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Measurement & Analysis of superconducting microwave beam splitters

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Abstract

In Quantum Information Science, the possibility of doing information processing with Quantum Mechanics is investigated. Some important ingredients that are required to do such processing are the ability to create quantum superposition states, and to transfer quantum states over long distances without losing coherence. Photons are the perfect candidate for transferring quantum states over long distances, and creating superposition can be achieved using beam splitters. A beam splitter divides an incoming beam into two beams, each with half of the incident power.

Recent progress has been made towards doing quantum information processes with superconducting microwave circuits. The equivalent of a beam splitter in a microwave circuit is a quadrature hybrid.

In my semester project I measured and analyzed such quadrature hybrids made from superconducting Niobium coplanar waveguide on a microchip. Scattering parameters of the circuit were measured and compared to the theoretical ideal circuit response, and also a numerical simulation was carried out in Microwave Office to see if the devices can be used for microwave and optics experiments.

Two of three devices measured compared well with the ideal model, with some imperfections that could be accounted for as being due to deviation of the impedances of the transmission lines from the designed values.

The result may be used to design better performing devices in the future.

1 Introduction

In quantum mechanics experiments with optical photons, a beam splitter is often used to get superposition states. In Section 1.1, a basic experiment with optical photons is described. (Mach-Zehnder interferometer)

The beam splitter is also an important component for similar experiments in superconducting microwave circuits. A so called quadrature hybrid can be used as a beam splitter for such circuits. In a previous semester work in the quantum device lab at the ETH, quadrature hybrids were designed for superconducting niobium on sapphire substrates.[1]

In this project I have to measure and analyze these beam splitters. So I tried to find out if the measured plots look really the same as the theoretically predicted ones and if they do not, I wanted to find out reasons for the failure. I used Mathematica and Microwave Office to simulate the theory and also to change the theoretical setup to an imperfect one as in the experiment.

In the next section I will describe what we can use beam splitters for. Then some explanations about how the microwave beam splitter works will follow.

1.1 Optical experiments with beam splitters

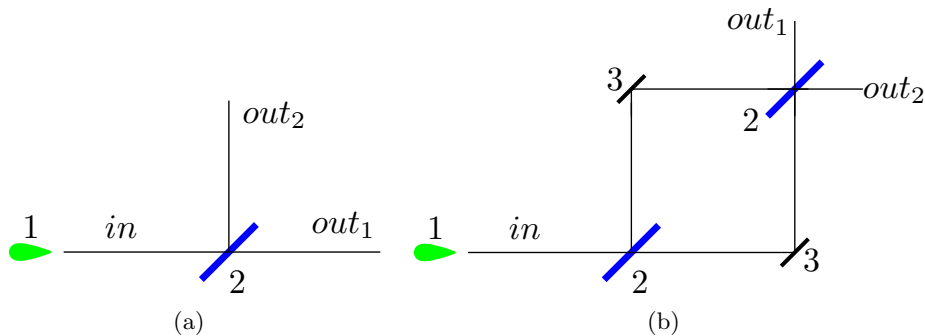


Figure 1.1: The two experiments mentioned in this section with 1: the single photon source, 2: beam splitter and 3: mirror. The incoming beam is labeled with *in*. In (a) the transmitted one is *out_t* and the reflected one is *out_r*. The setup in (b) leads to an interference of the transmitted and reflected waves, so the outgoing waves are just called *out₁* and *out₂*.

Experiments as the one shown in figure 1.1 (a) were first done by Leonard Mandel. We have a single photon source which sends a photon to a half silvered mirror. The mirror acts as a beam splitter, because it transmits half of the beam and reflects the other half. Whenever one of the detectors detects a photon it saves the actual timestamp. Then the data of the two detectors are compared. This results in the

fact, that never both detect a photon at the same time. This means, that photon either takes one way or another (classically).

A team at CNRS (National Center for Scientific Research, France) extended the experimental set-up by another beam splitter and two mirrors to get the same one as shown in 1.1 (b) . This is called a Mach-Zehnder interferometer. But the interference character of the results must be explained somehow with the wave character of light which does not match with the particle idea of the first experiment. [2]

The result of this experiments shows the wave-particle duality of light which can't be explained classically. Therefore we need quantum theory to provide an explanation of both phenomena.

Quantum theory says that if there is no measurement between the two beam splitters, the particle is in a superposition state of both ways. Changing the experimental set-up in such a way, that a qubit is put between the beam splitters on each line leads to an application of beam splitters in quantum information processes. To excite the qubit we need microwaves and therefore a microwave beam splitter. The design and the properties of such a device will be discussed in the next sections.

1.2 Microwave beam splitter

1.2.1 Microwave electronic circuits

One of the simplest circuits is a start port and an end port connected by a transmission line. This circuit is characterized by the impedance and the length of the transmission line. Running this circuit means to send a microwave from one port to the other. By connecting an additional port to this simple circuit more complicated ones can be build. In practice many networks can be described as a cascade connection of two port networks. The values for the reflected and transmitted wave amplitudes are somehow a superposition of the individual circuits. A theoretical prediction of these values can be done by analyzing the network. How to do this is described in Section 1.2.3. The following analysis of the circuits is taken from the book Microwave Engineering. [3]

1.2.2 The quadrature hybrid

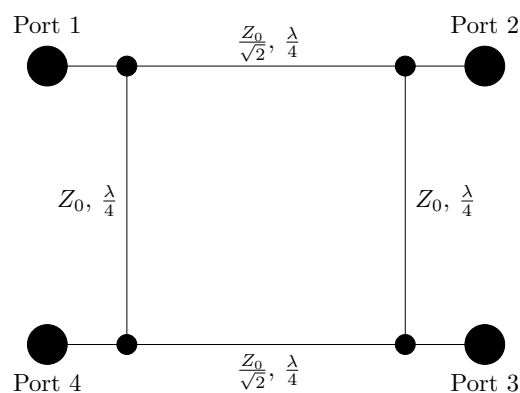


Figure 1.2: Scheme of a beam splitter

The Picture (1.2) shows a so called quadrature hybrid. It consists of four ports which are connected by transmission lines of the same length, but not the same impedance. The line between port 1 and port 2 abbreviated by 12 and the 43 line has an impedance of $\frac{Z_0}{\sqrt{2}}$ while (14) and (23) have an impedance of Z_0 .

The lengths of the transmission lines is given by the fraction $\frac{\lambda}{4}$. That means, that the outcome depends from the microwave frequency. The required frequency is called the design frequency f_{design} . It can be calculated using the formula $\lambda \cdot f_{design} = c'$, with $c' = \frac{c}{\sqrt{\epsilon}}$ and ϵ the dielectric constant. [3]

A more detailed analysis of the circuit can be found in 1.2.4. Here just the main result: Running this device by a microwave with f_{design} at port 1 leads to the following outputs on the different points:

- port 1 = no power (matched)
- port 2 = half power ($\equiv -3$ dB)
- port 3 = half power ($\equiv -3$ dB)
- port 4 = no power

Additionally, there will be a phase shift of 90 degrees between the wave at port 2 and port 3. Therefore this circuit can be used as a microwave beam splitter.

Based on this theoretical reflections Tobias Frey designed in his semester thesis beam splitter for different f_{design} . The f_{design} of the measured beam splitters are listed in Table 1.1.

Name	f_{design}
T1	7 GHz
T4	8 GHz
T5	9 GHz

Table 1.1: Measured beam splitters

1.2.3 Microwave electronic circuit analysis

To describe a microwave two-port network, the ABCD or transmission matrix is very useful. With $V_{1,2}$ the voltages at port 1,2 and $I_{1,2}$ the different currents, the ABCD matrix holds the following matrix equation:

$$\begin{bmatrix} V_1 \\ V_2 \end{bmatrix} = \begin{bmatrix} A & B \\ C & D \end{bmatrix} \begin{bmatrix} I_1 \\ I_2 \end{bmatrix}$$

To analyze a 3 port network (1,2,3), it can be divided into 2 two-port networks (1,2) (2,3). The matrix for the whole network is the matrix product of the two individual transmission matrices. The matrices for the common two-port circuits can be found e.g. in [3].

To compare the incident and reflected waves at different ports the so called scattering matrix (S matrix) is more useful. Describing a N-port network with the voltage of

the incident waves V_n^+ and the voltage of the reflected waves V_n^- , for a port n , there is this matrix equation for S :

$$\begin{bmatrix} V_1^- \\ \vdots \\ V_N^- \end{bmatrix} = \begin{bmatrix} S_{11} & \dots & S_{1N} \\ \vdots & \ddots & \vdots \\ S_{N1} & \dots & S_{NN} \end{bmatrix} \begin{bmatrix} V_1^+ \\ \vdots \\ V_N^+ \end{bmatrix}$$

The entries S_{ij} mean that port j is driven by a voltage V_j^+ and at port i a reflected wave with an amplitude V_i^- comes out.

There are transformation equations between the S and the ABCD matrix. Once the ABCD matrix for the beam splitter circuit is found, means to be able to write down the corresponding scattering matrix, from which the needed information can be derived more easily.

1.2.4 The quadrature hybrid analysis

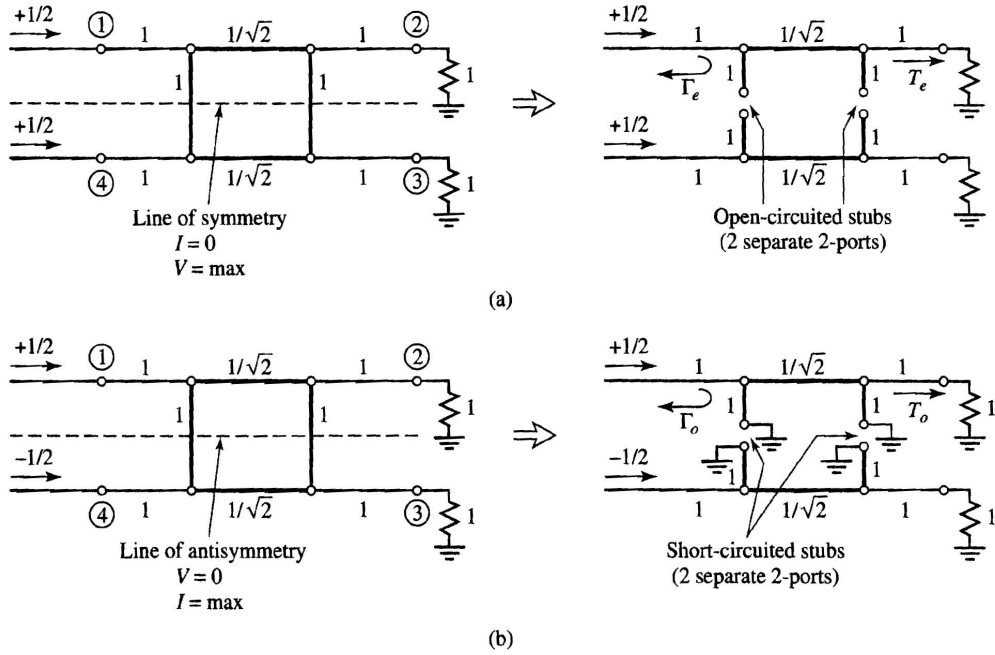


Figure 1.3: Decomposition of the quadrature hybrid circuit into an even- and an odd-mode extinction. (a) is even mode and (b) is odd mode. Taken from [3] p. 381, Figure 7.23

We decompose the circuit into a superposition of an even and an odd mode (figure 1.3). This results in having 2 separated two-port networks which can be analyzed individually. The outcome at the different ports for the whole circuit then can be found by the different superposition. As mentioned in Section 1.2.3, the best way to analyze a two-port network is to investigate the ABCD matrices. The even circuit consists of 3 matrices, one for the transmission line and 2 for the open-circuited stubs. Similar the odd one, but this one has short-circuited stubs.

With Z_0 set to 1, l_1 the length of the open circuited line (even mode) or the length of the short circuited line (odd mode), l_2 the length of transmission line and β_1, β_2 the phases, we get the following ABCD matrices.

ABCD:

even:

$$M_{shunt} = \begin{pmatrix} 1 & 0 \\ i \cdot \frac{1}{Z_0} \cdot \tan(\beta_1 \cdot l_1) & 1 \end{pmatrix}$$

$$M_{transmission} = \begin{pmatrix} \cos(\beta_2 \cdot l_2) & i \cdot \frac{Z_0}{\sqrt{2}} \cdot \sin(\beta_2 \cdot l_2) \\ i \cdot \frac{\sqrt{2}}{Z_0} \cdot \sin(\beta_2 \cdot l_2) & \cos(\beta_2 \cdot l_2) \end{pmatrix}$$

$$M_{even} = M_{shunt} \cdot M_{transmission} \cdot M_{shunt} = \begin{pmatrix} A & B \\ C & D \end{pmatrix}_{odd}$$

odd:

$$M_{shunt} = \begin{pmatrix} 1 & 0 \\ -i \cdot \frac{1}{Z_0} \cdot \tan(\beta_1 \cdot l_1) & 1 \end{pmatrix}$$

$$M_{transmission} = \begin{pmatrix} \cos(\beta_2 \cdot l_2) & i \cdot \frac{Z_0}{\sqrt{2}} \cdot \sin(\beta_2 \cdot l_2) \\ i \cdot \frac{\sqrt{2}}{Z_0} \cdot \sin(\beta_2 \cdot l_2) & \cos(\beta_2 \cdot l_2) \end{pmatrix}$$

$$M_{even} = M_{shunt} \cdot M_{transmission} \cdot M_{shunt} = \begin{pmatrix} A & B \\ C & D \end{pmatrix}_{even}$$

The next step is to find the corresponding S matrix to get the outcome by the following superposition:

$$C_{11} = \frac{1}{2} \cdot S_{11even} + \frac{1}{2} \cdot S_{11odd}$$

$$C_{21} = \frac{1}{2} \cdot S_{21even} + \frac{1}{2} \cdot S_{21odd}$$

$$C_{31} = \frac{1}{2} \cdot S_{21even} - \frac{1}{2} \cdot S_{21odd}$$

$$C_{41} = \frac{1}{2} \cdot S_{11even} - \frac{1}{2} \cdot S_{11odd}$$

Only S_{11} and S_{12} are required, so the conversions which have to be calculated are:

$$S_{11} = \frac{A + B/Z_0 - C \cdot Z_0 - D}{A + B/Z_0 + C \cdot Z_0 + D}$$

$$S_{21} = \frac{2}{A + B/Z_0 + C \cdot Z_0 + D}$$

Definition of the used parameters ($l_1, l_2, \beta_1, \beta_2$):

As already mentioned we set $Z_0 = 1$. Further we have the dielectric constant ϵ and the design frequency f_d . So the following equations for the parameters are obtained:

$$\beta_1 = \beta_2 = \frac{2 \cdot \pi \cdot f}{c / \sqrt{\epsilon}}$$
$$l_1 = \frac{l_2}{2} = \frac{c}{\sqrt{\epsilon} \cdot f_d \cdot 8}$$

1.3 Measurement

In the beginning we just have a device without a chip and with no possibilities to connect the transmission lines to any cables. So we first solder PCBs onto the device to gain a possibility to connect it afterwards with some cables. This must be done very precisely, because an imperfect match of the transmission lines with the cables can lead to different results.

Then the chip is placed on the device in the clean room. Now the device is ready to be connected and microwaves can be sent through the chip.

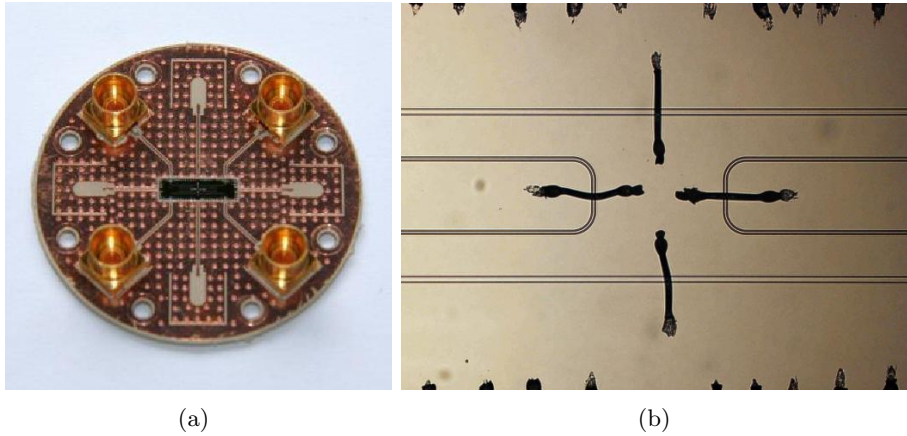


Figure 1.4: (a) shows the T5 device with the beam splitter chip. Figure (b) shows a zoom in of the beam splitter device. The four bold black lines are the bond wires, which connect the ground plane with the device and set it to ground level.

1.3.1 Measurement Setup

In order to measure a superconducting beam splitter the device has to be measured below the transition temperature of the niobium lines. That means the device has to be cooled down below 9.46 K. This is done by plunging it into liquid helium with a temperature of 4.2 K. To achieve this, a dipstick was available. Inside of this dipstick there are four microwave cables which connect the device in the socket on the bottom to four connectors on the top of the dipstick. After lowering the dipstick slowly into the helium dewar the measurement of the superconductive beam splitter can begin.

The measurement process is the following: One cable is always connected to the port 1 on the beam splitter and the other one is switched between the ports 2, 3 and 4. A 50Ω resistance is turned up on the 2 "free" ports, so that there are no reflections of the ports which are not measured at the moment.

At the beginning a whole spectrum from 1 GHz to 20 GHz is measured. But as the beam splitters were designed for f_{design} from 7 GHz to 9 GHz, the range was reduced to 4 GHz - 12 GHz. Plotting the data afterwards leads to the approximate frequency with which the device really (f_{work}). This one was always a bit smaller than f_{design} , which will be shortly discussed in section 2.1.2 on page 11.

Finally the device was measured for a 3 GHz range centered over the work frequency f_{work} .

1.3.2 Device Characterization

The device was measured by attaching it to the dipstick cables and which were attached to a network analyzer. A network analyzer can be used to analyze the properties of a certain network. For the amplitude and the phase of a signal(e.g. a microwave), transmission and reflection properties can be recorded. To measure the beam splitter a microwave is send from one port to another. Then the power and phase the outgoing wave is recorded. As described in the introduction (1.2.1) this measured data can show if the beam splitter works properly.

For this measurement the main settings to adjust are the frequency, the power of the source, number of points, 'IF bandwidth' and the averaging factor. All these settings can be saved with my own calibration (1.3.3) on the network analyzer.

To handle the outcome, the analyzer can be connected to a computer and with the software LabVIEW the data can be stored in .txt files for example.

In order to determine the properties of the device itself, whilst cooling down, a calibration is required.

1.3.3 Calibration

Because the cables are not completely lossless, they affect the magnitude of the outgoing signal.

- The two cables from the network analyzer to the dipstick

For the first measurements just some through calibrations are used. But then a full calibration with the calibration set which can be compared to a saved calibration on the machine was done. A full calibration means to measure both cables short, shunt and through.

Setting all parameters mentioned in 1.3.2 as they were needed for the beam splitter measurement before doing the calibration leads to the advantage that they are saved too, if we save the calibration on the network analyzer.

Therefore all the parameters are the same for each measurement, because by reloading the calibration the parameters are adjusted to the saved values too.

For the measurement of the T1 beam splitter the through calibration CAL34DH2 and for the T4 and T5 the full calibration CAL34DHF is used.

- The dipstick calibration

This one was done with a Niobium-through device and cooling the dipstick down to 4.2 K. While the device should be more or less lossless just the loss of the cables are measured and saved to a file. These data are then subtracted from the measured ones. This results in a quite good calibration of the dipstick cables. For all the measurements (T1,T4,T5) this calibration has been taken into account.

- Phase calibration

The different lengths of the dipstick cables have a crucial influence of the phase measurement. Therefore a phase calibration is necessary too. While measuring the amplitude for the dipstick calibration a phase measurement is carried out too. Then this data are subtracted from the measured data to have the different lengths of the dipstick cables cancelled out.

1.4 Simulation

To compare the measured data with the theoretical values we need some kind of simulation of such a circuit. The first idea was to take the equations we have from the circuit analysis in section 1.2.4 and plot them with Mathematica.

1.4.1 Ideal Model

The ideal model can be simulated with help of the software Mathematica. The main part was already done by Tobias Frey, by putting all the equations from section 1.2.4 in the Mathematica notebook 'hybrid5.nb'. Now the the design frequency for the different beam splitters has to be adjusted and the equations for the same frequency ranges as measured for the devices before, have to be plotted. In Chapter 2 the Mathematica plots are compared to the measured data. With Mathematica we can only simulate an ideal experimental setup. Different impedances on the chip and impedance mismatch in the setup can not easily be taken into consideration. This was achieved using numerical simulation software, as describes in the following section.

1.4.2 Numerical Simulation

With the software 'microwave office' a circuit can be build and different values can be measured. For the beam splitter the amplitudes of the different transmissions are important.

Figure 1.5 shows a picture of a beam splitter in a microwave office layout. It consists of 4 transmission lines and 4 ports. For the transmission lines the length, impedance and f_0 which is here f_{design} can be adjusted. After running the simulation for a chosen range the data can be plotted and the data points can even be exported to a '.txt' file for example.

There are a number of imperfections possible in the measured circuits. It is possible that the effective dielectric constant of the transmission lines and hence the propagation velocities of waves along the lines is different from the design. This would cause a different work frequency for the beam splitter.

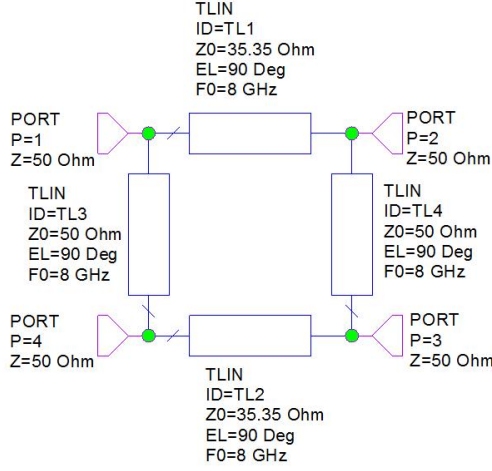


Figure 1.5: Microwave office layout of a beam splitter designed for 6.5 GHz

After measuring the beam splitter and finding out with which frequency it works, the following relation determines the effective dielectric constant ϵ_{eff} :(see 1.2.4)

$$\epsilon_{eff} = \left(\frac{c}{f \cdot 4 \cdot l_2} \right)^2.$$

l_2 is the length of the transmission lines. The values for the different designs are: $l_{2-T1} = 4,67mm$, $l_{2-T4} = 4,073mm$, $l_{2-T5} = 3,62mm$.

The characteristic impedances of the lines may also vary. This can lead to a ration between the impedances that is different from $\sqrt{2}$, and hence irregular splitting of the signal.

There can also be impedance mismatches in the setup, for example at the connection between the PDBs and the chip, between the PCB and the dipstick cables or between the dipstick and the cables of the network analyzer.

By tuning parameters in a numerical simulation and comparing to the measurement results, I tried to extract some information about the ϵ_{eff} . (See Section 2.2.3.) To design new circuits it is very important to find out which ϵ_{eff} these designs have.

2 Results

2.1 Experimental results

In this section the plots of the measured data are compared to the plots of the ideal model (1.4.1).

2.1.1 T1 7 GHz (floating central ground plane)

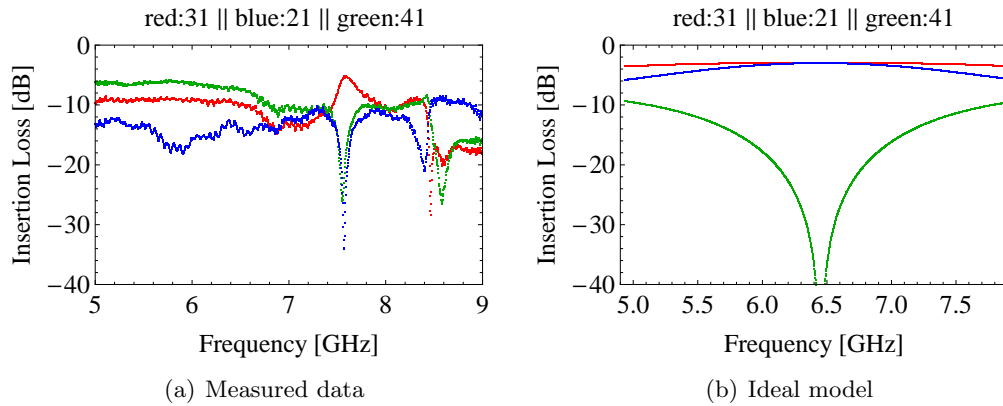


Figure 2.1: T1 with floating central ground plane

The beam splitter measurements started with the T1 chip. This one was designed for $f_{design} = 7\text{GHz}$. The figure (a) and (b) do not show any similar result. The measured one (a) has nowhere a dip in the black line which is the 14 connection while the other connections have some kind of a maximum. This chip with the floating ground plane did not work. Therefore the ground plane was bonded for this chip and for all the others too.

2.1.2 T1 7 GHz

Figure 2.2 (a) shows the result of the measurement of the T1 with the bonded ground plane. For the simulation, (b), f_{design} is changed to the approximate value of the measurement to have a better comparison. Now the measured plot looks much more similar in shape as the simulated than before. The main differences are, that the frequency is slightly shifted from f_{design} , that the 21 and the 31 plot have a gap in between and that there are oscillations which the Mathematica simulation does not show. The frequency shift is more or less the same which can be seen when measuring superconducting resonators which have the same line design. It is due to the fact, that the dielectric constant of the lines is slightly different from the value which has been calculated. Usually the shift is about $\frac{0.5}{7} \approx 7\%$

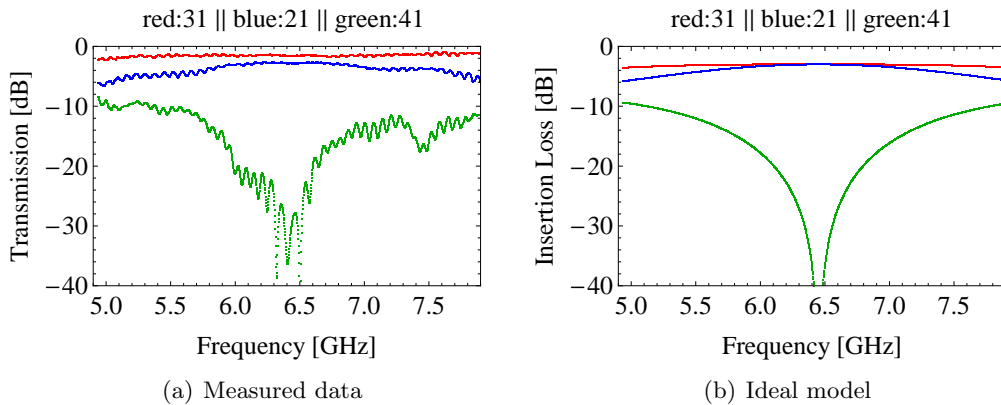


Figure 2.2: T1 at 6.45Ghz

The gap and the oscillations can not be explained if a perfect experimental setup is assumed. Therefore it is worth looking at the plots of another simulation too. In Chapter 2.2 there will be the microwave office simulation for the T1 beam splitter.

2.1.3 T4 8 GHz

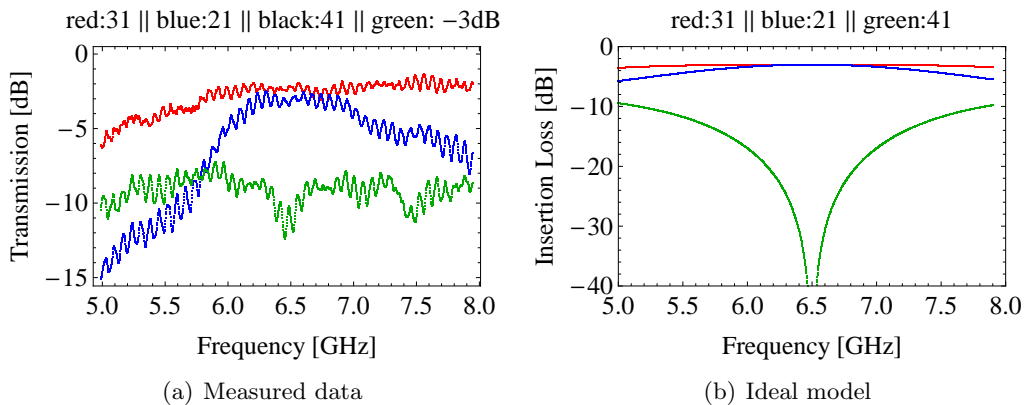


Figure 2.3: T4 at 6.50Ghz

The third chip was designed for 8 GHz. But the only frequency resembling to the theoretical plot can be seen at about 6.5 GHz. Figure 2.3 shows that even there the 41 line has no real dip as the simulation predicted. The blue line (21) has a too sharp peak, it declines very quickly before and after the 6.5 GHz. The red line is the most similar to the simulation, but compared to the results of the T1 in Section 2.1.2 this is not a satisfactory result either. Because this chip did not seem to work and looks so much different from the Mathematica simulation it would be useless to look at it for other simulations.

2.1.4 T5 9GHz

The last chip measured is the T5 with a f_{design} of 9GHz. In Figure 2.4 it can be seen that the red and the blue line which represent the 21 and the 31 connection look quite similar to the simulation Figure 2.4 (b). The 41 has a dip at about 8.1 GHz and its shape matches quite well with the theoretical one.

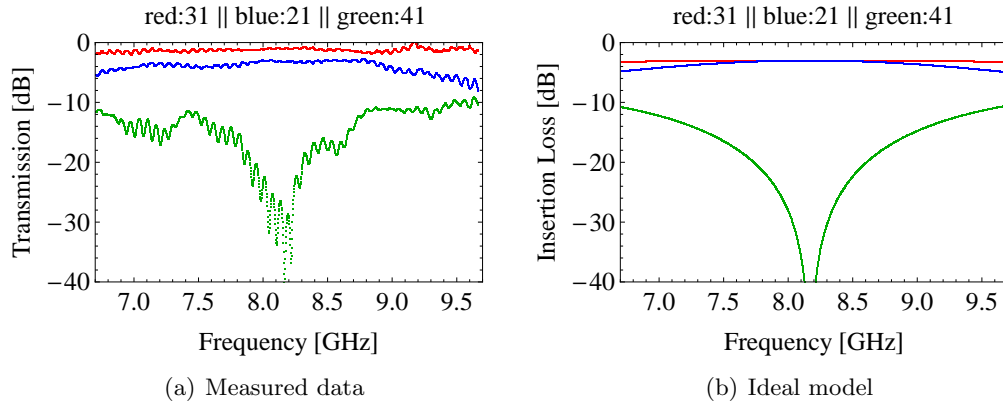


Figure 2.4: T5 at 8.17 GHz

There are the same differences as with the T1 in section 2.1.2. In Chapter 2.2 there is a simulation with Microwave Office which tries to simulate a non perfect experimental setup which should be able to explain these differences.

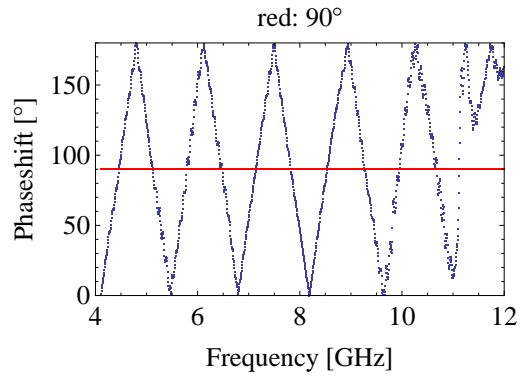
2.1.5 Phase measurement

The results of the phase measurement will just be discussed for one beam splitter because there are no similarity to the theoretical predicted values.

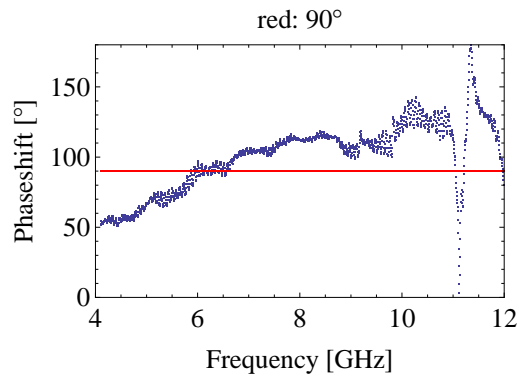
To check if the phase shift between the 21- and the 31-outgoing wave are really the predicted 90° , the difference between the phase of the 21 and the 31 wave is calculated and plotted. Because a difference of -270° means the same as a 90° difference it is possible to shift the range of the plot to $(0, \pi)$ as π equals 180° . Figure 2.5 shows these plots for the measured values before and after the dipstick calibration and the Mathematica simulation. As the simulation shows, there should be a 90° phase shift between the phase of the 21 and the 31 wave, at least for a certain range, which is approximately 1-2 GHz wide.

Neither before nor after the calibration this characteristic can be found within the plots of the measured data.

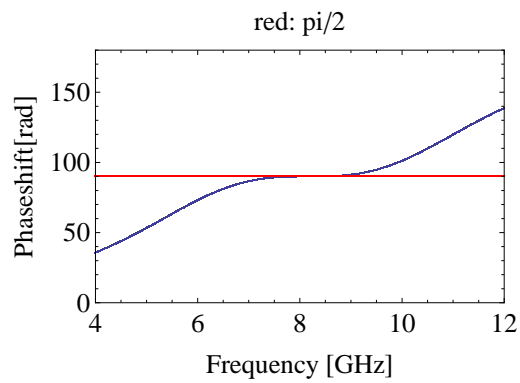
The phase measurement is very difficult because a calibration is never perfect and small changes to the lengths lead to a really different outcome.



(a) without phasecalibration



(b) with phasecalibration



(c) Ideal model

Figure 2.5: Phase shift between the phase of the 21 and the 31 wave. (a) and (b) are the measured data from the T5 beam splitter. (c) is the ideal model.

2.2 Simulation results

2.2.1 Dielectric constant

As mentioned in section 1.4.2 a different dielectric constant can lead to a different work frequency of the beam splitter. From the figures 2.6(p. 16) and 2.7(p. 16) the work frequencies can be obtained for the best matches of the simulation and theory. This is for T1: 6.45 GHz and for the T5: 8.17 GHz. The error is for both $\pm 0.15GHz$. The ϵ_{eff} can be calculated with the following formula:

$$\epsilon_{eff} = \left(\frac{c}{f \cdot 4 \cdot l_2} \right)^2.$$

For the T1 (l_2 of 4,67 mm) and the T5 ($l_{2-T5} = 3,62$ mm) we obtain the following results:

$$\epsilon_{eff-T1} = 6.2 \pm 0.29$$

$$\epsilon_{eff-T5} = 6.43 \pm 0.24$$

2.2.2 Circuit impedances

The first problem to solve is the gap between the 21 and the 31 plot. The simulation is normally run with the parameters indicated in the table 2.1. Then the Impedances are slightly altered until the plots look like the measured ones. But there is still some constant shift for 21 and 31, which could be due to the calibration which can not be done with perfect accuracy. So taking differences of the measured and simulated lines and adding the mean value of this difference to the theoretical values let the shift disappear.

Impedance of the 12/34 line (Z1)	35.35 Ω
Impedance of the 14/23 line (Z2)	50 Ω
Length of the transm. lines (p1)	$\frac{\lambda}{4} = 90^\circ$
Frequency(T1/T5) (f_0)	6.45 Ghz / 8.17 Ghz

Table 2.1: mwo settings (normal)

The results and the used parameters are shown in Figure 2.6 and Figure 2.7

The red and the blue line, that means the 21 and the 31 connection are really very close to the simulated shapes as can be seen in Figure 2.6. The 41 line is for some ranges few decibels away from the theoretical predicted line, but nevertheless the shape with the dip is quite good.

Figure 2.7 shows that the 21 and 31 lines for the T5 are okay too but the 41 line could not be simulated well. The problem is, that the bigger gap between the red and blue line lead to other impedances than the ones used with the T1. Adjusting the gap to the measured one always resulted in this shape of the 41 plot.

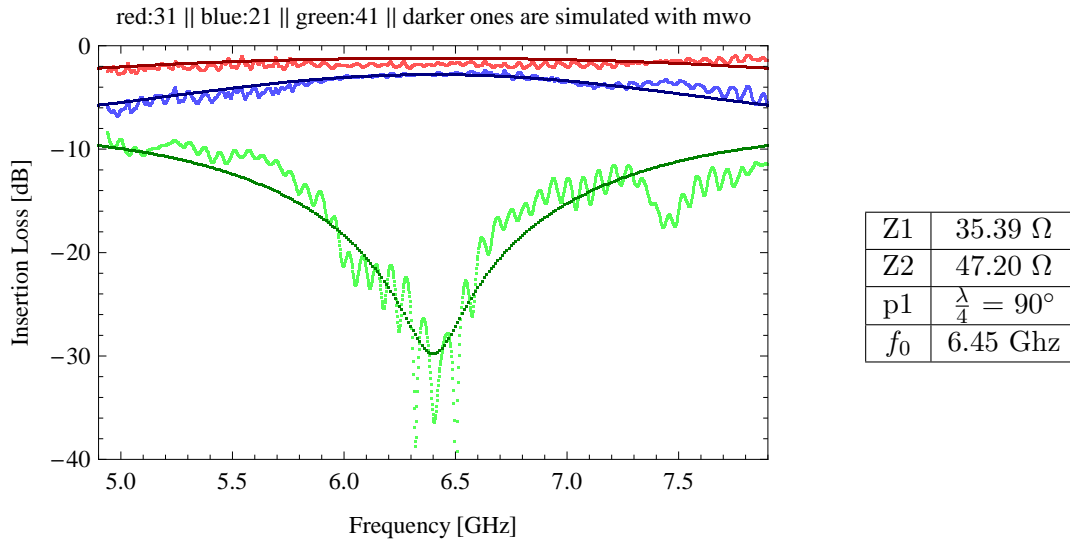


Figure 2.6: T1 beam splitter and settings for the mwo simulation

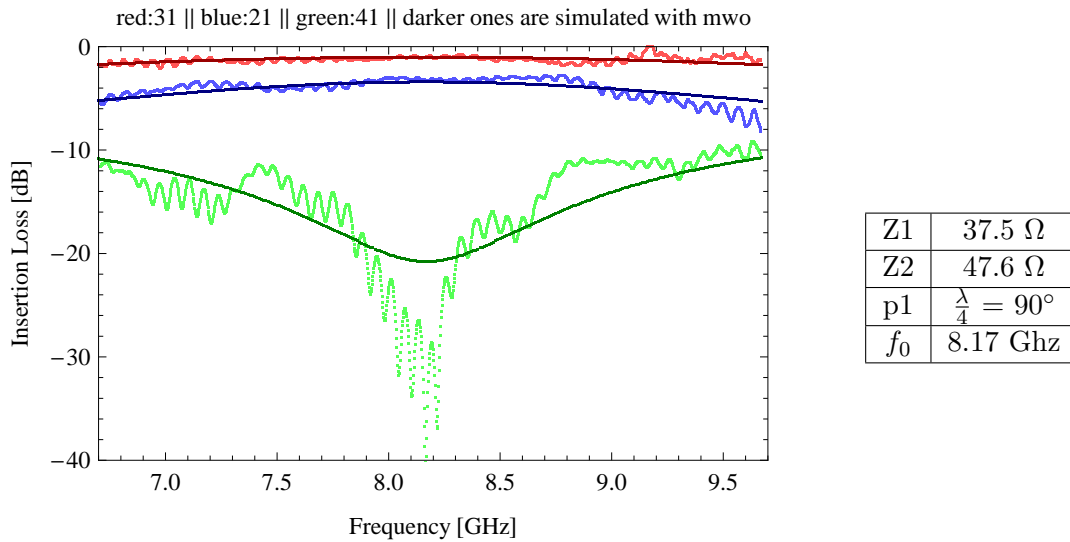


Figure 2.7: T5 beam splitter and settings for the mwo simulation

The T1 beam splitter could be simulated quite well. But the T5 one had such a big gap, so that changing of the impedances always led to a bad shape of the 41 plot. Now the simulated plots look more or less like the measured ones, except for all the oscillations. But with Microwave Office there is way to simulate these oscillations if they are due to impedance mismatches somewhere in the experimental setup.

2.2.3 Impedance mismatch

The first aim was to find out where the reflections which equal the oscillations in the plot happen. So the different length scales from the experimental setup are used for

the additional transmission lines. The result is, that a reasonable frequency of the resonances only can be achieved if there are lengths about one meter. Therefore the reflections will be somewhere on the dipstick cables, on the connections or perhaps even the cables could have a slight offset from the given 50Ω . Now all of the dipstick cables are measured to see if this leads really to some nice simulation for the oscillations.

The lengths of the cables are:

- cable 1 = 162 cm
- cable 2 = 147 cm
- cable 3 = 164 cm
- cable 4 = 151 cm

All of them measured with an error of ± 2 cm. For the simulation the exact measuring results are used. But they have to be written as a phase. For that the following equation is used with $\epsilon = 2.1$ and $f = f_d$:

$$phase = \frac{length \cdot 360^\circ}{\frac{c/\sqrt{\epsilon}}{f}}$$

This results in:

- cable 1 (T1 / T5) = $18170^\circ / 23016^\circ$
- cable 2 (T1 / T5) = $16488^\circ / 20885^\circ$
- cable 3 (T1 / T5) = $18283^\circ / 23158^\circ$
- cable 4 (T1 / T5) = $16937^\circ / 21453^\circ$

For the simulation only the impedances are changed and fixed length are taken, because changing the lengths in a reasonable range does not change the result so much.

The Figures 2.8 and 2.9 show the result of this simulation. In the table next to the plots there are the impedances for the additional transmission lines which are used for the plot. Z_{o1} means the impedance of the transmission line which was added in front of port 1.

From the figures it can be seen that the oscillations simulation is quite near to the measured one, what means that the chosen lengths and impedances are ok.

The general shape of the plots does not change that much, therefore we have still a quite good approximation for the T1 beam splitter (2.8) but for the T5 (2.9) the problem with the bad 41 line still remains.

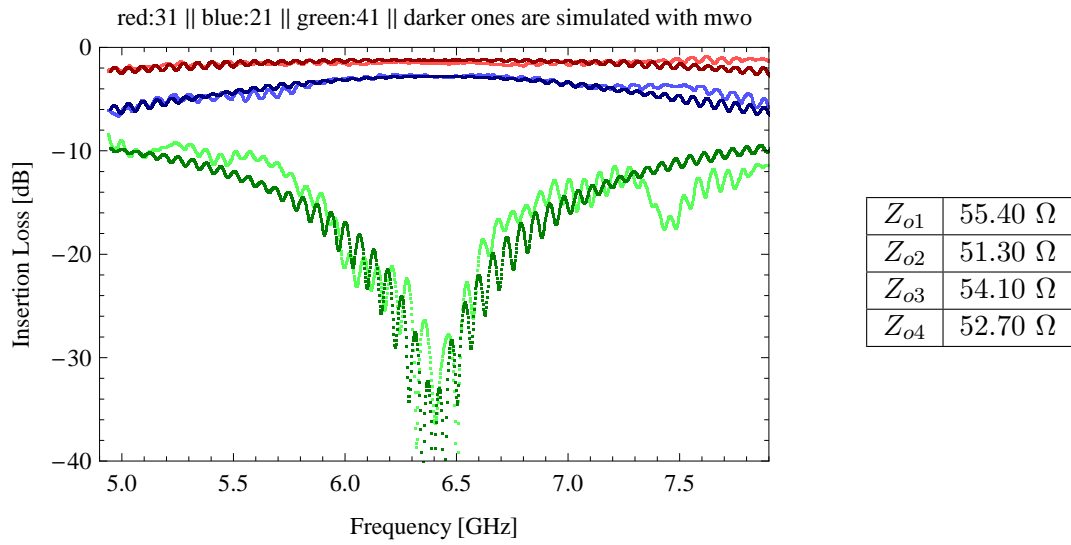


Figure 2.8: T1 beam splitter and settings for the mwo-oscillation-simulation

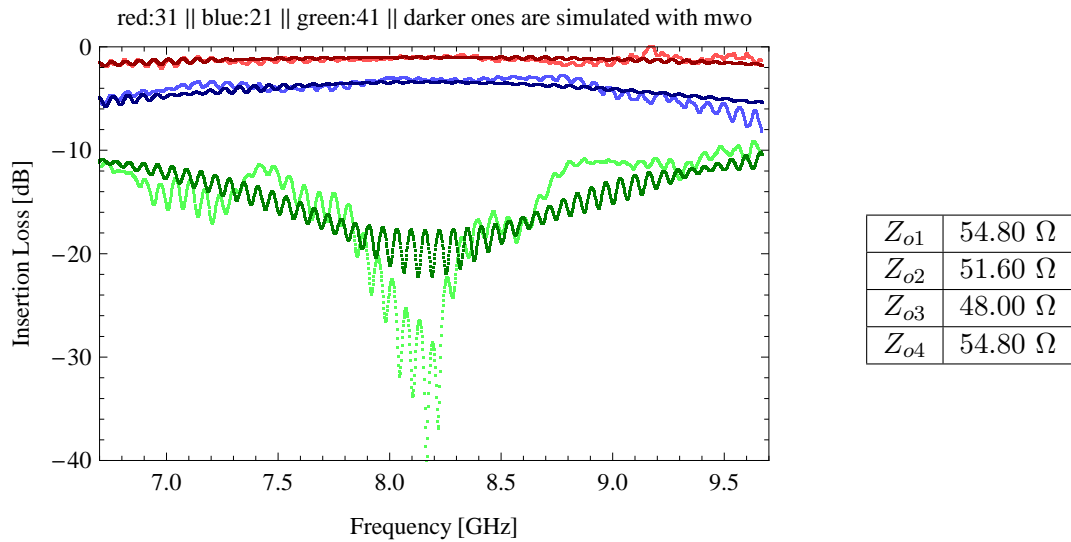


Figure 2.9: T5 beam splitter and settings for the mwo-oscillation-simulation

3 Conclusion

In this semester thesis three microwave beam splitters with different design frequencies are measured and analyzed. The measurements are first compared to an ideal model and afterwards a numeric simulation is done.

The comparison to the ideal model shows that the designed beam splitters basically work if we bond the central plane to the chip to set it to ground level. The beam from port one is divided into two parts which comes out at port 2 and port 3 while port 4 is isolated.

The phase measurement does not lead to reasonable results but it is not sure if there is really no phase shift or if the phase just cannot be measured exactly enough the way it is done in this work.

The measurement of the T4 beam splitter does not end in a satisfactory result either. But because the T1 and the T5 worked, it is more likely that just the chip of the T4 was somehow bad, than that the whole beam splitter design itself does not work.

Then the measurements are compared to the numerical simulation. This leads to the following differences to the perfect beam splitter:

The first difference is that the frequency with which the beam splitter works is lower than the f_{design} . Because this frequency shift also appears with resonators it is not a characteristic of the beam splitter itself. It is explained by a different ϵ_{eff} from the designed one. In Section 2.2.1 the ϵ_{eff} for the T1 and the T5 are calculated and we get the following values:

$$\epsilon_{eff-T1} = 6.2 \pm 0.29$$

$$\epsilon_{eff-T5} = 6.43 \pm 0.24$$

Then there is a gap between the amplitude of the 21 and 31 outgoing beam. This could be because the impedances on the chip match not exactly the theoretical values. The mwo simulation shows that an offset of about 5% from the 50Ω can lead to a 1 dB gap.

The last big differences are the oscillations. There is a detailed explanation for these oscillations in section 2.2.3. The comparison with the numerical simulation results in the fact that the oscillations are due to impedance mismatch between the dipstick cables and the PCBs/connectors. This leads to reflections and these can be seen as oscillations in the measurement. With mismatch of at most 10% from the 50Ω the oscillations can be simulated quite well.

With this results the next design of the beam splitters can be done with a different ϵ_{eff} and perhaps some small changes of the impedances, to get a result which matches the ideal model better.

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