THE COMPUTER-AIDED MICROWAVE DESIGN SYSTEM (CAMDS): IMPROVEMENT, VERIFICATION, AND DEVICE FABRICATION

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Title

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The Supervisory Committee certifies that this ***disquisition*** complies with North Dakota State University's regulations and meets the accepted standards for the degree of

MASTER OF SCIENCE

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ABSTRACT

This paper presents a review of the Computer-Aided Microwave Design System (CAMDS) as originally developed by Divya Bais. Its goal was to deal with microwave design and analysis problems presented in standard textbooks such as David Pozar's *Microwave Engineering*. This work presents improvements to CAMDS and verifies its performance. The paper focusses on passive devices using microstrip transmission lines such as filters or stub tuners. Designs developed with CAMDS are compared with those reported by Pozar, simulated using the Agilent Advanced Design System (ADS), and then fabricated using an ADS layout. In appropriate cases, device performance is checked using independent computer analysis or measurement of the device response using a microwave network analyzer. The main results are an improved version of CAMDS and rigorous verification of its capabilities to produce useful designs for practical passive microwave devices.

ACKNOWLEDGMENTS

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CHAPTER 1. INTRODUCTION

Much of modern radio-frequency communications occurs in the microwave region of the frequency spectrum. This band extends from about 300 MHz to as high as 300 GHz. The microwave engineering student is usually introduced to the design and analysis of devices in the lower portion of this frequency range or the range of about 500 MHz to 10 GHz. Design and analysis of these devices is customarily done with the aid of digital computers and programs specifically formulated to serve the needs of the designer working in this frequency range.

This paper presents the software and hardware verification of example problems from a standard advanced microwave engineering textbook [1] using the Agilent Advanced Design System ADS [2], the Computer-Aided Microwave Design System (CAMDS) [3], and independent computer analysis using MATLAB. This work also checks to see if the results generated by CAMDS as developed by Bais [4] are similar to those of Pozar. Furthermore, it focuses on fabrication of these example problems and checking their response using a network analyzer to see if these problems are practically realizable. This paper deals only with microstrip lines. The scattering parameters are mostly used in this paper. This paper suggests improvements in Bais [4]. Numerical examples have been solved using CAMDS to show the usefulness of the software. These numerical results are compared with the experimental results. This paper also gives a user manual for CAMDS. Some example problems have been verified with MATLAB also. The ADS software that has been used is an industry-standard microwave engineering computer-aided-design (CAD) program. Agilent ADS allows microwave engineers to analyze, design, and simulate active and passive microwave components and systems.

1.1 Project Overview

This paper is organized in eight chapters. The first chapter lays out the introduction about the project. It discusses the basic concepts involved with CAMDS and ADS. The second chapter gives a detailed explanation about the scattering parameters. Scattering parameters are used in this paper in analysis and in the measurement phase. The third chapter reviews the CAMDS software. The fourth chapter deals with microstrip. It provides formulas for the effective dielectric constant and characteristic impedance of microstrip lines. It gives detailed steps for microstrip problems using the CAMDS software and explains basic microstrip concepts. The fifth chapter discusses microwave filters. It deals with stepped-impedance low-pass filters and the design of low-pass filters using stubs. It also explains the design of a stepped-impedance filter and the design of a low-pass filter using stubs with ADS. This chapter also includes detailed instructions for solving these filter problems using the CAMDS software. This is done to verify that the results generated using this software are the same as those obtained in Pozar. The fifth chapter also shows the experimental results obtained after fabricating the device with a comparison with an analytical solution. The sixth chapter presents impedance matching which is also known as tuning. Two types of matching networks are discussed in this section: the L match and single-stub tuning. Results obtained from CAMDS are compared with Pozar. The seventh chapter discusses a microwave design project presented in Bais [4] and suggests improvements to that work. Conclusions and recommendations for future work are given in the eighth chapter.

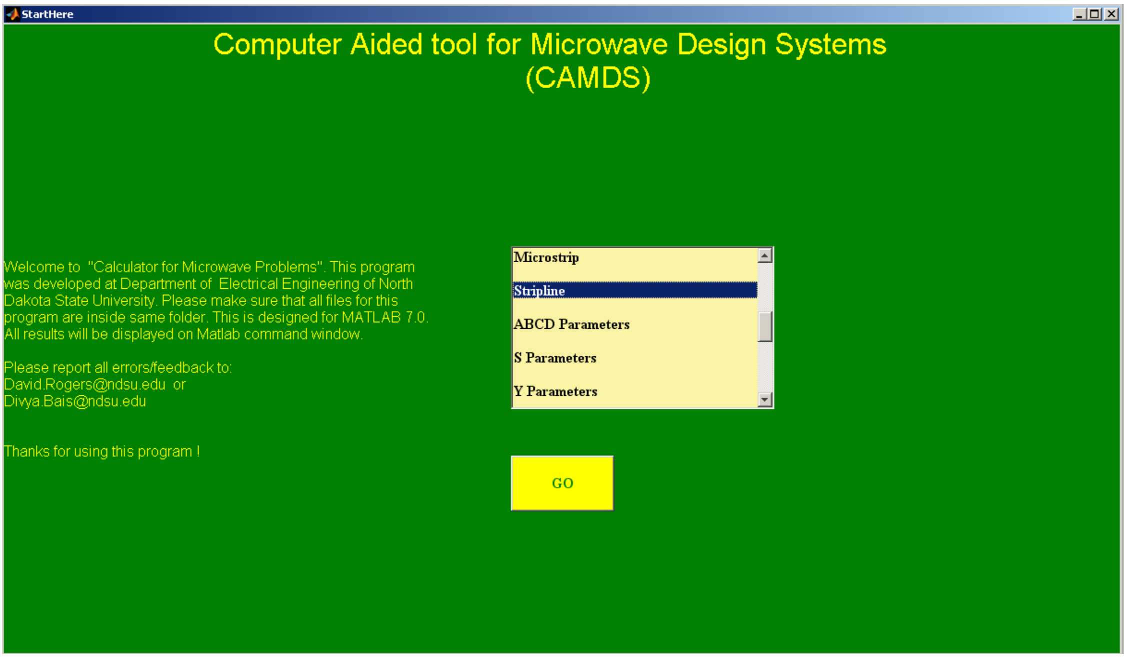
1.2 Advanced Design System (ADS)

The Advanced Design System (ADS) is a leading design automation system used for RF, microwave and high-speed digital applications. It provides an integrated environment for designing RF electronic products. It is easy to use and self-explanatory. The designer uses ADS to design a circuit schematic and produce a layout to meet certain design goals. A major advantage of ADS is that the user can change one or more design parameter values and quickly see the effect on the output without re-simulation of the entire design. ADS has a large library of transmission-line and passive component models [2].

1.3 Computer-Aided Microwave Design System (CAMDS)

The Computer-Aided Microwave Design System is structured to help student engineers solve problems in microwave engineering. It is a graphical user interface (GUI) program written in MATLAB 7. This software is used to solve problems such as filters designed using Kuroda's identities, stepped-impedance filters and impedance matching devices. Microwave engineering requires the understanding and use of complex mathematical calculations. Various graphical-user interface CAD tools are available in CAMDS to solve these microwave problems. CAMDS is a collection of scripts or .m files. It is an interactive program. Most of the files are capable of running independently. CAMDS was developed using MATLAB to overcome some problems related to the use of CAD tools. They include maintenance and operation of such tools and the extra time required by the students and instructors to learn to use such tools. CAMDS overcomes these disadvantages because MATLAB is widely used and can be easily installed on computers. Moreover, CAMDS itself is self-explanatory and easy to use [4].

CAMDS uses only one GUI in the suite as shown in Fig. 1.1. The StartHere.m file helps the user to navigate. A user can choose a program to be executed and then press the GO button to run it. The screen shot of the start page of the CAMDS software is shown in Fig. 1.1. Additional suggestions for the use of CAMDS occur later in this paper, starting in Chapter 3.



Computer Aided tool for Microwave Design Systems
(CAMDS)

Welcome to "Calculator for Microwave Problems". This program was developed at Department of Electrical Engineering of North Dakota State University. Please make sure that all files for this program are inside same folder. This is designed for MATLAB 7.0. All results will be displayed on Matlab command window.

Please report all errors/feedback to:
David.Rogers@ndsu.edu or
Divya.Bais@ndsu.edu

Thanks for using this program !

Fig. 1.1. The CAMDS “Start” page.

CHAPTER 2. THE SCATTERING PARAMETERS

The scattering or S parameters describe the electrical behavior of various electrical networks. S parameters do not use short- and open-circuited networks to characterize an electrical network. Instead, matched loads are used. These terminations are used at high signal frequencies thus making measurements possible. Scattering parameters are defined by using incident and reflected waves instead of port voltages and currents [5]. A two-port network with its incident and reflected waves is shown in the Fig. 2.1. Here $a_1$and a_2 are the incident waves, and $b_1$and b_2 are the reflected waves.

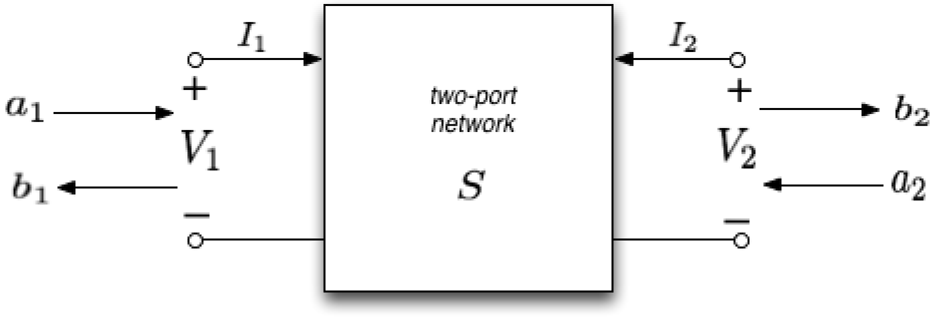


Fig. 2.1. Incident and reflected waves in a two-port network.

The relation between the incident and reflected waves and the scattering matrix is as follows:

$$\begin{pmatrix} b_1 \\ b_2 \end{pmatrix} = \begin{pmatrix} S_{11} & S_{12} \\ S_{21} & S_{22} \end{pmatrix} \begin{pmatrix} a_1 \\ a_2 \end{pmatrix}. \tag{2.1}$$

Expanding the matrix into equations gives:

$$b_1 = S_{11} a_1 + S_{12} a_2 \tag{2.2}$$

and

$$b_2 = S_{21} a_1 + S_{22} a_2. \tag{2.3}$$

Each equation gives the relationships between the incident and reflected waves at network ports 1 and 2 with parameters S_{11}, S_{12} , S_{21} and S_{22}. The S parameters are defined as follows:

$$S_{11} = \frac{b_1}{a_1} = \frac{V_1^-}{V_1^+}\bigg|_{V_2^+=0}, \tag{2.4}$$

$$S_{21} = \frac{b_2}{a_1} = \frac{V_2^-}{V_1^+}\bigg|_{V_2^+=0}, \tag{2.5}$$

$$S_{12} = \frac{b_1}{a_2} = \frac{V_1^-}{V_2^+}\bigg|_{V_1^+=0}, \tag{2.6}$$

and

$$S_{22} = \frac{b_2}{a_2} = \frac{V_2^-}{V_2^+}\bigg|_{V_1^+=0}. \tag{2.7}$$

The description of each S parameter is as follows:

S_{11}= input port voltage reflection coefficient,

S_{12}= reverse voltage gain,

S_{21}= forward voltage gain, and

S_{22}= output port voltage reflection coefficient.

Also, V_1^+ and V_1^- are the incident and reflected voltages at the input port while V_2^+ and V_2^- are the incident and reflected voltages at the output port.

The S parameters are better suited for microwave circuit design than impedance and admittance parameters because impedance measurement requires measurement of voltage and current which is difficult at microwave frequencies. Commercial software also uses S parameters for circuit analysis and design [6].

The scattering parameters are often used in this paper. Pozar [1] presents an extensive discussion of what is commonly known about the S-parameters. The only S-parameter components used commonly in this paper are S_{11} and S_{21}. S_{11} is the voltage reflection coefficient at the input. Often it is desired that the device match the impedance of the system. If this is the case, the magnitude of S_{11} will be small or, ideally, zero. S_{21} is very useful since it requires that the source impedance and the load impedance of the device be the system characteristic impedance, Z_o. This is the situation almost universally seen in this work. S_{21} is the ratio of the backward traveling voltage from the perspective of the output port to the forward traveling voltage at the input port. This is commonly referred to as the voltage gain. It is conveniently expressed in dB ($20 \log_{10} |S_{21}|$). If the output voltage is greater than the input voltage, S_{21} in dB will be greater than zero. This is often the case in active devices. If the output voltage is less than the input voltage, S_{21} in dB will be less than zero. This is most common with passive devices. For passive devices we often refer to the attenuation of the device. For the devices considered in this paper, the attenuation is simply the absolute value of S_{21} in dB. If an individual element in a device under study is not operated at matched conditions, often these elements and its neighbor elements can first be analyzed using the ABCD or chain matrix [1]. Then the characteristics of the scattering parameters may be applied to the overall device provided that the device is operated under matched conditions.

All of the devices in this paper that have been designed using CAMDS can be verified or analyzed with computer programs written using standard computer code. Each device can be viewed as a cascade of two-port devices or as the parallel combination of two or more cascades of two-port devices. Each device can be characterized by its ABCD or “chain” matrix. A cascade of devices can be viewed as the overall ABCD matrix formed by the product of each individual ABCD matrix taken one by one from source to load. In the case of a parallel combination of two cascades, the two overall ABCD matrices can be combined by first converting each to an overall admittance matrix (or Y-matrix) and then by using the well-known result that the combined overall admittance matrix will be the sum of the two individual overall admittance matrices. Since we are usually interested in the scattering parameters, the combined overall admittance matrix is then converted to a scattering matrix. Each additional parallel cascade can be accounted for by adding its admittance matrix to the previously obtained combined admittance matrix. From the combined matrix the individual elements of the scattering matrix of greatest interest are S_{21} and S_{11}. S_{21} gives the device voltage gain under matched conditions. S_{11} is the voltage reflection coefficient at the input given that the output is matched. The focus of this paper is that situation in which whatever simple or complicated device might be under study, it will be studied under matched conditions, which is the most common situation in microwave engineering practice. The phrase “matched conditions” here indicates that the source impedance at the input and the load impedance at the output are both equal to a standard impedance, Z_o, which is usually 50 Ω.

S_{21} is of greatest interest for devices like microwave filters or couplers. S_{11} is important for devices whose primary function is impedance matching. All the devices in this paper are customarily used under matched conditions. If this is not the case, a more generalized version of scattering parameters could be used as suggested by Brown *et al* [7]. Considering the matched conditions mentioned previously, the device input impedance as a complex number can be calculated directly using S_{11} [1]. The device designer than analyzes the input impedance as a function of frequency to evaluate the merit or utility for a certain type of matching device such as a single-stub tuner. At the same time, the designer can view S_{21} in dB to investigate the transmission characteristics of the device. In the case of a filter or a coupler, usually S_{21} in dB is of primary importance while S_{11} is of secondary importance. For a filter, S_{21} in dB should be zero in the passband and negative outside of the passband. Often the value of S_{21} in dB at the transition point between passband and stopband (or band edge) is specified at a cutoff frequency.

Two typical examples of this are the stepped-impedance filter and the filter constructed using stubs. For a coupler such as the ninety-degree quadrature hybrid [1], S_{21} in dB will be 3 dB below the input signal at the usual output ports and nonexistent in the isolated port ($S_{21} = 0$ or S_{21} in dB approaches negative infinity).

CHAPTER 3. CAMDS

The use of a CAD tool has become an important part of radio-frequency (RF) and microwave engineering courses. The study of microwave engineering requires understanding the concepts involved and developing strong analytical skills for implementing these concepts through complicated and lengthy mathematical solutions [4]. Although it is important to be well acquainted with hand calculations for the designer to understand the method, use of a CAD tool has been part of course work in many universities [8]-[10]. This chapter discusses Bais's Computer-Aided Microwave Design System (CAMDS) which was developed with undergraduate and graduate students in mind [11]. The CAMDS software was written in MATLAB to deal with many of the problems presented in microwave engineering textbooks such as Pozar [1].

3.1. Advantages and Disadvantages of CAMDS

Azemi and Stook clearly identify the advantages and disadvantages of CAD tools such as CAMDS in [9],[10]. A major advantage is the capability to solve complicated problems that would be rather unrealistic for paper-and-pen solutions. Another advantage is the possibility of increasing student interest in the subject [4]. This tool can benefit advanced undergraduate and graduate students as they develop microwave devices by providing soft design and simulation capabilities [8].

As for disadvantages, many CAD tools require a special computer configuration. Some CAD tools require a license or fee which might be beyond the means of the student or the school. Moreover, the time and energy required to learn new software can be a major problem [11]. CAMDS can be used by any student who has access to a computer that has MATLAB installed. It includes 93 pages of code, but is less than 1 MB in size.

3.2. Uses of CAMDS

CAMDS overcomes some of the disadvantages given above while providing some advantages. CAMDS was written using MATLAB so the user doesn’t have to learn a new programming language since MATLAB is included in almost all the electrical and computer engineering programs at the undergraduate and graduate level in most universities. CAMDS can be used in upper-division courses or at the graduate level. Moreover CAMDS itself is quite user friendly.

3.3. CAMDS Structure

CAMDS is a selection of scripts or .m files. Most of the files are capable of running independently. Files for filters have subroutines. The file called “takename.m” cannot run independently. Other files to fetch input from the user call this file. CAMDS as a package includes just one graphical user interface (GUI) named StartHere.m. This file helps the user to navigate through the software easily [4].

3.4. Capabilities of CAMDS

CAMDS is useful in solving problems involving microstrip, stripline, waveguides, transmission parameters, impedance matching and filter design. For the waveguide problem the user can calculate up to ten propagating modes for a given signal frequency in the waveguide. This feature is included in the design program for the waveguide. For the stub tuner, CAMDS is capable of plotting a graph for reflection coefficient vs. frequency for a defined band. The filters section in CAMDS is unique even though the current version of CAMDS is limited to filters with no more than six elements [11].

3.5. A Brief User Guide for CAMDS

This is a brief user guide for the CAMDS software. The user follows the steps listed below to install and run CAMDS [12]:

1) Store all files in CAMDS at one location, for example, “CAMDS_folder”.
2) Open MATLAB.
3) Change MATLAB’s current directory from “work” to “CAMDS_folder”.
4) Type “guide” at the command prompt.
5) Open StartHere.m from the CAMDS folder.
6) Press the “play” button (little triangular symbol in the menu bar) from StartHere.fig.
7) Choose the program you want to run from the list box and press the “Go” button.
8) Refer to the appropriate chapters later in this paper and in Bais [4] for specific examples.

CHAPTER 4. MICROSTRIP

Transmission lines in which the conducting metal surfaces that are etched on a dielectric surface lie completely on a parallel plane are known as planar transmission lines [1]. There are several common forms of planar transmission lines: microstrip, stripline, twinstrip, slotline, coplanar, suspended stripline and finline. Only microstrip planar transmission line will be discussed in this paper since it is so widely used.

Microstrip lines can be fabricated with a photolithographic process or on a milling machine. Various passive and active microwave devices are suitable for implementation with microstrip [13]. Bahl and Trivedi define a microstrip line as a "transmission line that consists of a strip conductor and a ground plane separated by a dielectric medium" [14]. A conductor of width W is applied on a thin substrate of thickness d which has a relative permittivity ϵ_r. In the absence of a dielectric ($\epsilon_r = 1$), the line can be considered as a two-wire line consisting of two strip conductors each of width W and separated by a distance of 2d with a simple TEM transmission line phase velocity equal to the velocity of light [1].

In practice the dielectric does not fill the region above the strip. This complicates the behavior and analysis of an actual microstrip line since it cannot support a TEM wave. At lower frequencies the wave is almost TEM (quasi-TEM), but at higher frequencies the travelling mode no longer remains quasi-TEM due to dispersion caused by the changing effective dielectric constant and characteristic impedance. Hybrid modes (coupled TE and TM modes) travel in a microstrip at high microwave frequencies [4].

Good approximations for the phase velocity and propagation constant can be obtained from the quasi-static solution [1]. These can be expressed as as follows:

$$V_p = \frac{c}{\sqrt{\epsilon_e}} \tag{4.1}$$

and $$\beta = k_0 \sqrt{\epsilon_e} \tag{4.2}$$

where ϵ_e is the effective dielectric constant of the microstrip line and k_0 is the propagation constant in a vacuum. The effective dielectric constant satisfies the relation $1 < \epsilon_e < \epsilon_r$ and depends on the substrate thickness d and the strip width W.

The analytical expression for the effective dielectric constant in a dispersive microstrip line is given by [4]:

$$\epsilon_e(f) = \epsilon_r - \frac{(\epsilon_r - \epsilon_e)}{1+G\frac{f^2}{f_p^2}}, \tag{4.3}$$

where $\epsilon_e(f)$ is the effective dielectric at that frequency in GHz, ϵ_e is the static effective dielectric constant, $G = \frac{\epsilon_e}{\epsilon_r}$, $\mu = \mu_o\mu_r$ and $f_p = \frac{Z_o}{2\mu d}$. Note that Z_o is the impedance of the line, d is the substrate thickness, μ_o is the permeability in free space and μ_r is the relative permeability of the material [4].

Wheeler and Schneider give the following expression for the effective dielectric constant [15]:

$$\epsilon_e = \frac{\epsilon_r+1}{2} + \frac{\epsilon_r-1}{2}\frac{1}{\sqrt{1+\frac{12d}{W}}}. \tag{4.4}$$

Equation (4.4) is used by Pozar [1] and in CAMDS. Bahl and Trivedi have given expressions for Z_0 and ϵ_e. Their formulas for the characteristic impedance, Z_0, and the effective dielectric constant are given in equations (4.5) and (4.6). Expressions for $\frac{W}{d}$ follow as (4.7)-4.8).

For $\frac{W}{d} \le 1$,

$$Z_0 = \frac{60}{\sqrt{\epsilon_e}}\ln(8\,\frac{d}{W} + 0.25\,\frac{W}{d}), \tag{4.5}$$

where

$$\epsilon_e = \frac{\epsilon_r+1}{2} + \frac{\epsilon_r-1}{2}\left[\left(1 + 12\frac{\mathrm{d}}{w}\right)^{-1/2} + 0.04\left(1-\frac{w}{d}\right)^2\right].$$

For $\frac{W}{d} \geq 1,$

$$Z_0 = \frac{120\,\frac{\pi}{\sqrt{\epsilon_e}}}{\frac{W}{d}+1.393+0.667\ln\left(\frac{W}{d}+1.444\right)}\,, \tag{4.6}$$

where

$$\epsilon_e = \frac{\epsilon_r+1}{2} + \frac{\epsilon_r-1}{2}\left(1+12\frac{d}{w}\right)^{-1/2}.$$

Pozar and CAMDS use only the second expression for ϵ_e as shown above. For the given characteristic impedance and dielectric constant, the value for $\frac{W}{d}$ is given as follows.

For $\frac{W}{d} \leq 2,$

$$\frac{W}{d} = \frac{8\exp(A)}{\exp(2A)-2}\,. \tag{4.7}$$

For $\frac{W}{d} \geq 2,$

$$\frac{W}{d} = \frac{2}{\pi}\left[B-1-\ln(2B-1)+\frac{\epsilon_r-1}{2\epsilon_r}\left\{ln(B-1)+0.39-\frac{0.61}{\epsilon_r}\right\}\right], \tag{4.8}$$

where

$$A = \frac{Z_0}{60}\sqrt{\frac{\epsilon_r+1}{2}}+\frac{\epsilon_r-1}{\epsilon_r+1}\left(0.23+\frac{0.11}{\epsilon_r}\right)$$

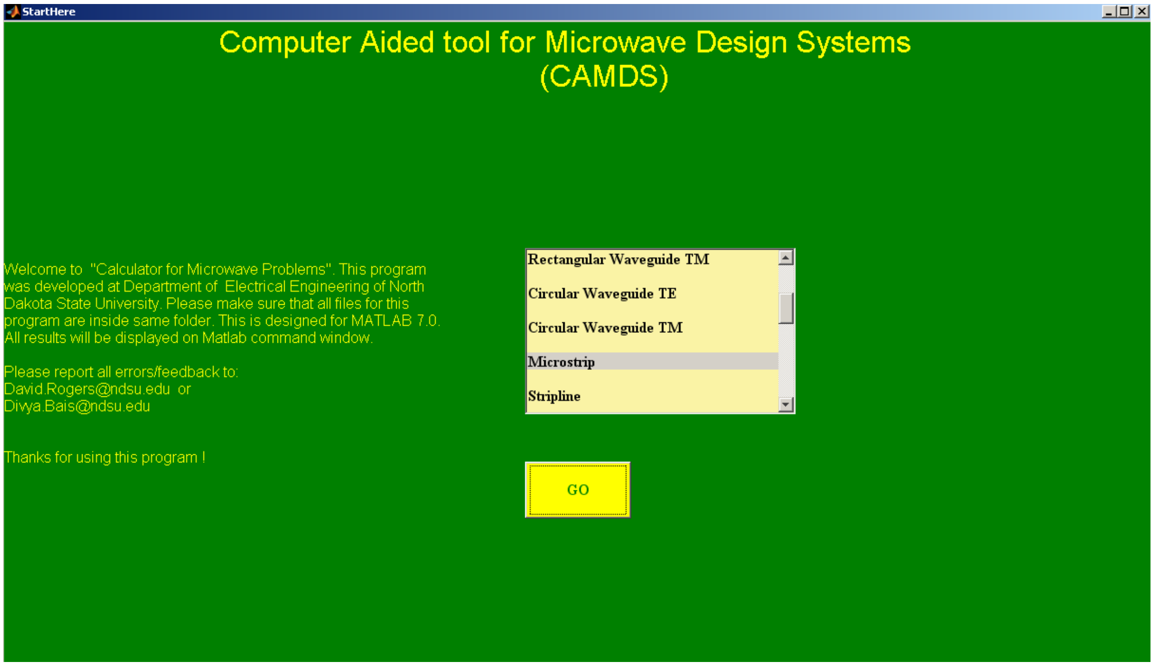
and

$$B = \frac{377\,\pi}{2\,Z_0\,\sqrt{\epsilon_r}}\,.$$

To verify the functionality of the CAMDS software developed by Bais, an example from Pozar (Example 3.7) is solved using this software. The width and length of a microstrip line for a characteristic impedance of 50 Ω and a phase shift of 90° are required. The thickness of the substrate d is given as 0.127 cm and ϵ_r = 2.2. CAMDS is used for calculating the design parameters of the microstrip. CAMDS has two procedures available: design and analysis. The "microstrip.m" file contains the code. The design part of the software assumes that the user knows the characteristic impedance whereas the analysis part assumes the user knows the $\frac{W}{d}$ ratio (the ratio of the conductor width to the substrate thickness).

To solve the above problem using CAMDS, a detailed description of the steps to be followed is given below.

1) Open StartHere.fig by typing "guide" in the command prompt and then select the run button from the menu. A start window will open. From the drop-down menu the user selects Microstrip as shown in the Fig. 4.1.



Computer Aided tool for Microwave Design Systems (CAMDS)

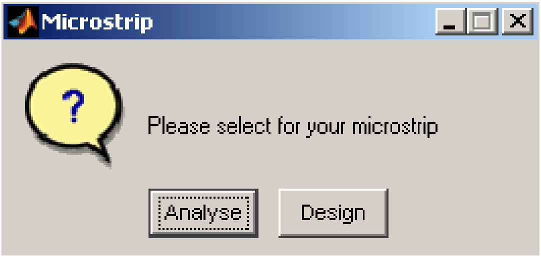
Welcome to "Calculator for Microwave Problems". This program was developed at Department of Electrical Engineering of North Dakota State University. Please make sure that all files for this program are inside same folder. This is designed for MATLAB 7.0. All results will be displayed on Matlab command window.

Please report all errors/feedback to:
David.Rogers@ndsu.edu or
Divya.Bais@ndsu.edu

Thanks for using this program !

Fig. 4.1. Start page with Microstrip selected from the drop-down menu.

2) Next the user chooses either to analyze a microstrip line or to design a microstrip line. For the Pozar example the user chooses Design from the menu (Fig. 4.2).



Please select for your microstrip

Fig. 4.2. Question box.

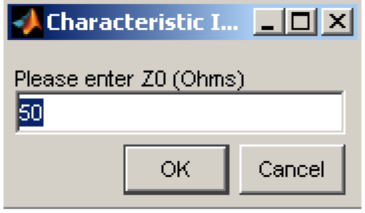
3) As per the given example problem the user enters the relative permittivity as 2.2 as shown in the Fig. 4.3.

Please enter Relative Permitivity

2.2

Fig. 4.3. Box to enter relative permittivity.

4) The characteristic impedance is given as 50 Ω in the given problem as shown below in Fig. 4.4.

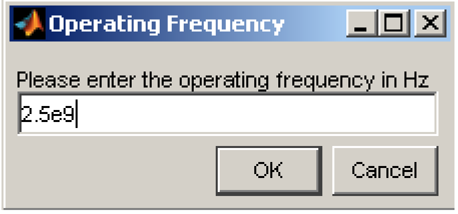


Please enter Z0 (Ohms)

50

Fig. 4.4. Box to input the characteristic impedance.

5) The given problem has an operating frequency of 2.5 GHz (Fig. 4.5).

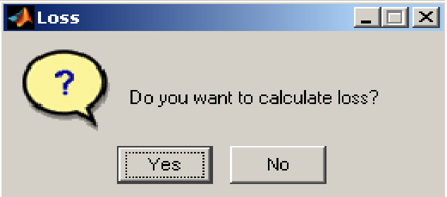


Please enter the operating frequency in Hz

2.5e9

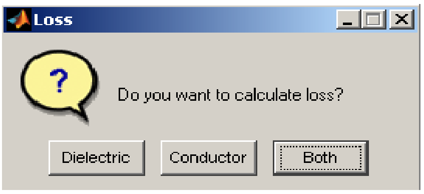
Fig. 4.5. Box to enter the operating frequency.

6) A question box will appear asking if the user wants to calculate the loss. The user may choose Yes as shown in Fig. 4.6. There are two types of loss: dielectric and conductor. A box will appear asking the user to select the type of loss. There are three options: dielectric, conductor or both, as shown in the Fig. 4.7. Here the user chooses dielectric.



Do you want to calculate loss?

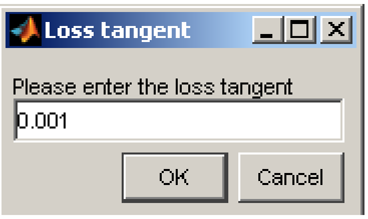
Fig. 4.6. Question box.



Do you want to calculate loss?

Fig. 4.7. Box to select the type of loss for the microstrip.

7) The user enters the value of the loss tangent as 0.001. This value is selected to demonstrate the CAMDS software but was not given in the problem.



Please enter the loss tangent

0.001

Fig. 4.8. Box to enter the loss tangent value.

8) The output is displayed in the command window.

The values that were displayed in the command window are different from the values stated in Bais [4]. This difference in the output is due to the significant improvement in the microstrip code introduced in the present work. The improvement in the code changed the values of phase velocity, guide wavelength, the propagation constant (beta), the filling factor, the capacitance per unit length of the line and the dielectric loss.

The output obtained using the improved code is as given below:

```
The Relative Permitivity is= 2.2
The characteristic impedance is 50
The effective dielectric constant is 1.8712
W/d ratio is 3.08117
Operating Frequency in Hz is 2.5e+009
k0 per meter is 52.3599
The angular velocity in rad/sec is 1.5708e+010
Phase velocity vp in m/s is 2.19311e+008
Guide wavelength Lambda_g in meters is 0.0877245
beta in per meter is 71.6241
Filling Factor in Hz is 0.853571
Capacitance per unit length of the line in farads is 9.11946e-011
Dielectric loss in Np/m is 0.0672498.
```

The values that were obtained prior to this improvement as stated in [4] in the code are as follows: the phase velocity was obtained as 2.30268e+008, the guide wavelength lambda in meters was 0.0921072, β was obtained as 88.8739, the filling factor in Hz was 0.7353228, the capacitance of the line was 8.68553e-011 and the dielectric loss in Np/m was 0.0565205.

Thus due to the improvements in the code, CAMDS generates results that are consistent with those stated in Pozar. Note that the user must consider the available number of significant figures in the input data and then apply that information manually to the data provided by CAMDS.

Returning now to the microstrip example suggested by Pozar (his Example 3.7), the width and the length of a microstrip line are required. Using the results from the improved version of the CAMDS microstrip code, the user has obtained $\frac{W}{d} = 3.08117$ and a guide wavelength, λ_g, of 0.0877245 meters. Using $d = 0.127$ cm, the user can calculate $W = 0.391$ cm. Pozar requires a quarter-wavelength line. Thus the user can calculate the required line length as $\frac{\lambda_g}{4} = 2.19$ cm. The improved version of CAMDS yields exactly the same results as those shown in Pozar.

This example shows that the improved CAMDS does solve the problem correctly but still leaves some simple decisions to the student [4].

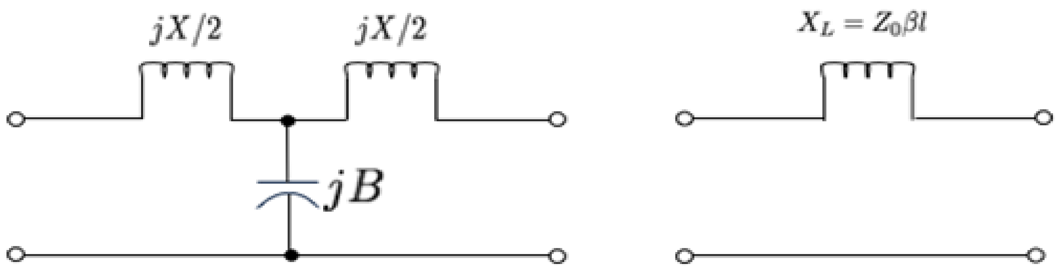
CHAPTER 5. MICROWAVE FILTERS

A microwave filter is a two-port network used to control the frequency response at a certain point in a microwave system by providing transmission at the frequencies within the passband of the filter and attenuation in its stopband [1]. There are two methods of filter design, the image parameter method and the insertion loss method [4]. Both of these circuits have lumped elements. For the practical circuits at microwave frequencies, the lumped-element circuit is transformed into transmission line sections using Richard’s transformation and Kuroda’s identities [1]. This section of the paper deals with the transmission-line filters using stepped-impedance filters and filters constructed using stubs. CAMDS transforms the lumped-element filter generated from insertion loss method using Kuroda’s identities [4] into a transmission-line filter. Filters are classified depending on their response type. The commonly used ones are Butterworth and Chebyshev filters. The Butterworth has a flat passband with no ripples whereas the Chebyshev response has ripples in the passband. In a Chebyshev filter it is observed that an increase in the ripple in the passband is also accompanied by a sharper slope in the stopband.

5.1 Stepped-Impedance Filter

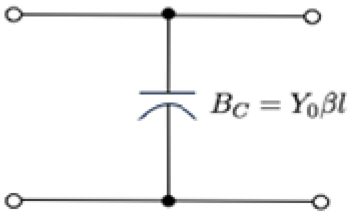
The stepped-impedance filter is a low-pass filter that can be implemented in microstrip. It uses alternating very high and very low characteristic impedance lines. It is also referred to a “hi-Z and low-Z” filter. It is superior to a low-pass filter designed using stubs since it uses less space and is easy to implement.

There are three equivalent circuits for the transmission line circuits that are useful in the design of the filters, as shown in Fig. 5.1, where X and X_L are inductive reactances and B is a susceptance. Y_0 is the reciprocal of Z_0.



(a) T-equivalent circuit for transmission line section $\beta l << \frac{\pi}{2}$.

(b) Equivalent circuit for small βl and large Z_0.



(c) Equivalent circuit for small βl and small Z_0.

Fig. 5.1. Transmission line equivalent circuits for: (a) small βl, (b) small βl and large Z_0, and (c) small βl and small Z_0.

In the stepped-impedance filter, the series inductors of a low-pass prototype are replaced with a high characteristic impedance line with $Z_0 = Z_h$ and shunt capacitors are replaced by a low impedance section with $Z_0 = Z_l$. The ratio Z_h / Z_l should be high.

Pozar [1] shows that the electrical length of the transmission line section can be calculated as determined by the following equations. For the inductor,

$$\beta l = \frac{R_g \, L_g}{Z_h} \quad \text{(inductor)}, \tag{5.1}$$

where R_g is the system (characteristic) impedance, L_g is the inductance, and l is the physical length. In this paper, $R_g = Z_0$. For the capacitor,

$$\beta l = \frac{Z_l C_g}{R_g} \quad \text{(capacitor)}, \tag{5.2}$$

where C_g is the capacitance. The lengths of the microstrip lines can be calculated as follows:

$$L_{cn} = \frac{g_n Z_l}{R_g \beta} \tag{5.3}$$

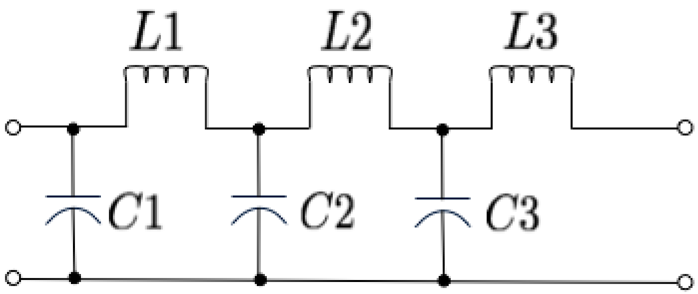
and

$$L_{ln} = \frac{g_n R_g}{Z_h \beta}, \tag{5.4}$$

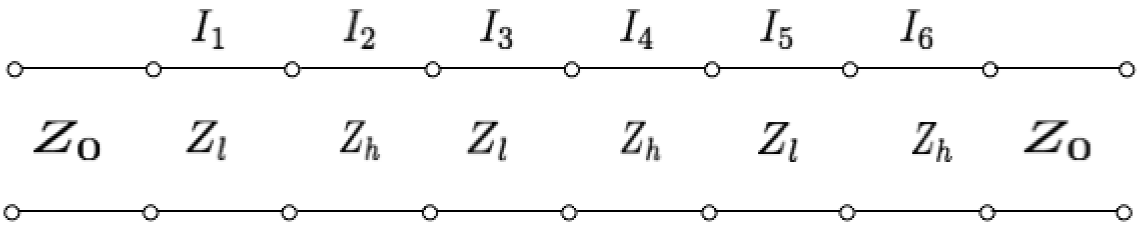
where L_{cn} and L_{ln} give the lengths of the equivalent transmission lines. L_g and C_g are the normalized element values, and g_n is the low-pass prototype value [1].

The development of the stepped-impedance filter from a lumped-element circuit sixth-order prototype to the microstrip implementation is shown in Fig. 5.2.

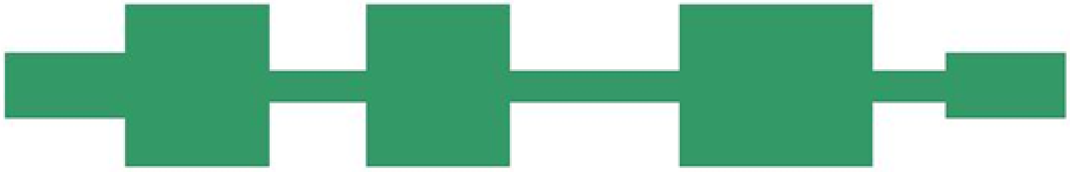
As an example of the filter, consider a study of Example 8.6 from Pozar [1] with CAMDS and ADS. The detailed values obtained for the stepped-impedance low-pass filter using Pozar are listed in Table 5.1 in which the material described in Table 5.2 was used.



(a) Sixth-order low-pass filter prototype.



(b) Stepped-impedance implementation.



(c) Microstrip-line filter layout.

Fig. 5.2. Progression from: (a) sixth-order lumped-element prototype through (b) transmission-line equivalent circuit to (c) microstrip implementation of a stepped-impedance filter.

Table 5.1. Values computed using the substrate described in Table 5.2.

Section	Characteristic Impedance (Z_i) in ohms	Electrical Length βl_i	Microstrip Width (W_i) in mm	Microstrip Length (L_i) in mm
L_1	20	11.8^o	11.3	2.05
L_2	120	33.8^o	0.428	6.63
L_3	20	44.3^o	11.3	7.69
L_4	120	46.1^o	0.428	9.04
L_5	20	32.4^o	11.3	5.63
L_6	120	12.3^o	0.428	2.41

Table 5.2. Electrical and physical properties of the substrate described in Table 5.1.

Substrate			Conductor	
Dielectric Constant	Substrate Thickness	Loss Tangent	Copper Thickness	Conductivity
4.2	0.158 cm	0.02	1 mil	5.8×10^7 S/m

The values given in Table 5.1 were confirmed independently using CAMDS, ADS and MATLAB. The design was simulated using ADS. This yielded the results described below.

The schematic (Fig. 5.3) which was generated using ADS uses a function (var function) which is a tuning function used in the ADS software. When we simulated the schematic without the var function, the response which we obtained was different from that of Pozar [1] and from the MATLAB result. Example 8.6 in Pozar specifies that there be more than a 20-dB insertion loss at 4 GHz. ADS did not obtain this result. Thus the var function was used to tune the values of the lengths and the widths to obtain the desired response. The difference from the response obtained with the original schematic was because the values of width and length given in Pozar [1] cannot generate the same response with more than 20 db insertion loss at 4 GHz when it is applied practically. So the var function tunes the values of length and width to obtain a cutoff frequency of 2.5 GHz and a 20-dB insertion loss at 4 GHz.

The new values for length and width that were obtained using the tuning function to obtain the response as given in Pozar are shown in Table 5.3.

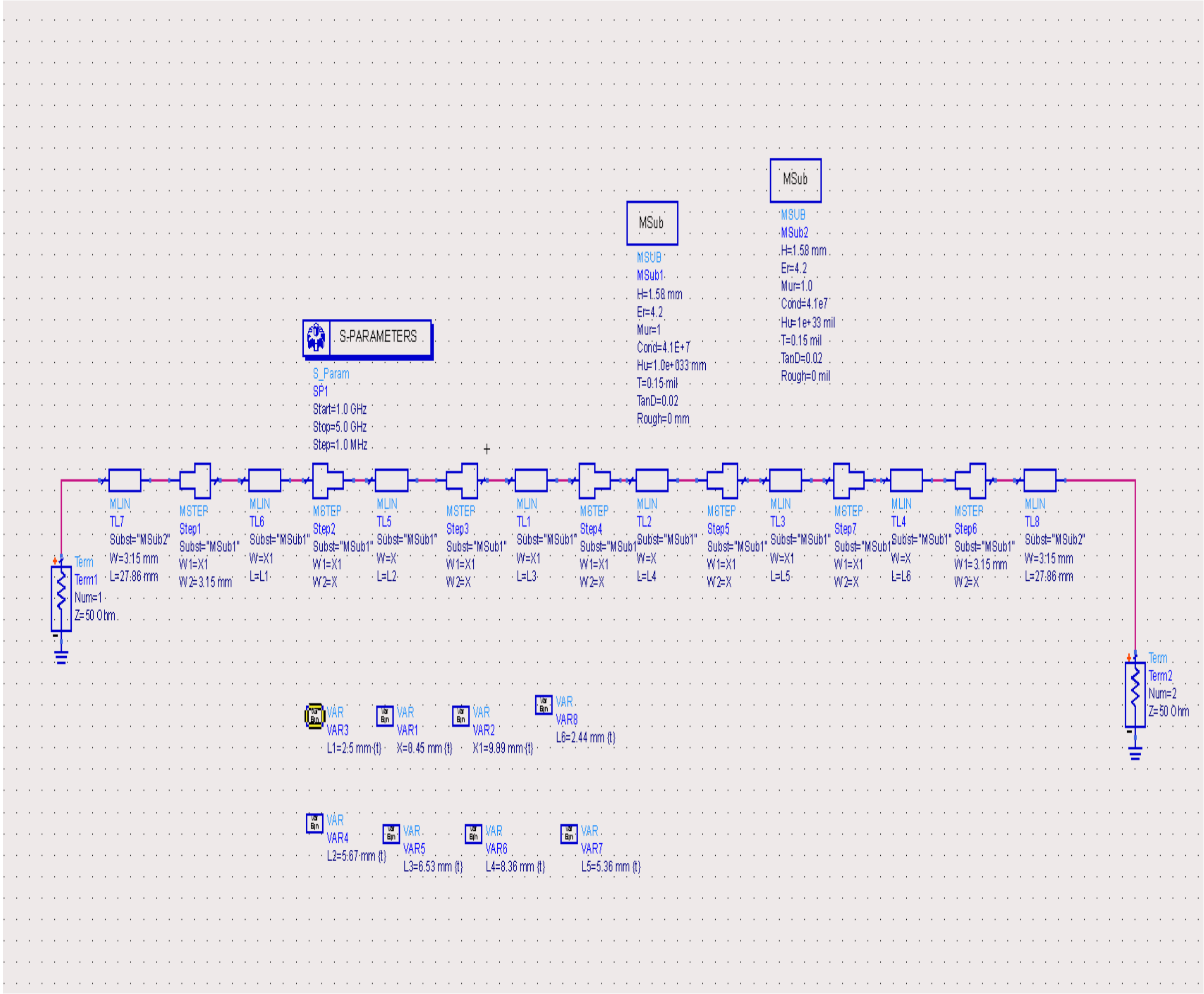


Fig. 5.3. ADS schematic of stepped-impedance filter.

Table 5.3. Filter dimensions as determined by ADS.

Section	Microstrip Width (W_i) in mm	Microstrip Length (L_i) in mm
L_1	9.89	2.50
L_2	0.45	5.67
L_3	9.89	6.53
L_4	0.45	8.36
L_5	9.89	5.36
L_6	0.45	2.44

The lengths and widths vary slightly from the values given in Pozar [1]. Pozar's results are theoretical numerical results. The above values of lengths and widths are experimental values. The ADS layout of the stepped-impedance is shown in the Fig. 5.4. ADS is able to compensate for edge effects at the junctions between elements and for the modal effects of the low-impedance elements.

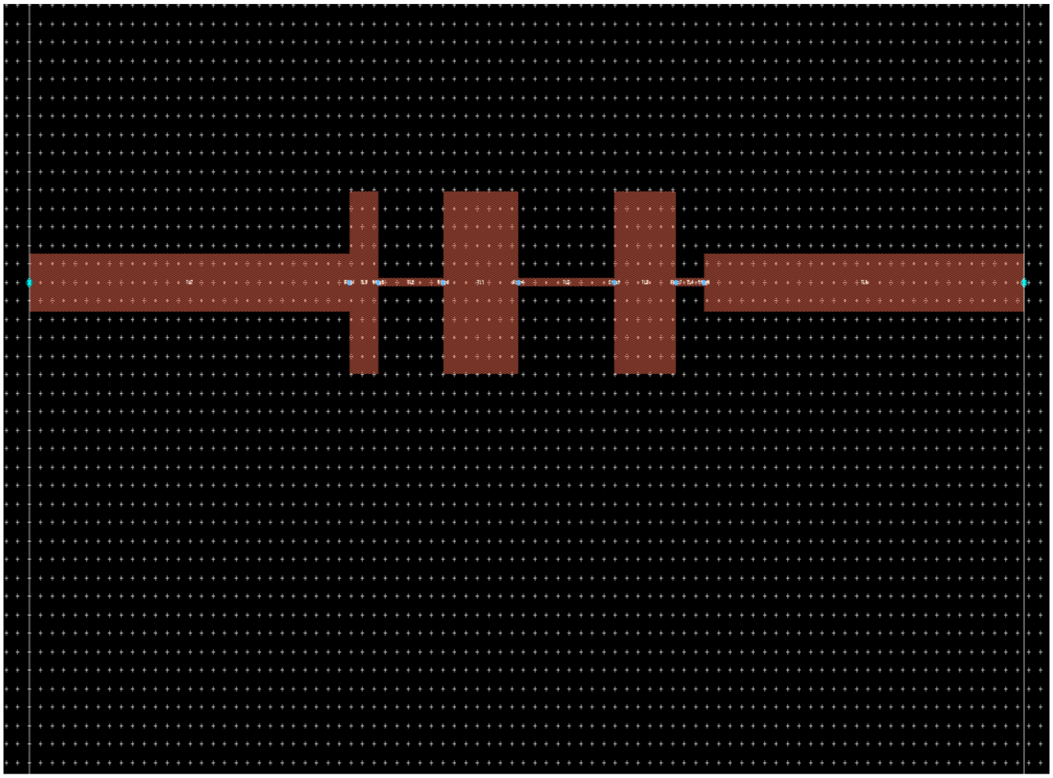


Fig. 5.4. ADS layout of stepped-impedance filter.

The ADS program also provided an analysis of the device performance as shown in Fig. 5.5. The response obtained has a cutoff frequency of 2.5 GHz and 20-dB insertion loss at 4 GHz. Fig. 5.5 is taken directly from ADS. Of particular interest is S_{21} expressed in dB or $20 \log_{10} |S_{21}|$.. This is shown in Fig. 5.5 and indicated as dB(S(2,1)).

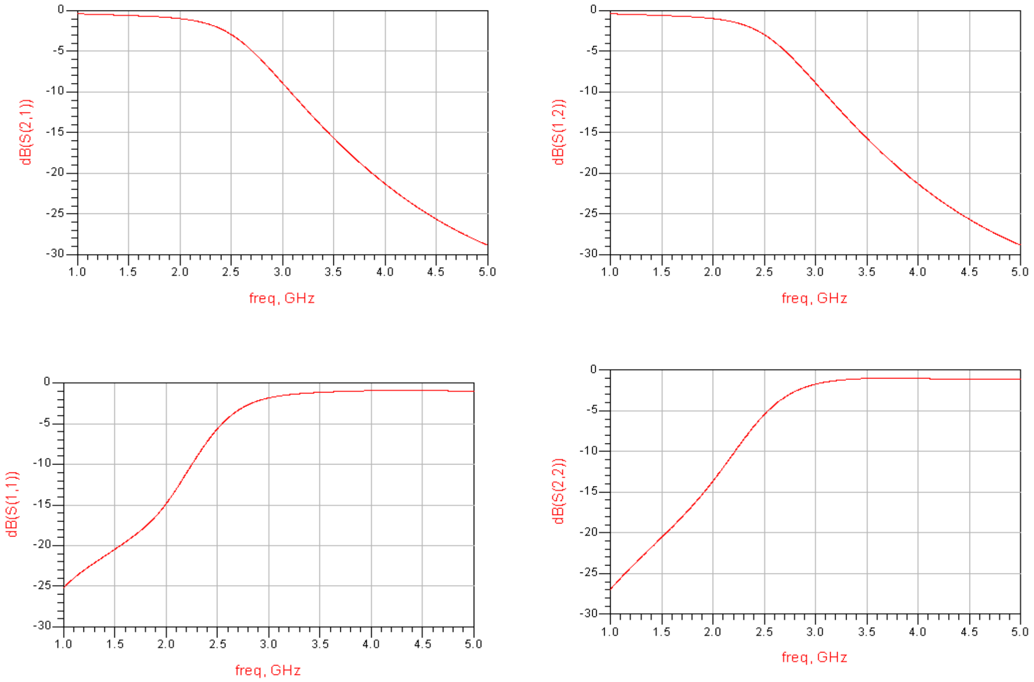


Fig. 5.5. ADS calculations for the scattering parameters S_{11}, S_{12}, S_{21} and S_{22}, expressed in dB.

The device layout shown in Fig. 5.4 is one that can be constructed using commercially available copperclad circuit board. The analysis shown in Fig. 5.5 is reasonably consistent with the theoretical predictions reported by Pozar. As Pozar states, the microstrip implementation is within about 0.5 dB of the lumped-element simulation for the frequency range 0 to 3 GHz. As the frequency increased from 3 GHz to 4 GHz, the microstrip implementation continues to serve as a low-pass filter but the attenuation is reduced by a few dB. The lumped element prediction of Pozar was verified using MATLAB and the result is presented in Fig. 5.6. Above 4 GHz the microstrip implementation performance deteriorated substantially as can be seen by comparison of Fig 5.6 (a) and Fig 5.6 (b). Fig. 5.6 was obtained by using the ABCD matrix of the each element, computing the product of the cascade of ABCD matrices and extracting S_{21} throughout the entire frequency range.

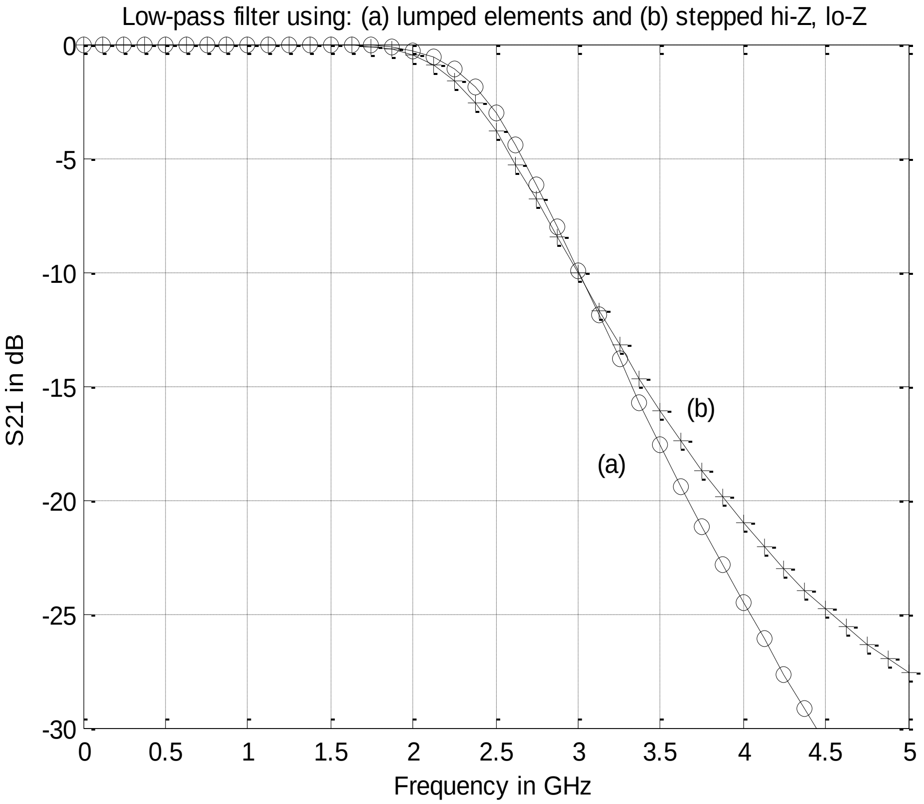


Fig.5.6. S_{21} in dB versus frequency in GHz for the low-pass filter implemented using: (a) lumped elements and (b) microstrip lines.

Fig 5.6 shows how closely the microstrip device approximates the lumped-element performance, with each device giving performances close to the design specifications at 2.5 GHz and at 4.0 GHz. Beyond 3.5 to 4.0 GHz, the stepped-impedance performance starts to differ from the lumped-element ideal. Study of its performance beyond 6 MHz indicates that the microstrip elements no longer provide a satisfactory approximation of the lumped-element filter for that higher frequency range. If suppressing frequency components in this range were necessary, additional filtering would have to be employed.

The stepped-impedance filter that was fabricated is shown in Fig. 5.7.

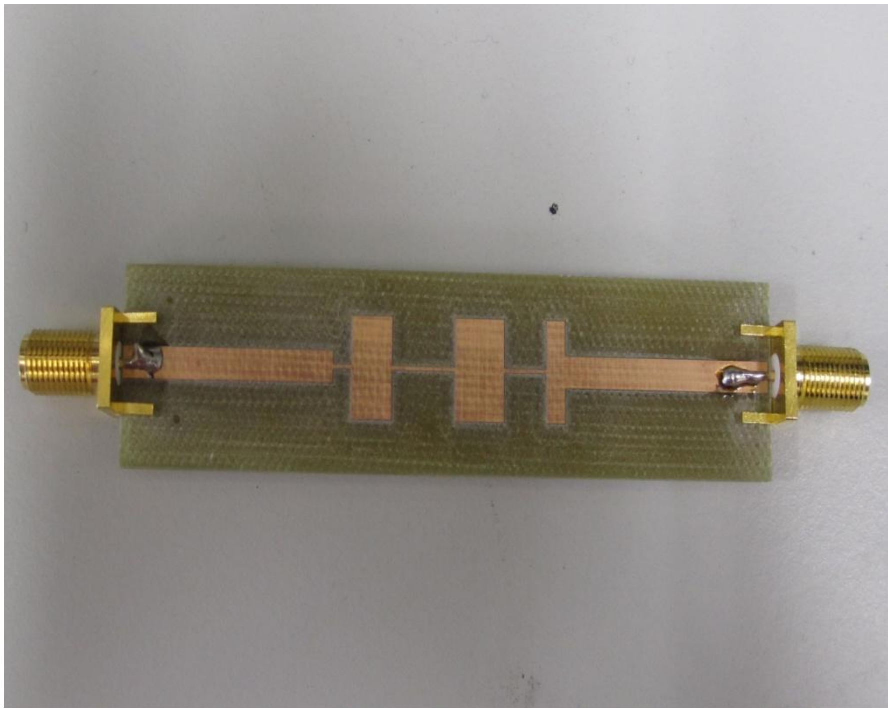


Fig. 5.7. Fabricated stepped-impedance filter.

The actual performance of the filter was obtained using an Agilent E5071C network analyzer as is shown in Fig. 5.8. Figs. 5.9 and 5.10 show the experimental response obtained using the network analyzer. The response that was generated produced a graph that had a cutoff frequency of 2.5 GHz and had more than a 20-dB insertion loss at 4 GHz. The response obtained with the fabricated device is consistent with that specified in Pozar. Thus this proves that the example problem given in Pozar is realizable in practice. The section that follows presents the verification of this same example problem using CAMDS to check its functionality. It also explains the complete steps necessary to study such a filter problems using the CAMDS software.

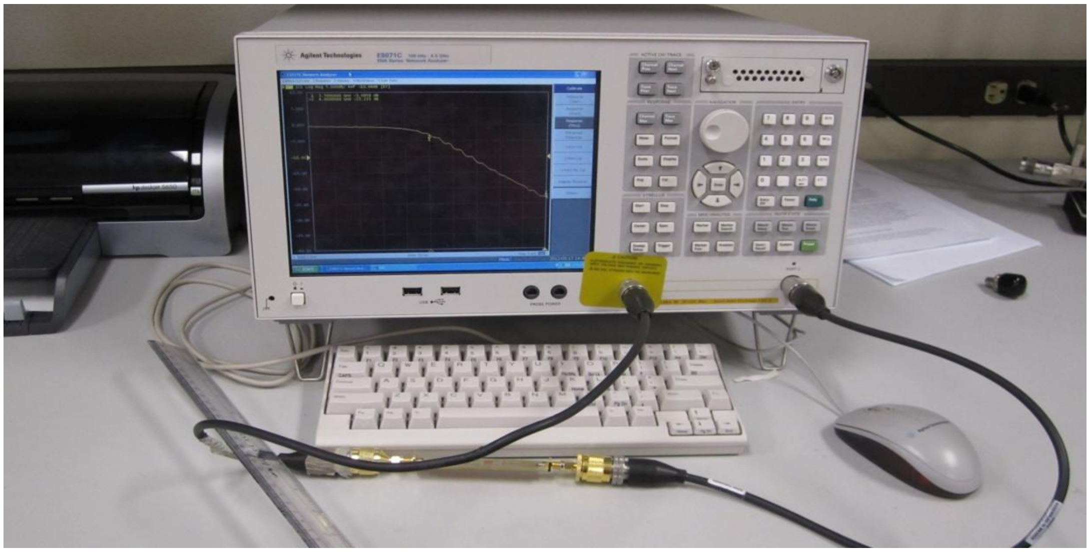
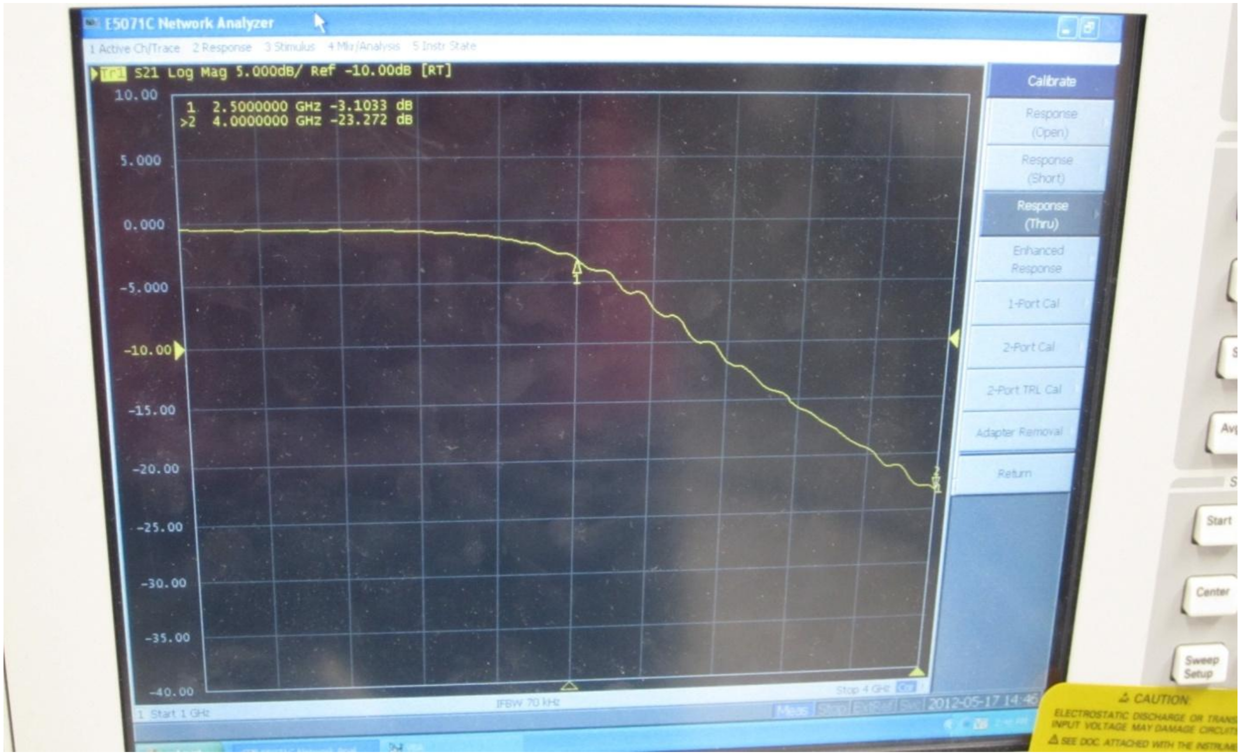


Fig. 5.8. Experimental setup with the network analyzer of the stepped-impedance filter.



E5071C Network Analyzer

Tr1 S21 Log Mag 5.000dB/ Ref -10.00dB [RT]

```
 1  2.5000000 GHz -3.1033 dB
>2  4.0000000 GHz -23.272 dB
```

Fig. 5.9. Clear view of the response obtained from the network analyzer.

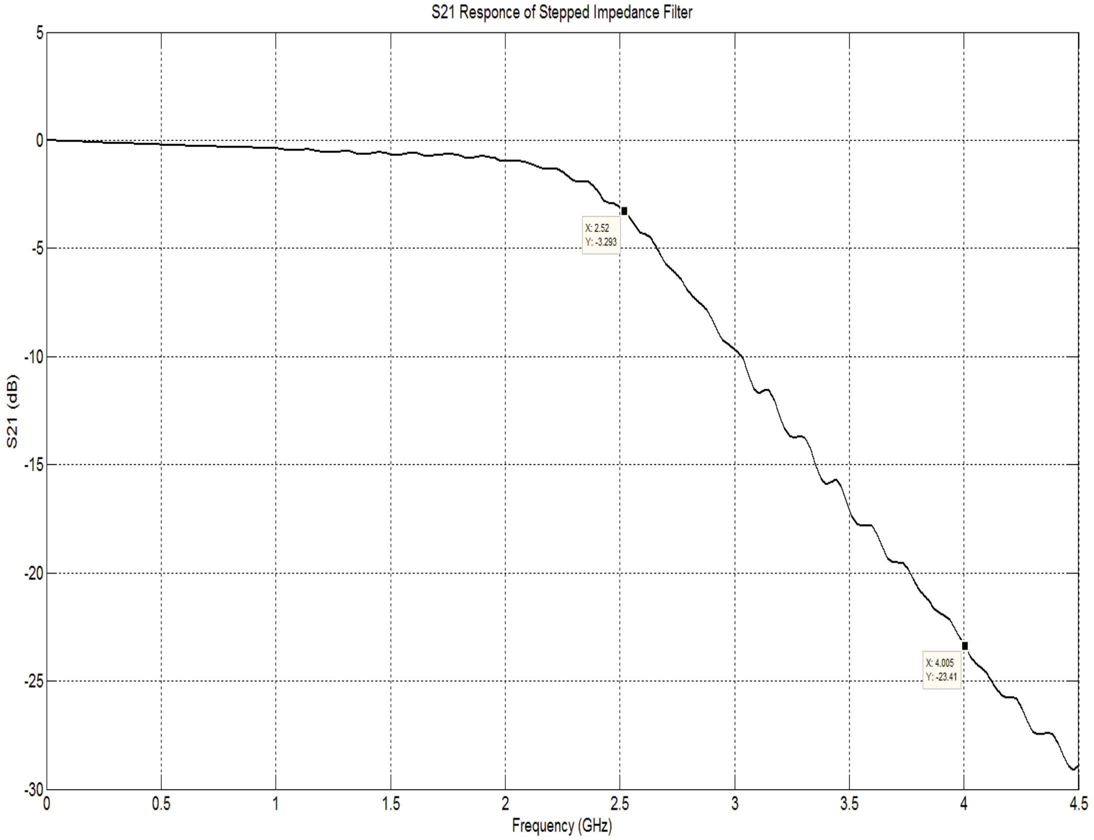


Fig. 5.10. S_{21} in dB vs. frequency in GHz for stepped-impedance filter using network analyzer.

The CAMDS software was verified by solving the same example from Pozar as considered above. To review, the user intends to design a stepped-impedance low-pass filter having a maximally flat response with a cutoff frequency of 2.5 GHz and a 20-dB insertion loss at 4 GHz. The impedance is given as 50 Ω, the highest line impedance is given as 120 Ω and lowest line impedance is 20 Ω. A microstrip substrate having d = 0.158 cm and ε_r = 4.2 was to be used.

The steps to solve the above problem using CAMDS are as follows.

1) Select “Stepped Impedance Low Pass Filter” from StartHere.fig and then press Go.

2) Enter the order of the filter. In the above problem the order of the filter is 6 as shown in Fig. 5.11.

Please give the order of Filter

6

Fig. 5.11. Box to input the order of the filter.

3) Enter the filter impedance as shown in Fig 5.12.

Please enter the filter impedance

50

Fig. 5.12. Box to input the filter impedance.

4) Enter the highest practical line impedance. In the above problem it is given as 120 Ω as shown in Fig. 5.13.

Please enter the highest Impedance of line Zh

120

Fig. 5.13. Box to input the highest practical line impedance.

5) Enter the lowest practical line impedance. In the above problem it is given as 20 Ω as given in Fig. 5.14.

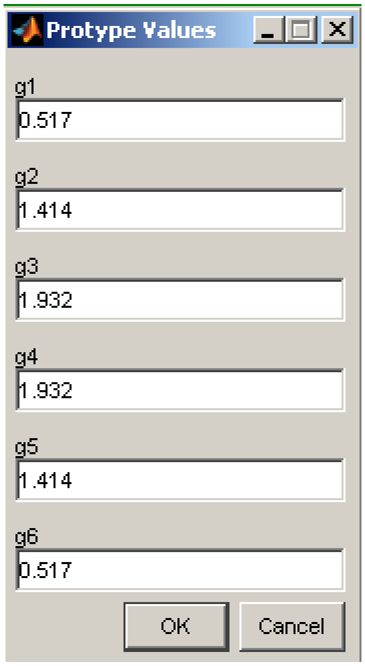
Zl

Please enter the lowest Impedance of line Zl

20

Fig. 5.14. Box to input the lowest practical line impedance.

6) Enter the prototype values for the given problem as shown in Fig 5.15. A table of prototypes values is given in Pozar [1].

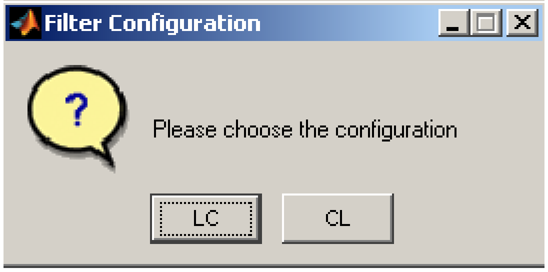


Protype Values

g1: 0.517
g2: 1.414
g3: 1.932
g4: 1.932
g5: 1.414
g6: 0.517

Fig. 5.15. Box to input the prototype value.

7) Choose the CL configuration for the above problem as in Fig. 5.16.

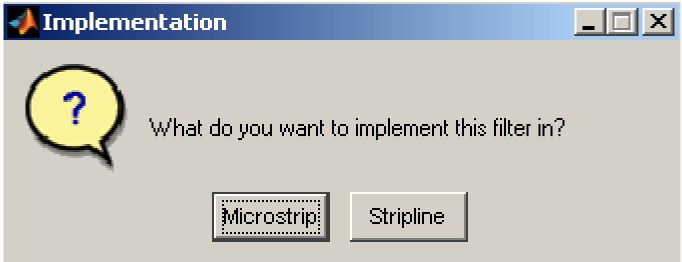


Filter Configuration

Please choose the configuration

Fig. 5.16. Question box.

8) As shown in Fig. 5.17, choose Microstrip.


Implementation

What do you want to implement this filter in?

Fig. 5.17. Question box.

9) Enter the relative permittivity. For the above it is 4.2. Fig. 5.18 below shows the input box for the relative permittivity.


Relative Permit...

Please enter Relative Permitivity

4.2

Fig. 5.18. Box to input the relative permittivity.

10) Enter the thickness as 0.158e-2 as given in the problem. Fig. 5.19 shows the input box for the thickness.

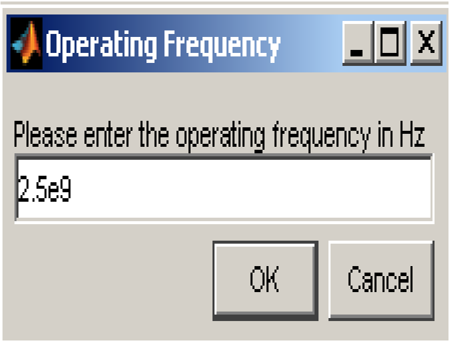

d

Please enter thickness of dielectric slab (d) in meters

0.158e-2

Fig. 5.19. Box to input the thickness.

11) Enter the value of the operating frequency as 2.5 GHz is shown in Fig. 5.20.



Please enter the operating frequency in Hz

2.5e9

Fig. 5.20. Box to input the operating frequency.

The output that was obtained in the command window is as follows. Bais [4] gives values for the line lengths for this example that differ significantly from those given by Pozar and from those obtained here. The updated output which was obtained is shown below.

```
The order of filter is 6
The Filter impedance is 50
The highest line impedance is 120
The lowest line impedance is 20
The filter configuration is CL
Filter is implemented on a microstrip
The Relative Permitivity is  4.2
The dielectic slab thickness in meters is 0.00158
The operating frequency in Hz is 2.5e+009
For element of prototype value = 0.517  Impedance = 20 Ohms   electrical length =
11.8488 degrees  width = 0.011268 meters  length=0.0020883 meters
For element of prototype value = 1.414  Impedance = 120 Ohms   electrical length =
33.7568 degrees  width = 0.00043025 meters   length=0.0066789 meters
```

For element of prototype value = 1.932 Impedance = 20 Ohms electrical length = 44.2782 degrees width = 0.011268 meters length=0.007804 meters

For element of prototype value = 1.932 Impedance = 120 Ohms electrical length = 46.1231 degrees width = 0.00043025 meters length=0.0091257 meters

For element of prototype value = 1.414 Impedance = 20 Ohms electrical length = 32.4065 degrees width = 0.011268 meters length=0.0057116 meters

For element of prototype value = 0.517 Impedance = 120 Ohms electrical length = 12.3425 degrees width = 0.00043025 meters length=0.002442 meters.

The output that was generated using CAMDS showed results that are consistent with Pozar. The results shown in Bais [4] for lengths are slightly different. This example problem from Pozar is practically realizable as was shown earlier in this section.

5.2 Filter Design Using Stubs

A stub is a very useful tool when designing microwave circuits. It can consist of a section of open- or short-circuited transmission line. It can be used in many applications such as impedance matching or filter design by strategic placement along the main transmission-line circuit in order to achieve some desired effect. The stub of length l, located at a distance d, from a load or source provides a required impedance for the circuit. These parameters can be altered to create reactive or susceptive elements in a transmission line circuit. This property is used to create capacitors and inductors in the circuit when use of the lumped element is inconvenient or impractical.

One very important use of stubs is in the design and implementation of filters. The lumped-element filter generally works well at low frequencies, but there are many disadvantages when they are applied at microwave frequencies. First, when using analytically designed lumped-element filters, actual components are only available in certain values. Therefore, desired component values may need to be approximated by using multiple components. Another disadvantage of using lumped elements is that at microwave frequencies, the trace distances between elements are non-negligible. This could lead to undesired behaviors in the circuit [1].

To implement low-pass filters with certain cutoff frequencies in the microwave range, it is useful to employ Richard's transformation and Kuroda's identities [4] which focus on uses of $\lambda/8$ transmission lines, for which $jX = jZ_o$. Richard's idea is to use the variable Z_o (determined by the width of the microstrip, for example) to create equivalent lumped elements from transmission lines. A lumped low-pass prototype filter can be implemented using $\lambda/8$ lines of appropriate Z_o to replace lumped L and C elements. So if we need an inductance of L for a prototype filter normalized to a cutoff frequency $\omega_c = 1$ and admittance $g_o = 1$, we can substitute a $\lambda/8$ transmission-line stub that has $Z_o = L$. The last step of the filter design will be to scale the design to the desired ω_c and Zo (typically 50 Ω).

Kuroda's idea is to use the $\lambda/8$ line of appropriate Zo to transform awkward or unrealizable elements to those with practical values and geometry. As an example, the series inductive stub (represented by the inductor in Fig. 5.21) can be replaced by a shunt capacitive stub and a series $\lambda/8$ transmission line, with different values of characteristic impedance determined by a constant. Z_1 and Z_2 as shown in Fig. 5.21 are transmission-line characteristic impedances. The constant $n^2 = 1 + Z_1/Z_2$.

The Kuroda identities convert a series element and transmission line into a shunt element and transmission line, and vice versa. The first two Kuroda identities are illustrated in the Fig. 5.21 below, where each box represents a unit element or a transmission line. The inductors and capacitors represent short-circuited and open-circuited stubs, respectively.

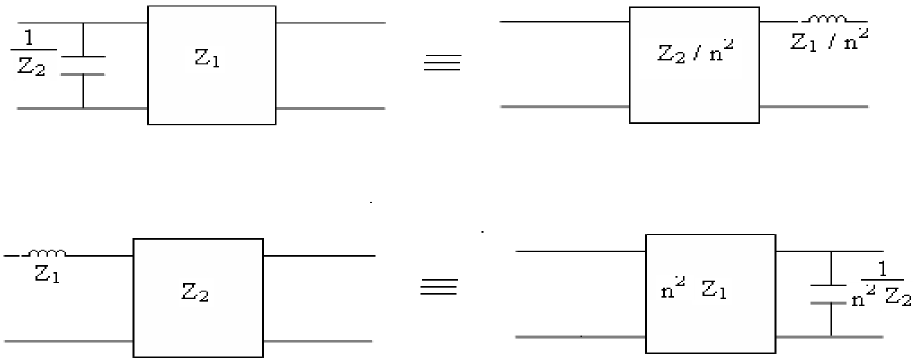


Fig. 5.21. Two of Kuroda’s identities.

The values obtained for a low-pass filter design using stubs following Pozar are listed below. The example problem from Pozar has a 3-dB equal-ripple third-order characteristic, a cutoff frequency of 4 GHz and an impedance of 50 Ω. So the normalized prototype elements values for this filter are as follows:

$$g_1 = 3.3487 = L_1$$

$$g_2 = 0.7117 = C_2$$

$$g_3 = 3.3487 = L_3$$

$$g_4 = 1.0000 = R_L$$

The above problem was verified using ADS to check if it can be implemented practically. The same problem was solved using CAMDS [3] to check the validity of the software. The schematic of the above problem using ADS is shown in Fig. 5.22 following by the layout in Fig. 5.23. The layout was generated from the schematic which is shown in Fig 5.23. The layout generated a very thin 217.5-Ω line of width 0.064 mm.

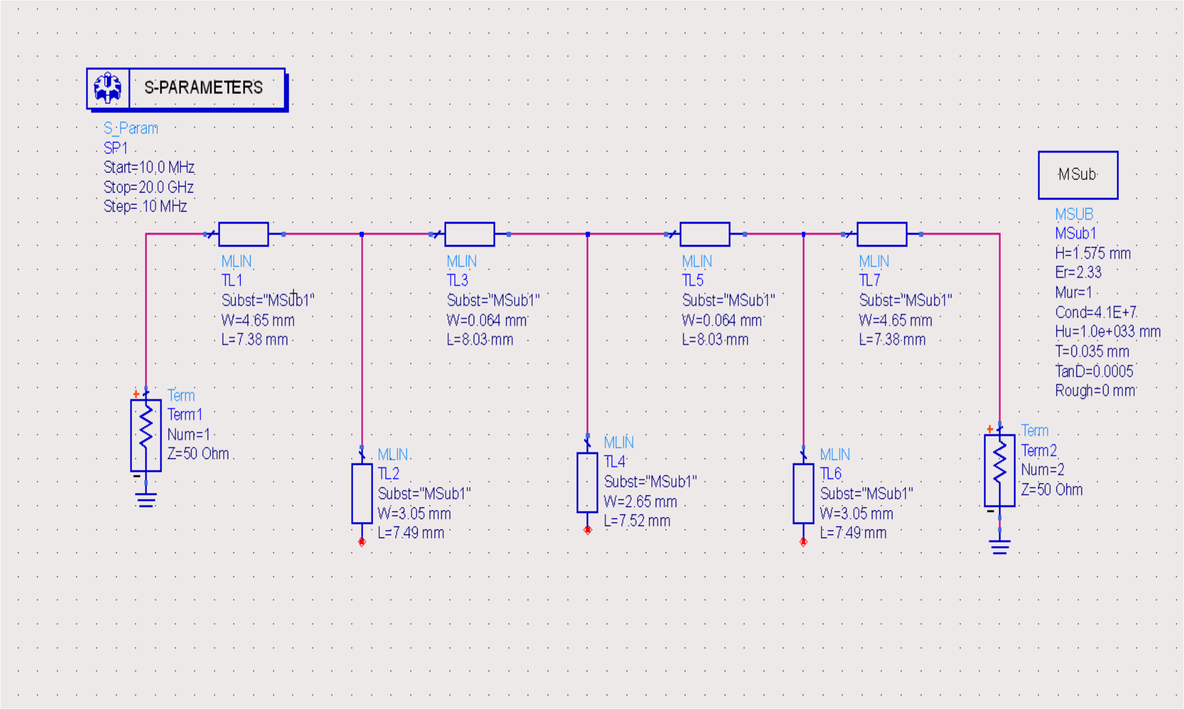


Fig. 5.22. Filter schematic for the low-pass filter using stubs.

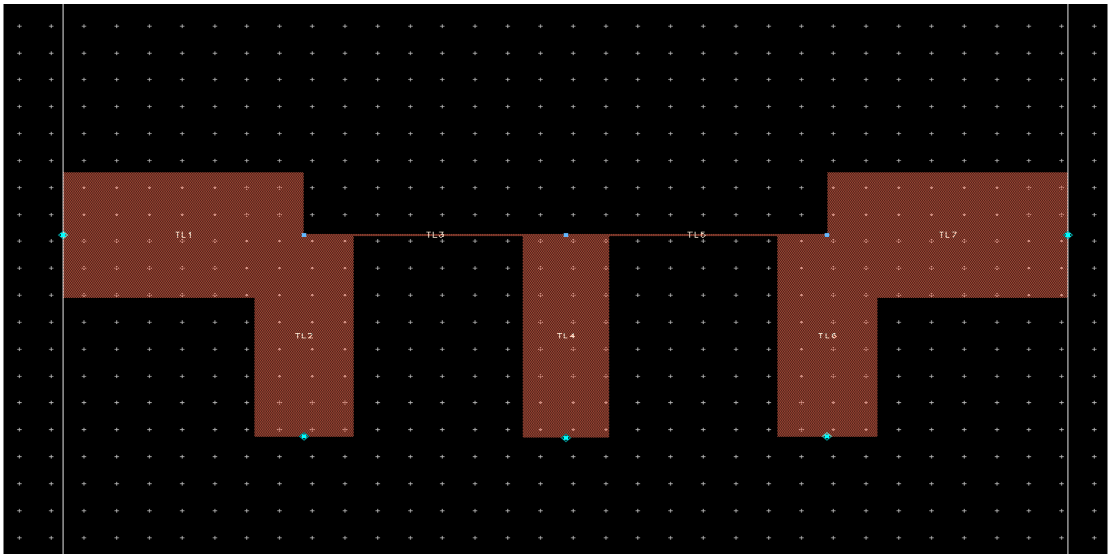


Fig. 5.23. Physical layout of the low-pass filter using stubs.

The ADS simulation of the schematic generated the scattering parameter results as shown in Fig. 5.24. As in Fig. 5.5, of particular interest is S_{21} which is indicated as dB(S(2,1)). This is the magnitude of S_{21} expressed in dB.

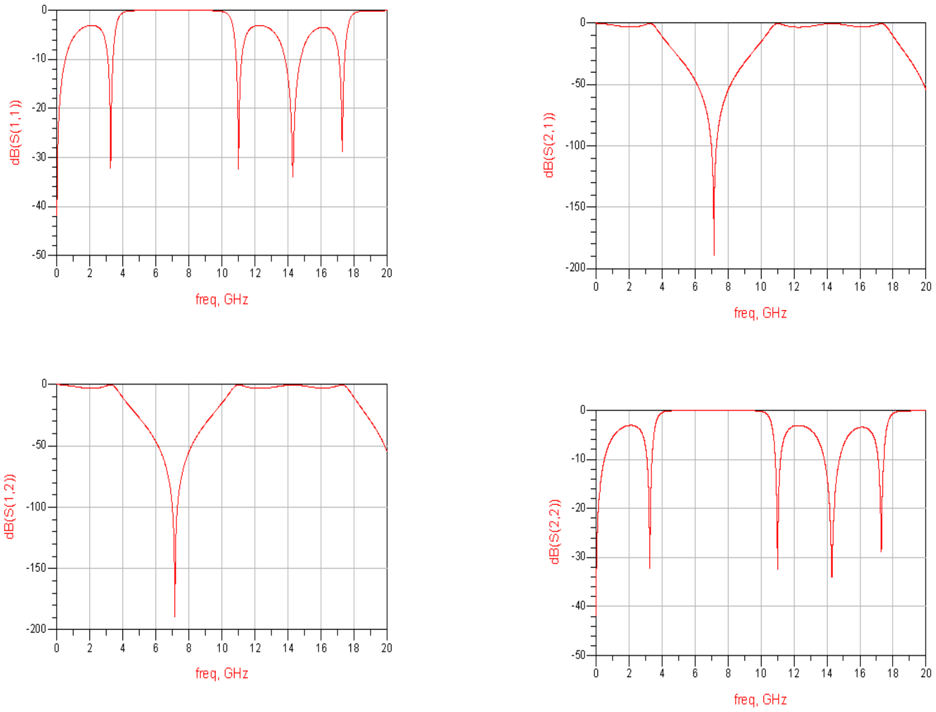


Fig. 5.24. Scattering parameters obtained using ADS for the low-pass filter using stubs.

The response obtained from ADS (dB(S(2,1)) is very similar to the graph given in Pozar. It had a cutoff of 4 GHz. The same example was implemented using MATLAB for the lumped-element and distributed-element cases. The result that was obtained using MATLAB is shown in Fig. 5.25. The response that was obtained is very similar to the one obtained using either ADS or Pozar.

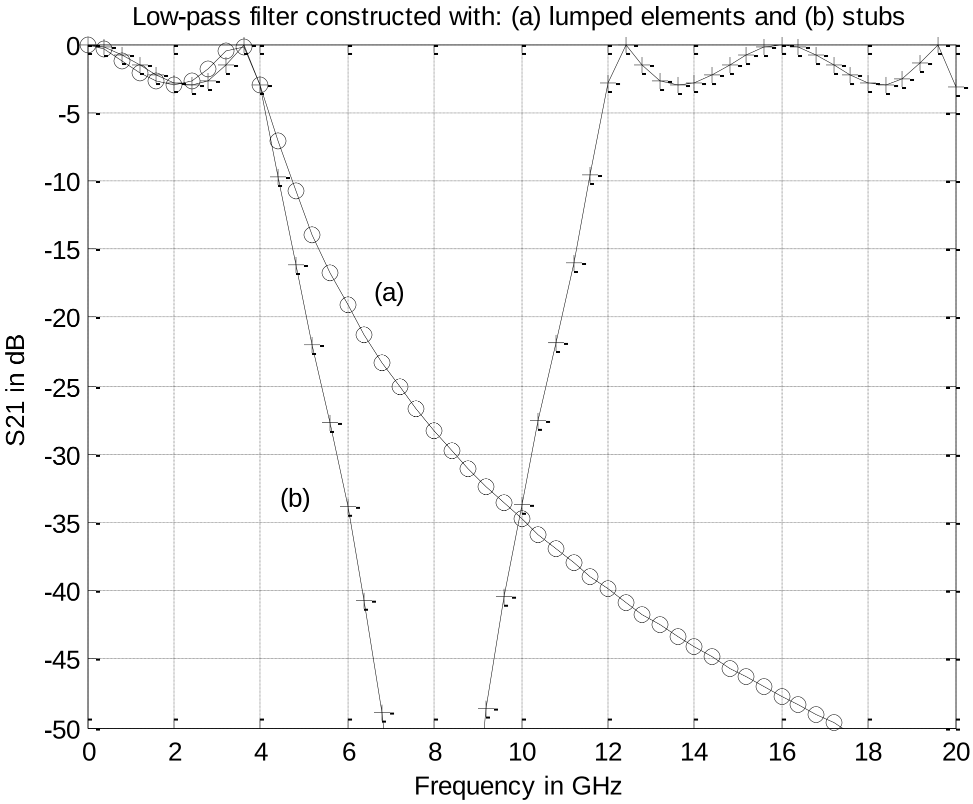


Fig. 5.25. MATLAB response of the lumped-element and distributed-element low-pass filter example.

This example was fabricated on a copperclad board (see Fig. 5.26). The fabrication produced a very thin 217.5-Ω line of width 0.064 mm. This example is very hard to implement practically. The thin line that was generated had a tendency to break and was almost invisible. This example problem is practically realizable but the implementation is difficult and has a lot of disadvantages because of the thin line that was generated.

The measured performance of the device is shown in Fig. 5.27. The response has many small ripples in it. One reason for the ripples might be because the filter is a Chebyshev filter which has ripples in the passband. Another reason might be the errors caused by the milling machine in the fabrication of the 217.5-Ω line. The cutoff frequency was greater than 4 GHz.

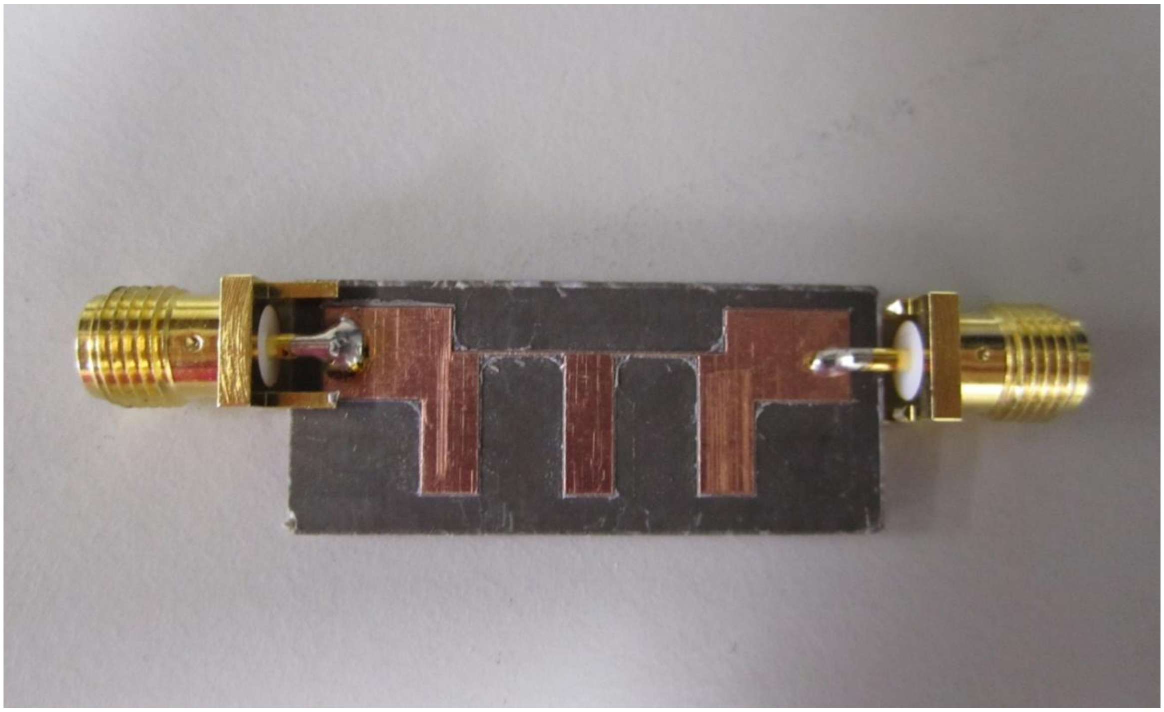


Fig. 5.26. Fabrication of low-pass filter using stubs.

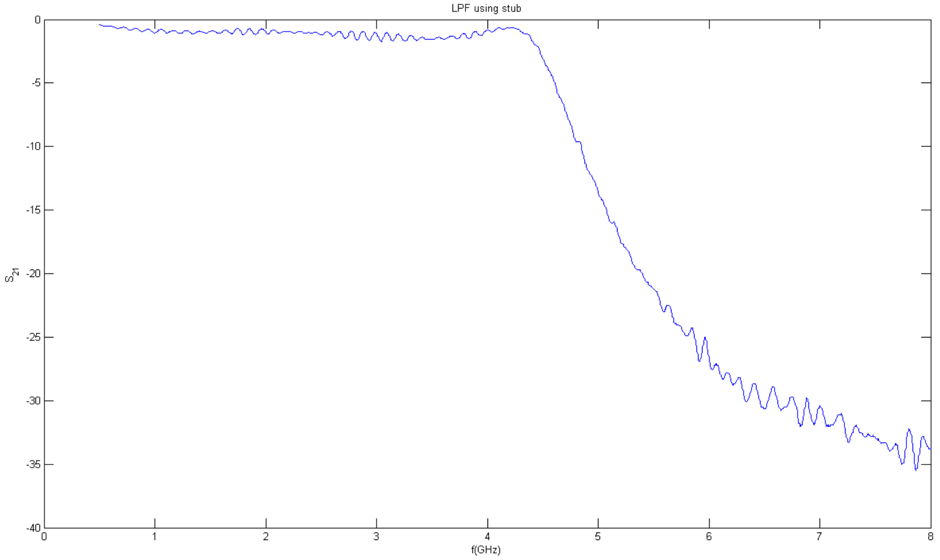


Fig. 5.27. ADS display of S_{21} in dB vs. frequency in GHz using the network analyzer.

Many difficulties were faced while implementing this filter. The thin line tended to break even if only a little pressure was put on the fabricated device. This device is physically realizable but the fabricated device must be handled carefully.

The same problem was implemented using CAMDS to check its functionality. The detailed procedure to solve the above problem using CAMDS is given below.

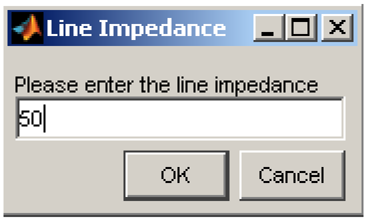
1) Select “Kuroda’s Low-pass Filter” from StartHere.fig and then click on “GO”.
2) Enter the order of the filter as shown in Fig. 5.28. For the above problem the order is 3.

Please give the order of filter

3

Fig. 5.28. Box to enter the order of the filter.

3) Enter the line impedance as 50 Ω as shown in the Fig. 5.29.



Please enter the line impedance

50

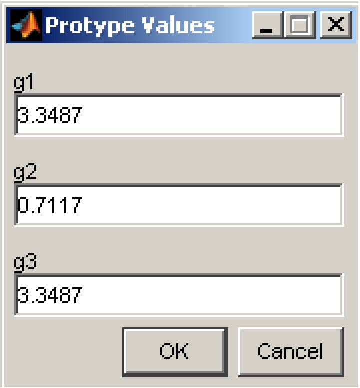
Fig. 5.29. Box to input the line impedance.

4) Select “other” from the question box as shown in Fig. 5.30.

Please select your filter

Fig. 5.30. Question box.

5) Enter the prototype values of the elements as shown in Fig. 5.31.



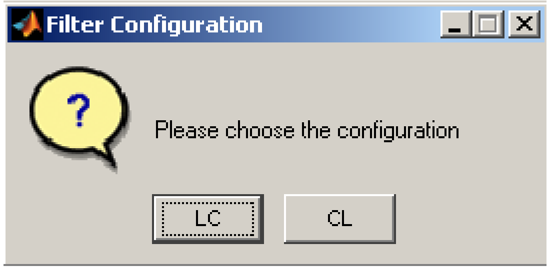
g1 3.3487

g2 0.7117

g3 3.3487

Fig. 5.31. Box to input the prototype values.

6) Choose the "LC" configuration as shown in the Fig. 5.32.



Please choose the configuration

Fig. 5.32. Question box for the filter configuration.

7) The output will be displayed in the command window. The output that was generated is shown below:

```
The order of filter is 3
The line impedance is 50
The filter configuration is LC
Starting from right end (load end) of the filter the line and open circuited stub values are:
Open-Circuited Stub impedance 6.493117e+001
Followed by line of impedance 2.174350e+002
Followed by open stub of impedance 7.025432e+001
```

Followed by line of impedance 2.174350e+002

Followed by open stub of impedance 6.493117e+001.

The output obtained using CAMDS produced the same results as Pozar. Thus this verified that the CAMDS could produce correct and accurate results for Kuroda’s low-pass filter. These values obtained from CAMDS can be used to implement the device practically. The example problem from Pozar has been verified using ADS, CAMDS and MATLAB demonstrating that this example problem is practically realizable.

CHAPTER 6. IMPEDANCE MATCHING

Impedance matching refers to matching a load impedance to a source such that maximum power transfer occurs. This avoids unnecessary loss of power. Often the source and load impedance is the same as the system impedance, Z_0, in a microwave network. If the load impedance, Z_L, is different from Z_0, an impedance matching network such as that shown in Fig. 6.1 might be necessary. Ideally a matching network is constructed using reactive components so that the network is lossless.

The importance of impedance matching is as follows [1]:

1) It delivers maximum power to the load when it is matched to the line.
2) It improves the signal-to-noise ratio of the sensitive receiver components such as the antenna, low-noise amplifier, etc.
3) It reduces amplitude and phase errors in the power distribution networks such as antenna array feed networks.

Two types of matching networks are discussed in this chapter: the L match and the single-stub tuner. Most microwave devices work over a band of frequencies and not for just one design frequency. Waveguides and transmission lines generally have long electrical lengths. Electrical lengths are functions of frequency. Small changes in frequency can cause considerably large changes in the electrical length. The impedance of transmission-line devices is dependent on the electrical length of the devices. A matching network is inserted between the line and the load [4]. An impedance matching network that can match the load to the line at one frequency may act differently at another frequency [4]. Two different methods for designing the matching network between a load and a line are the Smith chart method and the analytical method. CAMDS uses the analytical method to find a matching network for a given load and line. A figure showing a lossless network matching a load impedance, $Z_L = R_L + jX_L$, to a transmission line as reported in [1] is given in Fig. 6.1.

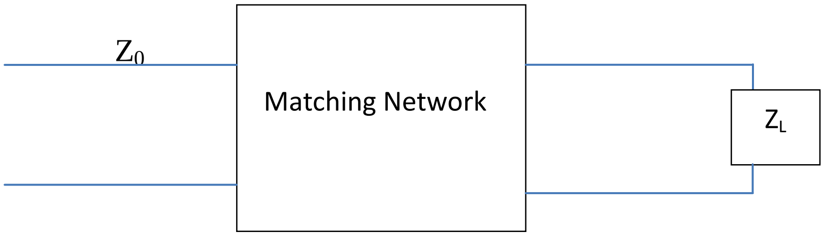


Fig. 6.1. A matching network.

6.1. The L Match

The L match is the simplest type of matching network. It uses two reactive elements to match the line to the load. The normalized load impedance is given as $Z_L = \frac{Z_L}{Z_0}$ = r +jx where Z_L is the load impedance and Z_0 is the characteristic impedance. There are two configurations for this network. If Z_L is inside the 1+jx circle on the Smith chart, then the circuit in Fig. 6.2 should be used.

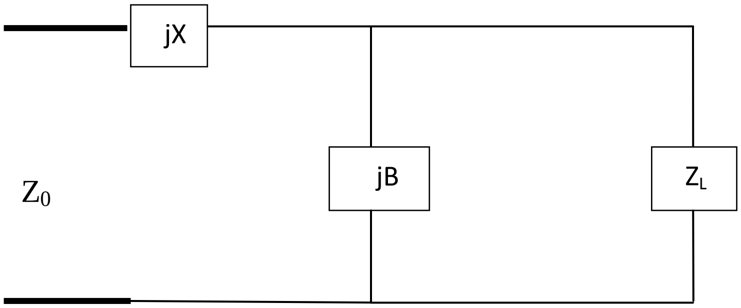


Fig. 6.2. Circuit for Z_L inside the 1+ jx circle.

If Z_L is outside the 1+jx circle, then the circuit in Fig. 6.3 is used. The 1+jx resistance circle

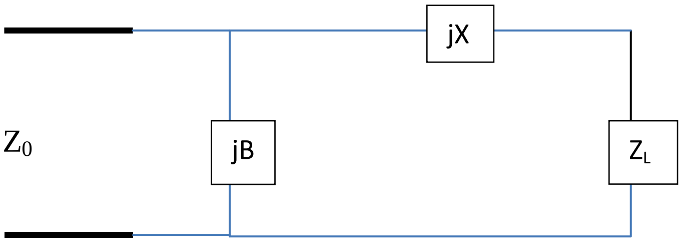


Fig. 6.3. Circuit for Z_L outside the 1+ jx circle.

on the Smith chart is the circle for which r = 1. In both configurations the reactive element may be an inductor or a capacitor [1]. The value of X and B can be either positive or negative. Thus there are four L-match circuits for each configuration. Consider the Fig 6.2. The impedance seen looking into the matching circuit should be

$$Z_0 = jX + \frac{1}{jB+(\frac{1}{R_{L+jX_L}})} \ . \tag{6.1}$$

Solving the above equation for X and B gives the following equations:

$$B = \frac{X_L \pm \sqrt{\frac{R_L}{Z_0}}\sqrt{R_L^2+X_L^2-Z_0R_L}}{R_L^2+X_L^2} \tag{6.2}$$

and

$$X = \frac{1}{B} + \frac{X_L Z_0}{R_0} - \frac{Z_0}{BR_L} \ . \tag{6.3}$$

Similarly, for Fig. 6.3, when Z_L is outside the 1+jx circle, the admittance seen looking into the matching network should be equal to $\frac{1}{Z_0}$. Thus,

$$\frac{1}{Z_0} = jB + \frac{1}{j(X+X_L)+R_L} \ . \tag{6.4}$$

Solving (6.4) for X and B gives the following equations:

$$X = \pm\sqrt{R_L(Z_0 - R_L)} - X_L \tag{6.5}$$

and

$$B = \pm\frac{\sqrt{\frac{(Z_0 - R_L)}{R_L}}}{Z_0}\ . \tag{6.6}$$

The sign of X and B determines if it is a capacitance or an inductance.

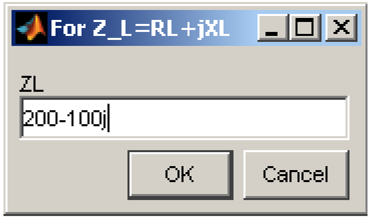
The value of the capacitor or inductor is calculated as follows:

$$L = \frac{X_L}{2\pi f}\ \text{henry} \tag{6.7}$$

and
$$C = \frac{1}{2\pi f X_C}\ \text{farad.} \tag{6.8}$$

To verify CAMDS, an example problem from Pozar [1] is solved. In this section a user is asked to design an L-section matching network to match a series RC-load with an impedance Z_L = 200 – j 100 Ω to a 100-Ω line at a frequency of 500 MHz . The steps used to solve the above example problem are given below. The procedure to use to design this network is given below:

1) Go to the StartHere.fig page, click on L Match and then select GO.
2) Once the user presses GO, CAMDS will ask for the load impedance (Z_L). The user enters 200 - j100 as shown in Fig. 6.4.



ZL

200-100j

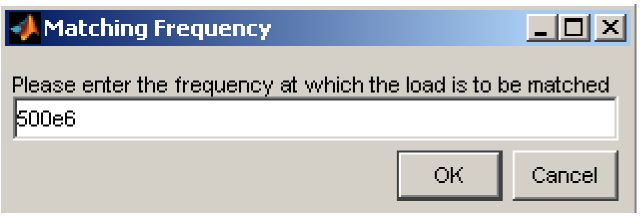
Fig. 6.4. Input box for Z_L.

3) Enter the characteristic impedance as per the given example problem. For the above problem the characteristic impedance is 100 Ω (Fig. 6.5).

Z0
100

Fig. 6.5. Box to input characteristic impedance.

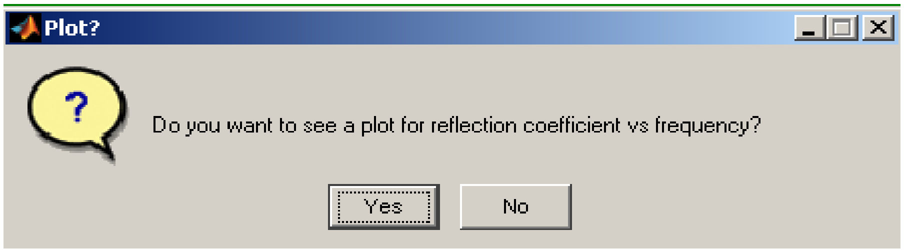
4) Enter the design frequency for the match as shown in Fig. 6.6.



Please enter the frequency at which the load is to be matched
500e6

Fig. 6.6 Input box for the design frequency.

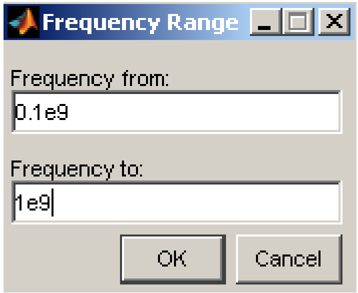
5) Then a question box will appear asking if the user wants to plot the reflection coefficient vs. frequency. Click on Yes (Fig. 6.7). If the user clicks No it will generate an output in the command window without any graph.



Do you want to see a plot for reflection coefficient vs frequency?

Fig. 6.7. Question box.

6) Enter the frequency range for the plot and then press OK as shown in Fig. 6.8. For the above problem the range is 100 MHz to 1 GHz.



Frequency from: 0.1e9

Frequency to: 1e9

Fig. 6.8. Input box asking frequency range.

7) The output shown in the command window for the above problem is as follows. It produces two solutions for the given problem. It produces results for b and x on the Smith chart and gives values for the capacitance and inductance. The solution to the above problem using CAMDS is as follows:

```
The load impedance is 200-100i
The characteristic impedance is 100
The load is inside 1+jx circle in Smith Chart
SOLUTION 1
b on Smith chart is at 0.289898
x on Smith Chart (reactance) is at 1.22474
B is a capacitor of value in farad 9.22774e-013
X is a inductor of value in henry 3.89848e-008
SOLUTION 2
b on Smith chart is at -0.689898
x on Smith Chart is at -1.22474
```

X is a capacitor of value in farad 2.59899e-012

B is a inductor of value in henry 4.61387e-008

8) The following plot (Fig. 6.9) was obtained using the CAMDS software.

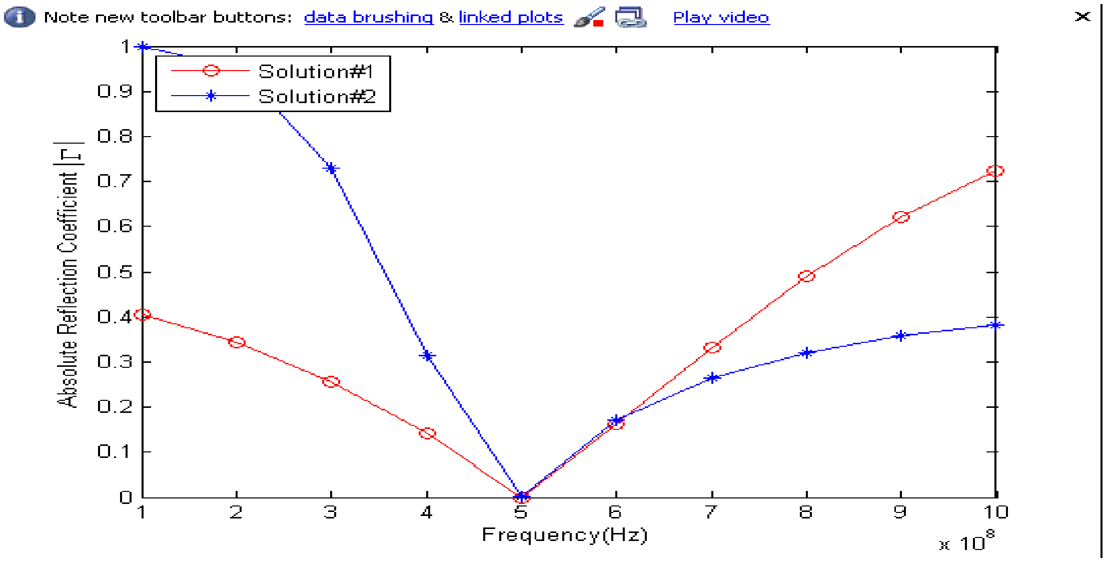


Fig. 6.9. Plot of the reflection coefficient vs. frequency for the L match using CAMDS.

The results produced by CAMDS are similar to those shown in Pozar [1]. CAMDS produces an accurate and fast result as compared to an analytical pen-and-paper solution.

As has been shown, CAMDS produces the design for the L-match network given the source impedance, the load impedance, and the design frequency. As another example, consider a source impedance of 50-Ω, a load impedance of 100-Ω, and an operating frequency of 1.5 GHz. This is of educational interest since the 100-Ω load impedance can be provided in the laboratory by a 50-Ω load as seen through an appropriately designed quarter-wavelength impedance transformer. The L-match routine in CAMDS returns:

The load impedance is 100

The characteristic impedance is 50

The load is inside 1+jx circle in Smith Chart

SOLUTION 1

b on Smith chart is at 0.5

x on Smith Chart (reactance) is at 1

B is a capacitor of value in farad 1.06103e-012

X is a inductor of value in henry 5.30516e-009

SOLUTION 2

b on Smith chart is at -0.5

x on Smith Chart is at -1

X is a capacitor of value in farad 2.12207e-012

B is a inductor of value in henry 1.06103e-008.

The first solution is a series inductance of value 5.30516 nH and a shunt capacitor of value 1.06103 pF, which will be called the LC solution. The second solution is a series capacitance of value 2.12207 pF and a shunt inductor of value 10.6103 nH, which will be called the CL solution.

Since in the laboratory the system impedance is 50-Ω and the voltage gain is often of great interest, the CAMDS result is here demonstrated by plotting S_{21} in dB versus frequency (Fig. 6.10). Note that the expected ideal value of 0 dB is definitely achieved at the design frequency.

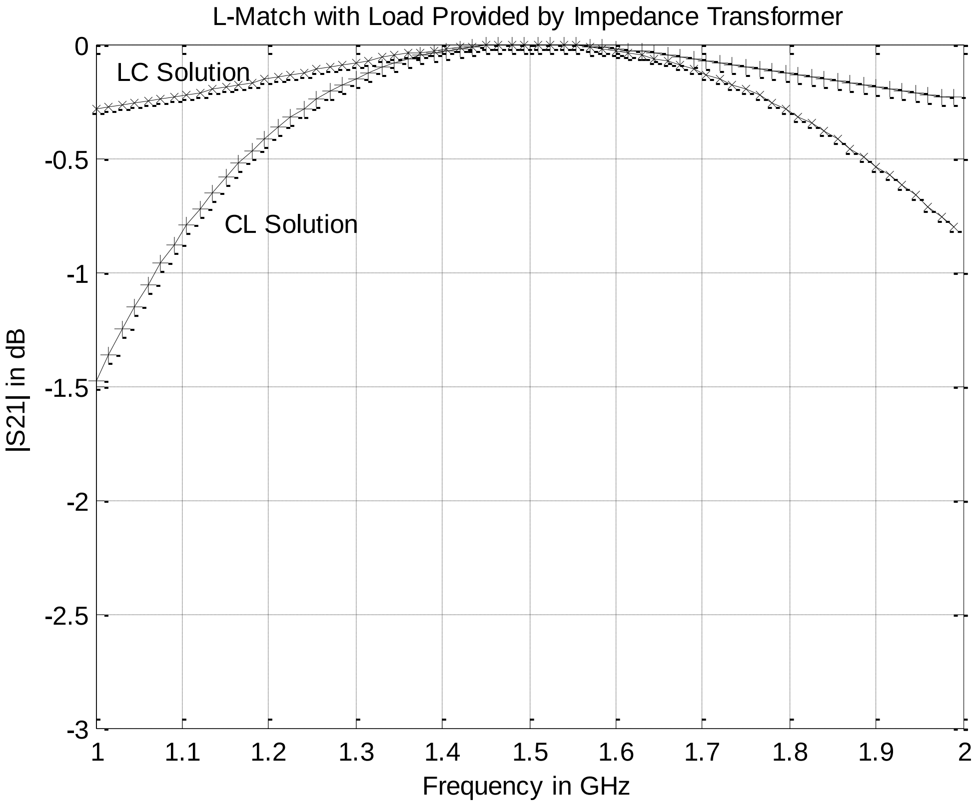


Fig. 6.10. Plot obtained using MATLAB for S_{21} in dB versus frequency.

6.2. Single-Stub Tuner

In a single-stub tuner a transmission line (a stub) is connected either in parallel or in series with the transmission feed line at a certain distance d from the load. It uses a single open-circuited or short circuited stub. There are two design parameters for the single-stub tuner. The first one is the location of the stub with reference to the load. The second one is the length of the stub line. In single-stub tuning the distance d from the load and susceptance or the reactance provided by the series or shunt stub are the only two adjustable parameters. There are two types of single-stub tuning. They are as follows: 1) single-stub shunt tuning and 2) single-stub series tuning. Fig. 6.11 shows the single-stub shunt and single-stub series tuners. The stub is connected in parallel for the single-stub shunt tuner, and the stub is connected in series for the single-stub series tuner. The stub can be short circuited or open circuited. The open-circuited stub length and short-circuited stub lengths are as follows [1]:

$$\frac{l_0}{\lambda} = \frac{1}{2\pi}\tan^{-1}\frac{B}{Y_0}\,, \tag{6.9}$$

and

$$\frac{l_s}{\lambda} = \frac{1}{2\pi}\tan^{-1}\frac{B}{Y_0}\,, \tag{6.10}$$

where $Y_0 = \frac{1}{Z_0}$ and $B = \frac{R_L^2 t - (Z_0 - X_L t)(X_L + Z_0 t)}{Z_0[R_L^2 + (X_L + Z_0 t)^2]}$, l_0 is the length of the open-circuited stub and l_s is the length of the short-circuited stub.

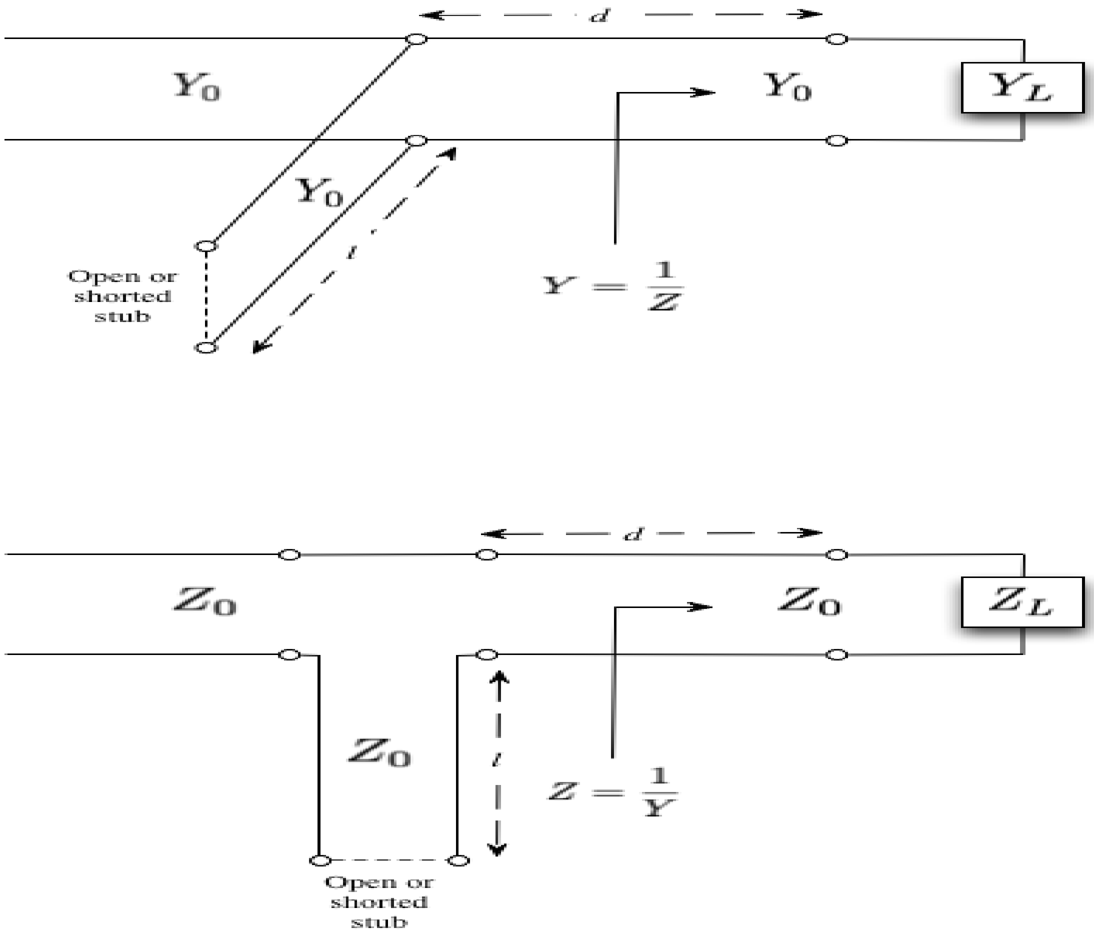
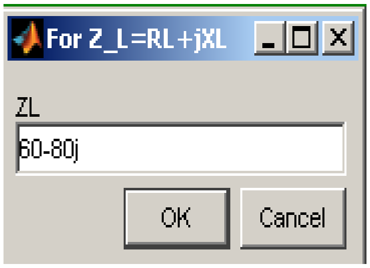


Fig. 6.11. Single-stub tuning: (a) shunt stub and (b) series stub.

To check the CAMDS software, we verify it by solving a problem from [1]. The problem requires the user to design a single-stub short-circuited matching network for a load impedance of 60 - j80 Ω to match this load to 50 Ω at 2 GHz and to plot the reflection coefficient vs. frequency for the range of 1 GHz to 3 GHz. The procedure to solve this problem is as follows:

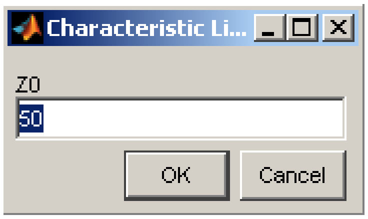
1) Select single stub-shunt tuner from StartHere.fig and then click GO.
2) Once the Go button is pressed, a box will pop up asking for the load impedance Z_L. Enter the desired value of Z_L. In the above problem the load impedance is 60 - j80 Ω. Fig. 6.12 shows the box for the load impedance. Enter the value and then press OK.



ZL
60-80j

Fig. 6.12. Box to enter the value of load impedance.

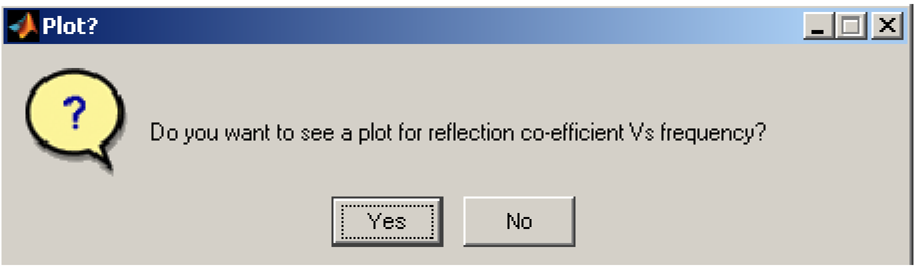
3) Enter the value of the characteristic impedance and then press OK. In the above problem the value for characteristic impedance is 50 Ω. Fig. 6.13 shows the box for the characteristic impedance.



Z0
50

Fig. 6.13. Box to enter the characteristic impedance.

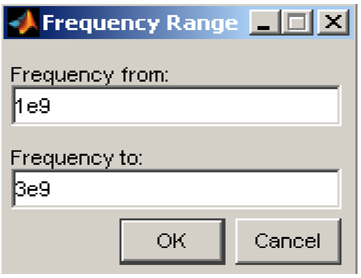
4) A question box asking the user if they want the plot for reflection coefficient vs. frequency appears as in Fig. 6.14. Press "Yes" to plot the response.



Do you want to see a plot for reflection co-efficient Vs frequency?

Fig. 6.14. Question box.

5) Once the user clicks Yes, a box will pop up asking for the frequency range. As per the example problem from Pozar, the frequency range should be 1 GHz to 3 GHz, as shown in the Fig. 6.15.

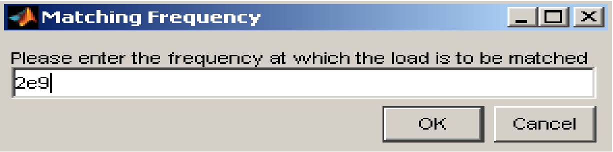


Frequency from: 1e9

Frequency to: 3e9

Fig. 6.15. Box to enter frequency range.

6) Enter a frequency of 2 GHz at which the load is to be matched and then press OK, as shown in Fig. 6.16.



Please enter the frequency at which the load is to be matched 2e9

Fig. 6.16. Box to input the matching frequency.

7) A question box asking for the stub type will appear. Select the stub type that is required for the design. Fig. 6.17 shows the stub type as short as given in Pozar.

The shunt stub is:

Fig. 6.17. Question box asking for the stub type.

8) The command window will generate two solutions for the problem. It will calculate the distance of the stub from the load, the open-circuited stub length and the short-circuited stub length in terms of wavelength. The output that was generated in the command window is as follows:

```
SOLUTION 1
The distance of stub from load in terms of wavelength is=1.104232e-001
The open-circuited stub length in terms of wavelength is 3.449746e-001
The short-circuited stub length in terms of wavelength is 9.497462e-002
SOLUTION 2
The distance of stub from load in terms of wavelength is=2.594445e-001
The open-circuited stub length in terms of wavelength is 1.550254e-001
The short-circuited stub length in terms of wavelength is 4.050254e-001.
```

9) The response obtained for the reflection coefficient vs. frequency is as shown in Fig. 6.18. It shows the responses for both of the solutions. The results obtained using CAMDS are the same as those of Pozar.

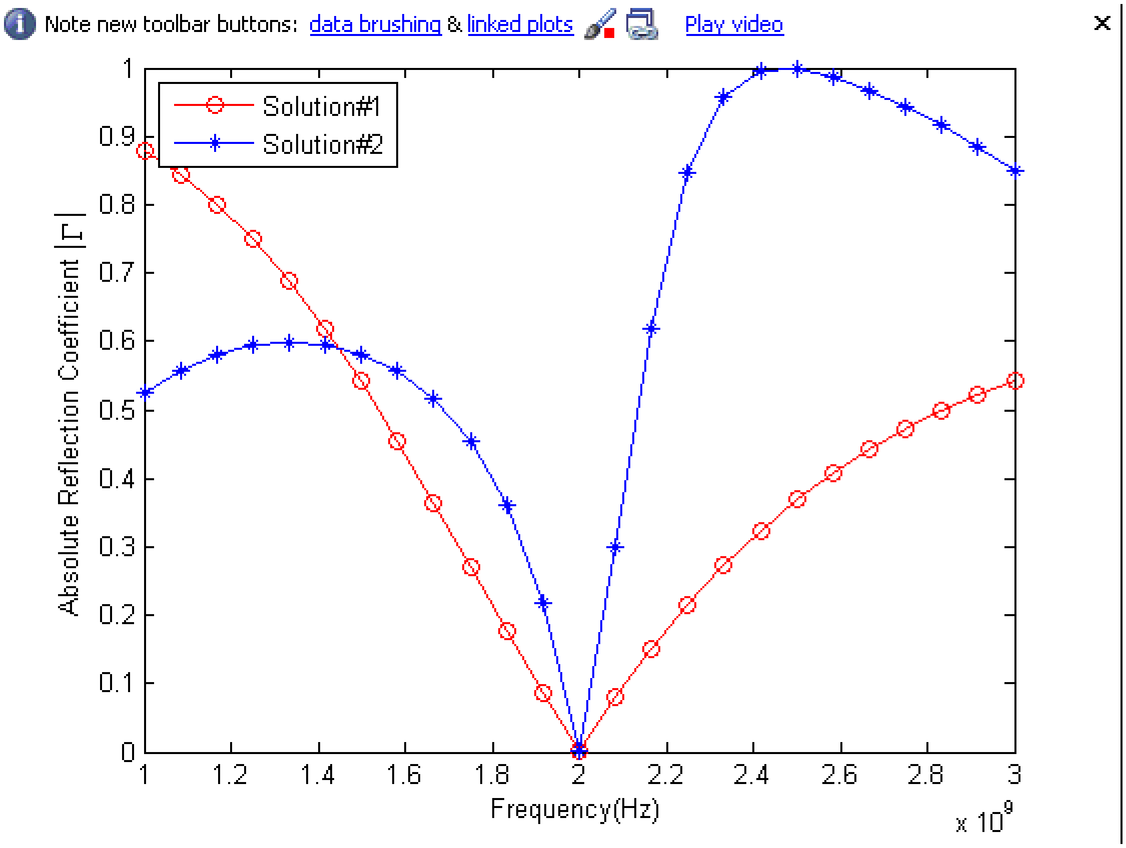


Fig. 6.18. Plot obtained for the reflection coefficient vs. frequency.

In the above example, CAMDS correctly produced the design for a single-stub impedance matching network given the source impedance, the load impedance, and the design frequency. As another example, consider a source impedance of 50 Ω, a load impedance of 100 Ω, and an operating frequency of 1.5 GHz. As with the L match, this is of educational interest since the 100-Ω load impedance can be provided in the laboratory by a 50-Ω load as seen through an appropriately designed quarter-wavelength impedance transformer. The single-stub routine in CAMDS returns:

SOLUTION 1

The distance of stub from load in terms of wavelength is=1.520434e-001

The open-circuited stub length in terms of wavelength is 4.020434e-001

The short-circuited stub length in terms of wavelength is 1.520434e-001

SOLUTION 2

The distance of stub from load in terms of wavelength is=3.479566e-001

The open-circuited stub length in terms of wavelength is 9.795664e-002

The short-circuited stub length in terms of wavelength is 3.479566e-001.

The first solution is an open-circuited stub of length 0.4020434 wavelengths located 0.1520434 wavelengths from the load. The second solution is an open-circuited stub of length 0.09795664 wavelengths located 0.3479566 wavelengths from the load.

As with the L-match, since in the laboratory the system impedance is 50-Ω and the voltage gain is often of great interest, the CAMDS result is here demonstrated by plotting S_{21} in dB versus frequency (Fig. 6.19). Note that the expected ideal value of 0 dB is definitely

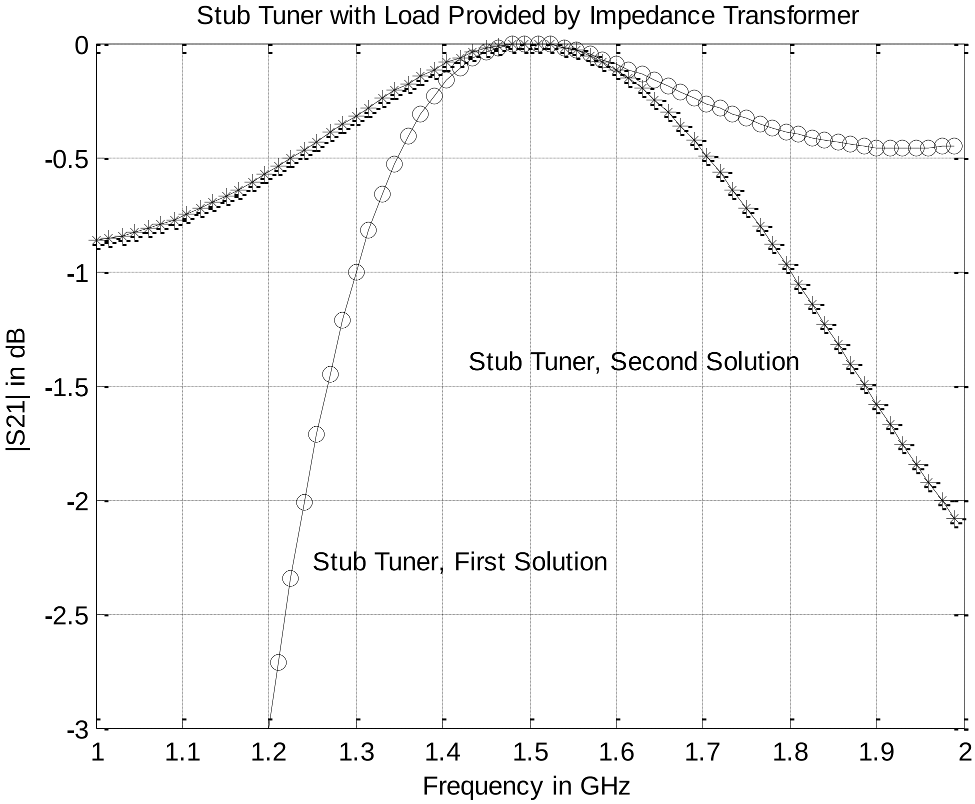


Fig. 6.19. Plot obtained using MATLAB for S_{21} in dB versus frequency.

achieved at the design frequency.

Comparison of Figs. 6-10 and 6-19 shows that the L match provides a significantly wider bandwidth. The stub solution has the advantage of the possibility of fabrication without requiring discrete components.

CHAPTER 7. IMPROVEMENTS AND SUGGESTIONS FOR CAMDS

This chapter describes improvements made in CAMDS [3]. It also describes the use of CAMDS in a class project for a university course in microwave engineering. Bais [4] suggested a class project using a third-order low-pass filter with a Butterworth characteristic designed with open-circuited stubs using microstrip lines. The cutoff frequency was 1.5 GHz. The source resistance, load resistance and characteristic impedance were each equal to 20 Ω.

Certain improvements were made in the microstrip code. The original CAMDS code used this formula for the effective dielectric constant:

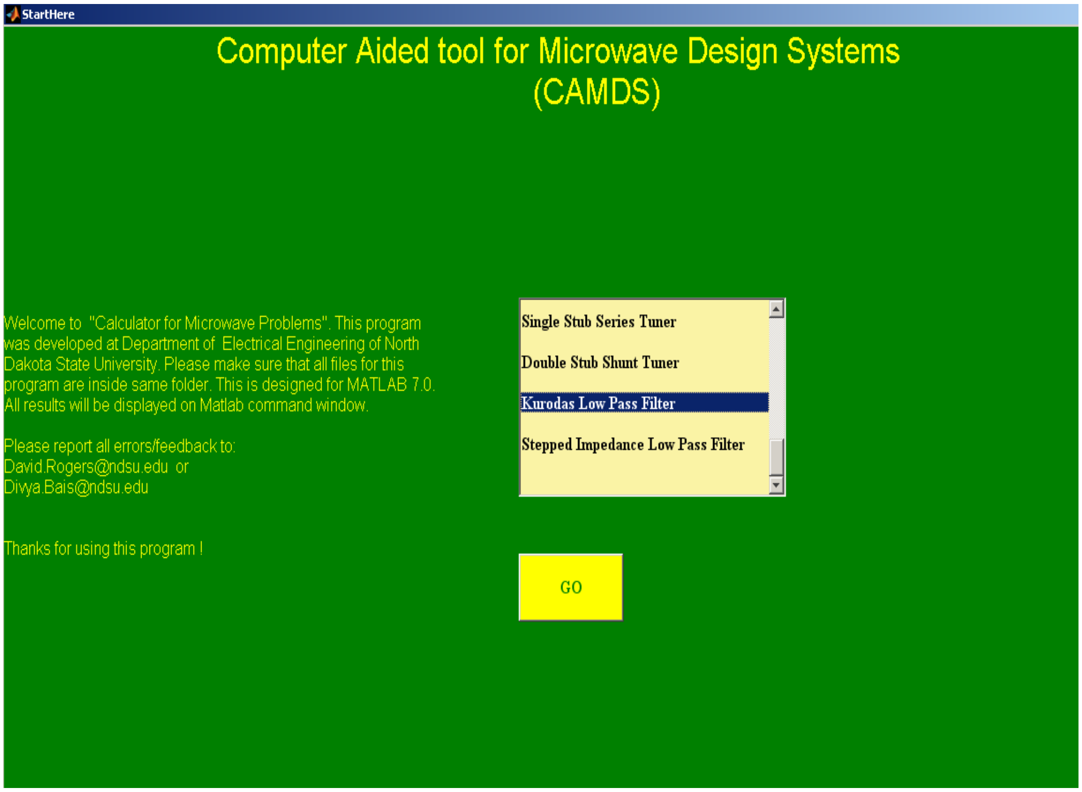
$$\epsilon_e = \left(\frac{\epsilon_r+1}{2} \right) + \left(\frac{\epsilon_r-1}{2} \right) \left(\frac{1}{\sqrt{1+12\frac{W}{d}}} \right),$$

which was corrected to:

$$\epsilon_e = \left(\frac{\epsilon_r+1}{2} \right) + \left(\frac{\epsilon_r-1}{2} \right) \left(\frac{1}{\sqrt{1+\frac{12d}{W}}} \right).$$

where $\frac{W}{d}$ is the microstrip line width divided by the substrate thickness. Furthermore, the calculation of the propagation constant was improved. These corrections led to changes in the values of effective dielectric constant, phase velocity, guide wavelength, propagation constant, filling factor in Hz and the capacitance per unit length of the line. In [4] the project description involves calculation of the dimensions of the physical filter using the design parameters, realization of the physical form of the filter on circuit board and checking the experimental result using the network analyzer. The steps to design this device with the improved result are given below:

1) The first step would be to design it using Kuroda’s identities. For this, start CAMDS by typing “guide” in the command prompt. This will open StartHere.fig. Then select Kuroda’s Low Pass Filter as shown in Fig. 7.1.



Computer Aided tool for Microwave Design Systems
(CAMDS)

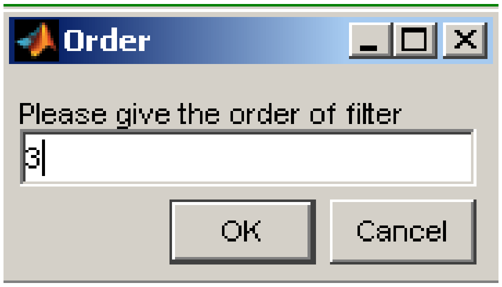
Welcome to "Calculator for Microwave Problems". This program was developed at Department of Electrical Engineering of North Dakota State University. Please make sure that all files for this program are inside same folder. This is designed for MATLAB 7.0. All results will be displayed on Matlab command window.

Please report all errors/feedback to:
David.Rogers@ndsu.edu or
Divya.Bais@ndsu.edu

Thanks for using this program !

Fig. 7.1. CAMDS start window with Kuroda’s Low Pass Filter selected.

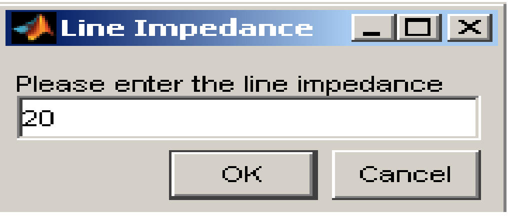
2) According to the project given in [4], enter the order of the filter as 3. Then click OK as shown in Fig. 7.2.



Please give the order of filter
3

Fig. 7.2. Box to input the order of the filter.

3) Input the line impedance as 20 Ω and then select OK as shown in Fig. 7.3.



Please enter the line impedance

20

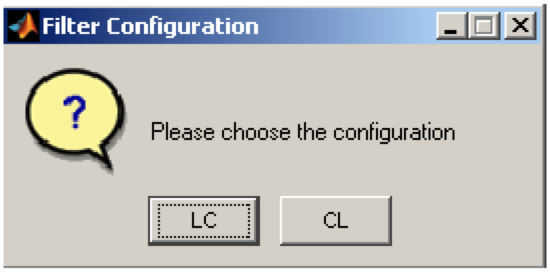
Fig. 7.3. Box to enter the line impedance.

4) As per the given project, select the filter type to be Butterworth as shown in Fig. 7.4.

Please select your filter

Fig. 7.4. Box to select the filter type.

5) Choose filter configuration as LC as shown below in Fig. 7.5.



Please choose the configuration

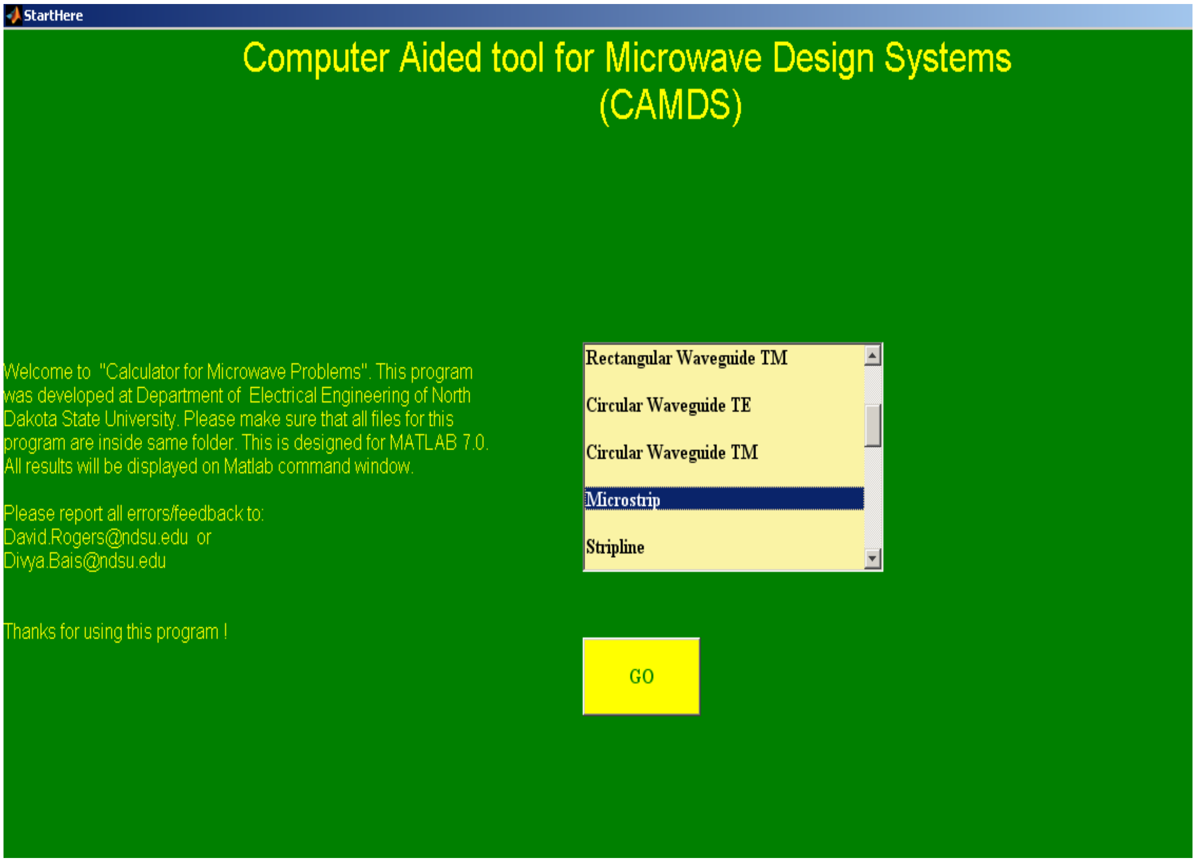
Fig. 7.5. Box to choose the filter configuration.

6) The command window of CAMDS provides the following results.

```
Open-Circuited Stub impedance= 40

Followed by line of impedance= 4.000000e+001

Followed by open stub of impedance =10

Followed by line of impedance= 4.000000e+001

Followed by open stub of impedance =4.000000e+001
```

The result shows that we have three transmission-line sections of 10 Ω, 20 Ω and 40 Ω each. These three microstrip sections now have to be designed. Due to the improvements made in the computer code for microstrip, new results are obtained. The design steps for the microstrip section are as follows:

1) Select microstrip from the startHere.fig and select Go, as in Fig. 7.6.



Computer Aided tool for Microwave Design Systems (CAMDS)

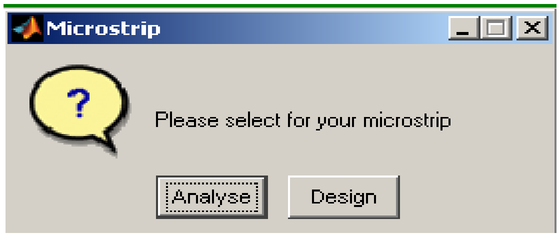
Welcome to "Calculator for Microwave Problems". This program was developed at Department of Electrical Engineering of North Dakota State University. Please make sure that all files for this program are inside same folder. This is designed for MATLAB 7.0. All results will be displayed on Matlab command window.

Please report all errors/feedback to:
David.Rogers@ndsu.edu or
Divya.Bais@ndsu.edu

Thanks for using this program !

Fig. 7.6. Start page showing “microstrip” selected.

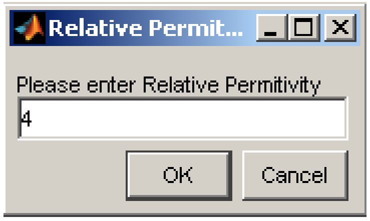
2) Choose Design from the next window as shown below in Fig. 7.7.



Please select for your microstrip

Fig. 7.7. Option box.

3) Enter a relative permitivity of 4 in the next box (Fig. 7.8).

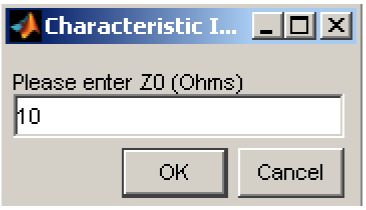


Please enter Relative Permittivity

4

Fig. 7.8. Box to input relative permitivity.

4) Input characteristic impedance equal to 10 Ω.

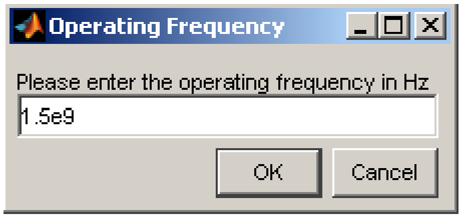


Please enter Z0 (Ohms)

10

Fig. 7.9. Input box for characteristic impedance.

5) Enter the operating frequency as 1.5 GHz as per the question.

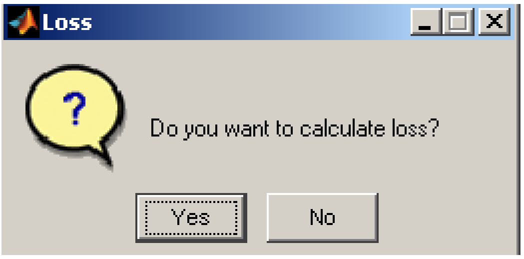


Please enter the operating frequency in Hz

1.5e9

Fig. 7.10. Input box for operating frequency.

6) Then a question box will appear (Fig. 7.11) asking if the user wants to calculate the loss. Here the user clicks NO and proceeds.



Do you want to calculate loss?

Fig. 7.11. Question box.

The command window will output the effective dielectric constant, W/d ratio, the angular velocity, phase velocity, guide wavelength, β, filling factor and capacitance.

The output obtained using the improved CAMDS code follows.

```
The Relative Permitivity is= 4
The characteristic impedance is 10
The effective dielectric constant is 3.64109
W/d ratio is 16.4834
Operating Frequency in Hz is 1.5e+009
k0 per meter is 31.4159
The angular velocity in rad/sec is 9.42478e+009
Phase velocity vp in m/s is 1.57219e+008
Guide wavelength Lambda_g in meters is 0.104813
beta in per meter is 59.9467
Filling Factor in Hz is 0.967142
Capacitance per unit length of the line in farads is 6.36054e-010
```

The same steps are repeated for characteristic impedances of 20 Ω and 40 Ω. The output displayed in the command window of the CAMDS software for 20 Ω is given below.

```
The Relative Permitivity is= 4
The characteristic impedance is 20
The effective dielectric constant is 3.42395
W/d ratio is 7.3367
Operating Frequency in Hz is 1.5e+009
k0 per meter is 31.4159
```

```
The angular velocity in rad/sec is 9.42478e+009
Phase velocity vp in m/s is 1.62128e+008
Guide wavelength Lambda_g in meters is 0.108085
beta in per meter is 58.1318
Filling Factor in Hz is 0.94392
Capacitance per unit length of the line in farads is 3.08399e-010.
```

Similarly for the characterisctic impedance of 40 **Ω**, the output obtained using the improved CAMDS software is as follows:

```
The Relative Permitivity is= 4
The characteristic impedance is 40
The effective dielectric constant is 3.16219
W/d ratio is 2.90469
Operating Frequency in Hz is 1.5e+009
k0 per meter is 31.4159
The angular velocity in rad/sec is 9.42478e+009
Phase velocity vp in m/s is 1.68705e+008
Guide wavelength Lambda_g in meters is 0.11247
beta in per meter is 55.8655
Filling Factor in Hz is 0.911684
Capacitance per unit length of the line in farads is 1.48188e-010.
```

The results obtained from the improved CAMDS software are shown in Table 7.1 for a substrate of thickness 0.0015748 meters.

Table 7.1. Improved project results obtained using CAMDS.

Characteristic Impedance (Ω)	$\frac{W}{d}$	W (meters)	Guide Wavelength (meters)	Section Length (meters)
10	16.48	0.025953	0.10481	0.01310
20	7.337	0.01154	0.10809	0.01351
40	2.905	0.004575	0.11247	0.01406

Table 7.1 above provides improvements to Table 7.1 in Bais [4] due mainly to the improvement made in the microstrip code. The main practical result was the reduction by about ten percent in the section lengths. The resulting project is interesting, but it is not physically realizable due to the excessive width of the 10-Ω line. A better option for a student project would be something like Pozar's example 8.6. Even his example 8.5 though difficult to fabricate can serve as a suitable project for the more advanced students. Details about these examples were provided earlier in Chapter 5 of this paper.

CHAPTER 8. CONCLUSION

In this paper the Computer-Aided Microwave Design System (CAMDS) as originally developed by Divya Bais was the central focus. This work presents improvements to CAMDS and verifies its performance. A context for this paper was developed by reviewing the scattering parameters since they are of such great importance throughout the paper. This was followed by a review of the basic processes involved in using CAMDS. The section of code in CAMDS that has such great importance is the script that performs the microstrip calculations. This material was reviewed and significant improvements in this script are reported. This improvement had a profound impact on the rest of the paper since this led to significant changes in the microstrip lines designed using CAMDS. Line dimensions calculated by CAMDS as a function of frequency, substrate thickness, and dielectric constant are now much more reliable than before.

For the devices considered in this paper, the improved CAMDS was the starting point. CAMDS was first used to obtain a recommended design. Then, for example, the improved CAMDS design results for microwave stepped-impedance filters or filters constructed with stubs were rigorously verified by comparison with results: (i) reported by Pozar, (ii) simulated by ADS, (iii) fabricated and tested using ADS layouts, and (iv) obtained by independent computer analysis. CAMDS designs for the L match and for single-stub tuners were carefully verified by comparison with results reported by Pozar and by independent computer analysis of the device designed using CAMDS. Taken together as a whole, this work shows that the improved CAMDS is a reliable package.

The work reported here builds on the comprehensive original work of Divya Bais (CAMDS). That work consisted of approximately 5,400 lines of computer code and dealt with a wide spectrum of devices including those designed not only in microstrip, but also in stripline and waveguide. The improved version of CAMDS and the experiences reported in this paper will provide future users with increased benefits due to the improvements made and the demonstrations of reliability. CAMDS is an excellent design tool for microwave engineering since it generates complete lists of parameters for a given specification and has established a pattern or structure for future inclusion of transmission lines implemented in other technologies and for future inclusion of more advanced microwave devices. It also could be enhanced by future improvement of the graphical user interface. The main results of this paper are an improved version of CAMDS and rigorous verification of its capabilities to produce useful designs for practical passive microwave devices.

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