Experiment 2 - Broadband Matching and 3D Electromagnetic Simulation Software.

S. Levy, Z. Ibragimov, D. Ackerman and H. Matzner.

May 3, 2009

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1 Prelab Exercise

1. For a single quarter wavelength transformer, how can the equation for its impedance be achieved, if the characteristic and the load impedances are known and real?

2. Find the characteristic impedances of the quarter wavelength transformers which match a load $Z_L = 100\ \Omega$ to a transmission line $Z_0 = 50\ \Omega$ at $f = 1.5\ GHz$ for:

   (a) a single transformer.

   (b) 3 binomial transformers.

   (c) 3 Chebyshev transformers with $\Gamma_m = 0.2$.

2 Background Theory

2.1 Introduction

In this experiment we will exercise a broadband matching technique based on series of quarter wavelength transformers. This type of matching is suitable especially for a nearly constant and real impedance load in a relevant frequency range. As the number of matching elements is increased, the matching level can be improved and/or frequency range can be increased. For a given matching level and frequency range, one can find the number of transforms needed in order to get the relevant performance. The main algorithms are the binomial and Chebyshev matching. The matched load circuit is shown in Figure 1. More details are presented in [1]

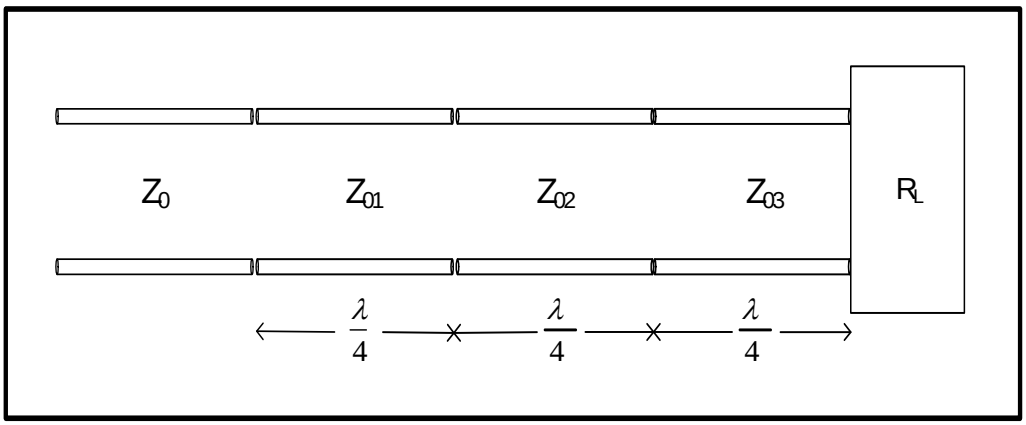

Figure 1 - Matching the load R_L with 3 quarter wavelength transformers.

$$\Gamma_0 = \frac{Z_L - Z_0}{Z_L + Z_0}$$

The fractional bandwidth of the transformers is given by:

$$\frac{\Delta f}{f_0} = 2 - \frac{4\theta_m}{\pi} = 2 - \frac{4}{\pi}\cos^{-1}\left[\frac{\Gamma_m}{\sqrt{1-\Gamma_m^2}} \cdot \frac{2\sqrt{Z_0 Z_L}}{|Z_L - Z_0|}\right]$$

Where Γ_m is the maximum value of the reflection coefficient magnitude, which can be tolerated at the input, and θ_m is the $\theta = \beta l$ where $\Gamma = \Gamma_m$ (the lower edge of the passband).

The fractional bandwidth is usually expressed in percentage, $100 \cdot \frac{\Delta f}{f_0}$ [%]. Note that the bandwidth increases as Z_L becomes closer to Z_0 (a less mismatched load).

2.2 Binomial Matching

In this algorithm, the reflection coefficient is a smooth function of frequency and has a maximal flat response near the design frequency.

The values of the characteristic impedances of the quarter wavelength transformers are given by:

$$Z_{0k} = Z_0 \left(\frac{R_L}{Z_0} \right)^{\frac{M_k}{2^N}} \qquad ; \qquad k = 1, 2, ...N$$

Where N is the number of transformers and

$$M_k = C_1 + C_2 + ... + C_k$$

Where

$$C_1 = 1, \qquad C_k = \frac{N!}{(N-k+1)!(k-1)!}$$

The maximum value of the reflection coefficient magnitude, Γ_m, which can be tolerated at the input is given by:

$$\Gamma_m = 2^N \left| A \right| \cos^N(\theta_m)$$

Where:

$$A = 2^{-N} \cdot \Gamma_0$$

Thus, θ_m can be computed using Γ_m by:

$$\theta_m = \cos^{-1} \left[\frac{1}{2} \cdot \left(\frac{\Gamma_m}{|A|} \right)^{\frac{1}{N}} \right]$$

When possible, one should use a table. Table 1 shows the values of the characteristic impedances for the binomial transformers.

Z_L/Z_0	$N=2$		$N=3$			$N=4$			
	Z_1/Z_0	Z_2/Z_0	Z_1/Z_0	Z_2/Z_0	Z_3/Z_0	Z_1/Z_0	Z_2/Z_0	Z_3/Z_0	Z_4/Z_0
1.0	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000
1.5	1.1067	1.3554	1.0520	1.2247	1.4259	1.0257	1.1351	1.3215	1.4624
2.0	1.1892	1.6818	1.0907	1.4142	1.8337	1.0444	1.2421	1.6102	1.9150
3.0	1.3161	2.2795	1.1479	1.7321	2.6135	1.0718	1.4105	2.1269	2.7990
4.0	1.4142	2.8285	1.1907	2.0000	3.3594	1.0919	1.5442	2.5903	3.6633
6.0	1.5651	3.8336	1.2544	2.4495	4.7832	1.1215	1.7553	3.4182	5.3500
8.0	1.6818	4.7568	1.3022	2.8284	6.1434	1.1436	1.9232	4.1597	6.9955
10.0	1.7783	5.6233	1.3409	3.1623	7.4577	1.1613	2.0651	4.8424	8.6110

Z_L/Z_0	$N=5$					$N=6$					
	Z_1/Z_0	Z_2/Z_0	Z_3/Z_0	Z_4/Z_0	Z_5/Z_0	Z_1/Z_0	Z_2/Z_0	Z_3/Z_0	Z_4/Z_0	Z_5/Z_0	Z_6/Z_0
1.0	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000
1.5	1.0128	1.0790	1.2247	1.3902	1.4810	1.0064	1.0454	1.1496	1.3048	1.4349	1.4905
2.0	1.0220	1.1391	1.4142	1.7558	1.9569	1.0110	1.0790	1.2693	1.5757	1.8536	1.9782
3.0	1.0354	1.2300	1.7321	2.4390	2.8974	1.0176	1.1288	1.4599	2.0549	2.6577	2.9481
4.0	1.0452	1.2995	2.0000	3.0781	3.8270	1.0225	1.1661	1.6129	2.4800	3.4302	3.9120
6.0	1.0596	1.4055	2.4495	4.2689	5.6625	1.0296	1.2219	1.8573	3.2305	4.9104	5.8275
8.0	1.0703	1.4870	2.8284	5.3800	7.4745	1.0349	1.2640	2.0539	3.8950	6.3291	7.7302
10.0	1.0789	1.5541	3.1623	6.4346	9.2687	1.0392	1.2982	2.2215	4.5015	7.7030	9.6228

Table 1: Values of the characteristic impedances of binomial transformers.

2.2.1 Example

Match the load $Z_L = 75\ \Omega$ by two quarter wavelength microstrip transformers to a transmission line with $Z_0 = 50\ \Omega$. Use binomial matching for a match at $f = 1\ GHz$. The microstrip has a permittivity of $\varepsilon_r = 4.9$, height of substrate is $h = 1.6\ mm$, height of conductive layer is $T = 0.02\ mm$ and a loss tangent of $\tan\delta = 0.018$.

2.2.2 Solution

Calculating the length of each transform:

$f = 1\ GHz \ \rightarrow\ \lambda = \frac{c}{f\cdot\sqrt{\varepsilon_r}} = 0.138\ m \ \rightarrow\ L = \frac{\lambda}{4} = 3.4\ cm.$

Using Table 1 for $\frac{Z_L}{Z_0} = 1.5$ and $N = 2$ will yield $Z_1 = 55.3\ \Omega$ and $Z_2 = 67.77\ \Omega$.

Using the tool LineCalc (or calculating by the formula for $\frac{w}{d}$ for microstrip) will yield $w_1 = 2.44\ mm$ and $w_2 = 1.65\ mm$.

An example for the layout is shown in Figure 2.

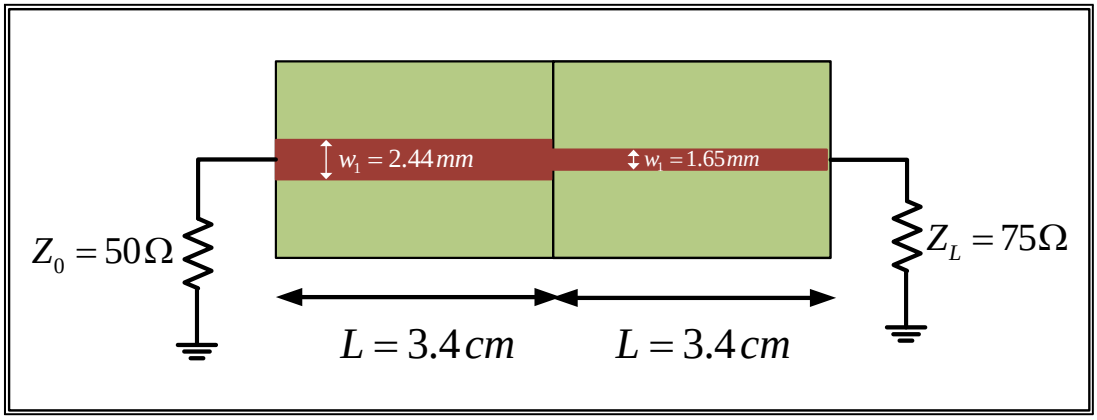

Figure 2 - An example of a load matched by 2 qarter wavelength microstrip transformers.

2.3 Chebyshev Matching

In this case, a ripple in the matched frequency range is defined, but the number of transformers can be slightly reduced relative to the binomial case for a given bandwidth.

$$\sec\theta_m = \cosh\left[\frac{1}{N}\cosh^{-1}\left(\frac{\Gamma}{\Gamma_m}\right)\right]$$

Table 2 shows the values of the characteristic impedances for the Chebyshev transformers.

	$N = 2$				$N = 3$					
	$\Gamma_m = 0.05$		$\Gamma_m = 0.20$		$\Gamma_m = 0.05$			$\Gamma_m = 0.20$		
Z_L/Z_0	Z_1/Z_0	Z_2/Z_0	Z_1/Z_0	Z_2/Z_0	Z_1/Z_0	Z_2/Z_0	Z_3/Z_0	Z_1/Z_0	Z_2/Z_0	Z_3/Z_0
1.0	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000
1.5	1.1347	1.3219	1.2247	1.2247	1.1029	1.2247	1.3601	1.2247	1.2247	1.2247
2.0	1.2193	1.6402	1.3161	1.5197	1.1475	1.4142	1.7429	1.2855	1.4142	1.5558
3.0	1.3494	2.2232	1.4565	2.0598	1.2171	1.7321	2.4649	1.3743	1.7321	2.1829
4.0	1.4500	2.7585	1.5651	2.5558	1.2662	2.0000	3.1591	1.4333	2.0000	2.7908
6.0	1.6047	3.7389	1.7321	3.4641	1.3383	2.4495	4.4833	1.5193	2.4495	3.9492
8.0	1.7244	4.6393	1.8612	4.2983	1.3944	2.8284	5.7372	1.5766	2.8284	5.0742
10.0	1.8233	5.4845	1.9680	5.0813	1.4385	3.1623	6.9517	1.6415	3.1623	6.0920

	$N = 4$							
	$\Gamma_m = 0.05$				$\Gamma_m = 0.20$			
Z_L/Z_0	Z_1/Z_0	Z_2/Z_0	Z_3/Z_0	Z_4/Z_0	Z_1/Z_0	Z_2/Z_0	Z_3/Z_0	Z_4/Z_0
1.0	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000
1.5	1.0892	1.1742	1.2775	1.3772	1.2247	1.2247	1.2247	1.2247
2.0	1.1201	1.2979	1.5409	1.7855	1.2727	1.3634	1.4669	1.5715
3.0	1.1586	1.4876	2.0167	2.5893	1.4879	1.5819	1.8965	2.0163
4.0	1.1906	1.6414	2.4369	3.3597	1.3692	1.7490	2.2870	2.9214
6.0	1.2290	1.8773	3.1961	4.8820	1.4415	2.0231	2.9657	4.1623
8.0	1.2583	2.0657	3.8728	6.3578	1.4914	2.2428	3.5670	5.3641
10.0	1.2832	2.2268	4.4907	7.7930	1.5163	2.4210	4.1305	6.5950

Table 2: Values of the characteristic impedances of Chebyshev transformers.

In case that the value of the load is smaller than the value of the characteristic impedance of the transmission line - replace the values, find the characteristic impedance of the transformers by using the table, and then change the order of the transformers: the left one will be now the right one, etc.

3 Experiment Procedure

3.1 ADS Simulation

Match a load $Z_L = 100\ \Omega$ to a transmission line $Z_0 = 50\ \Omega$ at $f = 1.5\ GHz$. Use 'Prelab Exercise' question 1 and match for the cases:

a single transformer.
3 binomial transformers.
3 Chebyshev transformers with $\Gamma_m = 0.2$.

1. Match the load to the transmission line by an ideal transmission lines, as shown for a single ideal transformer in Figure 1.

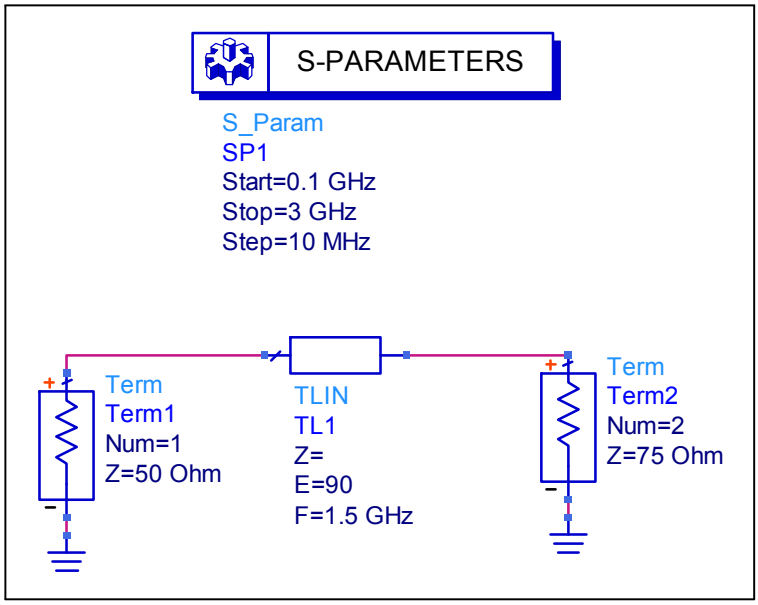

Figure 1 - An ADS example of a single ideal transformer.

Draw the graph of S_{11} in the frequency range of $100\ MHz - 3\ GHz$ for each case and measure the bandwidth. Why can we treat the graph of S_{11} as the graph of the reflection coefficient?

2. Now, each transformer will be a microstrip with a substrate FR4 with a permittivity of $\varepsilon_r = 4.9$, height of substrate is $h = 1.6\ mm$, height of conductive layer is $T = 0.02\ mm$ and a loss tangent of $\tan\delta = 0.018$.

An ADS example of two microstrip transformers is shown in Figure 2.

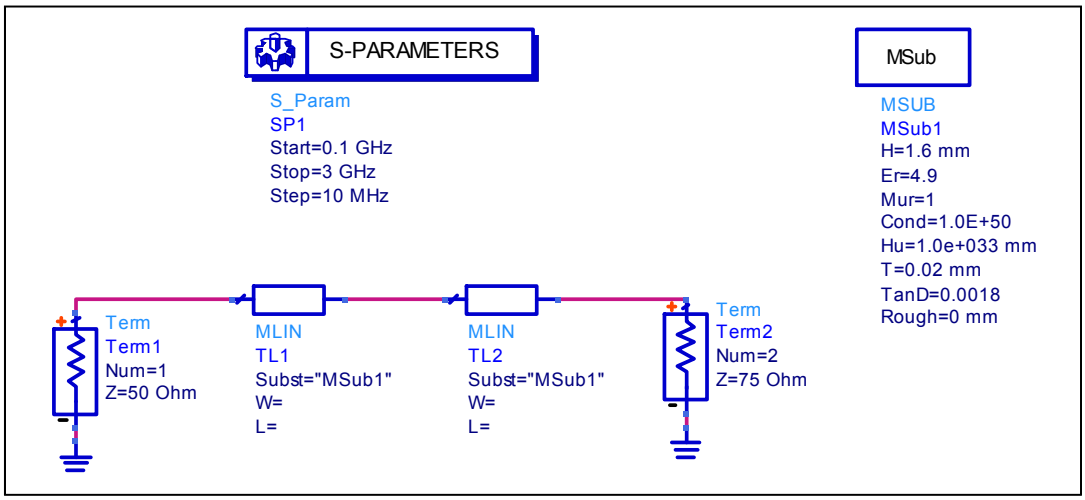

Figure 2 - An ADS example of a single microstrip transformer.

1. Draw the graph of S_{11} in the frequency range of 100 $MHz - 3$ GHz for each case and measure the bandwidth.

Compare the bandwidths for all cases, and compare them to theoretical bandwidth with $\Gamma_m = 0.2$. What is the value of SWR for this case?

3. Draw the graph of S_{11} in the frequency range of 100 $MHz - 20$ GHz for the case of 3 binomial transformers (microstrip and ideal) and compare the graphs.

3.2 CST Simulation

CST - Microwave Studio is a software package for solving 3D electromagnetic equations. We will learn how to use this software by an example of a simulation of a T-type microstrip divider, step by step. Figure 3 shows a splitter with and without a transformer.

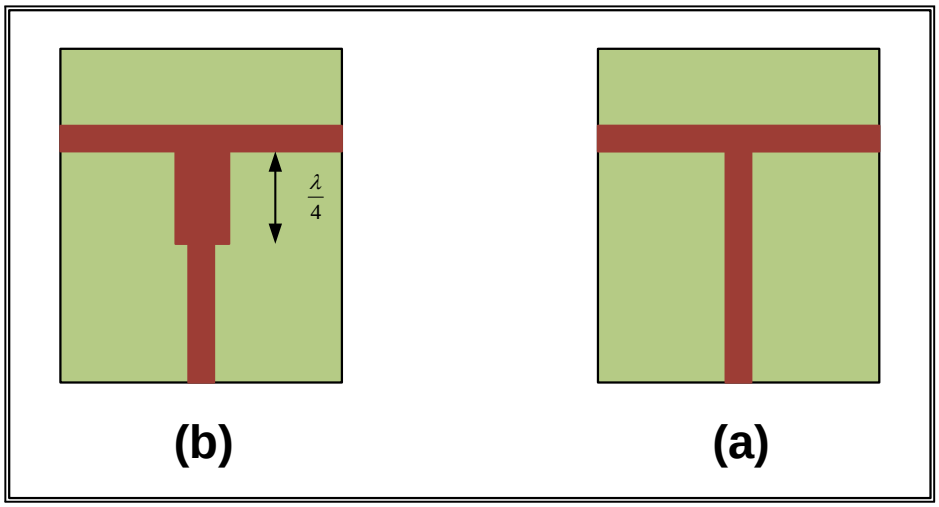

Figure 3 - Microstrip splitter (a) without matching, and (b) with matching.

3.2.1 Starting the simulation

Double click CST icon, as shown in Figure 4.

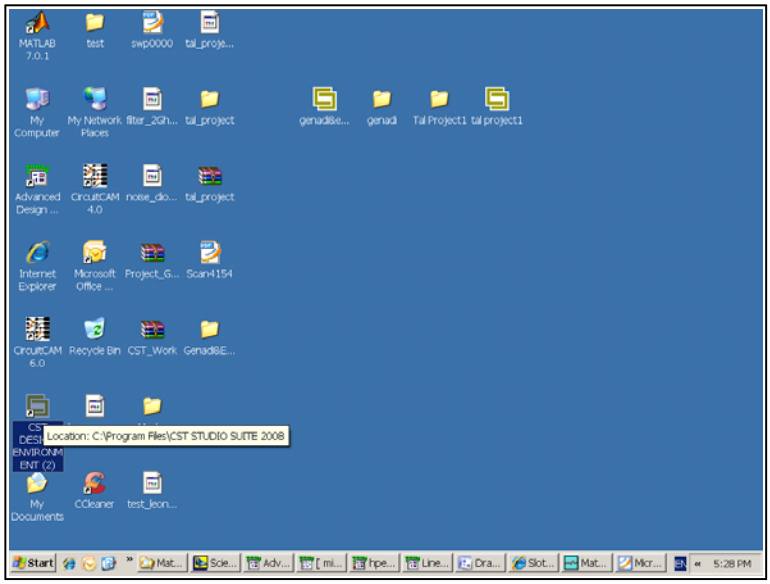

Figure 4 - Double click on the CST icon.

Choose the CST Microwave Studio option, as shown in Figure 7.

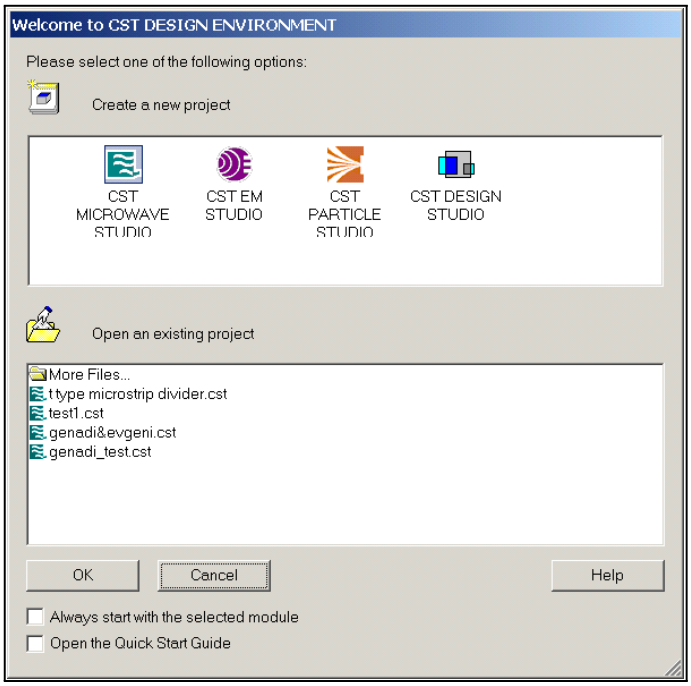

Figure 7 - Choose CST Microwave Studio icon.

Choose antenna (planar) template. Each template has a special choice of boundary conditions and geometry, as described in Figure 5.

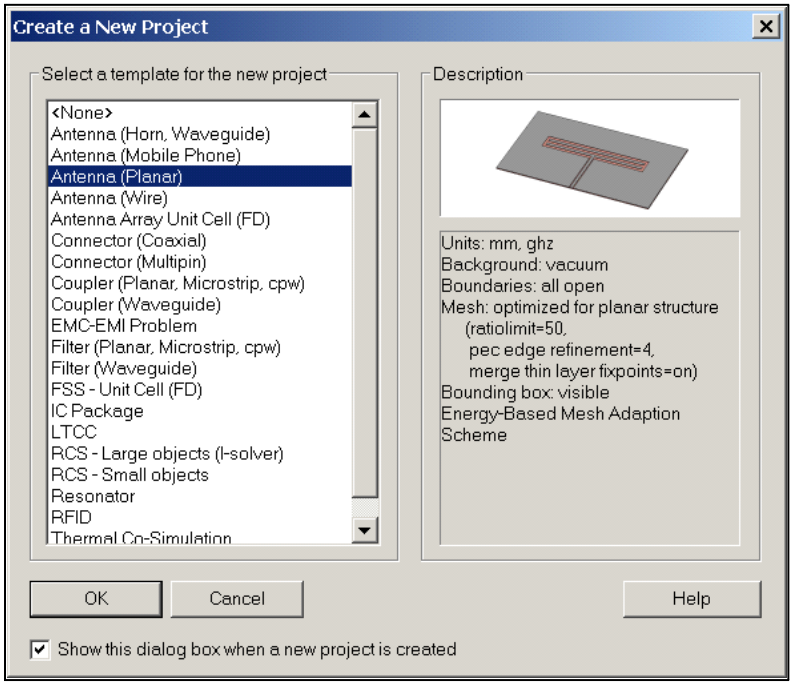

Figure 5 - Choose antenna (planar) template.

3.2.2 Defining the Parameters

First, define the parameters, as shown in Table 3.

Name	***Value***	***Description***
xg	50	Ground x dimension
yg	100	Ground y dimension
t	0.02	Metal thickness
hs	1.6	Substrate thickness
w	2.84	Microstrip line width
LL	70	Length of main line

Table 3 - Parameters Definition

3.2.3 Building the Component

Building the Ground We will start with the ground component. Lower left window is for the parameters and their values. For the ground we choose a brick and, press the escape button and then entering the component name,

dimensions and material, as shown in Figure 7.

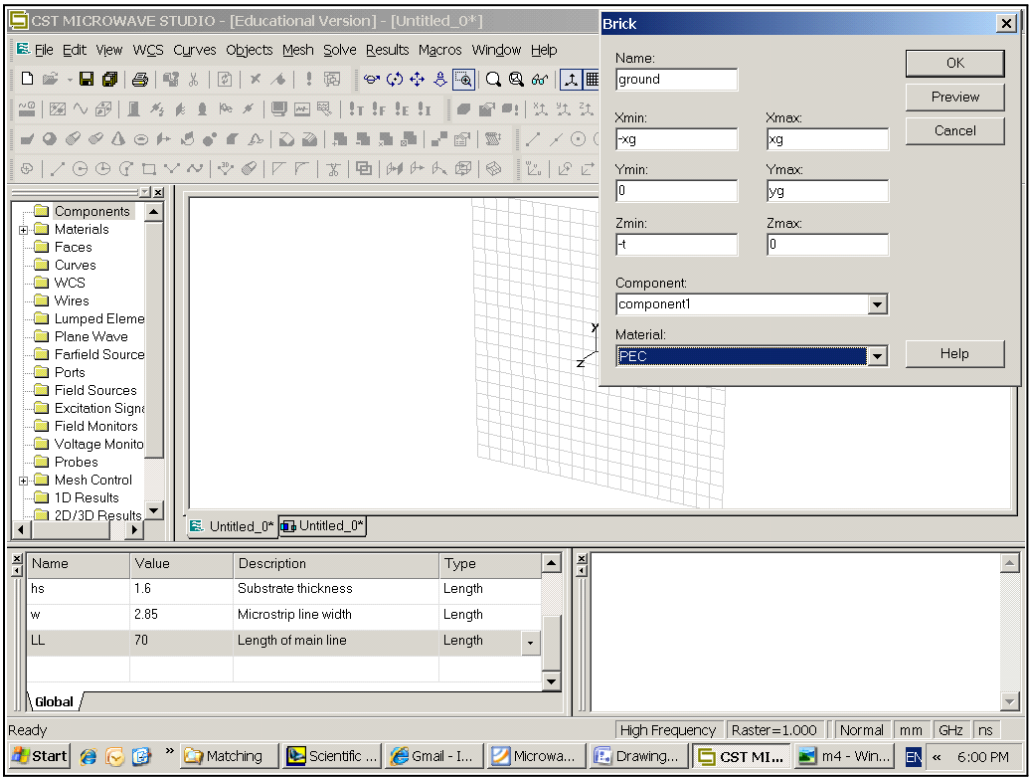

Figure 7 - Building the ground.

The material of the ground brick is PEC (Perfect Electric Conductor). The dimensions of the brick are $-xg \leq x \leq xg, \quad 0 \leq y \leq yg, \quad -t < z < 0$.

Building the substrate Next we build the FR4 substrate, again with a brick. We now have to choose the material of the substrate. You can choose it from the library, as shown in Figure 8.

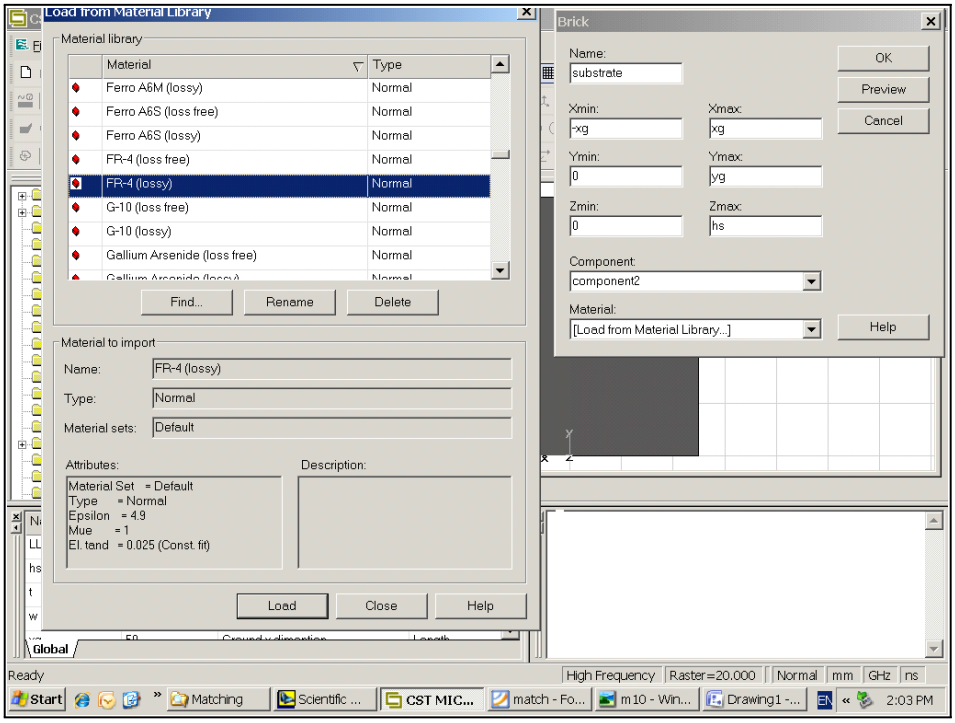

Figure 8 - Choosing the material for the substrate.

Find the Width of the Microstrip Line Choose Macros -> Calculate -> Calculate analytic Line Impedance, then you get a the needed window. You can find that the needed width of the microstrip line is 2.84 mm for 50 Ω, as shown in Figure 9.

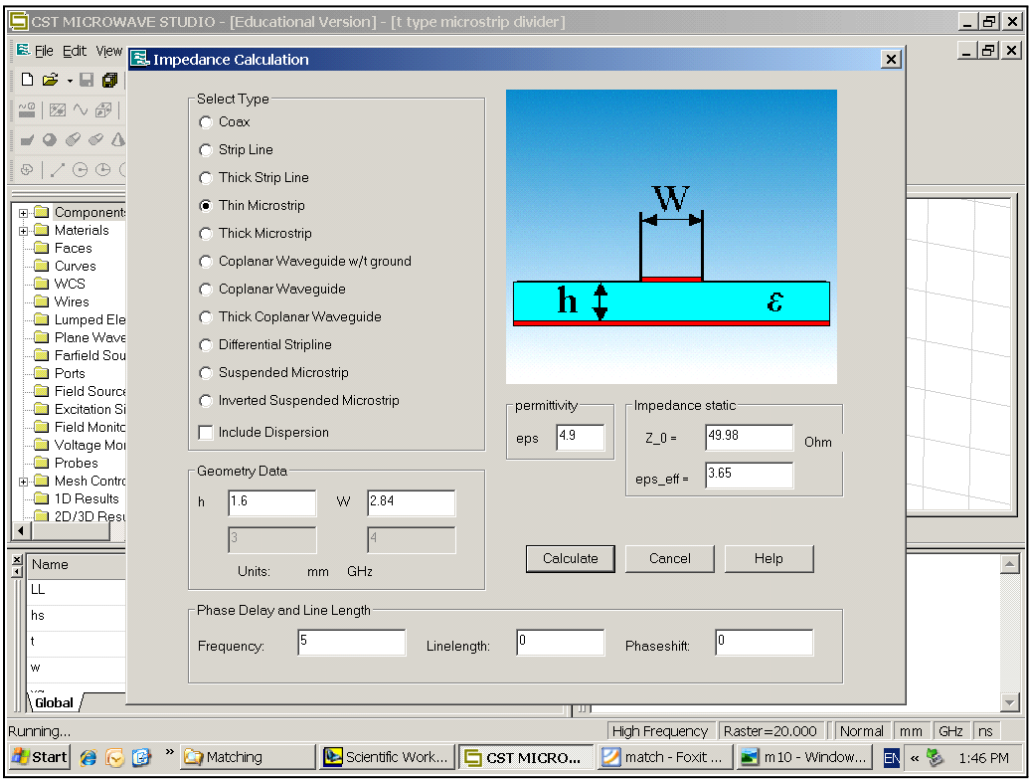

Figure 9 - Impedance calculation.

Building the Divider We use the Extrude option, which enables us to define a polygon in a plane, and then inverting it to a body, as shown in Figure 10.

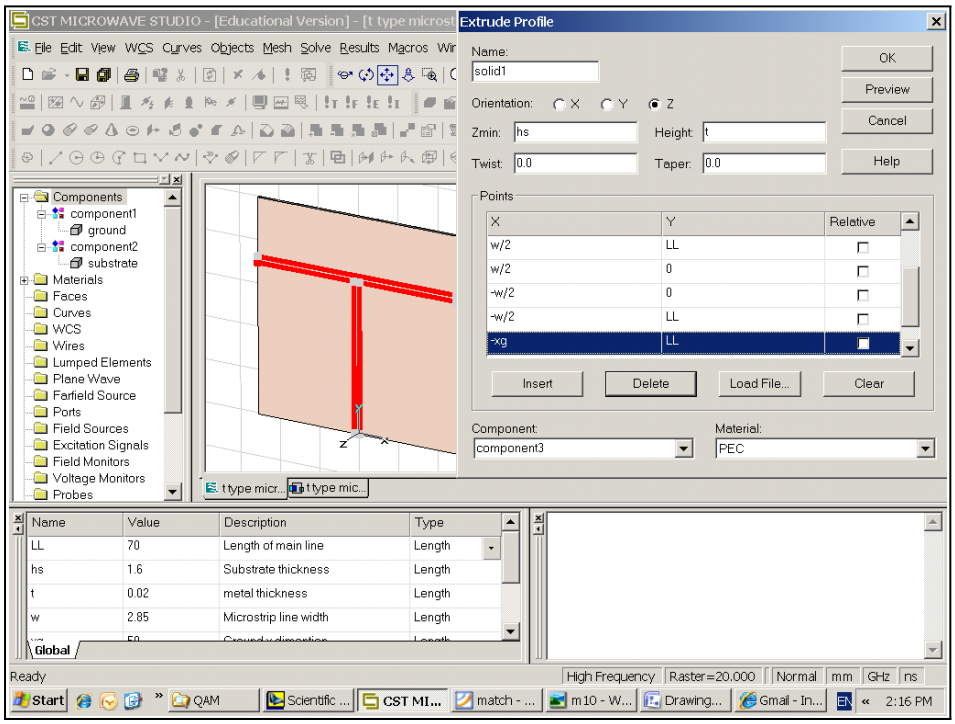

Figure 10 - Building the divider.

3.2.4 Define the Ports

In this case, we will choose simple waveguide ports, as shown in Figure 11. Another option is a coaxial port, but then we have to first build coaxial connectors.

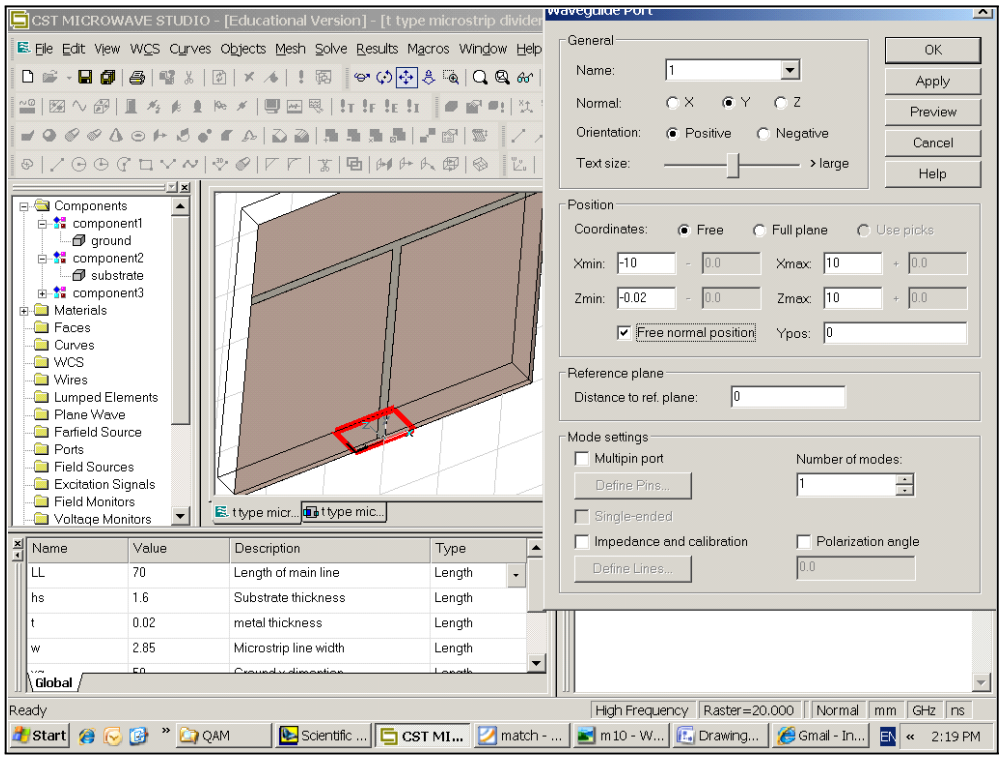

Figure 11 - Define a port.

The model should look like Figure 12 (make sure that the numbers of the ports are facing out).

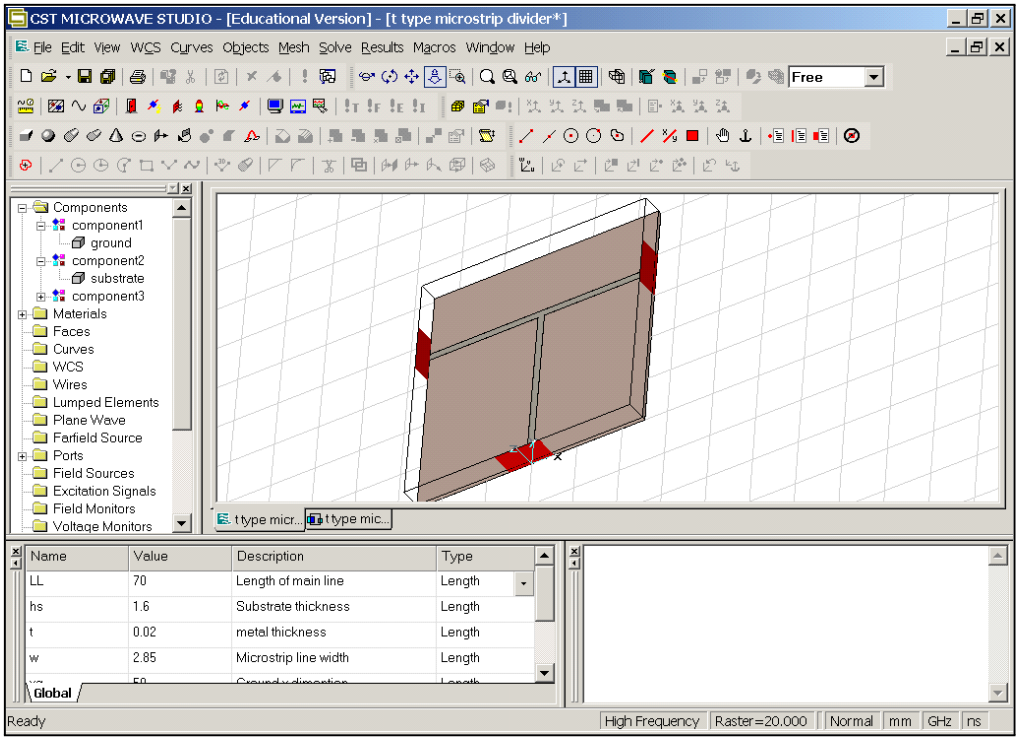

Figure 12 - The divider with all 3 ports.

3.2.5 Running the Simulation

Choosing a frequency range by entering the ˜ icon, and choose the frequency range of $0 - 2\ GHz$, as shown in Figure 13.

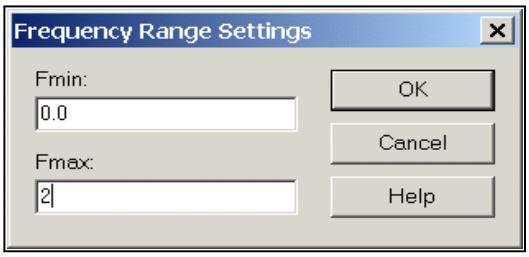

Figure 13 - Choosing the frequency range of the simulation.

Choose the transient solver and then start. Here we choose to calculate only the input port (no. 1), as shown in Figure 14.

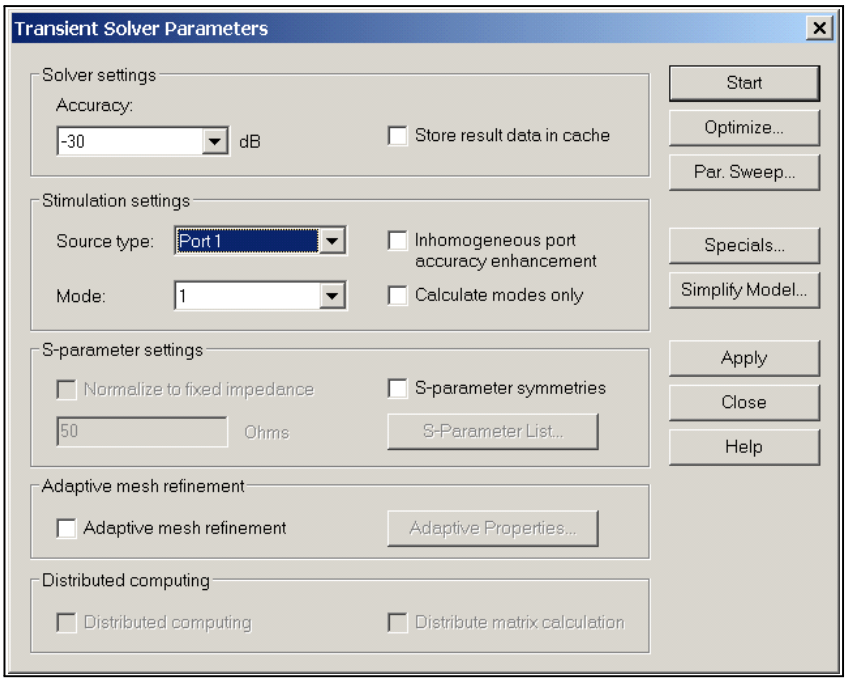

Figure 14 - Running the simulation using the transient solver.

3.2.6 Results

You can see the scattering parameters by pressing 1D results from the navigating tree, and then $|S|$ $[dB]$. The scattering parameters magnitude (in dB) should look like Figure 15.

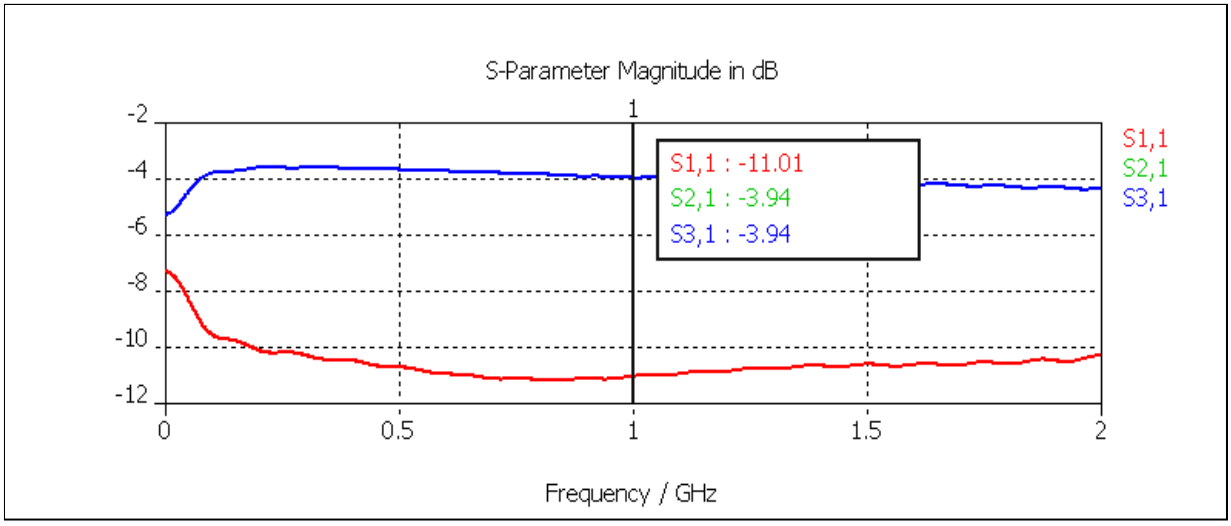

Figure 15 - S1,1 / S2,1 / S3,1 magnitude (in dB).

It is shown that the matching level is about $S_{11} \approx -11\ dB$ and the transmission to the ports are approximately $S_{21} = S_{31} \approx -4\ \ dB$ at $f = 1\ GHz$. The scattering parameters phase (in degrees) should look like Figure 16.

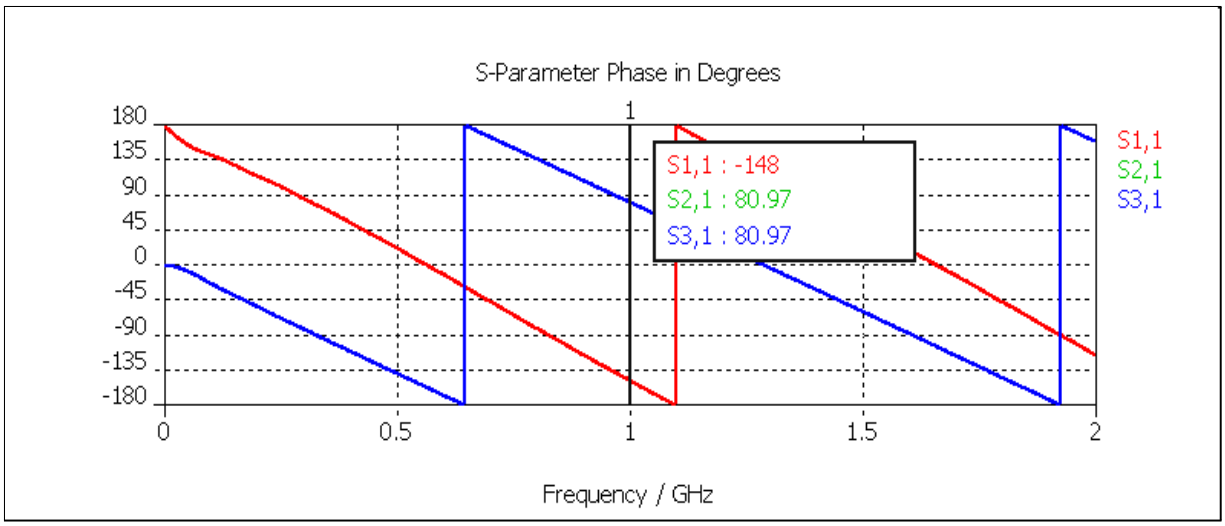

Figure 16 - S1,1 / S2,1 / S3,1 phase (in degrees).

3.2.7 Adding a Single Transformer

Calculate the impedance of a single quarter-wave transformer to match an impedance of 50 Ω to 25 Ω and find the width of the strip for the microstrip transformer. Add two new parameters: 'wtransformer' with the value of the width you found, and 'Ltransformer' with the length of the transformer which correspond to $f = 1\ GHz$. Construct the transformer, as shown in Figure 17, and simulate again.

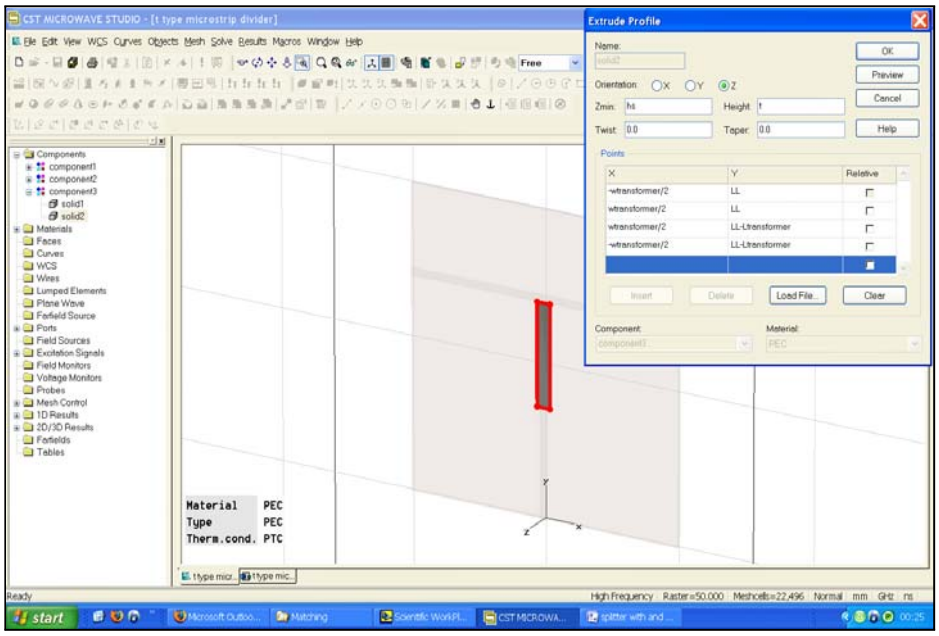

Figure 17 - Adding a transformer to the spliter.

Observe the graphs of the scattering parameters (magnitude and phase) and compare them to the graphs without the matching.

3.3 Measurements

1. Measure the S-parameters of the 1:2 microstrip divider (magnitude and phase).

2. Measure the S-parameters of the 1:2 microstrip divider matched by the parasitic transformer (magnitude and phase).

3. Compare your measurements results.

References

[1] David M. Pozar, "Microwave Engineering", John Wiley & Sons, 3rd ed., 2005, ch. 5.