Project 3

Directional couplers and power dividers

This project is focused on the design of directional couplers and power dividers which are necessary components for measurement and communication systems. These circuits require single-mode propagation transmission lines with several impedances on single microwave substrate to be designed.

Choose a proper commercially available substrate, a type of transmission line utilized and on frequency $f = f_0$ design:

1) A coupled-line directional coupler with coupling factor:
    a) 20 dB,
    b) 10 dB,
    c) 6 dB,
    d) 3 dB.
2) A 3 dB branch-line coupler with
    a) two branches,
    b) three branches.
3) A 3 dB rat race coupler with circumference:
    a) 3/2 λ_g long,
    b) λ_g long with phase invertor.
4) A 3 dB Wilkinson power divider
    a) uncompensated,
    b) compensated with the widest possible bandwidth and $S_{11} < -20$ dB.

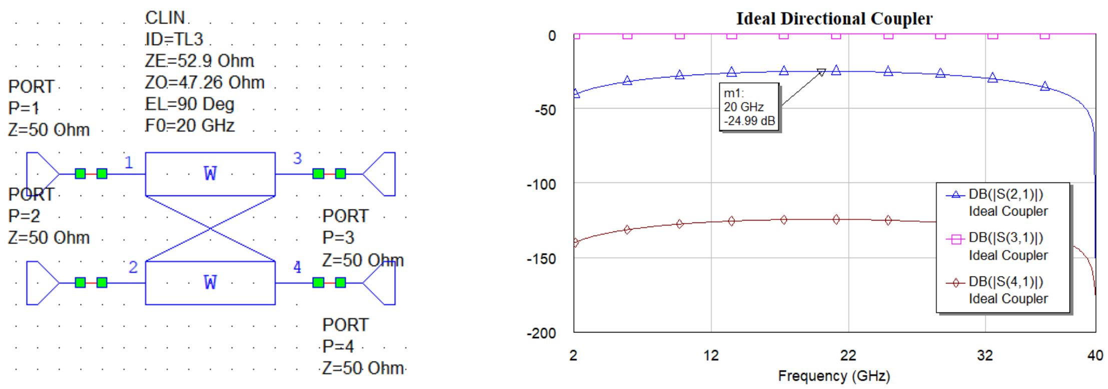
In the frequency band 0.1 f_0 to 2 f_0, determine the frequency dependences of the amplitudes of their basic S-parameters.
On frequency $f = f_0$, determine the phases of their transmit S-parameters.
All circuits are to be designed as ideal ones without considering discontinuities.
Suppose available etching technology with achievable minimal trace width and gap width as 0.1 mm.
In tasks 1c) and d) it is necessary to make the gap smaller than the fabrication limit.
In one case of circuit 1), both circuits 2) and 3a) must also include in the design the influence of discontinuities. Try to match the parameters of the circuits with discontinuities and ideal circuits as best as you can. This could be achieved by properly choosing the substrate in a way that a quarter-wavelength is several times longer than the width of a line. Show the final AWR schematics and produce a layout for these circuits.

Project solution procedure

Task 1:

It is feasible to fabricate a coupled-line directional coupler using coupled microstrip lines, or coupled striplines. To design the directional coupler with wanted coupling factor it is necessary to compute the even and odd impedances of coupled lines with a field distribution corresponding to even and odd modes, respectively. The whole procedure of coupled-line directional coupler design is shown on Slide 86 of the lecture.

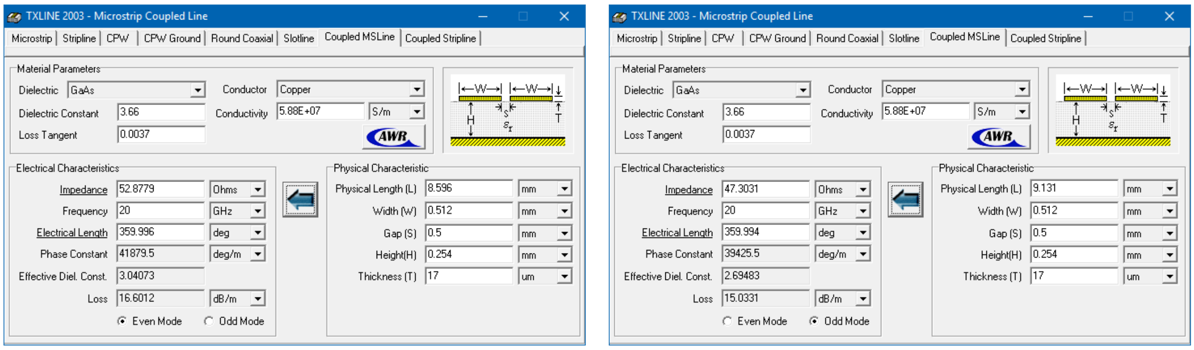
Now design a directional coupler with coupling factor C = 25 dB, center frequency 20 GHz and with the characteristic impedance of the connecting lines Z_v = 50 Ω. From the equation on Slide 86 the resulting Z_{ve} = 52.90 Ω and Z_{vo} = 47.26 Ω. It is a good idea to check and see that it always holds $Z_v = \sqrt{Z_{ve}Z_{vo}}$. At this point, it is already possible to utilize AWR to check this result. Open AWR, set the frequency range, create a schematic and place an element from the folder Transmission Lines→Phase→CLIN in it. Set the even and odd impedances, electrical length should be 90 deg (the shortest possible to have a wide bandwidth) and f_0 is the design frequency. The schematic and the result is shown in Fig. 1. Transmission to port number 2 from port 1, *i.e.,* S_{21}, has an absolute value −25 dB, insertion loss S_{31} is 0 dB and isolation S_{41} is almost zero in linear scale (−125 dB).



a) b)

Fig. 1 a) Schematic of the ideal directional coupler, b) transmissions of the directional coupler fed via port 1. Coupling is C = 25 dB.

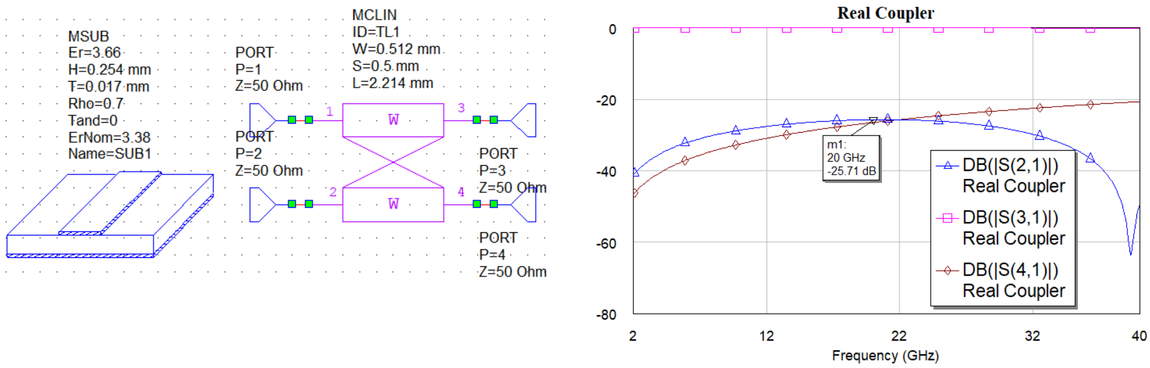
Up to now it was not necessary to select the actual physical type of the transmission line. We will choose the microstrip line to be utilized in this design because 25 dB coupling is quite low and the microstrip is good enough for that purpose. The substrate will be, *e.g.,* RO4350 with ε_r = 3.66, tgδ = 0.0037, h = 0.254 mm and t = 17 µm. First of all, design a 50 Ω microstrip line using TXLine with this substrate at the design frequency f_0. In my case, the width of the microstrip is w = 0.54 mm. This is actually a good starting point for coupled lines design. Switch TXLine to Coupled MSLine tab, set the computed width of the microstrip and then set a huge gap, *e.g.,* S = 2 mm. The computed impedance of even and odd modes will be almost the same and close to 50 Ω. We need to reach the point when the difference between even and odd impedances is Z_{ve}−Z_{vo} = 5.5 Ω by making the gap smaller which makes the difference between even and odd impedances higher. Changing the width of the strips change both impedances. It is necessary to find dimensions where both impedances approx. reach the computed impedances as shown in Fig. 2.



a) b)

Fig. 2 Filled parameters of microstrip coupled lines in TXLine and computed impedances of a) even and b) odd modes.

For both modes find their wavelengths by changing physical length L to produce an electrical length of 360 deg. In my case it is λ_{ge} = 8.596 mm and λ_{go} = 9.131 mm. The average wavelength of the guided wave is $\lambda_{gs} = 2\frac{\lambda_{ge}\lambda_{go}}{\lambda_{ge}+\lambda_{go}} = 8.855$ mm. The optimal physical length of the coupled lines should be $L = \lambda_{gs}/4 = 2.214$ mm. It can be checked using AWR by creating a new schematic and placing an element Microstrip→Coupled Lines→MCLIN there. Set all necessary parameters to it, define the proper substrate using an MSUB element and analyze the transmission coefficients of the structure. The schematic and resulting graph is shown in Fig. 3.



a) b)

Fig. 3 a) schematic and b) resulting parameters of a directional coupler designed using microstrip lines.

Coupling S_{21} is almost exactly –25 dB, but isolation S_{41} is just slightly lower at design frequency f_0. It means that this coupler has very bad directivity, *i.e.,* the power traveling from the input port to the coupled and isolated port is comparable. The phase of direct transmission S_{31}, coupling transmission S_{21} and isolated signal S_{41} differs mutually by 90 deg. as shown in Fig. 4. The coupled and isolated signals have opposite phases.

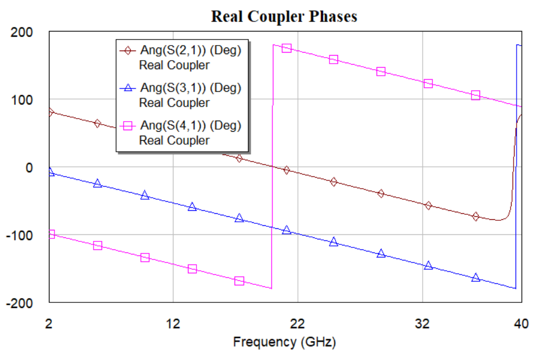


Fig. 4 Phases of transmission coefficients.

This is the end of the design and all coupled-line directional couplers should be designed like this. To design directional couplers with a higher coupling factor it is necessary to utilize a stripline transmission line, otherwise it is not possible to fulfil the manufacturing limitations when the gap should be wider than 0.1 mm. To define a stripline circuit define the substrate by the element Substrates→SSUB and coupled lines as Stripline→Coupled Lines→SCLIN. For any single directional coupler also design connecting 50 Ω lines. Connecting 50 Ω lines should be connected to coupled lines using proper discontinuities as shown in Fig. 5.

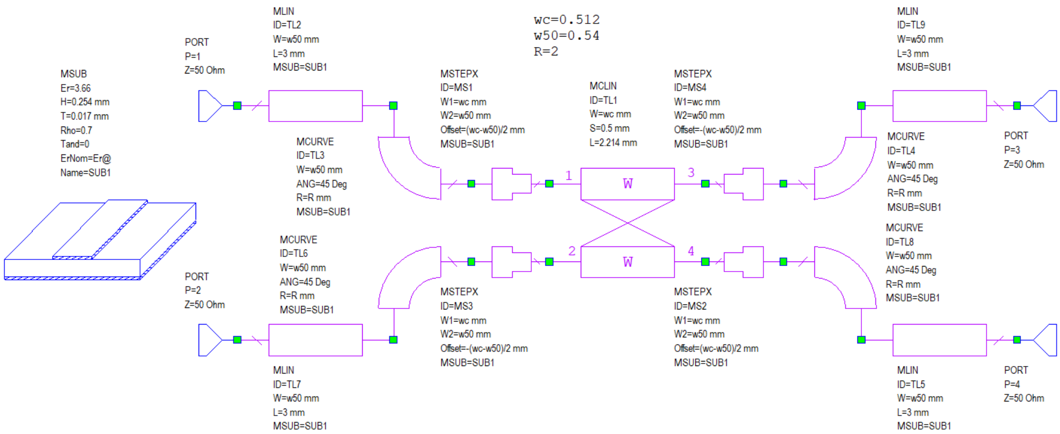
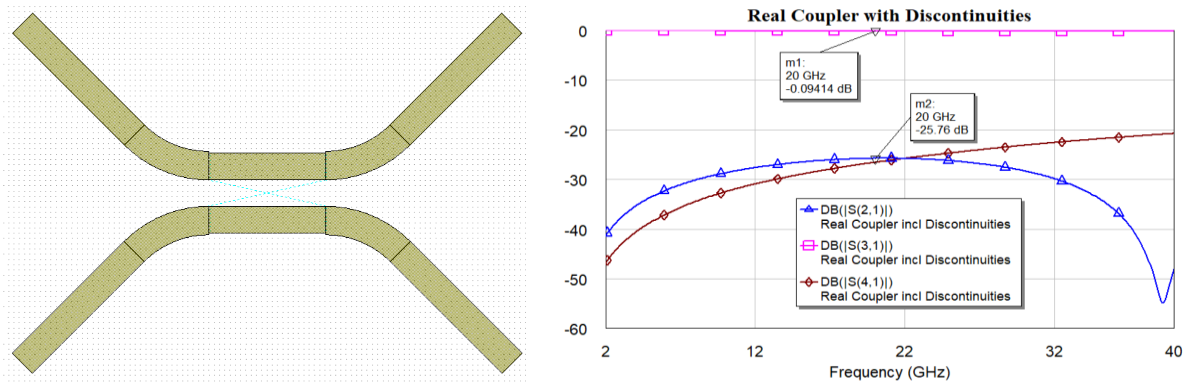


Fig. 5 Directional coupler connected to 50 Ω lines using MSTEPX discontinuities.

The Microstrip→Junctions→MSTEPX element represents discontinuity caused by the transition between lines with different widths. Moreover, this element allows offset in position to be defined. In AWR it generally holds that port no. 1 is marked by a small line crossing the end of an element. It is necessary to define width W1 of MSTEPX on the correct end of the element. Generally, the X-models are based on electromagnetic field simulation and the model's parameters are saved in precomputed results in an AWR installation folder where they are available for several specific permittivity values. The property ErNom of substrate definition is the permittivity value, which is utilized for X-models. Hence, keep in mind that whenever are you working with X-models, property ErNom of the substrate has to be properly set. In Help(F1)→AWR Microwave Office Element Catalog→A. Supplemental Model Information→X-models can be found in a list of available permittivity values for X-models. By setting ErNom=Er@, the value Er of the substrate is automatically utilized.

To produce a layout of this circuit click on the View Layout button (). All elements in the schematic are represented by its layout representation and it is necessary to connect them together. It can be done by pressing Ctrl+A and clicking on the Snap Together button (). The final layout will probably be wrong and it will be necessary to flip and rotate some individual elements in the layout manually. After a rough correction of the positions of some layout elements, try using Ctrl+A and Snap Together again. Or, you can select some specific elements by clicking and pressing the Shift button and applying Snap Together for those elements only. The first selected item stays in its original place. The final layout and its parameters could look like those in Fig. 6. In this case it was not necessary to tune the parameters of the coupled lines after adding discontinuities, but in the case of a directional coupler with higher coupling it is usually necessary. By adding 50 Ω connecting lines, the insertion loss increases up to 0.1 dB at f_0.



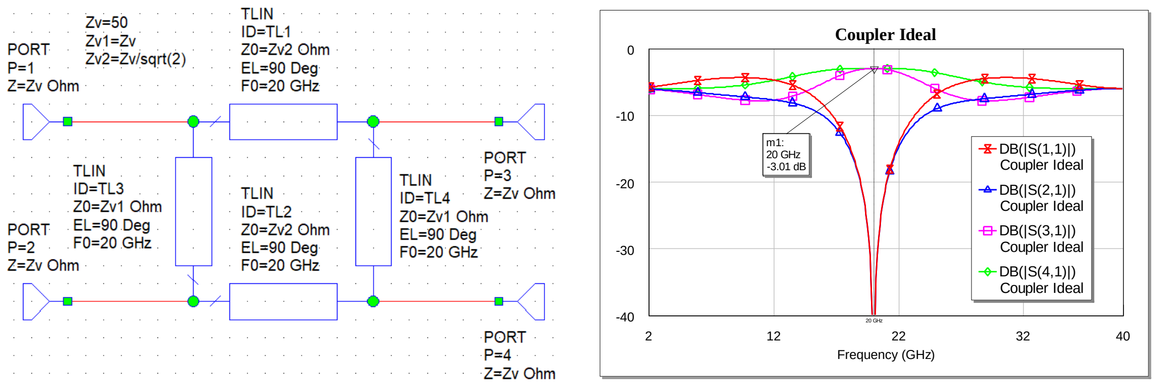
a) b)

Fig. 6 a) layout and b) parameters of the final design of the directional coupler.

Task 2:

Design procedures are described on Slides 94 and 97 of the lectures. Compute suitable impedances of transmission lines, make an ideal connection between them in AWR, include discontinuities, reduce its influence and compose the final layout. We will design just two branch-line coupler in detail and not actually use a suitable substrate for that purpose to see what the effect of a bad substrate choice is. The design frequency will be 20 GHz.

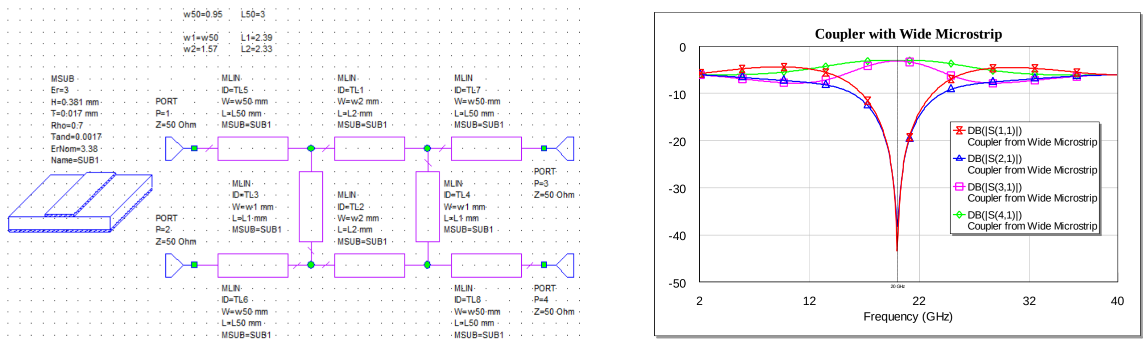
First of all, we compute the impedances of the lines in the 3 dB two branch coupler, which are Z_{v1} = 50 Ω, Z_{v2} = 35.6 Ω for connecting line impedance Z_v = 50 Ω. Let's check if these results are correct by connecting ideal transmission line elements in AWR from Transmission Lines→Phase→TLIN. The resulting schematic and transmission coefficients are shown in Fig. 7. Impedance Z_v is defined as variable (equation, icon) Zv=50 and is also set as the impedance of all ports. Tuning of Z_v has actually no effect on the resulting parameters, because this structure has directional properties naturally using whatever type of transmission line. At the design frequency 20 GHz isolation S_{21} is ideally infinite and the input power from port 1 is ideally divided between ports 3 and 4 with 90 deg phase difference.



a) b)

Fig. 7 a) schematic and b) parameters of the ideal two branch-line 3 dB coupler.

To minimize the effects of discontinuities in the branch-line coupler, the individual lines (with 90 deg. of electrical length) should be several times longer than its width. Keep in mind that the resulting physical length of lines is mainly affected by the permittivity of the substrate and its width mainly by its height. At our design frequency we will choose substrate Isola Astra MT77 with ε_r = 3.0, tgδ = 0.0017, t = 17µm and h = 0.381 mm. The resulting dimensions of the individual lines can be found in Fig. 8.



a) b)

Fig. 8 a) schematic and b) parameters of a two branch-line coupler without discontinuities.

Transmission coefficients in Fig. 8 look fine, almost as in the previous ideal case, but the shape of individual lines is more or less square which is not ideal. The connecting 50 Ω lines TL5-8 were not included in the ideal case but are necessary for embedding the branch-line coupler into any real circuit and doesn't worsen the resulting performance of the circuit. The addition of proper discontinuity models in the positions of line connections is shown in Fig. 9. MTEE$ elements simulate the influence of real line connections. The '$' sign in the element's name represents "intelligent" elements in AWR which can determine the widths of the surrounding elements automatically and it is not necessary to fill them manually. The resulting transmission coefficients are shown in Fig. 10.

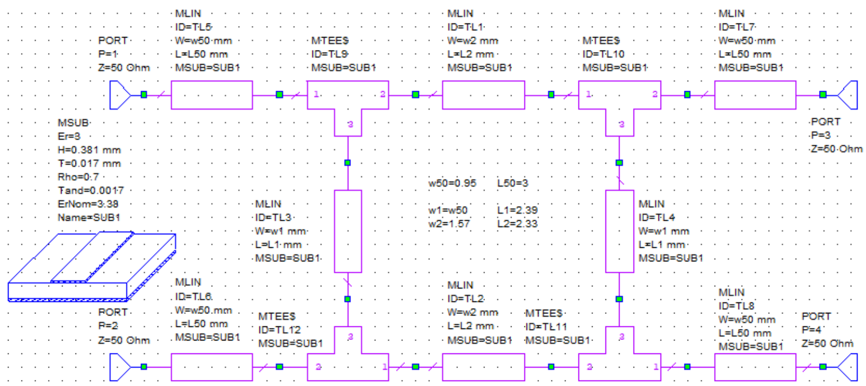


Fig. 9 Branch-line coupler with discontinuity models.

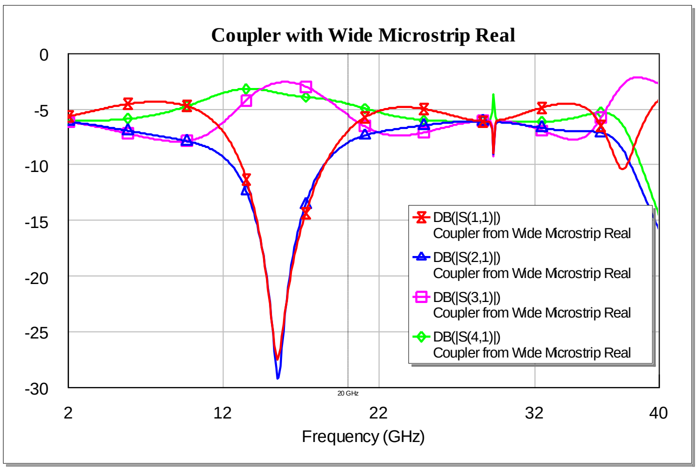


Fig. 10 Transmission coefficients of branch-line coupler distorted by discontinuities.

The resulting characteristics of the circuit are significantly detuned and asymmetrical. To correct the transmission characteristics, it is necessary to tune the lengths of branches TL1-4. In this case, which is quite bad, it is also suitable to tune the width of the lines with Z_{v2} impedance. The resulting layout shown in Fig. 11 shows the fact that the branch-line coupler fabricated using the wrong substrate cannot be considered as a circuit based on reflections between ideally connected transmission lines with different impedances anymore. All connections (discontinuities) themselves have non-negligible electrical size and significantly affect the final performance of the branch-line coupler.

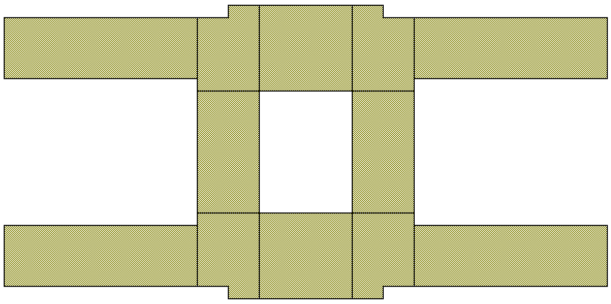


Fig. 11 Layout of tuned two branch-line coupler.

A better choice of substrate would be the same type, but thinner, *e.g.,* with h = 0.127 mm, or a different one with higher relative permittivity to make the width of the transmission lines narrower.

Task 3:

The design procedure is stated on Slide 99 of the lecture's presentation. A conventional 3 dB rat-race coupler consists of three λ/4 sections and one 3λ/4 section with impedances Z_{v1}=Z_{v2}=70.7 Ω. The schematic of an ideal 3 dB coupler at f_0 = 20 GHz is shown in Fig. 12 featuring ideally connected ideal transmission lines with ideal resulting parameters. When the input signal is port no. 1, the outputs are ports 3 and 2 (in phase) and port 4 is isolated. When port 3 is the input the output ports are 1 and 4 (out of phase) and port 2 is isolated. The structure is symmetrical and ports 2 and 4 can be also utilized as inputs with their respective outputs.

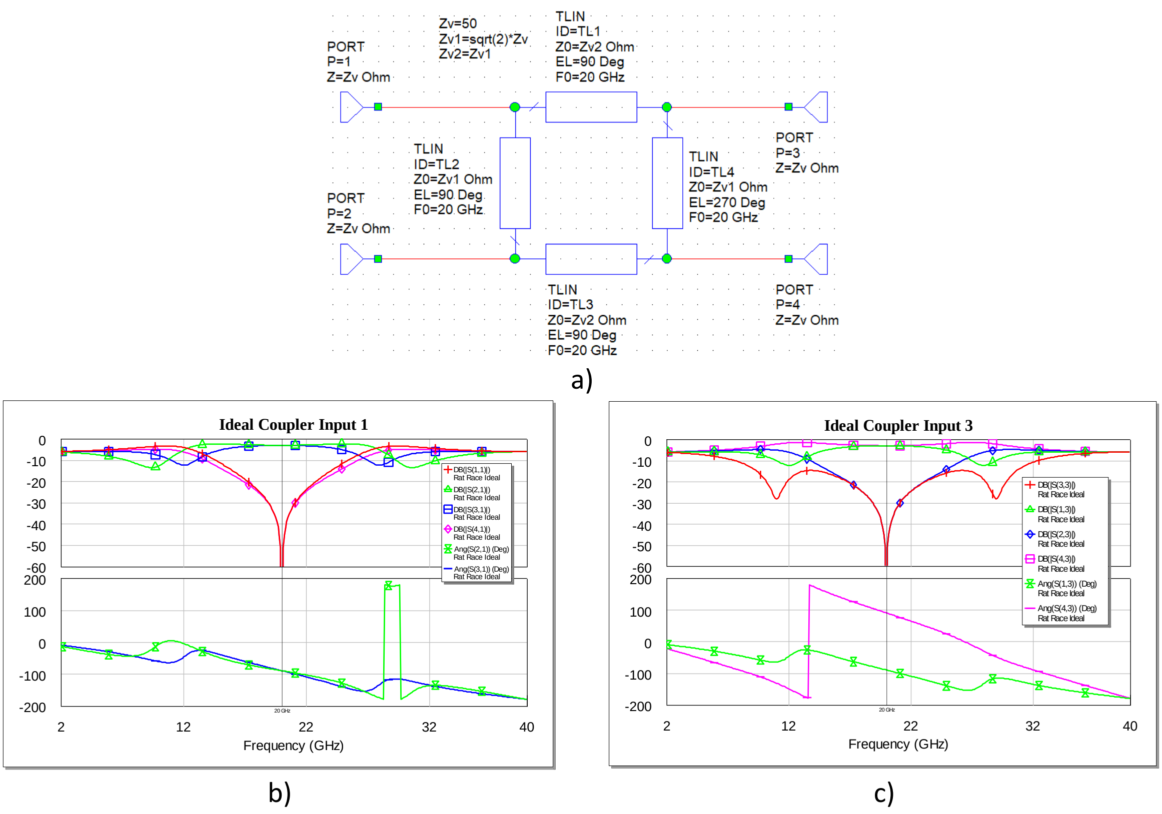


Fig. 12 a) schematic of ideal rat-race coupler, b) parameters of the coupler when fed into port 1, c) parameters of the coupler when fed into port 3.

This circuit should be designed to include discontinuities and the final layout is required. It is usually difficult to design the layout correctly because the coupler generally consists of curved lines and the layout has to be consistent. As in the previous task (branch-line coupler design), it is necessary to correctly choose the substrate to obtain λ/4 lines several times longer than wide. An example of the starting point of the design on substrate Rogers RO3003 with h = 0.127 mm is shown in Fig. 13. Marking line lengths L1, 2 and 3 follow the conventions from the lecture slides.

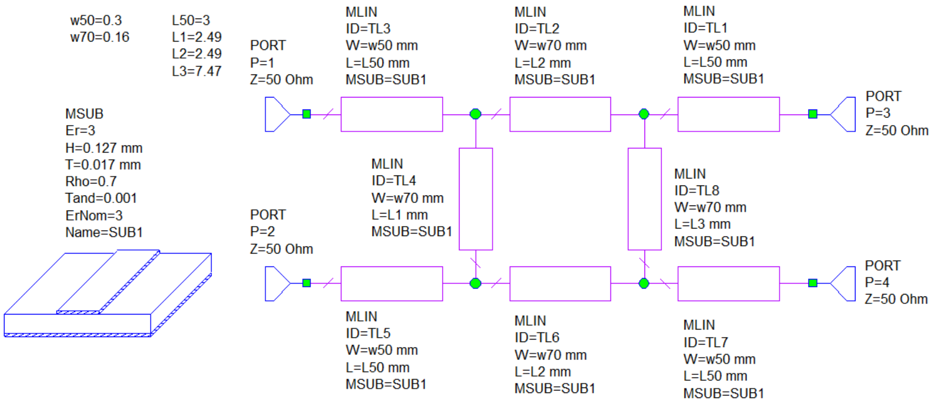


Fig. 13 Schematic of a rat-race coupler designed with microstrip lines and without discontinuities.

Line length and width are entered using equations and all lines are ideally connected microstrip lines. Input lines have an impedance of 50 Ω and are necessary in the schematic for the final design. S-parameters of this circuit are very close to the previous ideal case. The next step consists of the proper curvature of all lines to make a rough layout appearance. You can utilize whatever type of elements from Microstrip→Bends, but it is better to use the simple ones. There are several variants of how to organize the lines to produce a consistent layout and Fig. 14 is just one of them. Fig. 15 shows the layout of the rat-race coupler without discontinuities. The schematic does not contain discontinuities yet and serves only to check if the final shape of the coupler is feasible or not. In the case when the lines are several times longer than wide, discontinuities do not ruin the circuit's parameters much. Proper parametrization of an element's dimensions is usually necessary. Constant π is _PI in AWR equations and the name of the variable followed by a colon (*e.g.,* LR1:) shows the value of the variable after a simulation run (key F8). The order of equation evaluation goes from the upper-left corner to the lower-right corner of the schematic. It is necessary to follow this rule when using the output of one equation as the input of another one.

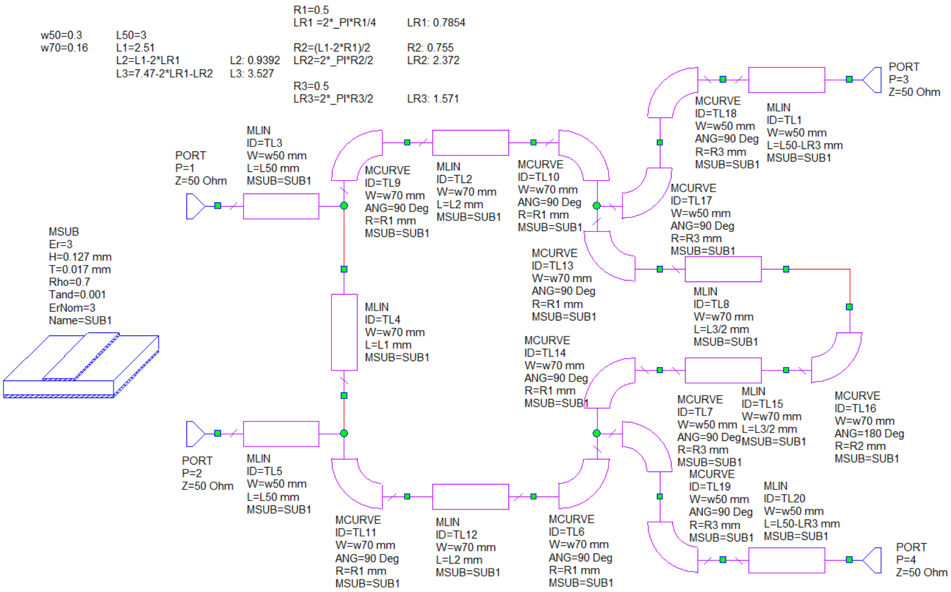


Fig. 14 Schematic of the rat-race coupler with curved transmission lines, but without discontinuities.

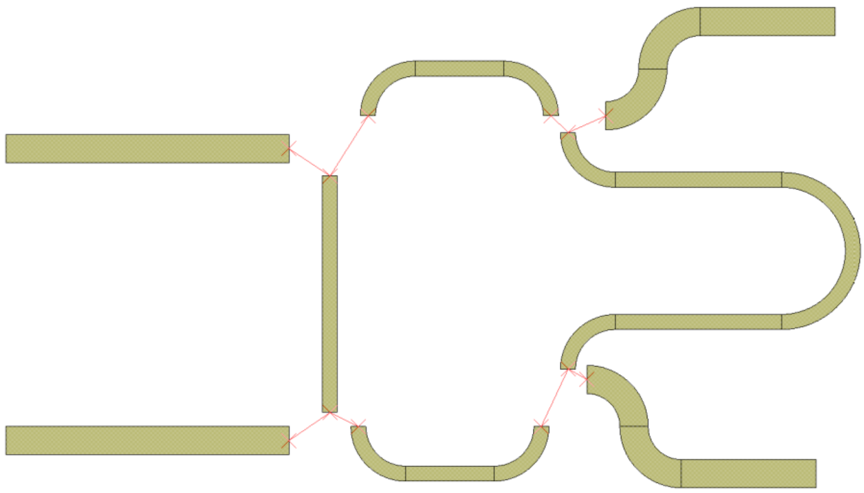


Fig. 15 Layout of the rat-race coupler with curved transmission lines, but without discontinuities.

S-parameters of this structure should still be very similar to the ideal case, but a slight tuning of lengths L1 and L2 could be necessary to compensate for slightly different electrical lengths of the curved lines. The final schematic, including all discontinuities, is shown in Fig. 16.

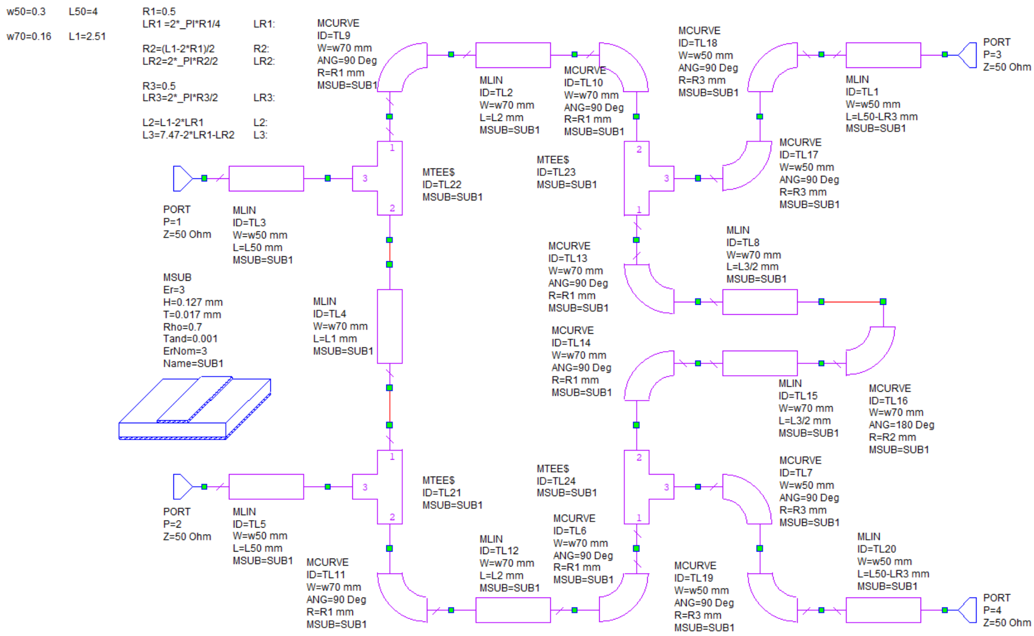


Fig. 16 Final schematic of the rat-race coupler including all discontinuities.

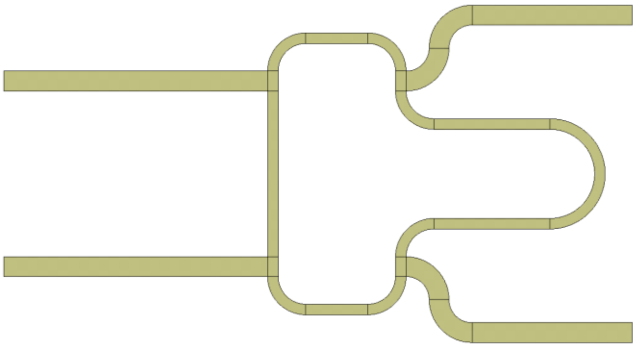
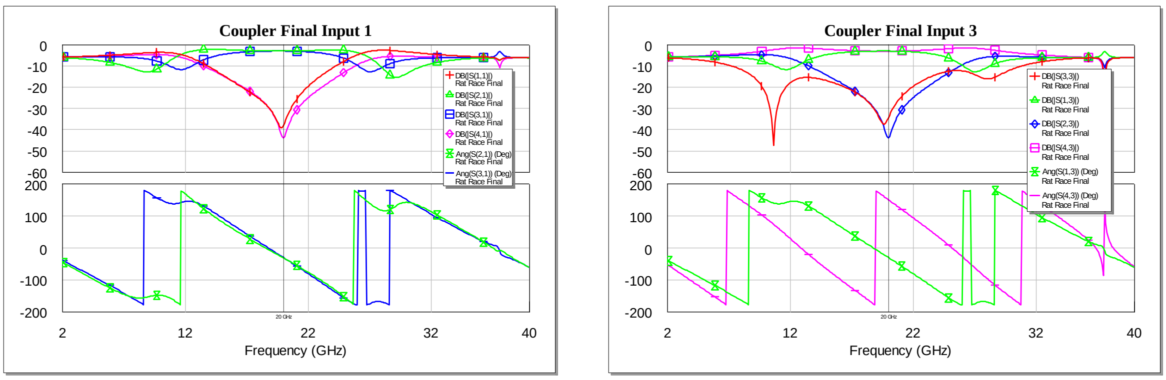


Fig. 17 Final layout of the rat-race coupler.

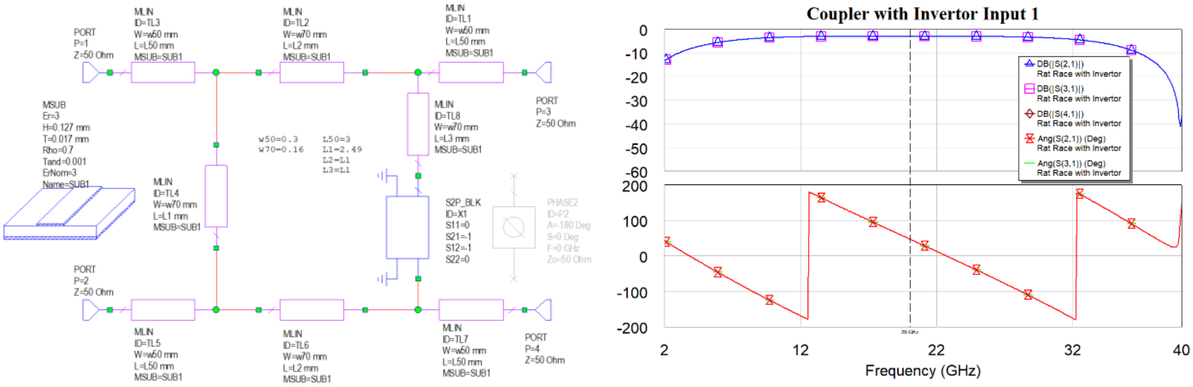
Adding all discontinuities makes it possible to complete the whole layout. A slight change of lengths L1, 2 and 3 could be necessary to compensate for the influence of discontinuities. It is also necessary to preserve the same electrical lengths of the 50 Ω input lines, because the outputs of the rat-race coupler are positioned on diagonal ports (*e.g.,* input 1, outputs 2 and 3), otherwise it would ruin the phase shift between the output signals. The parameters of the final coupler can be seen in Fig. 18.



a) b)

Fig. 18 a) S-parameters of the final rat-race coupler when fed a) into port 1, b) into port 3.

The main disadvantage of a conventional rat-race coupler with overall circumference 3λ/2 is its relatively narrow working bandwidth. Making the bandwidth wider is possible by shortening line L3 using just a λ/4-long line and a phase inverter. The specific physical implementation of the phase inverter is beyond the focus of this project, hence we will just use the ideal one and the schematic will not contain discontinuities. More details can be found on Slide 103 of the lectures. The schematic and S-parameters of the rat-race coupler with phase inverter is shown in Fig. 19. Isolation S_{41} is below the graph range.

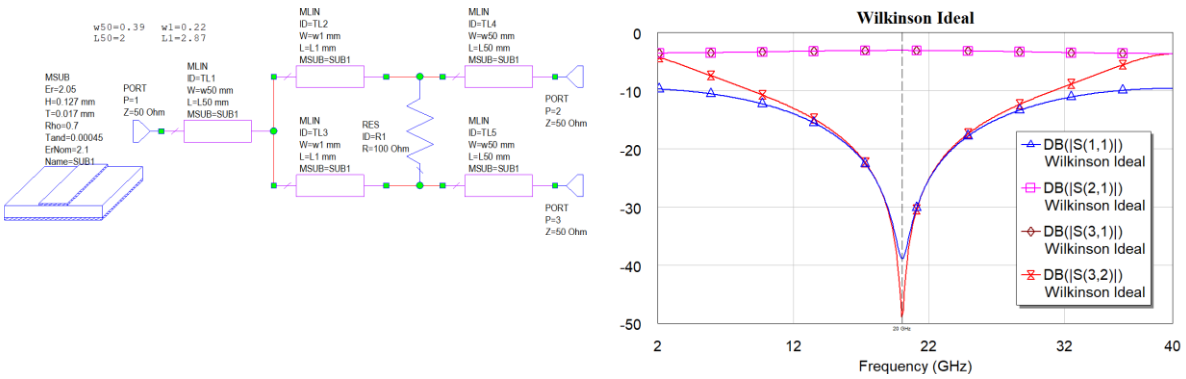


a) b)

Fig. 19 a) schematic of the rat-race coupler with ideal phase inverter, b) its parameters.

Using an ideal inverter, the reachable bandwidth is significantly wider. The element General→Network Blocks→S2P_BLK with transmissions −1 can be utilized as an inverter. Another option is General→Passive→Phase→PHASE2.

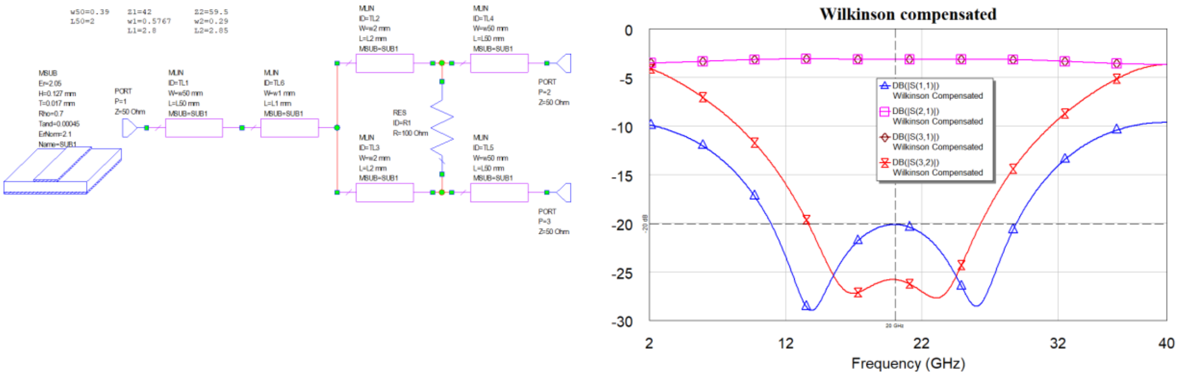
Task 4:
An uncompensated 3 dB Wilkinson power divider is shown on Slide 107 of the lectures. It consists of two 70.7 Ω λ/4 long lines and one 100 Ω resistor. We will design the divider using microstrip lines without concerning any discontinuities and using just an ideal resistor. The schematic and resulting S-parameters of the divider with f_0 = 20 GHz on a CuFlon substrate from Crane is shown in Fig. 20.



a) b)

Fig. 20 a) schematic of an ideal Wilkinson power divider, b) its S-parameters.

The compensated Wilkinson power divider is described on Slide 110. It additionally contains a λ/4 impedance transformer which significantly improves the bandwidth of the divider. Tune the impedance of the transformer to widen the bandwidth as much as possible with $S_{11} < -20$ dB. An example of the design using microstrip lines without discontinuities and an ideal 100 Ω resistor is shown in Fig. 21.



a) b)

Fig. 21 a) schematic of a compensated Wilkinson power divider, b) its S-parameters.