency to a higher frequency value.</td>
</tr>
<tr>
<td>The connection between the tapline and the resonator</td>
<td>23d B – 24 dB</td>
<td>No significant change</td>
<td>No significant shift</td>
<td>Minute change in the bending area.</td>
</tr>
<tr>
<td>Tip of the resonator, close to the narrow line segments</td>
<td>26 dB – 28 dB (from narrow line segment to the side of resonator)</td>
<td>No significant change</td>
<td>No significant shift</td>
<td>It still has the same center frequency because this fault does not affect the coupling coefficient of between the second resonator and the third resonator.</td>
</tr>
<tr>
<td>Tip of the resonator, the side of the resonator</td>
<td>25 dB – 28 dB</td>
<td>No significant change</td>
<td>No significant shift</td>
<td>Improvement is insignificant, since the narrow line segment is much longer than the length of the particle.</td>
</tr>
</tbody>
</table>
Table 4.4. Effect of particulate contamination at the narrow line segments.

<table>
<thead>
<tr>
<th>Narrow line segments</th>
<th>Surface / Side protrusion</th>
<th>S11</th>
<th>S21</th>
<th>Frequency shift</th>
<th>Reason</th>
</tr>
</thead>
<tbody>
<tr>
<td>On narrow line segments covered by the contact pad</td>
<td>Surface (height &lt; 3µm)</td>
<td>No significant change</td>
<td>No significant change</td>
<td>No significant change</td>
<td>Insignificant if all switches at OFF state. However, this contamination impedes the switch contacting pad, thus leading to a stuck-at-OFF fault when switch needs to be turned ON.</td>
</tr>
<tr>
<td>On narrow line segments that is not covered by the contact pad</td>
<td>Side protrusion (&lt;10% of the width of the narrow line)</td>
<td>No significant change</td>
<td>No significant change</td>
<td>No significant change</td>
<td>No significant effect at any switching state.</td>
</tr>
<tr>
<td>Particulate contamination located in the middle of the gap of two narrow line segments.</td>
<td>Surface protrusion (&lt;10% of the width of the narrow line segments, and height does not impede the switch)</td>
<td>No significant change</td>
<td>No significant change</td>
<td>No significant change</td>
<td>No significant effect at any switching state due to the small size of the particulate contamination and the contamination does not join the two narrow line segments together to form a short circuit.</td>
</tr>
</tbody>
</table>
Figure 4.4 The location of the particle contamination on the first hairpin resonator.
4.1.4 Summary of the effect of particulate contamination

From the simulation analysis, it can be concluded that if the filter is contaminated by randomly scattering 5µm gold particles at the MEMS switch biasing circuit and at region more than 5µm away, the filter response would not be affected.

Particulate contamination leads to:

i. surface and side protrusion on the 50 ohm tapline, especially near the surface mount connector
ii. side protrusion on the tip of the hairpin resonator away from the narrow line segment, especially those hairpins adjacent to the tapline may lower the return loss.

Some contamination may increase the performance of the filter. This was observed when particle contamination leads to:

iii. side protrusion near the line segments of the first and third resonators hairpins’ tip
iv. the inner bend of the middle hairpin resonator

Due to symmetry, a side protrusion on the third hairpin resonator will lead to an almost similar filter response as to when a side protrusion occurs at the first resonator. Similarly, a side protrusion on the left arm of a resonator will bring about comparable response as to when a side protrusion occurs on the right arm.

Gold particle contamination of the diameter that is 5µm or less will not have any effect on the filter response if:

i. it occurs in the region further than 5µm away from the filter structure
ii. it occurs on the biasing lines
iii. it leads to surface protrusion on the filter
iv. it occurs at the narrow line segments (as long as the contamination does not impede the MEMS switch operation)
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4.2 Physical defects

4.2.1 Broken structures
Parts of the filter structure may be accidentally etched away when the photo-resist mask used is too small or the concentration of the etching solution is too thick. Over-etching may lead to the disappearing of parts of the filter, mainly at the narrow line segments due to their smaller dimension. If breakage occurs at the line segment that is connected to the resonator as shown in Figure 4.5(a), the filter will have deteriorated insertion and return loss. For example when all the switches are in the OFF state, the broken narrow line segment leads to return loss of about 7 dB and shifts the center frequency higher due to the decrease in the length of the resonator. The deterioration is especially noticeable when the breakage occurs in the second resonator, as shown in Figure 4.6 (a). Also, since the path from the resonator to the switch-able line segments is broken, the filter looses its tunability.

If the breakage occurs at the outer line segment as shown in Figure 4.6 (b), the filter is still tunable though it may suffers minor performance deterioration. Breakage in the middle line segment is not considered as the MEMS switch contact pad may be large enough to reconnect the break.

Figure 4.5 (a) Broken line segment near the tip of the hairpin resonator. (b) Broken microstrip line on the narrow line segment further away from the hairpin resonator.
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Figure 4.6 Return loss (a) and insertion loss (b) curves of the filter with breakage on the first narrow line segment on different resonators. Breakage at the second resonator causes most deterioration.
4.2.2 Short circuit

Though highly unlikely, short circuit caused by under-etching may happen at the gap between the grounding pad of the MEMS switches’ actuation pad and the narrow line segments as this location has the smallest gap in the whole structure. When this happens, the current that flows through the resonator into the narrow line segments will be grounded before it reaches the end of the tip of the microstrip filter narrow line segment, causing complete filter failure.

![Figure 4.7](image) Under-etching causing short circuits at different part of the narrow line segments. Black dots represent short circuit caused by under-etching.

4.2.3 Parametric variations

Geometrical errors of between ±15µm on the filter structure caused by etching variation have been simulated. Analysis of the filter response shows that geometrical errors on the hairpin resonator, narrow line segments, taplines and biasing lines only shift the center frequency by 1% at most and cause minor reduction in the return loss.

This is mainly due to the relatively large dimension of the filter structure when compared to the potential geometrical error. Moreover, since in actual fabrication the geometrical variations will be much less than ±15µm, this error may be safely ignored.
4.3 MEMS Switch Failure

MEMS switch failure is perhaps the most probable defect which will occur during fabrication and normal operating times [47]. During the wet release stage in the fabrication process, the MEMS switch may get stuck-at-ON due to the strong capillary force that pulls down the contact pad onto the signal lines of the filter [47]. During normal operating times, repeated switching between the ON and OFF state accumulates the charges trapped on the substrate, generating electrostatic force. Over time, these charges are large enough to generate its own electrostatic force to hold the switch at ON permanently even without any biasing voltage [47]. The MEMS switch may get stuck-at-OFF during fabrication if there is a broken biasing lines or incomplete release of the sacrificial layer between the contact bar and narrow lines blocking their contact.

Switch stuck-at-ON is modeled as a short circuit between the narrow lines segments and stuck-at-OFF is modeled as an open circuit. A combinations of multiple stuck-at-ON and stuck-at-OFF switch failures can be modeled but in this work, any combination of switch failure is disregarded as the resulting faulty behavior is too complicated to generalize. More importantly, once a switch fails, usually the device is rendered useless. In addition, though not shown here it was found that if two or more switches are stuck-at-ON / OFF the response of the filter will be dominated by the most deteriorated response of the individual defective switches. Therefore, only analysis of one single switch failure is taken into consideration.

If a MEMS switch which is supposed to be OFF but it got stuck at ON, it causes the length of the resonator to become longer and hence decreases the center frequency of the filter. For example, all switches should be turned OFF to tune the filter center frequency to 10GHz but if switch 1 is stuck-at-ON, the center frequency drops to 9.85GHz. Similarly, any switch which is stuck-at-OFF will increase the filter center frequency. This effect is especially apparent if the defective switch is on the middle hairpin resonator. Since the even number MEMS switches (2, 4, 6, 8, 10 and 12) only connect the outer line segments to the hairpin resonators when the odd number switch (1, 3, 5, 7, 9 and 11) is ON, any defective even number switches will only shows up when the all the odd switches are connected first.

Table 4.5 shows the simulated parameters of the filter when switch is stuck-at-ON. In this table, the defective even number switches are considered when the filter is on 9.6 GHz settings (all odd switches are ON). The defective odd number switches are considered when the filter is on 10.0 GHz settings (all switch are OFF). From the table due to symmetry of the filter design, defects
in the pairs of switches (1, 11), (2, 12), (3, 9), (4, 10), (5, 7) and (6, 8) produce similar
deterioration in the bandwidth and center frequency and the filter exhibits similar insertion loss.
Defects in the middle hairpin (5, 7) and (6, 8) switch pairs even produce similar return loss
curve.

Table 4.5 Summary of the output frequency response of single stuck-at-ON fault of each switch.

<table>
<thead>
<tr>
<th>Switch no.</th>
<th>Lower -3 dB (GHz)</th>
<th>Upper -3 dB (GHz)</th>
<th>Center frequency (GHz)</th>
<th>S11 (dB)</th>
<th>S21 (dB)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>9.695</td>
<td>10.018</td>
<td>9.8565</td>
<td>3.3</td>
<td>4.796</td>
</tr>
<tr>
<td>7</td>
<td>9.633</td>
<td>10.028</td>
<td>9.8305</td>
<td>3.071</td>
<td>5.03</td>
</tr>
<tr>
<td>11</td>
<td>9.693</td>
<td>10.017</td>
<td>9.855</td>
<td>4.8</td>
<td>5.371</td>
</tr>
<tr>
<td>2</td>
<td>9.335</td>
<td>9.651</td>
<td>9.493</td>
<td>3.45</td>
<td>5.0</td>
</tr>
<tr>
<td>6</td>
<td>9.3</td>
<td>9.664</td>
<td>9.482</td>
<td>4.87</td>
<td>3.64</td>
</tr>
<tr>
<td>8</td>
<td>9.299</td>
<td>9.663</td>
<td>9.481</td>
<td>4.81</td>
<td>3.65</td>
</tr>
</tbody>
</table>
4.4 Limitation of the analysis

Admittedly, the analysis carried out above was focused on the specific 10 GHz hairpin filter design. Generalization on the effects of the defects on a common filter will be far too complex and will require a much more extensive work. This work however, successfully demonstrates how the analysis on a defective MEMS filter can be conducted. The analysis on defective filter response carried out in this chapter has:

1. identified the possible effects from the different defects in the filter
2. revealed the depth of impact of each defect, which would allow designer to optimize design in certain area (e.g. tip of hairpin resonators must be accurate and free from geometrical error while surface inaccuracy can be tolerated)
3. allowed the defects to be identified, or at least the general location and type of the defect that causes the filter faulty behavior
4. showed that symmetry of the filter design may hide many defects
5. led to the development of BISR (later chapter) in case of MEMS switch failure which can be replicated for study into other filter structures.

This analysis does not take into account the combination of two or more faults that may occur simultaneously. Also, the exact cause and location of the faults cannot be accurately pinpointed by just looking at the defective response alone. Nevertheless through this work, it offers a good first guess on the possible causes of the faulty behavior and leads the search for the fault.

In future, a probabilistic design can be used to simulate the effects of the combination of faults on the behaviors of the device. This is further discussed in Chapter 6 in the future work for this study.
5. Built-In Self Repairable Design

This chapter presents a tunable filter design that is able to “self-repair” or maintain normal operation even though the MEMS switches that are used to tune the filter have failed after a long operating cycle. Some of the filter structural parameters such as length of narrow line segments have to be optimized to minimize filter performance degradation once the self-repair mechanism is in effect.

The design of a Built-In Self Repairable (BISR) MEMS device was notably investigated by Xiong et. al. for a microaccelerometer [14, 40]. In the design, the microaccelerometer sensing structures are separated into modules where each module can be turned OFF when it fails. To compensate for the loss of the sensing modules, the device turns to redundant modules which were added into the microaccelerometer from the beginning of its design.

For the RF MEMS filter, after a long operating cycle the MEMS switches used in the filter are the most probable defects that may occur. The switches either fail to switch or stuck at ON even when no actuation voltage is applied due to dielectric charging or stiction force holding the switch contact down, shorting the filter’s narrow line segments. This failure usually occurs after hundreds of million switch cycles. When this happens, the filter response changes and it lost its tunability. In this chapter, the tunable RF filter is redesigned so that it can ‘repair’ itself in the event of switch failure through redundant MEMS switch.
5.1 Symmetry and Redundancy

The RF MEMS filter designed in this work has symmetries at the switches on the hairpin resonators’ end. For example in the first resonator, the Switch 3 and 4 are at symmetry with Switch 1 and 2. Therefore, switching Switch 1 ON produces the same effect as switching Switch 3 ON, and switching Switch 1 and 2 ON is the same as switching Switch 3 and 4. This makes Switch 3 and 4 the potential ‘redundant’ switches that can be used to ‘repair’ Switch 1 and 2 later. Simulation results in Figure 5.1 below shows that Switch 3 and 4 produces similar filter response to Switch 1 and 2.

Figure 5.1 Insertion loss when Switch 3, 5, and 9 are ON is similar to when Switch 1, 5, and 9 are ON.

Figure 5.2 Insertion loss when Switch 1, 2, 5, 6, 9, and 10 are ON is similar to when Switch 3, 4, 5, 6, 9 and 10 are ON.
Similarly, Switch 7 and 8 can replace Switch 5 and 6, and Switch 11 and 12 can replace Switch 9 and 10. Note however, as shown in Figure 5.2, that the filter response is not exactly the same when the ‘redundant’ switches are used, and some fine-tuning of the filter structure is needed to ensure similar performance is retained.

5.2 Filter Redesign with BISR

The filter was designed to switch between 9.3GHz, 9.6GHz and 10GHz. However, by using the symmetry and ‘redundant’ switching as suggested above, the filter switched between 9.6GHz, 9.8GHz and 10GHz. Therefore, the layout of the filter needs to be reconsidered to reposition the center frequency, and fine-tuning measures added to make the filter perform similarly when redundant structures are in effect. Before redesigning the filter, the biasing line for each of the MEMS switches has to be separated so that each of the switches can be independently biased. The grounding line for the switches remains the same.

5.2.1 Hairpin Resonator

In order to redesign the filter, the resonators are separated and considered individually. Starting with the first resonator, the length of the second and third narrow line segments are adjusted to obtain the desired center frequency where:

a. 10 GHz without any switching  
b. 9.6GHz when either Switch 1 or 3 is ON  
c. 9.3GHz when either Switch 1 & 2 or Switch 3 & 4 are ON

In order to reduce the required length of the second narrow line segment that is connected to Switch 3, a low impedance area in the middle of the second narrow line segment is introduced. For the same purpose, a low impedance area is also introduced onto the tip of the third narrow line segment connected to Switch 4. Figure 5.3 shows the amended layout.

Similarly, the second resonator’s line segments are adjusted to obtain the right center frequency. However, since the required narrow line segments are not as long as that required by the first resonator, the low impedance area are not introduced for designing the second resonator. Figure 5.4 shows the layout of the second resonator together with its MEMS switch biasing lines. Figure 5.5 shows amended the third resonator.
Figure 5.3 (a) Layout of the filter’s first hairpin resonator together with input signal tapline and weak coupling on the output signal tapline. (b) The zoomed in on the MEMS switches biasing circuit and the adjustment of the narrow line segments on the first hairpin resonator.

Figure 5.4 (a) Layout of the filter’s second resonator with weak coupling for both the input and output signal taplines. (b) Highlight the adjustment of the narrow line segments.
5.2.2 External quality factor value and Coupling Coefficient value

Figure 5.6 shows the layout of the filter structure used to measure the external quality factor of the input and output signal. The external quality factor, \( Q_e \), is calculated using:

\[
Q_e = \frac{f_c}{f_{2(-3dB)} - f_{1(-3dB)}}
\]

(25)

where \( f_c \) is the center frequency of the passband, \( f_{2(-3dB)} \) is the upper limit of the -3 dB of the passband and \( f_{1(-3dB)} \) is the lower limit of the -3 dB of the passband. The external quality factors are calculated and plotted with respect to \( t \), which is the distance between the base of the hairpin resonator to the location of the signal tapline on the resonator for both the input signal tapline and the output signal tapline. From the result is shown in Figure 5.7, the external quality factor of the input signal and the output signal are slightly different from each other. This is because the first and third hairpin resonators have slightly different structure. A \( t \) of less than 0.8 mm is used for the design of the input, but a slightly shorter \( t \) of less than 0.75 mm is used for the output. This \( t \) value is chosen for the required external quality factor that is calculated from Equation 25.
Figure 5.6 Layout of the filter’s hairpin resonator together with the signal tapline for weak coupling to determine the external quality factor value for both (a) the input signal tapline into the modified first hairpin resonator, (b) the output signal tapline from the modified first hairpin resonator. $t$ is the tap position of the tapline on the resonator.

Figure 5.7 External quality factors, $Q_e$ of the modified resonator versus the length of $t$ for (a) input signal external quality factor and (b) output signal external quality factor of the filter.
To measure the coupling coefficient against the gap between the resonators, the layout shown in Figure 5.8 is used. All the switches are OFF. The coupling coefficients between the hairpin resonators, $M$, are calculated using:

$$M = \frac{f_{\text{high}}^2 - f_{\text{low}}^2}{f_{\text{high}}^2 + f_{\text{low}}^2}$$  \hspace{1cm} (26)$$

where $f_{\text{high}}$ is the frequency of the upper peak and $f_{\text{low}}$ is the frequency of the lower peak. These coupling coefficient values are then plotted against the spacing between the two resonators as shown in the following Figure 5.7.

![Figure 5.8 Layout of the structure for measuring the coupling coefficient between the two resonators: (a) between first and second resonators, (b) between the second and third resonators.](image)

As shown in Figure 5.9, the coupling coefficient between the first and second resonators is different compared to the coupling coefficient between the second and third resonators. This is because the third resonator designed is slightly different from that of the first resonator. Note that the decrease in the coupling coefficient due to the biasing of the MEMS switches is not taken into consideration of the design. A gap of less than 0.8 mm between the first and second resonator is used whilst a gap of less than 0.7 mm between the second and third resonators is used to achieve a coupling coefficient of more than 0.020. This is to fulfill the design requirement for the original 3-pole Chebyshev filter.
Figure 5.9 (a) Graph of coupling coefficient value between the first and the second resonators versus the width of the gap between them. (b) Graph of coupling coefficient value between the second and the third resonators versus the width of the gap between them.

The redesigned filter is then fine tuned through simulation using Sonnet by:

a. adjusting the location of the signal tapline
b. moving the resonators closer to each other, decreasing the gap and thus enhancing the external quality factor and the coupling coefficient between the resonators
c. increasing or decreasing the narrow line segment length and low impedance area until an optimized filter response is obtained. The final filter design is shown in Figure 5.10.
5.3 Performance of the Redesign BISR Filter

With the redesigned filter, we aim to achieve a center frequency of:

a. 10.0 GHz, where all the switches are OFF.

b. 9.6 GHz, where Switch 1, 7 and 9 must be turned ON, with Switch 3, 5 and 11 acting as the redundant or backup switch.

c. 9.3 GHz, where Switch 1, 2, 7, 8, 9 and 10 must be turned ON, with Switch 3, 4, 5, 6, 11 and 12 acting as the redundant or backup switch.

Simulation results show that the redesigned filter behaves similarly to the original filter design. Figure 5.11 illustrates that in the redesigned filter, the return loss produced using the intended switches is the same as using the redundant switches. The insertion loss of the filter shows the similar characteristics as shown in Figure 5.12.

To demonstrate the BISR mechanism, Figure 5.13 shows that when Switch 1 fails to switch ON, reverting to Switch 3 will produce similar filter response. Similarly, when both Switch 1 and 2 fail to switch ON, turning to Switch 3 and 4 will maintain the filter response as shown in Figure 5.14. To demonstrate the redundancy technique when there is a stuck-at-ON switch failure, consider the filter when it returns from switching state (1, 2, 7, 8, 9, 10) to (1, 7, 9) but Switch 2 is stuck-at-ON. To overcome this problem, Switch 1 can be turned off the remove the effect of failed Switch 2. Then Switch 3 is turned ON to generate effectively the switching set (3, 7, 9) which, as Figure 5.13 has shown, produces the same response as (1, 7, 9).

Unfortunately, this redundancy technique would not be able to maintain the filter response if Switch 1, 7 or 9 is stuck-at-ON. To make the BISR works for all switch failure, the filter needs complete redesign. However, it does demonstrate how symmetries and redundancies in filter design can be exploited for BISR.
Figure 5.11 Return loss of the redesign filter with intended switches turned ON (1, 7, 9, and 1, 2, 7, 8, 9, 10) is similar to when the redundant switches (3, 5, 11 and 3, 4, 5, 6, 11, 12) are turned ON.

Figure 5.12 Insertion loss of the filter with intended switches turned ON (1, 7, 9 and 1, 2, 7, 8, 9, 10) is similar to when the redundant switches (3, 5, 11 and 3, 4, 5, 6, 11, 12) are turned ON.
Figure 5.13 Insertion loss when switches 1, 7, and 9 are ON and it is comparable to the response when switches 3, 7, and 9 are ON.

Figure 5.14 Insertion loss when switches 1, 2, 7, 8, 9 and 10 are ON and it is comparable to the response when switches 3, 4, 7, 8, 9 and 10 are ON.
5.4 Simplified BISR Filter design

A faster method is needed for designing a simpler BISR function for the filter. As a result, a simpler procedure for the design is studied in this chapter. This simpler method is less time consuming. This method will obtain the same output frequency response as the output frequency response from the filter that is designed using the former method. The method here will make the backup / redundant structure on the filter looks identical in shapes and sizes to the original structure.

The original biasing lines for the MEMS switches of the original filter are removed. The separate biasing lines for controlling each of the MEMS switches are introduced into this filter. Analysis from the last redesigned filter shows that there are similarities between the output frequency response of when switches 1, 7 and 9, are ON and when switches 3, 5 and 11 are ON. Another similarity between the output frequency responses is when switches 1, 2, 7, 8, 9 and 10 are ON and when switches 3, 4, 5, 6, 11 and 12 are ON. Hence, this filter with a modified biasing line can be used as the basic design of the BISR filter using “redundant structures” method.

An adjustment on the length of the second narrow line segments in all the resonators is done to increase the center frequency of the filter with switching condition of 1, 7, 9 and switching condition of 3, 5, 11 to 9.6 GHz. In addition to the increase in the length of the second narrow line segments, the third narrow line segments of all three resonators are lengthened. This will tune the center frequency to about 9.3 GHz for the switching condition of 1, 2, 7, 8, 9, 10 and 3, 4, 5, 6, 11, 12 biased to ON state. The insertion loss at the center frequency of 9.3 GHz is about 7 dB for both switching conditions. The center frequency for all switches at the OFF state still remains at 10.0 GHz.

Next, the location of the tapline is adjusted using the external quality factor illustrated in Figure 5.6. The width of the gaps between resonators is adjusted using the coupling coefficient value in Figure 5.8. The final simplified and modified tunable bandpass filter with the BISR function layout is shown in the following Figure 5.15 together with the enlarge view of the “redundant structures” for this simplified BISR filter. The return loss (Figure 5.16) and the insertion loss (Figure 5.17) of the simplified BISR filter are similar to the simulation results obtained from the former BISR filter.
Furthermore, when this modified filter with BISR function is used as a tunable bandpass filter, the center frequency obtained from three tuning ranges agrees with the center frequency from the calculation of the length of the resonator using the half-wavelength resonator.

Figure 5.15 Layout of the filter with BISR function designed using the “redundant structures” method. The zoom in view is the “redundant structures”.

Figure 5.16 Return loss for the simplified BISR filter with all tuning/switching conditions.
Figure 5.17 Insertion loss curve for the simplified BISR filter with all the required switching conditions.

The method proposed above for designing the filter with simplified BISR function is plausible. This filter is designed with separate biasing circuit line for each of the MEMS switch for the individual control of the switches. The length of the narrow line segments for both arms of the hairpin resonators are adjusted equally to achieve the required tuning center frequency.
5.5 Limitation of the BISR Filter design

5.5.1 Filter design specific
This classification can only be used for this specific tunable filter. The findings cannot be generalized to other tunable filter. The most important structures in this tunable filter are the switching area and the MEMS switches. The switching areas are the narrow line segments and the functionality of the MEMS switches. A small change in the filter design will affect the output frequency response of the filter other than the changes on the MEMS biasing line. Hence, any changes in the design of the filter or the MEMS switches might change the effects of the fault on the filter. The whole process of mapping the fault and effect has to be done on the filter with the small changes.

5.5.2 Combination of two or more faults
This analysis does not take into account the combination of two or more faults that happen on the filter simultaneously, and also on different locations of the faulty filter. This analysis will be able to detect the combine fault of the stuck-at-on and stuck-at-off fault only. These combined faults have to be tested using three of the filter settings, that is, for tuning to the center frequency of 10.0 GHz, 9.6 GHz and 9.3 GHz.

The other kind of faults such as particulate contamination, broken structures, short circuit and parametric variations can only be properly detected if it is a single fault occurring on the filter at one time. If the combined faults are required for this testing, a new set of combined faults testing has to be done using the required combined faults.

5.5.3 BISR Filter has to be implemented with another external system
These BISR filters have to be implemented together with another external system that is able to record the number of cycles that is being used by the MEMS switches. When the mean number of the switches’ lifetime cycles has reached its limit, the redundant structures of the whole filter will function as the main structures for tuning the filter. In addition, the main switches will be switched off completely and will not be used from that time onwards. Hence the lifetime of the external system has to be longer than the lifetime of the BISR filter.
Chapter 6

6. Conclusions and Future Works

6.1 Defects and Their Effects on RF Filter

The common defects on a tunable RF MEMS filter have been simulated and their effects on the RF filter response are analyzed. The filter under investigation is a newly designed 3-pole Chebyshev bandpass filter which switches between 9.3GHz, 9.6GHz and 10GHz. The defects that have been analyzed in this study are:

- a. gold particulate contamination
- b. geometrical variation which includes broken structure and short circuit
- c. MEMS switch stuck-at-ON and OFF

As expected, rather than obtaining specific faulty filter response with respect to individual defect, different general filter performance deterioration are observed with different nature of the defects. Therefore, rather than pinpointing the exact defects that cause the faulty response analyzing the faulty response can help the defect identification process by narrowing down the potential suspects. The study also enables the impact of each defect to be known, thus helping the designer to control sensitive design / fabrication parameters.

In future, a more general fault model for the tunable filter can be developed which also take into account overlapping multiple defects. The final aim is to provide accurate guesses to the defects that cause the faulty filter response.
For future works, a probabilistic design as in Figure 6.1 can be used to simulate the effects of the combination of faults on the behaviors of the device. The probabilistic design system analyzes uncertain parameter input of a system. These input parameters are the fault from geometrical variations (width of resonator, length of resonator, width of narrow line segment, length of narrow line segments, width of 50 ohms feedline, and width of the gap between two resonators), location of particulate contamination, stuck-at-on fault on switches and stuck-at-off fault on switches. These parameters are defined as random input variables and are characterized by their type of distribution and measurements in mean and standard deviation. The key outputs of the simulation are defined as random output combination of several faults on the filter. With the random output of the combined faults on the filter via Monte Carlo simulation, the most probable occurrence combination faults will be generated together with the probability value. This combination of faults on the filter is simulated to obtain the simulated output frequency response. Using the list of most probable occurrence combination of faults, the measured output frequency response can predict the possible faults on the faulty filter. The following is the schematic diagram on the proposed working of the probabilistic design system as referred earlier.

![Schematic diagram](image)

Figure 6.1 Schematic on the proposed working of Probabilistic Design System.
6.2 BISR Design

The second part of this work has demonstrated that the symmetries and redundancies in the filter design bring about the possibility of a Built-In Self Repairable mechanism to be developed for the device. To preserve the performance of the BISR filter, minor design parameters such as length of resonator’s end, low impedance patches and feedlines location have to be retuned.

For future work, the technique should be tested on real filter with the BISR implementation for all possible combination of switch failures. A microcontroller can be used to implement the scheme.
References


List of Publications


