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ECE424F Microwave Circuits

Experiment: Construction and Characterization of a Microstrip Filter

1. Purpose

The purpose of this experiment is to build and test a microstrip filter. The filter will be constructed using simple etching techniques applied a printed circuit board. The experiment consists of two parts. In part I the filter should be designed using Puff (an educational Computer Aided Design tool). In part II, the prepared filter should be characterized using a Scalar Network Analyzer and a Sweep Generator.

2. Theoretical Background

2.1 The microstrip line

A microstrip line is a transmission line consisting of a strip conductor of width w and thickness t, and a ground plane separated by a dielectric substrate of dielectric constant ε_r and height h. Figure 1.a illustrates the microstrip geometrical configuration.

The electromagnetic field lines in the microstrip are not entirely contained in the substrate (Figure 1.b.). Therefore, the dominant propagating mode on the microstrip is not a pure transverse electromagnetic mode (TEM mode) but a quasi-TEM (i.e. the longitudinal fields do not vanish but still they are small). This complicates the analysis for computing the propagation constant β and characteristic impedance Z_0. Nevertheless, for thin substrates ($h \ll \lambda$), an "equivalent" medium with effective dielectric constant $1 < \varepsilon_e < \varepsilon_r$ can be defined which can be considered as filling the entire space. Then the corresponding phase velocity and propagation constant can be expressed as $v_p = c/\sqrt{\varepsilon_e}$ and $\beta = k_o\sqrt{\varepsilon_e}$.

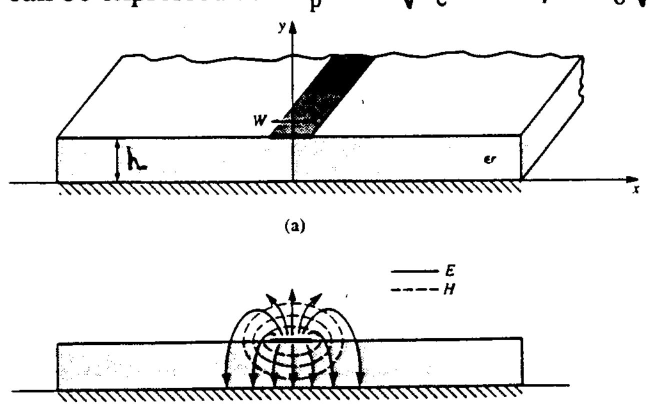


Figure 1

Both the effective dielectric constant and characteristic impedance depend on the ratio w/h and the substrate dielectric constant ε_r.

Effective dielectric constant:

$$\varepsilon_e \cong \frac{(\varepsilon_r + 1)}{2} + \frac{(\varepsilon_r - 1)}{2}\left(\frac{1}{\sqrt{1 + 12h/w}} + 0.04\left(1 - \frac{w}{h}\right)^2\right)$$

For w/h>>1 this yields :

$$\varepsilon_e \cong \frac{(\varepsilon_r + 1)}{2} + \frac{(\varepsilon_r - 1)}{2}\frac{1}{\sqrt{1 + 12h/w}}$$

from which $v_p = \frac{c}{\sqrt{\varepsilon_e}}$, $\beta = k_o\sqrt{\varepsilon_e}$.

Characteristic impedance:

$$Z_o = \begin{cases} \dfrac{60}{\sqrt{\varepsilon_e}}\ln\left(8\dfrac{h}{w} + 0.25\dfrac{w}{d}\right) & \text{for } w/h \le 1 \\[2ex] \dfrac{120\pi}{\sqrt{\varepsilon_e}\left[w/h + 1.393 + 0.667\ln(w/h + 1.444)\right]} & \text{for } w/h \ge 1 \end{cases}$$

Conductor losses:

The approximate attenuation due to ohmic losses is

$\alpha_c \cong \frac{R_s}{wZ_o}$ Np / m where the surface resistivity is $R_s = \sqrt{\omega\mu_o / 2\sigma}$.

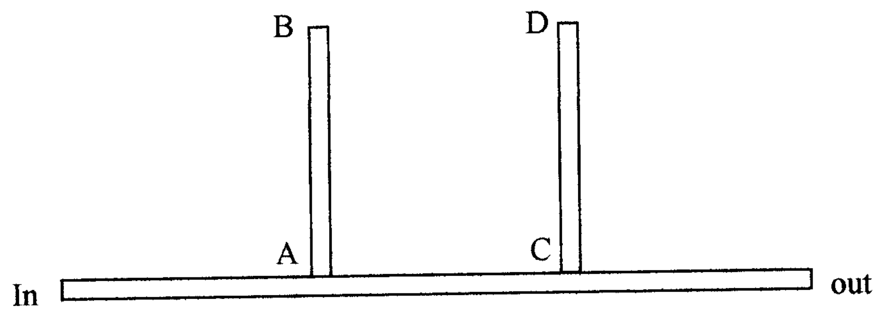
Dielectric losses:

The corresponding attenuation due to dielectric losses is

$\alpha_d = \frac{k_o\varepsilon_r(\varepsilon_e - 1)\tan\delta}{2\sqrt{\varepsilon_e}(\varepsilon_r - 1)}$ Np/m where $\tan\delta$ is the loss tangent of the substrate.

2.2 Microstrip filter

A microstrip stop-band filter can be constructed having a configuration as shown below:



where AB=CD= $\lambda/4$ at the design frequency.

Figure 2.

The filter consists of a through line between the input and output ports. Two quarter-wavelength shunt stubs are attached to the through line as shown in the figure. The input impedance of an open circuited stub of length l is given by:

$$Z_{in} = -jZ_o \cot(\beta l)$$

Away from resonance, the corresponding input impedance is very large (i.e. each shunt stub behaves like an open circuit) thus not affecting the through line. However, at the resonant frequency f_o, the corresponding stub length becomes $l = \lambda/4$ and $\beta l = \pi/2$ and each stub behaves like a short, therefore shorting out the through line running from input to output.

The corresponding input reflection coefficient is then

$$\Gamma_{in} = \frac{Z_{in} - Z_o}{Z_{in} + Z_o} .$$

The power reflected back to the source is $P_{in}|\Gamma_{in}|^2$ and thus the

$$\text{Return Loss} = -20\text{Log}|\Gamma_{in}| \text{ dB}.$$

On the other hand, the power delivered to a matched load attached to the output port is given by the expression

$$P_t = P_{in}\left(1 - |\Gamma_{in}|^2\right),$$

therefore the

$$\text{Insertion Loss} = -10\text{Log}(1 - |\Gamma_{in}|^2).$$

Note that the wavelength λ is not the free-space wavelength but the guided wavelength given by $\lambda = \lambda_o / \sqrt{\varepsilon_e}$.

3. Procedure

The experiment is divided into two parts. The first part concerns the design and construction of the filter. The second part concerns the testing and characterization of the filter.

3.1 Part I

Step 1: Design the filter

Design the filter shown in Figure 2 using the Puff design procedure as described in the next section. Try to answer all the questions that are raised in the Puff design procedure.

The design frequency of operation is $f_o = 1\text{GHz}$ and the substrate has the following characteristics :

Substrate thickness: 1.6 mm
Dielectric Constant: 4.5.

The width of the strips should be determined so that the characteristic impedance is 50 Ohms. The distance between the two stubs AC should also be determined in order to achieve maximum filter selectivity (i.e. a steep slope of the return loss about the 3dB points).

Step 2: Construct the filter

Once the geometrical parameters of the filter have been determined, construct the filter using the provided copper tape. Write your name on the ground-plane for identification purposes.

3.2 Puff design procedure

The working window is divided into the *Layout* Window (F1), the *Plot* Window (F2), the *Parts* Window (F3) and the *Board* window (F4). Also a Smith Chart and a rectangular plot are included for displaying the results of the analysis. To move from one window to another use the corresponding function keys F1 to F4. From each window, F10 toggles a small help window. To exit Puff you can use the Esc key.

The Layout window (F1) is used to construct the circuit.
The Plot window (F2) is used to perform the analysis.
The Parts window (F3) is used to define the circuit components (parts).
The Board window (F4) is used to define the substrate.

<u>Step 1: Define the substrate</u>

Using the F4 key access the board window to define the substrate. Use the cursor keys and the backspace for editing. In the first line, the normalization impedance for the Smith Chart is defined. This should be 50Ω. To type the Greek letter Ω use the combination Alt-o.

The second line calls for entering the design frequency. Enter 1 GHz.

The third line asks for the relative permittivity of the substrate, enter 4.5.

In the fourth line enter the thickness of the substrate 1.6 mm.

The fifth line defines the length and width of our substrate. Only square substrates are treated. In our case s=250.000 mm.

The fourth line asks for the distance between connectors (1,3) and (2,4). The connectors 1-4 shown in the Layout window help the circuit to communicate to the outside world. Enter a distance of 100.000 mm.

Finally use the Tab key to make sure that we are dealing with a microstrip substrate.

<u>Step 2: Define the parts</u>

Use the F3 key to jump to the Parts window. Enter the following lines:

a tline 50Ω 90°
b tline 50Ω 30°

Use the combination Alt-d to write the degree symbol.

The first line defines a transmission line named ,a, of characteristic impedance 50Ω and phase shift $\beta l = 90^{o}$ at the design frequency (i.e. a quarter wavelength long). While you are on the first line, press the = key. In the message box you will the see the physical length l and width w of the strip you need to use. The b-line is to be used for the distance AC in fig. 2. However, note that the 30-degrees is just a STARTING point and you should experiment with this length in order to achieve maximum selectivity.

Use the given approximate equations to verify that the Puff parameters indeed do generate a 50Ω impedance level and a phase shift of $\beta l = 90^{o}$ for the a-line.

Step 3: Circuit Layout

Press the F1 key to access the Layout window. Press the key a to access part-a. Part-a is now highlighted. To place a trace of the tline-a, simply move the cursor keys to the direction you want (left, right, up, down). To delete a trace, use Shift together with the desired cursor key. Also use Shift and the cursor keys to move around in the layout window. Use Ctrl-e at any time to erase your circuit. Use the a-line for defining the stubs AB and CD along with the input and output lines. In a similar way, place the b-line AC. You can always hit F10 for help.

Once you have designed the strips, go to the leftmost end of the through line and type 1. Then the input is connected to connector No. 1. Repeat for the rightmost end of the through line but now type 2 to access connector No. 2.

Step 4: Design & Analysis

Press the F2 key to go to the Plot window. Edit the number of points to be included in your frequency sweep analysis. Use the cursor keys to access the rectangular plot window. Edit the axes so that the sweep takes places between 0-2GHz and set the vertical axis from 0 to -25 dB. On the vertical axis S11 refers to the return loss while S12 refers to the insertion loss.

Type p and you will see the response of the circuit in front of you. Isn't this exciting?

Go back to the Parts Window and change the phase (i.e. length) of the b-line by steps of 30-degrees in the range $30^{o} \leq \theta_B \leq 180^{o}$. Each time repeat the analysis and try to determine which length yields (a) the higher slope of the return-loss around the 3 dB points and (b) a symmetric response with respect to the central frequency of 1 GHz. You may move the frequency marker using the Pgup and PgDn keys.

Once you have determined the length AC make a screen-dump of the corresponding analysis using the PrtSc key for future reference.

Puff Simulations. Discussion I

1. For your designed filter, compute (a) the corresponding bandwidth with respect to the 3dB points (b) the slope (selectivity) of the return-loss within the stop-band in dB/GHz.

2. Go to the layout window and delete one of the two stubs. Compare the filter responses with one and two stubs. What are the differences in terms of the bandwidth and the steepness of the filter's cutoff characteristics?

3. Replace the two lines of the parts window with

   a qline 50Ω 90^{o} 80Qd
   b qline 50Ω θ_B^{o} 80Qd

   Restore the filter to its initial configuration with both stubs present using the new line definitions shown above. Use the value θ_B that you determined as optimum during step 4. This now takes into account the dielectric losses in the substrate. In our case the substrate loss-tangent is about 0.01 and this is approximately accounted for by the factor 80Qd. Since under this model no conductor losses are accounted for, the filter's frequency response is ultimately considered dielectric-loss limited. Repeat the analysis and compare it to the initial lossless one. Is there any significant difference? Can the use of this rather lossy (but cheap) substrate at 1 GHz be justified ? Make a screen dump for future reference.

4. Extent the range of the analysis from 0-10 GHz. Repeat the analysis. Can you justify the periodic nature of the extended filter response ? Observe the behavior of the return loss at the central frequency of each period. How does it vary with frequency?

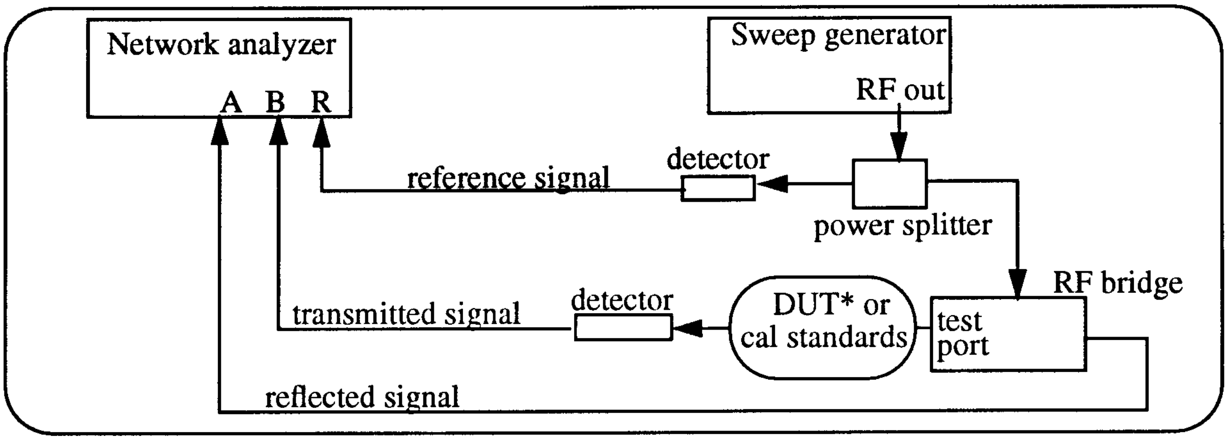
5. Replace 80Qd with 80Qc on the first two lines of the parts window. This time, the dielectric losses are assumed negligible and the filter is considered conductor-loss limited. Repeat the analysis in the range 0-10 GHz. Observe the behavior of the return loss with frequency and compare it with the case of the dielectric loss limited behavior. Can you deduce a way of differentiating between a dielectric-loss limited and a conductor-loss limited filter?

3.3 Part II

Measurement procedure:

1) Set the sweep generator frequency range to 100-1900 MHz and the output power to -10 dBm.

2) Ensure that the RF bridge and detectors are connected as follows:



*DUT = device under test, ie. your filter

3) Set the network analyzer to measure A/R (relative reflected power) on channel 1 and B/R (relative transmitted power) on channel 2. Powers are relative to R, the reference signal.

4) Calibrate channel 1: Using the soft keys on the network analyzer, select calibrate [CAL], then calibrate with the RF bridge test port connected to the shielded open and the short, in turn. Set channel 1 to display Measurement - Memory.

5) Calibrate channel 2: connect the RF bridge test port directly to the "B" detector. On the 8756A network analyzer, do channel 2 display -> memory. On the 8757D network analyzer, do calibrate through [THRU]. On both network analyzers, set channel 2 to display Measurement - Memory.

6) Check the calibration by ensuring that with the test port open, all of the power is reflected (ideally, channel 1 displays 0 dB and channel 2 displays -infinity), and with the test port connected directly to the "B" detector, all of the power is transmitted (ideally, channel 1 displays -infinity and channel 2 displays 0 dB). Adjust the scale and reference level of each channel as required to make these measurements.

7) Connect your filter between the test port and the "B" detector. Autoscale both channels. Note the 3 dB points of your filter.

8) Generate a hardcopy of the display by using the softkeys to plot [PLOT ALL]. On the 8757D the plot commands are under the System menu.

4. General Discussion

1. You can compute your filter's response using the Smith Chart. In order to do so, assume that the output port is terminated at the characteristic impedance Z_o. In this configuration, use the Smith chart to compute the input impedance Z_{in} as a function of the frequency. For your convenience, the Smith Chart calculations can be done in the reduced frequency range $0.75\text{ GHz} \le f \le 1.25\text{ GHz}$. Also you may assume no losses and that the input/output lines have negligible lengths (they just introduce a phase shift). In this way you can compute the associated return and insertion loss in the given frequency range.

2. On a rectangular graph, plot together the return loss simulated with Puff (first simulation with tlines and no losses) and computed by the Smith Chart. How do they compare ?

3. On a rectangular graph, plot together the measured and simulated by Puff (second simulation with qlines and 80Qd) insertion loss as a function of the frequency. Observe the differences in terms of (a) location of the central frequency (b) location of the 3dB points and corresponding bandwidth (c) filter selectivity (i.e. slope of the insertion loss).

4. You can account for the observed difference between the measured and simulated central frequency by assuming that the two stubs are actually longer than what their physical length is. This is because each open circuited (o.c.) stub induces a fringing field at its open end. This field can be modeled as a shunt fringing capacitance C_f attached to the open end. Equivalently, C_f can be accounted for by assuming that the open stub is actually longer than its physical length (a short section of an o.c. line behaves capacitively, remember?). Compute the required additional length ΔL and the corresponding fringing capacitance C_f. Note that Puff does not take into account this end effect.

5. Can you propose an equivalent lumped circuit for the microwave filter about the resonant frequency of 1GHz? You may also assume no losses and that the input/output lines have negligible lengths. <u>Hint:</u> Start by deriving an equivalent lumped circuit for each one of the two $\lambda/4$ stubs. Then try to determine how the circuit representing the stub CD is transformed to the input by the section AC.