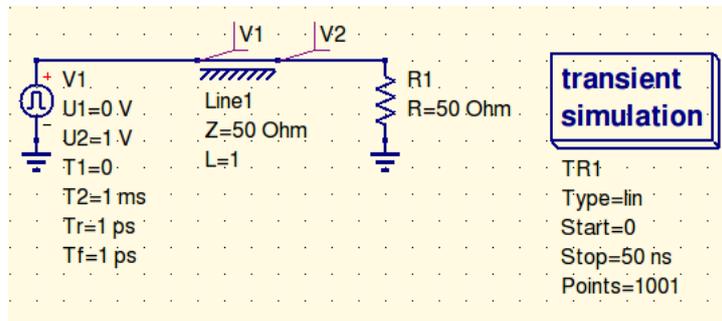# A Qucs Tutorial for RF

Transmission Lines

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1 Simple Transmission Line in the Time Domain

Let's start with a simple circuit composed of a voltage generator, a transmission line and a load. This will be our first circuit, which will be built step by step:

To start, go to the *sources* tab and select a *Voltage Pulse* source. Next, adjust the parameters of the source as depicted in the figure. In this case, we want to investigate the response to a step function. Hence, we have set the pulse width to 1 ms, which is several orders of magnitude longer than our simulation will last.

We choose the generic *transmission line* component for the transmission line. When setting the line length *do not* write *m* for the unit of length, as *m* is considered *mili*!
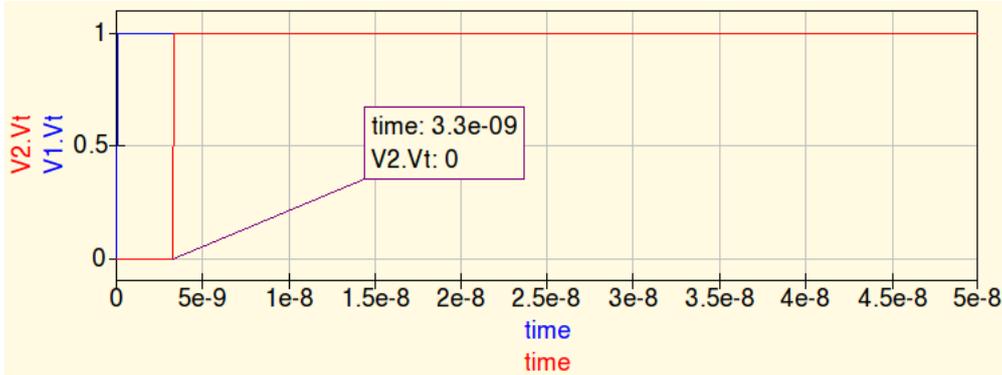
After placing the load resistor, we only have to insert a simulation. In this case, a *transient simulation* with the parameters adjusted as shown. The most important point is the final time and the time step or, as in the figure, the number of time points where the response will be computed.

Finally, we will attach markers to the nodes that we will like to watch. These will be named *V1* and *V2*, corresponding to the input and output port of the transmission line, respectively.

The simulation is started with <F2> or through the menu. In any case, we get an empty results page where we will insert a Cartesian plot from the *diagrams* palette.

We will select the traces named *V1.Vt* and *V2.Vt*. The prefix of these signals corresponds to the node name. Suffix *V* means voltage and suffix *t* means time-domain data.

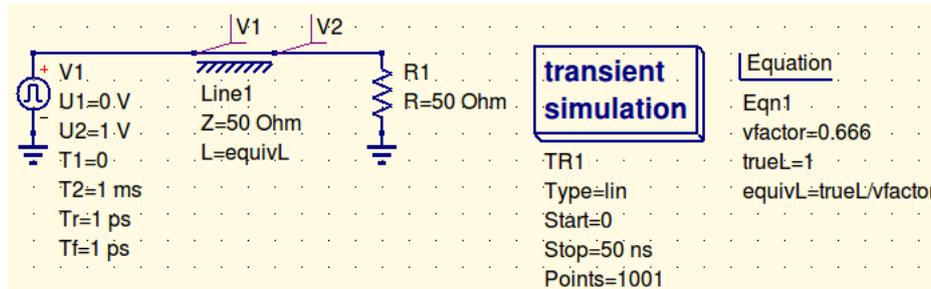If everything worked ok, we should see something like:

The marker on the graph is inserted with `<Ctrl-B>` or through the *insert* menu. After the box is inserted, we may navigate the waveform with the cursors to locate the time instant when the step is detected at the output $t = 3.3 \times 10^{-9}$.

Since the line length is 1 m, it follows that the propagation velocity along the line is $V_p = 1/3.3 \times 10^{-9} = 3 \times 10^8$ m/s.

It follows that Qucs is assuming that the transmission line uses air as the dielectric. While there are other kinds of transmission line in Qucs, we will try to include an arbitrary propagation factor. For instance, to model a lossless RG-58 coaxial line, we need a velocity factor of 0.66.

To achieve this, we may insert an *equation* item into our schematic sheet and add some equations to it:
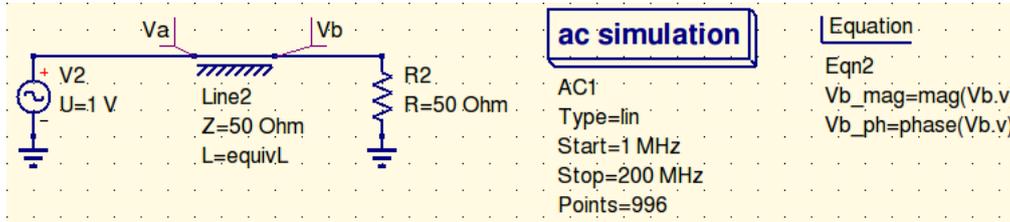

Now, if we wanted to change the physical length of the line, we would change *trueL*. The equivalent length is inserted into the length property of the transmission line component.

If we simulate this design, we will see that a 1 m line introduces a 5 ns delay, as corresponds to a propagation velocity of 0.66*c*.

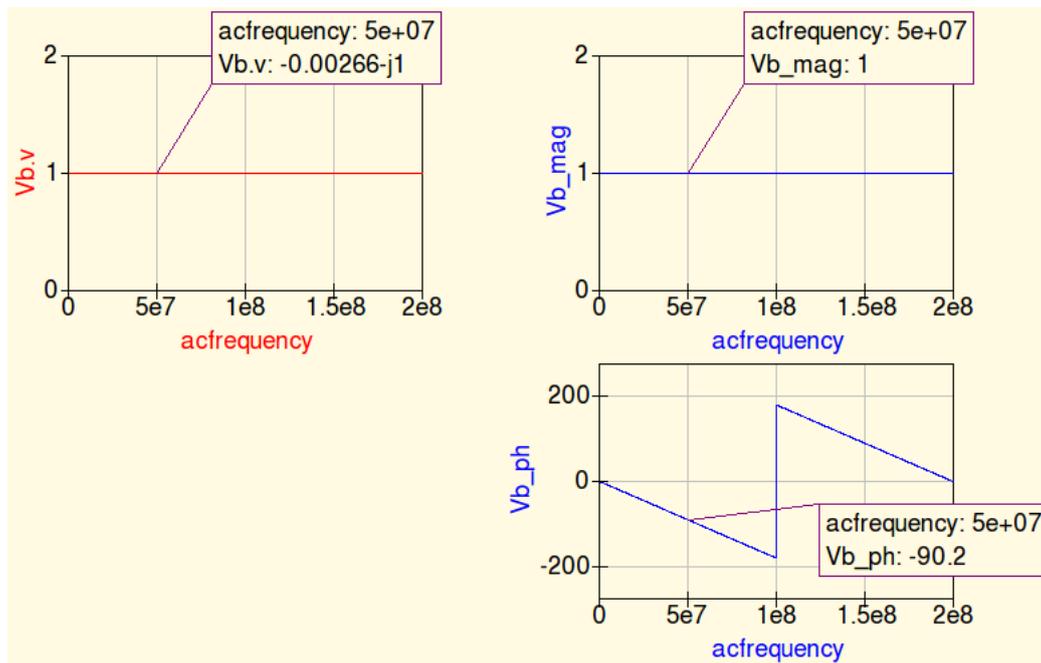# 2 Frequency Response of a Simple Transmission Line Circuit

The frequency response gives a lot of insight into a circuit's behavior. To plot a frequency response in Qucs we have to insert a specific source, an *ac Voltage Source*, and insert a specific kind of simulation, an *ac Simulation*.

To be able to plot the amplification and phase shift of the circuit, we will define some additional variables, *Vb_mag* and *Vb_ph*, inside a second *Equation* block:

To view the results, we will add some cartesian plots to our output tab. When choosing the variables to plot, we will use those with the suffix *.v*, as these correspond to the ac analysis that we have carried out.
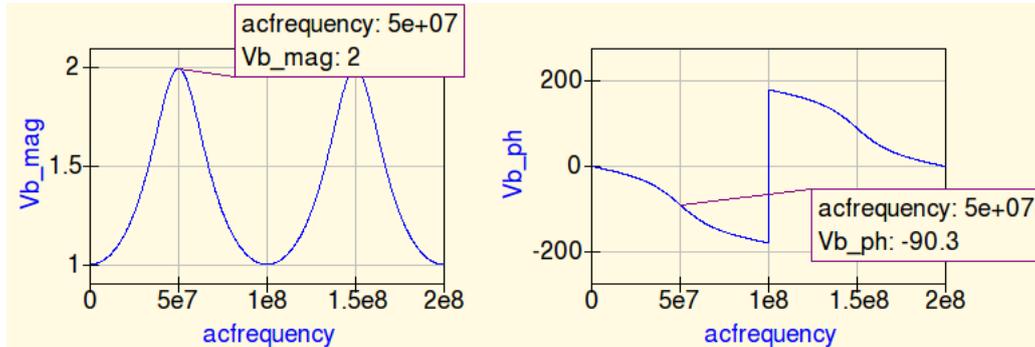
Note that we may directly plot Vb.v. This is equivalent to plotting the magnitude of the complex number Vb.v. However, when we put a marker on the graph, it displays the complex value. This may be handy for some applications:

The amplification and phase shift plots may be seen in blue in the right column of the previous figure. Some markers are included to show the amplification and phase shift at 50 MHz.

As the transmission line has $Z_0 = 50\Omega$ and is terminated in $Z_L = Z_0$, the output signal is simply $v_G(t - \tau)$. This means a constant modulus and a linear phase shift. For instance, the period at 50 MHz is $T = 20$ ns. If a sinusoidal of this frequency is delayed 5 ns, this amounts to $T/4$, i.e. a phase shift of -90°.
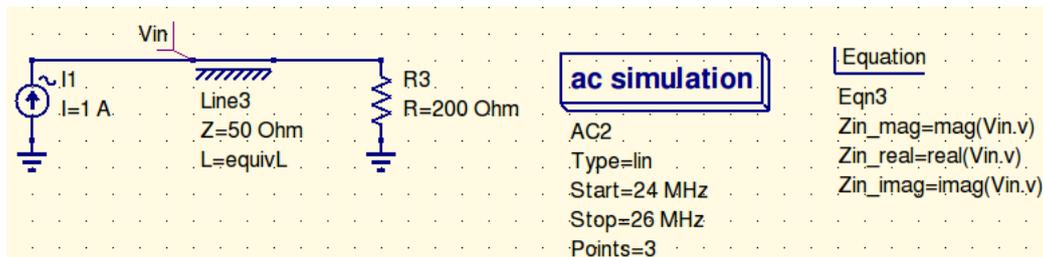
If the load resistance is not matched to Z_0, the output is no longer a delayed version of the input. This may be readily seen in the next figure, where $R_L = 100\Omega$.
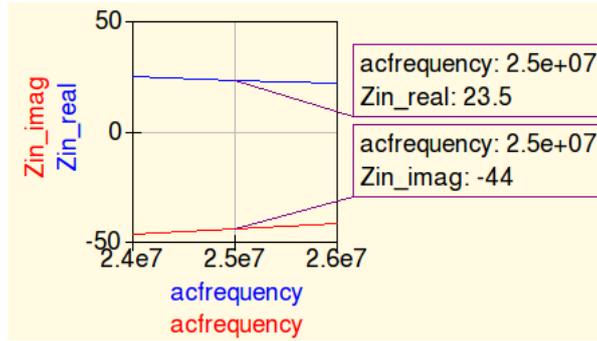

3 Input Impedance vs Frequency

Sometimes we wish to investigate the input impedance of a circuit. For instance, what is the input impedance of 1 m length of RG-58 coaxial line, terminated with 200Ω at the frequency of 25 MHz?

Input impedance is the ratio of input voltage to input current. So, if we use a current source of 1 A, the measured input voltage is already the input impedance. The required schematic is depicted next:

Note that we have set up a simulation with only 3 frequency points: we are interested in the response at 25 MHz but have also included 24 MHz and 26 MHz as the number of points has to be ≥ 2.

We have also defined the variables Zin_xxx to be able to plot them as desired. The obtained simulation is shown below:
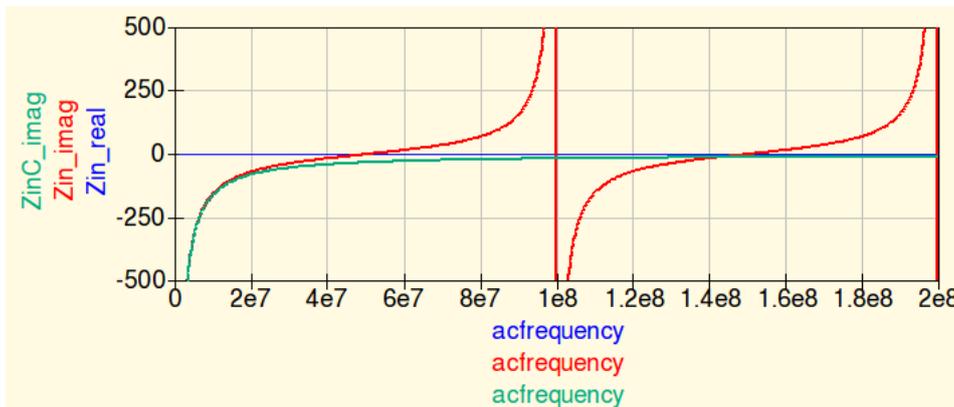
From this, we may answer the previous question: at 25 MHz, the input impedance of the circuit is $Z_{in} = 23.5 - j44\Omega$. This corresponds to a series RC combination, with $1/\omega C = 44$, i.e. $C = 72$ pF (and, of course, $R = 23.5\Omega$).

It is also quite interesting to simulate the input impedance of this circuit when the load is an open circuit. In this case, we might set up a wider frequency range, for instance between 1 MHz and 200 MHz.

The resulting plot clearly highlights the periodicity in the circuit's response. It also shows that the input resistance is 0 (there is only reactance). For low frequencies ($f < 50$ MHz), the impedance is capacitive (negative reactance), at $f = 50$ MHz the input impedance is zero and for frequencies $50f < 100$ (MHz) the input impedance is inductive (positive reactance).

It is also instructive to superimpose the input impedance of a 100 pF capacitor: the lumped capacitance of 1 m of RG-58 coaxial line. This is shown in green on the same plot:
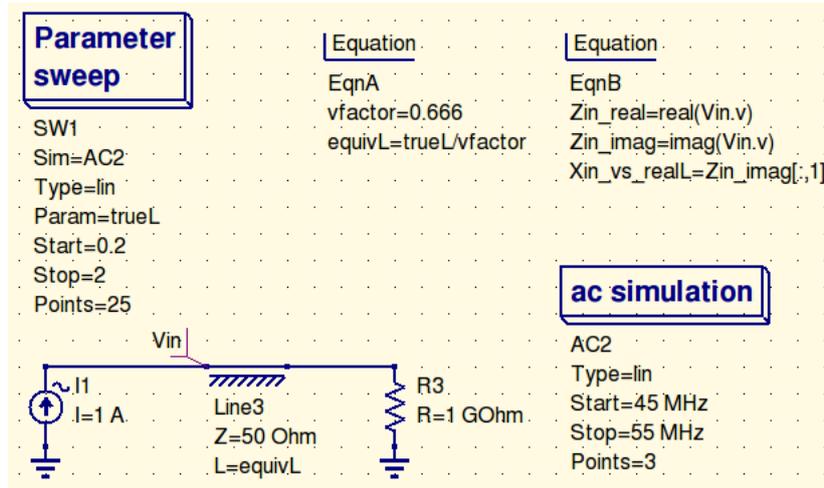

We conclude that the lumped capacitor is a reasonable approximation for low frequencies. However, the true impedance quickly deviates from this and becomes completely uncorrelated.

(Note: in the last plot, the y-axis range has been limited manually. The input impedance ideally reaches infinity!)

4 Input Impedance vs Line Length

Sometimes we wish to simulate the evolution of a quantity with respect to a circuit parameter. A significant and illustrative example in the context of this tutorial is the evolution of the input impedance of an open circuited transmission line with respect to the physical line length when operating at a fixed frequency.

Consider the case of a transmission line of length up to 2 m operating at a frequency of 50 MHz. This may be simulated by this setup:

Before explaining the exact meaning of the items in *EqnB*, we may have a look at the meaning of *Zin_imag* and *Xin_vs_realL*:
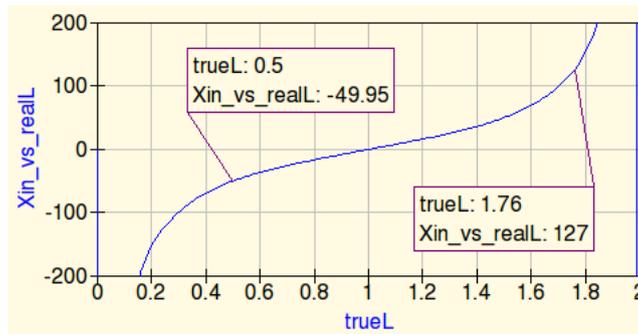
trueL	acfrequency	Zin_imag
0.2	4.5e7	-172
	5e7	-154
	5.5e7	-139
0.275	4.5e7	-122
	5e7	-108
	5.5e7	-97
0.35	4.5e7	-92.5
	5e7	-81.4
	5.5e7	-72.2
0.425	4.5e7	-72.8

trueL	Xin_vs_realL
0.2	-154
0.275	-108
0.35	-81.4
0.425	-63.3
0.5	-49.9
0.575	-39.3
0.65	-30.5
0.725	-22.9
0.8	-16.1
0.875	-9.82

We see that *Zin_imag* is a two-dimensional matrix: for each value of trueL, we have three values of Z_in_imag, one for each of the three frequencies (45, 50 and 55 MHz). Unfortunately there seems to be no way to have a CW analysis, i.e. a single frequency ac analysis!
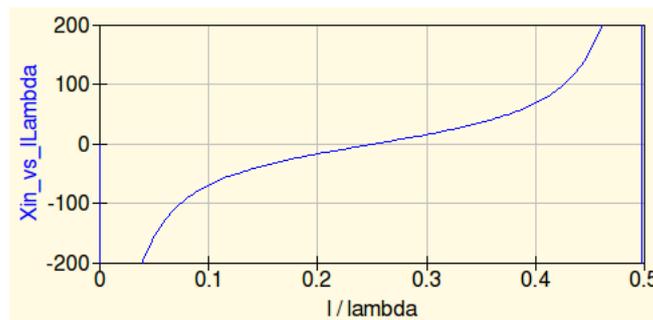
Our desired information is at 50 MHz, so we take all elements of the first dimension of *Zin_imag* (the first : and take the second element of the second dimension. Since the index starts at 0, this means writing [:,1].

So, let's see the graph of input reactance vs line length. To obtain the next graph, we have set the the velocity factor to 2/3 and we have incremented the number of points of the sweep to 201.

From this, we may conclude that, to synthesize an input impedance of $-j50\ \Omega$ we need 0.5 m of cable. Theoretically, the input impedance should be exactly $-j50\ \Omega$, and not $-j49.95\ \Omega$ but this is an error of only 0.1%, which should be negligible for most applications.

Perhaps we would like to see the previous graph with respect to the line length expressed in multiples of the wavelength $\lambda = V_p/f$, as in this figure:

To achieve this, we have added

```
LdivLambda=trueL/4
Xin_vs_lLambda=PlotVs(Xin_vs_realL,LdivLambda)
```

to the equations in the schematic and we have changed manually the x-axis of the plot to show `l / lambda`.

5 Microstrip Matching Circuit and Smith Charts

Sometimes we may also have the need to simulate a microstrip circuit. Consider, for instance, the problem of matching a load of 300 Ω to 50 Ω using a microstrip line on conventional FR4 substrate.

We may start firing the Line Calculation tool of Qucs. Once the correct substrate parameters are given, the tool computes the required trace width to achieve a certain characteristic impedance Z_0 and the trace length to achieve the desired electrical length (expressed in degrees, i.e. a length of 90° is equivalent to a $\lambda/4$). This figure illustrates common parameters for FR4:

FR4 parameters are not tightly specified by most manufacturers. As a consequence, the results should be treated with caution. In any case, we may conclude that a line width of 2.97 mm and line length of 40.8 mm are required for our design goal.

These parameters may be imported into a Qucs schematic with the Copy to Clipboard function. Once in Qucs, we may paste this into the schematic. We get much more components than we currently need, so we may just delete them, keeping only the *substrate* and the *microstrip line*.

Our current objective is to design a matching network. So, we will set up some simulations. Again, we will first simulate the input impedance of a given circuit. With this in mind, we include an 1 A current source and compute the input voltage.

From the input voltage, we will compute the input reflection coefficient as

$$\rho_{in} = \frac{Z_{in} - 50}{Z_{in} + 50} \tag{1}$$

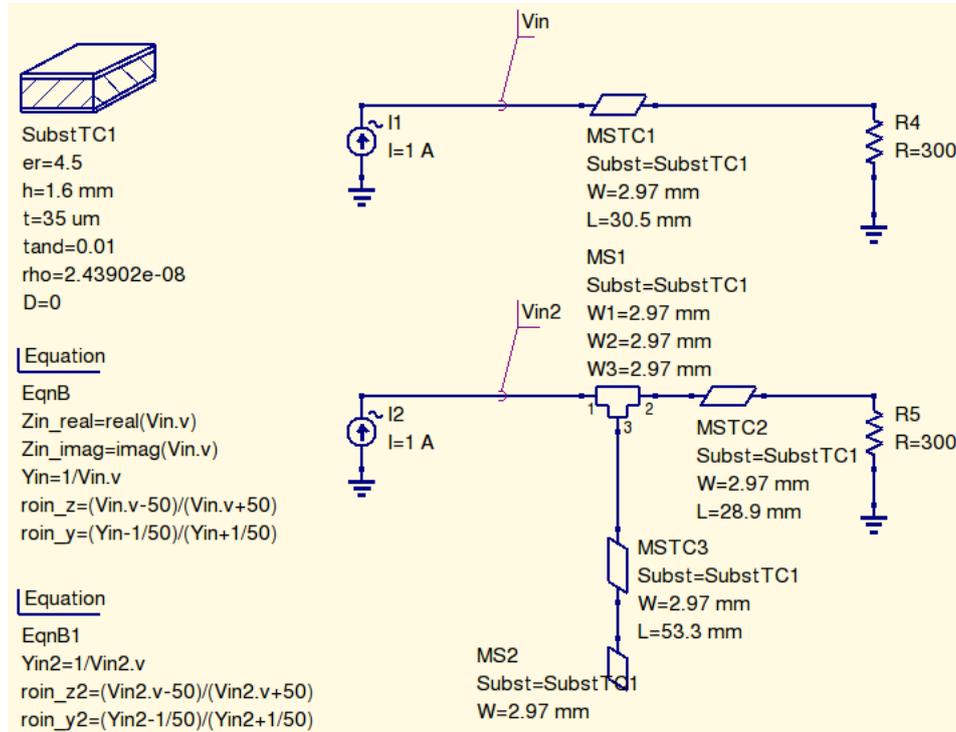This is achieved by the following equation entry:

```
roin_z=(Vin.v-50)/(Vin.v+50)
```

Microstrip matching requires parallel connections, so we will also need to compute the input admittance and its corresponding point in the Smith Chart:

```
Yin=1/Vin.v
roin_y=(Yin-1/50)/(Yin+1/50)
```
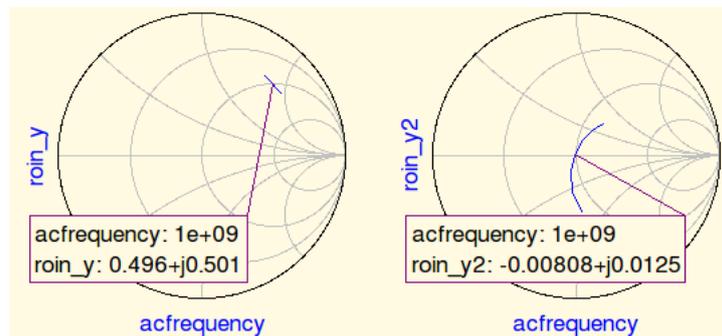
We may draw a schematic that looks as in the next figure:

On the top left side we have the substrate definition. The top circuit in the right simulates the input impedance of the load and a length of microstrip line.

The circuit in the bottom right side simulates a single-stub matching section. Each set of equations corresponds to one of the circuits.

The circuit is analyzed from 950 MHz to 1050 MHz (*ac simulation*) with 7 frequency points. The next figure shows the input reflection coefficients plotted on a Smith Chart:

The left plot shows how the input admittance may be transformed to lie on the circle $1 + jB$ with a length of line of 30.5 mm. The right Smitch Chart shows the input impedance after the matching stub, showing an excellent match at 1 GHz. Observe how a 5% increase or decrease in operating frequency translates into a reflection coefficient which is quite far from the origin.

To build the whole matching network we have included a *microstrip tee* and also a *microstrip open*. Real tees and real open circuits are not simple junctions and infinite impedances: their more or less accurate models are included in Qucs.

The following figures show another matching network and the achieved match: