

Laboratory 2 (w5-6)
2025/2026

Microwave Devices and Circuits

Online results submission

- many numerical values

	Z1	Z2	Z3	Z4	Z5	Z6	Z7
	148.33	155.88	202.12	164.35	180.91	30.29	185.19
	25.97	153.5	34.64	35.79	55.56	26.212	10.692
	0	0	0	0	0	0	0
	50	50	50	50	50	50	50



Online results submission

**Grade = Quality of the work +
+ Quality of the submission**

Short theory

The lossless line

$$V(z) = V_0^+ \cdot (e^{-j\beta \cdot z} + \Gamma \cdot e^{j\beta \cdot z})$$

$$I(z) = \frac{V_0^+}{Z_0} \cdot (e^{-j\beta \cdot z} - \Gamma \cdot e^{j\beta \cdot z})$$

- time-average Power flow along the line

$$P_{avg} = \frac{1}{2} \cdot \text{Re}\{V(z) \cdot I(z)^*\} = \frac{1}{2} \cdot \frac{|V_0^+|^2}{Z_0} \cdot \text{Re}\{1 - \Gamma^* \cdot e^{-2j\beta \cdot z} + \Gamma \cdot e^{2j\beta \cdot z} - |\Gamma|^2\}$$

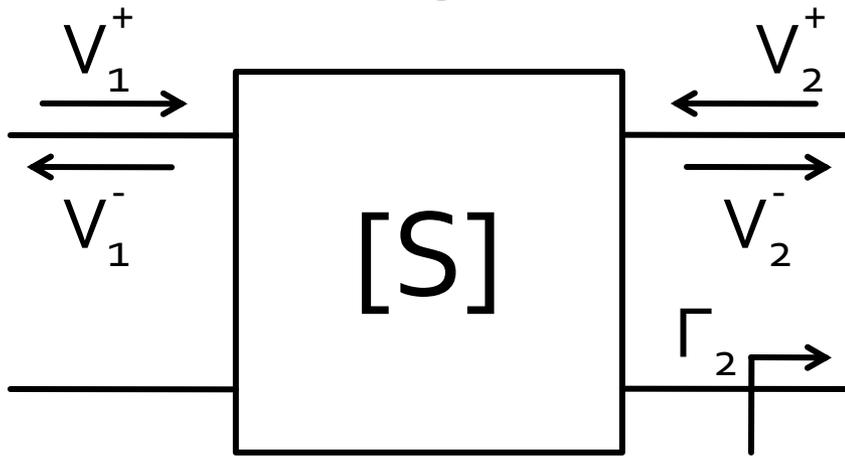
$$P_{avg} = \frac{1}{2} \cdot \frac{|V_0^+|^2}{Z_0} \cdot (1 - |\Gamma|^2)$$

$$(z - z^*) = \text{Im}$$

- Total power delivered to the load = Incident power – “Reflected” power
- Return “Loss” [dB] $\text{RL} = -20 \cdot \log|\Gamma|$ [dB]

Scattering matrix – S

- Scattering parameters



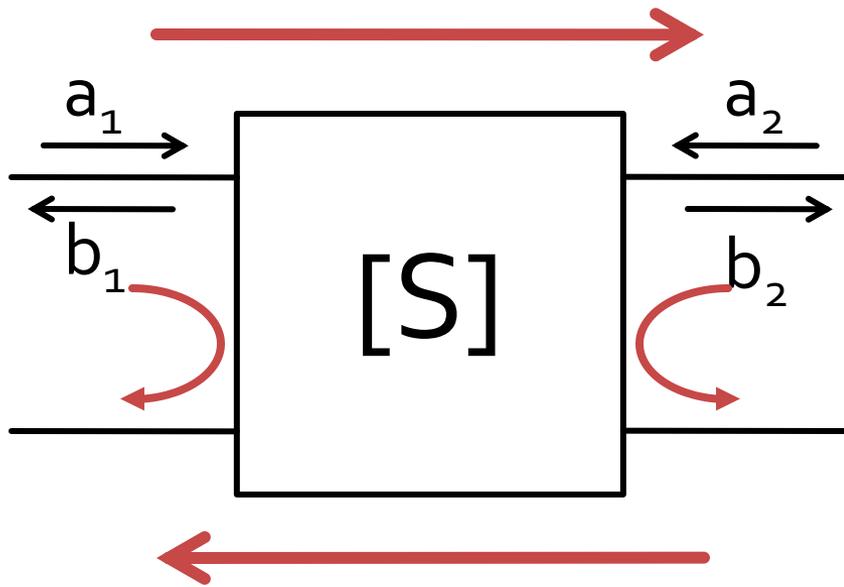
$$\begin{bmatrix} V_1^- \\ V_2^- \end{bmatrix} = \begin{bmatrix} S_{11} & S_{12} \\ S_{21} & S_{22} \end{bmatrix} \cdot \begin{bmatrix} V_1^+ \\ V_2^+ \end{bmatrix}$$

$$S_{11} = \left. \frac{V_1^-}{V_1^+} \right|_{V_2^+ = 0} \quad S_{21} = \left. \frac{V_2^-}{V_1^+} \right|_{V_2^+ = 0}$$

- $V_2^+ = 0$ meaning: port 2 is terminated in matched load to avoid reflections towards the port

$$\Gamma_2 = 0 \rightarrow V_2^+ = 0$$

Scattering matrix – S



$$\begin{bmatrix} b_1 \\ b_2 \end{bmatrix} = \begin{bmatrix} S_{11} & S_{12} \\ S_{21} & S_{22} \end{bmatrix} \cdot \begin{bmatrix} a_1 \\ a_2 \end{bmatrix}$$

$$S_{21} = \left. \frac{b_2}{a_1} \right|_{a_2=0}$$

$$|S_{21}|^2 = \frac{\text{Power in } Z_0 \text{ load}}{\text{Power from } Z_0 \text{ source}}$$

- a, b
 - information about signal power **AND** signal phase
- S_{ij}
 - network effect (gain) over signal power **including** phase information

Scattering matrix – S

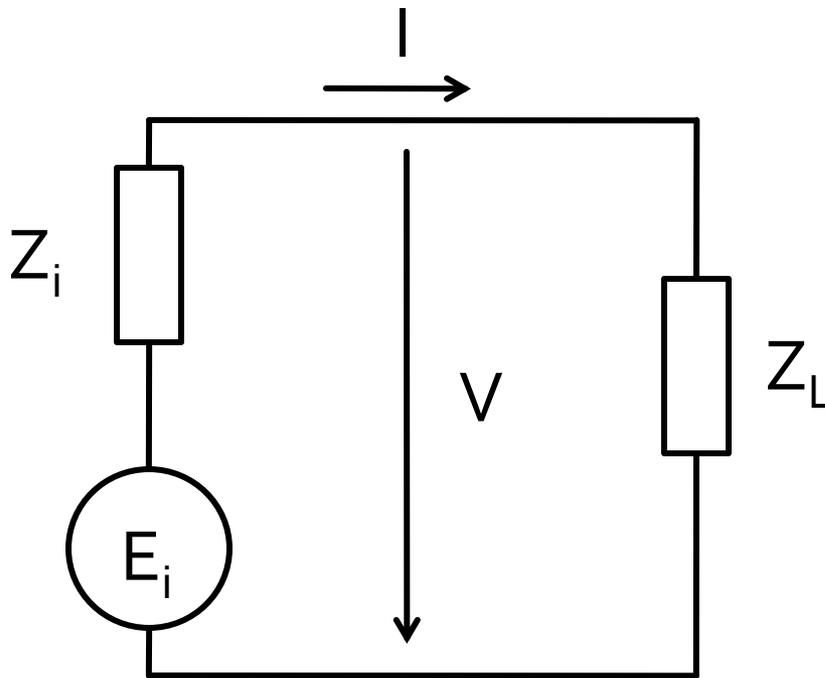
- S matrix can be extended to multiple ports

$$S_{ii} = \left. \frac{V_i^-}{V_i^+} \right|_{V_k^+ = 0, \forall k \neq i} \quad S_{ij} = \left. \frac{V_i^-}{V_j^+} \right|_{V_k^+ = 0, \forall k \neq j}$$

- S_{ii} is the reflection coefficient seen looking into port i when all other ports are terminated in matched loads
- S_{ij} is the transmission coefficient from port j (**second** index!) to port i (**first** index!) when all other ports are terminated in matched loads

Matching

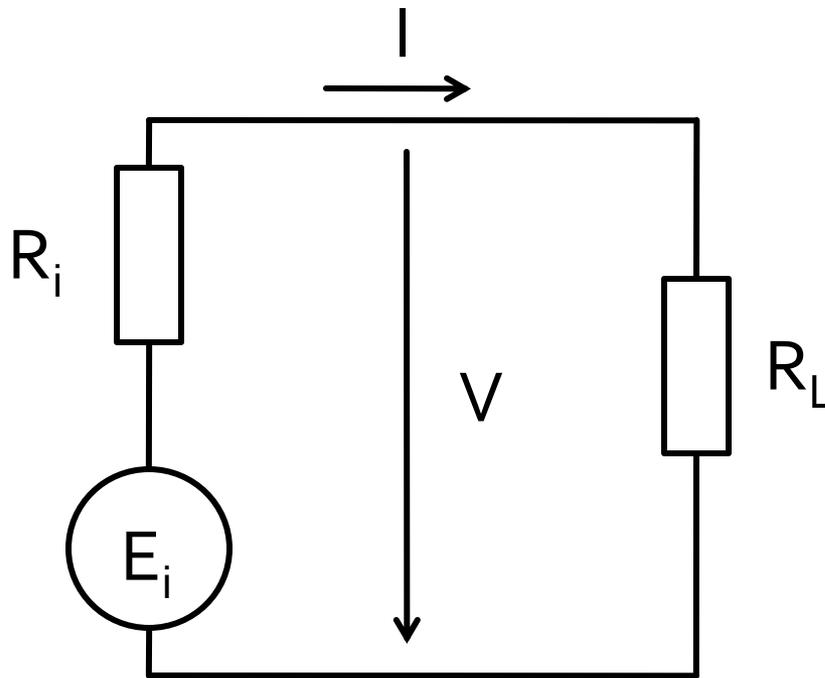
- Source matched to load ?



- impedance values ?
- existence of reflections ?

Matching, real impedances

- Source matched to load



$$I = \frac{E_i}{R_i + R_L}$$

$$V = \frac{E_i \cdot R_L}{R_i + R_L}$$

$$P_L = R_L \cdot I^2$$

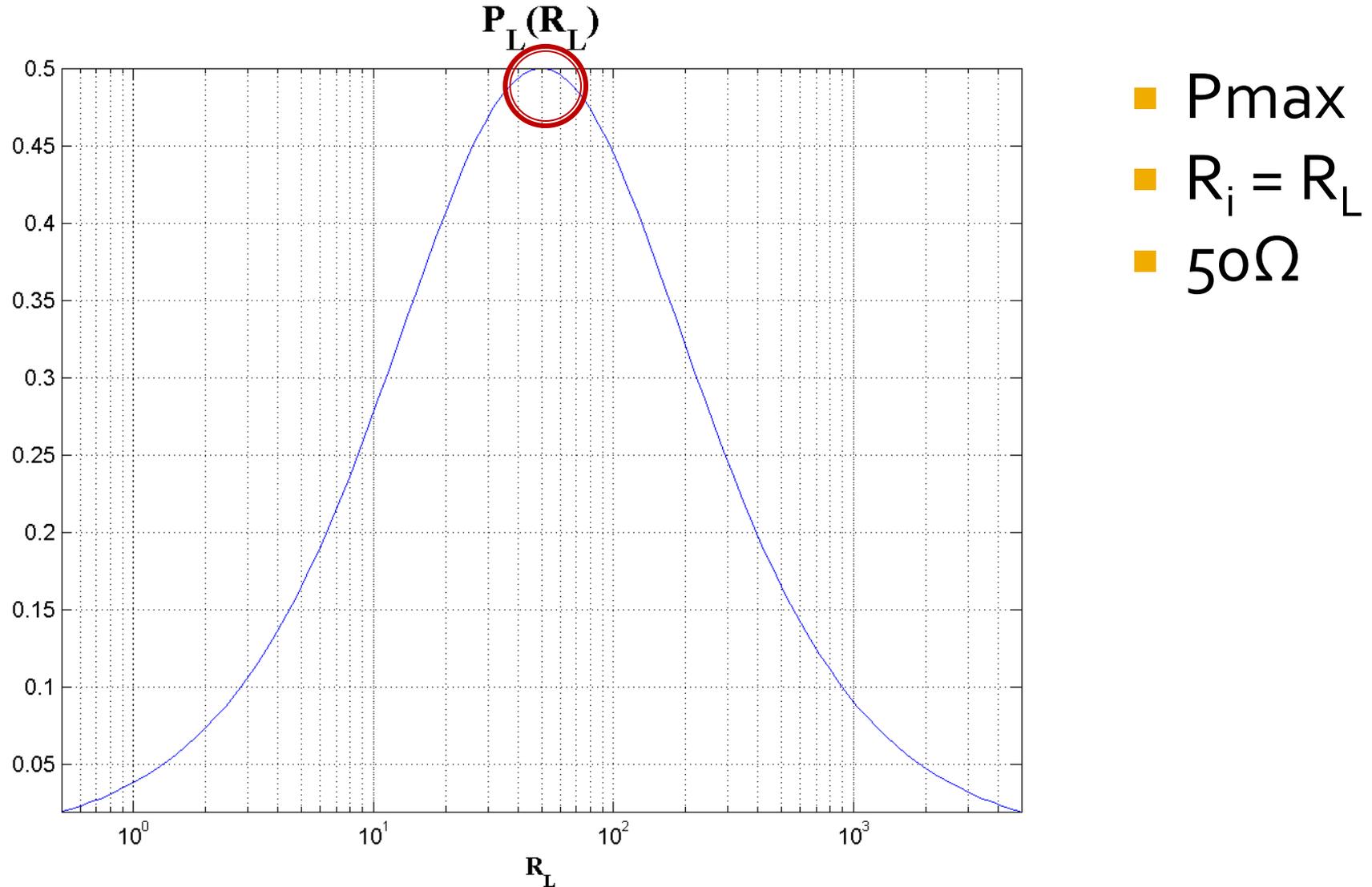
$$P_L = \frac{R_L \cdot E_i^2}{(R_i + R_L)^2}$$

Matching, real impedances

$$P_L = R_L \cdot I^2 \quad P_L = \frac{R_L \cdot E_i^2}{(R_i + R_L)^2}$$

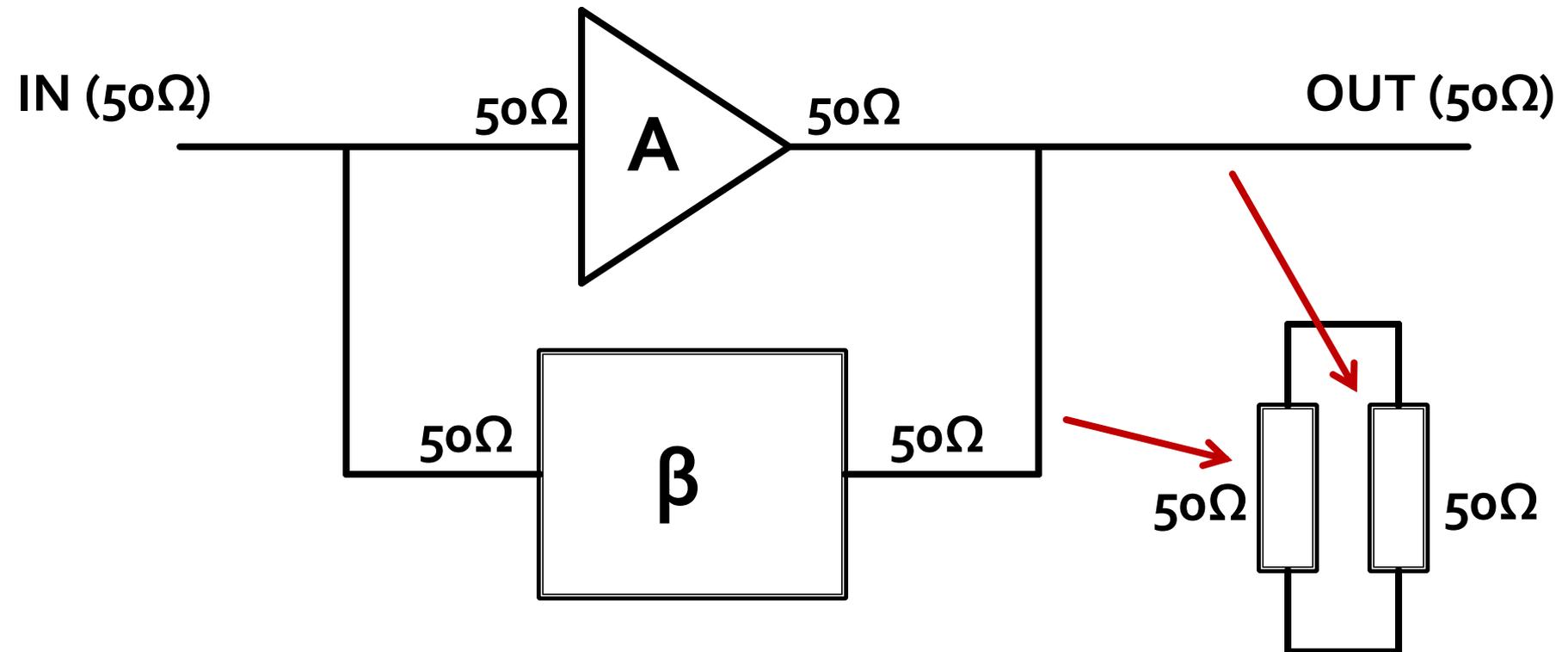
- Power dissipated on load
 - $R_i = 50\Omega$
 - $R_L = 0 \rightarrow P_L = 0$
 - $R_L = \infty \rightarrow P_L = 0$

Matching, real impedances

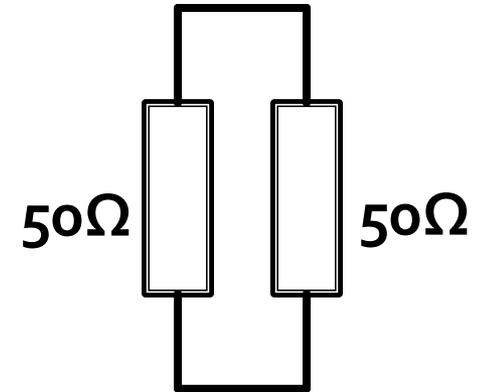
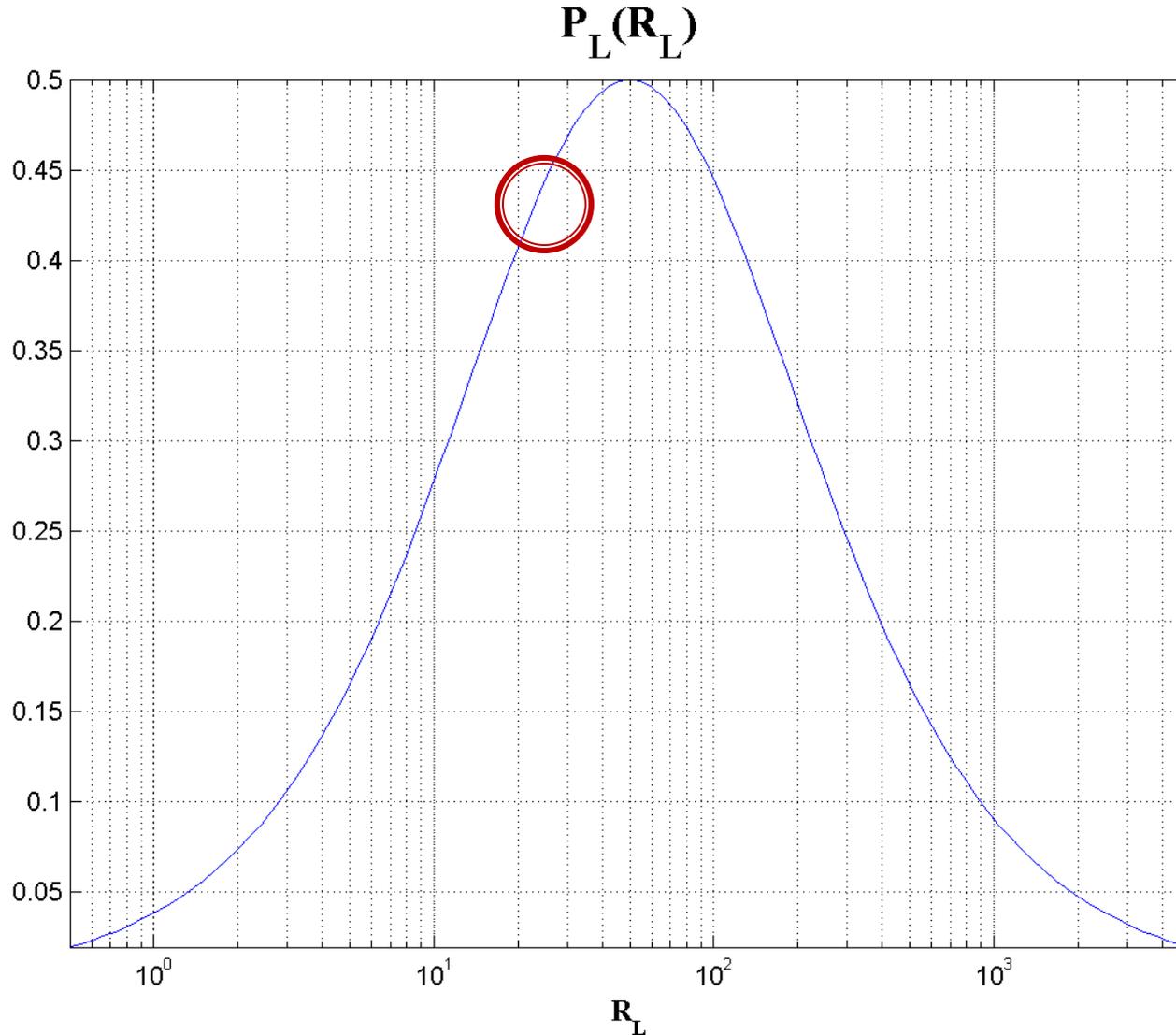


Matching

- feedback amplifier



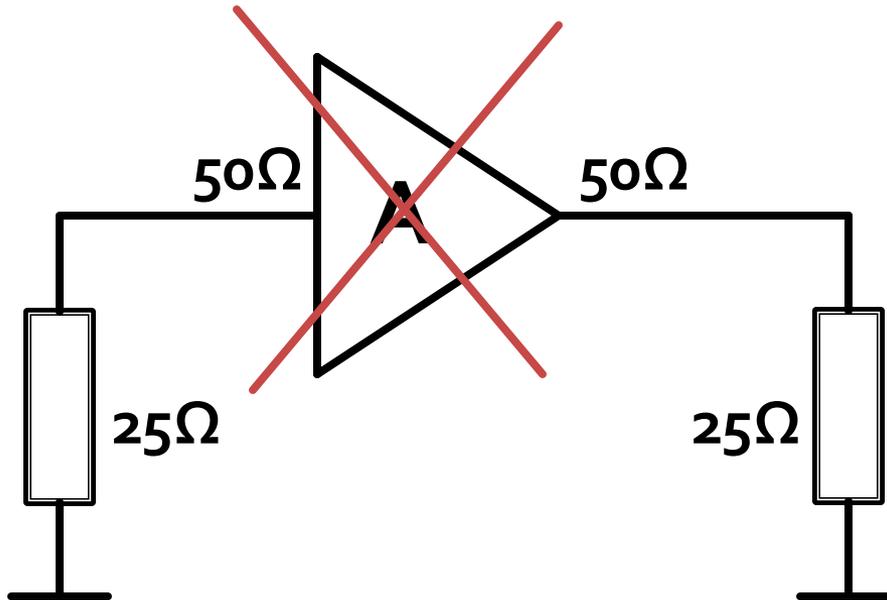
Adaptare , impedante reale



- 50Ω
- $50 \Omega || 50 \Omega = 25 \Omega$

Matching

- feedback amplifier



Power dividers and couplers

- Desired functionality:
 - division
 - combining
- of signal power

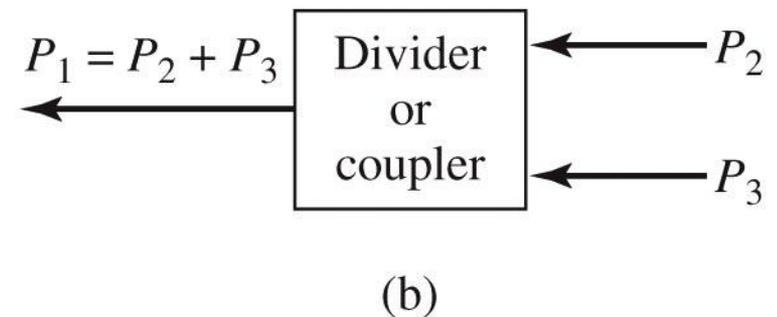
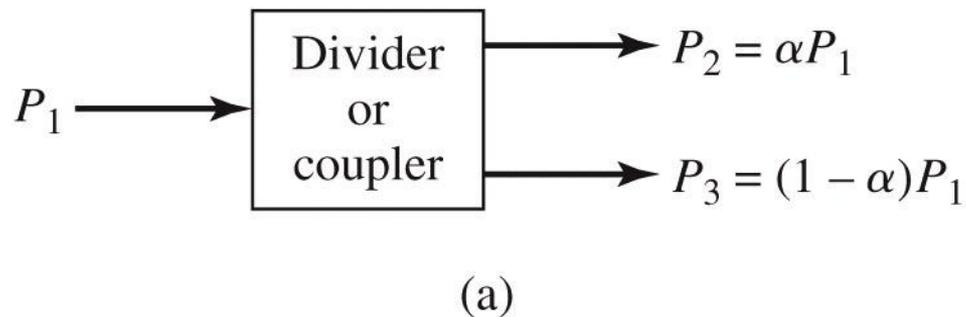


Figure 7.1
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Three-Port Networks

- also known as T-Junctions
- characterized by a 3×3 **S** matrix

$$[S] = \begin{bmatrix} S_{11} & S_{12} & S_{13} \\ S_{21} & S_{22} & S_{23} \\ S_{31} & S_{32} & S_{33} \end{bmatrix}$$

- the device is **reciprocal** if it does **not** contain:
 - anisotropic materials (usually ferrites)
 - active circuits
- to avoid power loss, we would like to have a network that is:
 - **lossless**, and
 - **matched at all ports**
 - to avoid reflection power “loss”

Three-Port Networks

$$[S] = \begin{bmatrix} 0 & S_{12} & S_{13} \\ S_{12} & 0 & S_{23} \\ S_{13} & S_{23} & 0 \end{bmatrix}$$

- 6 equations / 3 unknowns
 - **no solution is possible**
- A three-port network **cannot** be simultaneously:
 - reciprocal
 - lossless
 - matched at all ports

Four-Port Networks

- characterized by a 4×4 **S** matrix

$$[S] = \begin{bmatrix} S_{11} & S_{12} & S_{13} & S_{14} \\ S_{21} & S_{22} & S_{23} & S_{24} \\ S_{31} & S_{32} & S_{33} & S_{34} \\ S_{41} & S_{42} & S_{43} & S_{44} \end{bmatrix}$$

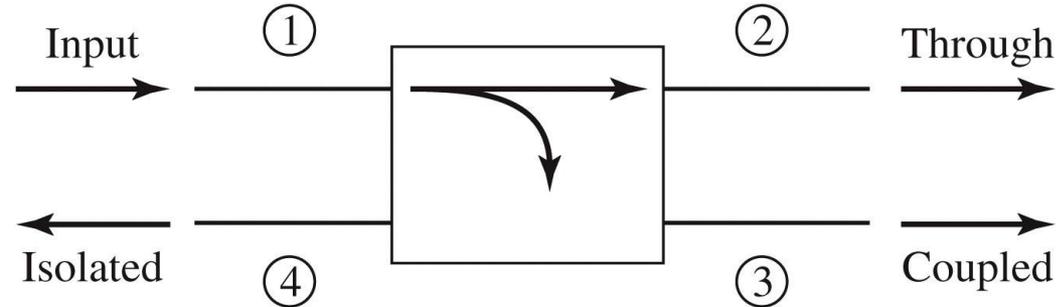
- the device is **reciprocal** if it does **not** contain:
 - anisotropic materials (usually ferrites)
 - active circuits
- to avoid power loss, we would like to have a network that is:
 - **lossless**, and
 - **matched at all ports**
 - to avoid reflection power “loss”

Four-Port Networks

- A four-port network simultaneously:
 - matched at all ports
 - reciprocal
 - lossless
- is **always directional**
 - the signal power injected into one port is transmitted **only towards two** of the other three ports

$$[S] = \begin{bmatrix} 0 & \alpha & \beta \cdot e^{j\theta} & 0 \\ \alpha & 0 & 0 & \beta \cdot e^{j\phi} \\ \beta \cdot e^{j\theta} & 0 & 0 & \alpha \\ 0 & \beta \cdot e^{j\phi} & \alpha & 0 \end{bmatrix}$$

Directional Coupler



$$|S_{12}|^2 = \alpha^2 = 1 - \beta^2$$

$$|S_{13}|^2 = \beta^2$$

Coupling

$$C = 10 \log \frac{P_1}{P_3} = -20 \cdot \log(\beta) [\text{dB}]$$

Directivity

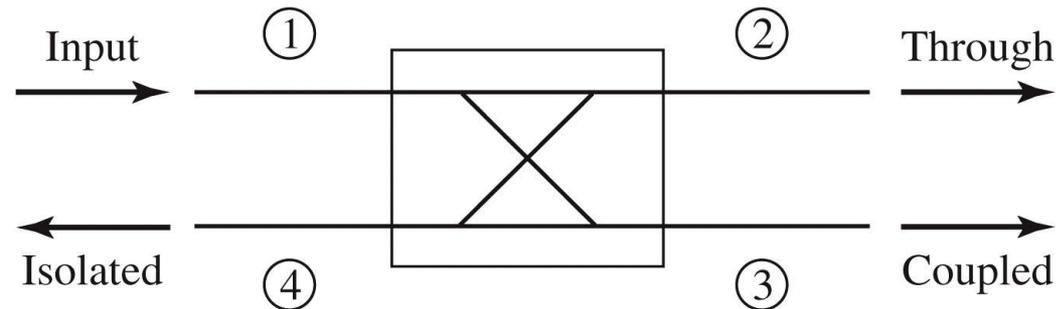
$$D = 10 \log \frac{P_3}{P_4} = 20 \cdot \log \left(\frac{\beta}{|S_{14}|} \right) [\text{dB}]$$

Isolation

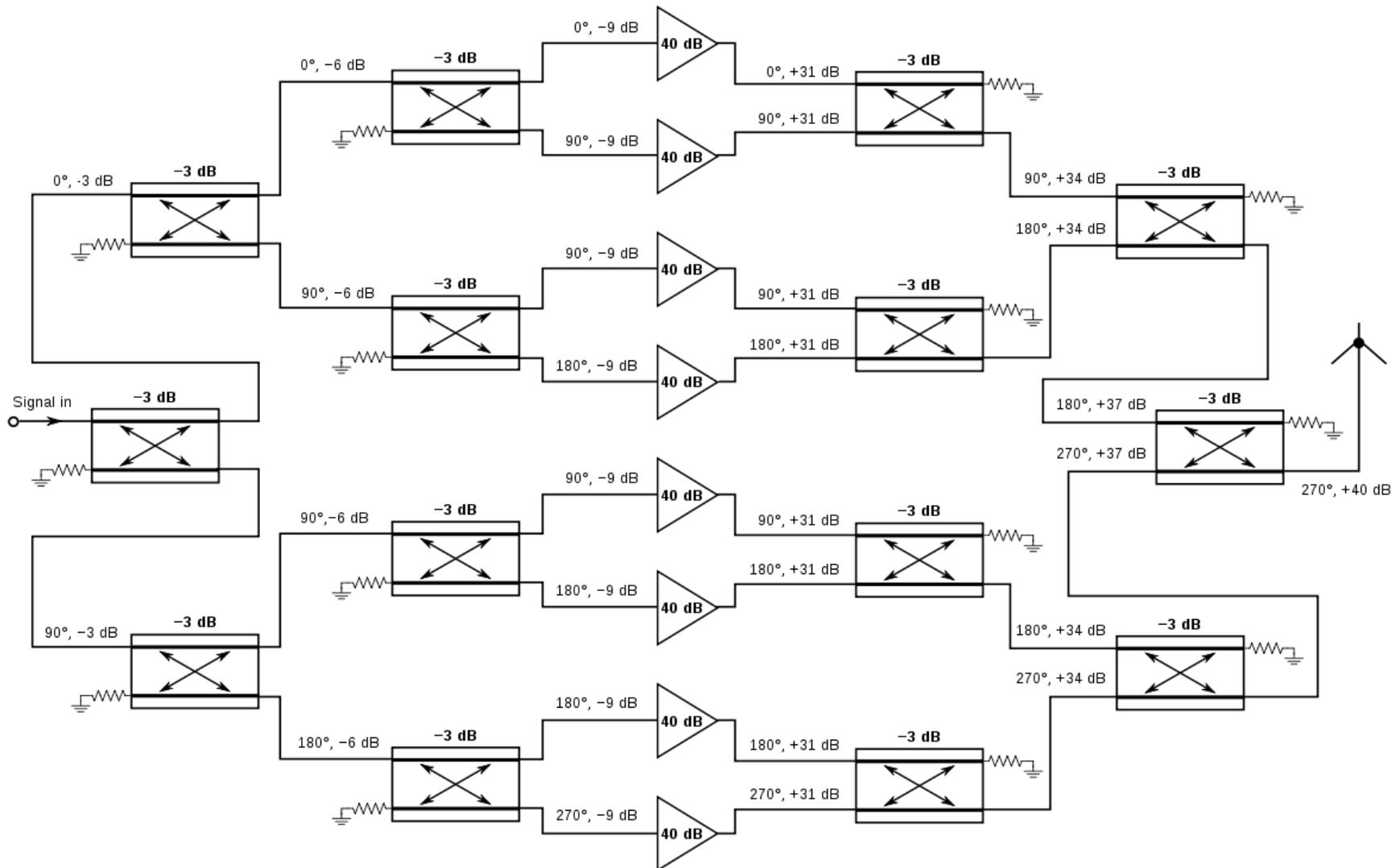
$$I = 10 \log \frac{P_1}{P_4} = -20 \cdot \log |S_{14}| [\text{dB}]$$

$$I = D + C, \text{ dB}$$

Figure 7.4
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Balanced amplifiers



The quadrature (90°) hybrid

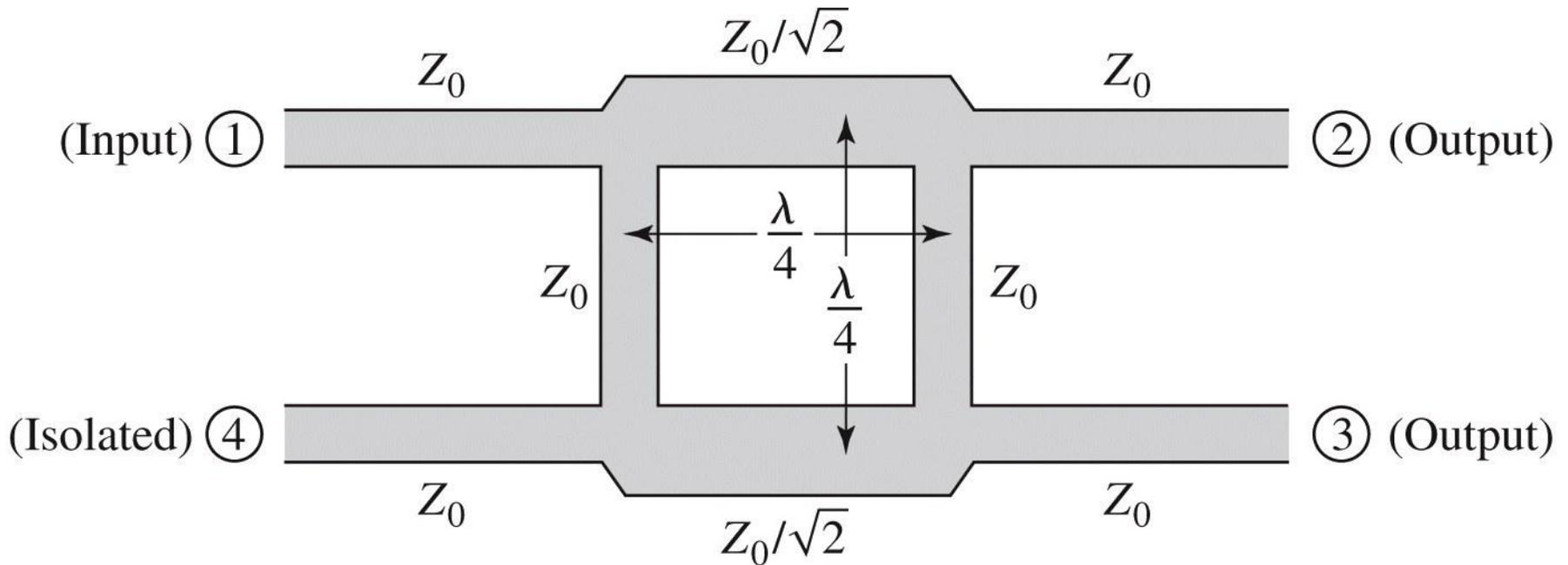
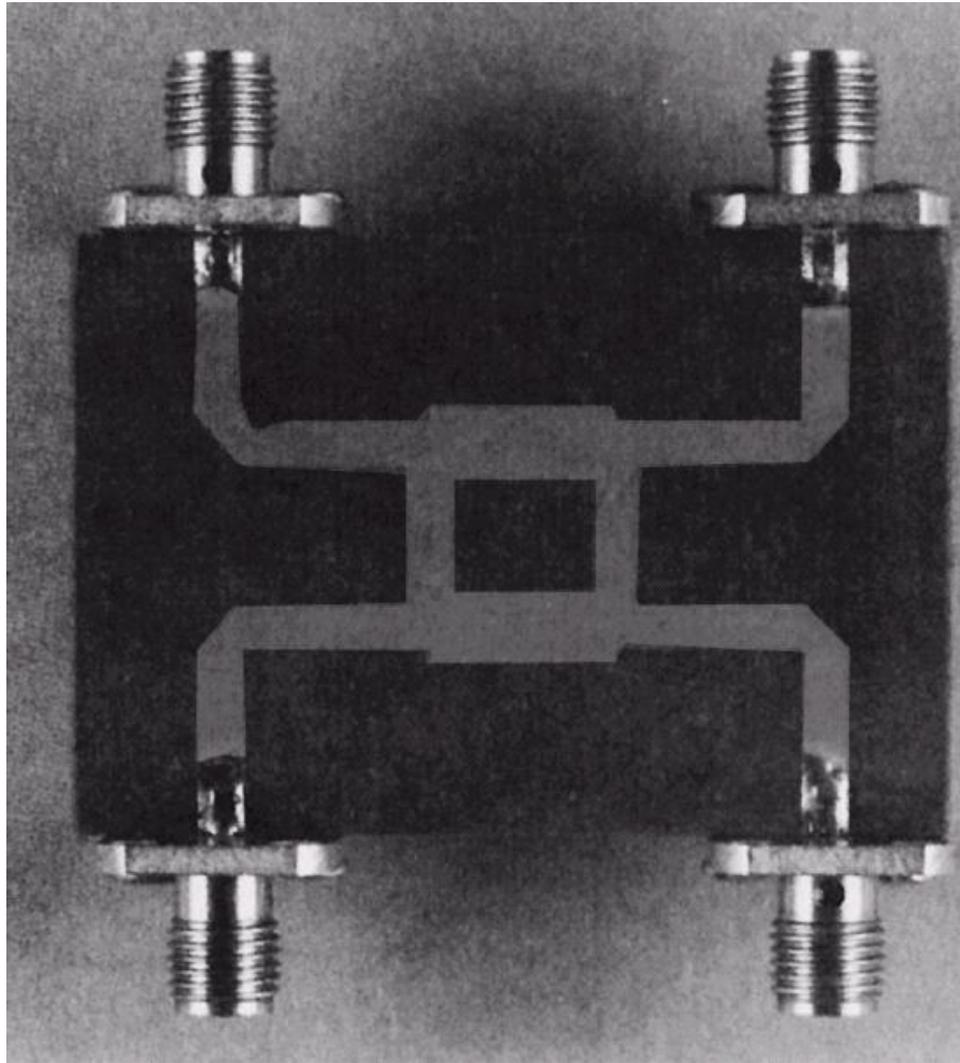


Figure 7.21
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$$[S] = \frac{-1}{\sqrt{2}} \begin{bmatrix} 0 & j & 1 & 0 \\ j & 0 & 0 & 1 \\ 1 & 0 & 0 & j \\ 0 & 1 & j & 0 \end{bmatrix}$$

The quadrature (90°) hybrid



The quadrature (90°) hybrid

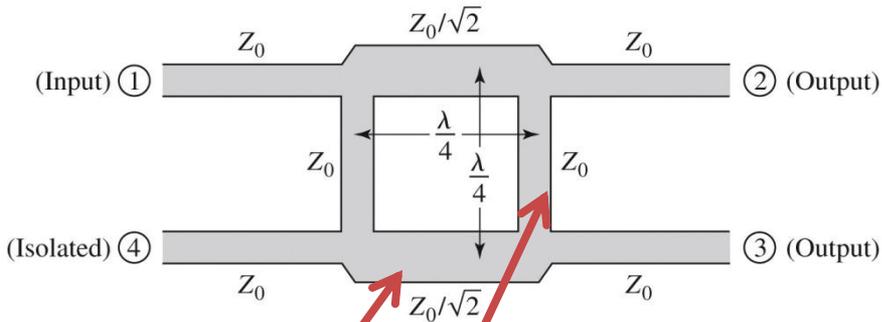


Figure 7.21
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$$y_2^2 = 1 + y_1^2$$

$$|\beta| = \frac{\sqrt{y_2^2 - 1}}{y_2}$$

$$C[\text{dB}] = -20 \cdot \log_{10} \frac{\sqrt{y_2^2 - 1}}{y_2}$$

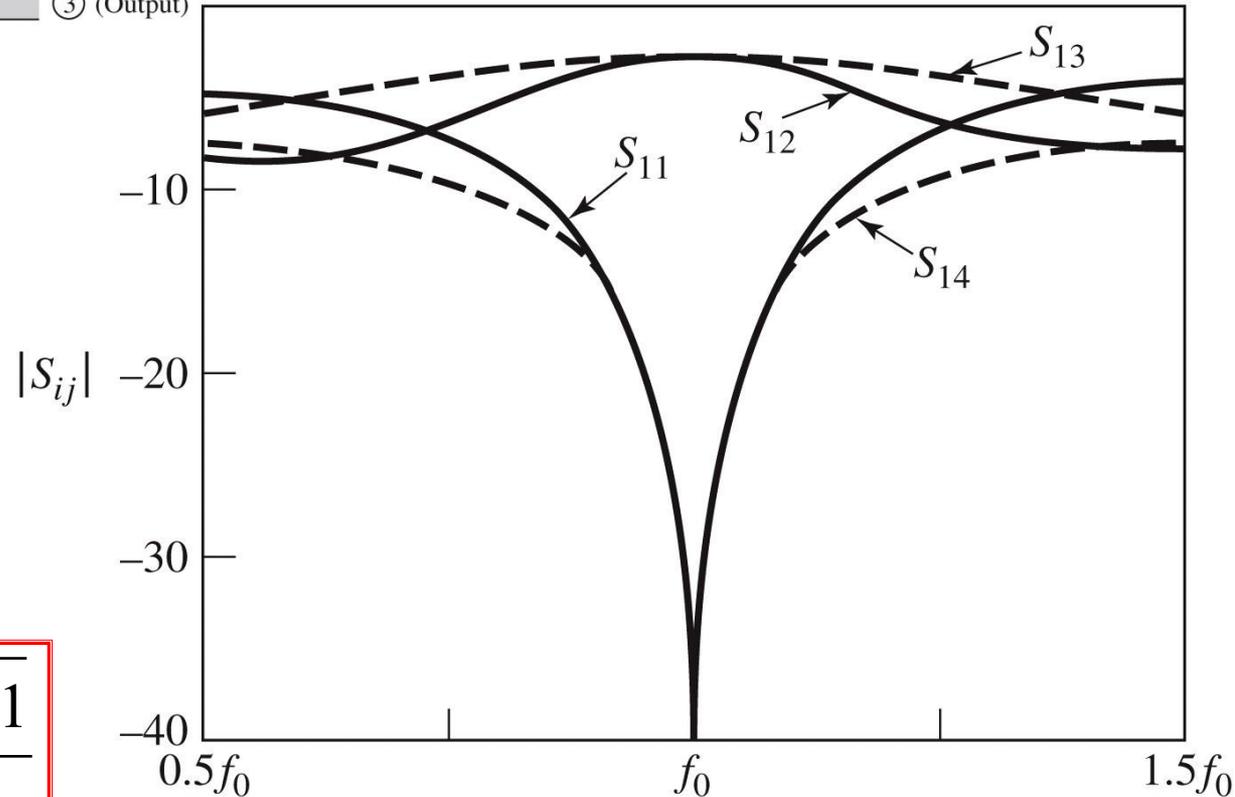
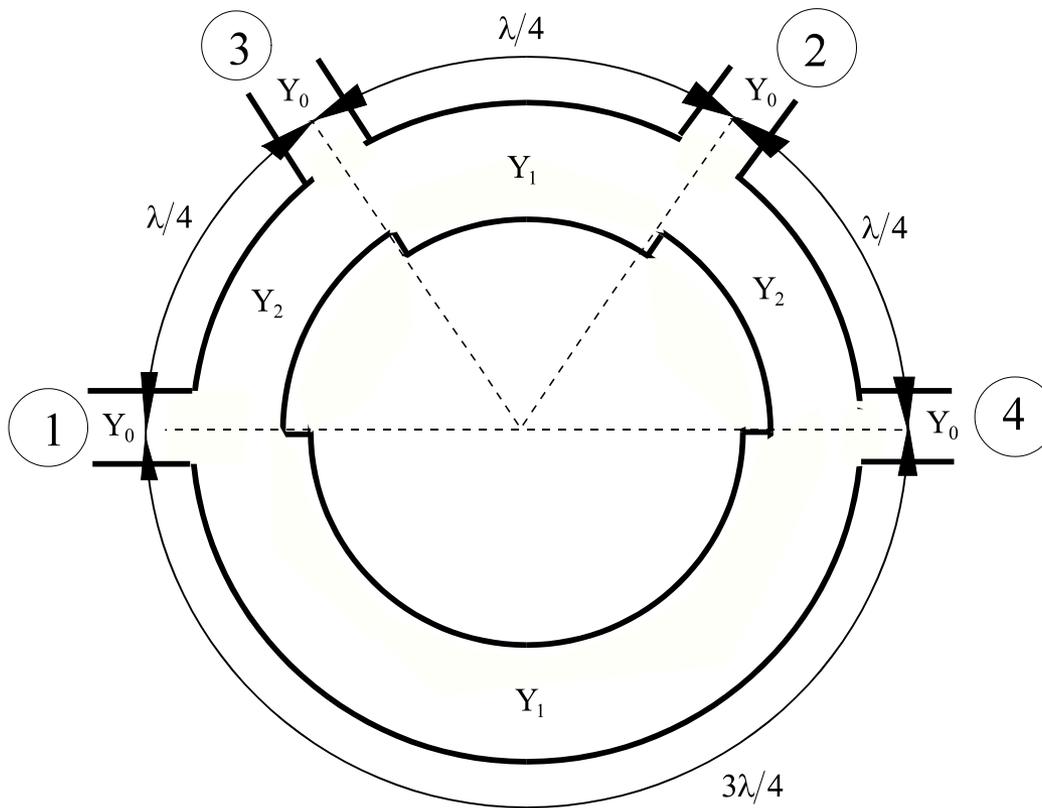


Figure 7.25
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The 180° ring hybrid (rat-race)



The 180° ring hybrid (rat-race)

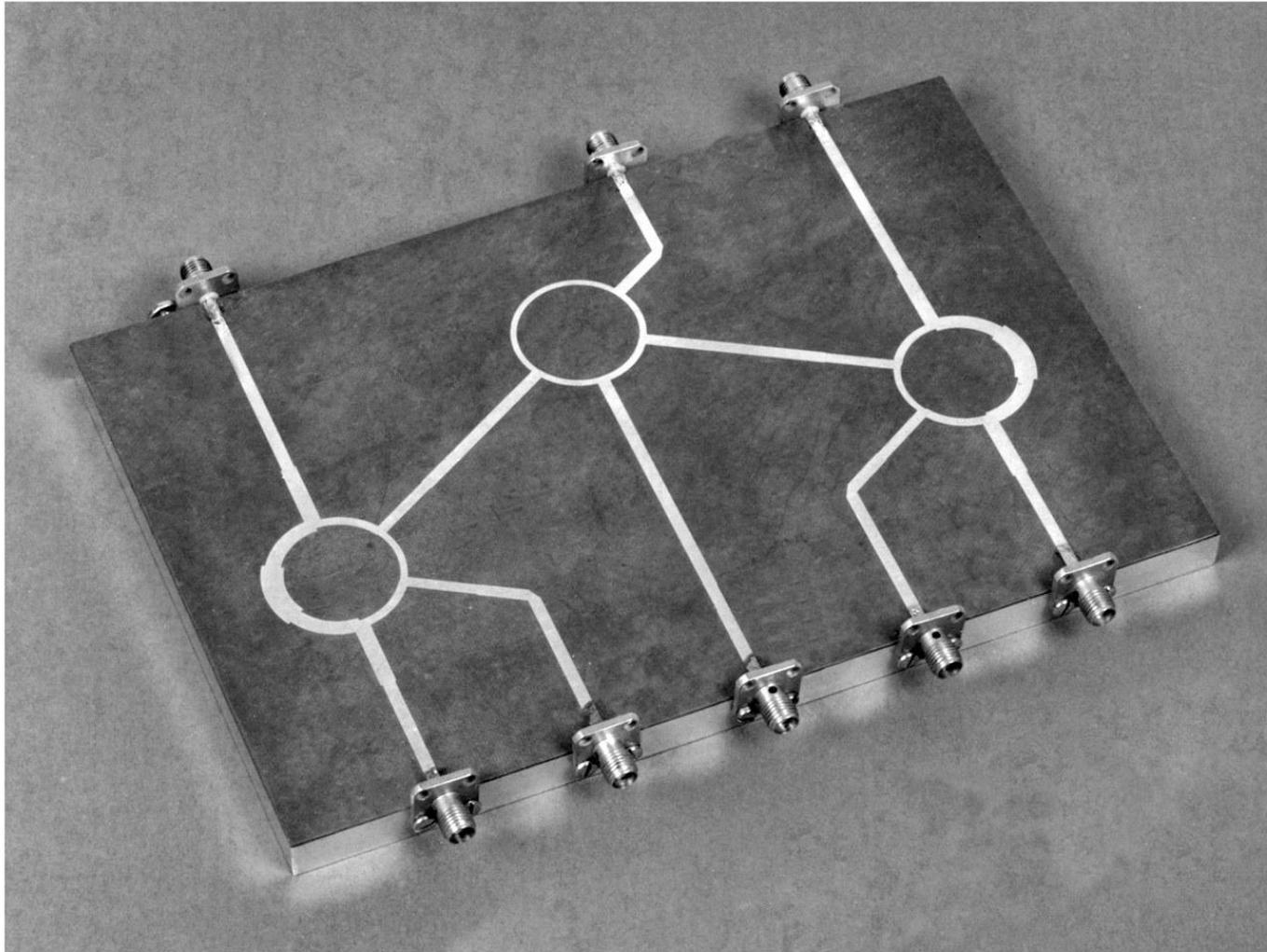
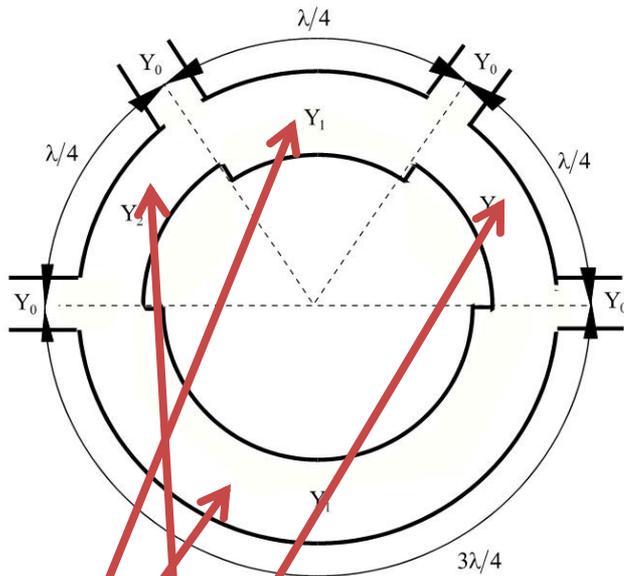


Figure 7.43
Courtesy of M. D. Abouzahra, MIT Lincoln Laboratory, Lexington, Mass.

The 180° ring hybrid (rat-race)



$$y_1^2 + y_2^2 = 1$$

$$|\beta| = y_1$$

$$C \text{ [dB]} = -20 \cdot \log_{10}(y_1)$$

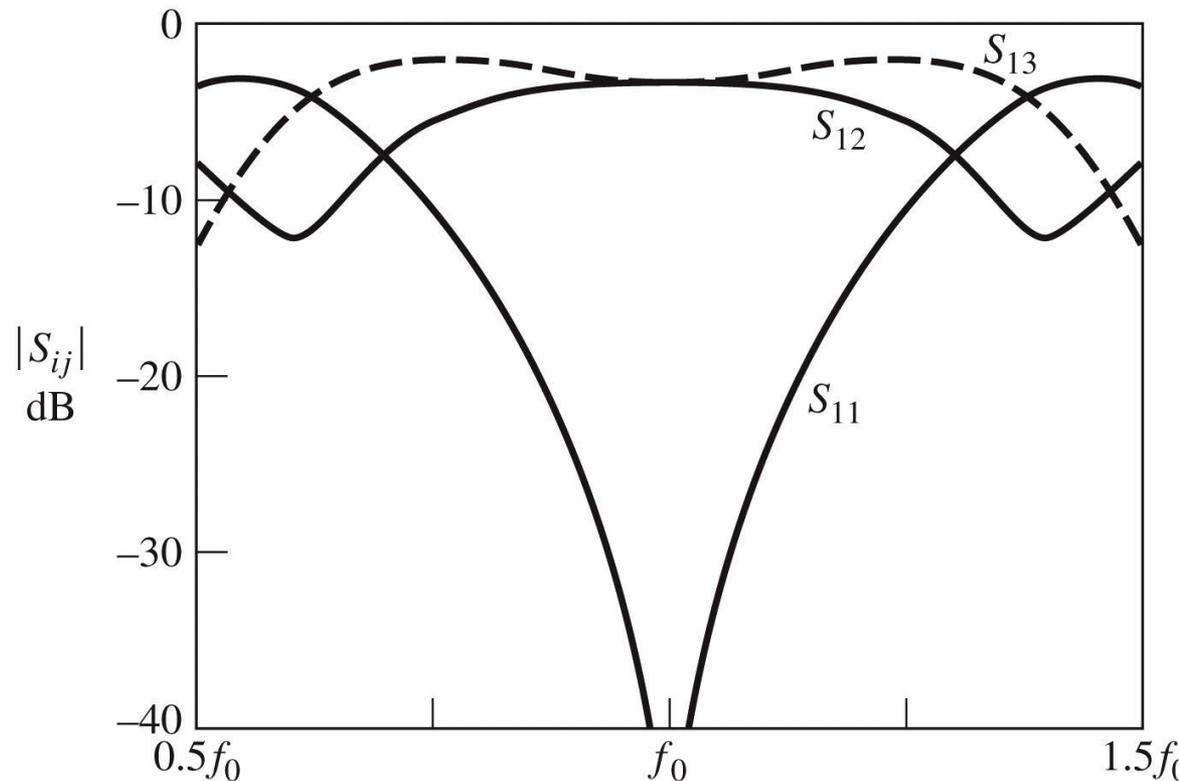


Figure 7.46
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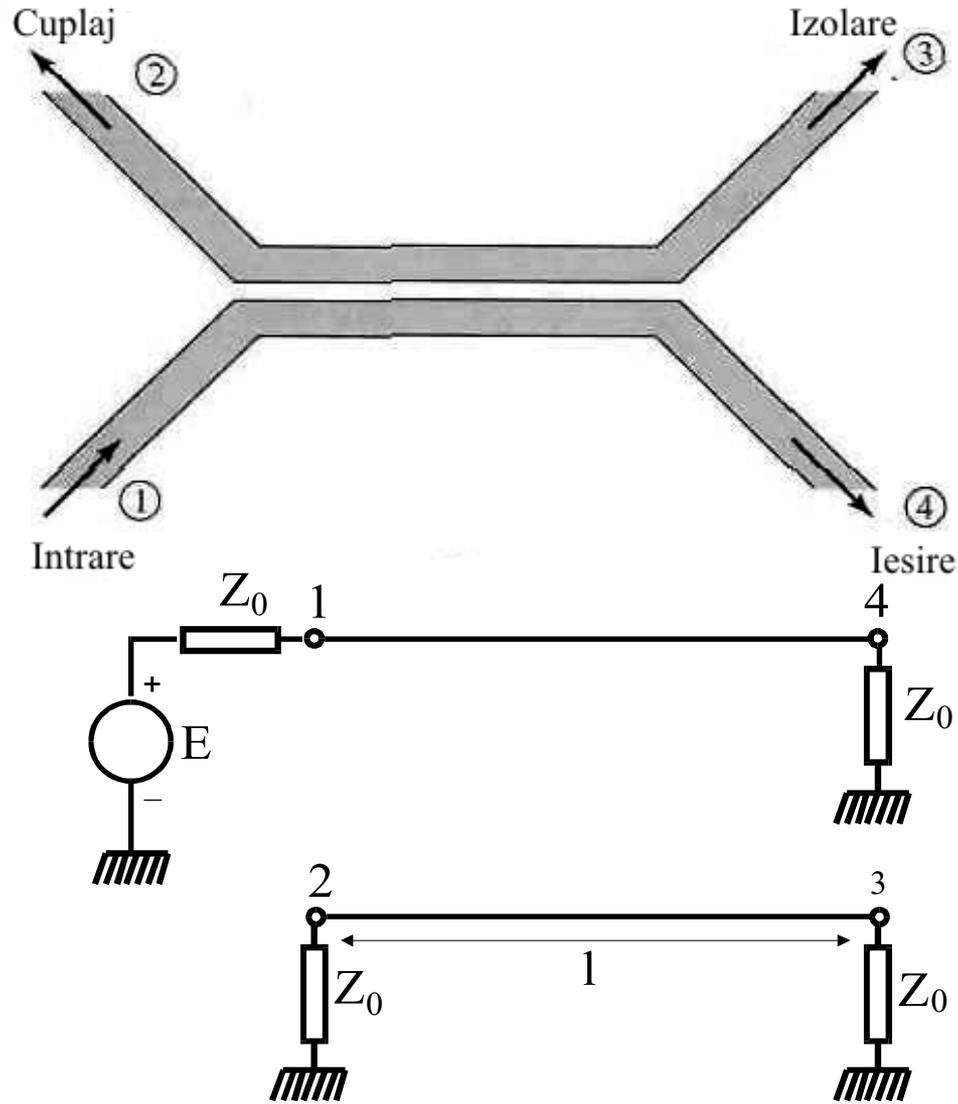
Network Analysis

- Each matrix is best suited for a particular mode of port excitation (V, I)
 - matrix H in common emitter connection for TB: I_B, V_{CE}
 - matrices provide the associated quantities depending on the “attack” ones
- Traditional notation of Z, Y, G, H parameters is in lowercase (z, y, g, h)
- In microwave analysis we prefer the notation in uppercase to avoid confusion with the **normalized parameters**

$$z = \frac{Z}{Z_0} \quad y = \frac{Y}{Y_0} = \frac{1/Z}{1/Z_0} = \frac{Z_0}{Z} = Z_0 \cdot Y$$

$$z_{11} = \frac{Z_{11}}{Z_0} \quad y_{11} = \frac{Y_{11}}{Y_0} = Z_0 \cdot Y_{11}$$

Coupled Line Coupler



Coupled Lines

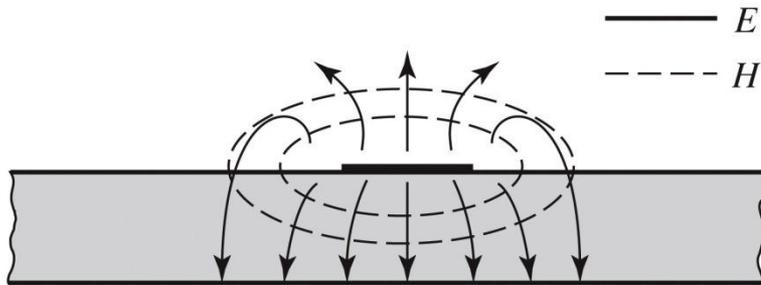
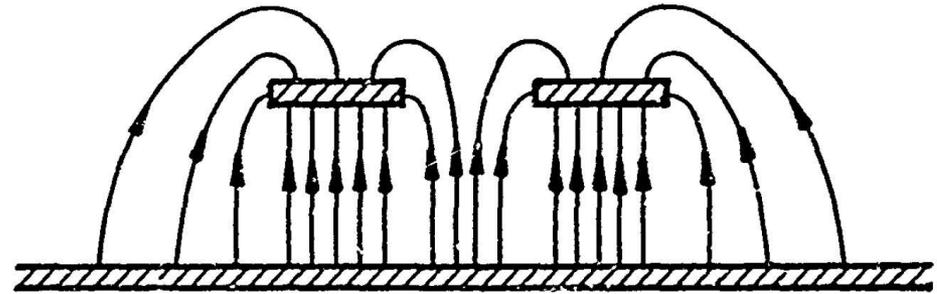
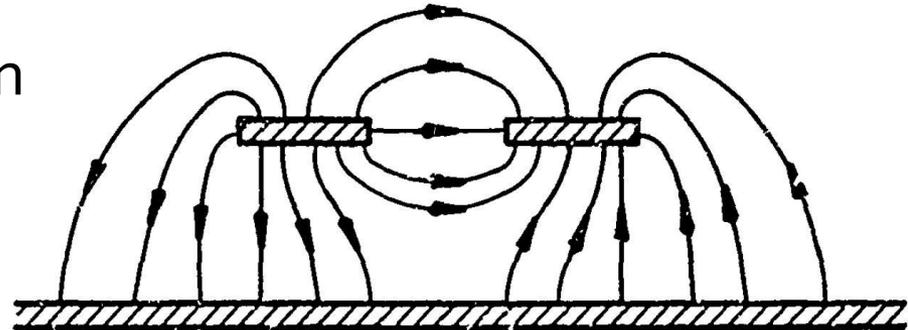


Figure 3.25b
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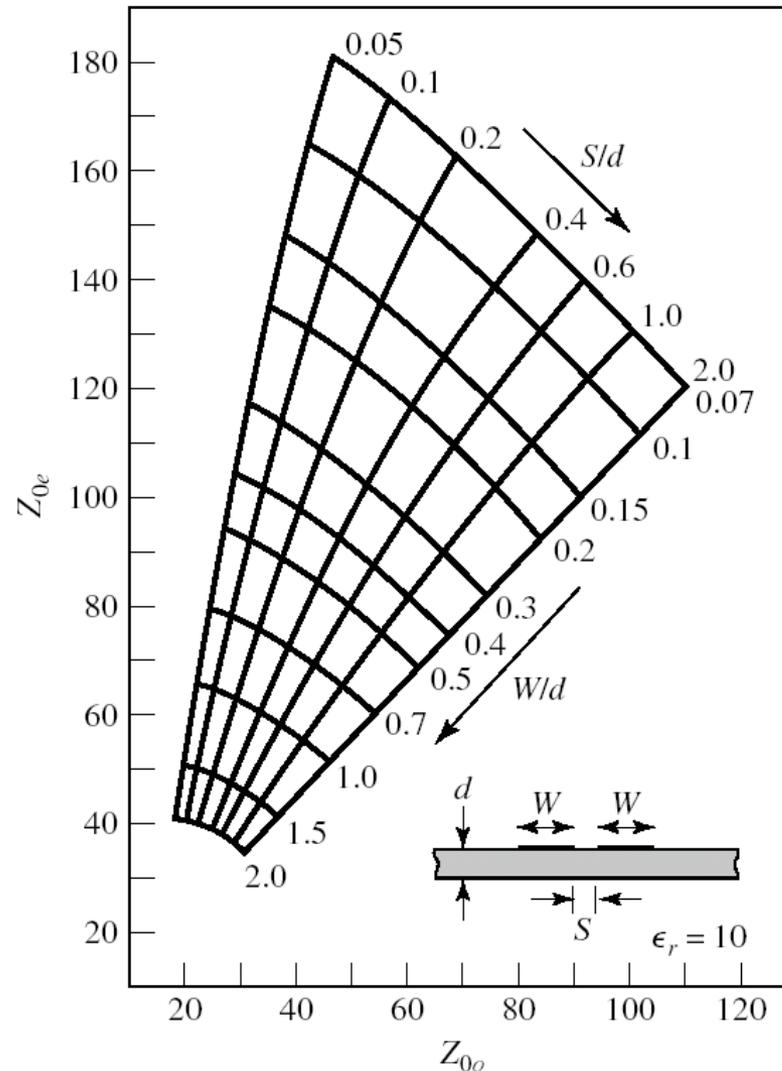
b) EVEN MODE ELECTRIC FIELD PATTERN (SCHEMATIC)



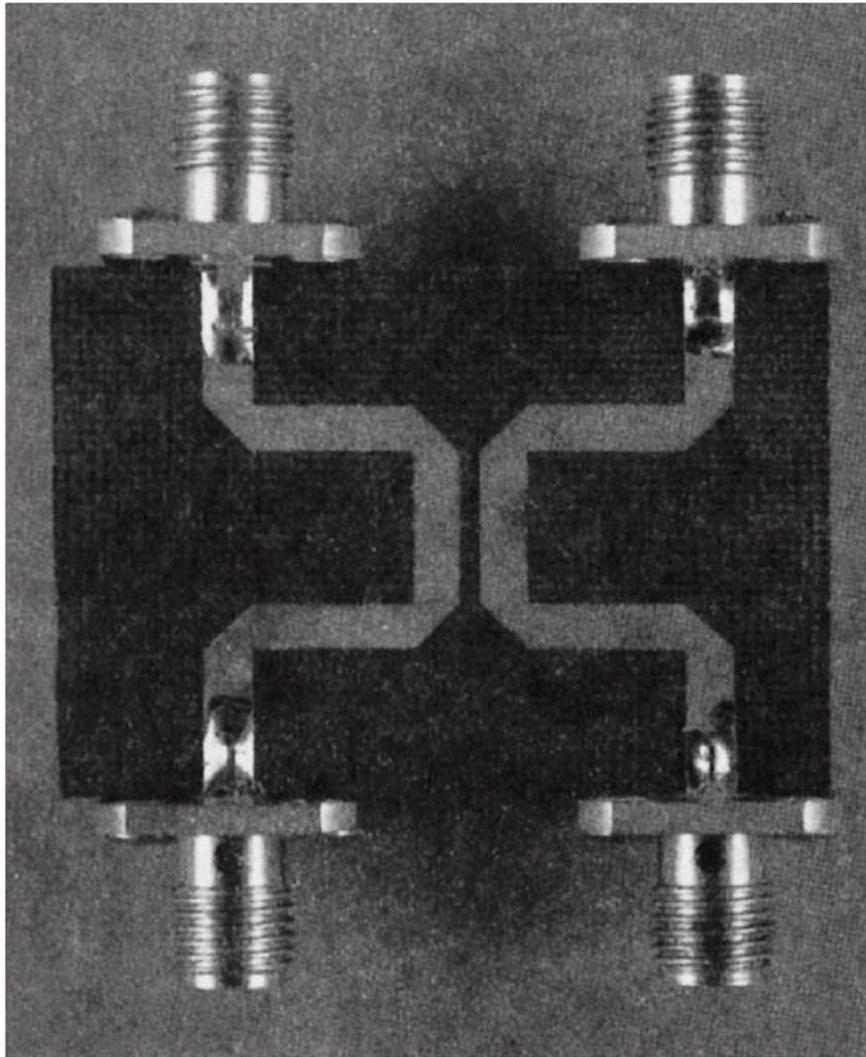
c) ODD MODE ELECTRIC FIELD PATTERN (SCHEMATIC)

- Even mode - characterizes the common mode signal on the two lines
- Odd mode - characterizes the differential mode signal between the two lines
- Each of the two modes is characterized by **different** characteristic impedances

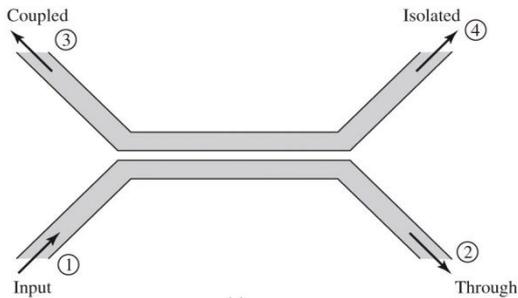
Even- and odd-mode characteristic impedance design data for coupled microstrip lines on a substrate with $\epsilon_r = 10$.



Coupled Line Coupler



Coupled Line Coupler



Coupling, Directivity (dB)

$$Z_{ce} Z_{co} = Z_0^2$$

$$|\beta| = \frac{Z_{ce} - Z_{co}}{Z_{ce} + Z_{co}}$$

$$C [\text{dB}] = -20 \cdot \log_{10} \left(\frac{Z_{ce} - Z_{co}}{Z_{ce} + Z_{co}} \right)$$

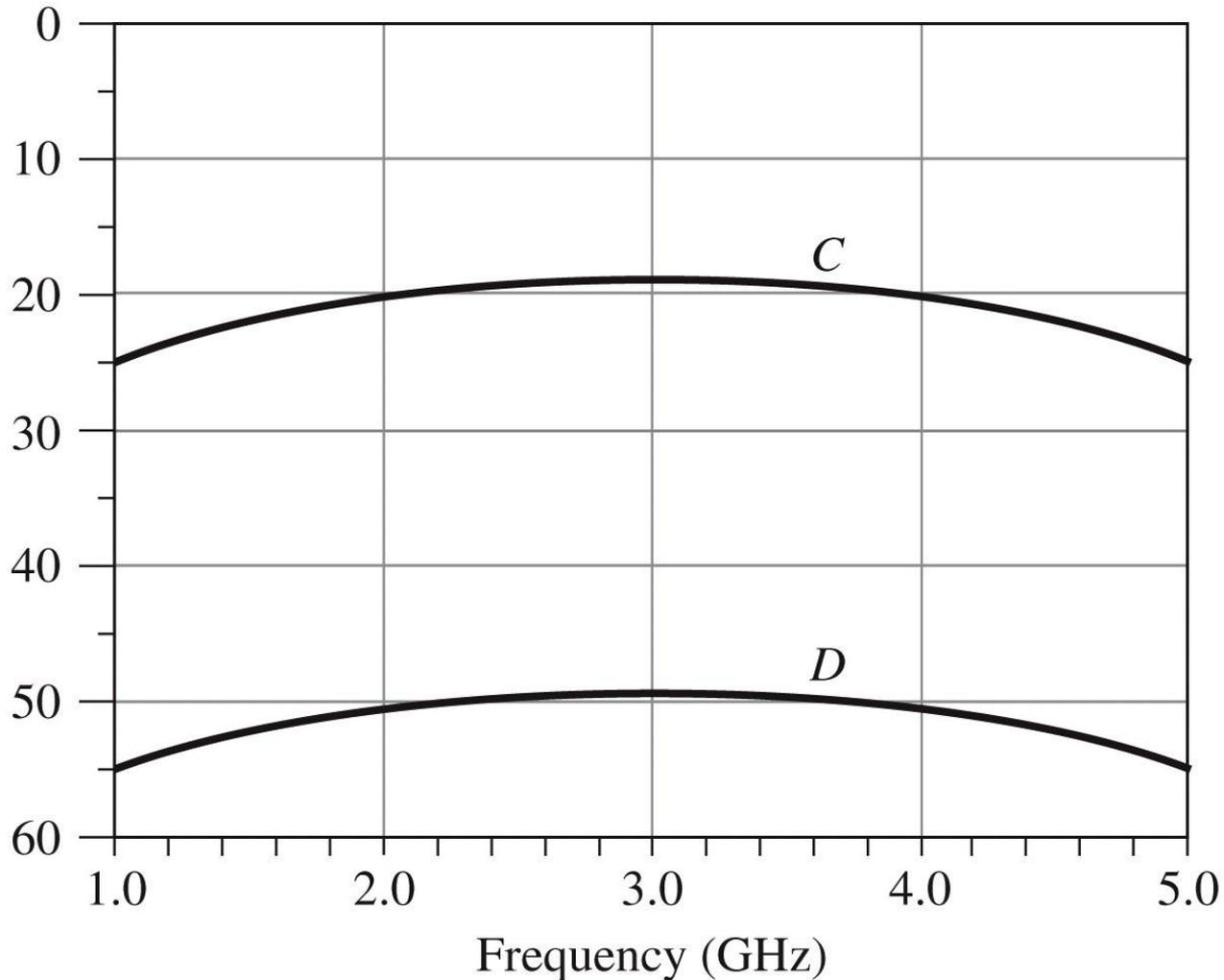


Figure 7.34
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Practical Procedure

Step 0

- Write by hand on a sheet of paper 100 times:
- **I solemnly promise to read the text
AND NOT to jump from picture to
picture**
- 😊

Step 0

- Log in on rf-opto
- Join the exam “Laboratory 2”
- Write down your **individual** data

Step 1

- Design/Compute the couplers
- Unlike lab 1 tuning **will not** be required
 - if the desired behavior is not obtained, check and/or repeat the computations
 - any attempt to compensate for the accuracy of the computations by tuning is **useless**

Step 1

- Please note that all examples in the lab manual are for **3dB** couplers (1/2: 1/2)
- In particular

$$\beta = 10^{-3/20} = \frac{1}{\sqrt{2}} = 0.7071$$

- Because your value is not 3dB (~~3dB~~), no 2 or $\sqrt{2}$ will appear in design relations and you must compute

$$\beta = 10^{-C[dB]/20} = \dots$$

Step 2

- Draw the schematic (identical with the one from the lab manual, excepting numerical values for TLines)
 - **WARNING!** For the first two couplers the relations provide the normalized admittances of the lines (y_1 and y_2) while in the schematic you must input the characteristic impedances

$$Z = \frac{Z_0}{y} \begin{cases} \rightarrow Z_1 = \frac{50\Omega}{y_1} \\ \rightarrow Z_2 = \frac{50\Omega}{y_2} \end{cases}$$

- **WARNING!** For the first two couplers the line impedances are equal two by two (diagonally) so you compute 2 values and insert 4 transmission lines (2 Z_1 and 2 Z_2)

Step 3

- Choose a port as input and plot the output power on all ports (including the one chosen as input) with signal inserted **on the previously selected port**
 - if for example you chose **Term2** – port no. **2** as input, then plot $\text{dB}(S(1,2))$, $\text{dB}(S(2,2))$, $\text{dB}(S(3,2))$, $\text{dB}(S(4,2))$ to plot the output power on all 4 ports with signal inserted on port 2

Step 4

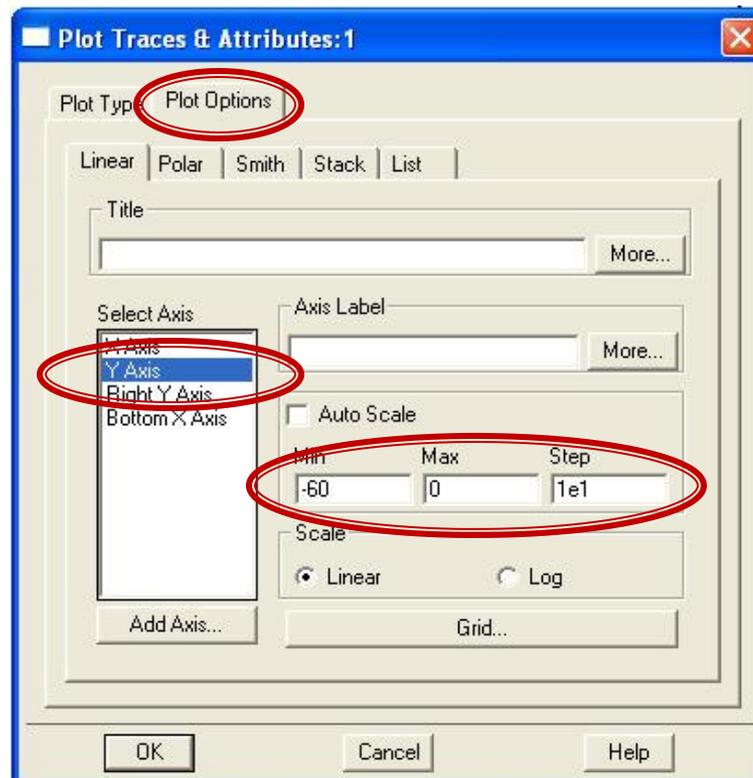
- If the results are not the desired ones, choose another port as input and repeat the plot procedure
 - desired results: at your frequency on 2 ports you get high values ($0 \div -10\text{dB}$ depending on the individual subject) and on the other 2 ports you get low values ($< -6\text{dB}$)
 - the couplers can be rotated usually so they function as couplers considering the input port in in more than one position

Step 5

- If necessary, **change** the y-axis scale for the plot
- The scale is logarithmic (dB), so, depending on the accuracy with which the calculations were made, impractical values can be obtained whose display is useless.
- Sufficient values are usually Min = -60, Max = 0, Step = 10 (remember that $10^{-60/10} = 0.000001$ enough accuracy most of the time)
 - for the coupled line coupler it may be necessary to have a lower Min (as in the example in the report ~ -110dB) or use two plots to display the results

Step 5

- To change the y-axis scale : double click on the plot, Plot Options tab, Y Axis, Min/Max/Step



Step 6

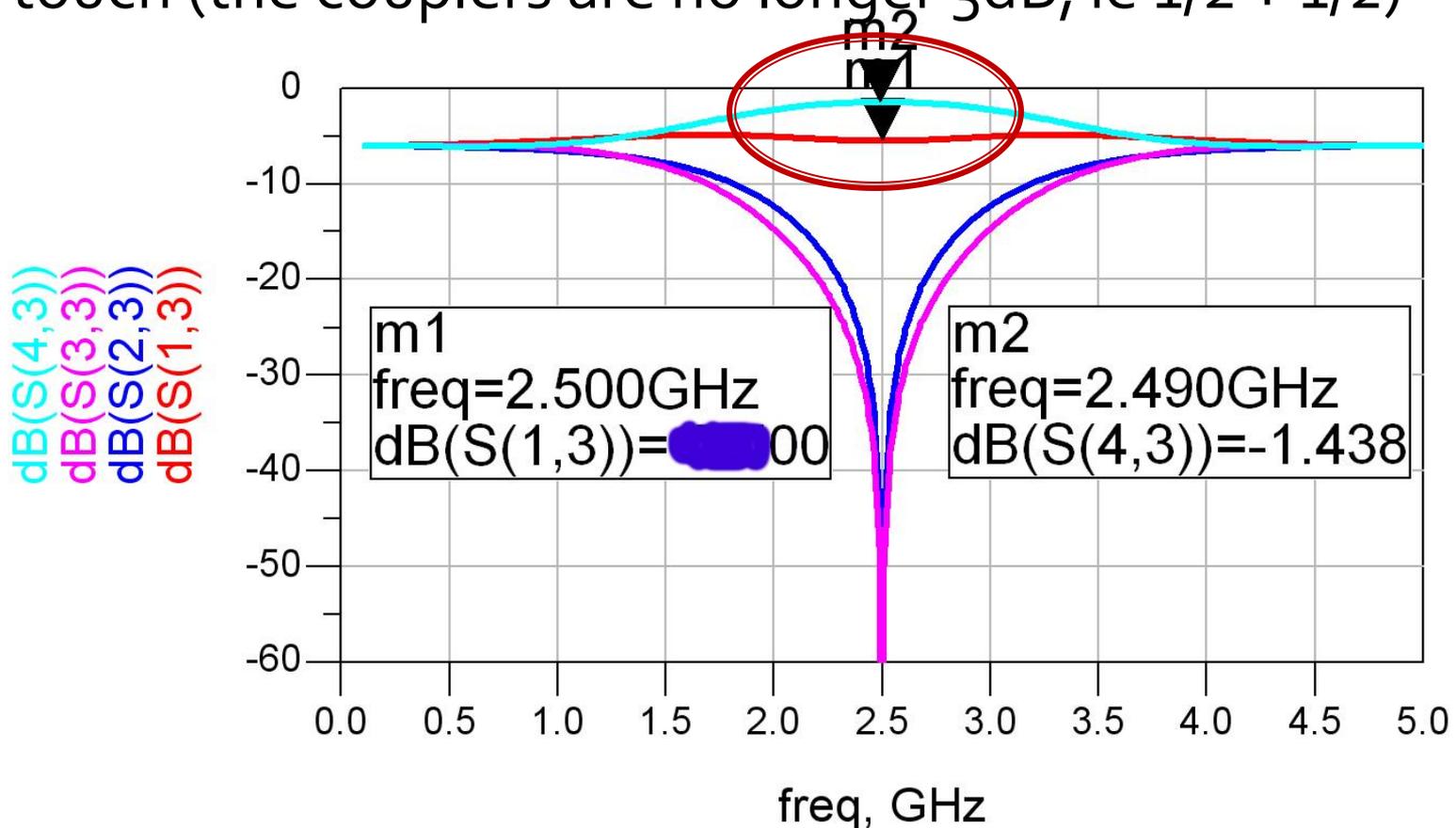
- Obtain 2 image files for uploading results to the server, one with the schematic and one with the plot (print screen or draw on paper then scan)

Step 7

- Correctly identify the ports in the results (identification must be submitted to the server)
- The text to be entered must be of the type: “3 – input, 4 – through, 1 – coupled, 2 – isolated” (the order is not important but consistency with plot and schematic **is**)

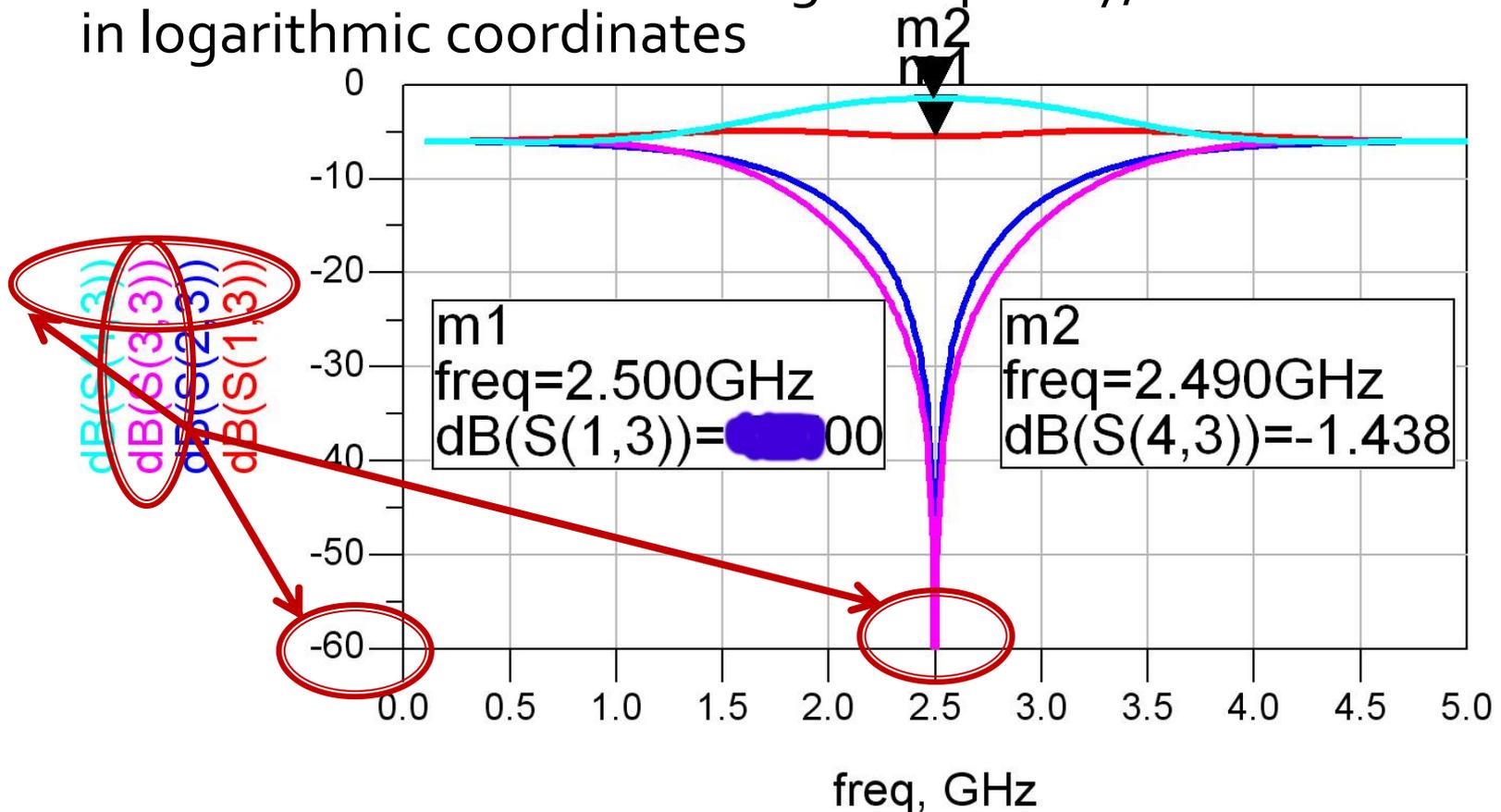
Step 7

- Note that the two curves with higher values no longer touch (the couplers are no longer 3dB, ie $1/2 \div 1/2$)



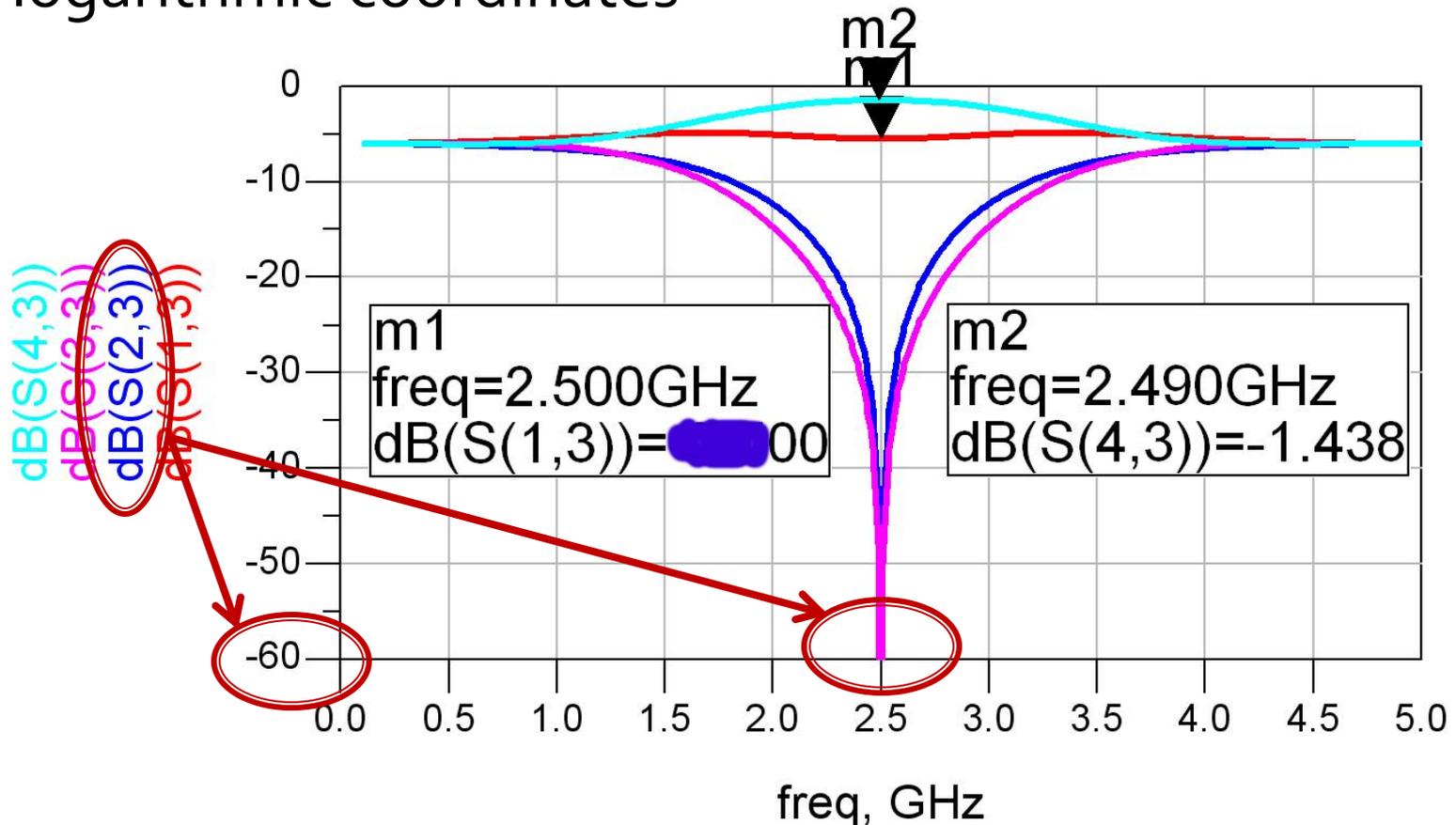
Step 7

- The **input** port is the second index, **common**, from the displayed results **and** $S(x, x)$ ($S(3,3)$ in next example) almost reaches 0 at the design frequency, ie $-X_0 \div X_{0dB}$ in logarithmic coordinates



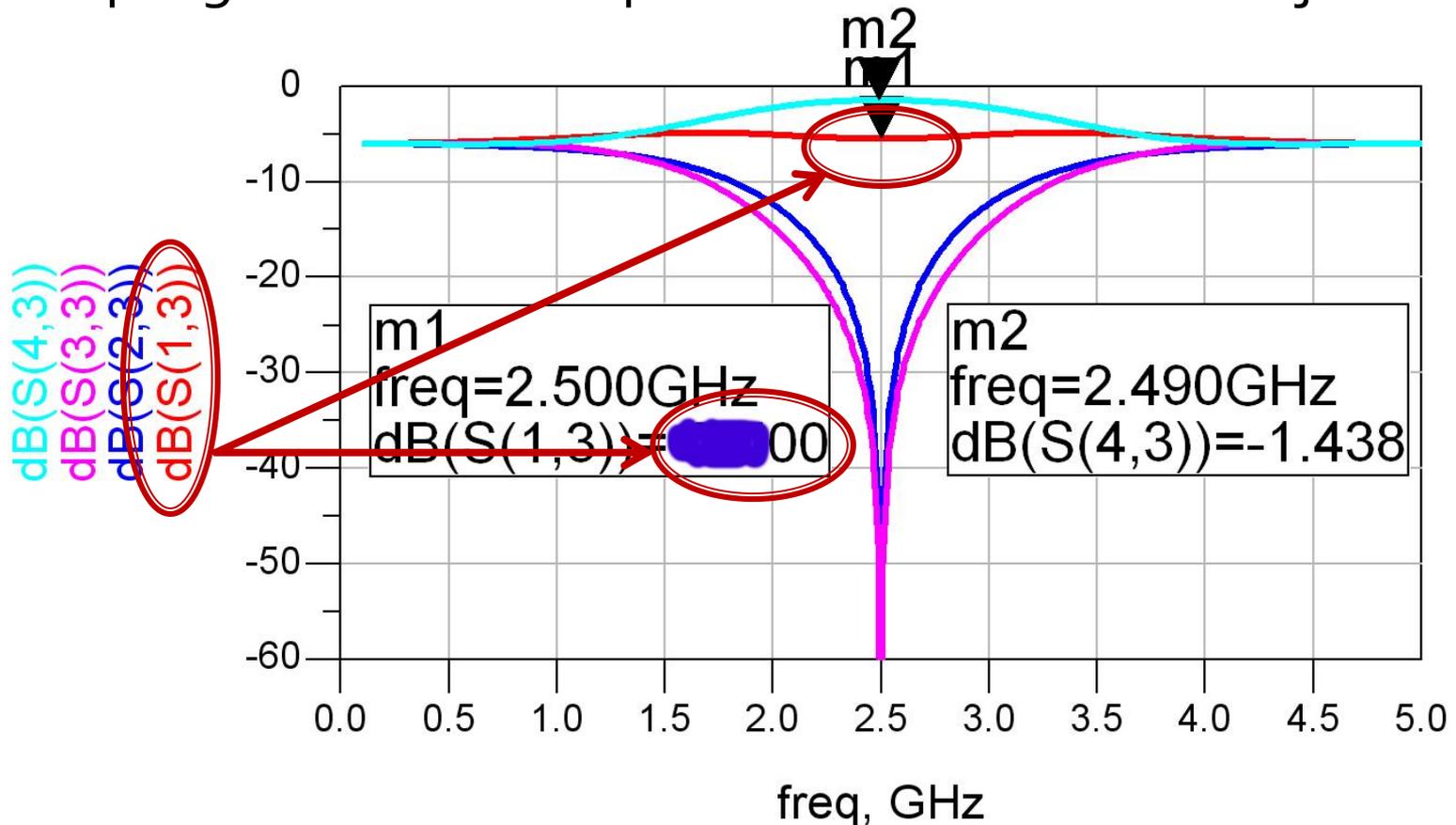
Step 7

- The **isolated** port is the second curve which almost reaches 0 at the design frequency, i.e. $-X_0 \div X_{00dB}$ in logarithmic coordinates



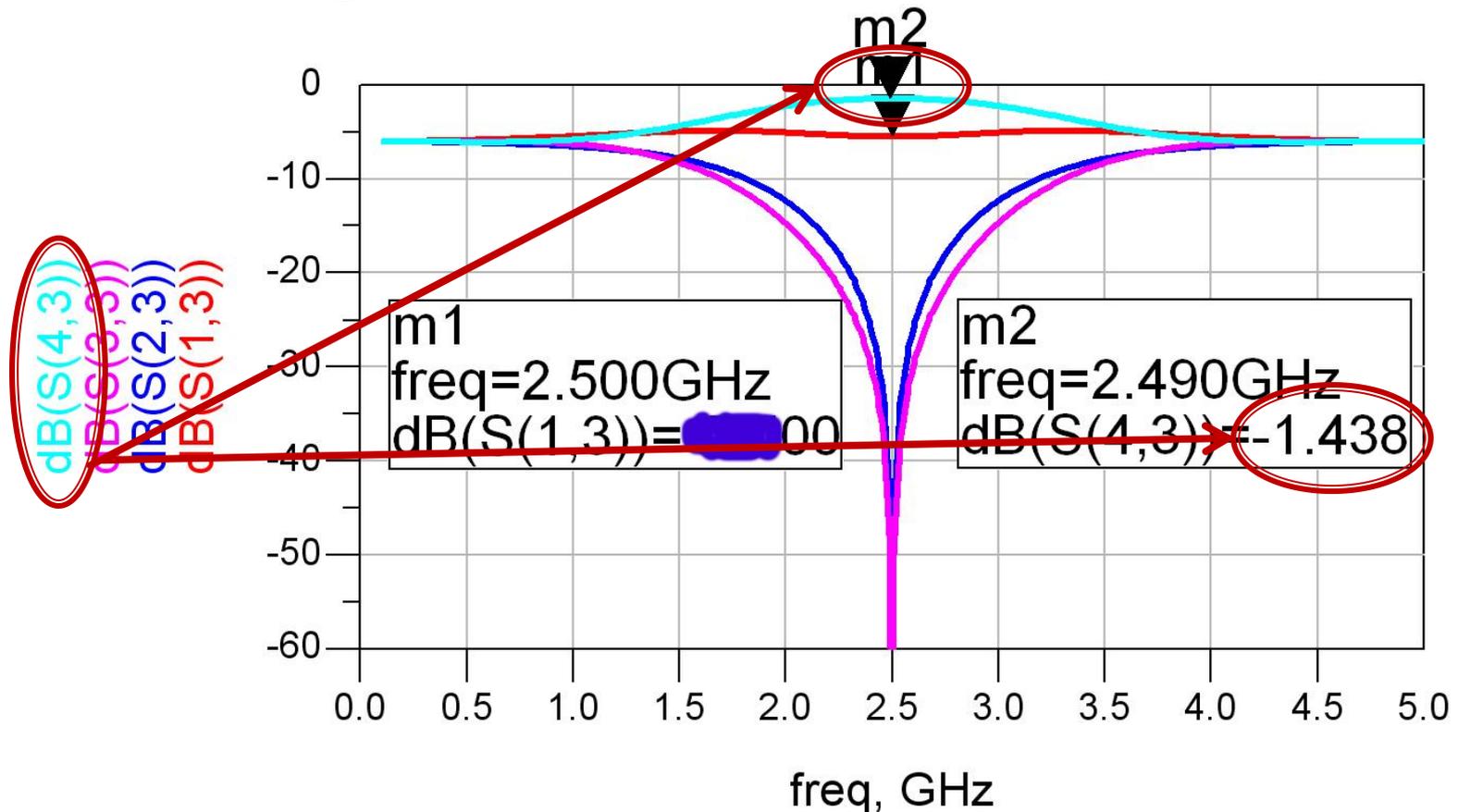
Step 7

- The **coupled** port corresponds to the curve at which a marker will indicate at the design frequency **exactly** the value of the coupling coefficient required in the individual subject



Step 7

- The **through** port corresponds to the last remaining curve ($\sim -1 \div -2$ dB)



Step 8

- Save the schematic with a different name (**Save As**)
 - the schematic for the other coupler is almost the same, most of the components can be kept

Steps 9 - 23

- **Repeat** steps 1-8 before but using different design formulas and changing the schematic as needed

Step 24

- **Carefully** submit the data for the on-line “exam” Laboratory 2 on the rf-opto server. For **each** of the 3 couplers you will need:
 - **image file** with the schematic (**enough resolution that the values of the components can be read**)
 - **image file** with results (**enough resolution that the text can be read**)
 - **text** with the correct identification of the ports (in relation to the schematic and plot)

Online results submission

**Grade = Quality of the work +
+ Quality of the submission**

Frequent mistakes

Mistakes 1

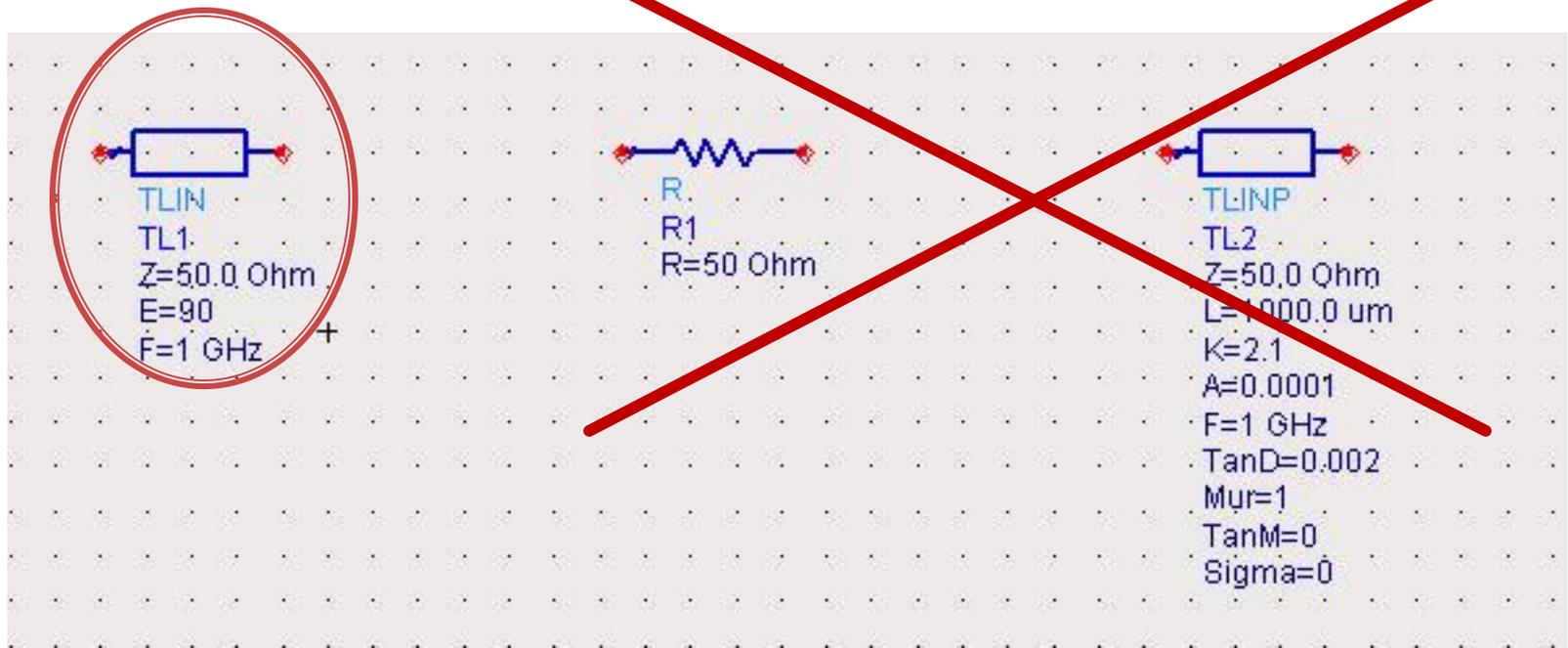
- Calculation errors (!Common)
 - due to the presence of square root and square, you will want to use **5-6 exact decimals** in the calculation so that the propagation of the errors does not change the result
 - for the first 2 couplers one of the values (y_2/y_1) is obtained directly from one equation, and you use the second equation to find the other value (y_1/y_2)
 - for the coupled line coupler you get a system of 2 equations with two unknowns, solve it is **as a system**

Mistakes 2

- Relationship misinterpretations (!Common)
 - The examples in the lab manual are for 3 dB couplers (because they are most common in practice). This led to the appearance of values equal to 2, $\sqrt{2}$, or to particular situations like $\gamma_1 = 1, Z_1 = 50\Omega, \gamma_1 = \gamma_2$
 - For your individual values this **does not** happen anymore, the calculations must be done with the initial relationships not the numerical ones in the example

Mistakes 3

- Putting in the schematic instead of the ideal transmission lines (**TLIN**) resistors or other parts (microstrip, physical etc.)



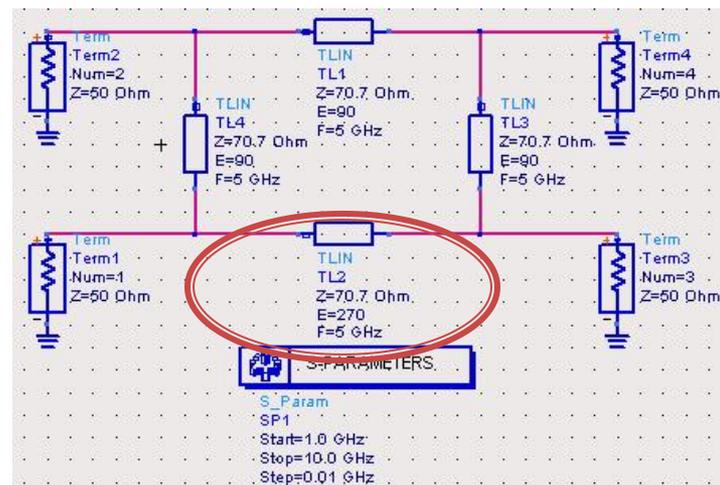
Mistakes 4

- Missing **ground** for terminators, resulting in a  floating circuit that cannot be simulated
- Putting in the schematic instead of terminators/ports (**TERM –Simulation S-param palette**) R_model or even R (Lumped Components palette)



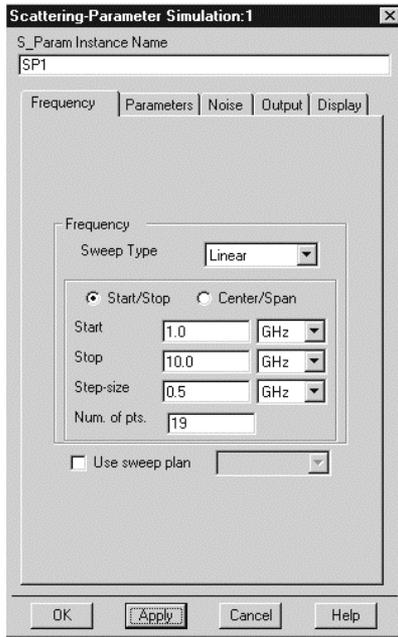
Mistakes 5

- Forgetting to change the frequency to the one from the individual subject on any of the transmission lines (**TLIN, CLIN**)
- Wrong electrical length (**!Common**)
 - almost all lines must stay at $E=90$
 - the only exception is the longer line in the **ring coupler ($E=270$)**



Mistakes 6

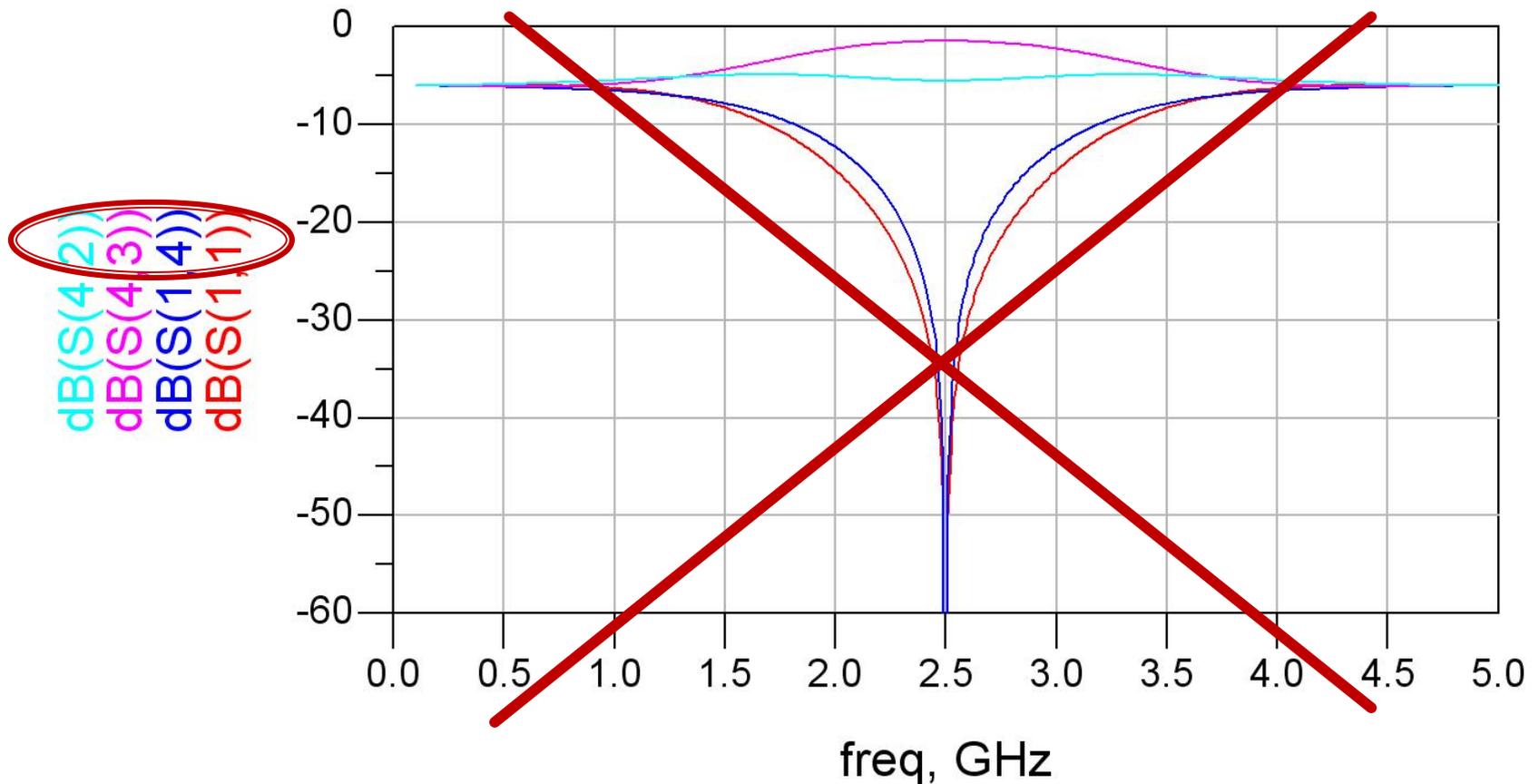
- Forgetting to change the parameters for the simulation
 - often **Start/Stop/Step size** stays at:
1GHz/10GHz/1GHz (undesirable)



- **Start/Stop/Step size**: should be changed to **$f_0 - \Delta f / f_0 + \Delta f / (0.05 \text{ GHz or even } 0.01 \text{ GHz})$**
- where Δf is applied symmetrically around the imposed f_0 such as the behavior of the coupler can be observed, if results show Δf was chosen too small, increase it and repeat simulation

Mistakes 7

- Wrong variables chosen to plot (comparing output for inputting signal on different ports is wrong), it is important that the **second index** is the **same**



Contact

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