

**THE DEVELOPMENT OF MATHEMATICAL MODELLING
REPRESENTING TUNING SLOT PARAMETERS VERSUS RESONANT
FREQUENCY**

By

FARAHATUL KHALIDA BINTI MOHAMAD

FINAL PROJECT REPORT

Submitted to the Electrical & Electronics Engineering Programme
in Partial Fulfillment of the Requirements
for the Degree
Bachelor of Engineering (Hons)
(Electrical & Electronics Engineering)

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CERTIFICATION OF APPROVAL

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A project dissertation submitted to the
Electrical & Electronics Engineering Programme
Universiti Teknologi PETRONAS
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Bachelor of Engineering (Hons)
(Electrical & Electronics Engineering)

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September 2014

CERTIFICATION OF ORIGINALITY

This is to certify that I am responsible for the work submitted in this project, that the original work is my own except as specified in the references and acknowledgements, and that the original work contained herein have not been undertaken or done by unspecified sources or persons.

Farahatul Khalida Binti Mohamad

ABSTRACT

To design a Dielectric Resonator Antenna (DRA) with desired resonant frequency, Heuristic method must be used. Thus, it consume a lot of time, effort and cost. It is because, currently there are no specific mathematical model to determine the resonant frequency. Eventhough, the resonant frequency can be obtained through simulation, but it will consume a lot of time an effort. Hence, this project is carried out to develop mathematical model which represent tuning slot parameters of DRA versus resonant frequency. The tuning slot parameters varied in this project is C-slot position from input port of antenna. The position of the slot from the input port of the antenna have been varied and resonant frequency at each position is determined. A series of preliminary simulation and design have been performed by utilizing CST Microwave Studio Software. From the simulations, the relationship between the C-slot position and resonant frequency is studied and a mathematical model is developed.

ACKNOWLEDGEMENTS

Alhamdulillah, praise to Allah, I have successfully completed the first phase and second phase of my Final Year Project (FYP) entitled Development of Mathematical Modelling Representing Tuning Slot Parameters versus Resonant Frequency. Without His blessing I would not be able to complete the project. This FYP course have provide a lot of new things to be learn and explore, allowing the students to play an active role in managing and completing the project.

I am glad to express my utmost appreciation to my FYP Supervisor, Mr M. Azman Bin Zakariya, for sincerely guiding and advising me throughout the first and second parts of my Final Year Project. The special thank goes to him for becoming my source of inspiration by giving me valuable information, suggestions and guidance throughout my final year period and also in preparation and completion of this reports and projects. Besides, I am also deeply grateful for his concern on my learning progress relating to the project and I believe all the knowledge that has been shared is priceless.

Apart from that, I would like to thank my co-supervisor, AP. Dr. Zuhairi Bin Hj. Baharudin for his generous assistance, guidance and advice. He had given his utmost guidance and help during the completion of the project, reports, as well as presentations. Thank you for willing to spend a lot of time in guiding me for completion of this project and thesis. I also would like to give appreciation to Mr. Adz Jamros Bin Jamali for his kind assistance and helps.

Besides that, I wish to thank all my friends and family for giving me full support through thick and thins until the completion of this project. I would like to thank again all the people that has helped me directly or indirectly throughout these final year period. Thank you.

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LIST OF ABBREVIATIONS

DRA	Dielectric Resonator Antenna
GPS	Global Positioning System
CDRA	Cylindrical Dielectric Resonator Antenna
CST	Computer Simulation Technology
EWGM	Effective Wave Guide Model
RDRA	Rectangular Dielectric Resonator Antenna
MSDRA	Multisegment Dielectric Resonator Antenna
MSA	Microstrip Antenna
FYP	Final Year Project
CCTO ($\text{CaCu}_3\text{Ti}_4\text{O}_{12}$)	Calcium Copper Titanium Oxide
FR4	Flame Retardant
IEEE	Institute of Electrical and Electronics Engineer
CFT	Curve Fitting Technique
SSE	Sum of Squared Error
RMSE	Root Mean Square Error
WLAN	Wireless Local Area Network

CHAPTER 1

INTRODUCTION

1.1 Background of Study

Recently, there are a lots of researches and study going on to improve and to develop new antenna that can fulfill various commercial and industrial needs. The great demand and revolution in the world of communication, communication industry and technology is progressing toward development of a more low cost and small size antennas such as dielectric resonator antenna (DRA). Basically, this type of antenna can adapt to almost any configuration. Therefore it is used in many applications such as wireless and satellite communication [1].

Generally, an antenna is a resonant device, therefore most of antenna can only operate properly and efficiently around its resonant point and within a limited bandwidth. Resonant frequency of an antenna is the frequency where the capacitive and inductive reactance cancel each other. As the result, at this frequency, the antenna appear purely resistive and the resistance is a combination of radiating and loss resistance. Figure 1.1 illustrate the concept of resonant frequency.

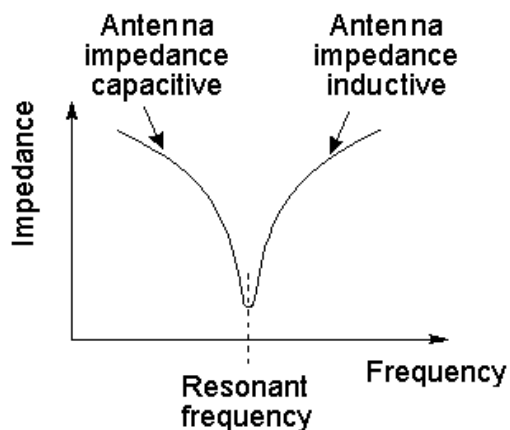


Figure 1.1 Resonant frequency

Basically, impedance is the relation of voltage and current at the input to the antenna. Power that is either radiated away or absorbed within the antenna is

represented by the real part of the antenna impedance. The power that is stored in the near field of the antenna is represented by the imaginary part of the impedance. An antenna input impedance varies with frequency even though the characteristic impedance of its feed remains unchanged. Impedance bandwidth is the frequency range where the antenna impedance can be match properly to its feed or source impedance.

A good impedance bandwidth is very important for all antenna design, because it will allows most of the energy to be transmitted to an antenna from a feed or a transmission system at a transmitter, and from an antenna to its load at a receiver in a wireless communication system [2]. If the antenna is not well matched, less power will be delivered to the antenna. As a result, this power will be reflected back. This loss of power is known as impedance mismatch. Hence, it is very important to match the antenna to its feed. The desired bandwidth is one of the determining factor used to decide upon an antenna. For example, many antenna types have very narrow bandwidths and cannot be used for wideband operation.

Antenna with different resonant frequency and impedance bandwidth have different application and may serve different purposes. For example the frequency band for FM radio is from 30 MHz to 300 MHz. However, for television, mobile phone and Global Positioning System (GPS), the frequency band is from 300 MHz to 3000 MHz. Thus, it explained the importance of resonant frequency in antenna design.

Therefore, in this project, the tuning of the DRA resonant frequency by using the C-shape of aperture slot will be study thoroughly and a mathematical model which represent the relationship between the slot parameter and resonant frequency will be develop.

1.2 Problem Statement

Resonant frequency is a very important element in designing or analysis of an antenna. Usually, it is obtained through measurement of antenna using network analyser (measure the fabricated antenna), simulation or for some antenna it can be calculated by using specific formula or mathematical model. However, for cylindrical

DRA (CDRA) with aperture C slot, there are no particular equation or mathematical model that can be used to determine resonance frequency.

Normally, a DRA is designed by using software or heuristic method. Running a simulation with a normal computer can take from an hour to a day. By using heuristic method, a number of antennas with different dimension and parameters are fabricated and measured until the antenna with desired resonant frequency is obtained (trial and error). Both of this method is time consuming and the cost of heuristic method can be very high. Apart from that, varying the slot parameters of DRA such as dimension and position will give a very different resonant frequency, thus it is vital to have a method that can easily predict the resonant frequency without consuming a lot of time.

Besides that, resonant frequency is also very critical in analysis of the designed antenna. By conventional method, the analysis will consumed a lot of time, cost and effort. In addition, the analysis also can be very complicated. Therefore, to overcome these problem, this project is carried out to formulate and develop a mathematical model which represent the relationship between slot parameters and resonant frequency. By utilizing the mathematical model, the resonant frequency of slot antenna can be easily predicted through calculations.

1.3 Objectives

The main objectives of this project are

1. To study the relationship between tuning slot parameters and the resonant frequency.
2. To develop a formulation of mathematical model which represent resonant frequency versus slot parameters.

1.4 Scope of Study

This project aim to develop a mathematical formula or equation which can be utilize to determine or calculate resonant frequency. This project only focused on cylindrical shape DRA (CDRA) for wireless application. The antenna designed is a dual band antenna as the selected operating frequency is 2.4 GHz and 5.0 GHz. Implementation of the coupling technique is using aperture coupling technique.

Energy of signal from microstrip line feeder is coupled to the CDRA through an aperture slot which is a C-shaped slot. Computer Simulation Technology (CST) software is used to design and simulate the antenna prior to development of model using Matlab.

The tuning slot parameters studied in this proposed project is slot position from input port of antenna. The effect of varying slot position to the resonance frequency and impedance bandwidth will be investigated. Consequently, the mathematical equation represent the relationship between slot parameters which is the position of the slot and the resonant frequency.

CHAPTER 2

LITERATURE REVIEW AND THEORETICAL BACKGROUND

Chapter two reviews the theoretical background and characteristic of the CDRA with C Aperture Slot. A review brief on different type of DRA and feeding mechanism used to excite the antenna is discussed. In addition, a detailed discussion on aperture coupling is presented. Finally, this chapter also presented a detailed literature on mathematical model of resonant frequency for different type of antennas.

2.1 Cylindrical Dielectric Resonator Antenna (CDRA) with C Aperture Slot

Nowadays, DRA antenna had gained a wide and significant interest from researchers, thus a lot of study, development and research on DRA antenna has been done in literature [3-17]. It is because, a small, miniaturized and low cost antennas like DRA antenna are very important for communication system for example in application for mobile handsets and other wireless devices [4-5]. In addition, due to its flexibility and versatility, it can be design to fulfill various requirement and needs for a wide range of communication application [6-7].

DRA has a lot of interesting characteristics. One of its major characteristics or features is it can be fabricated using a high dielectric constant material. Apart from that, it also covers wide range of frequency band and displays a high radiation efficiency, due to low conductor and surface wave losses. DRA can be excite from many type of feeding mechanism, namely microstrip feeder line, dielectric image line and coplanar waveguide lines [1]. The performance of DRAs is minimally affected by the presence of nearby noisy objects. Due to its attractive features, DRA has received a lot of attention from researchers worldwide.

There are many different types of DRAs found in literature such as Rectangular DRA, Cylindrical DRA and Hemispherical DRA [1-8]. The difference between types of DRA is the shape of its Dielectric Resonator (DR) and each of them can serve different purposes and have different applications. The CDRA is chosen in

this project because there are equations or model found in literatures [7-20] to calculate resonant frequency of various DRAs found, however none are found for CDRA with C aperture slot.

The selection of the coupling method plays an important role in determining the resulting radiation pattern of the antenna designed. One of the common technique of exciting a DRA is through aperture coupling. In this technique, there is no direct contact between the feed line and the radiating element. The coupling slot etched on the ground is used to excite the radiating element from the transmission line. The small rectangular slot is one of the most commonly used aperture slot [20]. However, the slot can be in various shape such as cross shape, annular shaped and C-shaped as shown in Figure 2.1. The aperture slot itself can be fed by a transmission line. Aperture coupling offers the advantage of having the feed network located below the ground plane, isolating the radiating aperture from any unwanted coupling or spurious radiation from the feed [1].

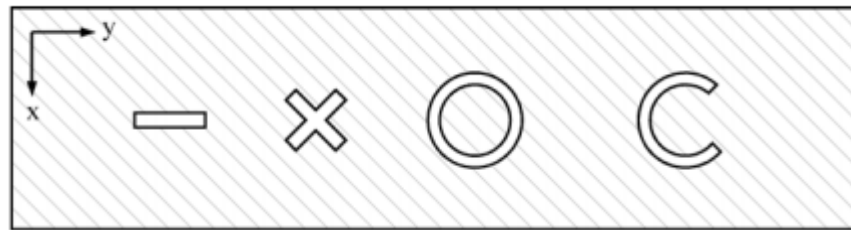


Figure 2.1 Various shape of aperture slot [1]

2.2 Mathematical Model of Resonant Frequency

The resonant frequency of DRA antenna can be obtained from simulation or by testing the antenna hardware using network analyzer. There are many literatures which studied and developed a model to calculate resonant frequency of DRA or other antenna [9-17]. However there are no literature that mention about any model to calculate resonant frequency of a CDRA with C slot aperture is found.

One of the literature that study on development of model to calculate resonant frequency mention about development of a new model which is Effective Wave Guide Model (EWGM) to predict resonant frequency of Rectangular DRA (RDRA) with higher accuracy is presented in literature [11]. In this literature, in order to compute effective dimensions of RDRA, correction factors are introduced by

considering the effect of relative permittivity and aspect ratios of RDRA. It is carried out in all dimensions to replace the dielectric resonator with effective waveguide cavity. To get the resonant frequency, fields within the cavity are analyzed [12-14]. From the analysis, a EWGM model is developed.

Apart from that, in [7, 15], the approximate equation used to calculate resonant frequency for $H_{11\delta}$ of conventional cylindrical DRA (CDRA) is given by:

$$f_r = \frac{6.324}{\alpha\sqrt{(\epsilon_r+2)}} \left(0.27 + 0.36 \left(\frac{a}{2h} \right) + 0.02 \left(\frac{a}{2h} \right)^2 \right) \quad (2.1)$$

Where;

ϵ_r = resonant dielectric constant

a = radius of CDRA

h = height of CDRA

This literature [7] presents a resonant frequency tuning of a miniaturized CDRA. The antenna is developed and simulated by using CST Microwave Studio. The objective of the simulation works produced an antenna that operates for Wireless Local Area Network (WLAN) frequency, which is at 2.45GHz [16].

Another literature [17] present a novel method to compute resonant frequency of Multisegment DRA (MSDRA). This method is developed based on Dielectric Waveguide Model (DWM). In this literature, it assume that the influence of each segment in the resonant frequency of the whole structure is proportional to its height. Weighted average model (WAM) is also introduced to compute resonant frequency. From the findings, the resonant frequency obtained using WAM have lower error compared to resonant frequency calculated using Modified Dielectric Waveguide Model (DWM).

On the other hand, literature [18] presented about developing mathematical formula for resonant frequency of compact Microstrip Antenna (MSA). In this literature, the slot in the rectangular MSA is etched at two different position such that the rectangular MSA produced the C-shape MSA and rectangular ring MSA [18-20]. The size of the slot are varied and the MSA antenna are simulated using IE3D software. The current distribution generated from the software is studied and analysed. From the analysis, resonant frequency model is developed.

Therefore, these are some of the model developed to calculate resonant frequency of different type of DRA and other antenna found in literatures. Based on these literatures, there are various methods that can be used to develop a mathematical model. Consequently, this project is carried out to develop a mathematical model that determined the resonant frequency of DRA with the function of C-shaped aperture slot parameter.

CHAPTER 3

METHODOLOGY / PROJECT WORK

Chapter three presents the research methodology of the mathematical model. The research methodology covers detailed steps from start until completion of the project. In this chapter, the project activities is also discussed. Project activities is the elaboration for research methodology. Gantt Chart and key milestone for both FYP 1 and FYP 2 is also presented in this chapter. Methodology is prepared to plan the steps taken to achieve the proposed objectives.

3.1 Research Methodology

The 3.1 is the overview of the research methodology for Final Year Project (FYP) 1 and 2. It illustrate the steps involved in the project work pertaining to project methodology.

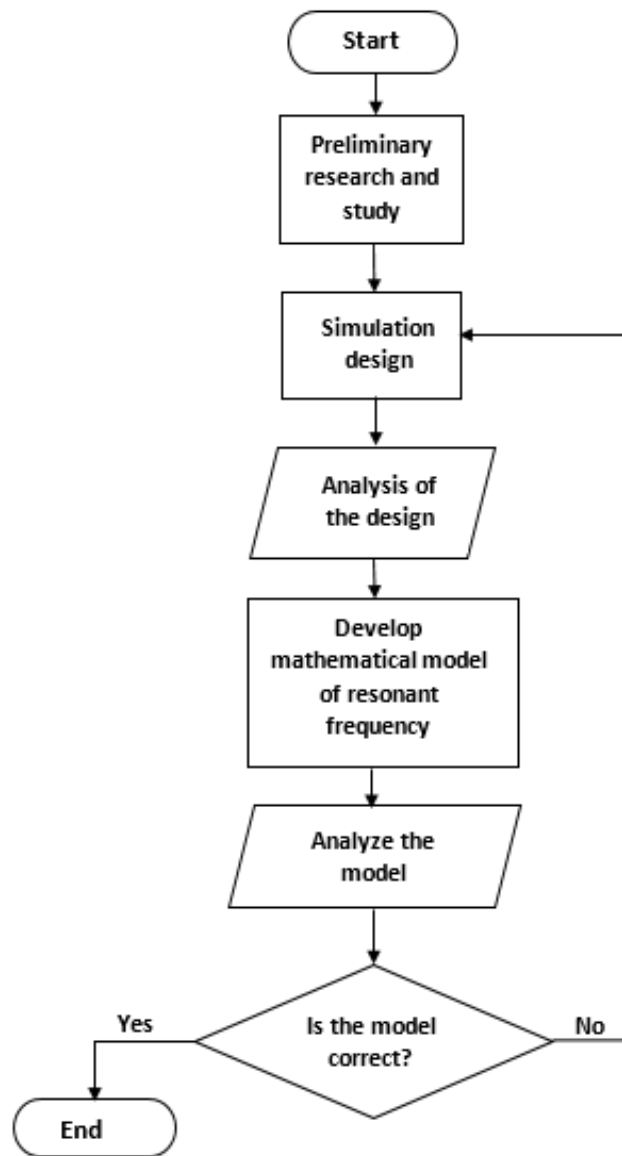


Figure 3.1 Methodology of project

As the project started, preliminary research is conducted which act as a foundation for understanding of the working principle and also tools used to develop and analyze the mathematical model. After that, proposal and the literature review for the project have been written. The next stage is simulation design. The simulation design of CDRA with C slot is done by using CST software as illustrated in Figure 3.2. In the simulation, the position of C-slot which is the tuning slot parameters is varied. The transient response is chosen to evaluate the performance of the antenna. From the simulation, the graph of return loss versus frequency is obtained and analyzed.



Figure 3.2 CST Microwave Studio

The resonant frequency obtained from simulation is then plotted in Matlab against position of C-slot. By utilizing Curve Fitting Tool (Cftool) in Matlab, the mathematical model of resonant frequency is developed. A few type of fit have been performed to select the type of fit which best fit with the data. Then, the model is analyzed, if the model is correct, the project is completed. The model is incorrect, another series of simulation design is carried out to obtain a better set of data. And the next stage is repeated until an accurate and correct model is manage to be obtained.

3.2 Project Activities

Project activities in the following figure is the elaboration for research methodology

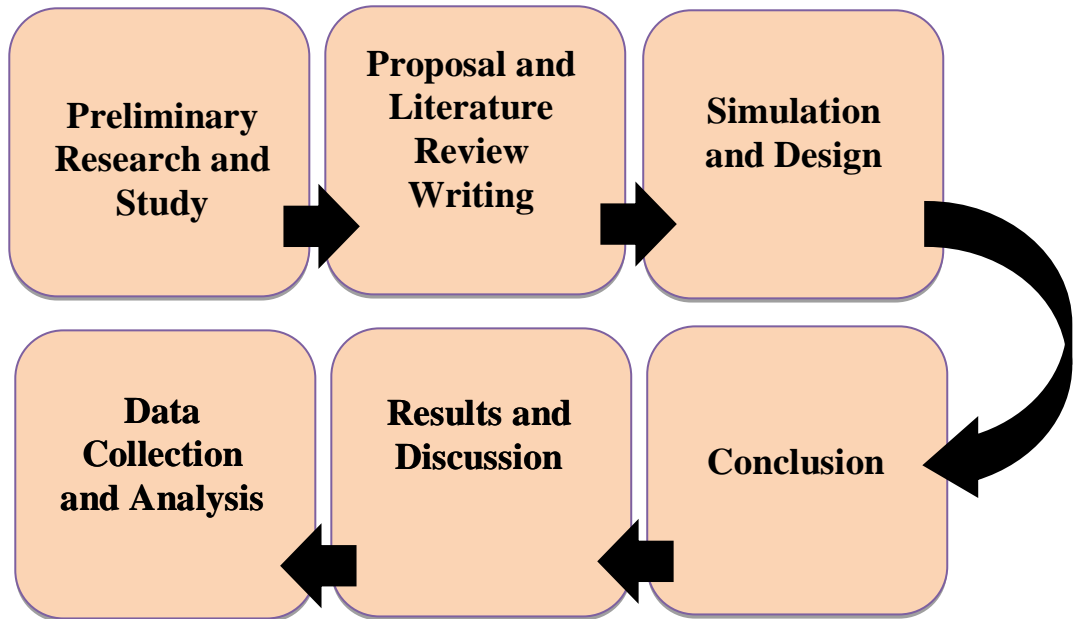


Figure 3.3 Project activities

1. Preliminary research and study:

Data and information related to the project is collected from various sources such as technical papers, journals, articles, and books. Conduct background study on the DRA design.

2. Proposal and literature review writing:

Identify and describes the problem statement and objectives of the project. Thus, the scope of study is narrowed to ensure the feasibility and relevancy of the project. Gantt chart and methodology is prepared to ensure the objective is achieved.

3. Simulation design:

Simulation design of aperture slot DRA is performed by utilizing CST software and the characteristic of the antenna are evaluated.

4. Data collection and analysis:

From the simulation result, data on slot parameter and resonant frequency of antenna is further analyzed to obtain the mathematical model. Matlab software is utilized in this stage.

5. Results and discussion:

From the data analysis, the results are obtained. The result are discussed and recommendation are made for further improvement.

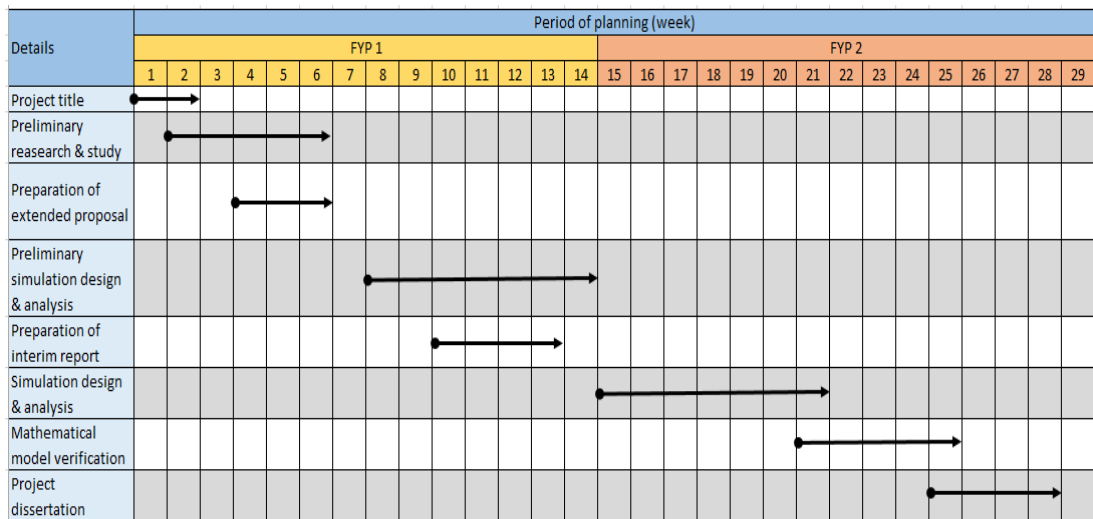
6. Conclusion:

The findings of the project are being conclude from the final results which is the mathematical equation.

3.3 Gantt Chart

The following table is Gantt chart for FYP 1 and FYP 2.

Table 3.1 Gantt chart for FYP1 and FYP 2



Gantt chart is done to ensure the feasibility of the project to be completed within time frame. Gantt chart is a form of project schedule, it illustrate the start and finish dates of each stage in the project completion progress.

3.4 Key Milestone

The following table shows the key milestone for FYP 1 and FYP 2.

Table 3.2 Key milestone for FYP 1 and FYP 2

Details	FYP 1														FYP 2															
	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	
	13/1 - 17/1	20/1 - 24/1	27/1 - 31/1	3/2 - 7/2	10/2 - 14/2	17/2 - 21/2	24/2 - 28/2	3/3 - 7/3	10/3 - 14/3	17/3 - 21/3	24/3 - 28/3	31/3 - 4/4	7/4 - 11/4	14/4 - 18/4	13/5 - 16/5	19/5 - 23/5	26/5 - 30/5	2/6 - 6/6	9/6 - 13/6	16/6 - 20/6	23/6 - 27/6	30/6 - 4/7	7/7 - 11/7	14/7 - 18/7	21/7 - 25/7	28/7 - 1/8	4/8 - 8/8	11/8 - 15/8		
Confirmation of project title		♦																												
Submission of extended proposal						♦																								
Submission of interim draft													♦																	
Submission of interim report														♦																
Completion of simulation design & analysis																						♦								
Completion of mathematical model verification																													♦	
Completion of project dissertation																														♦

To ensure the objectives of the project at each stage is achievable, a key milestone is made. Key milestone serve as the target, objectives or deadline that need to be accomplished. Key milestone also allows the progress of the project to be monitored.

CHAPTER 4

RESULTS AND DISCUSSION

Chapter four presents the simulation design of Cylindrical Dielectric Resonator Antenna (CDRA) with C aperture slot that have been done by using CST microwave software. This chapter also presents the mathematical model that have been developed for both 2.4 GHz and 5.0 GHz resonant frequency. The model is thoroughly analyzed and discussed in this chapter. The resonant frequency calculated by using the model is compared with resonant frequency obtained from simulation and the percentage error is calculated. In addition, the advantages of the model is also presented in this chapter.

4.1 Simulation Design

Preliminary simulation and design is carried out by utilizing CST microwave software as shown in the following figure. Figure 4.1 and 4.2 illustrate the front and back view of the antenna.

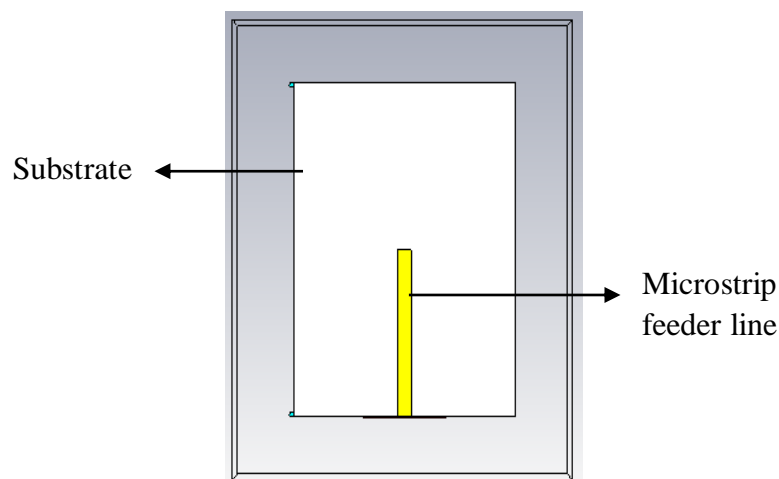


Figure 4.1 Front view of the simulated antenna

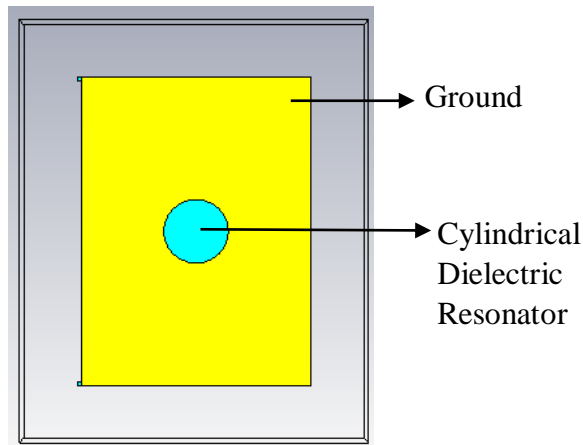


Figure 4.2 Back view of simulated antenna

For this preliminary design, Cylindrical DRA (CDRA) is used. Due to its simple field structure, it is easy to analyze compared to other DRA such as rectangular DRA. CDRA is also more directional and has a lower resonant frequency compared to rectangular and annular DRA. Thus, it is suitable for directional wireless application. In this simulation, the diameter of the CDR used is 14.4 mm, while the height is 3mm. The CCTO ($\text{CaCu}_3\text{Ti}_4\text{O}_{12}$) CDR have permittivity of 55.

Apart from that, microstrip with length, $L_m = 35\text{mm}$ and width, $W_m = 3\text{mm}$ is used as transmission line to excite the C shape aperture slot as shown in Figure 4.4. It is placed under the ground plane to give the advantage of the aperture coupling mechanism which reduces the unwanted coupling and superior radiation from the feed line. The material of the microstrip line is copper.

The coupling technique used is aperture coupling. The coupling slot etched on the ground plane is used to excite the radiating element from the transmission line. There are different shapes of coupling slot that can be used. However, for this project C shaped aperture slot is used. Maximum coupling between radiating element and transmission line can be achieved by placing the slot at the center of the DRA as shown in Figure 4.3. The length of the C-slot used in this simulation is $L_{C1} = 7\text{mm}$, the width is $W_C = 6\text{mm}$ and the gap between C-slot arm is $G = 3\text{mm}$.

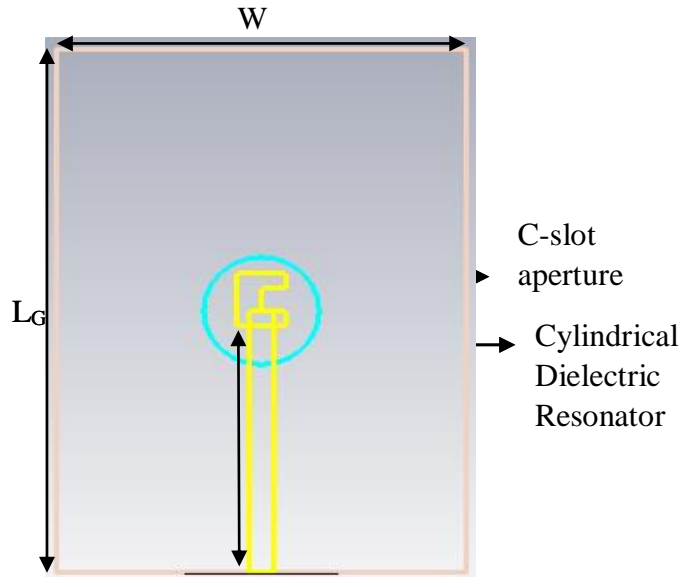


Figure 4.3 C-slot aperture and cylindrical dielectric resonator

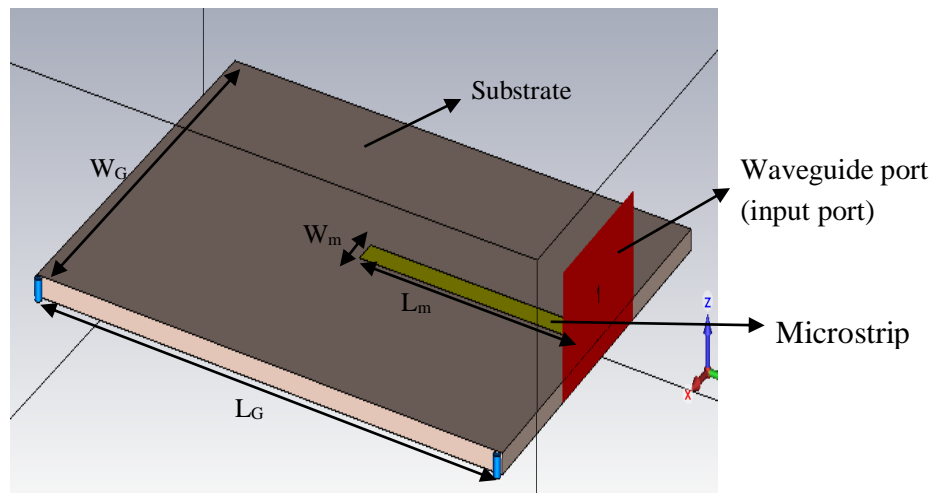
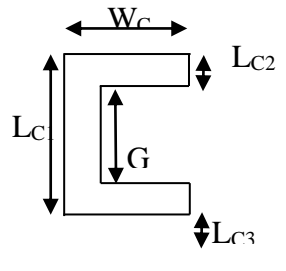


Figure 4.4 Perspective view of the simulated antenna

The x in Figure 4.3 is the position of C aperture slot from the input port. The dimension of the ground plane is 51mm x 70 mm x 1.768 mm, where $W_G = 51$ mm, $L_G = 70$ mm and $H_G = 1.768$ mm as depicted in Figure 4.4. For, the substrate, the FR4 board with permittivity, $\epsilon_s = 4.9$ and thickness 1.752 mm is utilize. The following table are the summary for details of the antenna design:

Table 4.1 Details of antenna design

	Dimension	Details
Microstrip line	$W_m \times L_m = 3\text{mm} \times 35\text{mm}$	Material = Copper
C slot	$L_{C2} = L_{C3} = 2\text{mm}$ $L_{C1} = 7\text{mm}, W_C = 6\text{mm},$ gap between arm, $G = 3\text{mm}$	
Ground plane	$W_G \times L_G \times H_G$ $= 51\text{mm} \times 70\text{mm} \times 1.768\text{mm}$	Copper layer= 0.016mm Substrate= FR4 FR4 dielectric constant= 4.9
Cylindrical Dielectric Resonator	Radius=7.2mm Height= 3mm	Material= CCTO CCTO dielectric constant= 55

In the simulation design, the x in Figure 4.3 which is the position of the slot from input port have been varied from 33 mm to 9 mm with 0.5 mm interval to obtained both 2.4 GHz and 5.0 GHz resonant frequency. Resonant frequency is the frequency which the antenna operate properly and efficiently. 2.4 GHz and 5.0 GHz is choosen for WLAN application. From the simulation, return loss, resonant frequency, bandwidth impedance, resistance, inductance and capacitance of the antenna is obtained.

4.2 Results and Discussion of Mathematical Model for 2.4 GHz Resonant Frequency.

The designed antenna is a dual band Cylindrical Dielectric Resonator (CDRA) antenna with C aperture slot. The antenna is designed to have 2.4 GHz and 5.0 GHz resonant frequency for wireless application. Therefore, there are two mathematical

model developed, each for 2.4 GHz and 5.0 GHz resonant frequency. This section presents the first mathematical model that have been developed, which is for 2.4 GHz resonant frequency.

4.2.1 Results and Data from Simulation and Design

The following graph is the graph of return loss (S_{11}) versus frequency obtained from CST software. The graph shows the resonant frequency and return loss for different position of Cslot from resonant frequency.

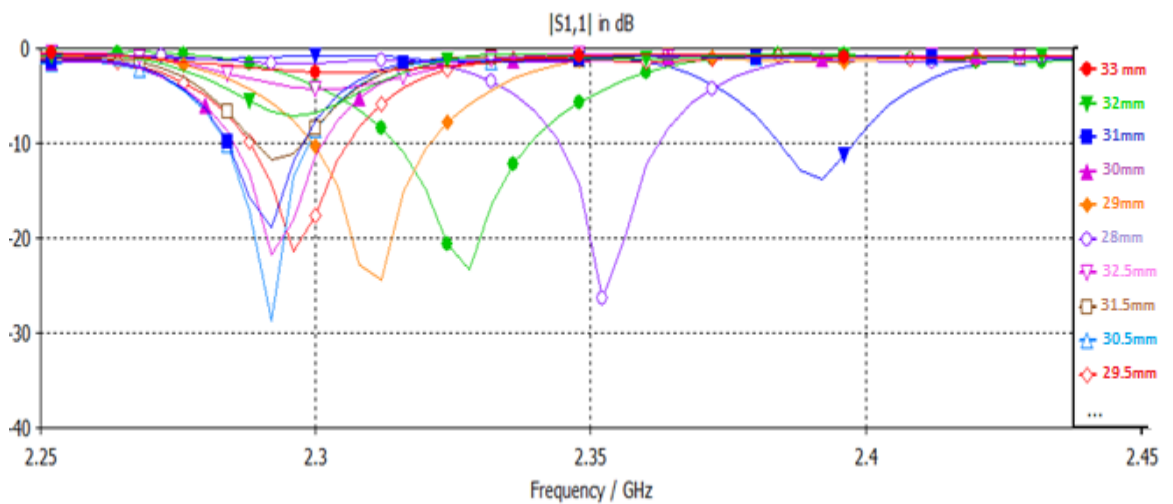


Figure 4.5 Graph of Return Loss versus Frequency (near 2.4GHz)

The graph shows that from 33 mm to 30 mm and from 27 mm to 9 mm position of C slot from input port, there are no resonant frequency close to 2.4 GHz. For position of C slot at 31.5 mm to 30.5 mm, the resonant frequency obtained is constant, which is 2.292 GHz. The resonant frequency is increasing as the position is varied from 30 mm to 27.5 mm.

Return loss (S_{11}), resonant frequency, impedance bandwidth, resistance, inductance and capacitance obtained from the graph is summarised in the following table.

Table 4.2 Summary of results from simulation for 2.4 GHz

C slot Position from input port	Return Loss S_{11} (dB)	Resonant Frequency (GHz)	Impedance Bandwidth (GHz)	R (ohm)	L	C
31.5 mm	-11.768	2.292	0.009081	74.5774	-1.4886 nH	3.2391 pF
31 mm	-18.784	2.292	0.013651	62.9372	81.9589 pF	-58.8322 pF
30.5 mm	-28.644	2.292	0.015302	50.4727	0.2560 nH	-18.8374 pF
30 mm	-21.404	2.2923	0.015948	42.027	-1.621 pF	26.2590 pF
29.5 mm	-21.415	2.296	0.018103	42.1814	-32.172 pF	0.14940 nF
29 mm	-24.43	2.312	0.021429	50.3008	0.4148 nH	-11.4236 pF
28.5 mm	-23.327	2.328	0.024784	57.2634	-58.592 pF	79.7694 pF
28 mm	-26.237	2.352	0.017989	46.8936	-0.2412 nH	18.9805 pF
27.5 mm	-13.739	2.392	0.013793	65.4421	-1.2255 nH	3.6125 pF

From the table , it can be observed that, the resonant frequencies which close to 2.4 GHz are only obtained for simulation of antenna with C-slot position at 31.5 mm to 27.5 mm from input port. Simulation with other position of C slot failed to obtain any resonant frequency near to 2.4 GHz. The closest resonant frequency to 2.4 GHz is obtained by simulation with 27.5 mm of C-slot position from input slot which is 2.392 GHz. As explained before, it is important to obtained the 2.4 GHz resonant frequency because the antenna is designed for wireless application.

Based on Table 4.2, the antenna capacitance and inductance obtained is very small which almost equal to zero. It is due to the fact that at resonant frequency, the antenna appear purely resistive as the inductance and capacitance of the antenna

cancel each other. At this frequency, the input impedance is equal or almost equal to antenna impedance, as a result the antenna is matched with its feed and maximum power is delivered to the antenna. The plot of return loss against frequency for each position of C-slot is attached in the appendices section.

4.2.2 Results and Analysis from Matlab

Curve fitting is a method of constructing a curve, or mathematical function that has the best fit to the set of data obtained from the simulation. The curve fitting technique is applied by utilizing curve fitting tool (cftool) in Matlab software. By using cftool, the set of data obtained from CST simulation is plotted and a curve that has the best fit is constructed. From the curve, a mathematical equation is modelled. Figure 4.7 is the fitting performed to the plot of resonant frequency obtained from simulation design.

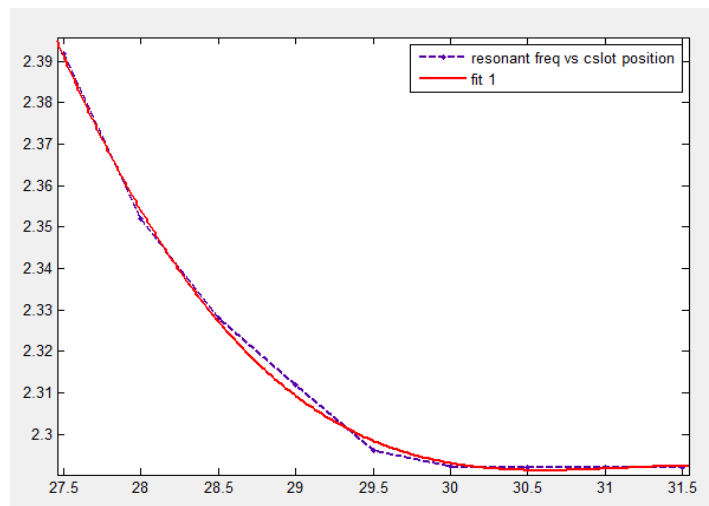


Figure 4.6 Curve fit and Graph of resonant frequency versus C slot position

The type of fitting used is cubic polynomial fit. Thus, the mathematical model will be in form of cubic polynomial equation.

From the fitting, the model obtained is:

$$f(x) = ax^3 + bx^2 + cx + d \quad (4.1)$$

Coefficients of the cubic polynomial model (with 95% confidence bounds) is:

$$a = -0.002254 \quad (-0.003333, -0.001174)$$

$b = 0.2103$ (0.1148, 0.3059)
 $c = -6.54$ (-9.357, -3.724)
 $d = 70.07$ (42.43, 97.71)
 $x =$ position of C slot from input port

By using this model, the resonant frequency of the antenna can be calculated by inserting the position of C-slot (distance of C-slot from input port) into the variable x .

Figure 4.7 is the residual plot of the model. Residual is the difference between the observed value of the dependent variable x and the predicted value (value from CST simulation). Residual can be calculated as shown the following formula:

$$\text{Residual} = \text{observed value} - \text{predicted value} \quad (4.2)$$

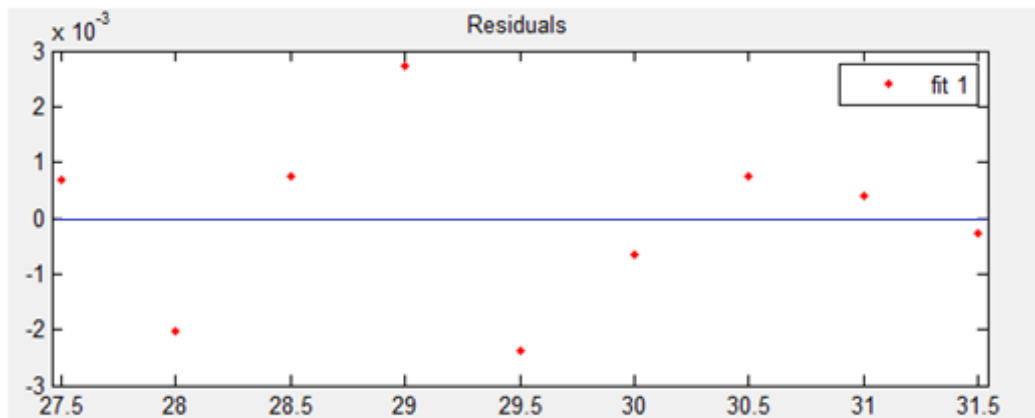


Figure 4.7 Residual plot of Mathematical model for 2.4 GHz model

If the line is a good fit for the set of data, the tabulation of residual plot will be random. If the line is a bad fit for the data, then the plot of the residual will have a pattern. From the figure above, the tabulation of the residual plot is random, thus it indicates that the line is a good fit for the set of data and the type of the fit chosen is the best fit which fit the data. It is because, ideally, the residual should be constant variance, unbiased and homoscedastic. Unbiased residual is residuals that have an average value of zero in any thin vertical strip, while a homoscedastic (same stretch)

residual is the spread of the residuals should be the same in any thin vertical strip. A fanning-out pattern on a residual plot indicates an increasing error variance, a funneling-in pattern indicates a decreasing error variance. Both of these pattern violate the constant-variance assumption. A curved pattern on a residual plot indicates that the functional form of the regression model is incorrect.

Theoretically, if the residual have a horizontal band appearance, it is reasonable to conclude that the constant variance, correct functional form and independence assumption is approximately hold. In this case, the residual plot is unbiased and homoscedastic and have no pattern. Hence, the regression performed has a constant variance, correct functional form and has independence variable.

Apart from plotting the residual, to analyze the goodness of the fit, the sum of squared error (SSE) can be calculated. SSE is a sum of the squared differences between each observation and the estimated or forecasted data. SSE calculates the sum of the squared errors of the prediction function.

$$SSE = \sum_{i=1}^N (x_i - \hat{x}_i)^2 \quad (4.3)$$

Where,

x_i = actual observation

\hat{x}_i = expected value from the fit

The calculated SSE for the fit is only 1.965e-005 which is very small (almost zero). It shows that the accuracy of the fit is very high.

In addition, R square also can be calculated to evaluate the model developed. R-square is the coefficient of determination, it indicates how well data points fit the model or curve. It also measured how close the data are to the fitted regression line. The higher the R square, the better the model fits the data. An R square of 1.0 or 100% indicates that the regression line perfectly fit the data.

$$R \text{ square} = 1 - \frac{SSE}{SST} \quad (4.4)$$

SSE= Sum of square error

SST= Total sum of error

$$SST = \sum_{i=1}^N (x_i - \bar{x}_i)^2 \quad (4.5)$$

Where

x_i = actual observation

\bar{x}_i = mean of predicted or forecasted data

The R square obtained for this model is 0.998 or 99.8% which is very high as it is close to 100%. However, there is some cases that if the model has too many predictors and higher order polynomials, it will model random noise in the data. This condition is known as over fitting the model and it produces misleadingly high R-square values and a lessened the ability and accuracy of the model to make prediction. Therefore, to avoid such case, another analysis must be carried out to analyze the model and not solely depends on R square.

Another method to verify the accuracy of the fit or model is by analyzing the adjusted R square. Adjusted R square compares the explanatory power of regression models that contain different numbers of predictors. Adjusted R square calculated by the Cftool for the fit is 0.9968 which is very high. It shows that the fit is a good fit because the higher the adjusted R square the higher the accuracy of the fit.

Root Mean Square Error (RMSE) measure how far a typical point will be from the regression line.

$$RMSE = \sqrt{\frac{1}{n} \sum_{i=1}^n (error_i)^2} \quad , \quad error_i = \hat{y}_i - y_i \quad (4.6)$$

Where,

\hat{y}_i = predicted value

y_i = observed value

The RMSE calculated is 0.001982 which is very small. Small value of RMSE shows that the difference between the predicted or forecasted value with the actual value is small. Hence, the accuracy of the model is very high.

All SSE, R square, adjusted R square and RMSE is calculated by cftool in Matlab. Based on these analysis and calculated errors, it is proven that the model developed to obtain 2.4 GHz resonant frequency and the fitting of the curve is accurate.

4.2.3 Error Calculation and Discussion

Apart from analyzing the residual, SSE, R square, adjusted R square and RMSE, further analysis have been done by comparing the value obtained from the model with the actual value from the simulation. Error have been calculated by using following formula.

$$\text{Error} = \frac{|\text{Calculated} - \text{simulated}|}{\text{simulated}} \times 100 \quad (4.7)$$

For the first model, which is the model developed for antenna with 2.4 GHz resonant frequency, the error calculated is as shown in the table 4.3.

$$f(x) = -0.002254x^3 + 0.2103x^2 - 6.54x + 70.07 \quad (4.8)$$

Table 4.3 Comparison of simulated and calculated data for 2.4 GHz model

Position, x (mm)	Simulated (GHz)	Calculated (GHz)	Error (%)
31.5	2.292	2.279	0.57
31	2.292	2.279	0.57
30.5	2.292	2.280	0.52
30	2.2923	2.282	0.45
29.5	2.296	2.288	0.35
29	2.312	2.299	0.56
28.5	2.328	2.318	0.43
28	2.352	2.345	0.30
27.5	2.392	2.38	0.50

By using the developed model, the resonant frequency is calculated by inserting the position of C-slot into variable x . The calculated resonant frequency is compared with the actual resonant frequency obtained from the simulation and error is calculated. Based on the Table 4.4, the calculated error for all position of C slot is very small which is below 1%. The highest error is only 0.57% which is when x is at 31.5 mm and 31 mm from input port. The smallest error is 0.30% when C slot is at 28 mm from input port. Small error indicates that this model have a very high accuracy.

4.3 Results and Discussion of Mathematical Model for 5.0 GHz Resonant Frequency.

4.3.1 Results and Data from Simulation and Design

Figure 4.8 is the graph of return loss (S_{11}) versus frequency which show the resonant frequency of each parameter sweep (position of C-slot from input port) obtained from simulation design utilizing CST software.

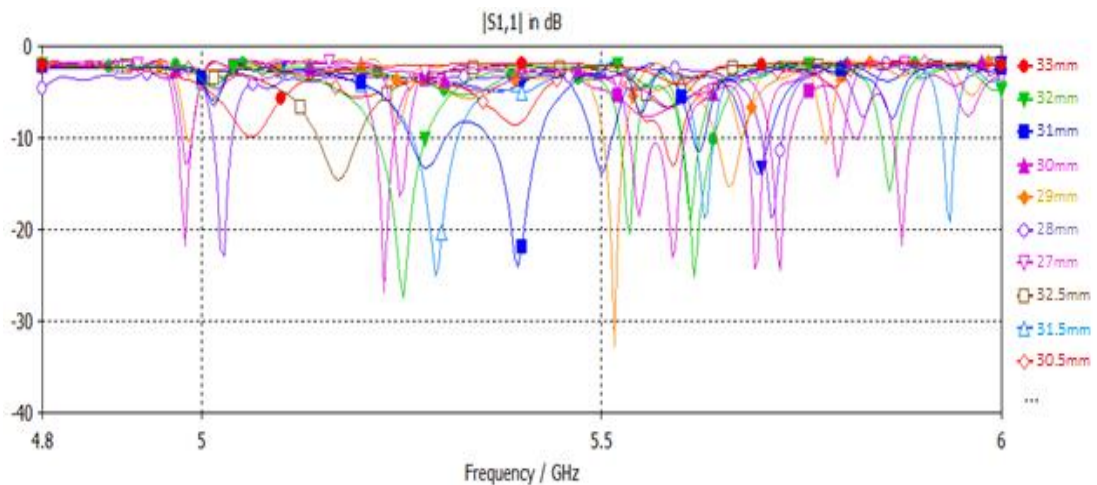


Figure 4.8 Graph of Return Loss versus Frequency (near 5.0 GHz)

The graph depicted that as the C-slot position is adjusted toward the input port with 0.5 mm interval for each position, the resonant frequency is decreasing. However, from all series of simulation, only from position 32 mm to 27.5 mm gives resonant frequency near to 5.0 GHz. At other positions, the antenna did not gives any

resonant frequency anywhere near or close to 5.0 GHz. As explained in previous section, the designed antenna is a dual band antenna for wireless application. Therefore it is important to obtained resonant frequency at 2.4 GHz and 5.0 GHz. The following table summarize the return loss (S_{11}), resonant frequency, impedance bandwidth, resistance, inductance and capacitance obtained from the graph.

Table 4.4 Summary of results from simulation for 5.0 GHz

Position from input port	Return Loss S_{11} (dB)	Resonant Frequency (GHz)	Impedance Bandwidth (GHz)	R (ohm)	L	C
32 mm	-18.81	5.86	0.020741	43.8488	0.3854 nH	-1.9139 pF
31.5 mm	-18.75	5.628	0.021816	43.5025	0.2455 nH	-3.2573 pF
31 mm	-11.368	5.624	0.013862	29.4455	0.1814 nH	-4.4144 pF
30.5 mm	-13.005	5.588	0.021633	32.2682	0.1444 nH	-5.6183 pF
30 mm	-22.587	5.5877	0.069181	41.261	0.2270 nH	-7.4240 pF
29.5 mm	-20.449	5.536	0.021767	55.2148	-0.2461 nH	3.3578 pF
29 mm	-32.672	5.516	0.027302	52.3269	14.2885 pF	-58.2647 pF
28.5 mm	-13.818	5.5	0.025862	35.4759	-0.2840 nH	2.9483 pF
28 mm	-22.837	5.028	0.023175	57.4688	65.8863 pF	-15.2074 pF
27.5 mm	-21.668	4.98	0.017201	42.8935	-92.2318 pF	11.0739 pF

The table shows that the impedance bandwidth obtained are mostly above 0.02 GHz. All the inductance and capacitance obtained at these resonant frequency is very small and almost equal to zero. The antenna appear purely resistive at resonant frequency as the inductance and capacitance of the antenna cancel each other. Due to

this reasons, all the resistance obtained is above 40 ohm, except at 31 mm, 30.5 mm and 28.5 mm. The return loss obtained at these position is only -11.368 dB, -13.005 dB and -13.818 dB respectively. It is found that, it produced low level of return loss as compared to other position. The return loss indicate the amount of power transmitted at that particular resonant frequency, the power that is not transmitted will be reflected back. The higher the resistivity of the antenna, the smaller the return loss. However, return loss below -10 dB is considered acceptable. At this point, 90% of output power is transferred to the antenna structure and radiate to free space.

4.3.2 Results and Analysis from Matlab

The second model for 5.0 GHz resonant frequency is obtained from Cftool in Matlab by performing curve fitting method to the plot of resonant frequency. The type of fit chosen is cubic polynomial fit because it is the best fit that match the plot of resonant frequency.

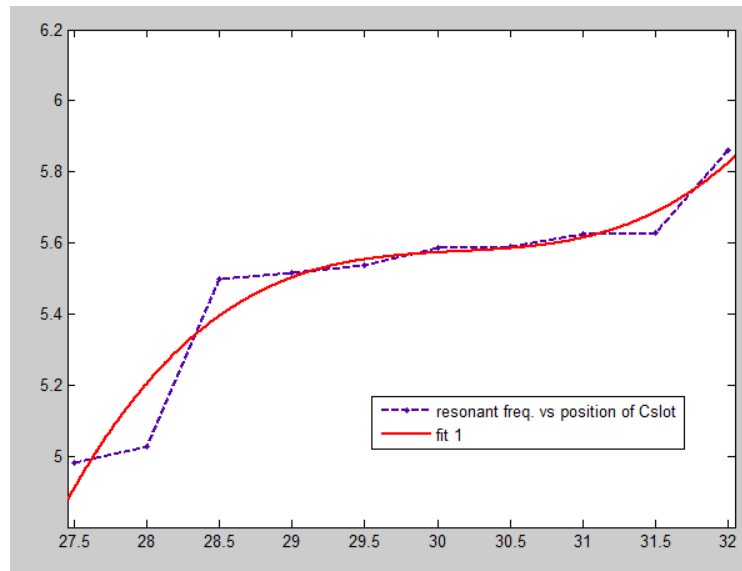


Figure 4.9 Curve fit and Graph of resonant frequency versus C slot position

In Figure 4.9, the blue line is the plot of resonant frequency against position of C-slot for 5.0 GHz, while the red line is the polynomial fit performed. From the fitting, the mathematical model of resonant frequency with the function of C-slot position from input port obtained is:

$$f(x) = ax^3 + bx^2 + cx + d \quad (4.9)$$

Coefficients of cubic polynomial model is (with 95% confidence bounds):

$$a = 0.03321 (0.0001362, 0.06627)$$

$$b = -3.003 (-5.954, -0.05095)$$

$$c = 90.53 (2.811, 178.2)$$

$$d = -904.4 (-1772, -36.56)$$

where x = position of C-slot from input port

To design an antenna with 5.0 GHz resonant frequency, the resonant frequency can be calculated by inserting the distance of C-slot from input port into variable x in the equation.

To verify or prove the accuracy and the goodness of the fit, there are several analysis and method that can be performed. Similar to mathematical model for 2.4 GHz, this model can be analysed by plotting the residual and calculating SSE, R square, adjusted R square and RMSE. Figure 4.10 is the tabulation of residual.

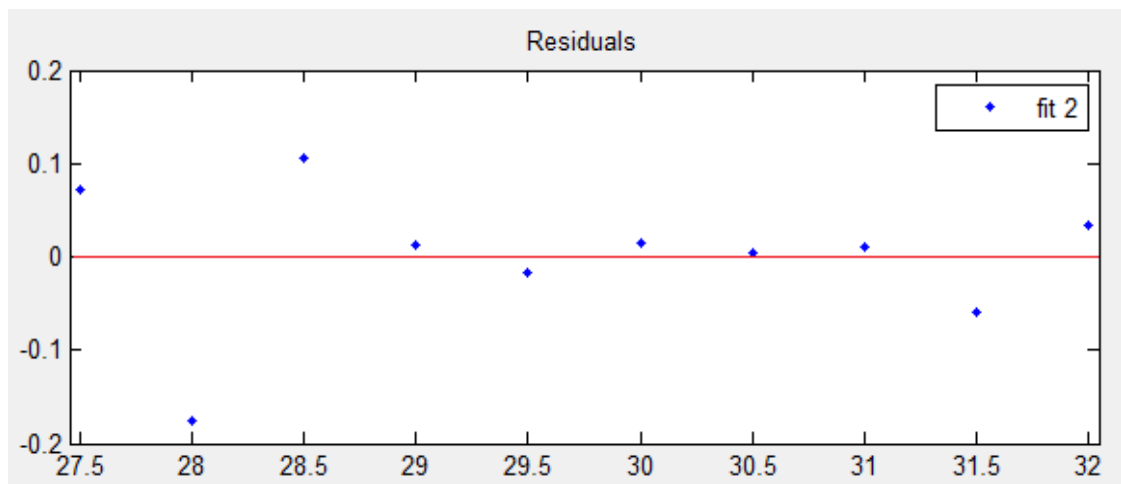


Figure 4.10 Residual plot of Mathematical model for 5.0 GHz model

The residual is the difference between the observed value of the dependent variable x and the predicted value (value from CST simulation). In Figure 4.10, the pattern of residual plot tabulation is random, therefore it means that the line is a good

fit for the set of data (resonant frequencies). Since, the residual plot is unbiased and homoscedastic and have no pattern. Hence, the regression performed has a constant variance, correct functional form and has independence variable.

The sum of the squared differences between each simulated and the estimated or forecasted data is very small as the SSE calculated by the Cftool is only 0.05289. Small SSE equivalent to high accuracy of the curve fit.

Apart from that, the R square calculated by the Cftool is 0.921 or 92.1%. Eventhough not as high as previous model, however it is still considered as high since it exceed 90%. R square is an indication of how well data points fit the model. A data that fit the model very well will give high value of R square. The value of R square=0.921 shows that the fit achieve 92.1% of the total variation in the data about the average.

In addition, the Cftool is also used calculate the adjusted R square. The adjusted R square obtained is 0.8815. The adjusted R-square statistic can be any value less than or equal to 1, with a value closer to 1 indicating a better fit. Negative values may yield when the model consist of terms that do not fit the model. As for this model, the value of adjusted R square obtained is positive. It indicates that all the terms fit the model.

Furthermore, the RMSE calculated is 0.09389. Lower values of RMSE indicate better or good fit and high accuracy. RMSE is a good measure for the accuracy of the model predicts the response, and is one of the most important criterion for fit since the main purpose of the model is prediction of resonant frequency. For this model, the RMSE is very low, which verified the accuracy of the model and the wellness of the fit.

4.3.3 Error Calculation and Discussion

Apart from analyzing the residual, SSE, R square, adjusted R square and RMSE, further analysis have been done by comparing the value obtained from the model with the actual value from the simulation. Error have been calculated by using following formula.

$$\text{Error} = \frac{|\text{Calculated} - \text{simulated}|}{\text{simulated}} \times 100 \quad (4.10)$$

Table 4.5 compares the simulated resonant frequency with calculated resonant frequency. It also shows the calculated error for the second model which is the model for 5.4 GHz resonant frequency.

$$f(x) = 0.03321x^3 - 3.003x^2 + 90.53x - 904.4 \quad (4.11)$$

Table 4.5 Comparison of simulated and calculated data for 5.0 GHz model

Position, x (mm)	Simulated (GHz)	Calculated (GHz)	Error (%)
32	5.86	5.713	2.51
31.5	5.628	5.576	0.92
31	5.624	5.506	2.10
30.5	5.588	5.48	1.93
30	5.5877	5.47	2.11
29.5	5.536	5.454	1.48
29	5.516	5.406	1.99
28.5	5.5	5.301	3.62
28	5.028	5.114	1.71
27.5	4.98	4.82	3.21

Based on the table, eventhough not as low as the first model, the error of calculated resonant frequency compared to simulated resonant frequency for each C-slot position is very low. The highest error is only 3.62% which is when C-slot is at 28.5 mm from the input port. While the lowest error is 0.92% when position of C-slot is 31.5 mm. From this table, it is proven that the second model also have a very high accuracy, up to 99.08%.

4.4 Advantages of Developed Models

As mentioned before, conventionally, the resonant frequency can be obtained either through simulation or by measuring the fabricated antenna using network analyzer. However, by utilizing the develop model, the time to determine resonant frequency of

a CDRA with C-slot can be reduced significantly. Table 4.6 shows comparison between the average time taken to determine resonant frequency of CDRA with C-slot by using network analyser and simulation with the time taken to determine resonant frequency through calculations.

Table 4.6 Time taken to determine resonant frequency for each method

Network Analyser	Mathematical Model	Simulation (CST software)
10 -20 minutes	1-3 minutes	15- 40 minutes

The analysis is evaluated by measuring the time taken to obtain the resonant frequency for each method by using stop watch. By using network analyzer, the average time taken to obtained resonant frequency is from 10 to 15 minutes (including time taken to set up the network analyzer). As for the mathematical model, the time taken to calculate the resonant frequency is only from 1 to 3 minutes. By using simulation, using a typical computer or laptop, the time taken for transient analysis may take up to 40 minutes (depending on the performance of the computer). However, by using high performance computer or super computer, the time taken will be shorter.

In addition, the time taken and cost to design a CDRA with C-slot also can be greatly reduced. It is because, currently, to design a CDRA with C-slot antenna, heuristic method is used. Heuristic method is a try and error method where a series of simulation design will be done until an antenna with desired resonant frequency is manage to be obtain. There are also a lot of antenna need to be fabricated until antenna with desired resonant frequency is obtained. However, with the developed model, the resonant frequency and the distance of C-slot can be obtained prior to simulation design and fabrication of antenna. Thus, the time and cost to design the antenna is lower.

CHAPTER 5

CONCLUSION AND RECOMMENDATION

5.1 Conclusion

This project is proposed to formulate a mathematical model which represent tuning slot parameters versus resonant frequency of DRA. The manipulated variable which is the tuning slot parameter that have been varied in this project is the C-slot position. A series of simulation and design has been carried out by using CST software to obtain the resonant frequency, return loss, impedance bandwidth, reactance, inductance and capacitance of the antenna at each position of C-slot.

From the data obtained, two mathematical model have been developed by using Cftool in Matlab for dual band antenna at 2.4 GHz and 5.0 GHz resonant frequency each. By utilizing Cftool, graph of resonant frequency versus C-slot position have been plotted. Cubic polynomial fit is chosen for both model as it give the best fit among all other type of it. To study and verify the accuracy of the models and the curve fit, thorough analysis and error calculation have been done. One of the analysis performed is by plotting the residual of the model. Both of the model's residual plot have random pattern, which show that, the line have a good fit with the plotted data.

Apart from residual, the SSE also have been calculated. The SSE for the first model is only $1.965e-005$, while for the second model is 0.05289. It shows that the accuracy of both fit is very high. In addition, the R square and adjusted R square are also calculated by Cftool. For the first model, the R square is 0.998 and the adjusted R square is 0.9968. As for the second model, calculated R square and adjusted R square is 0.921 and 0.8815. R square and adjusted R square is one of the indication of the model's accuracy. High R square and adjusted R square shows that the models have high accuracy.

Besides that, RMSE is also use as a method of analysis for the model. The RMSE for the first model is 0.001982 and for the second model is 0.09389. The

closer, the value of RMSE to zero, the smaller the difference between the predicted or forecasted value with the actual value. From the low RMSE obtained, both model have high accuracy as the difference of the predicted resonant frequency with the actual resonant frequency is very small.

The calculated resonant frequency from the developed mathematical model have been compared with the actual resonant frequency from CST simulation software. To analyse the accuracy of the model, error have been calculated. All the calculated error shown in Table 4.4 and Table 4.4 is very small and the differences between the actual and calculated value is very minimum. Thus, it is proven that, both of the mathematical model have a very high accuracy.

As a conclusion, the main objective of this project is achieved as the mathematical model that represent the position of C slot versus resonant frequency have been developed. From a series of analysis and calculation that have been done, it is proven that the models achieved high accuracy.

5.2 Recommendations

The discussed project in this thesis focused on developing a model of resonant frequency for CDRA with C-slot by using curve fitting technique. This model represent the relationship between positions of C-slot against resonant frequency. To improve the proposed model of resonant frequency, further study and research can be done to develop a more advanced model with the function of antenna's impedance (R, L and C) or other antenna parameters. The relationship between the antenna's resonant frequencies with antenna impedance also can be studied.

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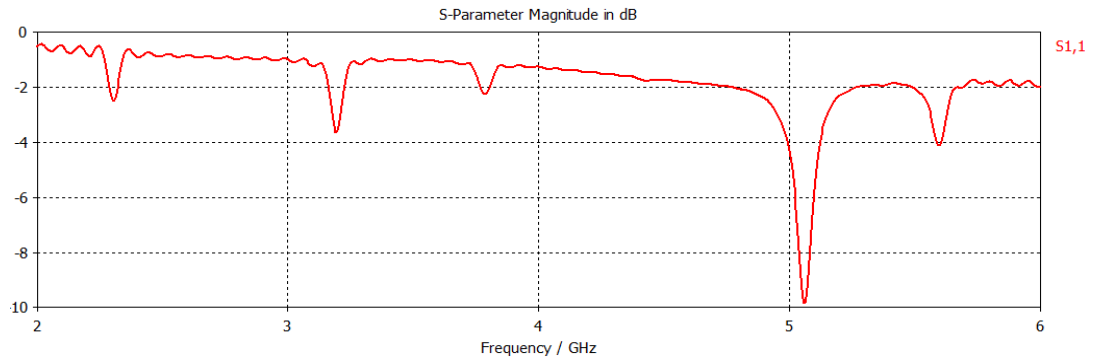
APPENDICES

APPENDIX A	Graph of Return Loss Against Frequency
APPENDIX B	Matlab Coding (First Model)
APPENDIX C	Matlab Coding (Second Model)

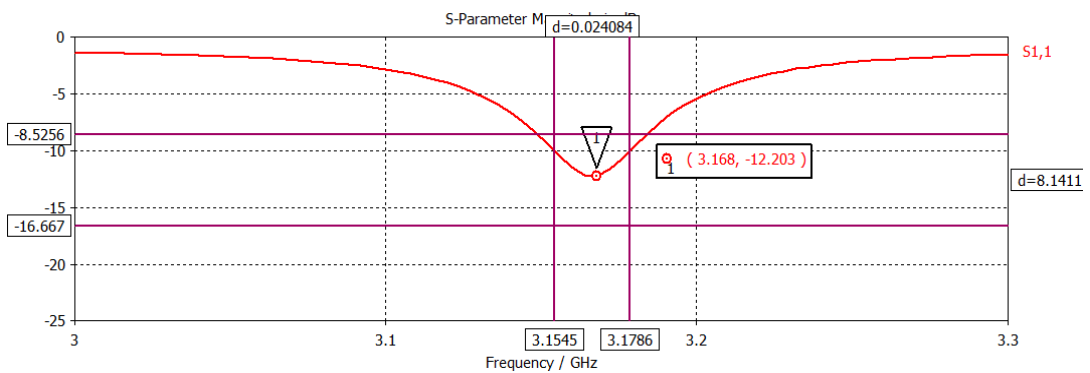
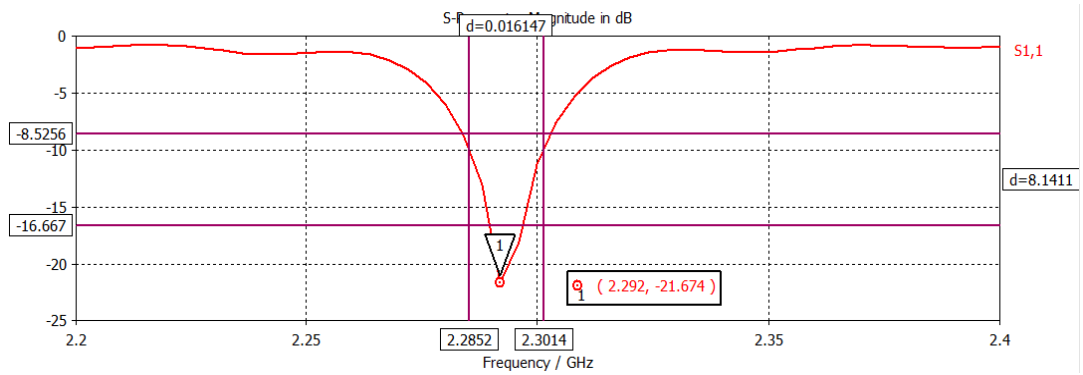
APPENDIX A

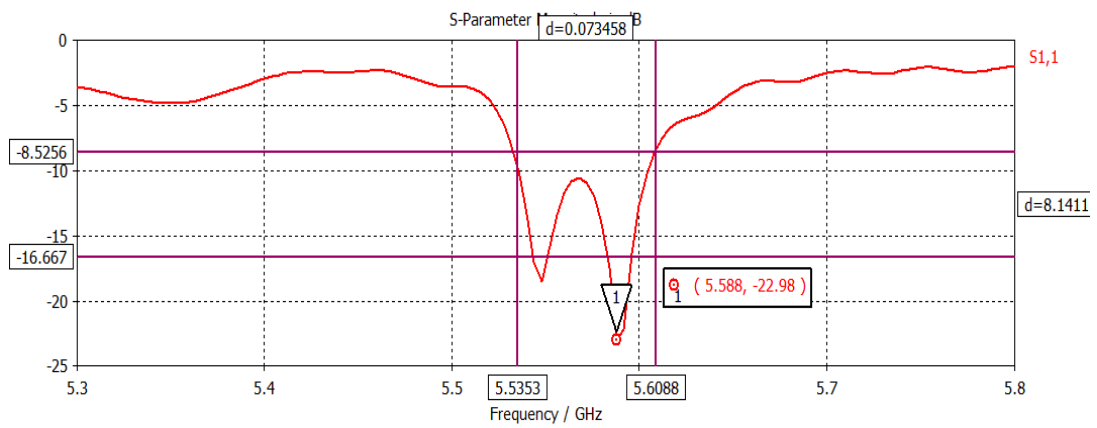
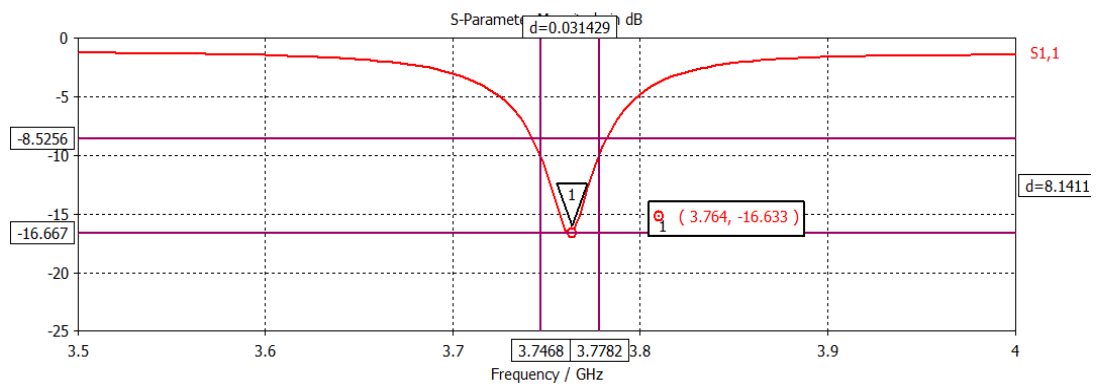
GRAPH OF RETURN LOSS AGAINST FREQUENCY

Position slot =33mm from input port

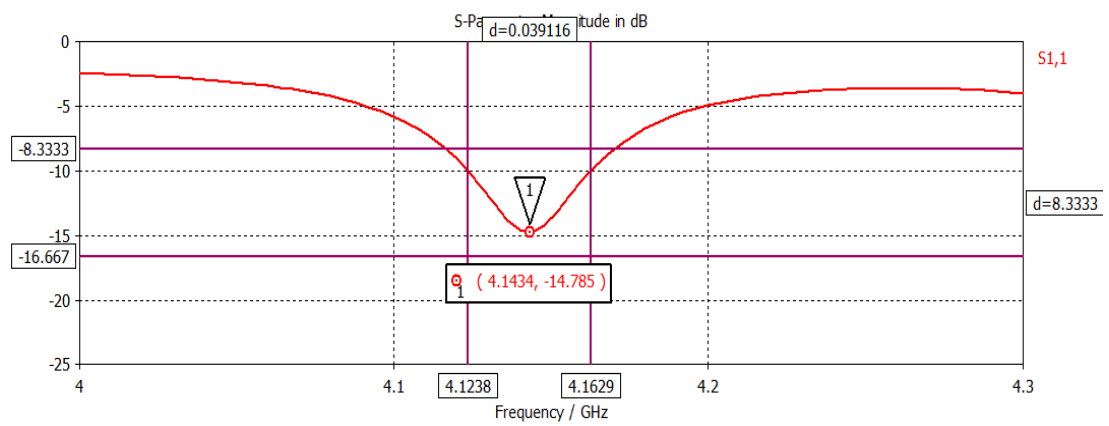


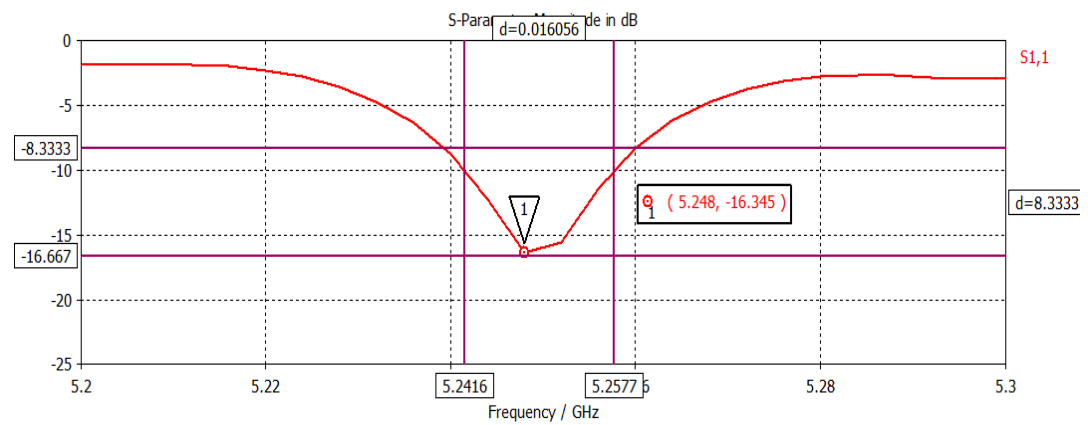
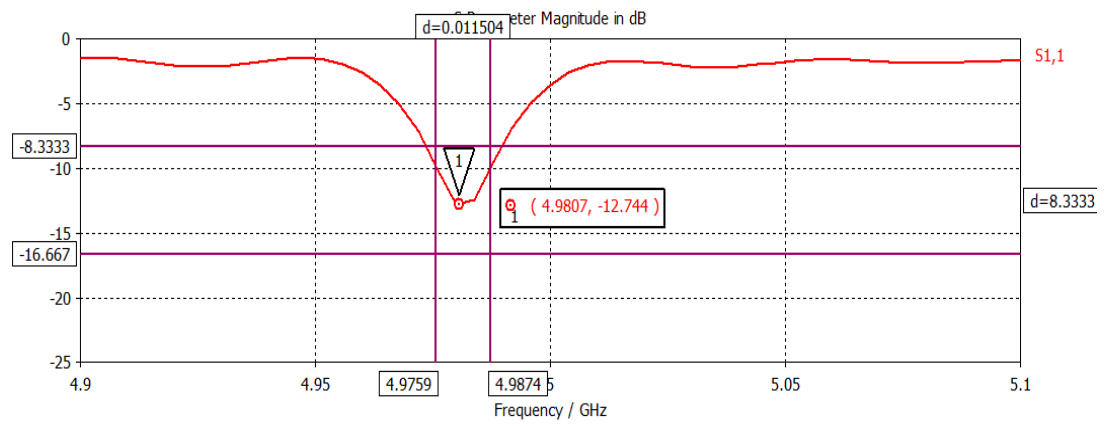
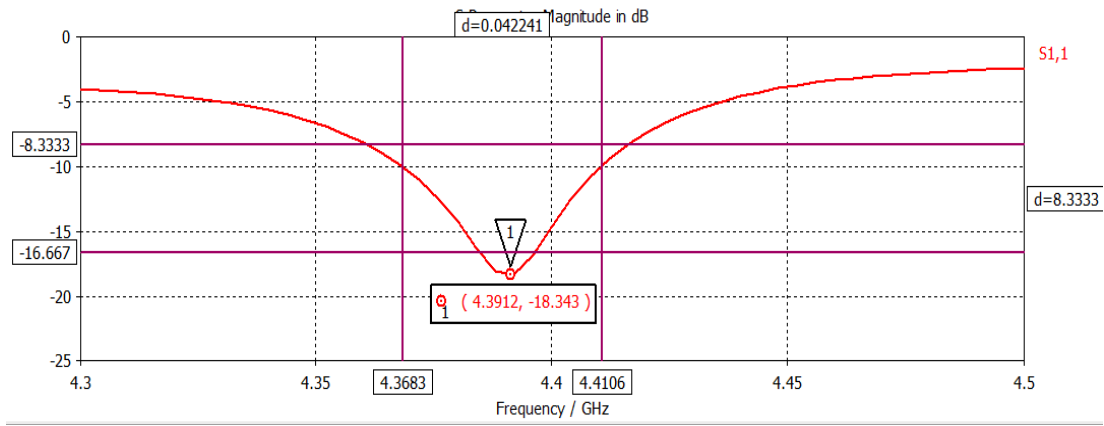
Position slot =30mm from input port

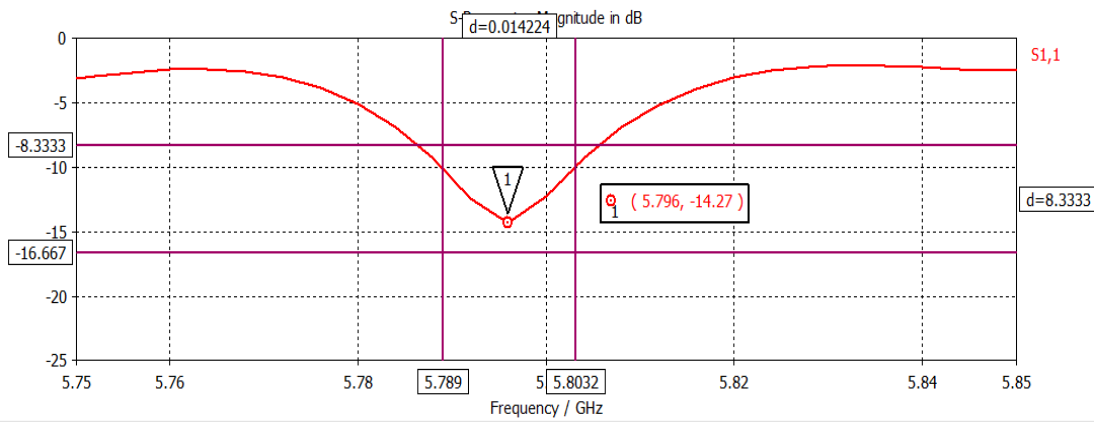
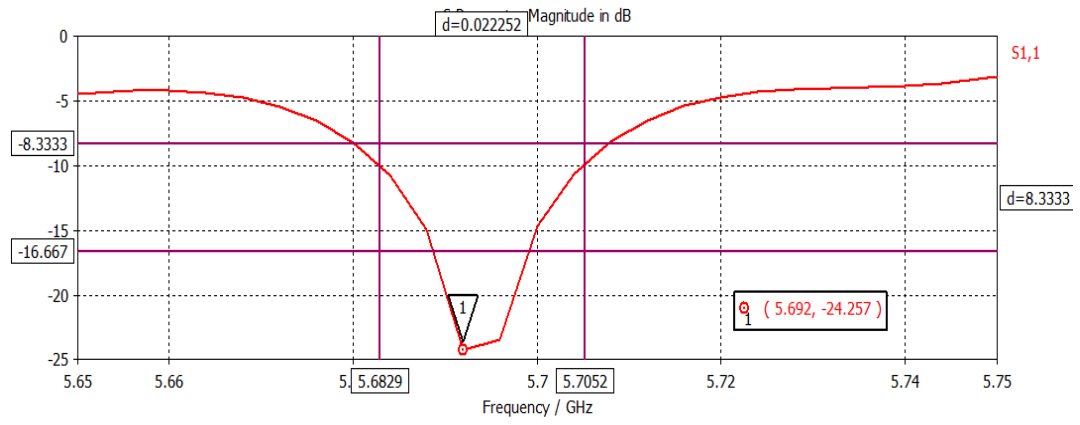




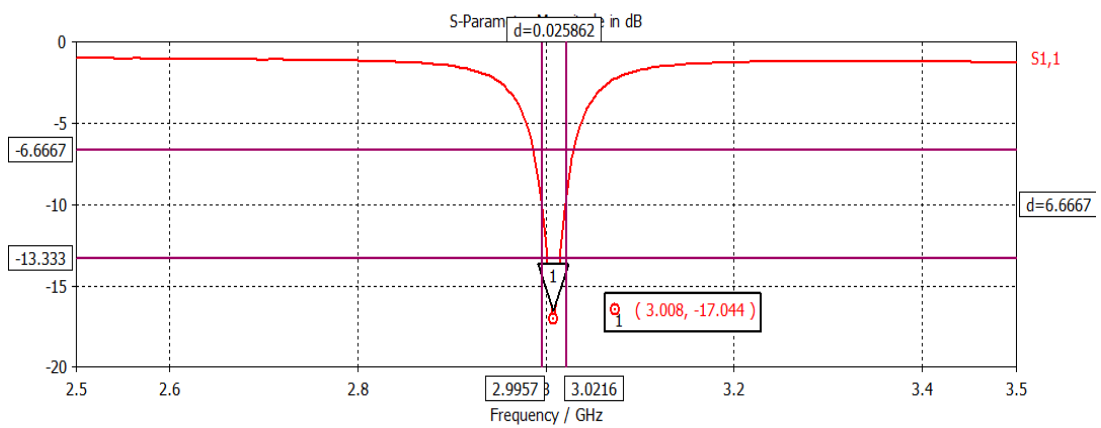
Position slot =27 mm from input port

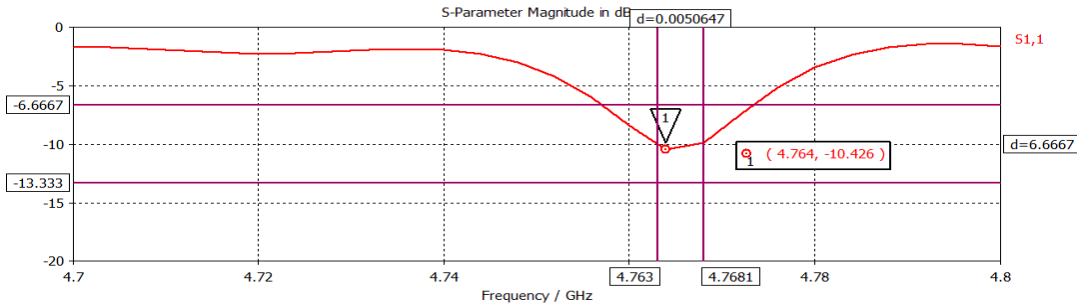
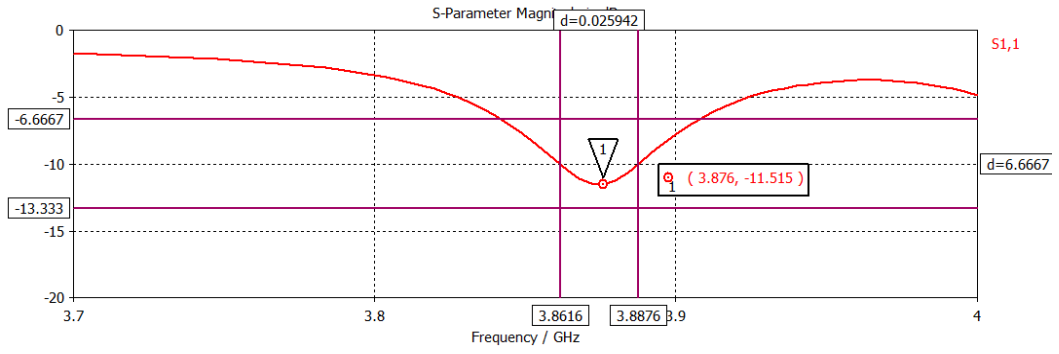




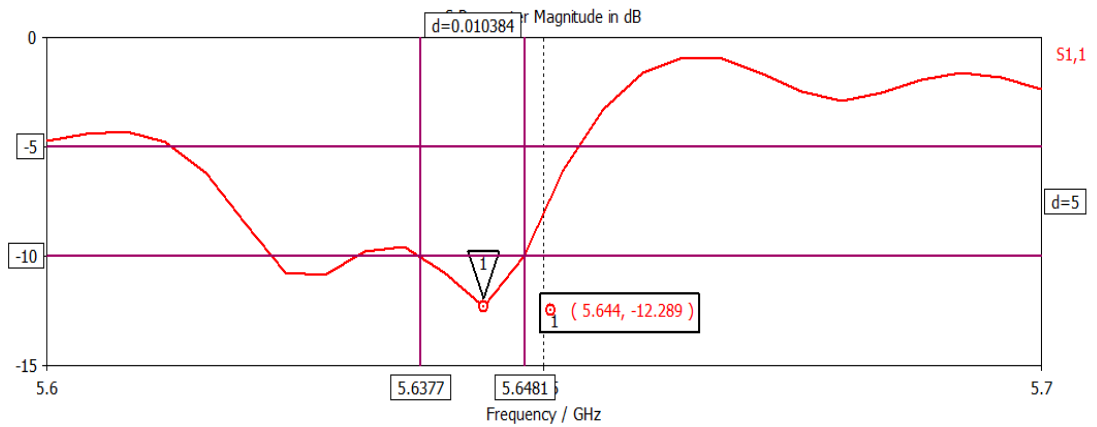
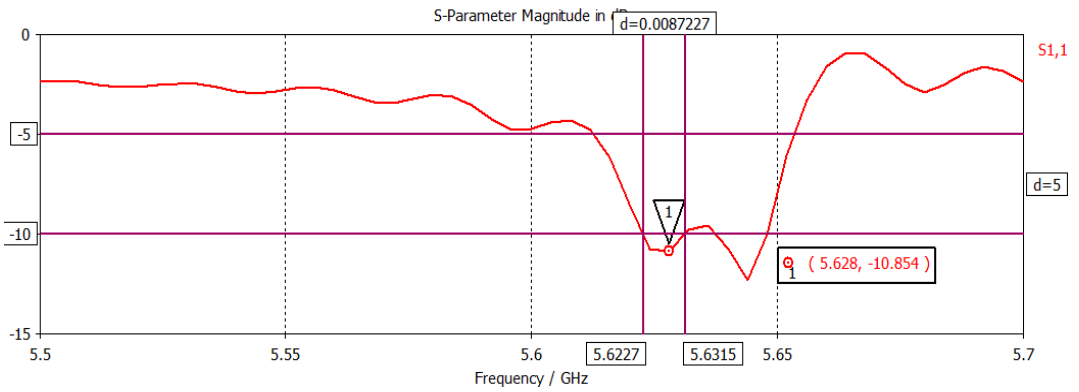


Position slot =24 mm from input port

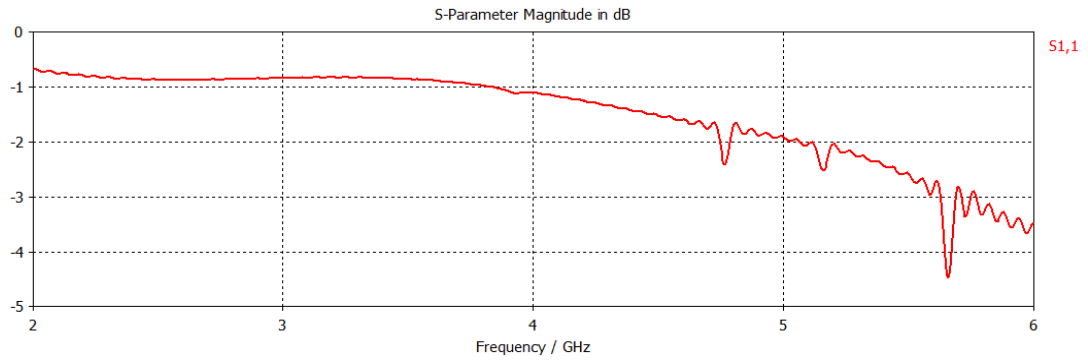




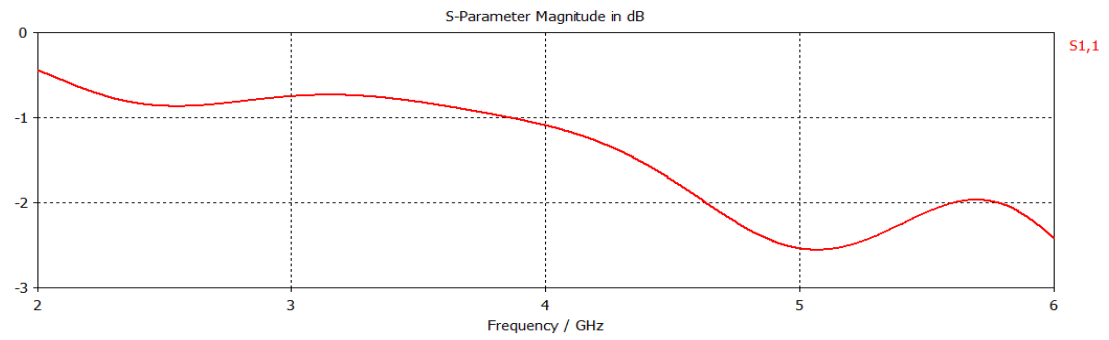
Position slot =21 mm from input port



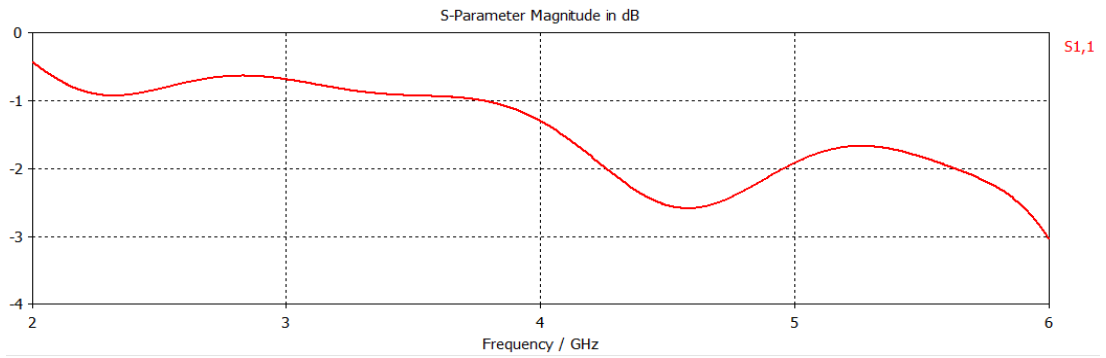
Position slot =18 mm from input port



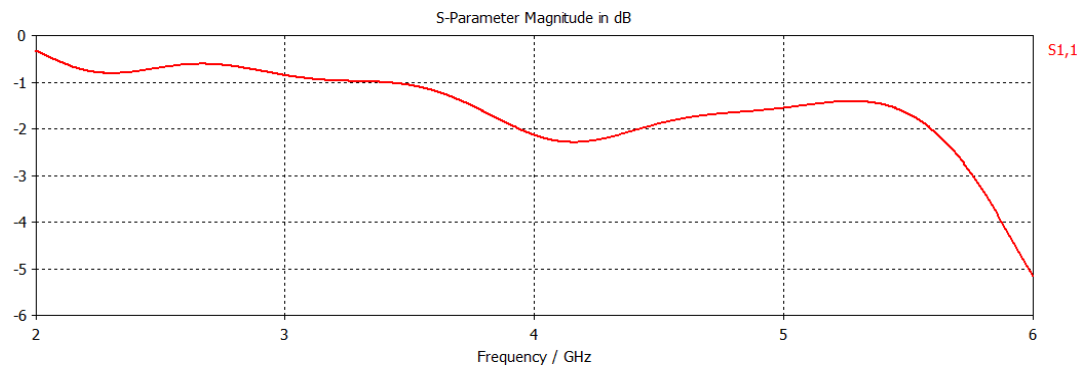
Position slot =15 mm from input port



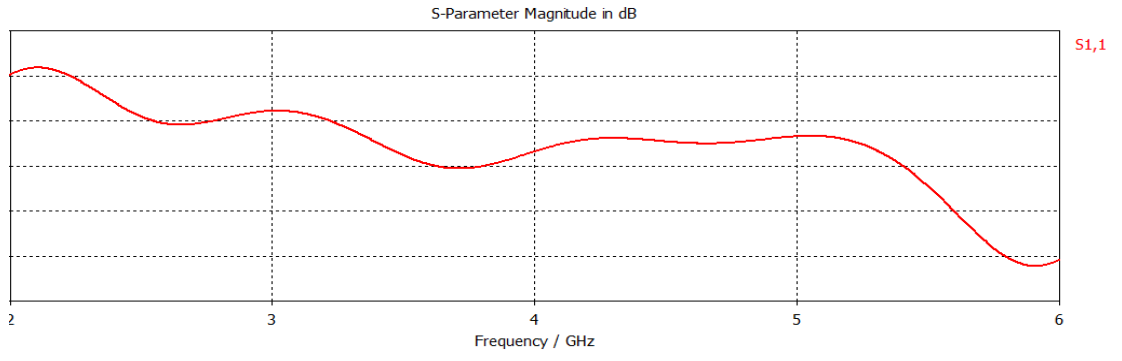
Position slot =12 mm from input port



Position slot =9 mm from input port



Position slot =6 mm from input port



APPENDIX B

MATLAB CODING (FIRST MODEL)

Main coding

```
clc,
clear,

x=[27.5:0.5:31.5];
y=[2.392 2.352 2.328 2.312 2.296 2.2923 2.292 2.292 2.292];

createFit2(x,y)
```

Function createfit2(x,y)

```
function createFit(x,y)
%CREATEFIT    Create plot of datasets and fits
%   CREATEFIT(X,Y)
%   Creates a plot, similar to the plot in the main curve fitting
%   window, using the data that you provide as input.  You can
%   apply this function to the same data you used with cftool
%   or with different data.  You may want to edit the function to
%   customize the code and this help message.
%
%   Number of datasets:  1
%   Number of fits:     1

% Data from dataset "resonant freq vs cslot position":
%   X = x:
%   Y = y:
%   Unweighted
%
% This function was automatically generated on 30-May-2014 00:17:53

% Set up figure to receive datasets and fits
f_ = clf;
figure(f_);
set(f_, 'Units', 'Pixels', 'Position', [621 109 688 489]);
legh_ = []; legt_ = {}; % handles and text for legend
xlim_ = [Inf -Inf]; % limits of x axis
ax_ = axes;
set(ax_, 'Units', 'normalized', 'OuterPosition', [0 0 1 1]);
set(ax_, 'Box', 'on');
axes(ax_); hold on;

% --- Plot data originally in dataset "resonant freq vs cslot
position"
x = x(:);
y = y(:);
h_ = line(x,y, 'Parent', ax_, 'Color', [0.333333 0 0.666667], ...
          'LineStyle', '--', 'LineWidth', 2, ...
          'Marker', '.', 'MarkerSize', 12);
```

```

xlim_(1) = min(xlim_(1),min(x));
xlim_(2) = max(xlim_(2),max(x));
legh_(end+1) = h_;
legt_{end+1} = 'resonant freq vs cslot position';

% Nudge axis limits beyond data limits
if all(isfinite(xlim_))
    xlim_ = xlim_ + [-1 1] * 0.01 * diff(xlim_);
    set(ax_, 'XLim',xlim_)
else
    set(ax_, 'XLim',[27.460000000000001, 31.539999999999999]);
end

% --- Create fit "fit 1"
ok_ = isfinite(x) & isfinite(y);
if ~all( ok_ )
    warning( 'GenerateMFile:IgnoringNansAndInfs', ...
            'Ignoring NaNs and Infs in data' );
end
ft_ = fittype('poly3');

% Fit this model using new data
cf_ = fit(x(ok_),y(ok_),ft_);

% Or use coefficients from the original fit:
if 0
    cv_ = { -0.0022538720538691371, 0.21032005771979737, -
6.5403280182702854, 70.069285353458895};
    cf_ = cfit(ft_,cv_{:});
end

% Plot this fit
h_ = plot(cf_,'fit',0.95);
legend off; % turn off legend from plot method call
set(h_(1),'Color',[1 0 0],...
    'LineStyle','-','LineWidth',2,...
    'Marker','none','MarkerSize',6);
legh_(end+1) = h_(1);
legt_{end+1} = 'fit 1';

% Done plotting data and fits.
hold off;
leginfo_ = {'Orientation','vertical','Location','NorthEast'};
h_ = legend(ax_,legh_,legt_,leginfo_{:}); % create legend
set(h_,'Interpreter','none');
xlabel(ax_,'');
ylabel(ax_,'');

```


APPENDIX C

MATLAB CODING (SECOND MODEL)

Main code

```
%use cubic polynomial

clc,
clear,

x=[27.5:0.5:32];
y=[4.98 5.028 5.5 5.516 5.536 5.5877 5.588 5.624 5.628 5.86];
%at 32mm change from 5.612 to 5.86

createfit53(x,y)
```

function createfit53(x,y)

```
function createFit(x,y)
%CREATEFIT Create plot of datasets and fits
% CREATEFIT(X,Y)
% Creates a plot, similar to the plot in the main curve fitting
% window, using the data that you provide as input. You can
% apply this function to the same data you used with cftool
% or with different data. You may want to edit the function to
% customize the code and this help message.
%
% Number of datasets: 1
% Number of fits: 1

% Data from dataset "resonant freq. vs position of Cslot":
% X = x:
% Y = y:
% Unweighted
%
% This function was automatically generated on 06-Jun-2014 17:09:34

% Set up figure to receive datasets and fits
f_ = clf;
figure(f_);
set(f_, 'Units', 'Pixels', 'Position', [659 129 688 489]);
leg_h_ = []; leg_t_ = {}; % handles and text for legend
xlim_ = [Inf -Inf]; % limits of x axis
ax_ = axes;
set(ax_, 'Units', 'normalized', 'OuterPosition', [0 0 1 1]);
set(ax_, 'Box', 'on');
axes(ax_); hold on;

% --- Plot data originally in dataset "resonant freq. vs position of
Cslot"
x = x(:);
y = y(:);
h_ = line(x,y, 'Parent', ax_, 'Color', [0.333333 0 0.666667], ...
'LineStyle', '--', 'LineWidth', 2, ...
```

```

    'Marker','.', 'MarkerSize',12);
xlim_(1) = min(xlim_(1),min(x));
xlim_(2) = max(xlim_(2),max(x));
legh_(end+1) = h_;
legt_{end+1} = 'resonant freq. vs position of Cslot';

% Nudge axis limits beyond data limits
if all(isfinite(xlim_))
    xlim_ = xlim_ + [-1 1] * 0.01 * diff(xlim_);
    set(ax_, 'XLim',xlim_)
else
    set(ax_, 'XLim',[27.454999999999998, 32.045000000000002]);
end

% --- Create fit "fit 1"
ok_ = isfinite(x) & isfinite(y);
if ~all( ok_ )
    warning( 'GenerateMFile:IgnoringNansAndInfs', ...
            'Ignoring NaNs and Infs in data' );
end
ft_ = fittype('poly3');

% Fit this model using new data
cf_ = fit(x(ok_),y(ok_),ft_);

% Or use coefficients from the original fit:
if 0
    cv_ = { 0.033205283605222, -3.0026442890387521,
            90.527135974970179, -904.40442848319447};
    cf_ = cfit(ft_,cv_{:});
end

% Plot this fit
h_ = plot(cf_,'fit',0.95);
legend off; % turn off legend from plot method call
set(h_(1), 'Color',[1 0 0],...
    'LineStyle','-','LineWidth',2,...
    'Marker','none','MarkerSize',6);
legh_(end+1) = h_(1);
legt_{end+1} = 'fit 1';

% Done plotting data and fits. Now finish up loose ends.
hold off;
leginfo_ = {'Orientation','vertical'};
h_ = legend(ax_,legh_,legt_,leginfo_{:}); % create and reposition
legend
set(h_,'Units','normalized');
t_ = get(h_,'Position');
t_(1:2) = [0.522287,0.819742];
set(h_,'Interpreter','none','Position',t_);
xlabel(ax_,'');
ylabel(ax_,'');

```