3-D Printed Heterogenous Substrate Bandpass Filters

Division of Engineering Programs

Master of Science Thesis

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A thesis presented to State University of New York at New Paltz
In Partial Fulfillment of the Requirements for Master of Science in Electrical Engineering

Fall 2021
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Approved on September 24, 2021
Submitted in partial fulfillment of the requirements for Master of Science degree in Electrical and computer Engineering at State University of New York at New Paltz
Dedication

This thesis would not have been made possible without the love and support of my parents, Munther and Nancy. All thanks be to our Savior Jesus Christ for the guidance, strength and health needed to complete this thesis according to his will.
Acknowledgements

I would like to express my sincerest appreciation for my thesis advisor, Dr. Reena Dahle for giving me her undying support regardless of the issue at hand. Her professionalism and motivation continue to inspire me ever since the beginning of my college career. I would also like to thank the members at the Dept. of Science and Art for their assistance with chemical supplies and vinyl cutting. A special thanks is also given to my colleague Vito Ciraco for his professional opinion.
Abstract

With the demand for increasing frequencies in today’s communications systems, compact integrated circuits are challenging to achieve. Compact filters have typically been realized by modifying the circuit design including using LC resonators, defective ground structures, and adjusting the length ratios of resonators. Heterogenous substrates with controlled regions of dielectric loading offer a new design approach when it comes to manufacturing an RF component. In this thesis, additive manufacturing is used to selectively place low-K and high-K dielectric materials to achieve a compact form factor, improved bandwidth, and higher suppression in re-entry modes. First, microstrip coupled strip lines are simulated to model the basic coupling effects of loading a substrate. Next, three 2.45GHz parallel coupled bandpass microstrip filters are designed with differing substrates: low-K, high-K and high-K loaded to analyze the impact of loading within the substrate. The filter substrates are manufactured using a dual-extrusion FDM 3-D printer to combine both dielectrics, low-K ABS, and high-K PrePerm ABS1000, into a single heterogeneous substrate. Compared to the low-K dielectric alternative, the high-K loaded filter demonstrated a 30.8% decrease in length, while maintaining similar bandwidth and suppression of re-entry modes. Compared to the high-K filter, the high-K loaded filter showed a 9.4dB reduction in re-entry mode suppression, while maintaining similar footprint size.
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Chapter 1

1. Introduction

1.1. Motivation

In modern and wireless communications systems, the need for compact integrated circuits is needed to meet the demand for increasing frequencies. Issues with manufacturing and EMI become the major concerns when producing these compact circuits. Solutions to these problems normally include expensive high precision manufacturing equipment or shielding materials to block interfering electromagnetic radiation. Compact filters have typically been realized by modifying the circuit design by using LC resonators, defective ground structures, and adjusting the length ratios of resonators. Another alternative cost-effective solution is to control the dielectric constant of the substrate. This is achieved by selectively loading certain areas of the substrate, creating a heterogenous substrate. Previous technologies struggled to effectively manufacture a multi-material substrate due to complications in manufacturing. One attempt at producing loaded substrates were studied previously by [1], using an apparatus with an open slot in the base substrate. This open slot was used to add in a separate block of dielectric material and systematically test the responses. Another attempt from [2] includes two separate substrates connected via copper tape. The major concerns with these approaches are the manufacturing challenges introduced such as the intrusion of air gaps between the sides of the slotted piece and the inability to easily change the location of the slot. With the advancement of additive manufacturing, a new generation of 3-D printing techniques and materials have enabled realization of complex geometries. Using dual extrusion, an integrated heterogenous substrate can be created that consists of varying dielectric materials.
1.2. Scope

Controlling the dielectric constant as a function of location within a substrate gives the designer greater flexibility. The RF device can be made compact or larger to account for limited footprint or limited resolution capabilities. As the dielectric constant is decreased, the guided wavelength of operation increases which directly increases the size of the circuit, and vice versa. The approach is to strategically load the substrate in the areas that have the largest impact on performance or size. As reported in [3] and [4], it is shown that loading the areas with high electric field density will have the greatest effect. Two microstrip devices are designed to evaluate the impact of a heterogenous substrate. First, coupled microstrip lines were chosen for their simplicity and ability to directly measure coupling between two conductors. Then a parallel coupled bandpass filter was designed and crafted to show how manufacturability can be improved with minimal compromise in performance. Both devices utilized dual extrusion 3-D printing technology to combine the effects of low-K and high-K substrates. This effectively reduces the cost of manufacturing and design, reduces the footprint, and decouples undesirable internal resonances within the device for stronger rejection in the re-entry modes. The microstrip lines were simulated and designed for 2.45GHz using Keysight ADS and a 3-D EM Software and manufactured using various techniques [5].
1.3. Overview

Chapter 2 provides a background on filter designs and some applications of 3-D printing in RF component design. Next, in chapter 3, the design and simulation of the coupled microstrip lines is presented. Chapter 4 discusses the different filter designs, whereas Chapter 5 presents the manufacturing process. Chapter 6 discusses the results obtained for all the designs and provides a comparison of all the designs’ dimensions and RF performance. Finally, chapter 7 provides conclusions and discusses future work.
Chapter 2

2. Literature Survey

2.1. Microwave Filters

A microwave filter is a two-port passive device that prevents unwanted signals and noise from entering a system, while maintaining strong signal integrity. This is especially useful in wireless communications or RF circuits, where a specific band of frequencies are utilized, and unwanted noise is rejected. Proper specifications of a filter include low loss, low cost, constrained dimensions and large data bandwidth. The overall performance of a filter can be described by the efficiency of the passing signal, the loss of the rejected signal, and the frequency bandwidth of operation. Shown in Figure 2.1, there are many types of responses that a filter can output based on its design. Each application will require a specific type of filter, or even combination of filters.

![Low pass lumped element filter circuit](image)

*Figure 2.1. Low pass lumped element filter circuit [6].*

A common configuration for a filter is to cascade a low pass and bandpass filter to maintain the bandwidth of the bandpass filter while also suppressing higher frequency resonant modes. It is generally used in applications that focus on a specific band of frequencies such as Wi-Fi communications. Filters are generally compared by their operational frequency, bandwidth,
insertion loss, package size and power capabilities. Not all filters are created equally, each type of filter has its own advantages and disadvantages. Some common types of microwave filters include lumped LC, microstrip and waveguide filters.

2.1.1 Lumped LC Filter

The lumped LC filter is the simplest type of filter consisting of real inductors and capacitors. Figure 2.2 illustrates a low pass filter of an “nth” order. Each additional order improves the cut-off response but also increases the length of the overall filter and its associated insertion loss.

Even though the lumped element filter is relatively easy to manufacture, the performance of the filter depends on the specifications of the components’ dimensions and self-resonant frequency, or SRF. At a certain frequency, capacitors and inductors will reach their self-resonant frequency and negatively affect the performance of the filter. This is usually combated by higher specification thin-film components that raise the SRF to around 15GHz in the Ku band [8]. However, this is not the most ideal solution since most lumped element components suffer from high loss and low tolerance manufacturing at higher frequencies. Additionally, the distance between each component is no longer negligible. A solution would be to utilize Richard’s transformation and Kuroda’s identities to convert the lumped elements into transmission line
equivalents and separate each component using the appropriate characteristic impedance transmission line [9].

2.1.2. Microstrip Filter

A microstrip relates to the family of parallel-plate coupled transmission lines, which consists of a thin strip conductor, dielectric substrate, and ground plane, which can be seen in Figure 2.3. These circuits are designed based on the conductor dimensions and substrate material properties.

![Figure 2.3. Microstrip line.](image)

The important material properties of the microstrip substrate include dielectric constant and loss tangent, which determine the resonant frequency and efficiency of the device. The loss tangent of the material determines the amount of RF power that is absorbed and converted into heat within the material. A material with high dielectric constant (high-K) will form dense electric fields within the dielectric, while a low dielectric constant (low-K) will form loose electric fields. Most microstrip line devices utilize the decoupling nature and lower loss of a low-K dielectric material for their substrate, while some use high-K for its strong dielectric strength and smaller form factor [2].
There is a wide range of design configurations for microstrip filters, and some include the combline, stepped impedance, hairpin and parallel coupled, as seen in Figure 2.4.

**Figure 2.4.** Microstrip filter configurations: (a) combline, (b) hairpin, (c) stepped impedance, and (d) parallel coupled [10].

Combline filters consist of an array of quarter-wave transformers that are usually capacitively coupled at one end. This produces a narrow bandwidth but is easily tuned by controlling the capacitive coupling of each stub end. Hairpin filters utilize half-wavelength resonators folded in a U-shape for compact operation. These resonators are spaced a quarter guided wavelength apart and are responsible for its narrow bandwidth response. Stepped impedance filters utilize sections that alternate between high impedance sections and low impedance sections, which mimics the lumped element model filter. Series inductors are replaced by high impedance sections, while shunt capacitors are replaced by low impedance sections. Lastly, the parallel coupled filter takes advantage of half wavelength resonators that are parallel to each other along a half wavelength distance. This organization of resonators allows for relatively dense coupling given the space.
2.1.3. Waveguide Filters

Shown in Figure 2.5, a waveguide device consists of a hollow metal cavity that is used to transmit electromagnetic waves with low loss at high frequencies. Since they consist of a hollow cavity, the propagation medium is air or vacuum, which has very low loss. They are known for their ability to support transverse electric (TE) and transverse magnetic (TM) modes of propagation, which can be useful in certain applications. Despite the low loss characteristic of these filters, they are known to be large, heavy, and costly due to their precise tolerances.

Figure 2.5. Rectangular waveguide [11].

2.1.4. Compact & Suppressive Filter Designs

Compact filters are usually designed by taking advantage of a specific technique that does not rely on a physical quarter wave or half wavelength resonator. An LC resonator designed by [12] at 2.4GHz requires a layout seen in Figure 2.6.
The filter was constructed using PCB fabrication and results in a filter size of 19.9mm x 10mm with a 20dB improvement in stop-band suppression. Issues with this design are clear once the design frequency is shifted upwards. The gaps and widths of the lines will continue to shrink until the PCB fabrication process is no longer able to produce reliable circuits.

Another method consists of utilizing a Split-Ring Resonator Defected Ground Structure (SRR DGS) shown by Figure 2.7 [13]. This design takes advantage of the coupling between the microstrip and the SRR DGS, which can be equivalent to a capacitor. For an ultra wideband (UWB) filter, the passband return loss ranges from 15dB in the low end to 9dB in the high end.
Additionally, the insertion loss is measured to be 1.6dB in the low end and up to 4dB in the high end of the passband.

Lastly, another form of a compact filter includes the microstrip stepped impedance resonator design published in [14]. This style of design combines a parallel coupled microstrip filter with a stepped impedance filter in order to suppress the first harmonic. The authors varied the length ratio of low impedance to high impedance resonators to achieve a wider band of higher order modes rejection.

![Figure 2.8.](image)

**Figure 2.8.** (a) Microstrip stepped impedance resonator bandpass filter and (b) insertion loss [14].
As shown in Figure 2.8 (b), the insertion loss in the first harmonic \(2f_0\) was suppressed by 55dB, while it was suppressed by 60dB and 40dB in the second \(3f_0\) and third \(4f_0\) harmonics.

## 2.2. Additive Manufacturing

3-D printing is a low cost and effective additive manufacturing approach. Unlike subtractive manufacturing, additive manufacturing allows for efficient use of material without waste. There are multiple types of 3-D printing technologies such as fused deposition modeling (FDM), stereolithography (SLA) and selective laser sintering (SLS). Each type of 3-D printing method has their benefits and disadvantages but the main concept between all these methods is that the final printed product is constructed and fused layer by layer.

### 2.2.1 Fused Deposition Modeling (FDM)

A standard FDM printer functions by extruding melted thermoplastic through a specifically sized nozzle layer by layer until the product is finished. There are four main types of FDM printers: Cartesian, Delta, Polar and Robotic arm as shown in Figure 2.9.

**Figure 2.9.** Configurations of FDM printers. (a) cartesian, (b) delta, (c) polar and (d) robotic arm [15].
Cartesian printing is accomplished by controlling the print head with stepper motors in the X, and Z axis, while the bed is controlled by the Y-axis motor. Most printers in today’s market consist of cartesian style FDM printers for their simplicity and quality of print. Delta printers utilize a stationary bed and a print-head that is controlled by three vertical rods using triangular coordinates. Polar printers have the print-head stationary but can rotate and move the bed using only two stepper motors. The use of a robotic arm can also be used for 3-D printing, which allows for much wider print volume and lower cost at the expense of print quality.

Some concerns with FDM printing include layer adhesion and resolution of prints. Since most FDM printers are limited by the print head extruding temperature, there are issues with layer adhesion for some materials. This is usually combated by printing in a strategical orientation where layer adhesion is no longer a concern for structural rigidity. Additionally, the resolution of these printers is limited by the size of the nozzle used by the print head. A standard sized nozzle is 0.4mm, which will produce a line of plastic approximately 0.4mm wide and 0.2mm in height. This results in visible layer lines, especially when using a larger sized nozzle.

2.2.2 Stereolithography (SLA)

Stereolithography printing is the very first style of 3-D printing, which begun in 1987. In its early stages, a photochemical process is used to cure resin layer by layer [16]. A modern approach functions uses the ability to cure photosensitive polymers with ultraviolet light in very thin layers. Compared to the FDM approach, SLA is an incredibly fast 3-D printing process that has a resolution limit of 0.01mm. This is essential for producing low loss lines which demand a smooth surface.
For an SLA printer, the build plate is submerged within the resin and a UV light-emitted diode (LED) flashes through a mask, which cures a single layer of the design. This process, as seen in Figure 2.10, is repeated until the product is finished and is responsible for creating smooth and glossy-like products with very little preparation. In terms of cost, the SLA printer is more costly, but the cost is justified by the resolution and print time.

2.2.3 Selective Laser Sintering (SLS)

Selective laser sintering uses a similar approach to SLA, except that a fine powder is used instead of a bath of resin. A laser is used to cure the powdered material layer by layer into a rigid solid [17]. This style of printing is a major improvement over other 3-D printing methods. Using SLS, layer adhesion is no longer a concern, and the flexibility of material usage is immensely increased. Today, SLS technology has progressed to metal 3-D printing objects that were not physically realizable with a CNC or metal casting. However, SLS is a costly manufacturing method since it’s in its early stages of production.
2.2.4 Why 3-D Printing?

Injection molding is an additional additive manufacturing process like 3-D printing. However, compared to a 3-D printer, the cost to maintain and operate an injection molding machine is very high. 3-D printing is an effective alternative to producing and testing a product to ensure full reliability and function before mass production. In fact, 3-D printing smaller batch productions, around 500 pieces, is more cost effective than injection molding. Additionally, additive manufacturing allows greater flexibility by manufacturing items that are not possible to realize with an injection molding machine. This is essential as the complexity of components continues to increase. There are several parameters that can be adjusted when 3-D printing. For instance, there are different styles of infill that range from standard lines to honeycomb structure as seen in Figure 2.11. Each of these can be utilized for faster production and their strength to weight ratio.

![Figure 2.11. Different infill types [18].](image)

Also, the infill ratio can be adjusted, which controls the amount of material that fills the space inside the model. In this case, the infill ratio is useful for controlling the dielectric constant of a material on demand.
In the past few years, 3-D printing has gained immense popularity in the enthusiast and manufacturing space, which has further strengthened the industry. Manipulating materials for printing is becoming increasingly popular as 3-D printers become widely available to the masses. Most materials are manipulated to allow for ease of printing resulting in less adhesion issues, less dimensional shrinking and lower melting temperatures. However, some materials are engineered to include special properties such as iron powder within the filament to allow for a cheaper alternative to metal 3-D printing. Additionally, there are filaments produced by Preperm that consist of an ABS filament infused with a high-K material such as the Preperm ABS1000.

2.2.5 3-D Printed Microwave Devices

Ever since the introduction of 3-D printing, opportunities to fabricate microwave devices using this technology have been explored. Figure 2.12 illustrates a substrate integrated waveguide filter that takes advantage of tuning the infill ratio of the substrate with a FDM 3-D printer.

![Figure 2.12. 3-D printed Substrate Integrated Waveguide (SIW) filter [19].](image)

By adjusting the infill ratio in the inner cavities, the dielectric constant and loss of the substrate can be reduced. Authors in [19] were able to improve insertion loss at their resonant frequency from -7.3dB to -3.7dB, compared to the 100% infill counterpart.
Another example of a 3-D printed microwave device, shown in Figure 2.13, includes a tunable mushroom resonator manufactured using an SLA printer.

![Figure 2.13. 3-D printed mushroom-shaped post resonator waveguide [20].](image)

The fabrication for this type of antenna would require milling techniques, which would add unnecessary cost due to the floating bridge between each post [20]. However, the lack of metalization is one compromise that was made when manufacturing this resonator. Fortunately, metalization is relatively easy and was accomplished using electroplating to establish a uniform coating.

Authors in [21] display yet another example of improving the performance of a microwave device with 3-D printing. As shown in Figure 2.14, two parallel coupled microstrip filters are constructed with different sidewall structures without the need of expensive machinery.
Another application of using 3-D printers to realize microwave devices includes modular designs. Figure 2.15 represents the modular tunable waveguide filter that was designed and fabricated by authors in [22]. This type of design aims at being as practical as possible, by being modular, tunable, and cost effective.

Using an aerosol-based 3-D printing, authors in [23] created the first fully 3-D printed mm-wave antenna. One of their fabricated filters are shown in Figure 2.16. Dielectric and silver ink were used in this process and required some additional sintering and baking steps after the filter was manufactured. The response of this filter matched simulated responses well, but there is still room for repeatability improvement.
The use of additive manufacturing has been used extensively in the design of unique RF structures as seen in literature, therefore there is a large opportunity to utilize this novel manufacturing process as well as materials in creating a more compact and efficient filter design.
Chapter 3

3. Coupled Microstrip line

A coupled line design consists of two conductor lines separated by a gap. This simple structure lays the foundation at which coupling, or crosstalk, can be measured and used effectively.

3.1 Coupled Microstrip line Theory

Shown in Figure 3.1 is the equivalent circuit of a coupled microstrip line. There is a measurable amount of mutual capacitance between each line, from each line down to ground, and an inductance along each line.

![Coupled microstrip line impedance](image)

Figure 17. Coupled microstrip line impedance [24].

The mutual capacitance and inductance between these lines are responsible for altering the impedance of the microstrip line as the characteristic impedance of a line is given by $Z_0 = \frac{L}{\sqrt{\mu c}}$.

Impedance is based on the distance between the pairs and the width of each conductor. However, there are different scenarios at which a signal can propagate between two separate conductor lines that determine the impedance of the lines. Figure 3.2 shows the different modes of possible excitation between the two lines. [24]
Figure 18. Excitation modes of coupled microstrip line [24].

The standard mode of excitation drives only one of the microstrip lines, while other conductor(s) is set to ground. The odd mode excites each microstrip line using differential voltage, while the even mode excites using common voltage. Based on the excitation, the behavior of a propagating wave will be affected. Figure 3.3 represents two scenarios when the coupled microstrip line is excited with even mode (a) and odd mode (b).

Figure 19. Pair of coupled microstrip lines under even mode (a) and odd mode (b) excitation [10].

During the even mode of excitation, the impedance of the line is given by $Z_{even} = \sqrt{\frac{L_{even}}{C_{even}}}$, where $L_{even}$ is the even mode inductance and $C_{even}$ is the even mode capacitance. As shown in Figure 3.3 (a), the inductance between each line is effectively doubled since the magnetic field lines face the same direction. On the other hand, the capacitance is canceled out since the net voltage between each line is zero.
During the odd mode of excitation, the impedance of the line is given by 
\[ Z_{odd} = \frac{L_{odd}}{\sqrt{C_{odd}}}, \]
where \( L_{odd} \) is the odd mode inductance and \( C_{odd} \) is the odd mode capacitance. As shown in Figure 3.3 (b), the capacitance between each line is doubled since the net voltage is the sum of the voltage on each line. On the other hand, the inductance between each line cancels out since each magnetic field produced by each line will face opposite directions.

3.2. Coupled Microstrip line Design

Before designing a coupled microstrip line microstrip, the characteristic impedance for each dielectric substrate was computed using LineCalc at 2.45GHz using the values listed in Table 3.1.

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Low-K</th>
<th>High-K</th>
<th>Loaded High-K</th>
<th>Loaded Low-K</th>
</tr>
</thead>
<tbody>
<tr>
<td>( \varepsilon_r )</td>
<td>1.77</td>
<td>7.18</td>
<td>x</td>
<td>x</td>
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<tr>
<td>( \delta )</td>
<td>0.009</td>
<td>0.014</td>
<td>x</td>
<td>x</td>
</tr>
<tr>
<td>Substrate Height (mil)</td>
<td>60</td>
<td>60</td>
<td>60</td>
<td>60</td>
</tr>
<tr>
<td>Conductor Thickness (mil)</td>
<td>3</td>
<td>3</td>
<td>3</td>
<td>3</td>
</tr>
<tr>
<td>Transmission Line Width (mm)</td>
<td>4.3</td>
<td>1.2</td>
<td>1.2</td>
<td>4.3</td>
</tr>
<tr>
<td>Transmission Line Length (mm)</td>
<td>50</td>
<td>50</td>
<td>50</td>
<td>50</td>
</tr>
</tbody>
</table>

Figure 3.4 represents the simple design at which four ports will be used to measure the scattering parameters of the end of each line.
When simulating the design, the line with Port 1 and Port 2 will be excited, while the second line will be the focus for evaluating the coupling between each line.

### 3.2.1 Low-K Coupled Microstrip line

The low-K design of the coupled microstrip line consists of two 50Ω lines separated by a gap of 5mm as seen in Figure 3.5. The scattering parameters will be evaluated and compared to the loaded high-K microstrip coupled line.
3.2.2 High-K Coupled Microstrip line

The high-K design of the coupled microstrip line also consists of two 50ohm lines separated by a gap of 5mm as seen in Figure 3.6. The scattering parameters will be evaluated and compared to the loaded low-K microstrip coupled line.

![Figure 22. 3-D model of high-K coupled microstrip line.](image)

3.2.3 Loaded Coupled Microstrip lines

The loaded coupled microstrip line will maintain the same design approach as the two previous lines. Shown in Figure 3.7 (a), a high-K dielectric is placed between and under the two low-K dielectric 50ohm lines, while Figure 3.7 (b) utilizes a low-K dielectric between the two 50ohm lines. Transmission line width will be held constant since a change in coupling is the focus of this study. This will result in a slight mismatch and increase the number of measured reflections.

![Figure 23. 3-D model of (a) loaded low-K and loaded high-K coupled microstrip line.](image)
Chapter 4

4. Parallel Coupled Filter Design

Before combining the low-K and high-K dielectric materials into one design, each filter was constructed separately and compared to the loaded filter to evaluate its impact on the filter’s footprint and performance. A parallel coupled filter was chosen for its dependence on the coupling of nearby lines as well as the need to realize high precision gap between these lines. Designing a bandpass filter requires the initial design of a reference low pass filter. Figure 4.1 depicts the lumped element model for a 3rd order Chebyshev low pass filter at 2.45GHz and its corresponding insertion loss response modelled in Keysight ADS [5].

Figure 24. (a) Lumped element model of low pass filter and (b) simulated insertion loss.
Once the low pass filter is constructed, the bandpass filter can be formed using impedance and frequency scaling as shown in equations (1) and (2). Equation (1) transforms the series inductor of the low pass filter into a series LC circuit, while equation (2) transforms the shunt capacitor into a parallel LC circuit [10].

\[
L' = \frac{R_o L}{\Delta w_c} \quad C' = \frac{\Delta}{R_o L w_c} \\
L' = \frac{R_o A}{w_c C} \quad C' = \frac{C}{R_o A w_c}
\]

(1) \hspace{2cm} (2)

The frequency of operation for this filter will be 2.45GHz. It will be based on the 3\textsuperscript{rd} order Chebyshev approximation. As seen by the lumped element model in Figure 4.2 (a), a bandpass filter is constructed based on the referenced low pass filter.

Figure 25. Lumped element model of bandpass filter (a) and responses (b).

Once the lumped element model was finished, the impedance normalized values were used to calculate the j-inverter impedances [10].
\[ Z_0J_1 = \frac{\pi \Delta}{\sqrt{2g_1}} \]  
(3)

\[ Z_0J_n = \frac{\pi \Delta}{2\sqrt{g_{n-1}g_n}} \]  
(4)

\[ Z_0J_{N+1} = \frac{\pi \Delta}{\sqrt{2g_Ng_{N+1}}} \]  
(5)

Using equations (3), (4) and (5), the impedances of each mode in the parallel coupled filter were computed. Finally, the equations (6) and (7) are used to calculate the even and odd mode impedances [10]. The impedance for both modes are listed in Table 4.1.

\[ Z_{0e} = Z_0[1 + JZ_0 + (JZ_0)^2] \]  
(6)

\[ Z_{0o} = Z_0[1 - JZ_0 + (JZ_0)^2] \]  
(7)

<table>
<thead>
<tr>
<th>( N )</th>
<th>( G )</th>
<th>( Z_0J ) (ohm)</th>
<th>( Z_{0o} ) (ohm)</th>
<th>( Z_{0e} ) (ohm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>1.6</td>
<td>0.31</td>
<td>39.2</td>
<td>70.6</td>
</tr>
<tr>
<td>2</td>
<td>1.1</td>
<td>0.12</td>
<td>44.8</td>
<td>56.6</td>
</tr>
<tr>
<td>3</td>
<td>1.6</td>
<td>0.12</td>
<td>44.8</td>
<td>56.6</td>
</tr>
<tr>
<td>4</td>
<td>1</td>
<td>0.31</td>
<td>39.2</td>
<td>70.6</td>
</tr>
</tbody>
</table>

Table 4.1. Parallel Coupled Filter Impedance Values

Each order of \( N \) included its own set of parallel coupled lines of specified length, width and gap. As shown in Figure 4.3, this 3\textsuperscript{rd} order filter included four sections with symmetry across the center. The first and fourth resonators share the same dimensions, while second and third resonators share the same dimensions.
Figure 4.4 illustrates the outline of the physical dimensions of a parallel coupled filter. These dimensions are dependent on the characteristic impedance $Z_0 J$ odd impedance $Z_{0o}$ and even impedance $Z_{0e}$.

![Figure 27. Physical Realization of Parallel Coupled Filter [10].](image)

4.1. Low-K Filter

When designing the low-K filter, the substrate and design specifications were entered into ADS LineCalc, which then output the corresponding dimensions for each order. All values for the low-K filter are listed in Table 4.2.
Table 4.2. Low-K Parallel Coupled Filter Ideal Dimensions

<table>
<thead>
<tr>
<th>N</th>
<th>Width (mm)</th>
<th>Gap (mm)</th>
<th>Length (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>4.6</td>
<td>0.31</td>
<td>25.4</td>
</tr>
<tr>
<td>2</td>
<td>5.4</td>
<td>1.7</td>
<td>25.1</td>
</tr>
<tr>
<td>3</td>
<td>5.4</td>
<td>1.7</td>
<td>25.1</td>
</tr>
<tr>
<td>4</td>
<td>4.6</td>
<td>0.31</td>
<td>25.4</td>
</tr>
</tbody>
</table>

Using these dimensions, the transmission model and EM model for the filter were generated as shown in Figure 4.5 and Figure 4.6. The filter exhibited a return loss of 24.5dB and insertion loss of 1.26dB at 2.45GH. Once the filter is verified through ADS, the filter was reconstructed in a 3-D EM Software to achieve a baseline for the loaded bandpass filter.

Figure 28. Transmission line model for low-K parallel coupled filter.

Figure 29. EM-Layout of low-K parallel coupled bandpass filter (a) and responses (b).
As seen in Figure 4.7, the low-K filter has a return loss of 33.9dB and an insertion loss of 1.26dB at 2.45GHz with a $S_{11}$ bandwidth of 29.8%.

![Figure 30. EM software model of low-K bandpass filter (a) and responses (b).](image)

The EM software was used to optimize the performance of the filter. Table 4.3 represents the dimensions of the low-K filter after optimization.

### Table 4.3. Low-K Parallel Coupled Filter EM Software Optimized Dimensions

<table>
<thead>
<tr>
<th>N</th>
<th>Width (mm)</th>
<th>Gap (mm)</th>
<th>Length (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>1.8</td>
<td>0.41</td>
<td>25.8</td>
</tr>
<tr>
<td>2</td>
<td>2.3</td>
<td>0.57</td>
<td>25.5</td>
</tr>
<tr>
<td>3</td>
<td>2.3</td>
<td>0.57</td>
<td>25.5</td>
</tr>
<tr>
<td>4</td>
<td>1.8</td>
<td>0.41</td>
<td>25.8</td>
</tr>
</tbody>
</table>
4.2. High-K Filter

When designing the high-K filter, the substrate and design specifications were also entered into ADS LineCalc. All values for the high-K filter are organized in Table 4.4. It is important to note that the first and fourth resonators have the smallest dimensions.

**Table 4.4. High-K Parallel Coupled Filter Ideal Dimensions**

<table>
<thead>
<tr>
<th>N</th>
<th>Width (mm)</th>
<th>Gap (mm)</th>
<th>Length (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>1.15</td>
<td>0.69</td>
<td>12.2</td>
</tr>
<tr>
<td>2</td>
<td>1.3</td>
<td>2</td>
<td>11.9</td>
</tr>
<tr>
<td>3</td>
<td>1.3</td>
<td>2</td>
<td>11.9</td>
</tr>
<tr>
<td>4</td>
<td>1.15</td>
<td>0.69</td>
<td>12.2</td>
</tr>
</tbody>
</table>

Using these dimensions, the ideal transmission model for the filter, shown in Figure 4.8 was constructed in ADS.

![Figure 31. Transmission line model for high-K parallel coupled filter.](image)

After the ideal transmission line model is created, the EM-Layout of the filter is generated.
Figure 32. EM-Layout of high-K parallel coupled bandpass filter (a) and responses (b).

Figure 4.9 shows that the filter produced a return loss of 34.5dB and insertion loss of 1.42dB at 2.45GHz. Once the filter is verified through ADS, the filter was also reconstructed in EM Software.

Figure 33. EM software model of low-K bandpass filter (a) and responses (b).
As seen in Figure 4.10, the high-K filter has a return loss of 38.8dB and an insertion loss of 1.42dB at 2.45GHz with a $S_{11}$ bandwidth of 29.65%.

<table>
<thead>
<tr>
<th>Table 4.5. High-K Parallel Coupled Filter EM Software Optimized Dimensions</th>
</tr>
</thead>
<tbody>
<tr>
<td>N</td>
</tr>
<tr>
<td>-----</td>
</tr>
<tr>
<td>1</td>
</tr>
<tr>
<td>2</td>
</tr>
<tr>
<td>3</td>
</tr>
<tr>
<td>4</td>
</tr>
</tbody>
</table>

The EM software was used to optimize the performance of the filter. Table 4.5 represents the dimensions of the high-K filter after optimization. It is important to note the smallest dimension is seen by the first and fourth resonators.

4.3. High-K Filter Loaded with Low-K

Using the high-K filter as the reference design, the low-K dielectric is selectively added to the substrate for loading to the outer resonators of the filter to increase the size of the smallest dimension on the filter and make it more manufacturable.
Shown in Figure 4.11, the dielectrically-loaded filter has a return loss of 30.8dB and insertion loss of 1.37dB with a $S_{11}$ bandwidth of 33.8%. Compared to the low-K and high-K filter responses, the loaded filter has about a 3dB decrease in return loss, but a 4% increase in bandwidth. Additionally, the insertion loss is seen to be the average of both the low-K and high-K losses.

Table 4.6. Loaded Parallel Coupled Filter EM Software Optimized Dimensions

<table>
<thead>
<tr>
<th>N</th>
<th>Width (mm)</th>
<th>Gap (mm)</th>
<th>Length (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>1.6</td>
<td>0.41</td>
<td>23.6</td>
</tr>
<tr>
<td>2</td>
<td>0.83</td>
<td>0.52</td>
<td>14.2</td>
</tr>
<tr>
<td>3</td>
<td>0.83</td>
<td>0.52</td>
<td>14.2</td>
</tr>
<tr>
<td>4</td>
<td>1.6</td>
<td>0.41</td>
<td>23.6</td>
</tr>
</tbody>
</table>
The EM software was used to optimize the performance of the filter. Table 4.6 represents the dimensions of the loaded filter after optimization. It is important to note that after loading the filter, the smallest width in the first and fourth coupled resonator grew 1.06mm.
Chapter 5

5. Manufacturing

5.1. 3-D Printed Material Characterization

RF material properties for pure 100% filled ABS 2.8 for dielectric constant and 0.0031 for the loss tangent [25]. However, these values may vary per filament manufacturer. The ABS filament used here is provided by WYZworks. The Preperm ABS1000 datasheet lists the dielectric constant at 10 and loss tangent of 0.003 at 2.4 GHz [26]. To characterize the material properties of the materials used in the designs, two approaches were used: a ring resonator and patch antenna.

5.1.1. Ring Resonator

A 2.4GHz ring resonator microstrip was fabricated as shown in Figure 5.1 to determine the dielectric constant and loss tangent of 30% infill ABS and the 100% infill Preperm ABS1000. MATLAB code was assembled to compute the dielectric constant and loss tangent at 2.4GHz based on resonances in the S21 plot.

![Figure 35. High-K (left) and low-K (right) 2.4GHz ring resonator.](image)
The high-K substrate was found to have a dielectric constant of around 7.18 and loss tangent of 0.0138, while the low-K substrate was found to have a dielectric constant of 1.77 and loss tangent of 0.0094.

5.1.2. Patch Antenna

Using these newly found values, a patch antenna was also designed and tested to further verify the dielectric constants. Table 5.1 lists the simulated dimensions for the patch antenna of both dielectrics

Table 5.1. Patch Antenna Conductor Dimensions

<table>
<thead>
<tr>
<th>Patch Antenna Parameters</th>
<th>High-K</th>
<th>Low-K</th>
</tr>
</thead>
<tbody>
<tr>
<td>Width (mm)</td>
<td>40.5</td>
<td>55.4</td>
</tr>
<tr>
<td>Length (mm)</td>
<td>21.8</td>
<td>47.8</td>
</tr>
<tr>
<td>Inset Feed Offset (mm)</td>
<td>3.75</td>
<td>11.4</td>
</tr>
<tr>
<td>Inset Feed Width (mm)</td>
<td>4.1</td>
<td>11.1</td>
</tr>
</tbody>
</table>

Figure 5.2 represents the layout at which each patch antenna will be manufactured.
Figure 37. High-K (left) and low-K (right) 2.45Ghz patch antenna.

After creating the patch antennas seen in Figure 5.3, the KeySight FieldFox N9913A was used to measure the return loss responses of each antenna.

Figure 38. (a) High-K and (b) low-K patch antenna return loss response.

As seen in Figure 5.4, both patch antennas are resonating at 2.45GHz, which reinforces the dielectric measurements taken by the ring resonators. It is also important to note that the low-K patch antenna has a return loss of -21.7dB with a calculated bandwidth percentage of 3.77%, while the high-K has a return loss of -24.1dB and a bandwidth percentage of 1.94%. As seen by the data, the bandwidth of the low-K is slightly larger than the simulated, which is the result of the lower effective loss tangent in the low-K due to air pockets.
5.2. 3-D Printing Process

The 3-D printer used to produce the substrates is a modified version of the Anet A8 printer, which is seen in Figure 5.5. It has been modified to include a secondary extruder for printing two different materials in a single print.

![Modified Dual Extruder Anet A8](image)

*Figure 39. Modified Dual Extruder Anet A8 [27].*

Precise calibration such as leveling the bed and setting the nozzle offsets is required for reliable printing. To further ensure a successful print and safety, the hot end must consist of all-metal that is capable of withstand temperatures of at least 300°C. In this case, an all metal E3-D V6 hot end is used for both extruders.

Printing this material is like printing ABS but requires much higher hot end temperature and slower printing speeds. The nozzle temperature was maintained at 275°C, part cooling fans must be off and print speeds were reduced to 10-20 mm/s to maintain strong layer adhesion. This material will easily warp without proper bed temperatures and preparation, requiring a bed temperature of at least 90°C. Additionally, the filament roll should be always placed in an air sealed
chamber to avoid any moisture absorption. The high-K substrate was printed at 100% infill to ensure there are no air gaps, while the low-K substrate was printed at 30% infill. The full printer settings for each material are listed in Table 5.2.

**Table 5.2.** Print Settings per Material

<table>
<thead>
<tr>
<th></th>
<th>Preperm ABS1000</th>
<th>ABS</th>
</tr>
</thead>
<tbody>
<tr>
<td>Nozzle Size (mm)</td>
<td>0.4</td>
<td>0.4</td>
</tr>
<tr>
<td>Extruder Temperature (°C)</td>
<td>275</td>
<td>255</td>
</tr>
<tr>
<td>Bed Temperature (°C)</td>
<td>85</td>
<td>85</td>
</tr>
<tr>
<td>Print Speed (mm/s)</td>
<td>20</td>
<td>45</td>
</tr>
<tr>
<td>Flow Rate (%)</td>
<td>105</td>
<td>93</td>
</tr>
<tr>
<td>Retraction Settings</td>
<td>45mm/s &amp; 1.5mm</td>
<td>45mm/s &amp; 1.5mm</td>
</tr>
<tr>
<td>Layer Height (mm)</td>
<td>0.2</td>
<td>0.2</td>
</tr>
<tr>
<td>Infill Density (%)</td>
<td>100</td>
<td>30</td>
</tr>
<tr>
<td>Print Cooling Fan (%)</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Slicer Used</td>
<td>IdeaMaker</td>
<td>IdeaMaker</td>
</tr>
</tbody>
</table>

Initially, the printer was set to 100% infill, and it was assumed to be true. However, after visual inspection it was noted that there were tiny air gaps within the infill layer lines, such as the air gaps seen in Figure 5.6.

*Figure 40. Cross-section of 3-D print.*
This is undesired since the material needs to be at 100% infill to fulfill the dielectric potential of the material. Thus, the flow rate of the printer was increased from 80% to 100% until all air gaps were filled.

5.3. Metal Deposition

Although relatively cheap and effective to manufacture, 3-D printed antennas lack metal deposition. Depending on the design, additional step for metal deposition is required in the manufacturing process.

5.3.1. Craft Cutter

As a cost-effective method, 3 mil thick copper tape is cut and shaped using a craft cutter with a custom cutting profile. Then the cut-out is lifted as one-piece using transfer tape and carefully placed onto the 3-D printed substrate. For the filters that were easily manufacturable, the craft cutter was used. Figure 5.7 shows the result of using a craft cutter to cut the low-K parallel coupled filter

![Low-K conductor cut using craft cutter.](image)
5.3.2. Photolithography

Not every filter design could be manufactured directly using the craft cutter. The high-K filter conductor proved to be impossible to cut effectively and reliably due to the small width lines and gaps in the first and fourth set of resonators. The copper tape would delaminate during the cutting process. As the costly alternative, photolithography and PCB etching was needed to reliably manufacture the high-K filter. For photolithography, a mask is needed to portray the design profile onto the copper tape. Since the photoresist sheet was a negative type of resist, a negative impression of the design was craft cut using vinyl as shown in Figure 5.8.

![Figure 42. Vinyl cut negative mask from craft cutter.](image)

The precision of the mask is essential to providing a clean and accurate impression of the filter. Two methods of creating the mask were used: using the craft cutter to cut vinyl and the 3-D printer to print a mask.
Shown in Figure 5.9, the vinyl cut mask was superior to the 3-D printed mask. Even when printing with the smallest size nozzle of 0.2mm, corners were rounded and transitions between changing widths were smoothed away. After producing the craft cut vinyl mask, a photosensitive sheet was laminated with heat onto the copper tape and the mask was pressed firmly against the copper tape. As shown by Figure 5.10, UV light was exposed through the mask using a UV oven, leaving the impression of the filter onto the photoresist.
Once the photoresist was baked in the UV oven, the uncured photoresist was removed with a developer solution consisting of sodium carbonate. The cured photoresist remained in preparation for etching using ferric chloride.

![Figure 45. Etched filters using PCB etching method.](image)

After the copper tape is etched, the result is shown in Figure 5.11. A total of three filters were etched per batch to increase the success and production rate.

![Figure 46. Final product of each bandpass filter.](image)

As shown in Figure 5.12, it is important to note that the loaded high-K filter is considerably smaller than the low-K filter, while having the same manufacturability. The high-K filter can only be manufactured using the PCB etching method, while both the loaded high-K filter and low-K filter could easily be cut using the craft cutter.
Chapter 6

6. Results

6.1. Coupled Microstrip line

The scattering parameters of a pair of low-K and high-K microstrip lines were first simulated individually to establish a baseline. Figure 6.1 shows the results of the low-K coupled microstrip line with a gap of 5mm.

![Low-K Microstrip Coupled Lines 5mm Gap](image)

**Figure 47.** Low-K coupled microstrip line 5mm gap scattering parameters.

At a 5mm gap spacing between the two 50Ω lines, the insertion loss of the excited line is maintained less than -0.5dB, and the return loss remains below the -25dB. When evaluating the power coupled to the second line, the S\textsubscript{31} scattering parameter remains below the -33dB line and the S\textsubscript{41} is consistently below -35dB.
Figure 6.2 represents the scattering parameters simulated from the high-K coupled microstrip line pair. When compared to the low-K coupled microstrip line pair, it is apparent that the high-K microstrip line resonates with more modes. At the same distance gap, the return loss is raised to just above the -20dB line, which represents the increase in reflections within the line. However, $S_{31}$ has decreased dramatically. Lastly, the power transfer from Port 1 to Port 4 has increased by about 10dB along the frequency range.

6.1.1 Low-K Loaded Microstrip Line

Parameterization of the loaded microstrip lines will include the percentage of dielectric under the 50ohm line. For example, at 100%, there will only be high-K underneath the 50ohm lines, while 50% will produce half high-K and low-K under the lines.
Figure 49. Low-K loaded coupled microstrip line (a) return loss and (b) insertion loss responses.

Figure 6.3 displays the return and insertion loss for each parameter sweep for volume percentage of high-K under the 50ohm lines. As the amount of high-K increases under the coupled lines, the power transferred to port 2 is decreasing since more power is being transferred to the coupled microstrip line.

Figure 50. Low-K loaded coupled microstrip line S31 scattering parameters.

Figure 6.4 represents the power from port 1 that is transmitted to port 3. At the design frequency of 2.45GHz, a change in coupling can be seen of nearly 16dB as a function of modifying the percentage of high-K material between the coupling lines.
Lastly, Figure 6.5 represents the $S_{41}$ parameter which refers to the power transfer from port 1 to port 4. Throughout the frequency range, the $S_{41}$ is reduced by at least 11dB, when compared to the standard low-K filter.

6.1.2. High-K Loaded Microstrip Line

Figure 6.6 displays the return and insertion loss for each parameter sweep for volume percentage of low-K. The return and insertion loss are greatly reduced in certain frequencies at 1.75GHz and 3.5GHz. Since transmission line width is held constant, there will be some amount of mismatch seen by the fluctuating response in the $S_{21}$. 
As seen in Figure 6.7, the $S_{31}$ increases very slightly along the frequency range by about 3dB at most.

As shown in Figure 6.8, the $S_{41}$ is seen to decrease as a function of increasing low-K volume under the 50ohm line. The average suppression along the frequency range is 5.6dB.
6.2. Parallel Coupled Filters

Once each bandpass filter is manufactured, the simulation results are compared to the measured results from the VNA.

![Image](image_url)

**Figure 55.** (a) Manufactured low-K bandpass filter, (b) passband response, (c) out-of-band response.

As seen in Figure 6.9(b), the measured low-K bandpass filter produced a return loss of 17.81dB and insertion loss of 1.01dB at 2.45GHz with a 26.12% S11 bandwidth. Compared to the simulated, the measured results have a 4% decrease in bandwidth and increased return loss. This can be explained by the surface roughness of the 3-D printed substrates that was not accounted for in simulations. Additionally, as seen in Figure 6.9(c), the re-entry mode of the filter at 5GHz has an insertion loss of 19dB.
The measured high-K bandpass filter shown Figure 6.10(b) produced a return loss of 28.1dB and insertion loss of 1.51dB at 2.45GHz with a 25.1% $S_{11}$ bandwidth. Compared to the simulated, the measured results have a 4.5% decrease in bandwidth and increased return loss of 10dB. Additionally, as seen in Figure 6.10(c), the re-entry mode of the filter at 5GHz has an insertion loss of 6.3dB, which is substantially higher than the low-K filter.
Figure 57. (a) Manufactured loaded bandpass filter, (b) passband response, (c) out-of-band response.

The measured loaded bandpass filter response shown in Figure 6.11(b), the produced a return loss of 25.1dB and insertion loss of 1.27dB at 2.45GHz with an 29.8% $S_{11}$ bandwidth. Compared to the simulated, the measured results have a 4% decrease in bandwidth and increased return loss of 5dB. Additionally, as seen by Figure 6.11(c), the re-entry mode of the filter at 5GHz has an insertion loss of 13.3dB, which is a 7dB improvement over the standard high-K filter.

Figure 58. Return loss response of each bandpass filter.
Shown in Figure 6.12, the bandwidth of the loaded filter is about 4-5% larger than both the high-K and low-K filter. This correlates with the results found by the authors in [1] stating that increasing the dielectric constant where electric fields are more pronounced, will shift higher resonances, which results in an increase in bandwidth.

Comparing the out-of-band responses of each filter, Figure 6.13 clearly shows that the loaded filter suppresses the undesirable re-entry at 5GHz seen in the high-K filter. Additionally, the third harmonic resonance at 7.5GHz is reduced from 1.72dB to 3.4dB.

Figure 59. Comparison of the return loss and insertion loss responses for all the bandpass filter designs.
Table 6.1. Comparison of all Measured Bandpass Filter Parameters

<table>
<thead>
<tr>
<th></th>
<th>Low-K Filter</th>
<th>High-K Filter</th>
<th>Loaded high-K</th>
</tr>
</thead>
<tbody>
<tr>
<td>$S_{11}$ 10dB Bandwidth %</td>
<td>26.1</td>
<td>25.1</td>
<td>29.8</td>
</tr>
<tr>
<td>$S_{21}$ 3dB Bandwidth %</td>
<td>28.2</td>
<td>30.3</td>
<td>31.3</td>
</tr>
<tr>
<td>Return Loss @ 2.45GHz (dB)</td>
<td>17.8</td>
<td>28.1</td>
<td>25.1</td>
</tr>
<tr>
<td>Insertion Loss @ 2.45GHz (dB)</td>
<td>1.01</td>
<td>1.51</td>
<td>1.27</td>
</tr>
<tr>
<td>Length (mm)</td>
<td>130</td>
<td>72</td>
<td>90</td>
</tr>
<tr>
<td>Re-entry @ 5GHz (dB)</td>
<td>-18.8</td>
<td>-3.7</td>
<td>-13.3</td>
</tr>
</tbody>
</table>

A comparison of the parameters of each filter is shown in Table 6.1. The results show that the loaded filter produced a larger bandwidth with an averaged insertion loss and major reduction in size. Compared to the low-K filter, dielectrically loading the filter, reduced the length by 30.8%, while maintaining similar insertion loss and re-entry suppression.
Chapter 7

7. Conclusion

7.1. Summary

This thesis explored the benefits of using 3-D printing to dielectrically load the substrate used in a bandpass filter design. By giving design engineers another design alternative, RF devices such as filters and antennas that utilize a dielectric substrate will perform more efficiently and at a much-reduced footprint than previous designs. 3-D printing is a relatively cost-effective option in terms of manufacturing substrates for RF devices. Manufacturing a parallel coupled bandpass filter requires high precision to reliably fabricate the tiny widths and gaps, which can be costly. This was avoided by improving the manufacturing ability of the device by enlarging the smallest dimension without changing the frequency of operation. This offered a more cost-effective manufacturing approach. Additionally, the performance of the filter was enhanced and resulted in an overall 4.5% increase in bandwidth. This is especially important for communications that utilize bandwidth for data transfer.

7.2. Future Work and Recommendations

7.2.1. Microstrip Coupled Matching

The coupling parameterization done earlier only focused on the change in the S-parameters as a secondary substrate was loaded. This parameterization did not account for the change in effective dielectric constant and is responsible for mismatch along the line. Future work can be done by improving the match by calculating the proper transmission line width for each microstrip
coupled line. Additionally, a focus on understanding how the transition from high-K to low-K affects higher order modes can be studied.

7.2.2. Other Metal Deposition Techniques

Additional work can be done by experimenting with other metal deposition methods. Two alternative methods include electroplating and aerosol 3-D printing. Electroplating is another method of metal deposition that could have been used to effectively create the top conductor portion of the filter. It is essentially used in deposition scenarios that need a large surface area to be coated evenly. Using copper sheets and copper sulfate, an object can be coated in copper once a voltage is applied to influence the transition of copper ions. This process is demonstrated by Figure 7.2.

![Figure 60. Copper Electroplating Process [28].](image)

A new method of depositing copper onto an object has recently been discovered and made economical. Using a printing style like FDM 3-D printers, nanosilver ink is atomized and sprayed through a nozzle using nitrogen gas [28]. Figure 7.3 illustrates the function of the nozzle.
This metal deposition method is superior to other methods due to its controllability versus the chaotic nature of using chemicals to etch or coat a surface. Additionally, structures down to the size of 20um can be effectively produced [29].
Appendix

Matlab code for Ring Resonator Calculation:

global structVNAdata;
   InLoss = max(structVNAdata.S21.dBVNA);
   InnerBand = structVNAdata.S21.dBVNA > (InLoss -3);
   InnerHighFreq = max(InnerBandFreqs);
   InnerLowFreq = min(InnerBandFreqs(InnerBandFreqs>0));
   OuterHighFreq = max(structVNAdata.S21.Frequency .* circshift(InnerBand,[0 1]));
   OuterLowFreq = min(BandLeftShift(BandLeftShift>0));
   HighSlope = (structVNAdata.S21.dBVNA(structVNAdata.S21.Frequency == InnerHighFreq) -
   structVNAdata.S21.dBVNA(structVNAdata.S21.Frequency == OuterHighFreq))/(InnerHighFreq -
   OuterHighFreq);
   LowSlope = (structVNAdata.S21.dBVNA(structVNAdata.S21.Frequency == InnerLowFreq) -
   structVNAdata.S21.dBVNA(structVNAdata.S21.Frequency == OuterLowFreq))/(InnerLowFreq -
   OuterLowFreq);
   InnerHighFreq)- HighSlope * InnerHighFreq;
   InnerLowFreq)- LowSlope * InnerLowFreq;
   FLow = ((InLoss -3)-LowIntercept)/LowSlope;
   FHigh = ((InLoss -3)-HighIntercept)/HighSlope;
   BandWidth = FHigh - FLow;
   n=1;  % resonance order for the S21 response
   f=maxS21Loc; % resonance frequency of that order for the S21 response
   BW3dB = BandWidth; % Bandwidth at -3dB
   LA= -1 * InLoss; % insertion loss at the resonance frequency
   t=60e-6; % thickness of the metal
   h=21e-4; % substrate thickness
   w=1.3e-3; % ring width
   rm=13e-3; % radius of the ring
   Zo= 50; % assume matched at 50 ohm
   cu_cond = 5.8e7; % copper conductivity
   rough = 15e-6; %RMS (root-mean-square) value of surface roughness
   c=3e8; % speed of light
   uo = 4*pi*1e-7; % The permeability of free space
   weff = w+ 1.25*(t/pi)*(1+log((2*h)/t)); % effective width
   M=1/sqrt(1+((12*h)/weff)); % paramter needed to calculate dielectric constant
   Eeff = ((n*c)/(2*pi*rm*F))^2; % effective dielectric constant
WLo=c/f; % wavelength at free space
skin_depth = sqrt(1/(cu_cond*pi*uo*f)); % skin depth
Rss = sqrt(pi*uo/cu_cond)*(1+(2/pi)*atan(1.4*((rough/skin_depth)^2))); % conductor resistance
cul1 = Rss/(Zo*h);
cul2 = (8.686*((weff/h)+(2/pi)*log(2*pi*exp((weff/(2*h)))+0.94)))*2;
cul3 = (weff/h)+((weff/pi*h)/((weff/(2*h)))+0.94);
cul4 = 1+((h/weff)*((h/pi*weff)*log(((2*h)/t)+1)-((1-(t)/(2*h)))))/((1+(t/(2*h))));
cul5 = ((8.686*Rss)/(2*pi*Zo*h))*(1-((weff/(2*h)))*cul4;
cul6 = ((8.686*Rss)/(2*pi*Zo*h))*(1-(weff/(4*h)))*((h/((pi*weff)+((h/((pi*weff)*log((4*pi*w)+1)-((1-(w)/(4*pi*w)))/(1+(t/(4*pi*w))))))));
cul7 = cul1*cul2*cul3*cul4;
if (w/h) > 2
  cu_loss = cul1*cul2*cul3*cul4; % conductor loss dB/unitlength
elseif (w/h) > (1/(2*pi)) & (w/h) <= 2
  cu_loss = cul5; % conductor loss dB/unitlength
elseif (w/h) < (1/(2*pi))
  cu_loss = cul6; % conductor loss dB/unitlength
end
E=((2*Eeff)+M-1)/(M+1); % dielectric constant
WLeff=WLo/sqrt(Eeff); % effective wavelength
Qo= f/(BW3dB*(1-10^(-LA/20))); % unloaded Quality factor
tot_loss = (8.686*pi)/(Qo*WLeff); % total losses dB/unitlength
%Qr = (Eeff*Zo)/(120*(pi^3)*((h/WLo)^2)*(1-((4*E)/3)+((8*(E^2))/15))) %radiation quality factor
%rad_loss = (8.686*pi)/(Qr*WLeff) % radiation losses dB/unitlength
di_loss = tot_loss - cu_loss; %rad_loss
% Results
loss_tangent= (di_loss*WLo*sqrt(Eeff)*E-1)/(8.686*pi*E*(Eeff-1));
set(handles.dielectric_box, 'string' , ['E = ', num2str(E),'   Loss tan = ', num2str(loss_tangent)]);
References


[7] Dr. Dahle, “Project 2 Stepped Impedance Filters”, State University of New York at New Paltz


