Qucs

A Tutorial

10dB Directional Coupler Design

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The below pictures shows two parallel conductor strips on a dielectric substrate with a backplane metalization. Both the conductor strips have the width W, the height t and the length l. There is a finite gap S between the conductors. The substrates height is denoted by h. With the gap between the conductor strips small enough a capacitive as well as inductive coupling occurs.

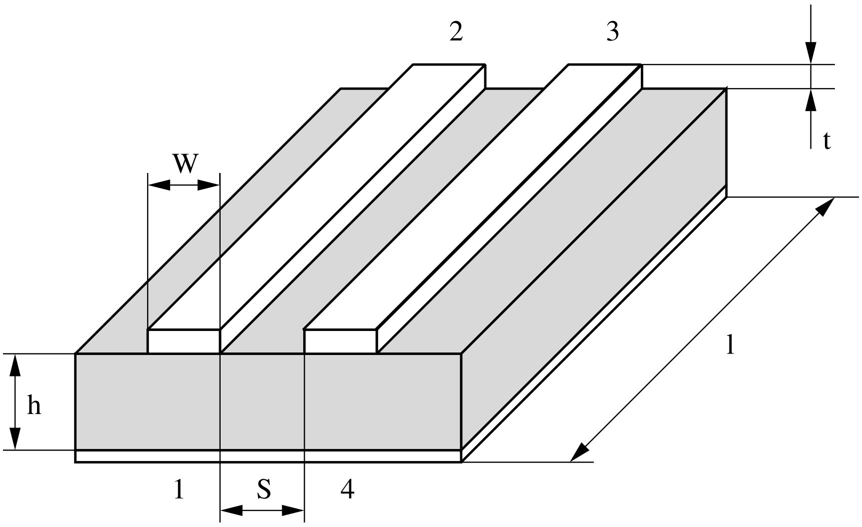

Figure 1: microstrip directional coupler

Such a microstrip structure is called “microstrip coupled lines”. Also defined in figure 1 the port numbers 1. . . 4.

Some boring theory beforehand

There are two types of directional couplers: backward (coupling from port 1 to port 4) and forward (coupling from port 1 to port 3) couplers.

The S-parameters of an ideal directional backward coupler are as follows – with C denoting the coupling coefficient.

$$S_{21} = \sqrt{1 - C^2}$$
$$S_{41} = C$$
$$S_{31} = 0$$
$$S_{11} = S_{22} = S_{33} = S_{44} = 0$$

In a three conductor system – as the microstrip coupled lines are – there are two types of modes: even and odd. Thus such a system is described by odd and even characteristic impedances ($Z_{L,o}$ and $Z_{L,e}$) and odd and even effective dielectric constants ($\varepsilon_{r,eff,o}$ and $\varepsilon_{r,eff,e}$). The characteristic equations for an ideal backward coupler are

$$\begin{aligned} \varepsilon_{r,eff,e} &= \varepsilon_{r,eff,o} \\ Z_{L,e} &\neq Z_{L,o} \end{aligned}$$

and those for an ideal forward coupler are

$$\begin{aligned} \varepsilon_{r,eff,e} &\neq \varepsilon_{r,eff,o} \\ Z_{L,e} &= Z_{L,o} \end{aligned}$$

The S-parameters of the ideal directional forward coupler are as follows.

$$\begin{aligned} S_{21} &= \sqrt{1 - C^2} \\ S_{31} &= C \\ S_{41} &= 0 \\ S_{11} = S_{22} = S_{33} = S_{44} &= 0 \end{aligned}$$

For both ideal – forward and backward – couplers the reflection coefficients are zero. Port 1 is called the **injection port**. Port 2 is the **transmission port**. In a backward coupler port 4 is the **coupled port** and port 3 is called the **isolated port**. In a forward coupler it's the other way around.

Please note: The given S-parameters for forward and backward couplers are valid for all side termination of each port with the reference impedance Z_L – usually 50Ω.

Design equations

In microwave labs backward line couplers are most wide spread. The basic design equations can be written as

$$\begin{aligned} C &= \frac{Z_{L,e} - Z_{L,o}}{Z_{L,e} + Z_{L,o}} \\ \beta \cdot l &= \frac{\pi}{2} \\ Z_L^2 &= Z_{L,o} \cdot Z_{L,e} \\ Z_{L,e} &= Z_L \cdot \sqrt{\frac{1 + C}{1 - C}} \\ Z_{L,o} &= Z_L \cdot \sqrt{\frac{1 - C}{1 + C}} \end{aligned}$$

With

$$\begin{aligned} \beta \cdot l &= \frac{\pi}{2} \\ \rightsquigarrow l &= \frac{\pi}{2 \cdot \beta} = \frac{\pi \cdot c}{2 \cdot \omega} = \frac{c}{4 \cdot f} = \frac{\lambda}{4} \end{aligned}$$

the length l of such a coupler is defined by a quarter wavelength. Both the characteristic impedances can be computed by the reference impedance Z_L, i.e. 50Ω, and the coupling coefficient C.

Applying the design equations

With the previous definitions it's easy to design the 10dB directional backward coupler. We have the reference impedance $Z_L = 50\Omega$ and the coupling coefficient C in dB. First we linearize the coupling coefficient.

$$\begin{aligned} C_{dB} &= -10\text{dB} \\ \leadsto C &= 10^{C_{dB}/20} = 10^{-0.5} \approx 0.316 \end{aligned}$$

Now we compute the even and odd impedances.

$$\begin{aligned} Z_{L,e} &= Z_L \cdot \sqrt{\frac{1+C}{1-C}} \approx 69.4\Omega \\ Z_{L,o} &= Z_L \cdot \sqrt{\frac{1-C}{1+C}} \approx 36.0\Omega \end{aligned}$$

What next?

All grey theory you may think... With the impedances at hand the engineer had to go into magic diagrams and find physical dimensions of his coupler. But now there is Qucs. Things get easier.

Just select **Tools** → **Line Calculation** in the menubar or press **Ctrl+3** to start the transmission line calculator.

Then choose **Coupled Microstrip** in the **Transmission Line Type** selection box. Something likely shown in figure 2 should appear.

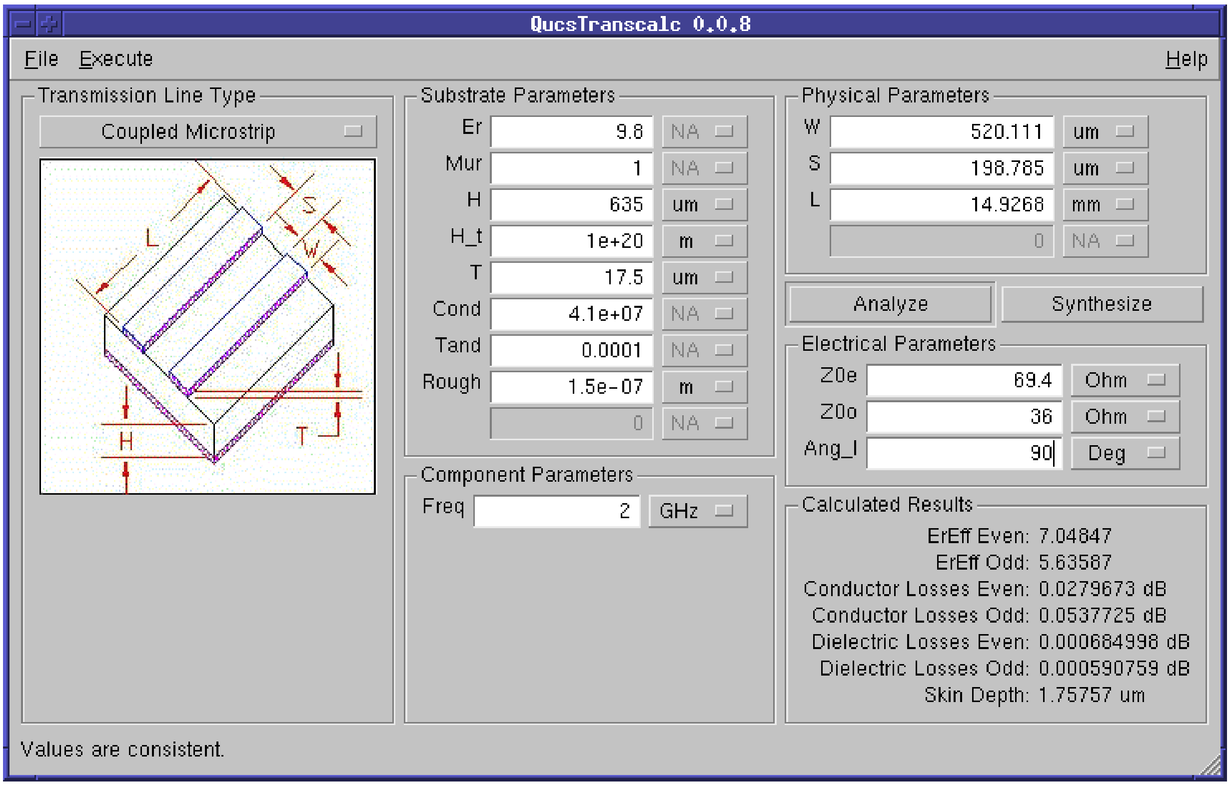

Figure 2: Qucs Transcalc screenshot

Type in the calculated **69.4** in the **Z0e** field, **36.0** in the **Z0o** field and **90** in the **Ang_l** field of the **Electrical Parameters** panel. The **Ang_l** field denotes the desired electrical length of the line (remember: $90° \simeq \pi/2$). Choose the **Deg** unit.

Our selected design frequency is 2GHz. Thus type in this value in the **Freq** field of the **Component Parameters** panel.

Then press the **Synthesize** button or press **F4**. The program calculates the physical parameters **W**, **S** and **L** in the **Physical Parameters** panel.

Please note: Depending on the substrate (shown in the **Substrate Parameters** panel) the calculated values may vary.

Finally we got

$$W = 520\mu\text{m}$$
$$S = 199\mu\text{m}$$
$$L = 14.93\text{mm}$$

All done with designing... Feel any better?

Verification of the design

Ok. Let's verify what we have designed so far. Choose **Execute** → **Copy to Clipboard** from the menubar or press **F2**. This copies the currently shown microstrip coupled line in Qucs Transcalc into the global clipboard.

Now switch to an empty Qucs schematic and press **Ctrl+V**. This inserts the previously entered clipboard content – and click with the left mouse button in order to place the selection into the schematic. This should give you something likely shown in figure 3.

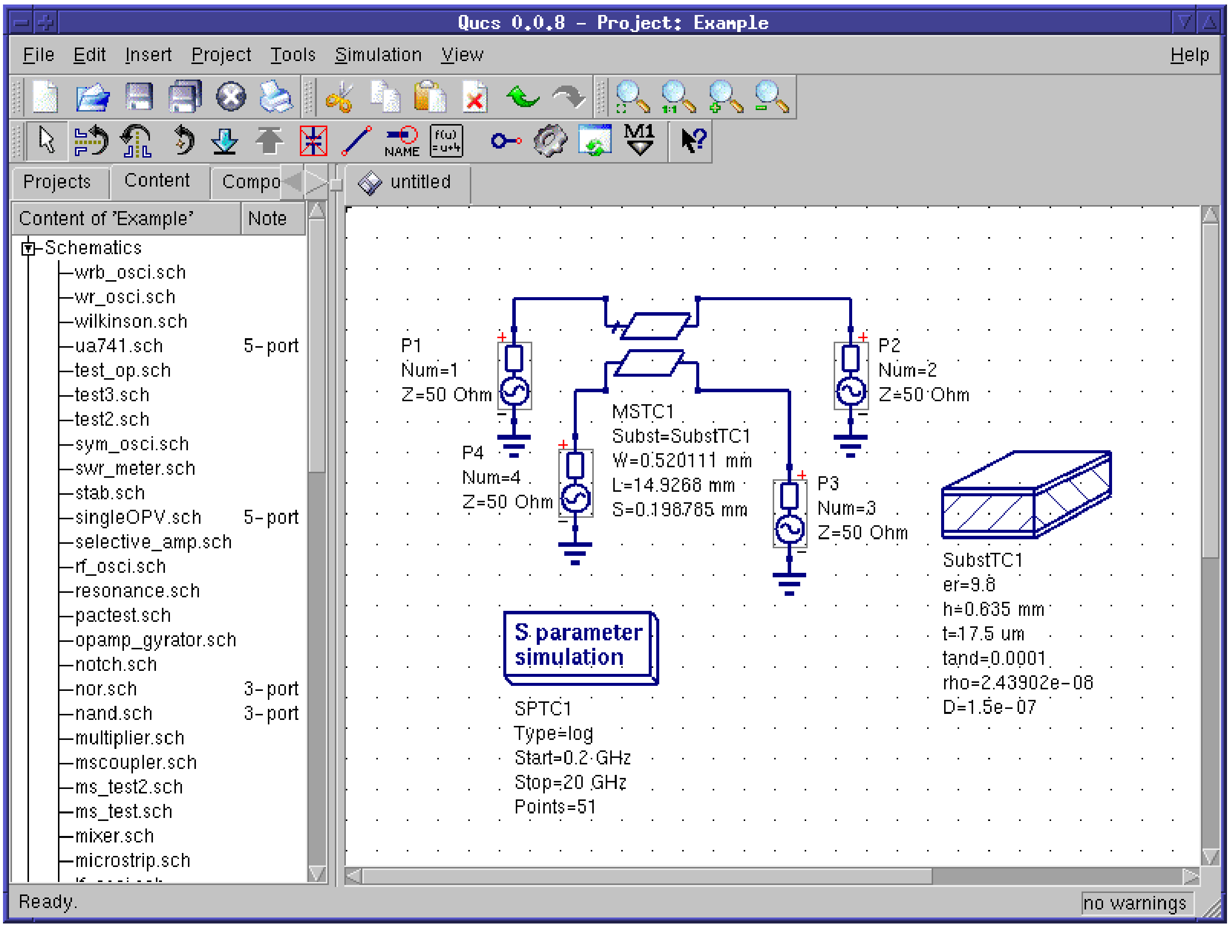

Figure 3: coupled microstrip lines in a Qucs schematic

Now press the equation button (shown in figure 4) in Qucs's toolbar.

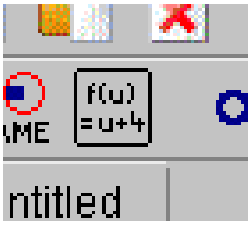

Figure 4: equation button

Place the equation into the schematic and enter the following equations. Press **Add** in the equation dialog (see figure 5) to add new equations. Finally press the **OK** button.

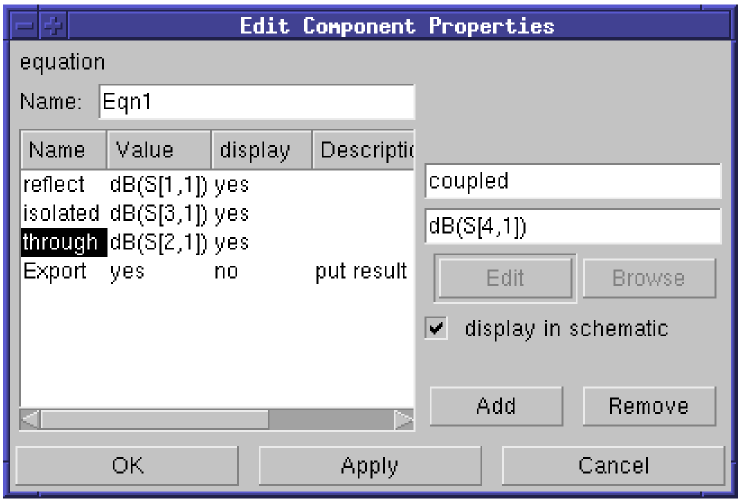

Figure 5: equation dialog

Also edit the properties of the **MSTC1** component reducing the number of digits. This will ensure that your technology is able to use these values when (if) they decide to produce your design.

Now edit the S-parameter simulation properties. You can do that either by double clicking the component and use the component dialog. Or you can directly click on the values in the schematic and fill in **0.2 GHz** for **Start**, **4.2 GHz** for **Stop** and **101** for **Points**.

Finally save your schematic by pressing **Ctrl+S**. Check whether all looks like as shown in figure 6.

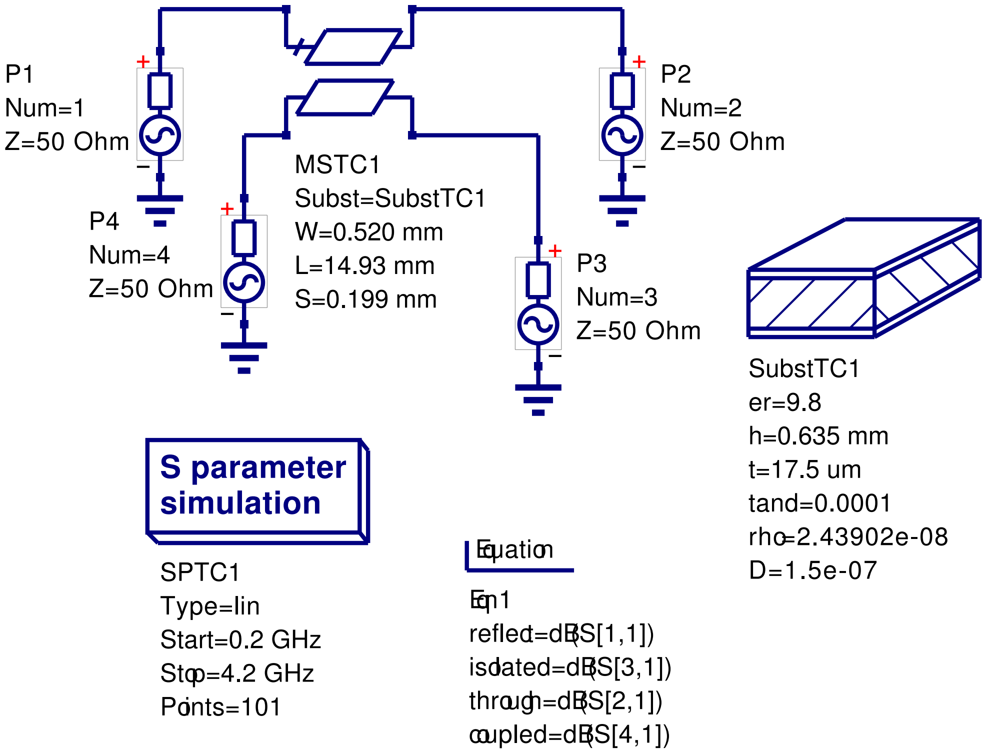

Figure 6: final microstrip coupler schematic

Now select **Simulation** → **Simulate** from the menubar or just press **F2** to simulate the schematic.

When the simulation windows disappears then choose a **Cartesian** diagram from the left hand selection view and place the diagram into the (yet empty) data display area. Double click the **through**, **reflect**, **isolated** and **coupled** data items in order to add it to the diagram within the diagram dialog as shown in figure 7.

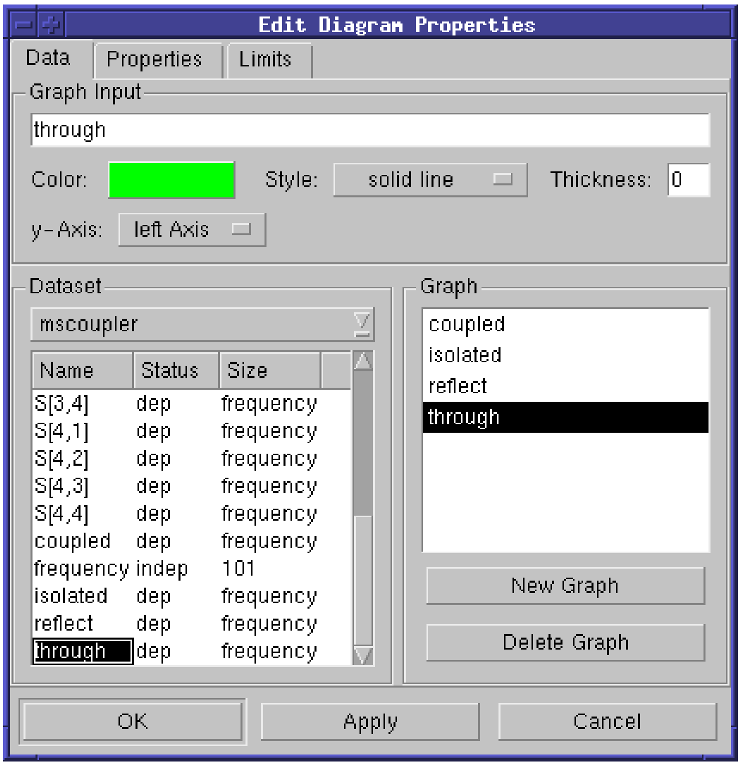

Figure 7: diagram dialog

Press **OK** to finish the diagram dialog. Afterwards you will see the following diagram.

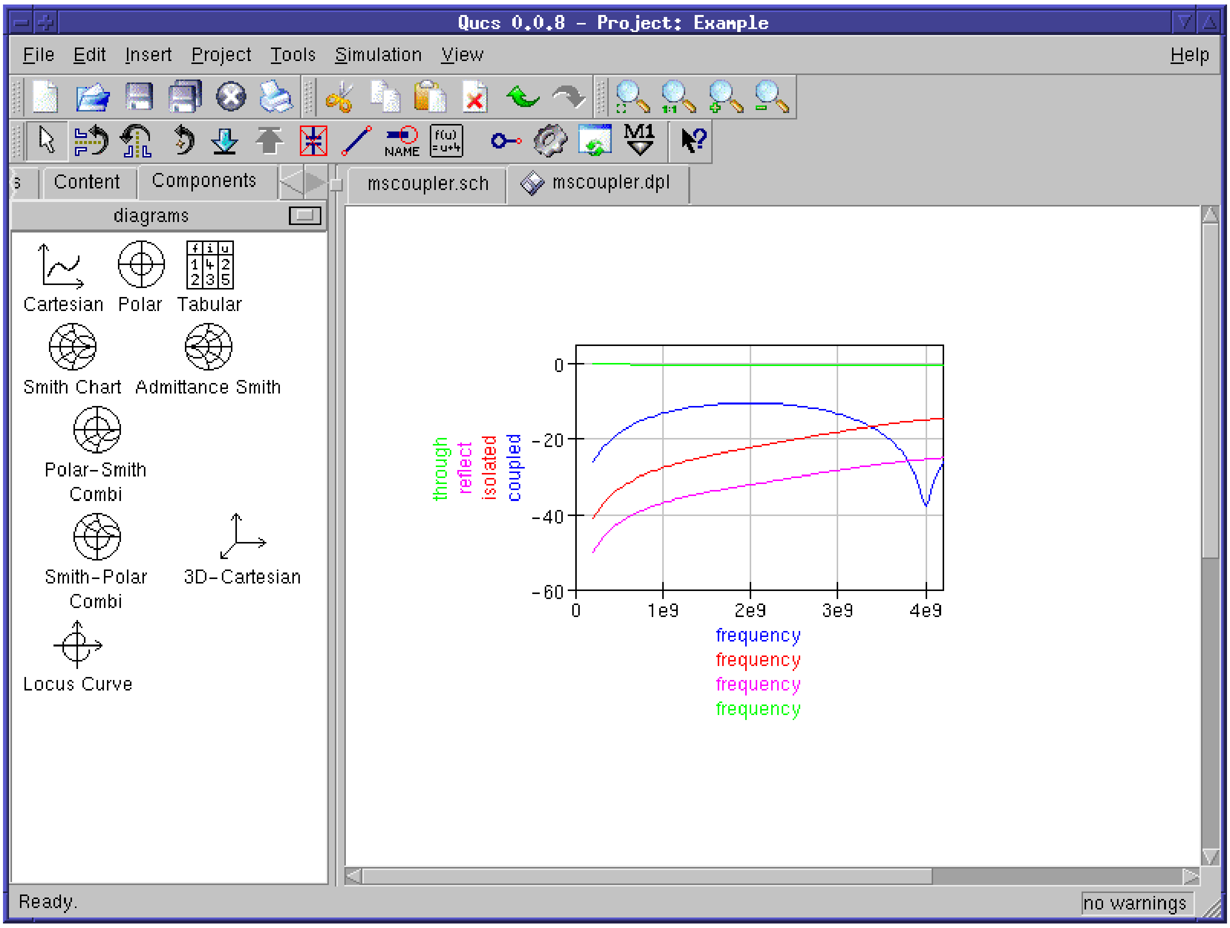

Figure 8: microstrip coupler simulation results

Suggested improvements

By use of the diagram dialog (double click the diagram) you may improve[1] the data visualization as you see it fit. I manually fixed the y-axis limits, set markers and set curve thickness to 2 points. Also I entered a common x-axis label. See figure 9 how it looks now.

[1]... to feel even better.

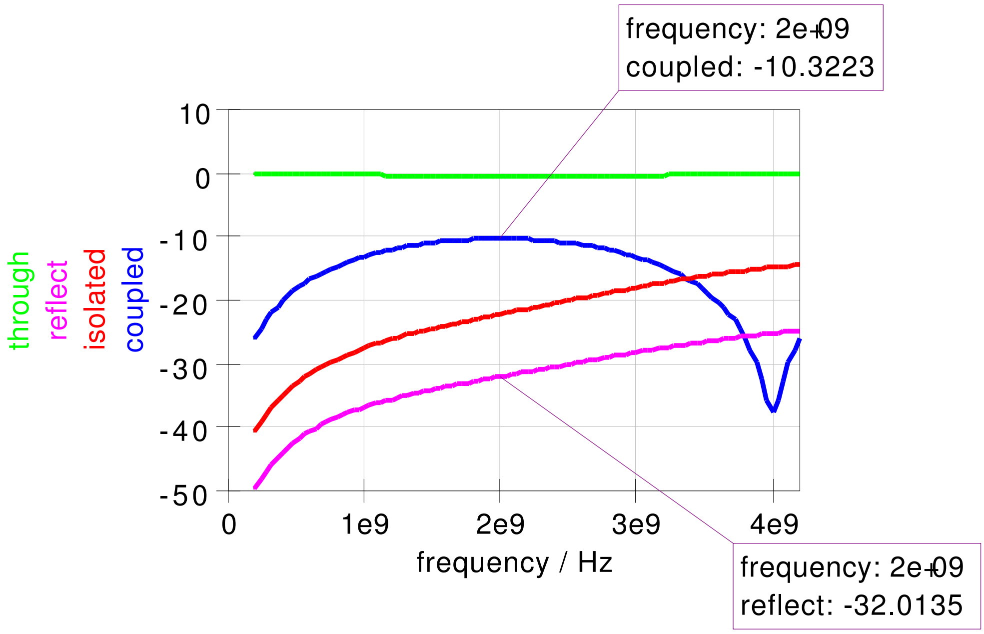

Figure 9: directional coupler simulation result diagram

The marker on the **coupled** curve shows a coupling factor of **-10.32** at a frequency of 2GHz (double click marker to change precision of the marker data). This is a bit way off for which we tried to design it for.

Seems like coupling between the lines is a bit too weak. So we reduce the gap between the strip conductors **S** by 16.5µm to be **0.1825 mm** and simulate again.

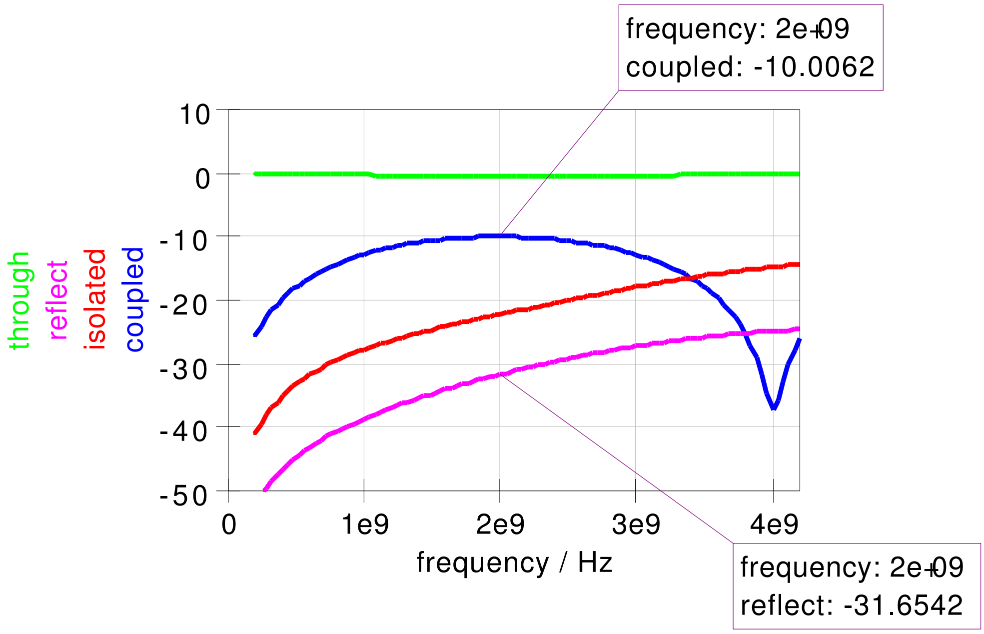

Figure 10: optimized directional coupler simulation result diagram

Finally a perfect[2] 10dB coupling as shown in figure 10.

Remaining thinkabouts

The diagram in figure 10 shows a reflection coefficient of about -31.7dB. The isolation (about -22.2dB) is not as good as planned as well. So – what happened with my design equations?

Have a look at figure 2. In the **Calculated Results** panel you see **ErEff Even** and **ErEff Odd** differing significantly which is not what we expect from an ideal backward coupler:

$$\varepsilon_{r,eff,e} = \varepsilon_{r,eff,o}$$

This "problem" arises from the fact that there are two dieletrica involved: air and the substrate. Part of the electromagnetic fields cross air and part of them the substrate. You can inhibit this by a dielectric overlay. It's more expensive to produce but improves your results.

[2]... to feel great.