**Lecture 7**
2018/2019

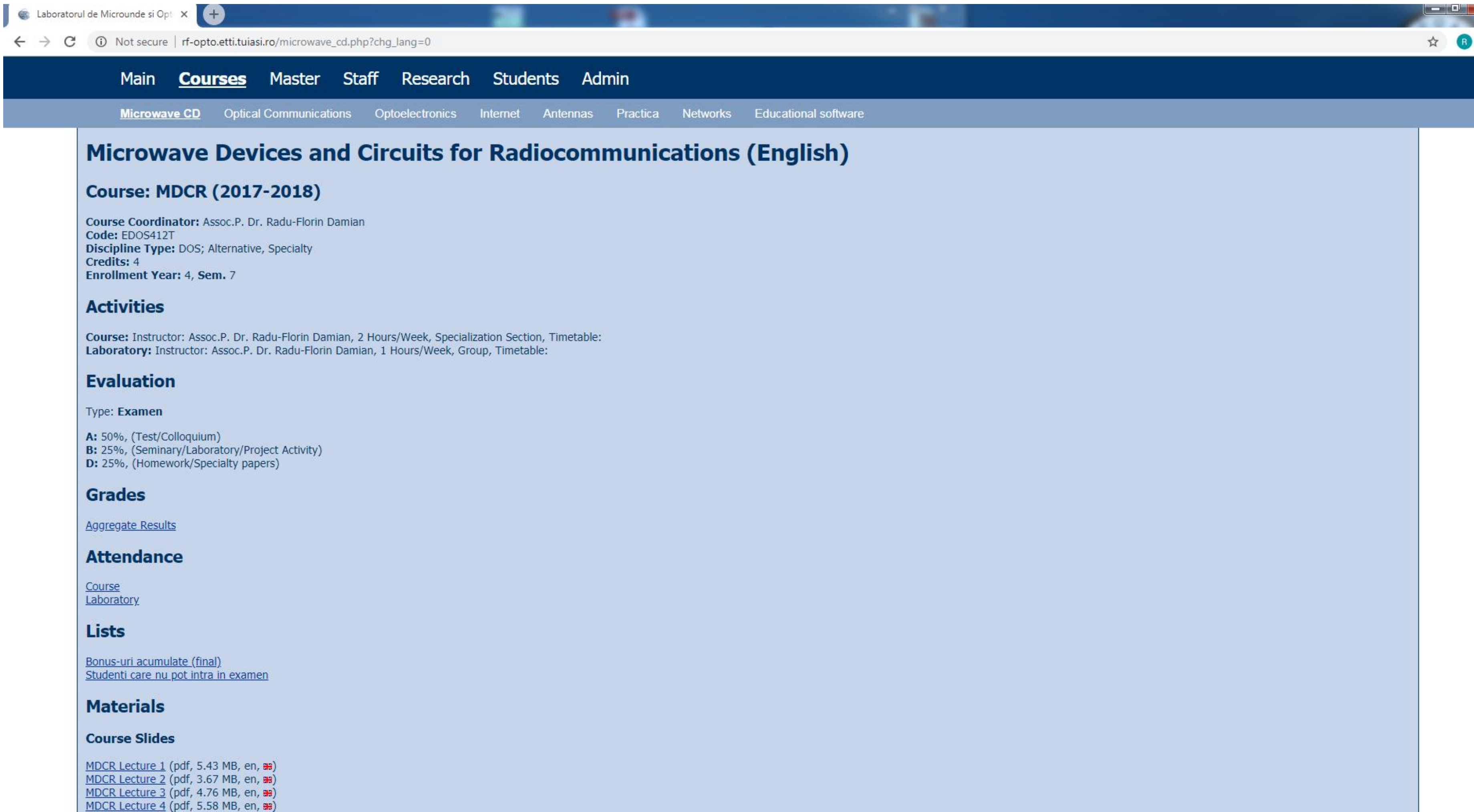
# Microwave Devices and Circuits for Radiocommunications

# 2018/2019

- 2C/1L, **MDCR**
- **Attendance at minimum 7 sessions (course + laboratory)**
- Lectures- **associate professor Radu Damian**
  - Friday 09-11, II.13
  - E – 50% final grade
  - **problems** + (2p atten. lect.) + (3 tests) + (bonus activity)
    - 3p=+0.5p
  - **all materials/equipments authorized**
- Laboratory – **associate professor Radu Damian**
  - Wednesday 12-14, II.12 odd weeks
  - L – 25% final grade
  - P – 25% final grade

# Materials

- http://rf-opto.etti.tuiasi.ro



Laboratorul de Microunde si Opt

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Main **Courses** Master Staff Research Students Admin

**Microwave CD** Optical Communications Optoelectronics Internet Antennas Practica Networks Educational software

## Microwave Devices and Circuits for Radiocommunications (English)

### Course: MDCR (2017-2018)

**Course Coordinator:** Assoc.P. Dr. Radu-Florin Damian
**Code:** EDOS412T
**Discipline Type:** DOS; Alternative, Specialty
**Credits:** 4
**Enrollment Year:** 4, **Sem.** 7

### Activities

**Course:** Instructor: Assoc.P. Dr. Radu-Florin Damian, 2 Hours/Week, Specialization Section, Timetable:
**Laboratory:** Instructor: Assoc.P. Dr. Radu-Florin Damian, 1 Hours/Week, Group, Timetable:

### Evaluation

Type: **Examen**

**A:** 50%, (Test/Colloquium)
**B:** 25%, (Seminary/Laboratory/Project Activity)
**D:** 25%, (Homework/Specialty papers)

### Grades

Aggregate Results

### Attendance

Course
Laboratory

### Lists

Bonus-uri acumulate (final)
Studenti care nu pot intra in examen

### Materials

**Course Slides**

MDCR Lecture 1 (pdf, 5.43 MB, en, )
MDCR Lecture 2 (pdf, 3.67 MB, en, )
MDCR Lecture 3 (pdf, 4.76 MB, en, )
MDCR Lecture 4 (pdf, 5.58 MB, en, )

# Examen: Logarithmic scales

**dB** $= 10 \cdot \log_{10} (P_2 / P_1)$

| | |
|---|---|
| 0 dB | = 1 |
| + 0.1 dB | = 1.023 (+2.3%) |
| + 3 dB | = 2 |
| + 5 dB | = 3 |
| + 10 dB | = 10 |
| -3 dB | = 0.5 |
| -10 dB | = 0.1 |
| -20 dB | = 0.01 |
| -30 dB | = 0.001 |

**dBm** $= 10 \cdot \log_{10} (P / 1\ \text{mW})$

| | |
|---|---|
| 0 dBm | = 1 mW |
| 3 dBm | = 2 mW |
| 5 dBm | = 3 mW |
| 10 dBm | = 10 mW |
| 20 dBm | = 100 mW |
| -3 dBm | = 0.5 mW |
| -10 dBm | = 100 µW |
| -30 dBm | = 1 µW |
| -60 dBm | = 1 nW |

[dBm] + [dB] = [dBm]

[dBm/Hz] + [dB] = [dBm/Hz]

[x] + [dB] = [x]

# Examen

- Complex numbers arithmetic**!!!!**
- $z = a + j \cdot b$ ; **$j^2 = -1$**

# Impedance Matching

# Matching , from the point of view of power transmission

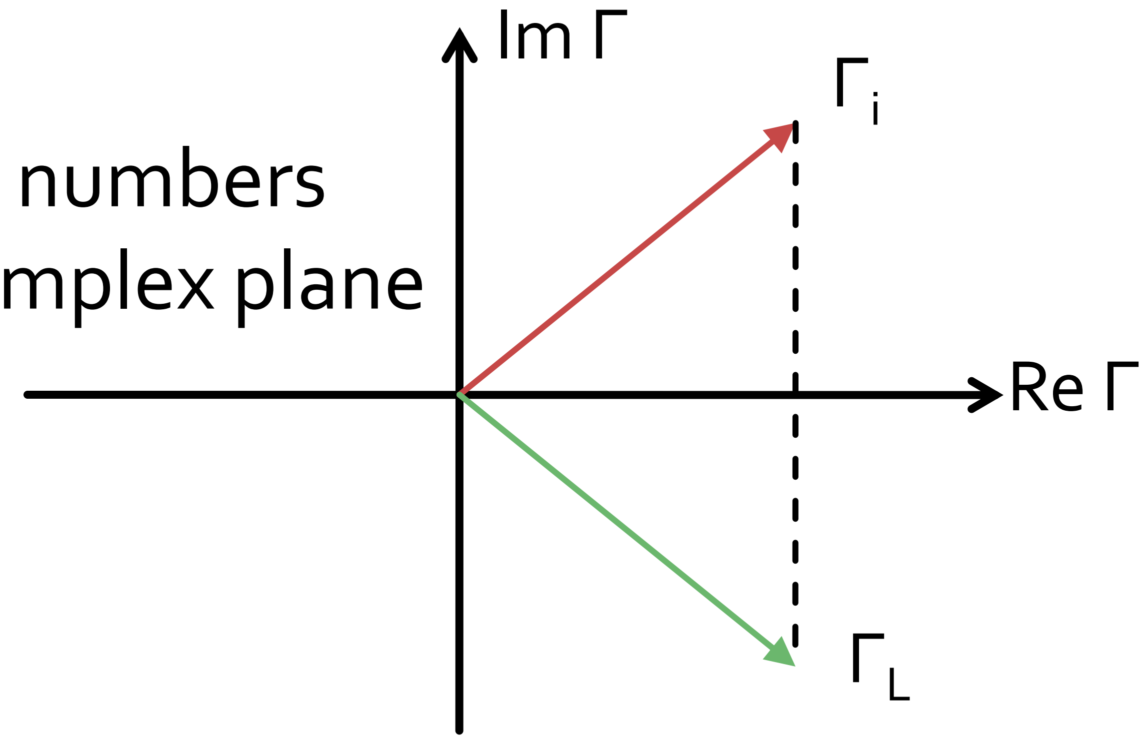
$$Z_L = Z_i^*$$

If we choose a real Zo

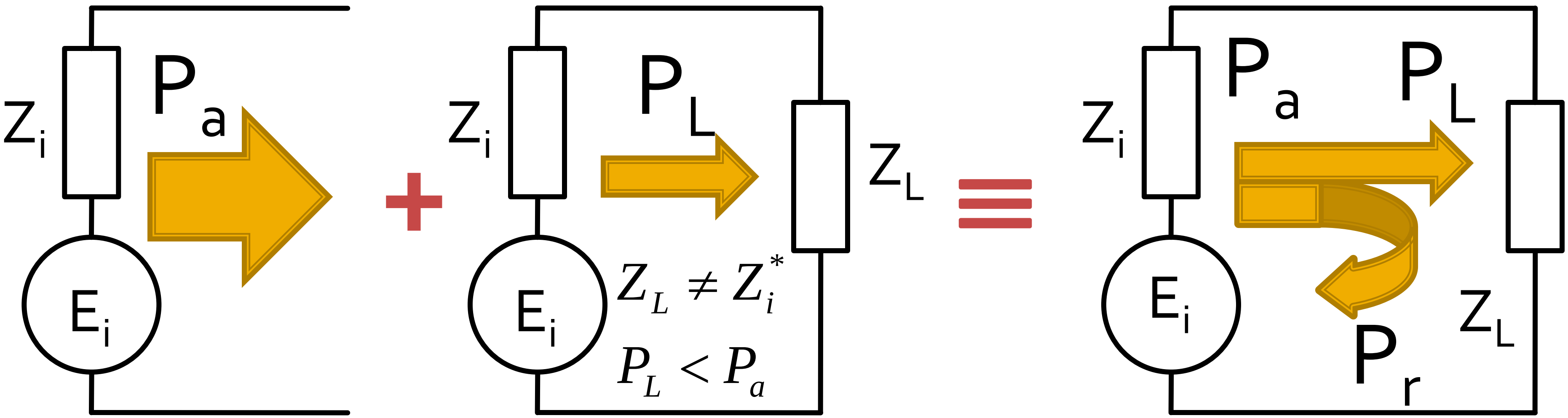
$$\Gamma = \frac{Z - Z_0}{Z + Z_0}$$

$$\Gamma_L = \Gamma_i^*$$

- complex numbers
- in the complex plane



# Reflection and power / Model



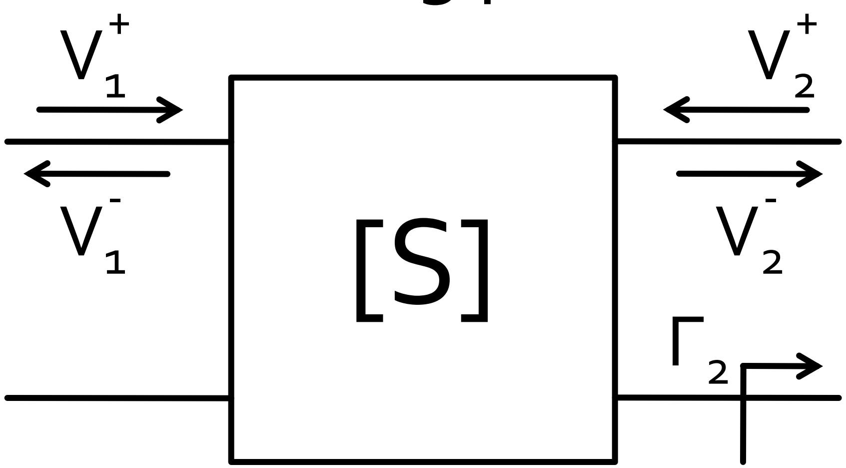

- The source has the ability to sent to the load a certain maximum power (available power) $P_a$
- For a particular load the power sent to the load is  less than the maximum (mismatch) $P_L < P_a$
- The phenomenon is **"as if"** (model) some of the power is reflected $P_r = P_a - P_L$
- The power is a **scalar !**

Lecture 3-4

# Microwave Network Analysis

# Scattering matrix – S

- Scattering parameters



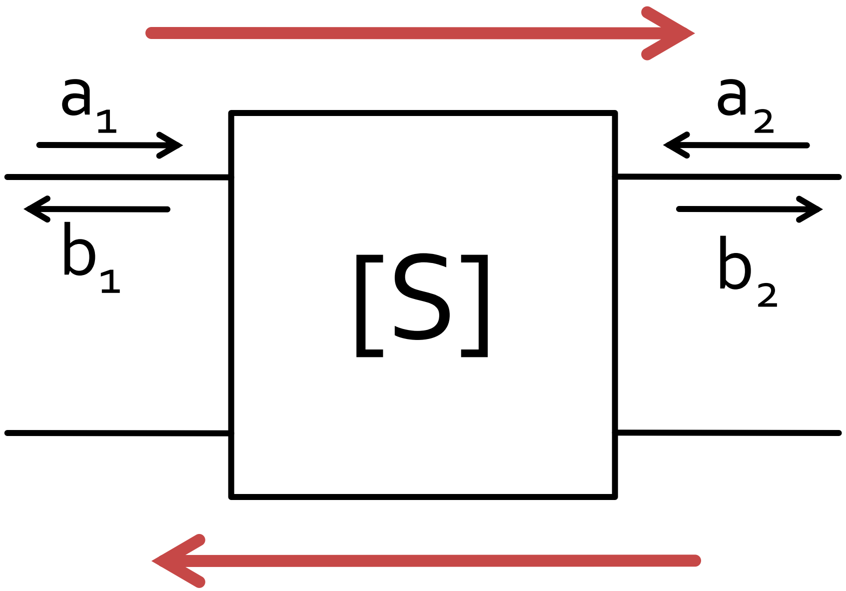

$$\begin{bmatrix} V_1^- \\ V_2^- \end{bmatrix} = \begin{bmatrix} S_{11} & S_{12} \\ S_{21} & S_{22} \end{bmatrix} \cdot \begin{bmatrix} V_1^+ \\ V_2^+ \end{bmatrix}$$

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

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

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

# Scattering matrix – S




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

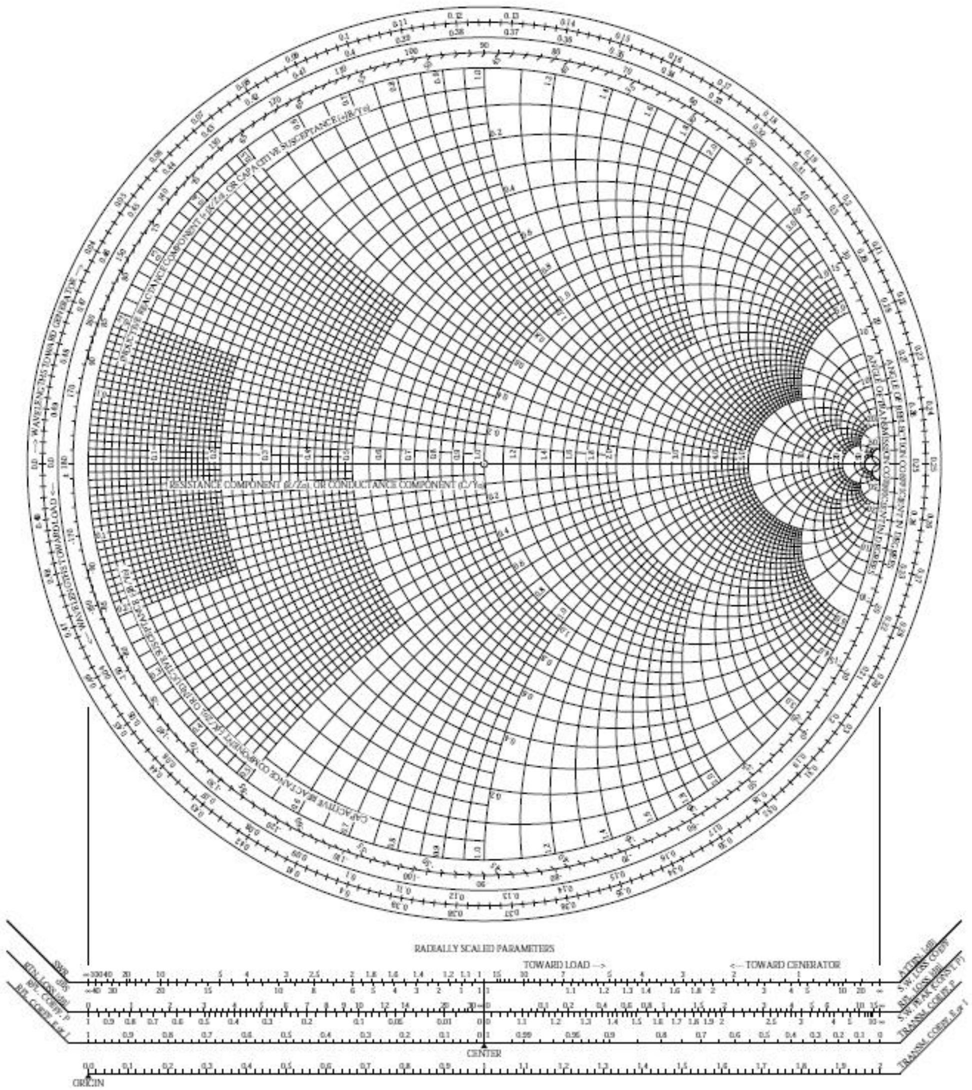
$$\left|S_{21}\right|^2 = \frac{Power\ in\ Z_0\ load}{Power\ \ from\ Z_0\ source}$$

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

Impedance Matching

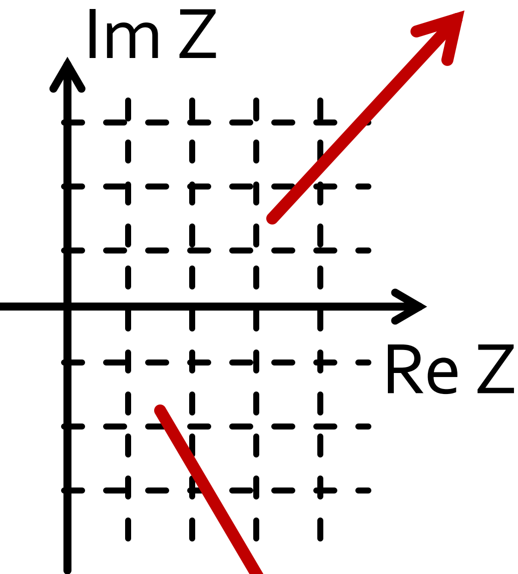
# The Smith Chart

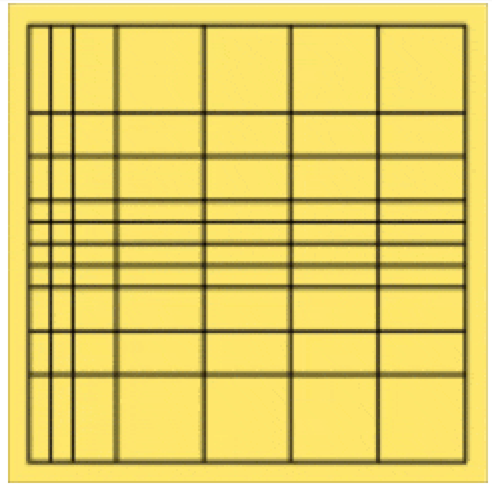
# The Smith Chart

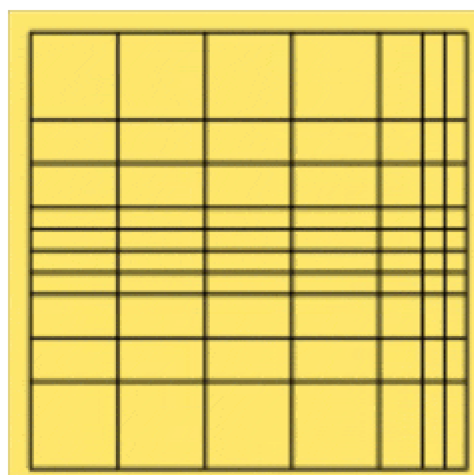


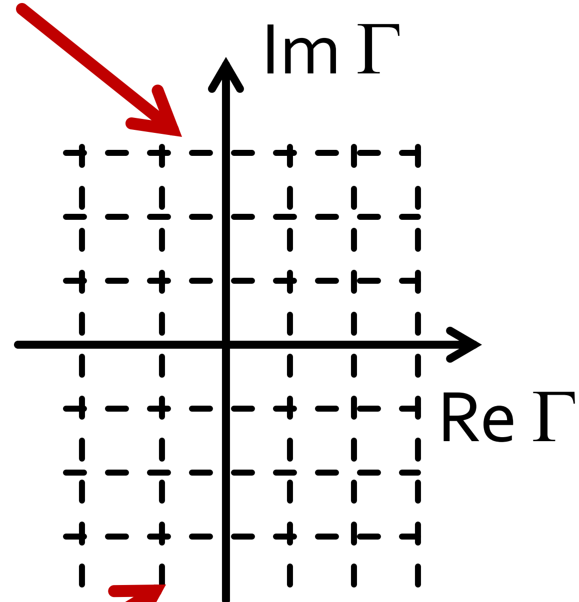
# The Smith Chart

$$\Gamma = \frac{Z_L - Z_0}{Z_L + Z_0} = \frac{z_L - 1}{z_L + 1}$$



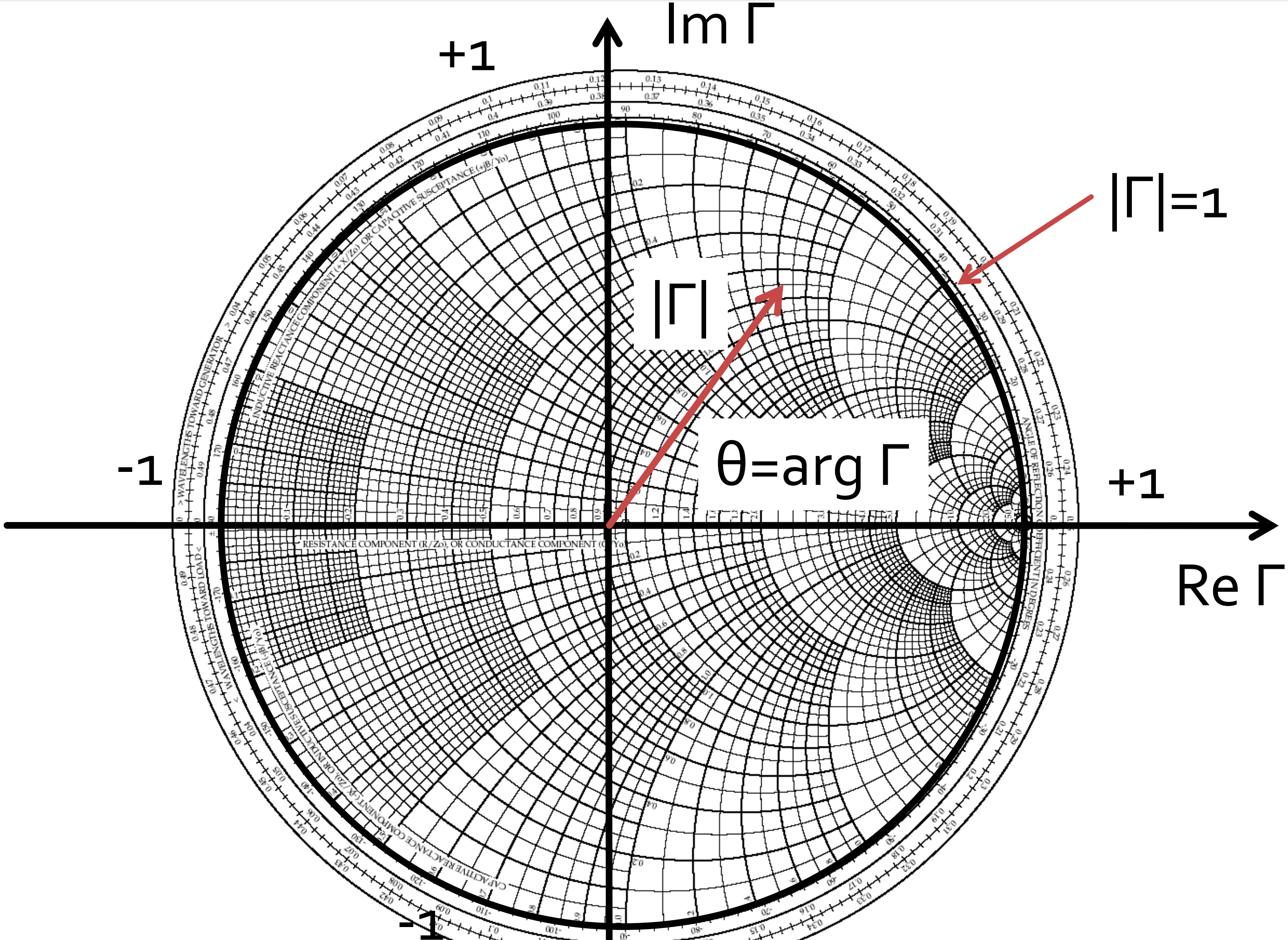





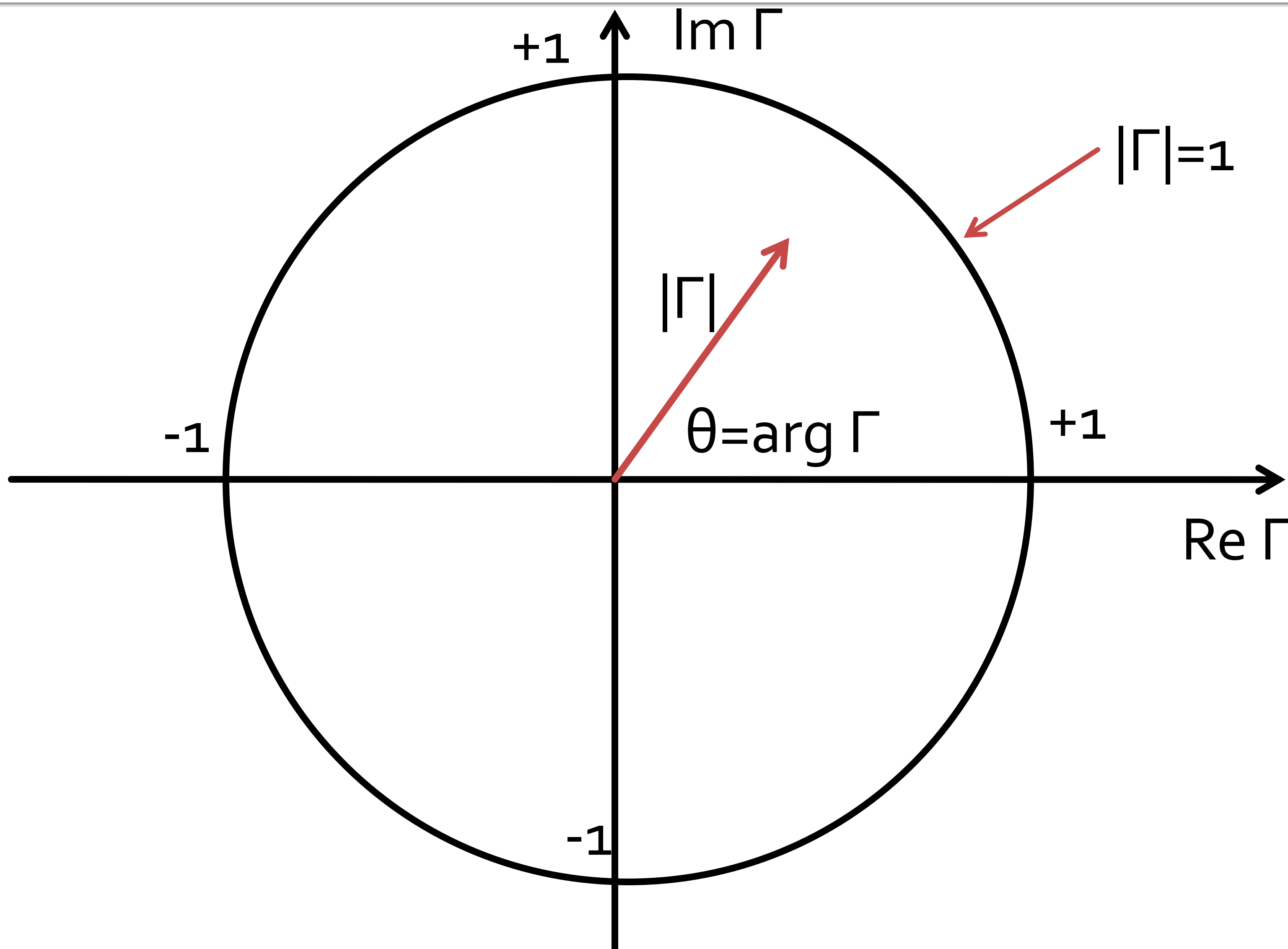



$$\Gamma = \frac{Z_L - Z_0}{Z_L + Z_0} = \frac{Y_0 - Y_L}{Y_0 + Y_L} = \frac{1 - y_L}{1 + y_L}$$

# The Smith Chart



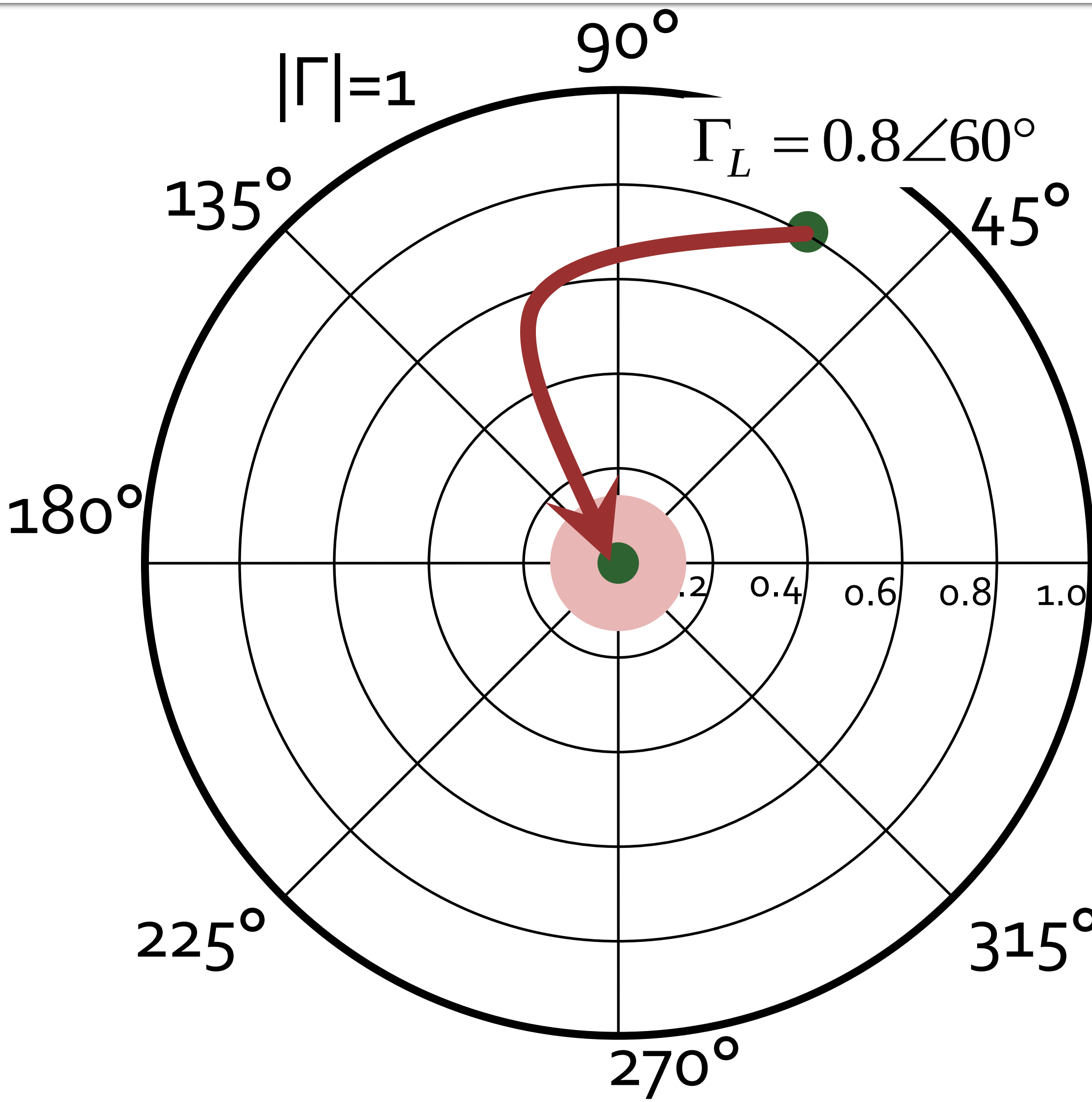
# The Smith Chart

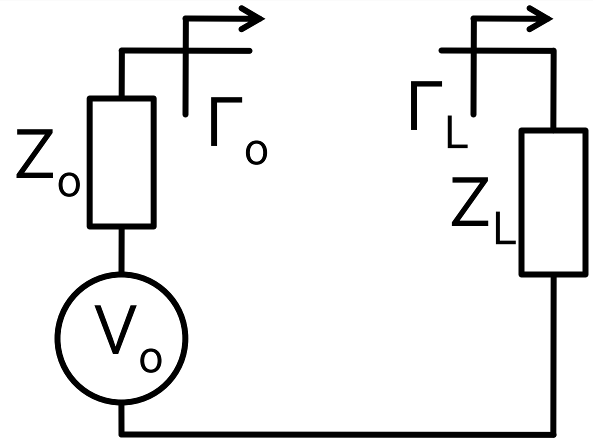


Impedance matching with lumped elements (L Networks)

# Impedance Matching

# The Smith Chart, reflection coefficient, impedance matching




Matching $Z_L$ load to $Z_o$ source.
We normalize $Z_L$ over $Z_o$

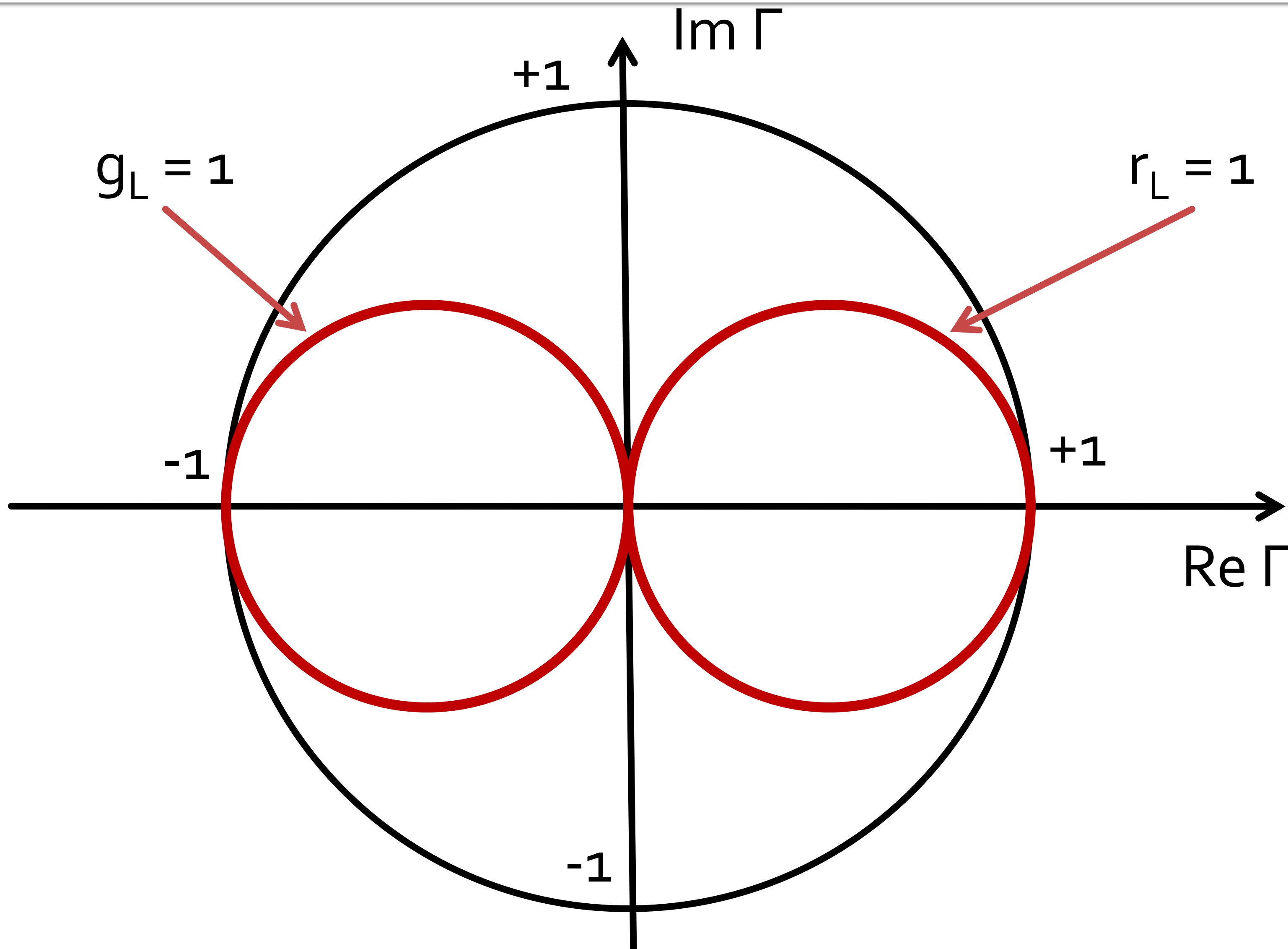
$$Z_L = 21.429\Omega + j \cdot 82.479\Omega$$
$$z_L = 0.429 + j \cdot 1.65$$
$$\Gamma_L = 0.8\angle 60°$$

We must move the point denoting the reflection coefficient in the area where with a $Z_o$ source we have:

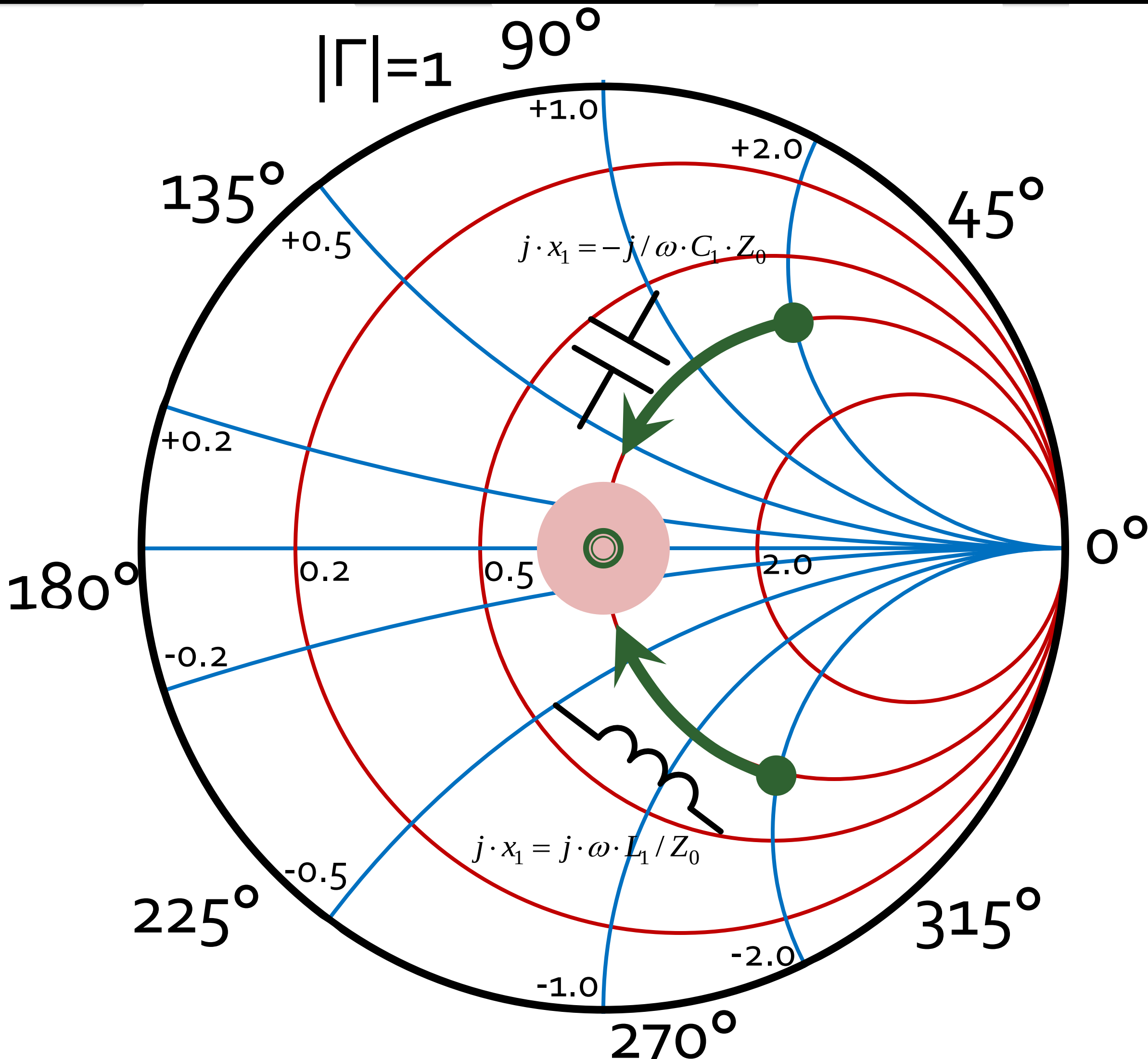
$\Gamma_0 = 0$ perfect match

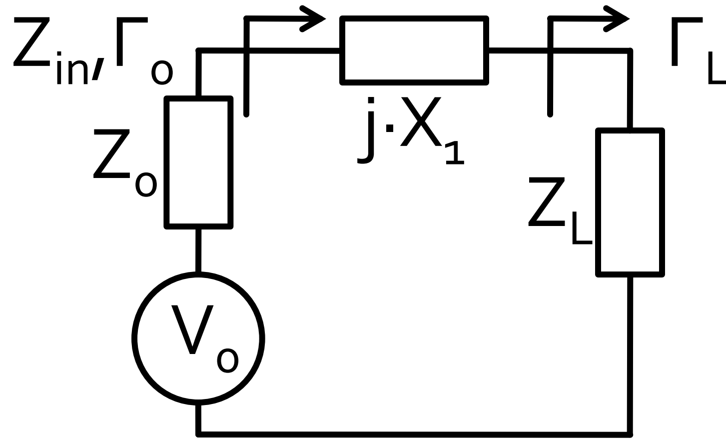
$|\Gamma_0| \leq \Gamma_m$ "good enough" match

# Smith chart, r=1 and g=1



# Matching, series reactance




$$z_L = r_L + j\cdot x_L$$

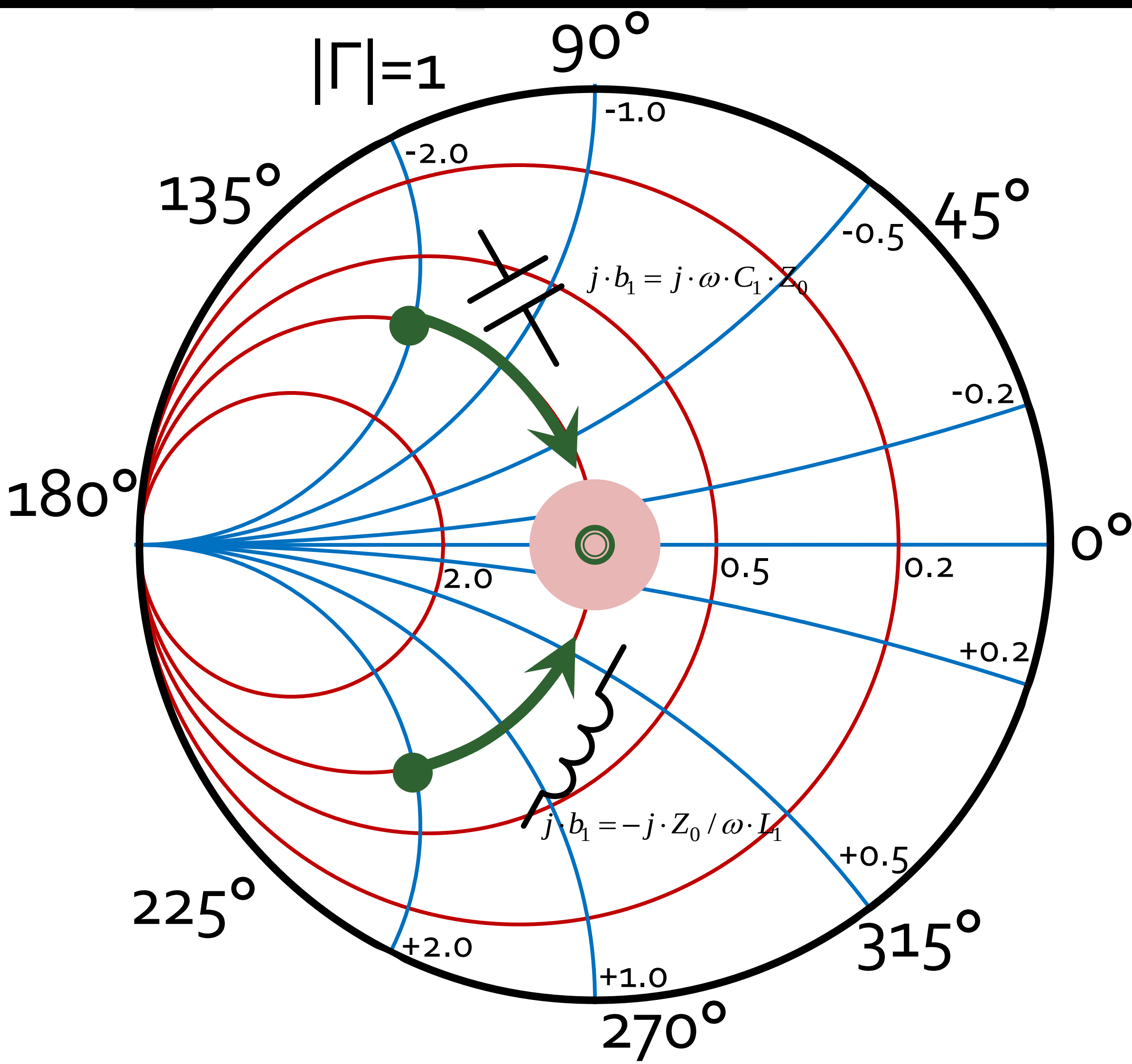
$$z_{in} = r_L + j\cdot(x_L + x_1)$$

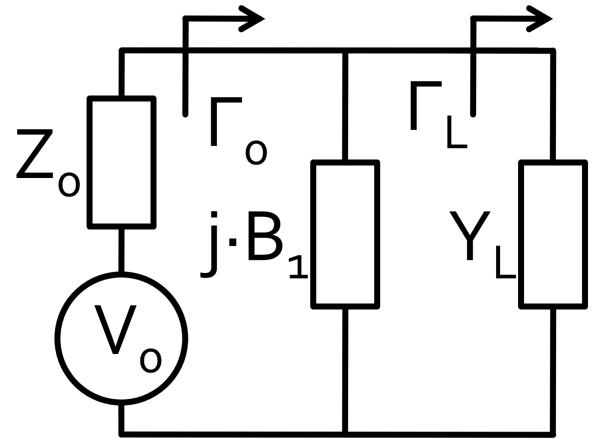
$$r_{in} = r_L$$

- Match can be obtained **if and only if** $r_L = 1$
- we compensate the reactive part of the load

$$j\cdot x_1 = -j\cdot x_L$$

# Matching, shunt susceptance




$$y_L = g_L + j \cdot b_L$$

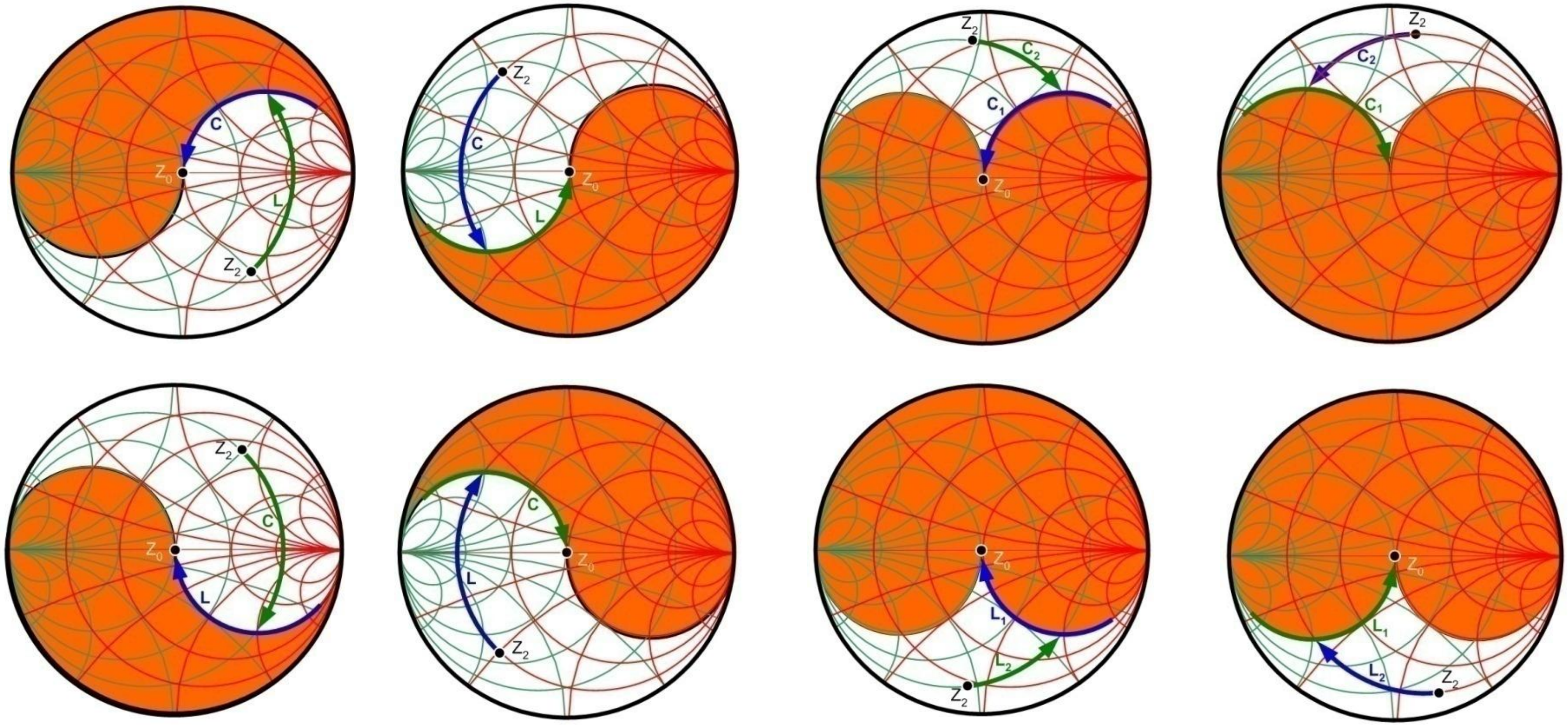
$$y_{in} = g_L + j \cdot (b_L + b_1)$$

$$g_{in} = g_L$$

- Match can be obtained **if and only if** $g_L = 1$
- we compensate the reactive part of the load

$$j \cdot b_1 = -j \cdot b_L$$

# Matching with 2 reactive elements (L Networks)

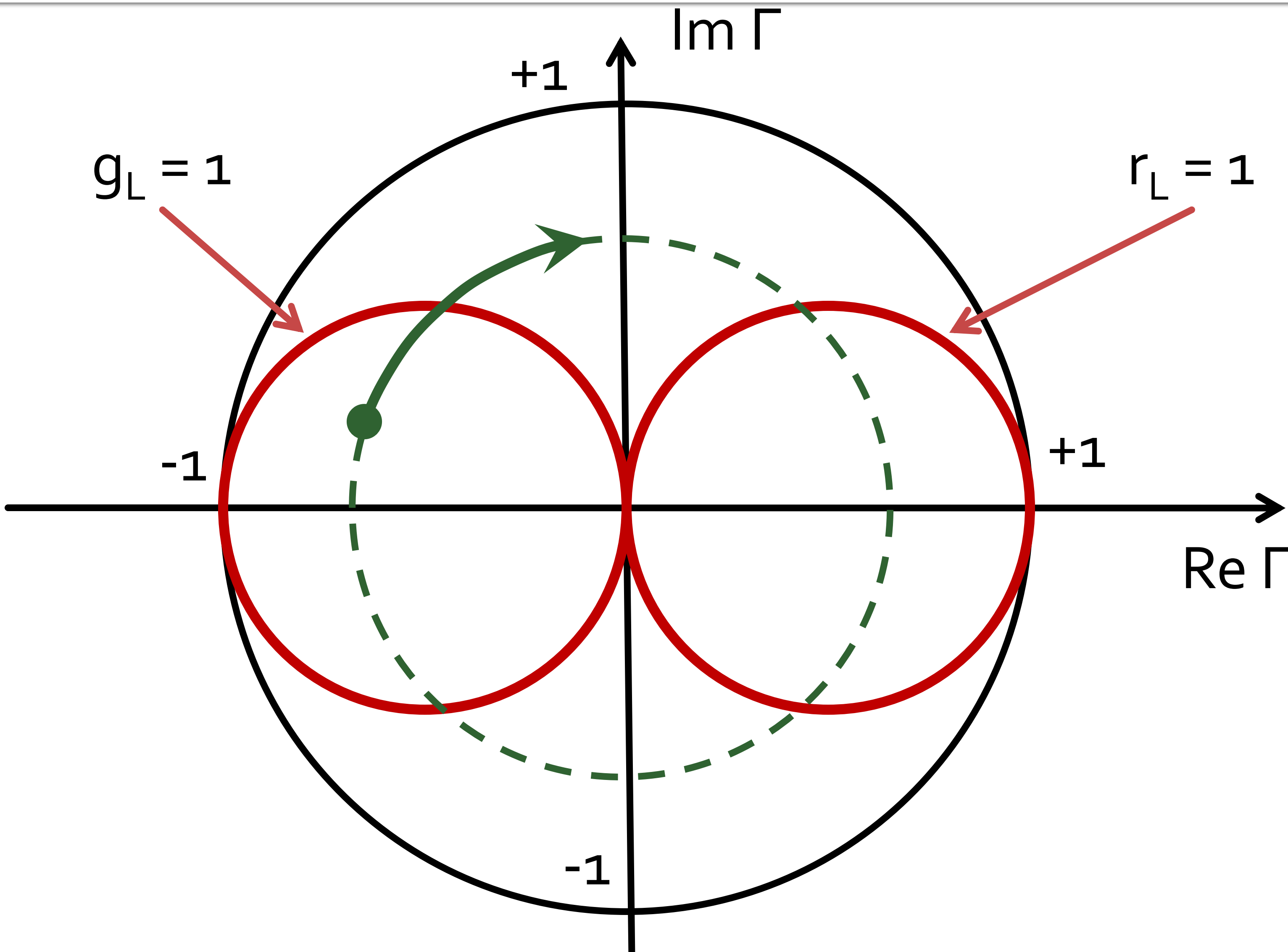



Forbidden area for current network

Impedance Matching with Stubs

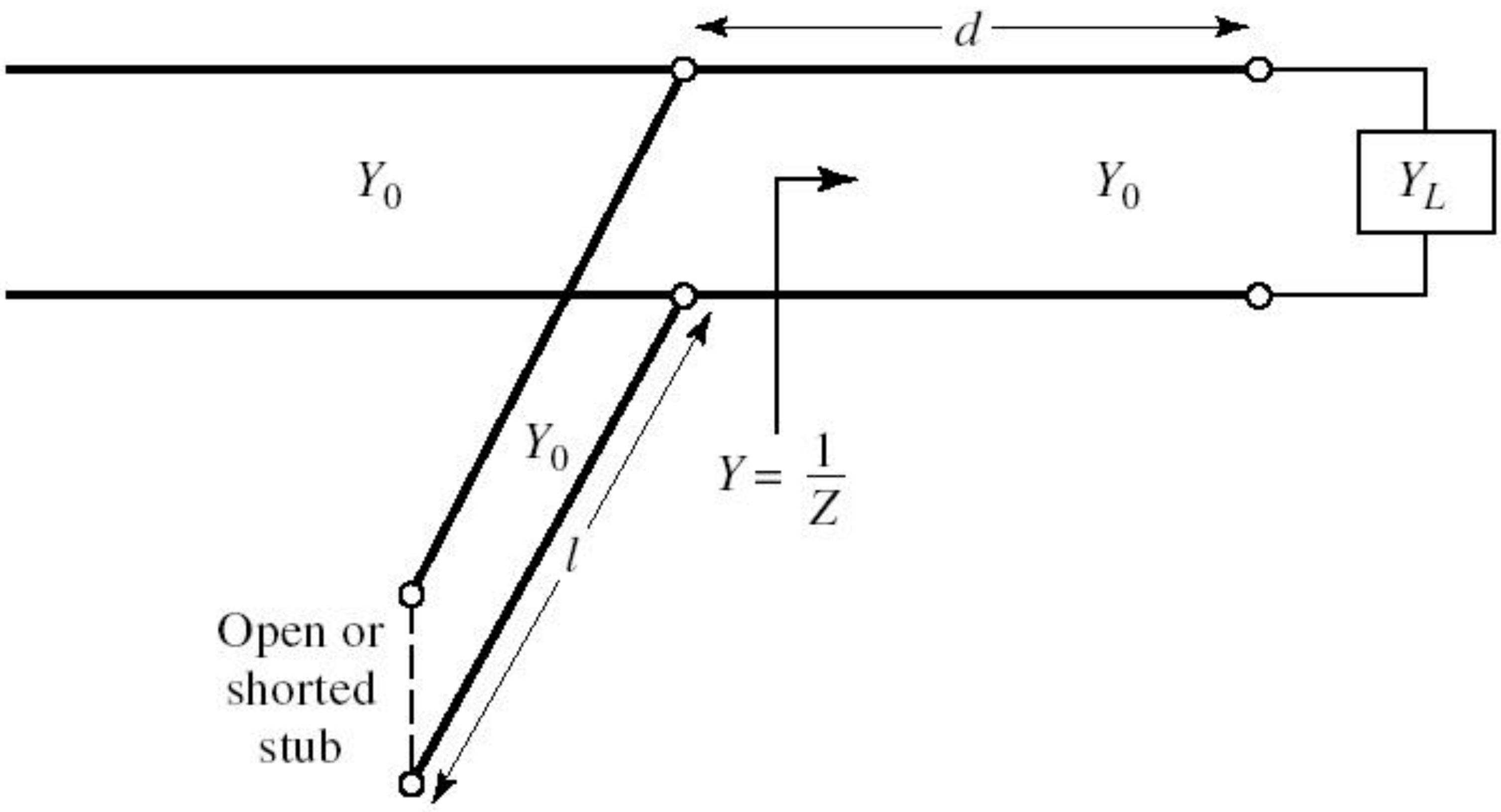
# Impedance Matching

# Smith chart, r=1 and g=1



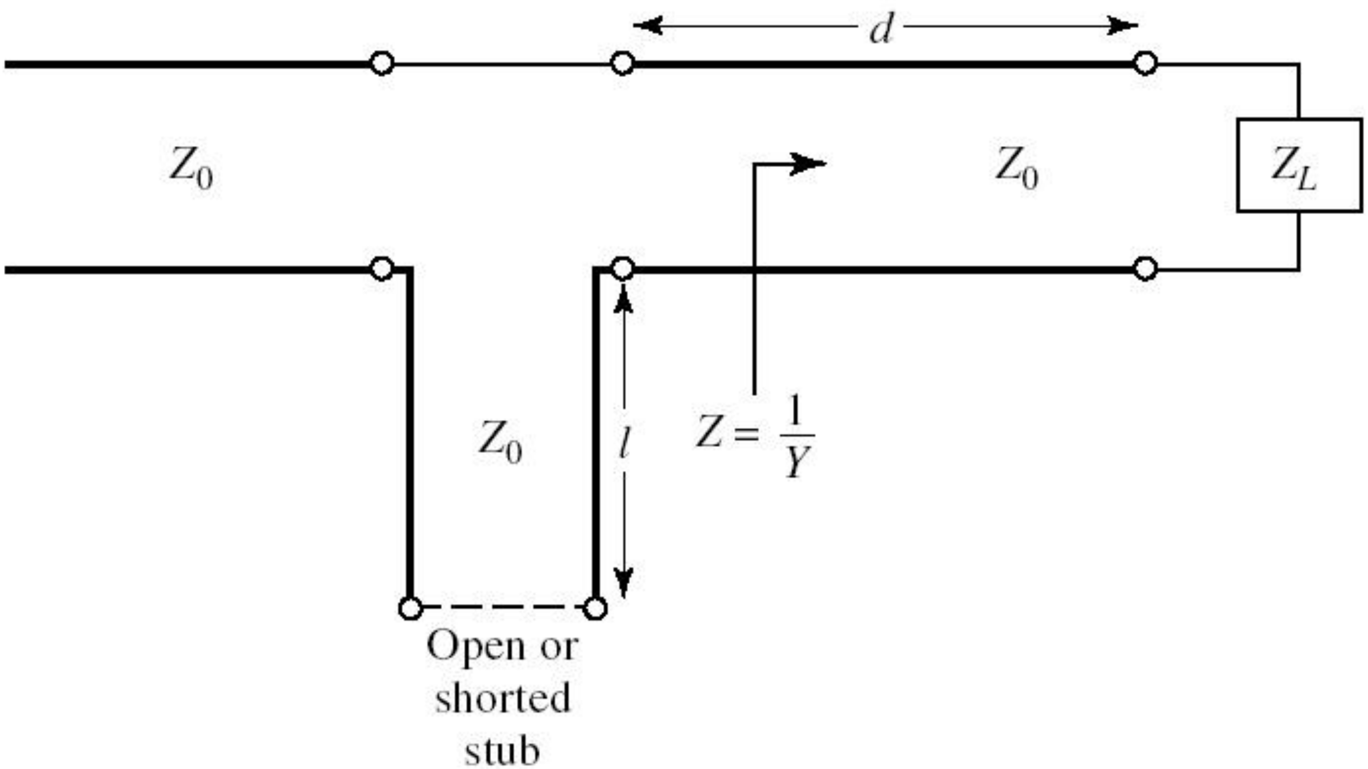
# Single stub tuning

- Shunt Stub



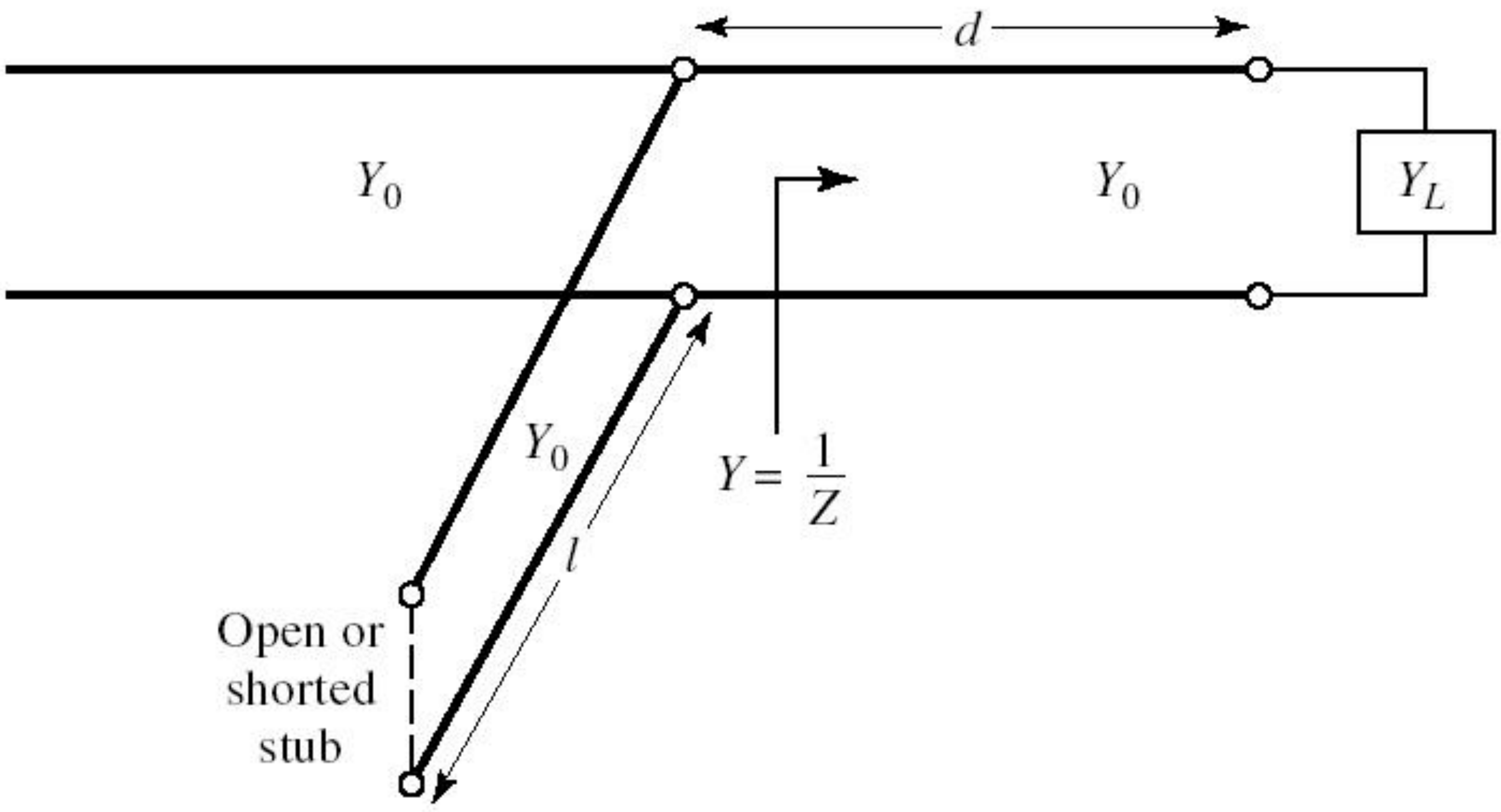
# Single stub tuning

- Series Stub
- difficult to realize in single conductor line technologies (microstrip)

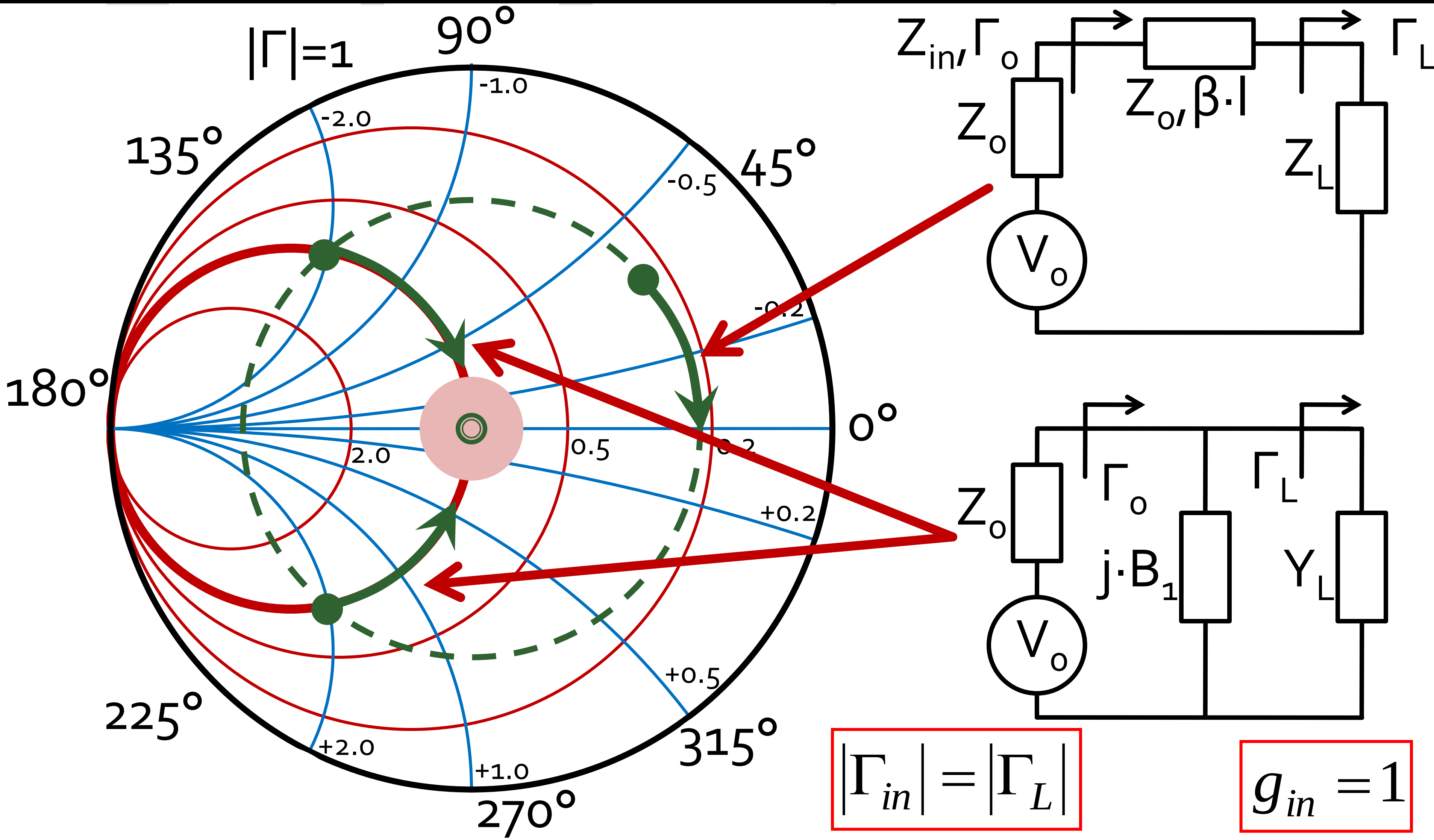


# Case 1, Shunt Stub

- Shunt stub



# Matching, series line + shunt susceptance




$$|\Gamma_{in}| = |\Gamma_L|$$

$$g_{in} = 1$$

# Analytical solution, Γ , shunt stub

$$\cos(\varphi + 2\theta) = -|\Gamma_S|$$

$$\theta_{sp} = \beta \cdot l = \tan^{-1} \frac{\mp 2 \cdot |\Gamma_S|}{\sqrt{1 - |\Gamma_S|^2}}$$

$$\Gamma_S = 0.593 \angle 46.85°$$

$$|\Gamma_S| = 0.593; \quad \varphi = 46.85° \qquad \cos(\varphi + 2\theta) = -0.593 \Rightarrow (\varphi + 2\theta) = \pm 126.35°$$

- The **sign** (+/-) chosen for the **series line** equation imposes the **sign** used for the **shunt stub** equation
  - **"+" solution**

    $$(46.85° + 2\theta) = +126.35° \qquad \theta = +39.7° \qquad \operatorname{Im} y_S = \frac{-2 \cdot |\Gamma_S|}{\sqrt{1 - |\Gamma_S|^2}} = -1.472$$

    $$\theta_{sp} = \tan^{-1}(\operatorname{Im} y_S) = -55.8° (+180°) \rightarrow \theta_{sp} = 124.2°$$

  - **"-" solution**

    $$(46.85° + 2\theta) = -126.35° \qquad \theta = -86.6° (+180°) \rightarrow \theta = 93.4°$$

    $$\operatorname{Im} y_S = \frac{+2 \cdot |\Gamma_S|}{\sqrt{1 - |\Gamma_S|^2}} = +1.472 \qquad \theta_{sp} = \tan^{-1}(\operatorname{Im} y_S) = 55.8°$$

# Analytical solution, Γ

$$(\varphi + 2\theta) = \begin{cases} +126.35^\circ \\ -126.35^\circ \end{cases} \quad \theta = \begin{cases} 39.7^\circ \\ 93.4^\circ \end{cases} \quad \mathrm{Im}\left[y_S(\theta)\right] = \begin{cases} -1.472 \\ +1.472 \end{cases} \quad \theta_{sp} = \begin{cases} -55.8^\circ + 180^\circ = 124.2^\circ \\ +55.8^\circ \end{cases}$$

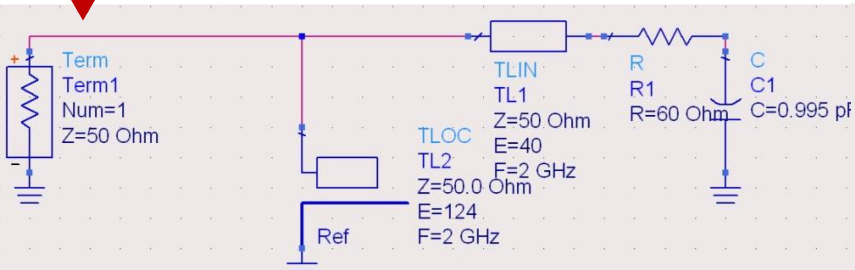
- We choose **one** of the two possible solutions
- The **sign** (+/-) chosen for the **series line** equation imposes the **sign** used for the **shunt stub** equation

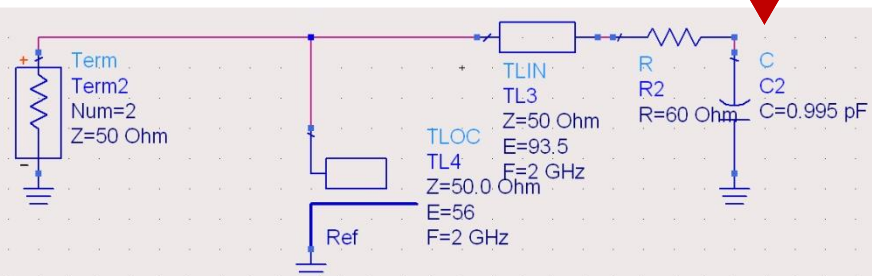
$$l_1 = \frac{39.7^\circ}{360^\circ} \cdot \lambda = 0.110 \cdot \lambda$$

$$l_2 = \frac{124.2^\circ}{360^\circ} \cdot \lambda = 0.345 \cdot \lambda$$

$$l_1 = \frac{93.4^\circ}{360^\circ} \cdot \lambda = 0.259 \cdot \lambda$$

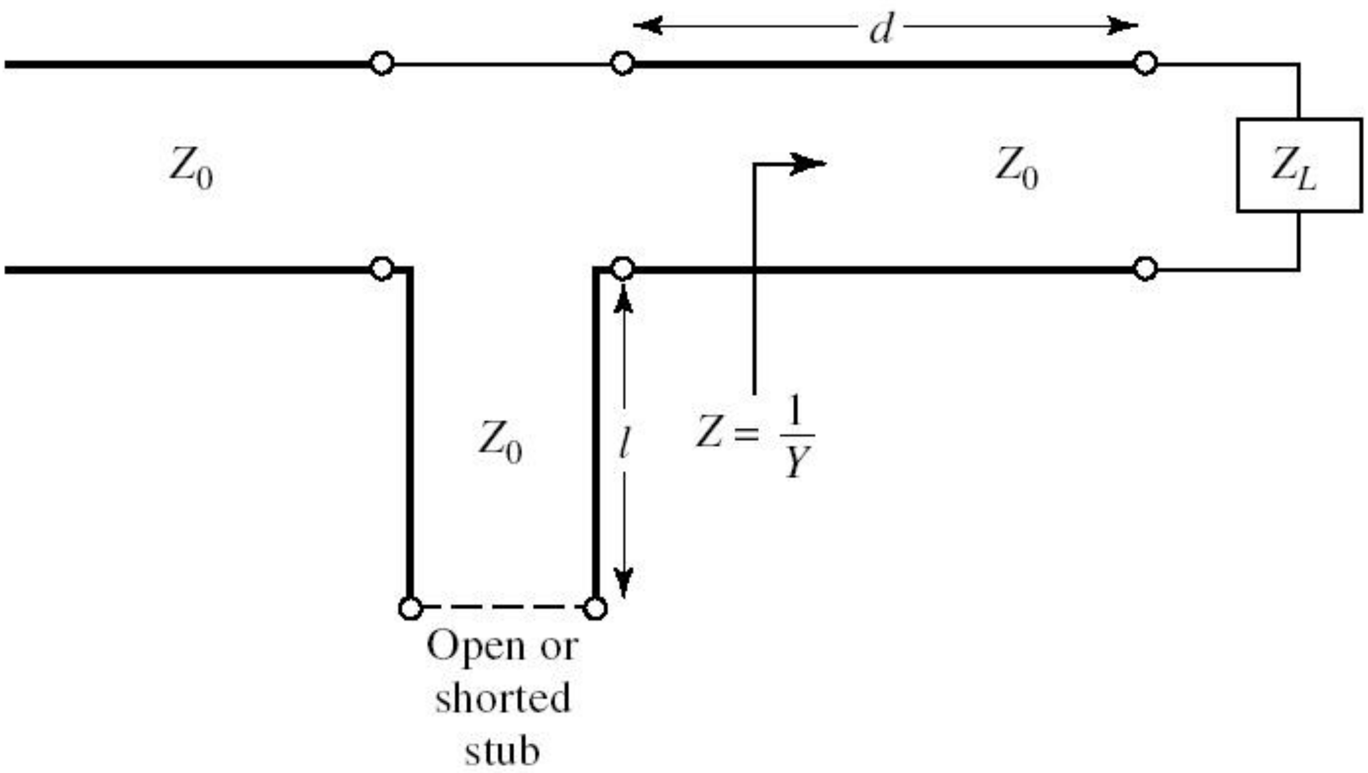
$$l_2 = \frac{55.8^\circ}{360^\circ} \cdot \lambda = 0.155 \cdot \lambda$$



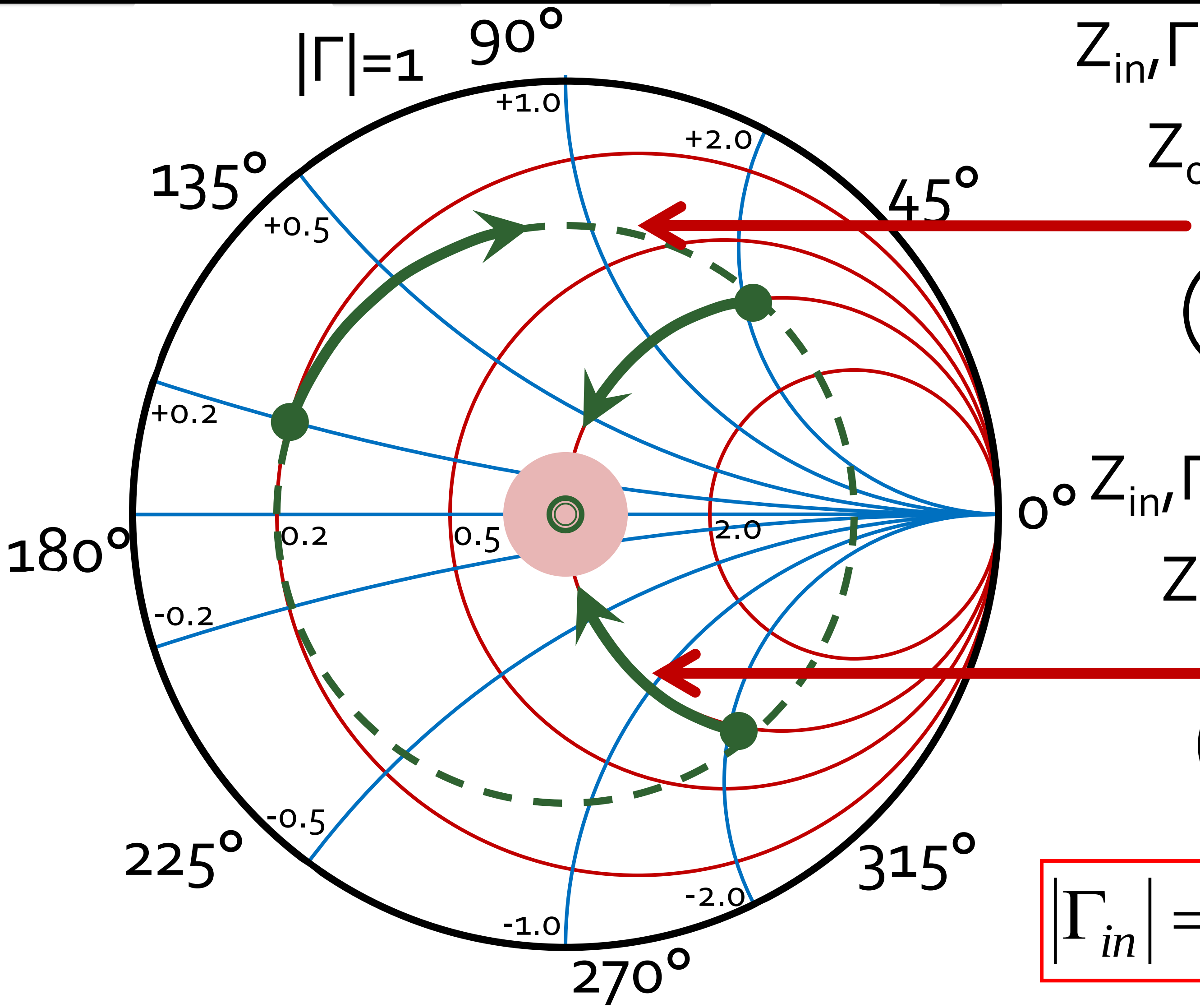



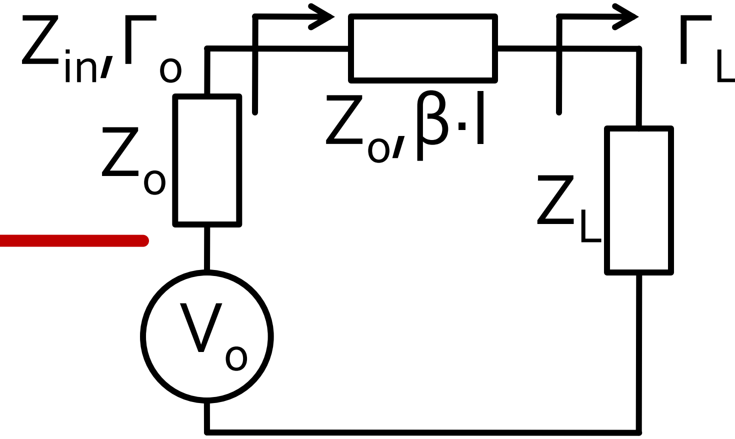
# Case 2, Series Stub

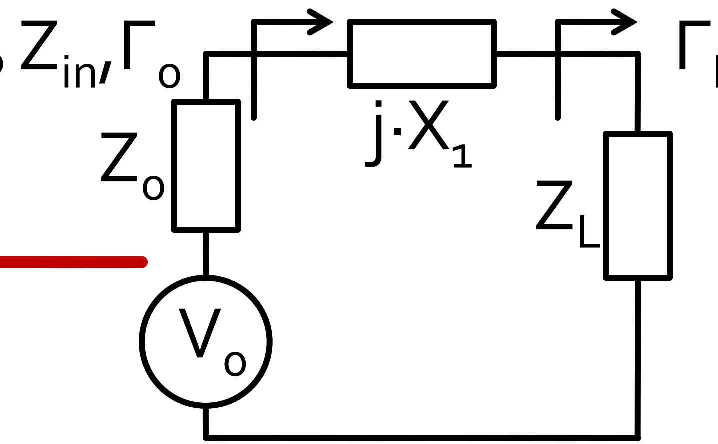
- Series Stub
- difficult to realize in single conductor line technologies (microstrip)



# Matching, series line + series reactance




$$\left|\Gamma_{in}\right| = \left|\Gamma_L\right| \qquad r_{in} = 1$$

# Analytical solution, Γ

$$\cos(\varphi + 2\theta) = |\Gamma_S|$$

$$\theta_{ss} = \beta \cdot l = \cot^{-1} \frac{\mp 2 \cdot |\Gamma_S|}{\sqrt{1 - |\Gamma_S|^2}}$$

$$\Gamma_S = 0.555\angle -29.92^\circ$$

$$|\Gamma_S| = 0.555; \quad \varphi = -29.92^\circ \qquad \cos(\varphi + 2\theta) = 0.555 \Rightarrow (\varphi + 2\theta) = \pm 56.28^\circ$$

- The **sign** (+/-) chosen for the **series line** equation imposes the **sign** used for the **series stub** equation
  - **"+" solution**

$$(-29.92^\circ + 2\theta) = +56.28^\circ \qquad \theta = 43.1^\circ \qquad \operatorname{Im} z_S = \frac{+2 \cdot |\Gamma_S|}{\sqrt{1 - |\Gamma_S|^2}} = +1.335$$

$$\theta_{ss} = -\cot^{-1}(\operatorname{Im} z_S) = -36.8^\circ (+180^\circ) \rightarrow \theta_{ss} = 143.2^\circ$$

  - **"-" solution**

$$(-29.92^\circ + 2\theta) = -56.28^\circ \qquad \theta = -13.2^\circ (+180^\circ) \rightarrow \theta = 166.8^\circ$$

$$\operatorname{Im} z_S = \frac{-2 \cdot |\Gamma_S|}{\sqrt{1 - |\Gamma_S|^2}} = -1.335 \qquad \theta_{ss} = -\cot^{-1}(\operatorname{Im} z_S) = 36.8^\circ$$

# Analytical solution, Γ

$$(\varphi + 2\theta) = \begin{cases} +56.28^\circ \\ -56.28^\circ \end{cases} \quad \theta = \begin{cases} 43.1^\circ \\ 166.8^\circ \end{cases} \quad \mathrm{Im}[z_S(\theta)] = \begin{cases} +1.335 \\ -1.335 \end{cases} \quad \theta_{ss} = \begin{cases} -36.8^\circ + 180^\circ = 143.2^\circ \\ +36.8^\circ \end{cases}$$

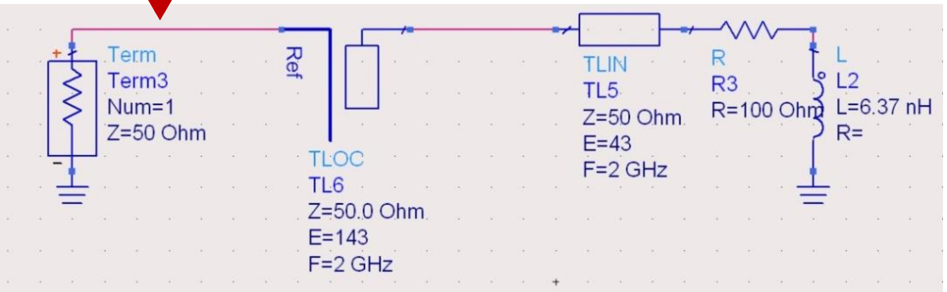
- We choose **one** of the two possible solutions
- The **sign** (+/-) chosen for the **series line** equation imposes the **sign** used for the **series stub** equation

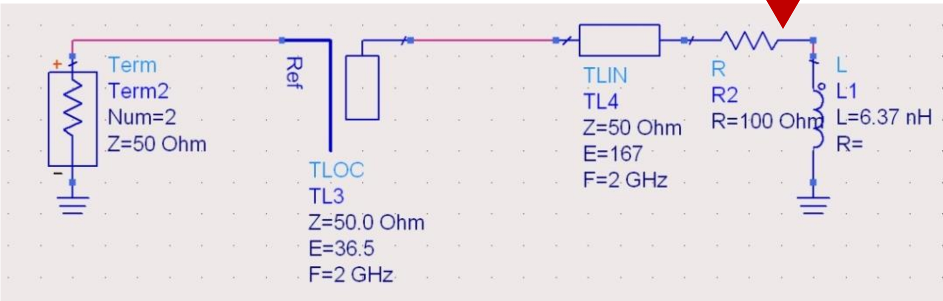
$$l_1 = \frac{43.1^\circ}{360^\circ} \cdot \lambda = 0.120 \cdot \lambda$$

$$l_2 = \frac{143.2^\circ}{360^\circ} \cdot \lambda = 0.398 \cdot \lambda$$

$$l_1 = \frac{166.8^\circ}{360^\circ} \cdot \lambda = 0.463 \cdot \lambda$$

$$l_2 = \frac{36.8^\circ}{360^\circ} \cdot \lambda = 0.102 \cdot \lambda$$



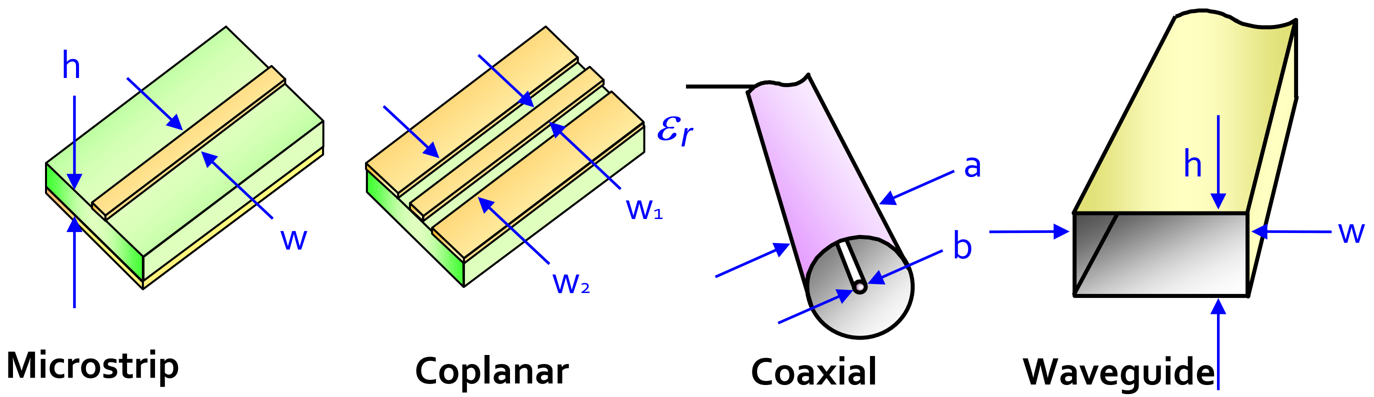



# Single stub tuning

- We choose one of the 8 possible solutions (series/shunt, oc./sc.), taking into account:
  - physical dimensions (area occupied on chip/board)
  - sensitivity of the match on length error ($\Delta\Gamma/\Delta E$, $\Delta\Gamma/\Delta l$)
  - convenient frequency behavior (bandwidth)

# Single stub tuning

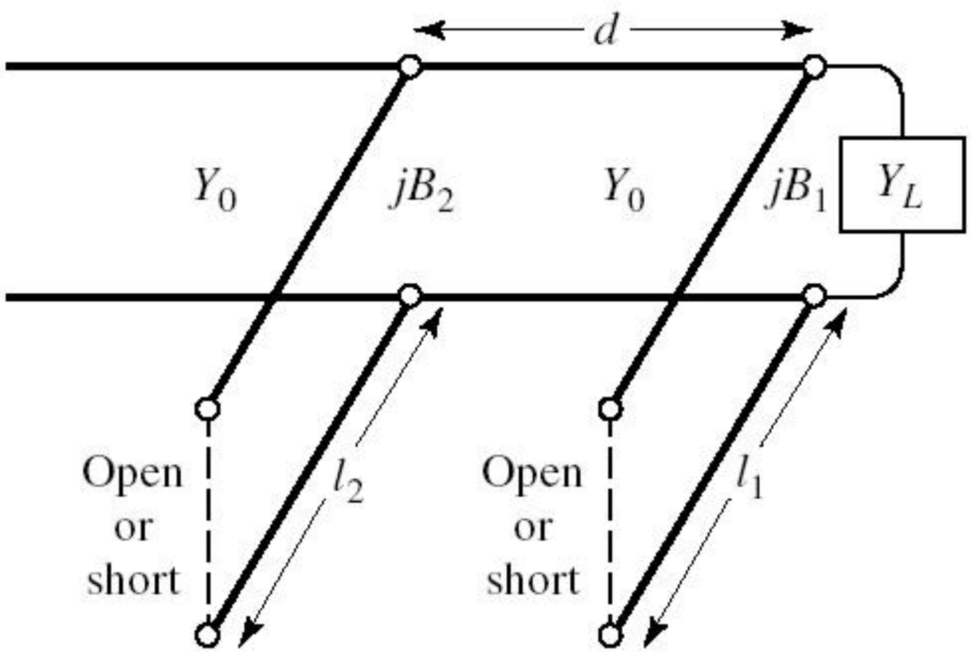
- We choose one of the 8 possible solutions (series/shunt, oc./sc.), taking into account :
  - physical realizability (in the line technology we use)




- Main disadvantage:
  - requires a variable length of line between the load and the stub

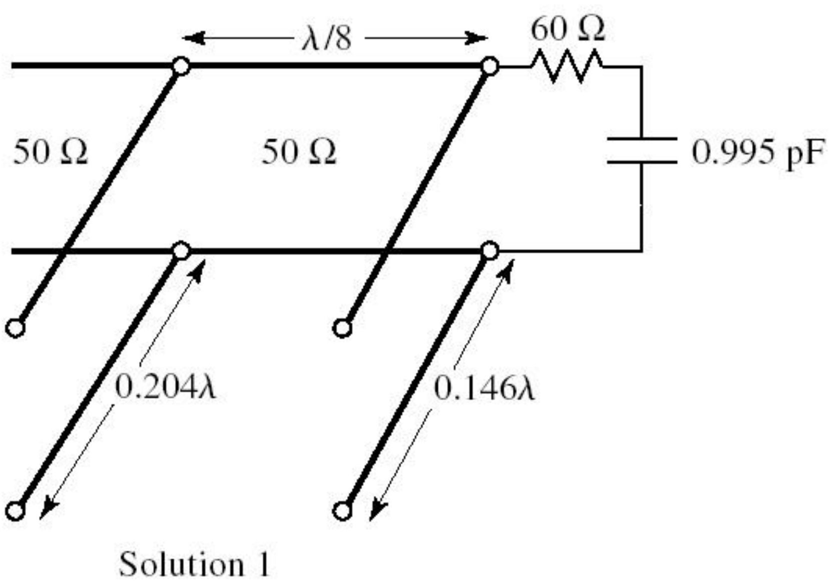
# Double stub tuning

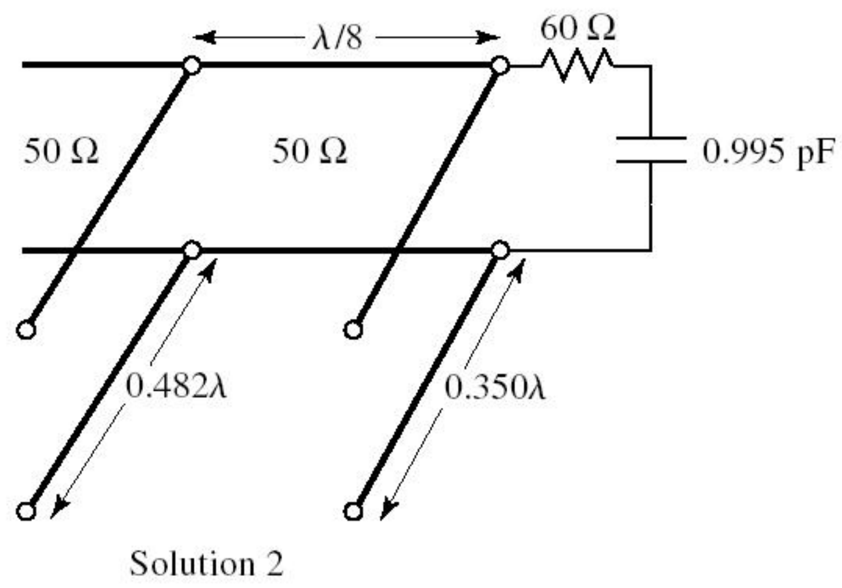
- Double stub tuning
- uses two tuning stubs in fixed positions (a fixed length of line between the stubs)



# Double stub tuning

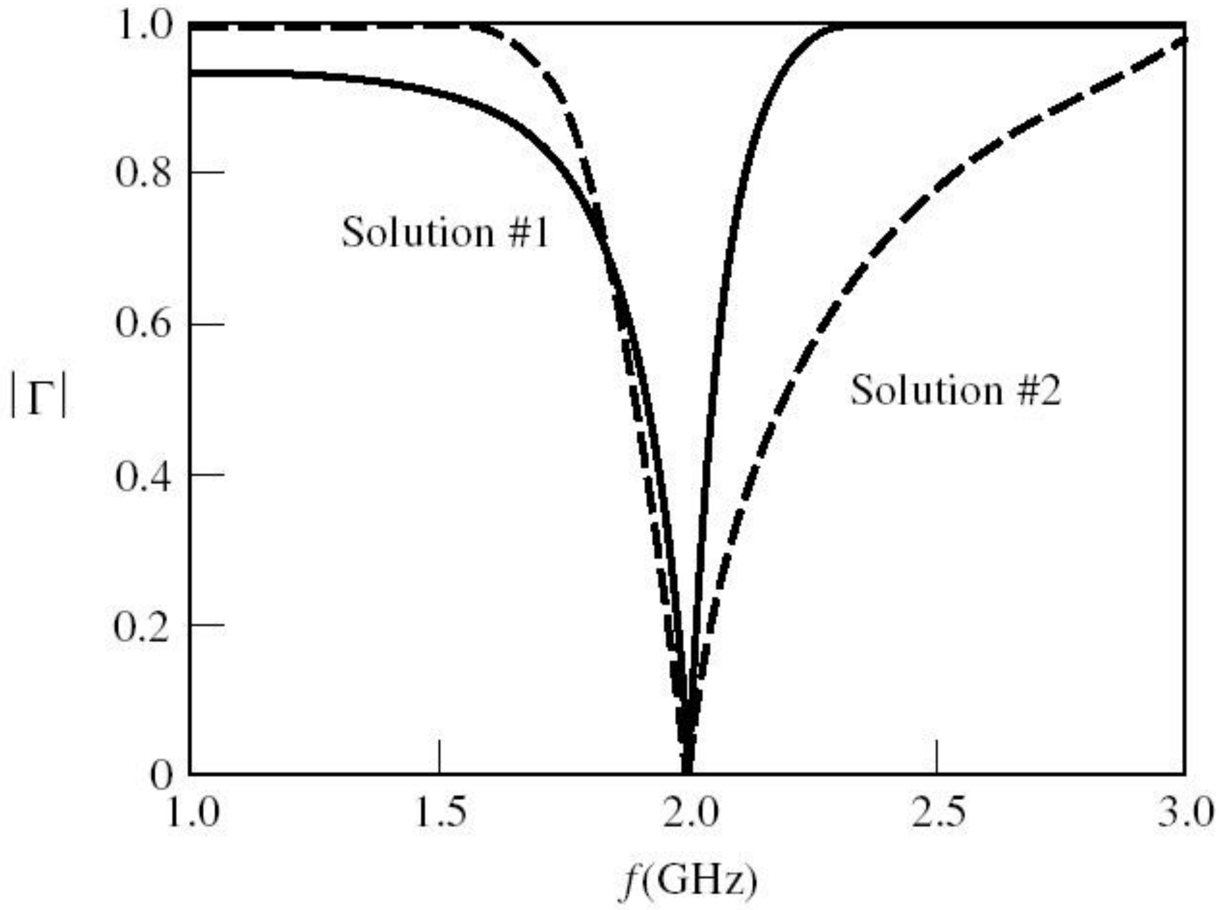
- same load: 60 Ω series with 0.995 pF at 2GHz
- two possible solutions



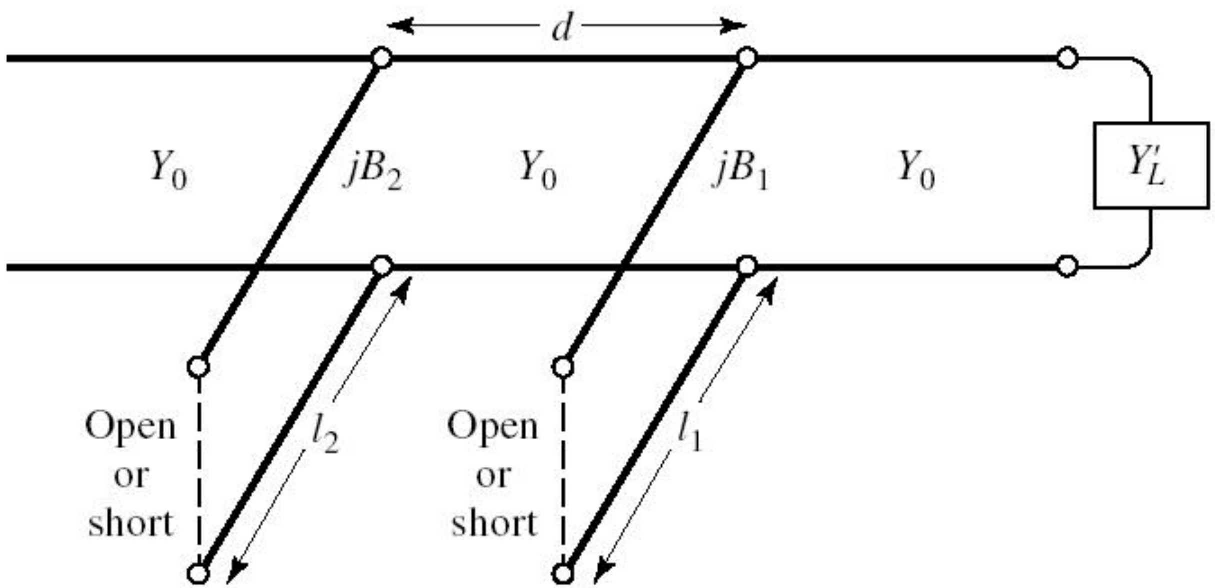
# Double stub tuning

- two possible solutions

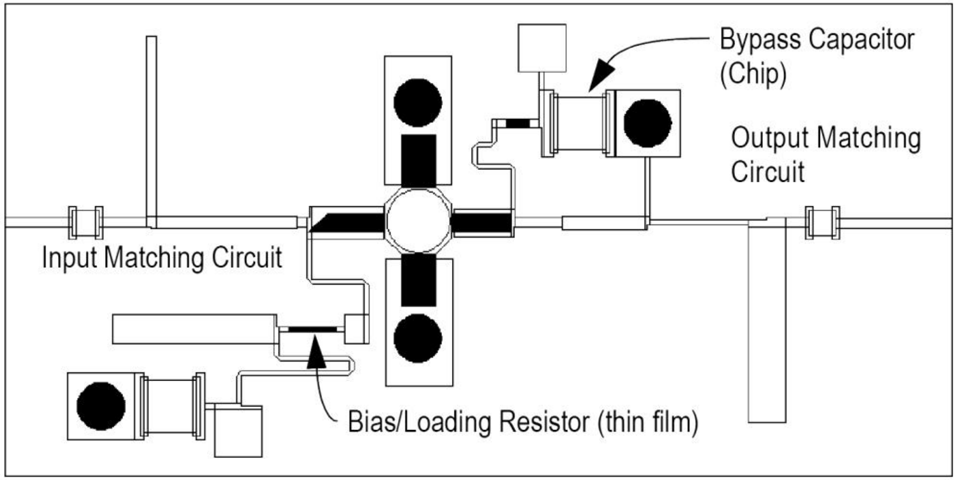


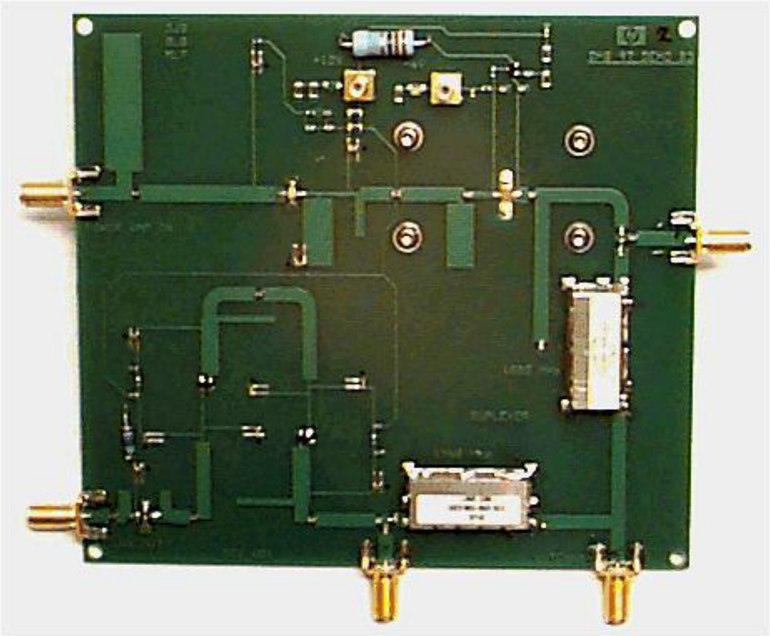
# Double stub tuning

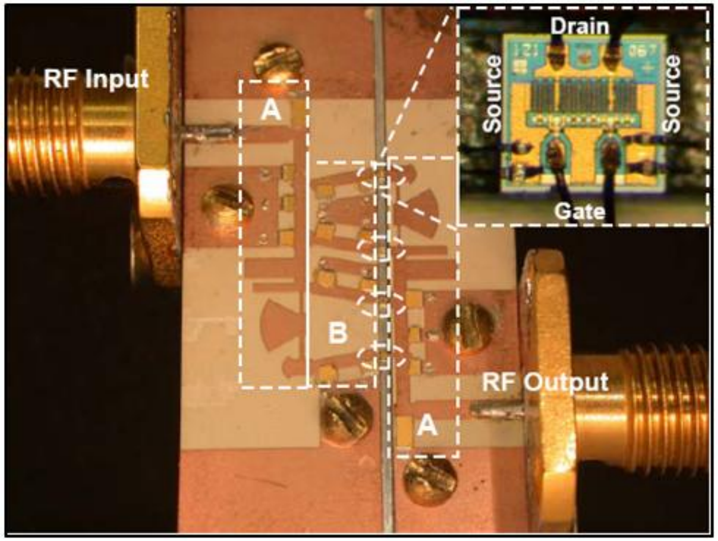
- Typically d=λ/8 or d=3λ/8
- **Not possible** for every load
  - unless we can add a specific length of line between the load and the first stub

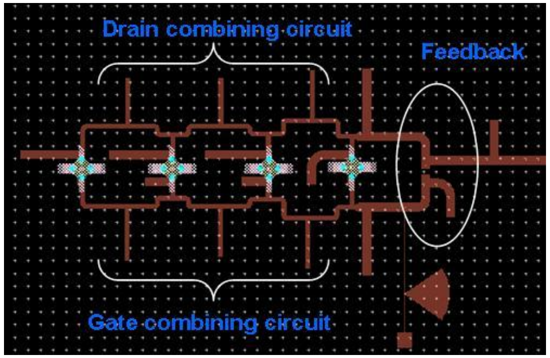


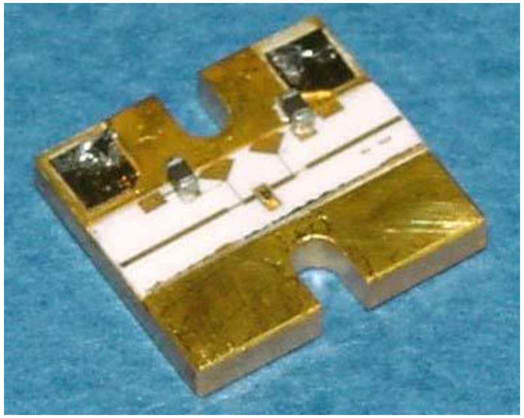
# Impedance Matching with Stubs



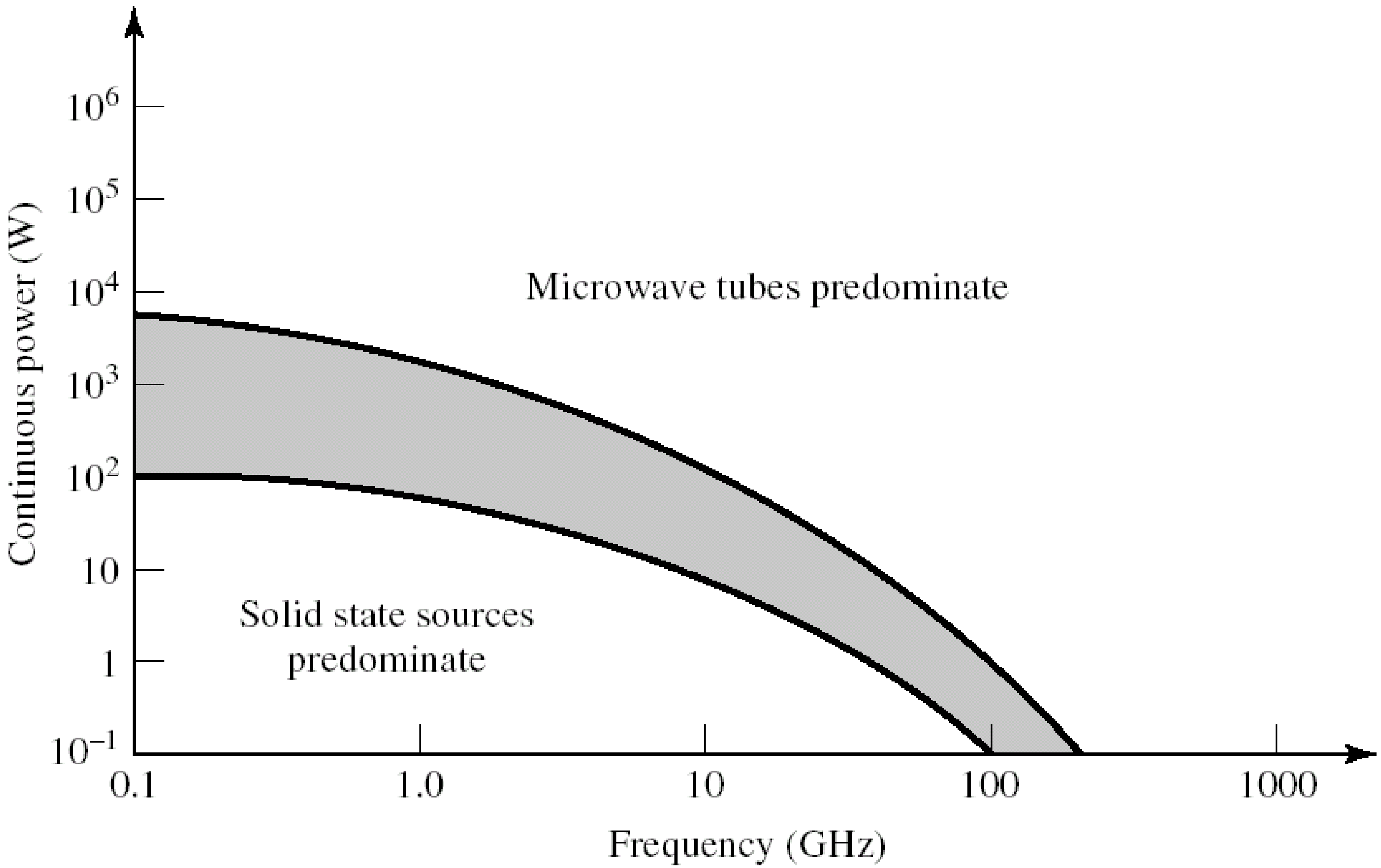


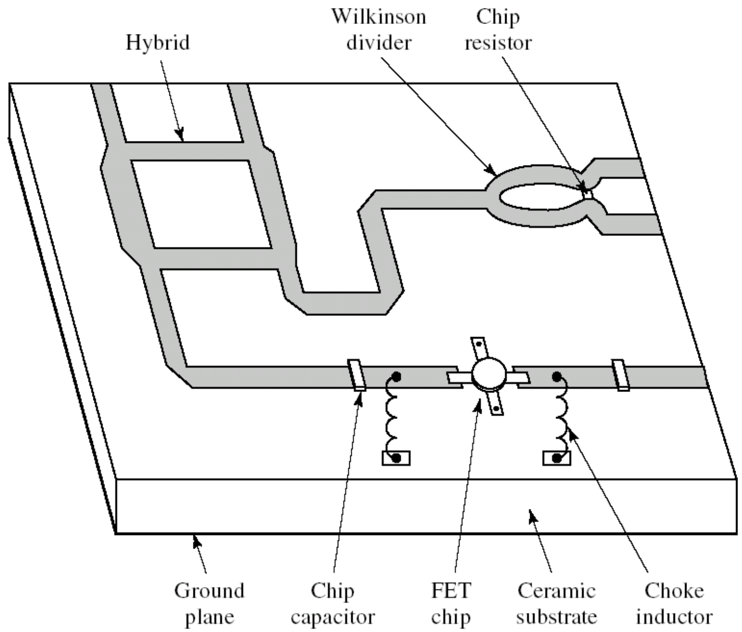



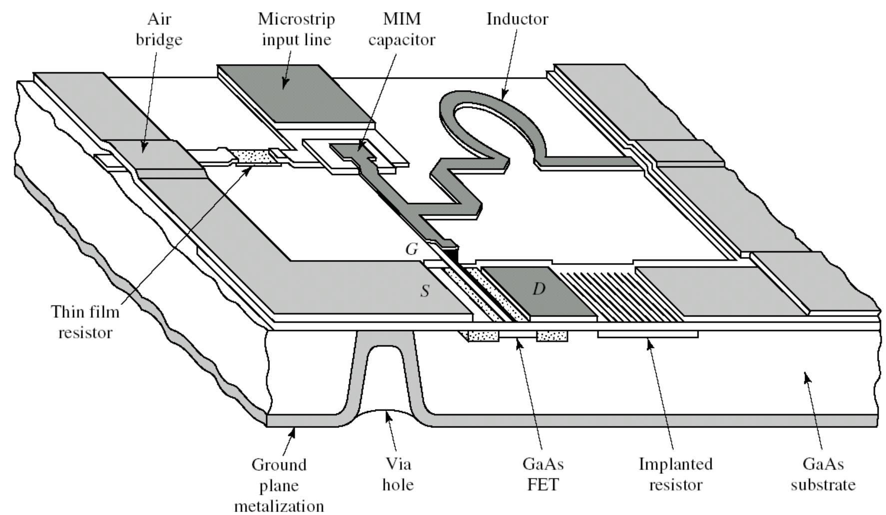
# Microwave Amplifiers

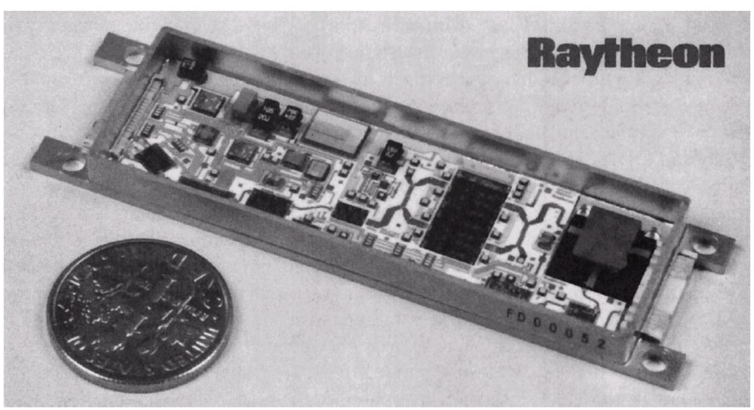
# Microwave Amplifiers

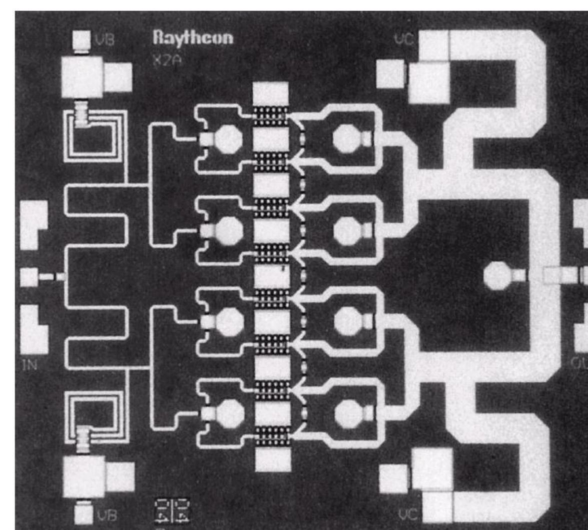


# Microwave Integrated Circuits

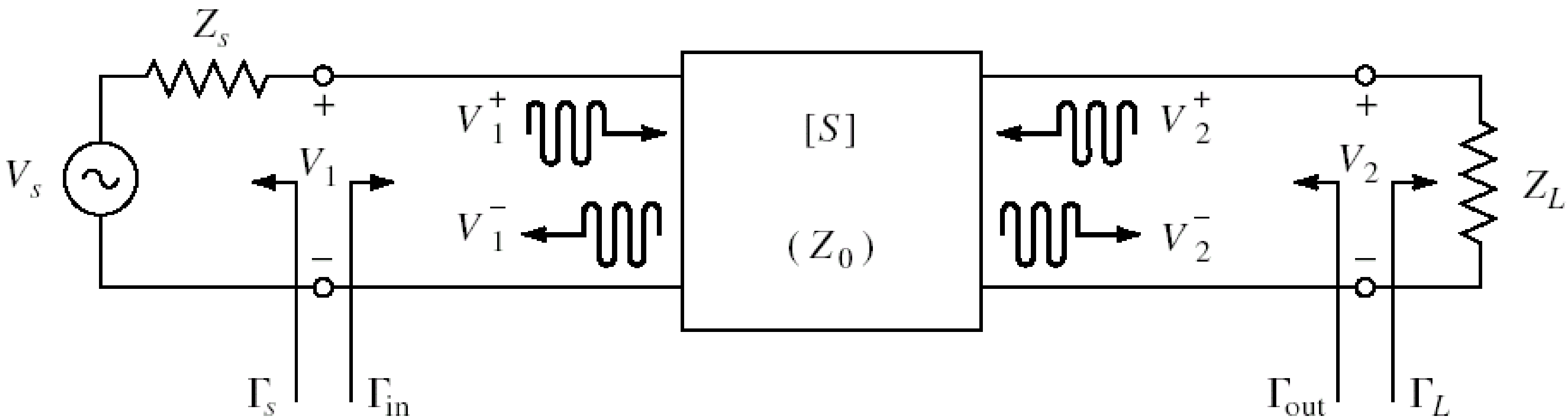


# Amplifier as two-port




- Charaterized with S parameters
- normalized at Zo (implicit 50Ω)
- Datasheets: S parameters for specific bias conditions

# Datasheets

CEL

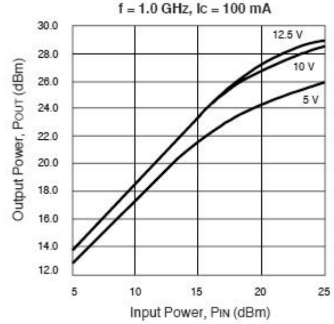
## NE46100 / NE46134

## NPN MEDIUM POWER MICROWAVE TRANSISTOR

### FEATURES

- **HIGH DYNAMIC RANGE**
- **LOW IM DISTORTION:** -40 dBc
- **HIGH OUTPUT POWER :** 27.5 dBm at TYP
- **LOW NOISE:** 1.5 dB TYP at 500 MHz
- **LOW COST**

NE46134
TYPICAL OUTPUT POWER
vs. INPUT POWER
f = 1.0 GHz, $I_C$ = 100 mA




### DESCRIPTION

The NE461 series of NPN silicon epitaxial bipolar transistors is designed for medium power applications requiring high dynamic range. This device exhibits an outstanding combination of high gain and low intermodulation distortion, as well as low noise figure. The NE461 series offers excellent performance and reliability at low cost through titanium, platinum, gold metallization system and direct nitride passivation of the surface of the chip. Devices are available in a low cost surface mount package (SOT-89) as well as in chip form.

### ELECTRICAL CHARACTERISTICS ($T_A$ = 25°C)

| | PART NUMBER<br>EIAJ[1] REGISTERED NUMBER<br>PACKAGE OUTLINE | | NE46100<br><br>00 (CHIP) | | | NE46134<br>2SC4536<br>34 | | |
|---|---|---|---|---|---|---|---|---|
| SYMBOLS | PARAMETERS AND CONDITIONS | UNITS | MIN | TYP | MAX | MIN | TYP | MAX |
| $f_T$ | Gain Bandwidth Product at $V_{CE}$ = 10 V, $I_C$ = 100 mA | GHz | | 5.5 | | | 5.5 | |
| $NF_{MIN}$ | Minimum Noise Figure[3] at $V_{CE}$ = 10 V, $I_C$ = 50 mA, 500 MHz<br>$V_{CE}$ = 10 V, $I_C$ = 50 mA, 1 GHz | dB<br>dB | | 1.5<br>2.0 | | | 1.5<br>2.0 | |
| $G_L$ | Linear Gain, $V_{CE}$ = 12.5 V, $I_C$ = 100 mA, 2.0 GHz<br>$V_{CE}$ = 12.5 V, $I_C$ = 100 mA, 1.0 GHz | dB<br>dB | | 9.0 | | | <br>8.0 | |
| $\lvert S_{21E}\rvert^2$ | Insertion Power Gain at 10 V, 50 mA, f = 1.0 GHz | dB | | 10.0 | | 5.5 | 7.0 | |
| $h_{FE}$ | DC Current Gain[2] at $V_{CE}$ = 10 V, $I_C$ = 50 mA | | 40 | | 200 | 40 | | 200 |
| $I_{CBO}$ | Collector Cutoff Current at $V_{CB}$ = 20 V, $I_E$ = 0 mA . | µA | | | 5.0 | | | 5.0 |
| $I_{EBO}$ | Emitter Cutoff Current at $V_{EB}$ = 2 V, $I_C$ = 0 mA | µA | | | 5.0 | | | 5.0 |
| $P_{1dB}$ | Output Power at 1 dB Compression, $V_{CE}$ = 12.5 V, $I_C$ = 100 mA, 2.0 GHz<br>$V_{CE}$ = 12.5 V, $I_C$ = 100 mA, 1.0 GHz | dBm<br>dBm | 27.0 | | | | <br>27.5 | |
| $IM_3$ | Intermodulation Distortion, 10 V, 100 mA, F1 = 1.0 GHz, F2 = 0.99 GHz, | | | | | | | |

# Datasheets

**NE46100**

**VCE = 5 V, IC = 50 mA**

| FREQUENCY (MHz) | S11 MAG | S11 ANG | S21 MAG | S21 ANG | S12 MAG | S12 ANG | S22 MAG | S22 ANG | K | MAG[2] (dB) |
|---|---|---|---|---|---|---|---|---|---|---|
| 100 | 0.778 | -137 | 26.776 | 114 | 0.028 | 30 | 0.555 | -102 | 0.16 | 29.8 |
| 200 | 0.815 | -159 | 14.407 | 100 | 0.035 | 29 | 0.434 | -135 | 0.36 | 26.2 |
| 500 | 0.826 | -177 | 5.855 | 84 | 0.040 | 38 | 0.400 | -162 | 0.75 | 21.7 |
| 800 | 0.827 | 176 | 3.682 | 76 | 0.052 | 43 | 0.402 | -169 | 0.91 | 18.5 |
| 1000 | 0.826 | 173 | 2.963 | 71 | 0.058 | 47 | 0.405 | -172 | 1.02 | 16.3 |
| 1200 | 0.825 | 170 | 2.441 | 66 | 0.064 | 47 | 0.412 | -174 | 1.08 | 14.0 |
| 1400 | 0.820 | 167 | 2.111 | 61 | 0.069 | 47 | 0.413 | -176 | 1.17 | 12.4 |
| 1600 | 0.828 | 165 | 1.863 | 57 | 0.078 | 54 | 0.426 | -177 | 1.15 | 11.4 |
| 1800 | 0.827 | 162 | 1.671 | 53 | 0.087 | 50 | 0.432 | -178 | 1.14 | 10.6 |
| 2000 | 0.828 | 159 | 1.484 | 49 | 0.093 | 50 | 0.431 | -180 | 1.17 | 9.5 |
| 2500 | 0.822 | 153 | 1.218 | 39 | 0.11 | 48 | 0.462 | 177 | 1.18 | 7.8 |
| 3000 | 0.818 | 148 | 1.010 | 30 | 0.135 | 46 | 0.490 | 174 | 1.16 | 6.3 |
| 3500 | 0.824 | 142 | 0.876 | 21 | 0.147 | 44 | 0.507 | 170 | 1.16 | 5.3 |
| 4000 | 0.812 | 137 | 0.762 | 13 | 0.168 | 38 | 0.535 | 167 | 1.14 | 4.3 |

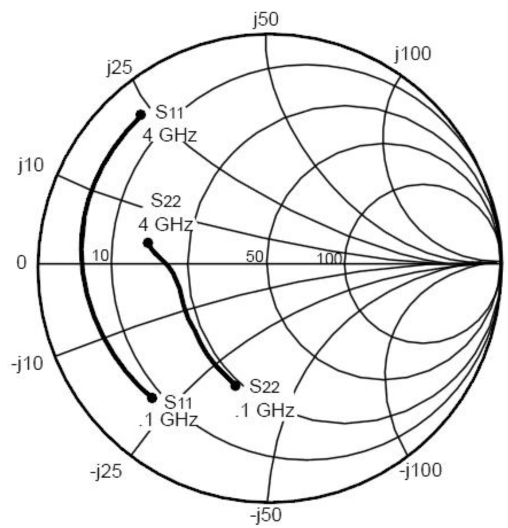
**VCE = 5 V, IC = 100 mA**

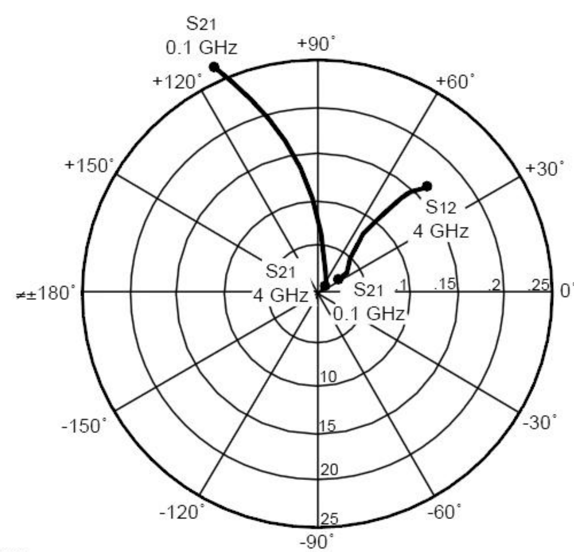
| FREQUENCY (MHz) | S11 MAG | S11 ANG | S21 MAG | S21 ANG | S12 MAG | S12 ANG | S22 MAG | S22 ANG | K | MAG[2] (dB) |
|---|---|---|---|---|---|---|---|---|---|---|
| 100 | 0.778 | -144 | 27.669 | 111 | 0.027 | 35 | 0.523 | -114 | 0.27 | 30.2 |
| 200 | 0.820 | -164 | 14.559 | 97 | 0.029 | 29 | 0.445 | -144 | 0.42 | 27.0 |
| 500 | 0.832 | -179 | 5.885 | 84 | 0.035 | 38 | 0.435 | -166 | 0.81 | 22.2 |
| 800 | 0.833 | 175 | 3.691 | 76 | 0.048 | 45 | 0.435 | -173 | 0.95 | 18.8 |
| 1000 | 0.831 | 172 | 2.980 | 71 | 0.056 | 51 | 0.437 | -176 | 1.05 | 16.0 |
| 1200 | 0.836 | 169 | 2.464 | 67 | 0.061 | 52 | 0.432 | -178 | 1.11 | 14.0 |
| 1400 | 0.829 | 166 | 2.121 | 61 | 0.072 | 53 | 0.447 | -180 | 1.12 | 12.6 |
| 1600 | 0.831 | 164 | 1.867 | 58 | 0.080 | 54 | 0.445 | 179 | 1.14 | 11.4 |

# Datasheets

## NE46100, NE46134

### TYPICAL COMMON EMITTER SCATTERING PARAMETERS[1] (TA = 25°C)



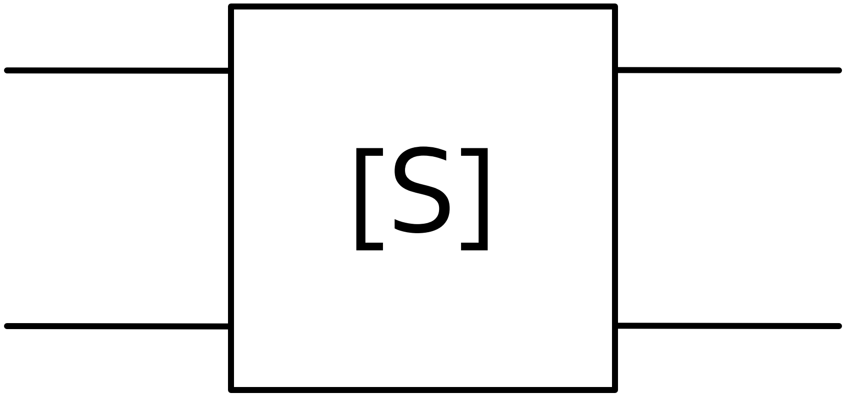

**Coordinates in Ohms**
**Frequency in GHz**
**VCE = 5 V, Ic = 50 mA**

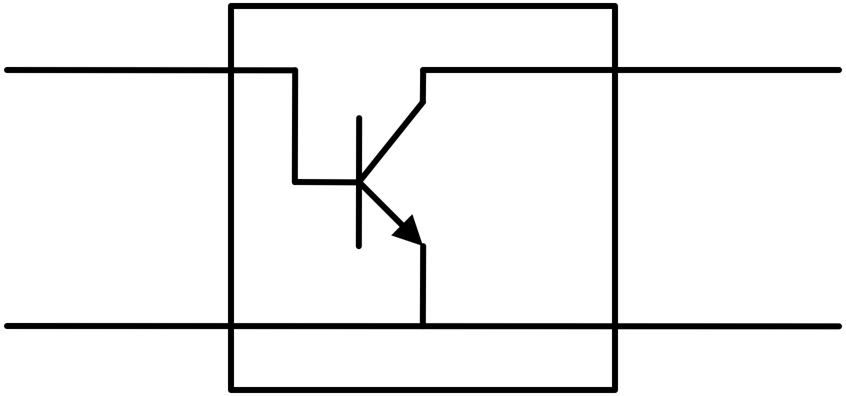
# S2P - Touchstone

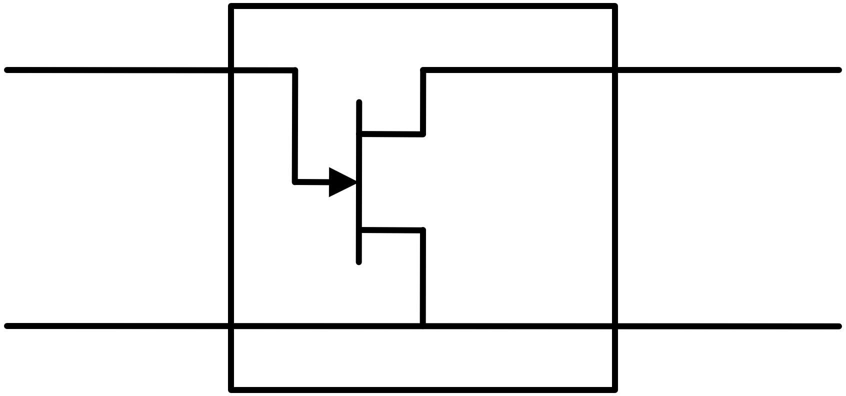
- Touchstone file format (*.s2p)

```
! SIEMENS Small Signal Semiconductors
! VDS = 3.5 V     ID = 15 mA
# GHz  S  MA  R  50
!  f        S11          S21          S12          S22
! GHz     MAG   ANG     MAG   ANG     MAG   ANG     MAG   ANG
 1.000 0.9800  -18.0   2.230  157.0  0.0240   74.0  0.6900  -15.0
 2.000 0.9500  -39.0   2.220  136.0  0.0450   57.0  0.6600  -30.0
 3.000 0.8900  -64.0   2.210  110.0  0.0680   40.0  0.6100  -45.0
 4.000 0.8200  -89.0   2.230   86.0  0.0850   23.0  0.5600  -62.0
 5.000 0.7400 -115.0   2.190   61.0  0.0990    7.0  0.4900  -80.0
 6.000 0.6500 -142.0   2.110   36.0  0.1070  -10.0  0.4100  -98.0
!
!  f      Fmin   Gammaopt  rn/50
! GHz      dB    MAG  ANG    -
 2.000     1.00  0.72   27   0.84
 4.000     1.40  0.64   61   0.58
```

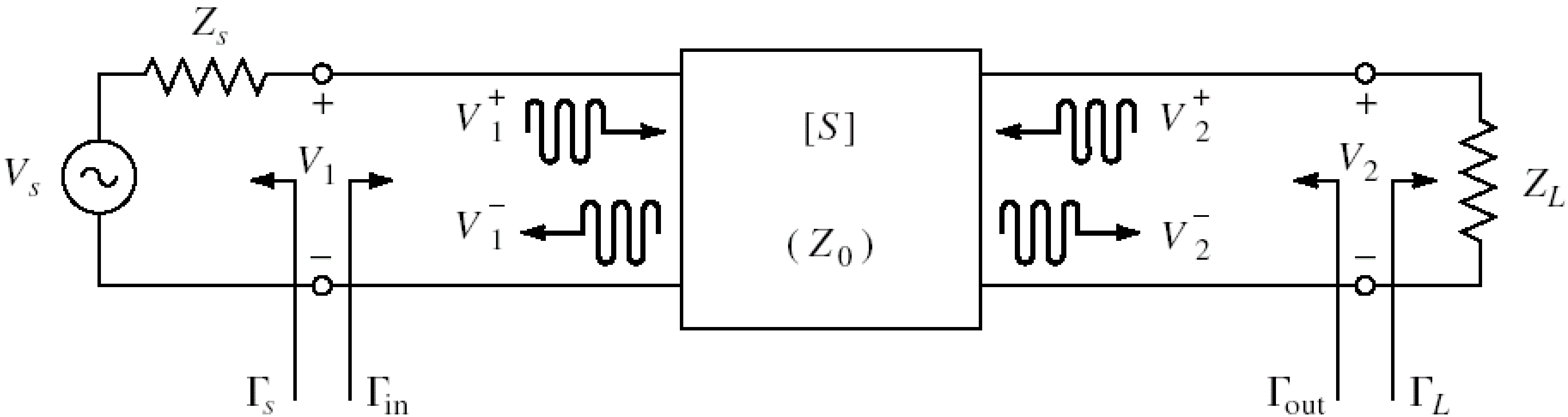
# S parameters for transistors





# Amplifier as two-port



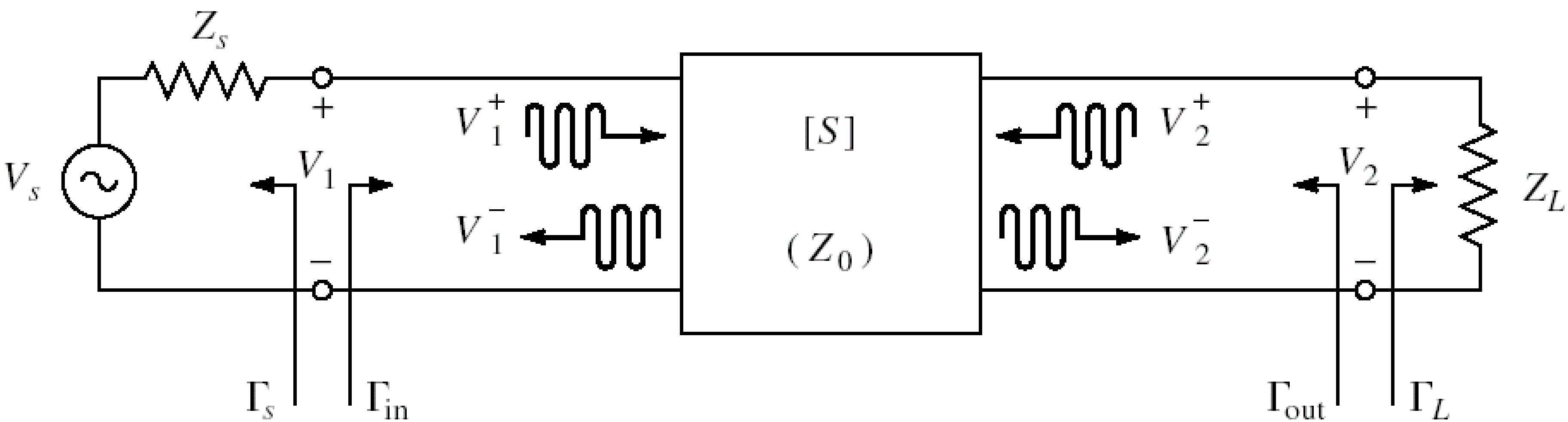

$$\Gamma_L = \frac{Z_L - Z_0}{Z_L + Z_0} \qquad \Gamma_S = \frac{Z_S - Z_0}{Z_S + Z_0} \qquad \begin{bmatrix} V_1^- \\ V_2^- \end{bmatrix} = \begin{bmatrix} S_{11} & S_{12} \\ S_{21} & S_{22} \end{bmatrix} \cdot \begin{bmatrix} V_1^+ \\ V_2^+ \end{bmatrix}$$

$$\Gamma_L = \frac{V_2^+}{V_2^-}$$

$$V_1^- = S_{11} \cdot V_1^+ + S_{12} \cdot V_2^+ = S_{11} \cdot V_1^+ + S_{12} \cdot \Gamma_L \cdot V_2^-$$

$$V_2^- = S_{21} \cdot V_1^+ + S_{22} \cdot V_2^+ = S_{21} \cdot V_1^+ + S_{22} \cdot \Gamma_L \cdot V_2^-$$

# Amplifier as two-port




$$V_1^- = S_{11} \cdot V_1^+ + S_{12} \cdot V_2^+ = S_{11} \cdot V_1^+ + S_{12} \cdot \Gamma_L \cdot V_2^-$$

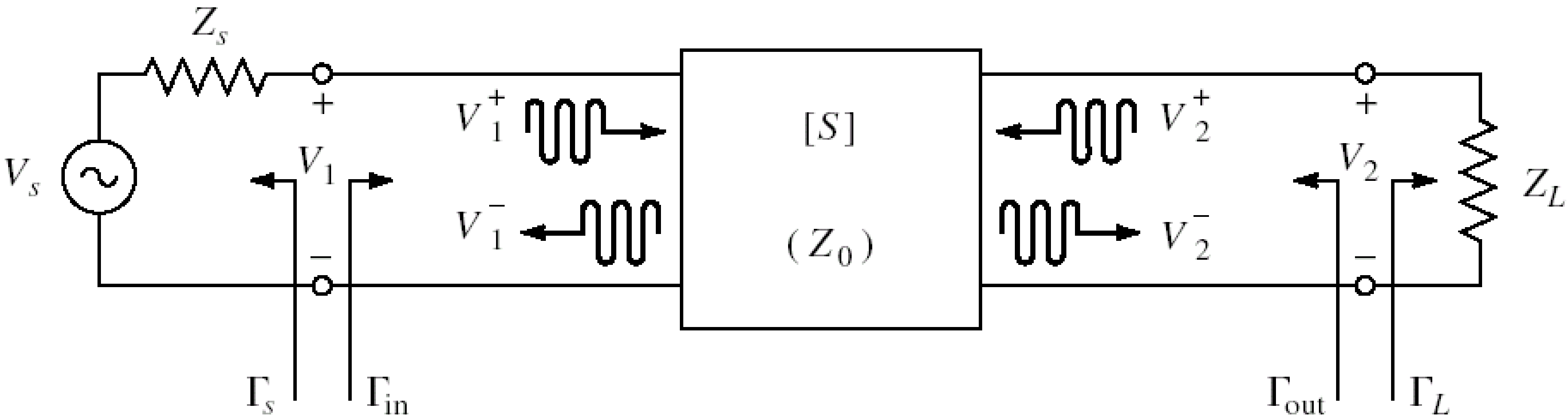
$$V_2^- = S_{21} \cdot V_1^+ + S_{22} \cdot V_2^+ = S_{21} \cdot V_1^+ + S_{22} \cdot \Gamma_L \cdot V_2^-$$

$$\Gamma_{in} = \frac{V_1^-}{V_1^+} = S_{11} + \frac{S_{12} \cdot S_{21} \cdot \Gamma_L}{1 - S_{22} \cdot \Gamma_L}$$

- similarly

$$\Gamma_{out} = \frac{V_2^-}{V_2^+} = S_{22} + \frac{S_{12} \cdot S_{21} \cdot \Gamma_S}{1 - S_{11} \cdot \Gamma_S}$$

# Amplifier as two-port




$$\Gamma_{in} = \frac{V_1^-}{V_1^+} = S_{11} + \frac{S_{12} \cdot S_{21} \cdot \Gamma_L}{1 - S_{22} \cdot \Gamma_L}$$

$$\Gamma_{out} = \frac{V_2^-}{V_2^+} = S_{22} + \frac{S_{12} \cdot S_{21} \cdot \Gamma_S}{1 - S_{11} \cdot \Gamma_S}$$

# Signal power

$$\Gamma_{in} = \frac{V_1^-}{V_1^+} = S_{11} + \frac{S_{12} \cdot S_{21} \cdot \Gamma_L}{1 - S_{22} \cdot \Gamma_L} \qquad \Gamma_{in} = \frac{Z_{in} - Z_0}{Z_{in} + Z_0}$$

$$V_1 = \frac{V_S \cdot Z_{in}}{Z_S + Z_{in}} = V_1^+ + V_1^- = V_1^+ \cdot (1 + \Gamma_{in}) \qquad V_1^+ = \frac{V_S}{2} \frac{(1 - \Gamma_S)}{(1 - \Gamma_S \cdot \Gamma_{in})}$$

- C3 $\quad P_{in} = \frac{1}{2 \cdot Z_0} \cdot \left|V_1^+\right|^2 \cdot \left(1 - \left|\Gamma_{in}\right|^2\right) \qquad P_L = \frac{1}{2 \cdot Z_0} \cdot \left|V_2^-\right|^2 \cdot \left(1 - \left|\Gamma_L\right|^2\right)$

$$P_{in} = \frac{\left|V_S\right|^2}{8 \cdot Z_0} \cdot \frac{\left|1 - \Gamma_S\right|^2}{\left|1 - \Gamma_S \cdot \Gamma_{in}\right|^2} \left(1 - \left|\Gamma_{in}\right|^2\right)$$

$$V_2^- = S_{21} \cdot V_1^+ + S_{22} \cdot V_2^+ = S_{21} \cdot V_1^+ + S_{22} \cdot \Gamma_L \cdot V_2^- \qquad V_2^- = \frac{S_{21} \cdot V_1^+}{1 - S_{22} \cdot \Gamma_L}$$

$$P_L = \frac{\left|V_1^+\right|^2}{2 \cdot Z_0} \cdot \frac{\left|S_{21}\right|^2}{\left|1 - S_{22} \cdot \Gamma_L\right|^2} \left(1 - \left|\Gamma_L\right|^2\right) \qquad P_L = \frac{\left|V_S\right|^2}{8 \cdot Z_0} \cdot \frac{\left|S_{21}\right|^2 \cdot \left(1 - \left|\Gamma_L\right|^2\right)}{\left|1 - S_{22} \cdot \Gamma_L\right|^2} \cdot \frac{\left|1 - \Gamma_S\right|^2}{\left|1 - \Gamma_S \cdot \Gamma_{in}\right|^2}$$

# Signal power

- Signal power

$$P_{in} = \frac{|V_S|^2}{8\cdot Z_0}\cdot\frac{|1-\Gamma_S|^2}{|1-\Gamma_S\cdot\Gamma_{in}|^2}\left(1-|\Gamma_{in}|^2\right)$$

$$P_L = \frac{|V_S|^2}{8\cdot Z_0}\cdot\frac{|S_{21}|^2\cdot\left(1-|\Gamma_L|^2\right)}{|1-S_{22}\cdot\Gamma_L|^2}\cdot\frac{|1-\Gamma_S|^2}{|1-\Gamma_S\cdot\Gamma_{in}|^2}$$

- Power available from the source

$$P_{av\,S} = P_{in}\Big|_{\Gamma_{in}=\Gamma_S^*} = \frac{|V_S|^2}{8\cdot Z_0}\cdot\frac{|1-\Gamma_S|^2}{\left(1-|\Gamma_S|^2\right)}$$

- Power available on the load (from the network)

$$P_{av\,L} = P_L\Big|_{\Gamma_L=\Gamma_{out}^*} = \frac{|V_S|^2}{8\cdot Z_0}\cdot\frac{|S_{21}|^2\cdot|1-\Gamma_S|^2}{|1-S_{11}\cdot\Gamma_S|^2\cdot\left(1-|\Gamma_{out}|^2\right)}$$

# Two-Port Power Gains

- Power Gain

$$G = \frac{P_L}{P_{in}} = \frac{|S_{21}|^2 \cdot \left(1 - |\Gamma_L|^2\right)}{\left(1 - |\Gamma_{in}|^2\right) \cdot |1 - S_{22} \cdot \Gamma_L|^2}$$

$$P_{in} = P_{in}\left(\Gamma_S, \Gamma_{in}\left(\Gamma_L\right), S\right)$$

$$P_L = P_L\left(\Gamma_S, \Gamma_{in}\left(\Gamma_L\right), S\right)$$

- The **actual** power gain **introduced** by the amplifier is less important because a higher gain may be accompanied by a **decrease** in input power (power actually drained from the source)
- We prefer to characterize the amplifier effect looking to the **power actually delivered to the load** in relation to the power **available from the source** (which is a constant)

# Two-Port Power Gains

- **Available** power gain

$$G_A = \frac{P_{av\,L}}{P_{av\,S}} = \frac{|S_{21}|^2 \cdot \left(1-|\Gamma_S|^2\right)}{|1-S_{22}\cdot\Gamma_L|^2 \cdot \left(1-|\Gamma_{out}|^2\right)}$$

- **Transducer** power gain

$$G_T = \frac{P_L}{P_{av\,S}} = \frac{|S_{21}|^2 \cdot \left(1-|\Gamma_S|^2\right)\cdot\left(1-|\Gamma_L|^2\right)}{|1-\Gamma_S\cdot\Gamma_{in}|^2 \cdot |1-S_{22}\cdot\Gamma_L|^2}$$

$$\Gamma_{in} = \Gamma_{in}(\Gamma_L)$$

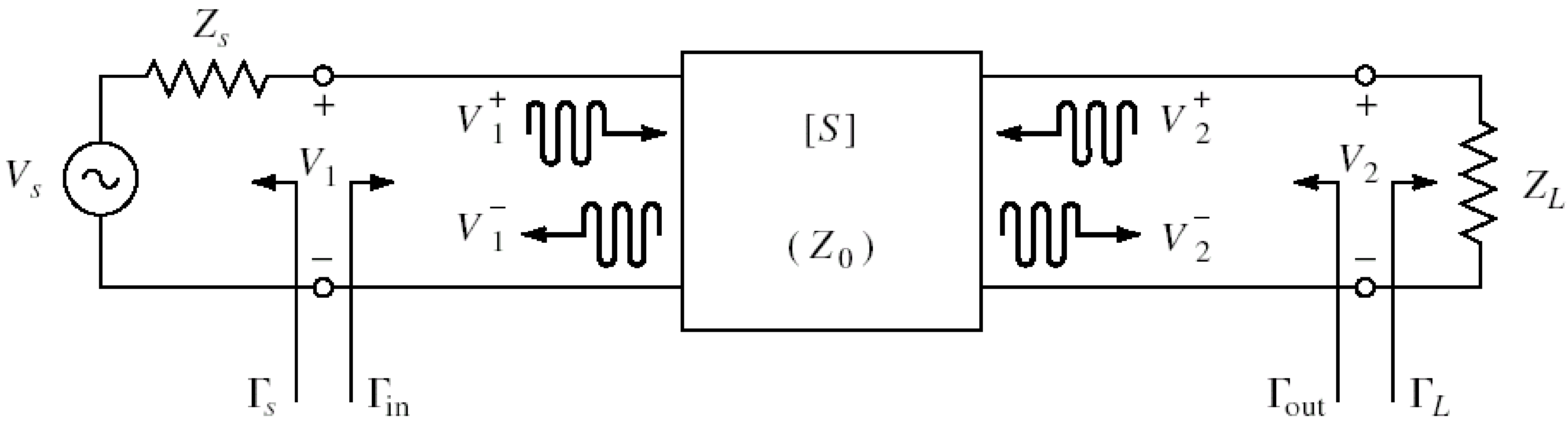
- **Unilateral transducer** power gain

$$G_{TU} = |S_{21}|^2 \cdot \frac{1-|\Gamma_S|^2}{|1-S_{11}\cdot\Gamma_S|^2} \cdot \frac{1-|\Gamma_L|^2}{|1-S_{22}\cdot\Gamma_L|^2}$$

$$S_{12} \cong 0 \qquad \Gamma_{in} = S_{11}$$

Input and output can be treated independently

# Amplifier as two-port

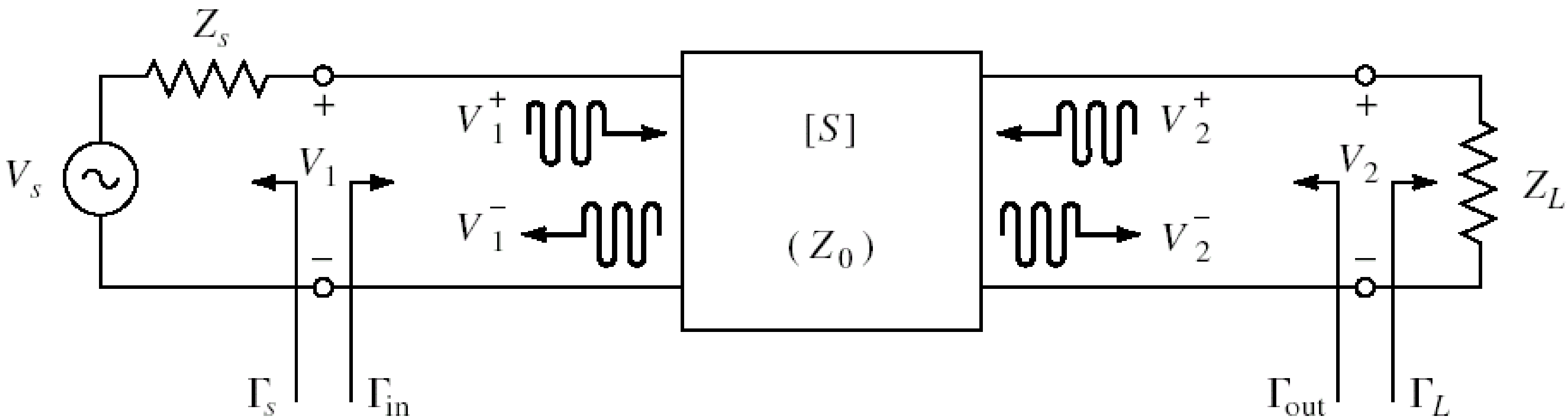



- For an amplifier two-port we are interested in:
  - stability
  - power gain
  - noise (sometimes – small signals)
  - linearity (sometimes – large signals)

Stability

# Microwave Amplifiers

# Amplifier as two-port




- For an amplifier two-port we are interested in:
  - **stability**
  - power gain
  - noise (sometimes – small signals)
  - linearity (sometimes – large signals)

# Stability

- L5 $\Gamma = \Gamma_r + j \cdot \Gamma_i$ $r_L = \dfrac{1 - \Gamma_r^2 - \Gamma_i^2}{(1 - \Gamma_r)^2 + \Gamma_i^2}$

  $Z_{in}$ $\Gamma_{in} = \Gamma_r + j \cdot \Gamma_i$

- instability

  $\mathrm{Re}\{Z_{in}\} < 0 \quad \Leftrightarrow \quad 1 - \Gamma_r^2 - \Gamma_i^2 < 0$ $|\Gamma_{in}| > 1$

- stability, $Z_{in}$
  - conditions to be met by $\Gamma_L$ to achieve (input) stability

    $|\Gamma_{in}| < 1$ $\left| S_{11} + \dfrac{S_{12} \cdot S_{21} \cdot \Gamma_L}{1 - S_{22} \cdot \Gamma_L} \right| < 1$

- similarly $Z_{out}$
  - conditions to be met by $\Gamma_S$ to achieve (output) stability

# Stability

$$|\Gamma_{in}| < 1 \qquad \left| S_{11} + \frac{S_{12} \cdot S_{21} \cdot \Gamma_L}{1 - S_{22} \cdot \Gamma_L} \right| < 1$$

- We can calculate conditions to be met by $\Gamma_L$ to achieve stability

$$|\Gamma_{out}| < 1 \qquad \left| S_{22} + \frac{S_{12} \cdot S_{21} \cdot \Gamma_S}{1 - S_{11} \cdot \Gamma_S} \right| < 1$$

- We can calculate conditions to be met by $\Gamma_S$ to achieve stability

# Stability

$$|\Gamma_{in}| < 1 \qquad \left| S_{11} + \frac{S_{12} \cdot S_{21} \cdot \Gamma_L}{1 - S_{22} \cdot \Gamma_L} \right| < 1$$

- The limit between stability/instability

$$|\Gamma_{in}| = 1 \qquad \left| S_{11} + \frac{S_{12} \cdot S_{21} \cdot \Gamma_L}{1 - S_{22} \cdot \Gamma_L} \right| = 1$$

$$|S_{11} \cdot (1 - S_{22} \cdot \Gamma_L) + S_{12} \cdot S_{21} \cdot \Gamma_L| = |1 - S_{22} \cdot \Gamma_L|$$

- determinant of the S matrix $\Delta = S_{11} \cdot S_{22} - S_{12} \cdot S_{21}$

$$|S_{11} - \Delta \cdot \Gamma_L| = |1 - S_{22} \cdot \Gamma_L|$$

$$|S_{11} - \Delta \cdot \Gamma_L|^2 = |1 - S_{22} \cdot \Gamma_L|^2$$

# Stability

$$|S_{11}-\Delta\cdot\Gamma_L|^2=|1-S_{22}\cdot\Gamma_L|^2$$

$$a\cdot a^*=|a|\cdot e^{j\theta}\cdot|a|\cdot e^{-j\theta}=|a|^2$$

$$|a+b|^2=(a+b)\cdot(a+b)^*=(a+b)\cdot\left(a^*+b^*\right)=|a|^2+|b|^2+a^*\cdot b+a\cdot b^*$$

$$|S_{11}|^2+|\Delta|^2\cdot|\Gamma_L|^2-\left(\Delta\cdot\Gamma_L\cdot S_{11}^*+\Delta^*\cdot\Gamma_L^*\cdot S_{11}\right)=1+|S_{22}|^2\cdot|\Gamma_L|^2-\left(S_{22}^*\cdot\Gamma_L^*+S_{22}\cdot\Gamma_L\right)$$

$$\left(|S_{22}|^2-|\Delta|^2\right)\cdot\Gamma_L\cdot\Gamma_L^*-\left(S_{22}-\Delta\cdot S_{11}^*\right)\cdot\Gamma_L-\left(S_{22}^*-\Delta^*\cdot S_{11}\right)\cdot\Gamma_L^*=|S_{11}|^2-1$$

$$\Gamma_L\cdot\Gamma_L^*-\frac{\left(S_{22}-\Delta\cdot S_{11}^*\right)\cdot\Gamma_L+\left(S_{22}^*-\Delta^*\cdot S_{11}\right)\cdot\Gamma_L^*}{|S_{22}|^2-|\Delta|^2}=\frac{|S_{11}|^2-1}{|S_{22}|^2-|\Delta|^2}\quad /+\frac{|S_{22}-\Delta\cdot S_{11}^*|^2}{\left(|S_{22}|^2-|\Delta|^2\right)^2}$$

$$\left|\Gamma_L-\frac{\left(S_{22}-\Delta\cdot S_{11}^*\right)^*}{|S_{22}|^2-|\Delta|^2}\right|^2=\frac{|S_{11}|^2-1}{|S_{22}|^2-|\Delta|^2}+\frac{|S_{22}-\Delta\cdot S_{11}^*|^2}{\left(|S_{22}|^2-|\Delta|^2\right)^2}$$

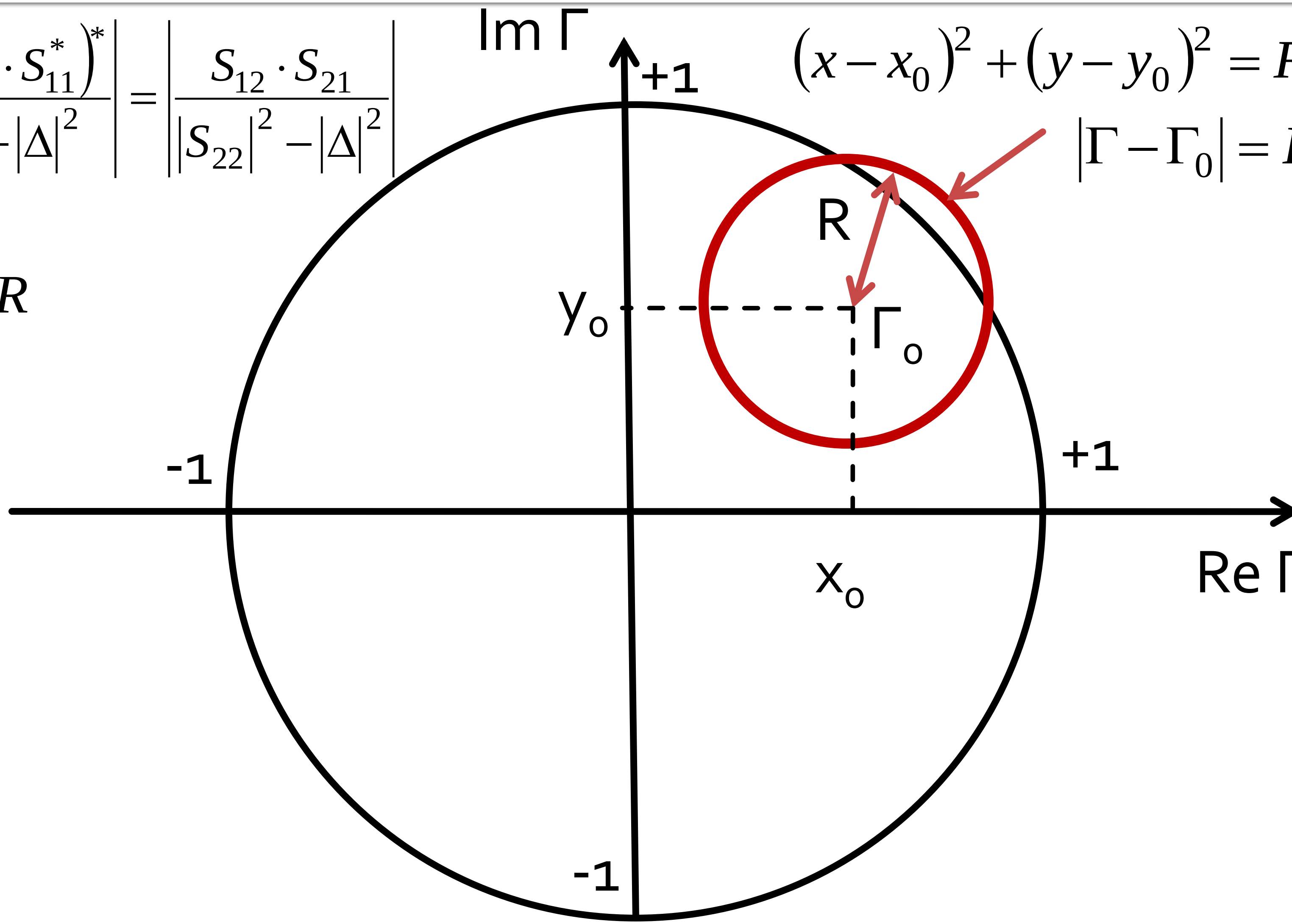
# Stability

$$\left|\Gamma_L - \frac{\left(S_{22} - \Delta \cdot S_{11}^*\right)^*}{\left|S_{22}\right|^2 - \left|\Delta\right|^2}\right| = \left|\frac{S_{12} \cdot S_{21}}{\left|S_{22}\right|^2 - \left|\Delta\right|^2}\right|$$

$$\left|\Gamma - \Gamma_0\right| = R$$

$$\left(x - x_0\right)^2 + \left(y - y_0\right)^2 = R^2$$

$$\left|\Gamma - \Gamma_0\right| = R$$



# Output stability circle (CSOUT)

$$\left|\Gamma_L - \frac{\left(S_{22} - \Delta \cdot S_{11}^*\right)^*}{\left|S_{22}\right|^2 - \left|\Delta\right|^2}\right| = \left|\frac{S_{12} \cdot S_{21}}{\left|S_{22}\right|^2 - \left|\Delta\right|^2}\right| \qquad \left|\Gamma_L - C_L\right| = R_L$$

- We obtain the equation of a circle in the complex plane, which represents the locus of $\Gamma_L$ for the **limit between stability and instability** ($|\Gamma_{in}| = 1$)
- This circle is the **output stability circle** ($\Gamma_L$)

$$C_L = \frac{\left(S_{22} - \Delta \cdot S_{11}^*\right)^*}{\left|S_{22}\right|^2 - \left|\Delta\right|^2} \qquad R_L = \frac{\left|S_{12} \cdot S_{21}\right|}{\left|\left|S_{22}\right|^2 - \left|\Delta\right|^2\right|}$$

# Input stability circle (CSIN)

- Similarly

$$|\Gamma_{out}| = 1 \qquad \left| S_{22} + \frac{S_{12} \cdot S_{21} \cdot \Gamma_S}{1 - S_{11} \cdot \Gamma_S} \right| = 1$$

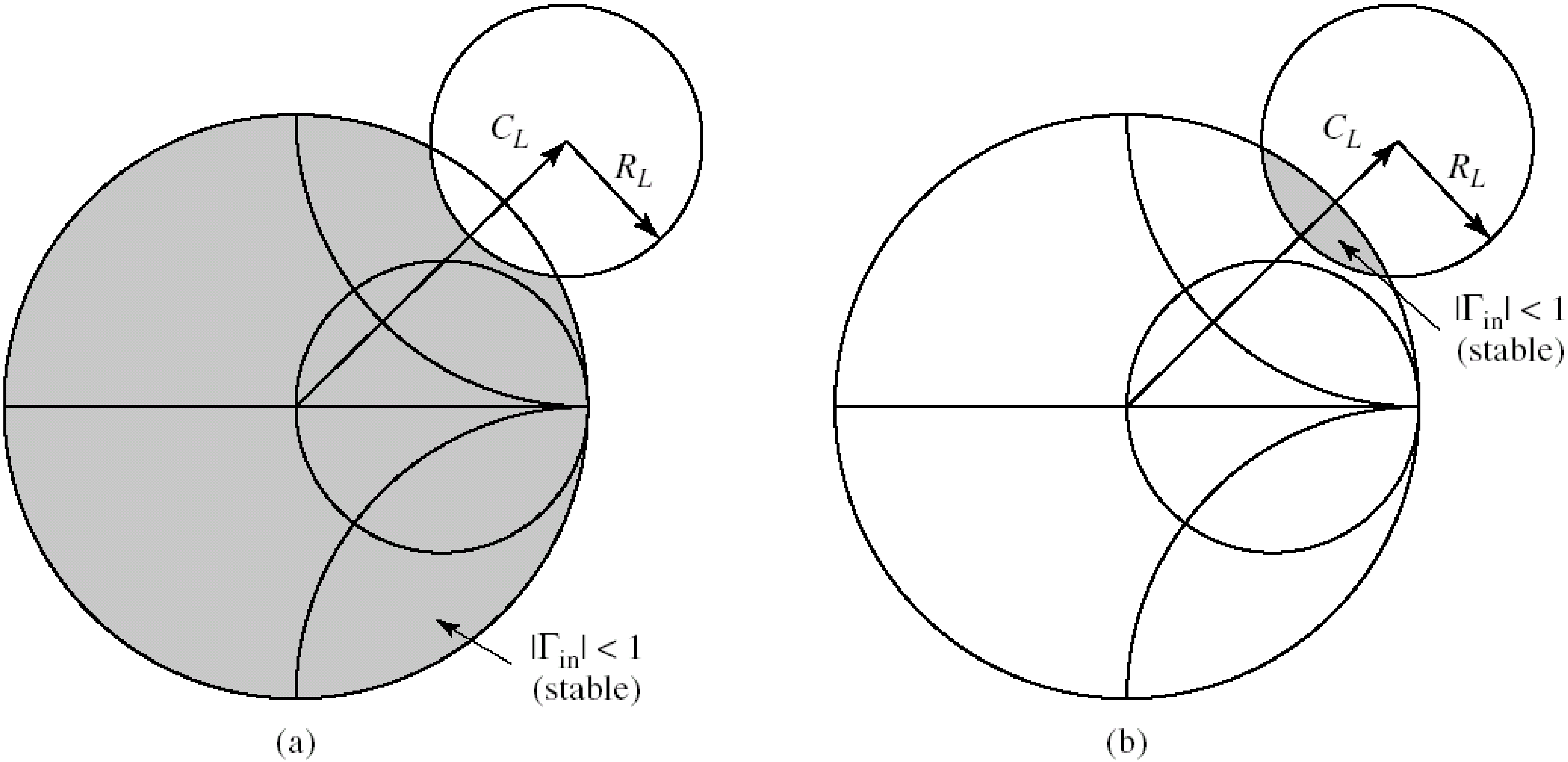
- We obtain the equation of a circle in the complex plane, which represents the locus of $\Gamma_S$ for the **limit between stability and instability** ($|\Gamma_{out}| = 1$)
- This circle is the **input stability circle** ($\Gamma_S$)

$$C_S = \frac{\left(S_{11} - \Delta \cdot S_{22}^*\right)^*}{|S_{11}|^2 - |\Delta|^2} \qquad R_S = \frac{|S_{12} \cdot S_{21}|}{\left||S_{11}|^2 - |\Delta|^2\right|}$$

# Output stability circle (CSOUT)

- The **output stability circle** represents the locus of $\Gamma_L$ for the **limit between stability and instability** ($|\Gamma_{in}| = 1$)
- The circle divides the complex planes in two areas, the **inside** and the **outside** of the circle
- The two areas will represent the locus of $\Gamma_L$ for stability ($|\Gamma_{in}|<1$) / instability ($|\Gamma_{in}|>1$)

# Output stability circle (CSOUT)




- Two cases possible: (a) stable outside/ (b) stable inside

# Output stability circle (CSOUT)

- Identification of the stability / instability regions
  - Center of the Smith Chart in $\Gamma_L$ complex plane correspond to $\Gamma_L = 0$
  - Input reflection coefficient

$$\Gamma_{in} = S_{11} + \frac{S_{12} \cdot S_{21} \cdot \Gamma_L}{1 - S_{22} \cdot \Gamma_L} \qquad \Gamma_{in}\Big|_{\Gamma_L = 0} = S_{11} \qquad \left|\Gamma_{in}\right|_{\Gamma_L = 0} = \left|S_{11}\right|$$

  - A decision can be made based on |S11| value the position of the center of the Smith chart (origin of the complex plane) relative to the circle

# Identification of the stability / instability regions

- Output stability circle
  - **|S11| < 1** → the center of the Smith chart on which $\Gamma_L$ is represented is a **stable point**, so it's placed in the stability region (most often situation)
  - |S11| > 1 → the center of the Smith chart on which $\Gamma_L$ is represented is a **unstable point**, so it's placed in the instability region
- Input stability circle
  - **|S22| < 1** → the center of the Smith chart on which $\Gamma_S$ is represented is a **stable point**, so it's placed in the stability region (most often situation)
  - |S22| > 1 → the center of the Smith chart on which $\Gamma_S$ is represented is a **unstable point**, so it's placed in the instability region

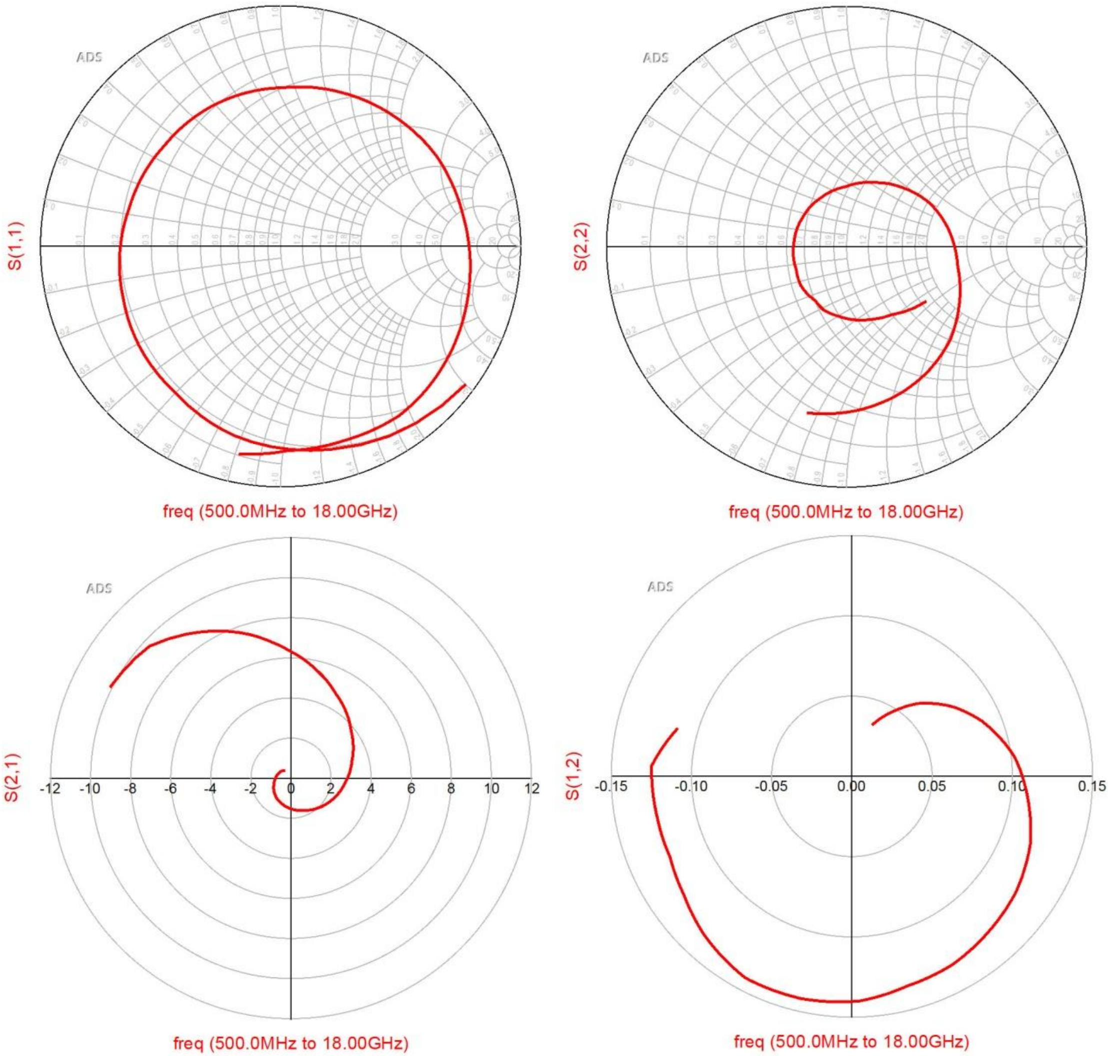
# Example

- ATF-34143 **at Vds=3V Id=20mA.**
- @5GHz
  - $S_{11} = 0.64\angle 139°$
  - $S_{12} = 0.119\angle -21°$
  - $S_{21} = 3.165\angle 16°$
  - $S_{22} = 0.22\angle 146°$

```
!ATF-34143
!S-PARAMETERS at Vds=3V  Id=20mA.   LAST UPDATED 01-29-99

# ghz s ma r 50

2.0  0.75  -126  6.306  90  0.088  23  0.26  -120
2.5  0.72  -145  5.438  75  0.095  15  0.25  -140
3.0  0.69  -162  4.762  62  0.102  7  0.23  -156
4.0  0.65  166  3.806  38  0.111  -8  0.22  174
5.0  0.64  139  3.165  16  0.119  -21  0.22  146
6.0  0.65  114  2.706  -5  0.125  -35  0.23  118
7.0  0.66  89  2.326  -27  0.129  -49  0.25  91
8.0  0.69  67  2.017  -47  0.133  -62  0.29  67
9.0  0.72  48  1.758  -66  0.135  -75  0.34  46

!FREQ  Fopt   GAMMA OPT     RN/Zo
!GHZ    dB    MAG    ANG     -

2.0  0.19  0.71  66  0.09
2.5  0.23  0.65  83  0.07
3.0  0.29  0.59  102  0.06
4.0  0.42  0.51  138  0.03
5.0  0.54  0.45  174  0.03
6.0  0.67  0.42  -151  0.05
7.0  0.79  0.42  -118  0.10
8.0  0.92  0.45  -88  0.18
9.0  1.04  0.51  -63  0.30
10.0  1.16  0.61  -43  0.46
```

# Example

- ATF-34143
- **at**
  - **Vds=3V**
  - **Id=20mA.**



# Solution + region identification

- S parameters
  - S11 = -0.483+0.42·j
  - S12 = 0.111-0.043·j
  - S21 = 3.042+0.872·j
  - S22 = -0.182+0.123·j
- | S22 | < 1
- $|C_L| < R_L$ , 0∈CSOUT
- The center of the Smith chart is placed inside the output stability circle (0∈CSOUT) and is a stable point
  - the inside of the output stability circle – stability region
  - the outside of the output stability circle – instability region

$$C_L = \frac{\left(S_{22} - \Delta \cdot S_{11}^*\right)^*}{\left|S_{22}\right|^2 - \left|\Delta\right|^2} = 3.931 - 0.897 \cdot j$$

$$\left|C_L\right| = 4.032$$

$$R_L = \frac{\left|S_{12} \cdot S_{21}\right|}{\left|\left|S_{22}\right|^2 - \left|\Delta\right|^2\right|} = 4.891$$

# Solution + region identification

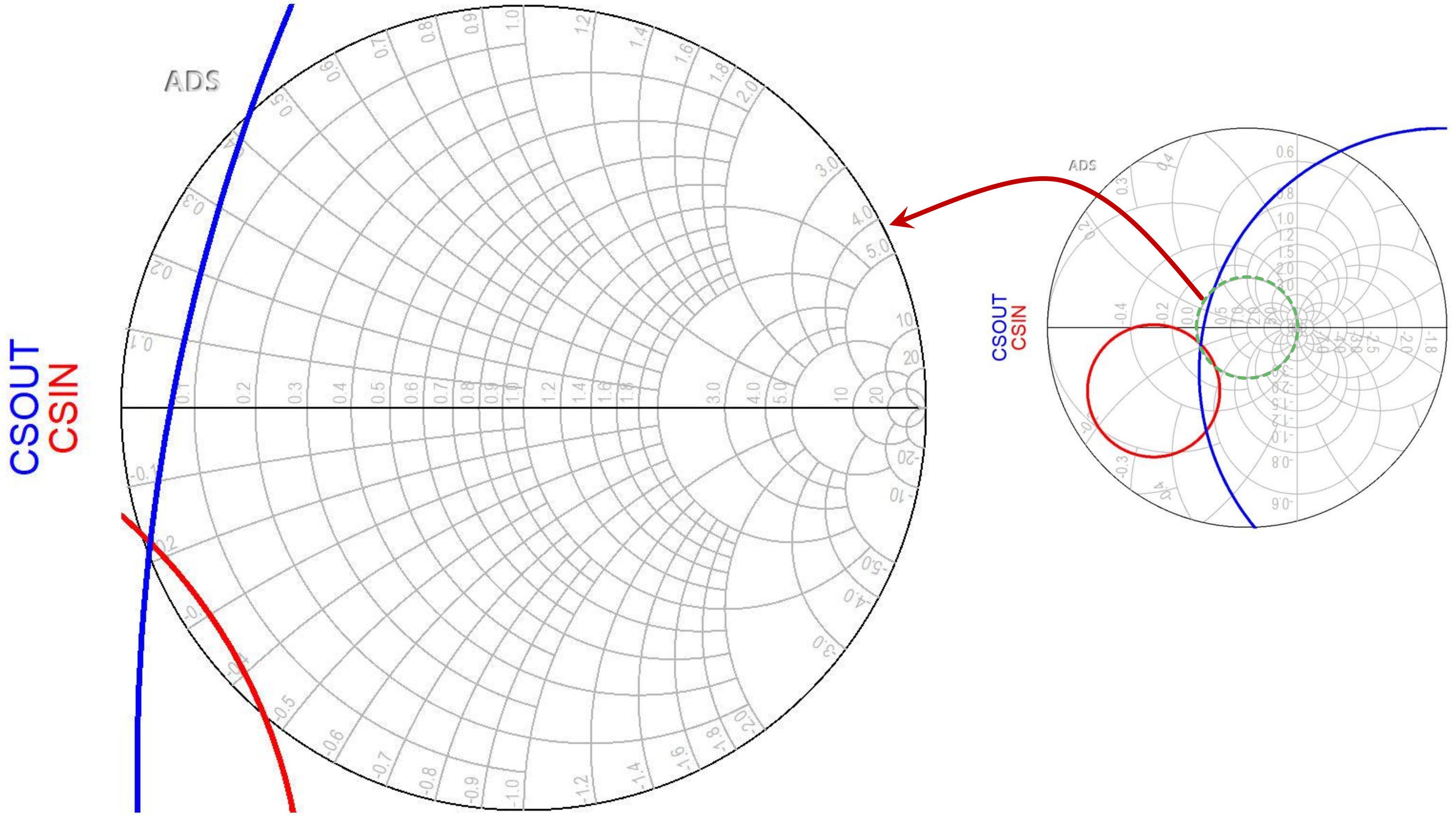
- S parameters
  - S11 = -0.483+0.42·j
  - S12 = 0.111-0.043·j
  - S21 = 3.042+0.872·j
  - S22 = -0.182+0.123·j
- | S11 | < 1
- $|C_S| > R_S$ , $0 \notin CSIN$
- The center of the Smith chart is placed outside the input stability circle ($0 \notin CSIN$) and is a stable point
  - the outside of the input stability circle – stability region
  - the inside of the input stability circle – instability region

$$C_S = \frac{\left(S_{11} - \Delta \cdot S_{22}^*\right)^*}{|S_{11}|^2 - |\Delta|^2} = -1.871 - 1.265 \cdot j$$

$$|C_S| = 2.259$$

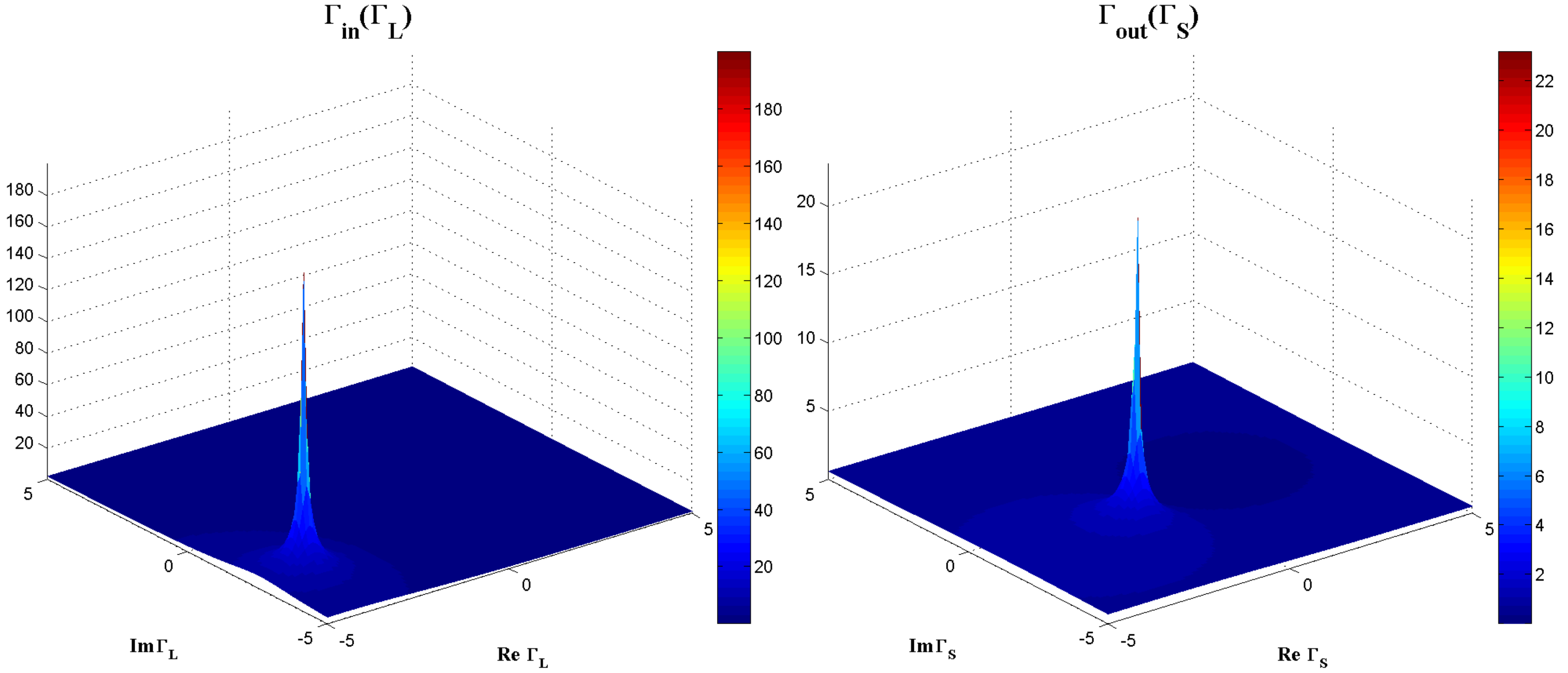
$$R_S = \frac{|S_{12} \cdot S_{21}|}{\left||S_{11}|^2 - |\Delta|^2\right|} = 1.325$$

# ADS



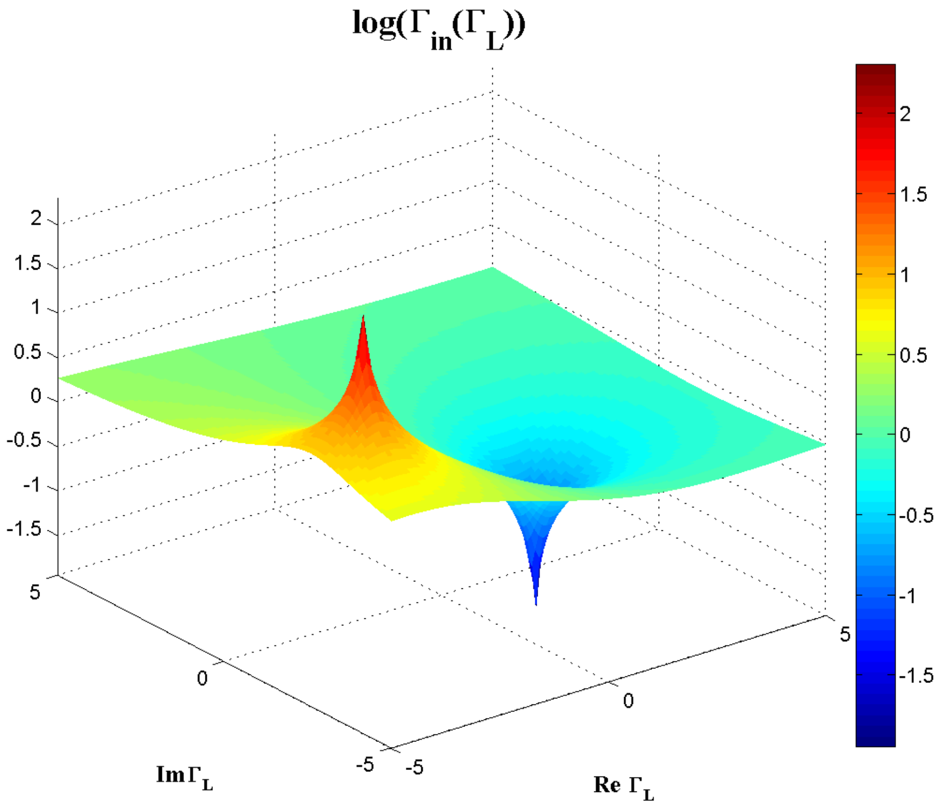
# 3D representation of $|\Gamma_{in}|$, $|\Gamma_{out}|$

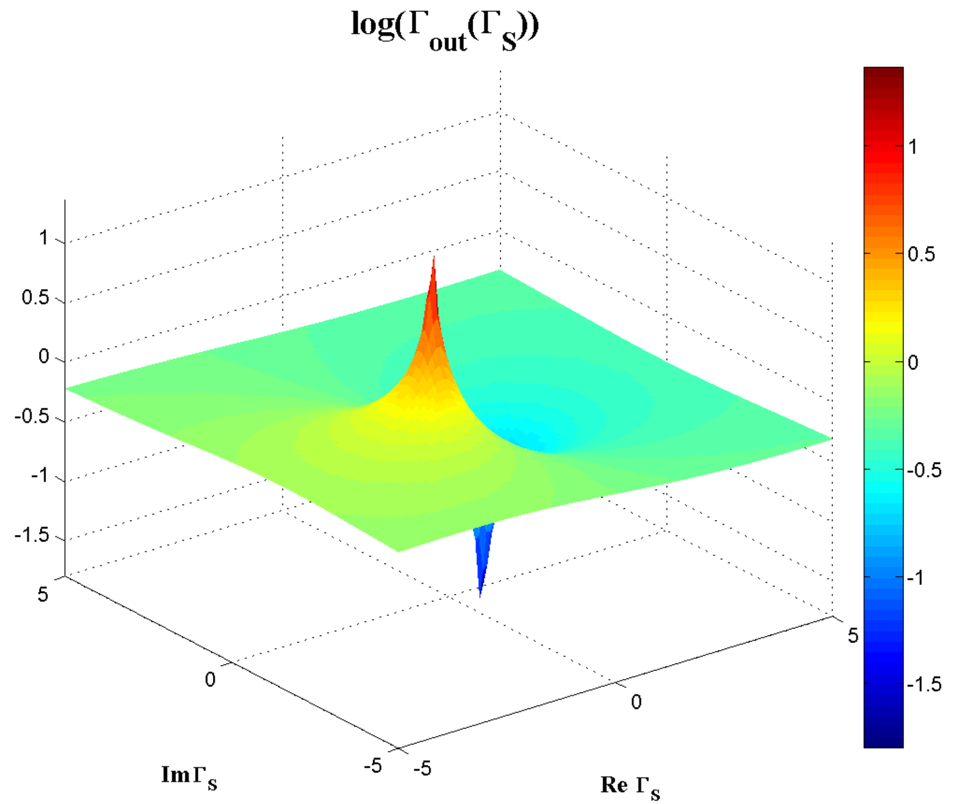
- High variations -> we change to z logarithmic scale



# 3D representation of $|\Gamma_{in}|$, $|\Gamma_{out}|$

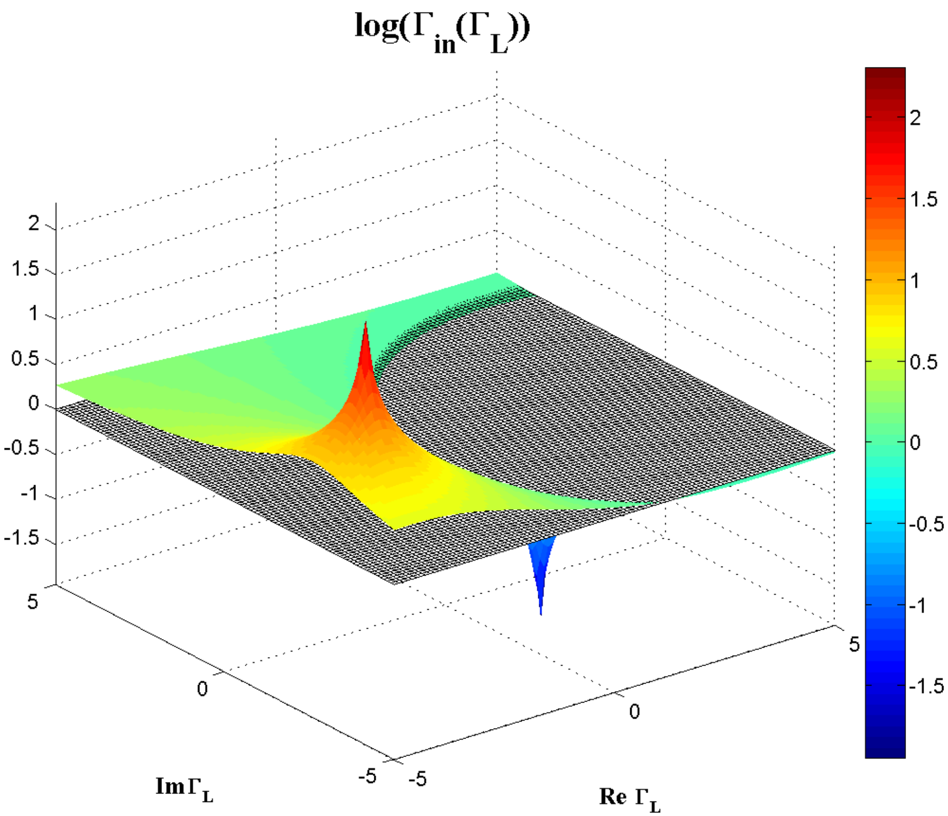
- $\log_{10}|\Gamma_{in}|$, $\log_{10}|\Gamma_{out}|$

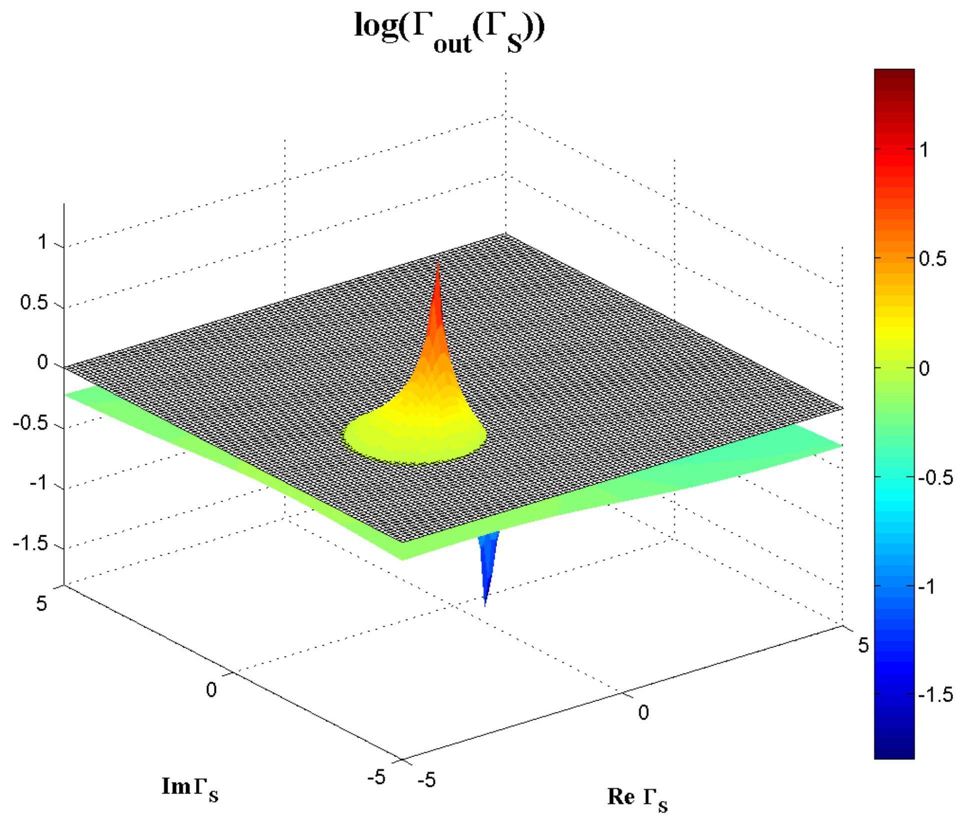


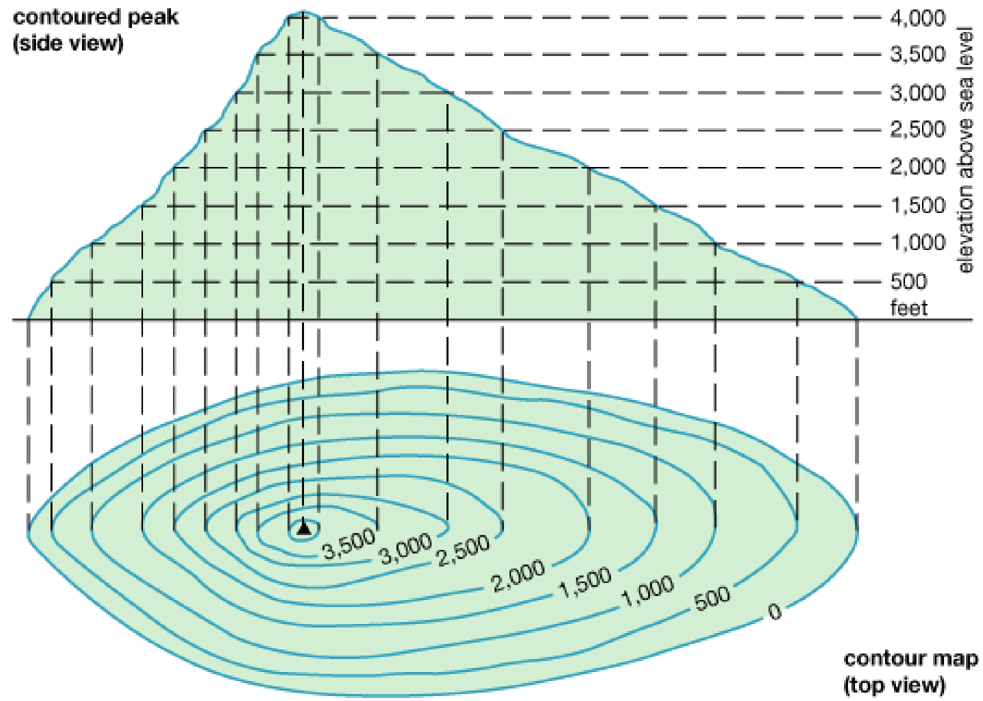
# 3D representation of $|\Gamma_{in}|$, $|\Gamma_{out}|$, $|\Gamma|=1$

- $|\Gamma| = 1 \rightarrow \log_{10}|\Gamma| = 0$, the intersection with the plane z = 0 is a circle

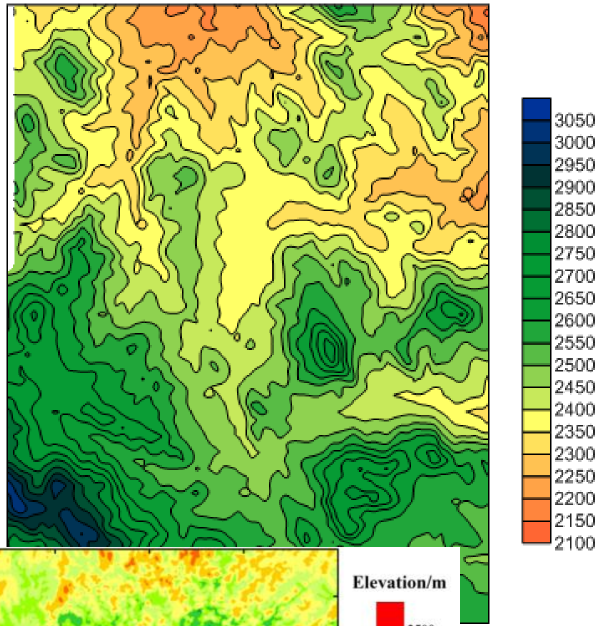


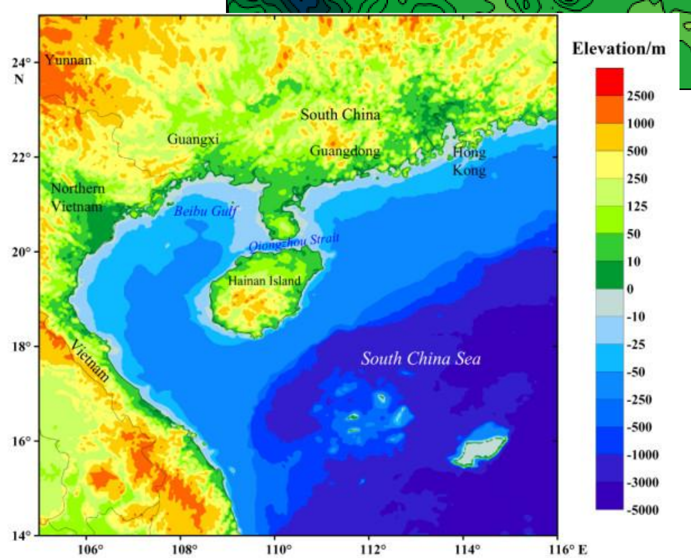



# Contour map/lines





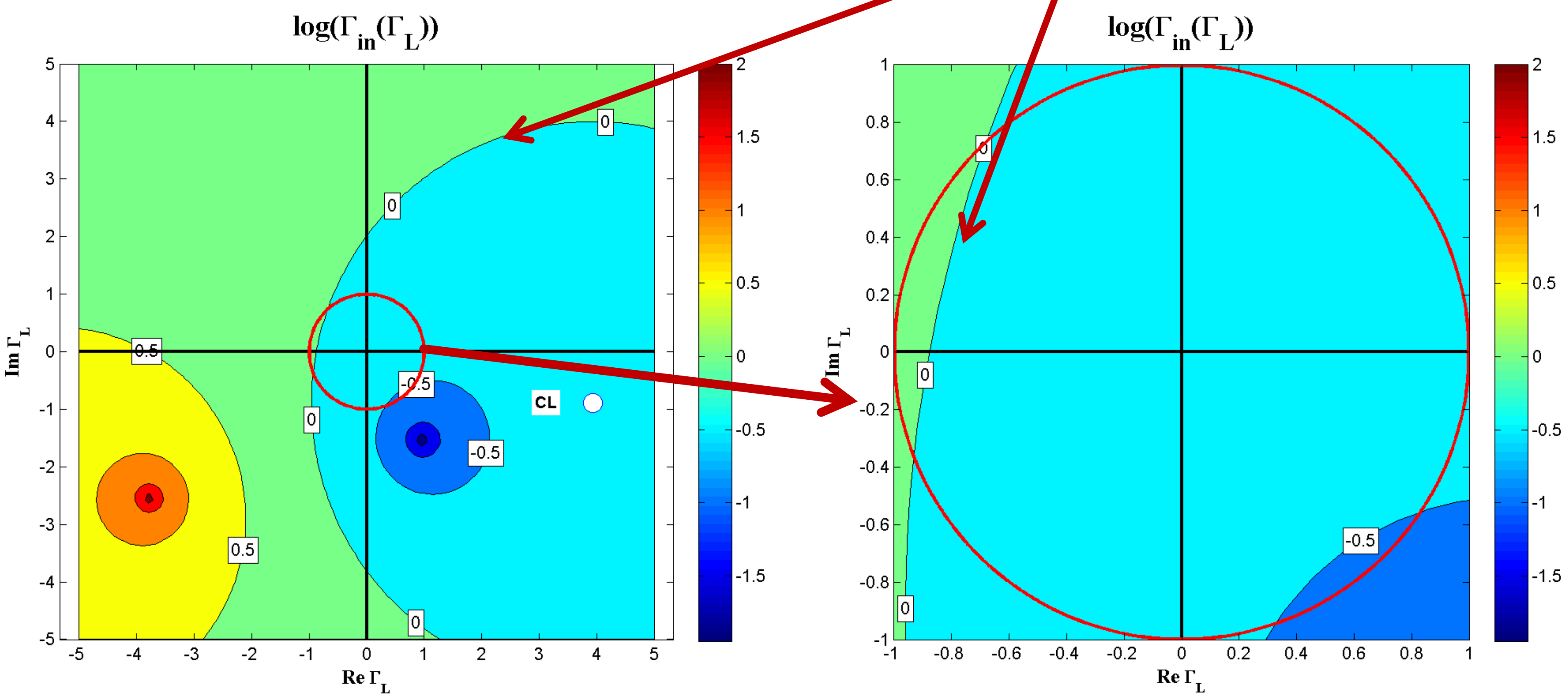



# Contour lines of $\log_{10}|\Gamma_{in}|$

- $\log_{10}|\Gamma_{in}| = 0$, $\Gamma_L$, CSOUT

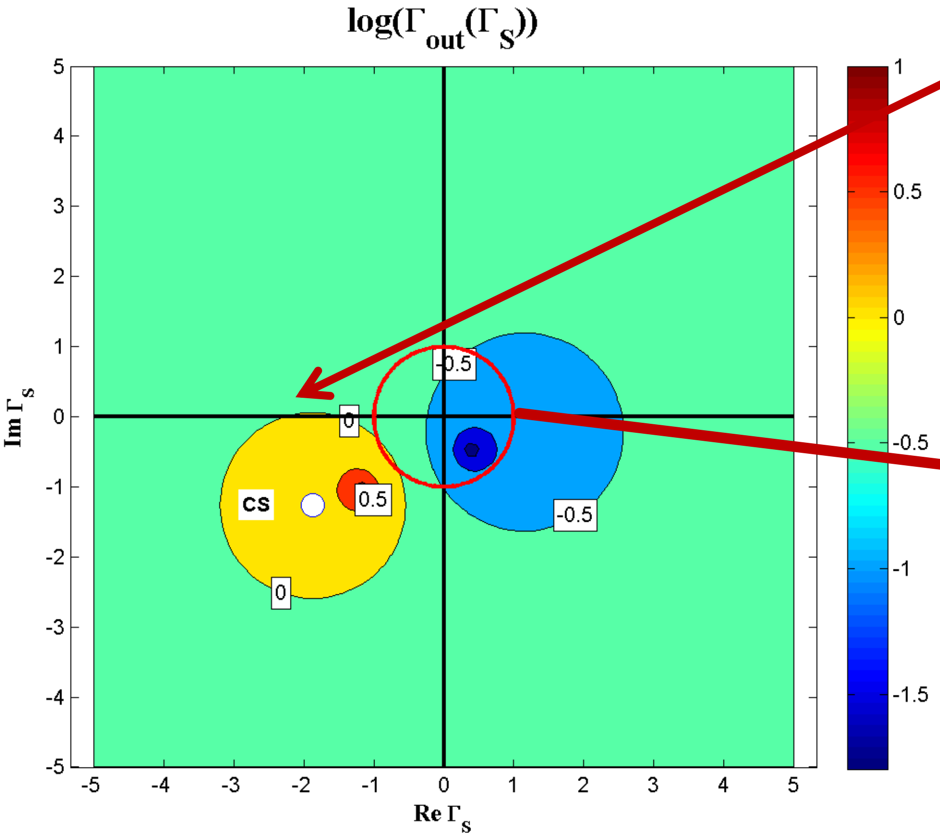
$\log_{10}|\Gamma_{in}| = 0$,
$|\Gamma_{in}| = 1$

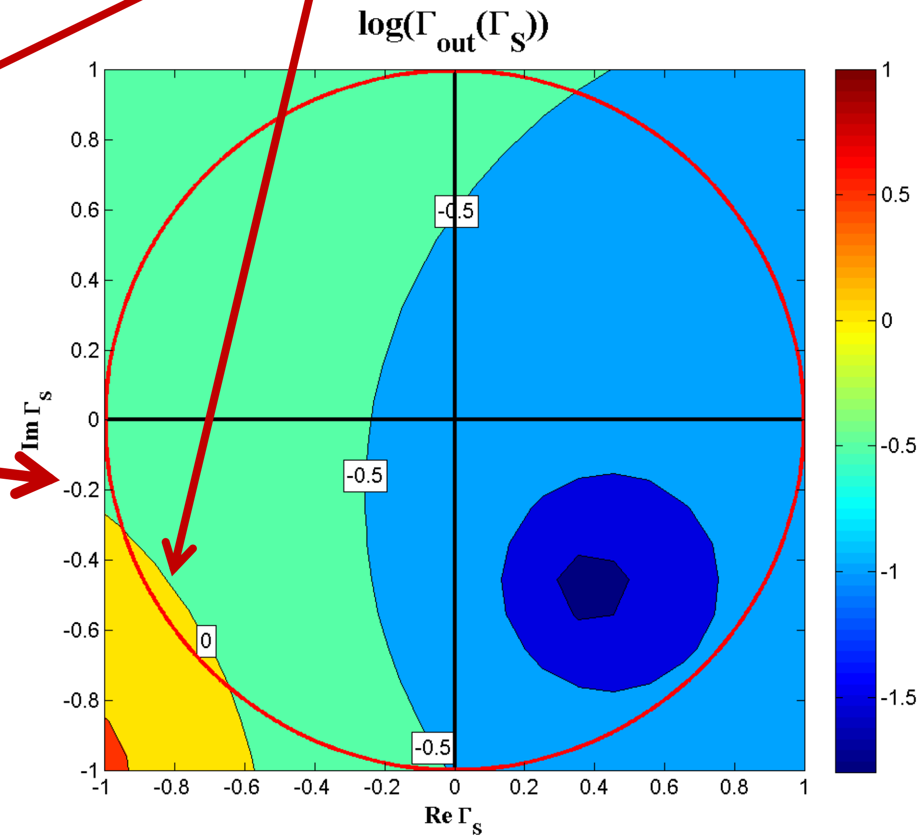


# Contour lines of $\log_{10}|\Gamma_{out}|$

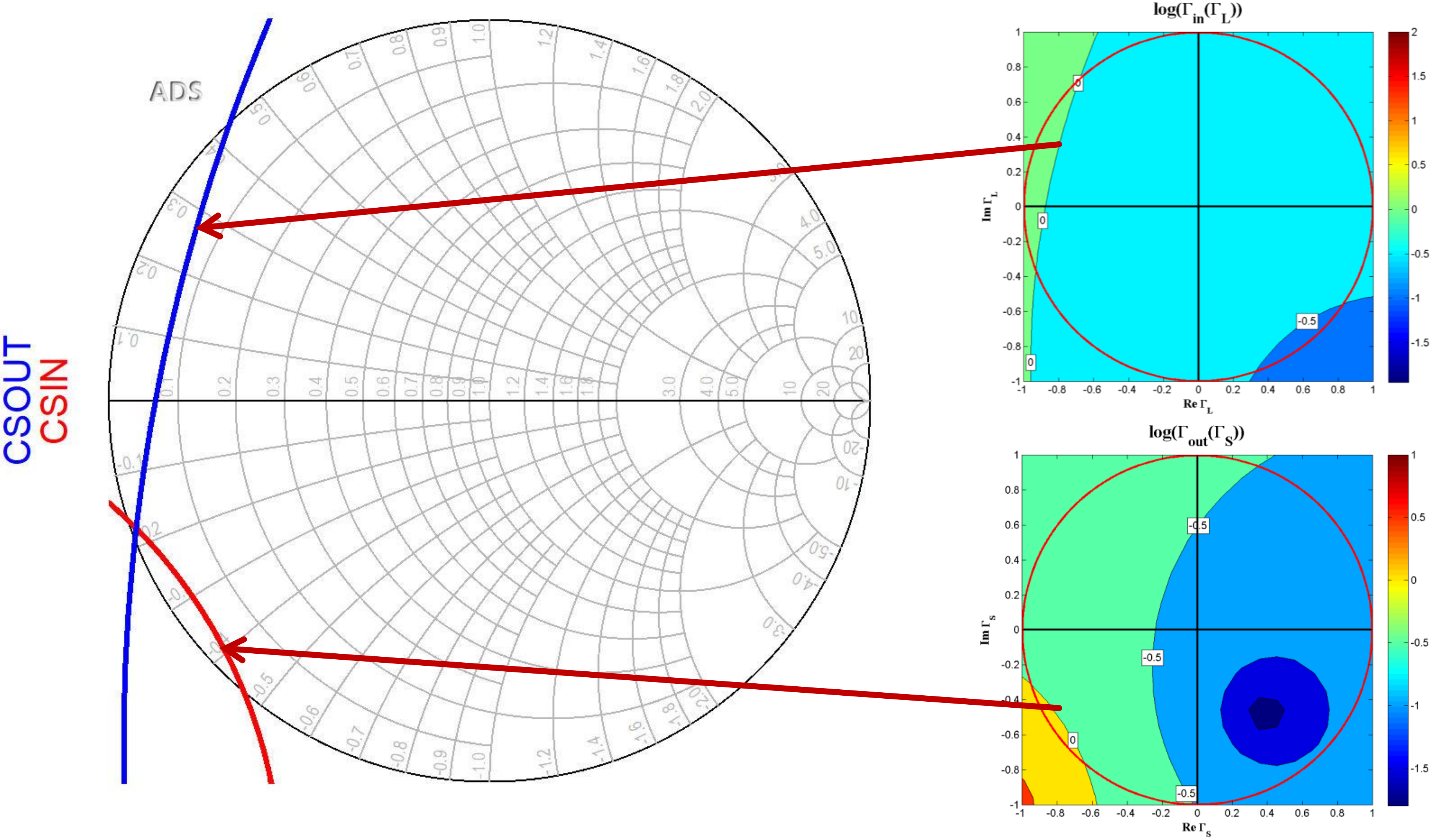
- $\log_{10}|\Gamma_{out}| = 0$, $\Gamma_S$, CSIN

$\log_{10}|\Gamma_{out}| = 0$,
$|\Gamma_{out}| = 1$



# CSIN, CSOUT



# Contact

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