

Lecture 6

2022/2023

Microwave Devices and Circuits for Radiocommunications

2022/2023

- 2C/1L, **MDCR**
- Attendance at minimum 7 sessions (course or laboratory)
- Lectures- **associate professor Radu Damian**
 - Tuesday 12-14, ~~Online~~, P8
 - E – 50% final grade
 - problems + (2p atten. lect.) + (3 tests) + (bonus activity)
 - first test L1: 21-28.02.2023 (t2 and t3 not announced, lecture)
 - 3att.=+0.5p
 - all materials/equipments authorized

2022/2023

- Laboratory – **associate professor Radu Damian**
 - Tuesday 08-12, 11.13 / (08:10)
 - L – 25% final grade
 - ADS, 4 sessions
 - Attendance + **personal results**
 - P – 25% final grade
 - ADS, 3 sessions (-1? 21.02.2022)
 - personal homework

Materials

■ <http://rf-opto.etti.tuiasi.ro>

The screenshot shows a web browser window with the URL http://rf-opto.etti.tuiasi.ro/microwave_cd.php?chg_lang=0. The page features a dark blue navigation bar with links for Main, Courses, Master, Staff, Research, Students, and Admin. Below this is a secondary navigation bar with links for Microwave CD, Optical Communications, Optoelectronics, Internet, Antennas, Practica, Networks, and Educational software. The main content area is titled "Microwave Devices and Circuits for Radiocommunications (English)" and includes details for the "Course: MDCR (2017-2018)".

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, [↗](#))

The right side of the image shows a zoomed-in view of the website's header and navigation. It features the "RF-OPTO" logo, the "ETTI" logo, and the University of Technical Sciences (UTS) logo. A red circle highlights the language selection menu, which includes "English" (with a UK flag) and "Romana" (with a Romanian flag). The navigation bar includes links for Main, Courses, Master, Staff, Research, Grades, Student List, Exams, and Photos.

Materials

- RF-OPTO
 - <http://rf-opto.etti.tuiasi.ro>
- **David Pozar, “Microwave Engineering”,**
Wiley; 4th edition , 2011
 - 1 exam problem ← Pozar
- Photos
 - sent by **email**/online exam
 - used at lectures/laboratory

Photos



Date:

Grupa	5304 (2015/2016)
Specializarea	Tehnologii si sisteme de telecomunicatii
Marca	5184

[Trimite email acestui student](#) | [Adauga acest student la lista \(0\)](#)

Detalii curente

Observatii

Finantare	Buget
Bursa	Fara Bursa



Date:

Grupa	5304 (2015/2016)
Specializarea	Tehnologii si sisteme de telecomunicatii
Marca	5244

[Trimite email acestui student](#) | [Adauga acest student la lista \(0\)](#)

Detalii curente

Observatii

Finantare	Buget
Bursa	Bursa de Studii



Date:

Grupa	5304 (2015/2016)
Specializarea	Tehnologii si sisteme de telecomunicatii
Marca	5184

[Acceseaza ca acest student](#)

Note obtinute

Disciplina	Tip	Data	Descriere	Nota	Procente	Obs.
TW			Tehnologii Web			
	N	17/01/2014	Nota Finala	10	-	
	A	17/01/2014	Colocviu Tehnologii Web 2013/2014	10	7.55	
	B	17/01/2014	Laborator Tehnologii Web 2013/2014	9	-	
	D	17/01/2014	Tema Tehnologii Web 2013/2014	9	-	

Profile photo

- Profile photo – online “exam”

Examene online: 2020/2021

Disciplina: MDC (Microwave Devices and Circuits (Engleza))

Pas 3

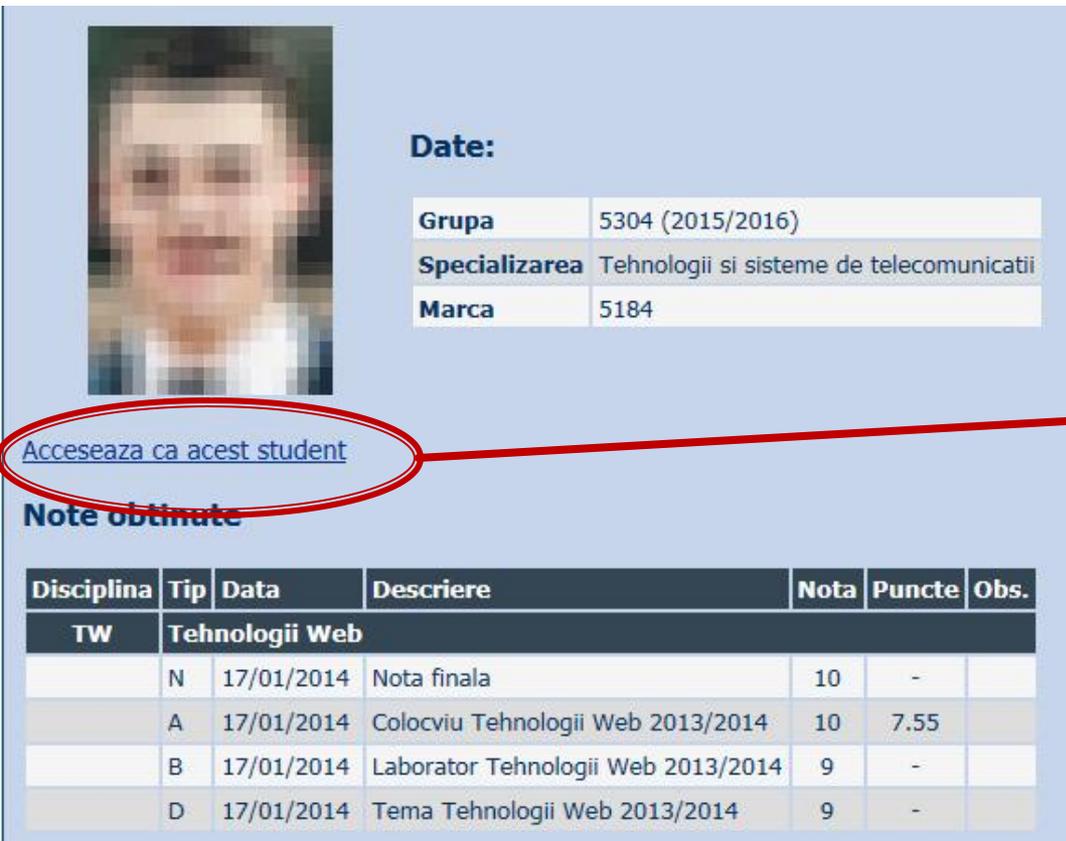
Nr.	Titlu	Start	Stop	Text
1	Profile photos	03/03/2021; 10:00	08/04/2021; 08:00	Online "exam" created f ..
2	Mini Test 1 (lecture 2)	03/03/2021; 15:35	03/03/2021; 15:50	The current test consis ..

Grupa	5304 (2015/2016)
Specializarea	Tehnologii si sisteme de telecomunicatii
Marca	5184



Access

■ Not customized



A student profile page with a photo of a man on the left. To the right, under the heading "Date:", is a table with student details. Below this is a link "Acceseaza ca acest student" circled in red. At the bottom is a table titled "Note obtinute" showing grades for various subjects.

Date:

Grupa	5304 (2015/2016)
Specializarea	Tehnologii si sisteme de telecomunicatii
Marca	5184

[Acceseaza ca acest student](#)

Note obtinute

Disciplina	Tip	Data	Descriere	Nota	Puncte	Obs.
TW			Tehnologii Web			
N		17/01/2014	Nota finala	10	-	
A		17/01/2014	Colocviu Tehnologii Web 2013/2014	10	7.55	
B		17/01/2014	Laborator Tehnologii Web 2013/2014	9	-	
D		17/01/2014	Tema Tehnologii Web 2013/2014	9	-	



A login form with fields for "Nume", "Email", and "Cod de verificare". The "Email" and "Cod de verificare" fields are circled in red. A red arrow points from the link in the previous image to the "Email" field. A verification code "344bd9f" is displayed below the "Cod de verificare" field. A "Trimite" button is at the bottom.

Nume
IACOBSCUN

Email

Cod de verificare

344bd9f

Trimite

Online

- access to **online exams** requires the **password** received by email

English | Romana |

Main Courses Master Staff Research **Student**

Grades Student List Exams Photos

POPESCU GOPO ION

Fotografia nu exista

Date:

Grupa	5700 (2019/2020)
Specializarea	Inginerie electronica si telecomunicatii
Marca	7000000

[Access the site as this student](#) | [request access to software](#)

Grades

Inca nu a fost notat.

Main Courses Master Staff Research

Grades **Student List** Exams Photos

Login

Use the last name and email stored in the database

Name
POPESCU GOPO

Email/Password

Write the code below

828f26b

Send

Online

- access email/password

Main Courses Master Staff Research

Grades Student List Exams Photos

POPESCU GOPO ION

Fotografia nu exista

Date:

Grupa	5700 (2019/2020)
Specializarea	Inginerie electronica si telec
Marca	7000000

You access the site as **this student!**

Main Courses Master Staff Research

Grades Student List Exams Photos

POPESCU GOPO ION

Fotografia nu exista

Date:

Grupa	5700 (2019/2020)
Specializarea	Inginerie electronica si telec
Marca	7000000

You access the site as this student **(including exams)!**

Password

■ received by email

Important message from RF-OPTO Inbox x

 **Radu-Florin Damian**
to me, POPESCU ▾

 Romanian ▾ > English ▾ [Translate message](#)



Laboratorul de Microunde si Optoelectronica
Facultatea de Electronica, Telecomunicatii si Tehnologia Informatiei
Universitatea Tehnica "Gh. Asachi" Iasi

In atentia: POPESCU GOPO ION

Parola pentru a accesa examenele pe server-ul **rf-opto** este
Parola: [REDACTED]

Identificati-va pe [server](#), cu parola, cat mai rapid, pentru confirmare.

Memorati acest mesaj intr-un loc sigur, pentru utilizare ulterioara

Attention: POPESCU GOPO ION

The password to access the exams on the **rf-opto** server is
Password: [REDACTED]

Login to the [server](#), with this password, as soon as possible, for confirmation.

Save this message in a safe place for later use

 Reply  Reply all  Forward

Subject

	Subject	Correspondents
★	Important message from RF-OPTO	⇒ POPESCU GOPO ION
★	Validation of MD/CR exam from 02/05/2020	[REDACTED]
★	[REDACTED]	[REDACTED]

From Me <rdamian@etti.tuiasi.ro> ★
Subject **Important message from RF-OPTO**
To [REDACTED]
Cc Me <rdamian@etti.tuiasi.ro> ★



Laboratorul de Microunde si Optoelectronica
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Password: [REDACTED]

Login to the [server](#), with this password, as soon as possible, for confirmation.

Save this message in a safe place for later use

Online exam manual

- The online exam app used for:
 - ~~lectures (attendance)~~
 - laboratory
 - project
 - ~~examinations~~

Materials

Other data

[Manual examen on-line](#) (pdf, 2.65 MB, ro, 🇷🇴)

[Simulare Examen](#) (video). (mp4, 65.12 MB, ro, 🇷🇴)

Microwave Devices and Circuits (Englis

Examen online

- always against a **timetable**
 - long period (lecture attendance/laboratory results)
 - ~~short period (tests: 15min, exam: 2h)~~

Announcement 23:59 (10/05/2020)	Support material 00:05 (11/05/2020)	Exam Topics 00:07 (11/05/2020)	Results 00:10 (11/05/2020)	End 00:20 (15/05/2020)	Confirmation 00:20 (16/05/2020)	Next timeframe in: 05 m 43 s Refresh now
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Announcement

This is a "fake" exam, introduced to familiarize you with the server interface and to perform the necessary actions during an exam: thesis scan, selfie, use email for co

Server Time

All exams are based on the server's time zone (it may be different from local time). For reference time on the server is now:

10/05/2020 23:59:16

Online results submission

- many numerical values/files

Schema finala	Rezultate - castig	Rezultate - zgomot	Fisier justificare calcul (factor andrei)	Fisier zap (optional)	T1, fisier parametri S	T2, fisier parametri S	Z1	Z2	Z3	Z4	Z5	Z6	Z7	Ze1	Zo1	Ze2	Zo2	Ze3	Zo3	Ze4	Zo4	Ze5	Zo5	Ze6
86 - 5428 - 259 ...	86 - 5428 - 260 ...	86 - 5428 - 261 ...	86 - 5428 - 316 ...	-	86 - 5428 - 314 ...	86 - 5428 - 315 ...	148.33	155.88	202.12	164.35	180.91	30.29	185.19	79.9	37	68.89	45.14	61.83	45.05	57.97	46.02	61.85	45.05	68.8
86 - 5622 - 259 ...	86 - 5622 - 260 ...	86 - 5622 - 261 ...	86 - 5622 - 316 ...	86 - 5622 - 262 ...	86 - 5622 - 314 ...	86 - 5622 - 315 ...	26.97	153.5	34.64	35.79	55.56	26.212	10.693	0	0	0	0	0	0	0	0	0	0	0
86 - 5488 - 259 ...	86 - 5488 - 260 ...	86 - 5488 - 261 ...	86 - 5488 - 316 ...	86 - 5488 - 262 ...	86 - 5488 - 314 ...	86 - 5488 - 315 ...	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
86 - 5391 - 259 ...	86 - 5391 - 260 ...	86 - 5391 - 261 ...	86 - 5391 - 316 ...	-	-	-	50	50	50	50	50	50	50	70.14	40.39	61.85	44.59	55.7	45.2	54.89	45.38	58.65	45.8	70.0
86 - 5664 - 259 ...	86 - 5664 - 260 ...	86 - 5664 - 261 ...	86 - 5664 - 316 ...	-	86 - 5664 - 314 ...	86 - 5664 - 315 ...	168.02	150.5	178.28	133.75	92.12	121.67	144.48	94.36	36.19	70.77	42.56	65.69	42.05	55.17	42.29	65.59	42.05	70.7
86 - 5665 - 259 ...	86 - 5665 - 260 ...	86 - 5665 - 261 ...	86 - 5665 - 316 ...	-	86 - 5665 - 314 ...	86 - 5665 - 315 ...	162.2	80.8	209.2	140.85	135.1	183.7	167.6	94.58	36.15	78.16	39.77	65.57	45.05	65.57	45.05	78.16	39.77	94.5
86 - 5433 - 259 ...	86 - 5433 - 260 ...	86 - 5433 - 261 ...	86 - 5433 - 316 ...	-	86 - 5433 - 314 ...	86 - 5433 - 315 ...	165.138	106.228	226.157	130.134	72.71	180.177	164.616	101.36	36.11	77.22	42.49	68.02	45.62	60	45.42	68.02	45.62	77.2
86 - 5608 - 259 ...	86 - 5608 - 260 ...	86 - 5608 - 261 ...	86 - 5608 - 316 ...	-	86 - 5608 - 314 ...	86 - 5608 - 315 ...	150.84	152.5	30.94	32.37	54.36	19.837	29.85	64.14	40.145	54.32	46.32	53.8	46.7	53.8	46.7	54.32	46.32	54.9
86 - 5555 - 259 ...	86 - 5555 - 260 ...	86 - 5555 - 261 ...	86 - 5555 - 316 ...	-	86 - 5555 - 314 ...	86 - 5555 - 315 ...	168.001	150.288	178.399	133.115	92.491	121.257	144.126	97.05	36.16	71.13	43.09	65.45	42.12	55.66	42.18	65.45	42.12	71.1

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	10.693
	0	0	0	0	0	0	0
	50	50	50	50	50	50	50



Online results submission

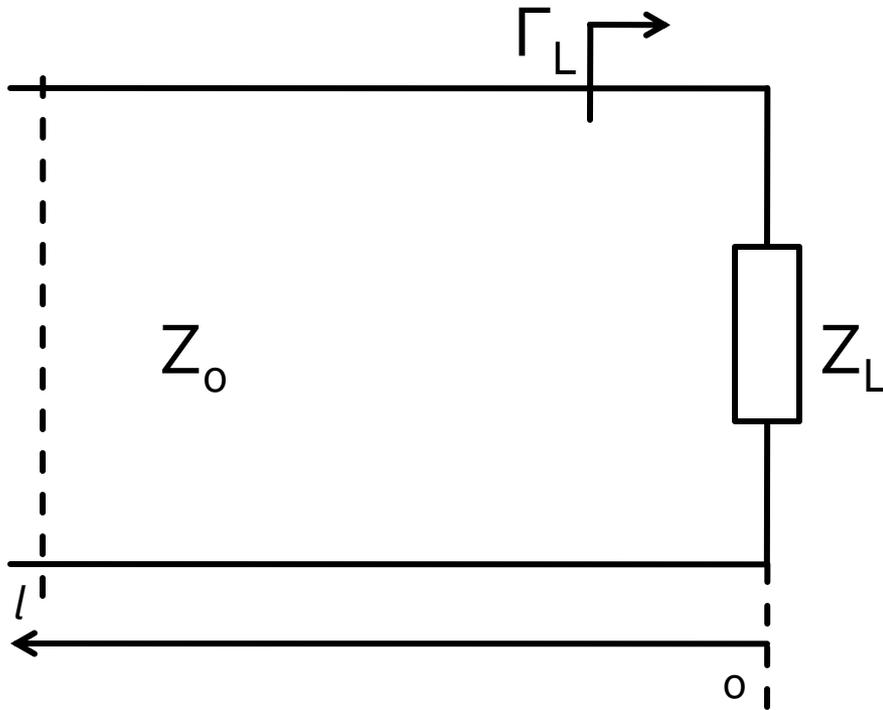
**Grade = Quality of the work +
+ Quality of the submission**

TEM transmission lines

Course Topics

- **Transmission lines**
- Impedance matching and tuning
- Directional couplers
- Power dividers
- Microwave amplifier design
- Microwave filters
- ~~Oscillators and mixers?~~

The lossless line



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

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

$$Z_L = \frac{V(0)}{I(0)} \quad Z_L = \frac{V_0^+ + V_0^-}{V_0^+ - V_0^-} \cdot Z_0$$

- voltage reflection coefficient

$$\Gamma = \frac{V_0^-}{V_0^+} = \frac{Z_L - Z_0}{Z_L + Z_0}$$

- Z_0 real

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

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

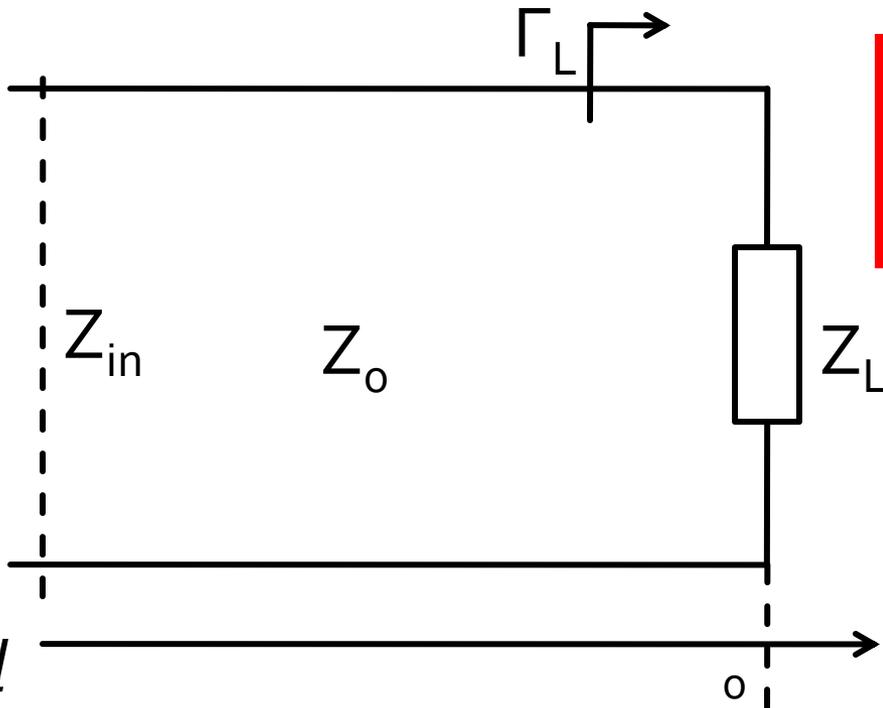
$$P_{avg} = \frac{1}{2} \cdot \frac{|V_0^+|^2}{Z_0} \cdot (1 - |\Gamma|^2)$$

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

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

The lossless line

- input impedance of a length l of transmission line with characteristic impedance Z_0 , loaded with an arbitrary impedance Z_L



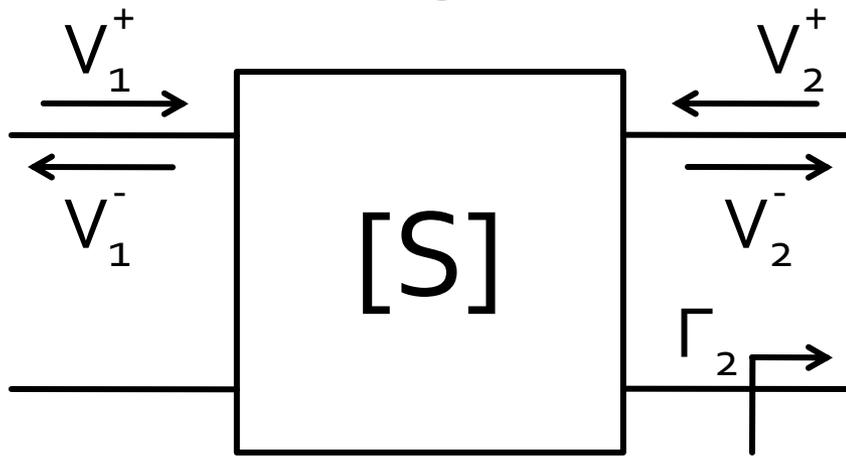
$$Z_{in} = Z_0 \cdot \frac{Z_L + j \cdot Z_0 \cdot \tan \beta \cdot l}{Z_0 + j \cdot Z_L \cdot \tan \beta \cdot l}$$

General theory

Microwave Network Analysis

Scattering matrix – S

- Scattering parameters



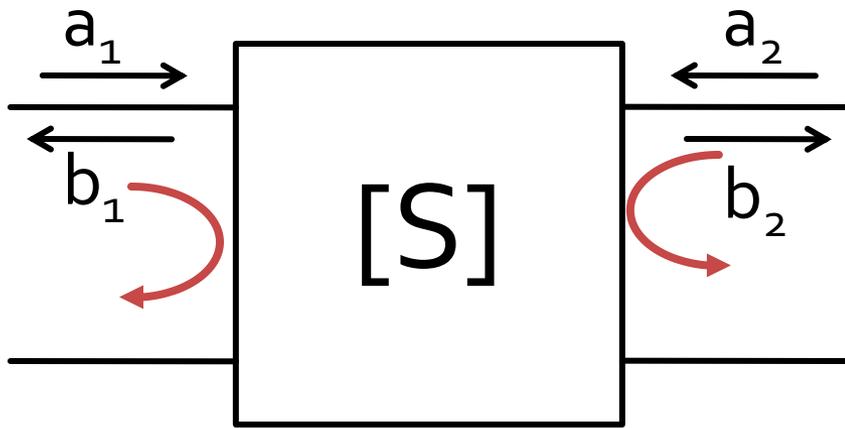
$$\begin{bmatrix} V_1^- \\ V_2^- \end{bmatrix} = \begin{bmatrix} S_{11} & S_{12} \\ S_{21} & S_{22} \end{bmatrix} \cdot \begin{bmatrix} V_1^+ \\ V_2^+ \end{bmatrix}$$

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

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

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

Scattering matrix – S

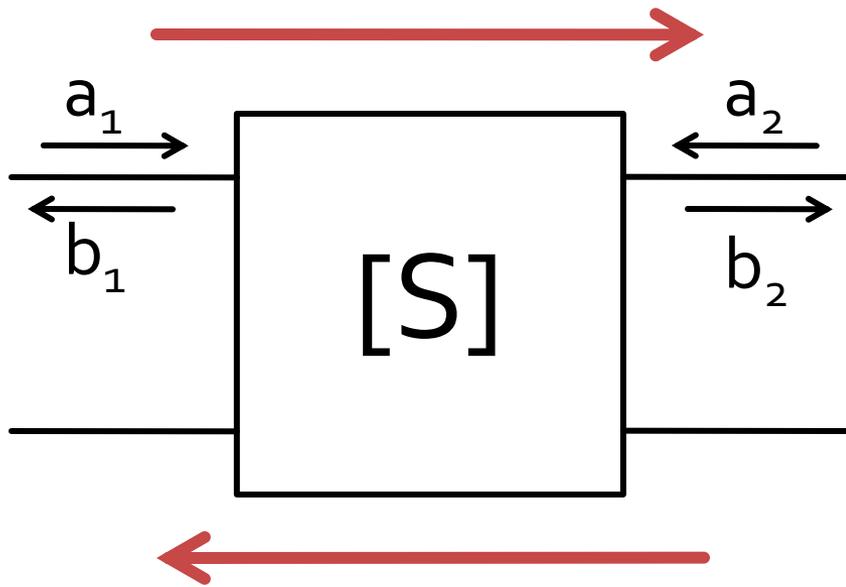


$$\begin{bmatrix} b_1 \\ b_2 \end{bmatrix} = \begin{bmatrix} S_{11} & S_{12} \\ S_{21} & S_{22} \end{bmatrix} \cdot \begin{bmatrix} a_1 \\ a_2 \end{bmatrix}$$

$$S_{11} = \left. \frac{b_1}{a_1} \right|_{a_2=0} \quad S_{22} = \left. \frac{b_2}{a_2} \right|_{a_1=0}$$

- S_{11} and S_{22} are reflection coefficients at ports 1 and 2 when the other port is matched

Scattering matrix – S

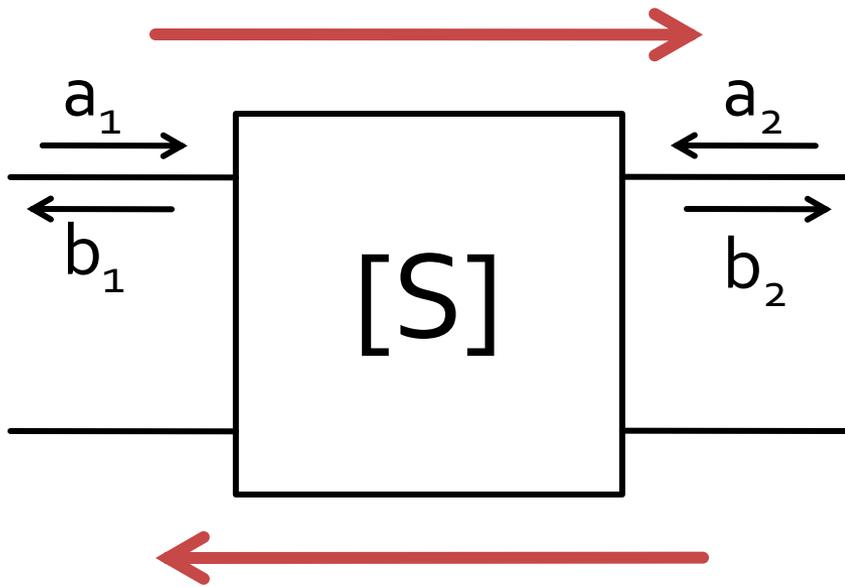


$$\begin{bmatrix} b_1 \\ b_2 \end{bmatrix} = \begin{bmatrix} S_{11} & S_{12} \\ S_{21} & S_{22} \end{bmatrix} \cdot \begin{bmatrix} a_1 \\ a_2 \end{bmatrix}$$

$$S_{21} = \left. \frac{b_2}{a_1} \right|_{a_2=0} \quad S_{12} = \left. \frac{b_1}{a_2} \right|_{a_1=0}$$

- S_{21} si S_{12} are signal amplitude gain when the other port is matched

Scattering matrix – S



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

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

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

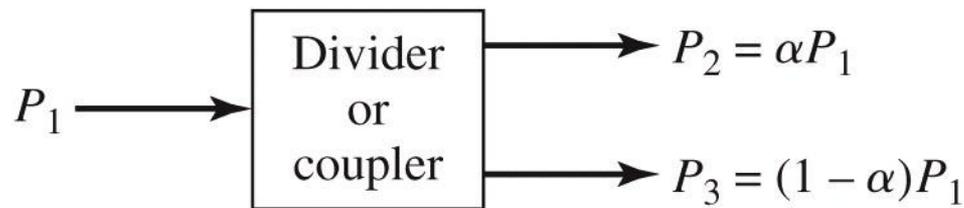
Power dividers and directional couplers

Course Topics

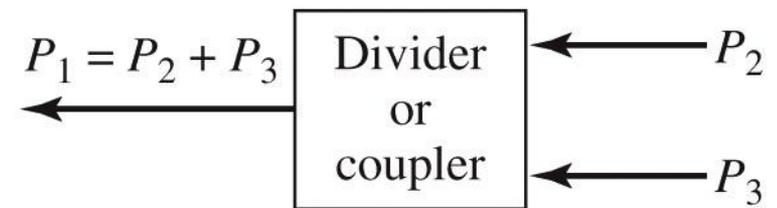
- Transmission lines
- Impedance matching and tuning
- **Directional couplers**
- **Power dividers**
- Microwave amplifier design
- Microwave filters
- ~~Oscillators and mixers~~

Power dividers and couplers

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



(a)



(b)

Three-Port Networks

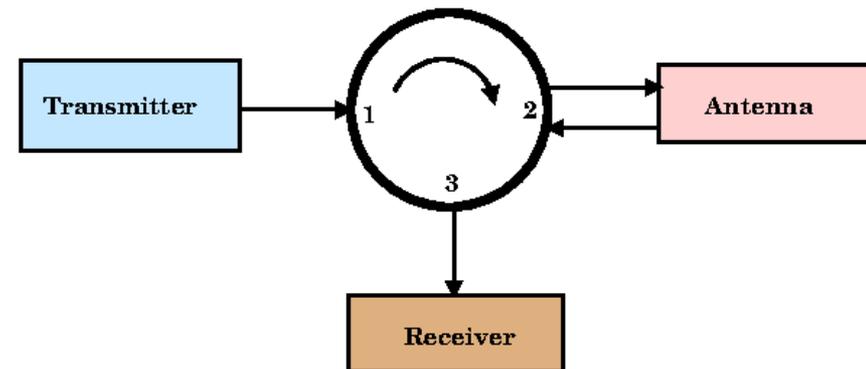
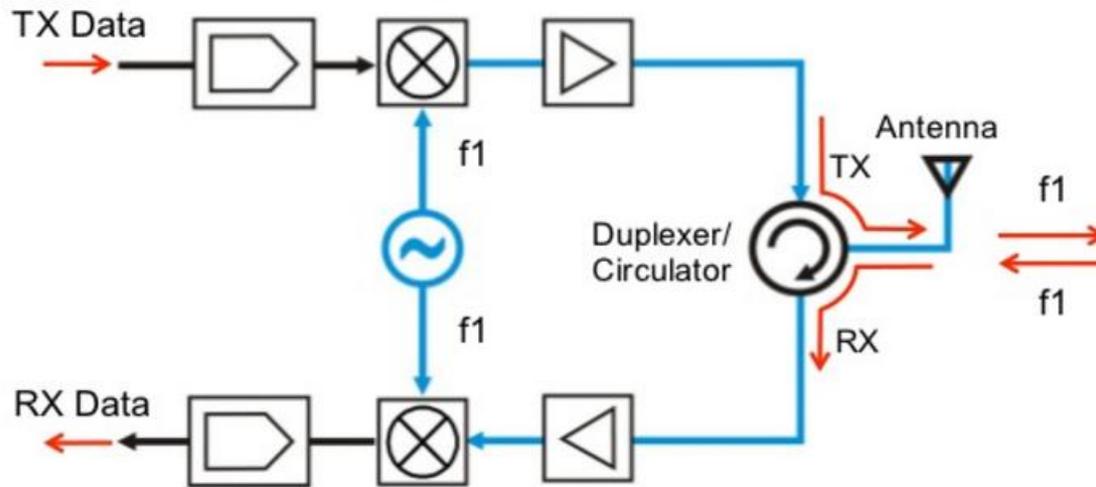
- also known as T-Junctions
- characterized by a 3×3 **S** matrix

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

- 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”

Nonreciprocal Three-Port Networks

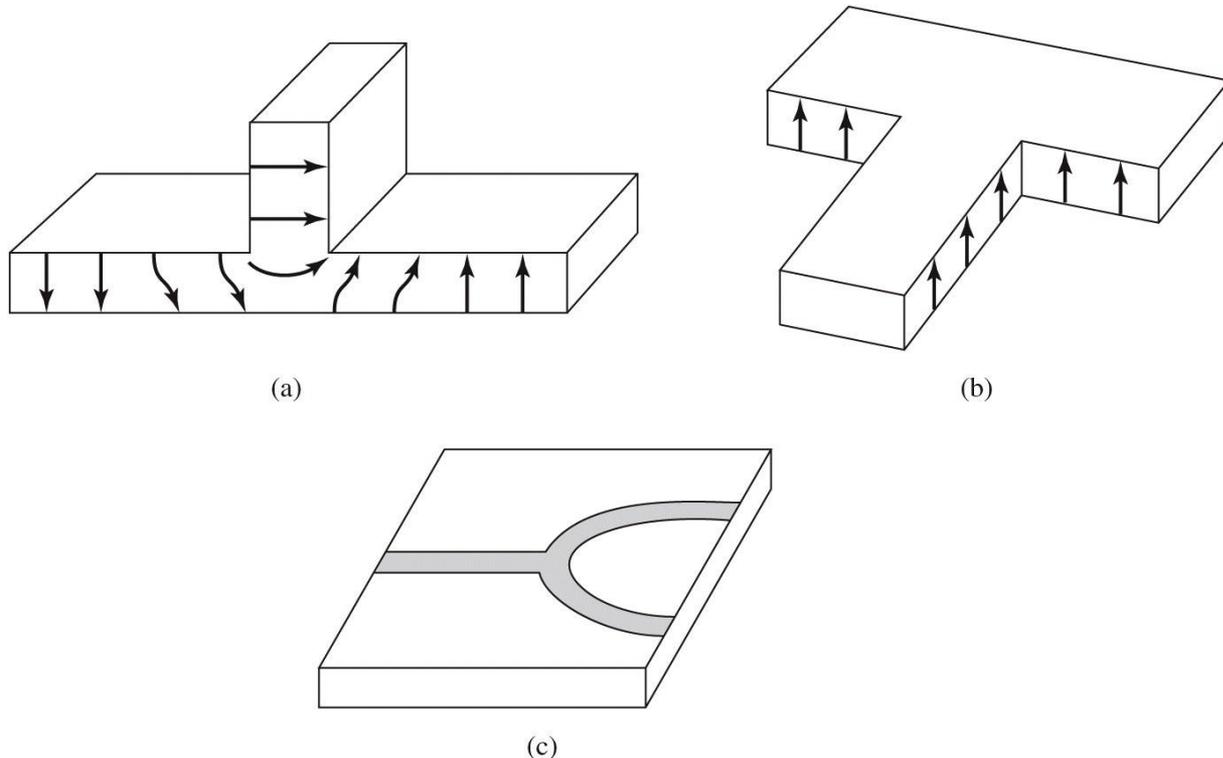
- circulator often found in duplexer



Power dividers

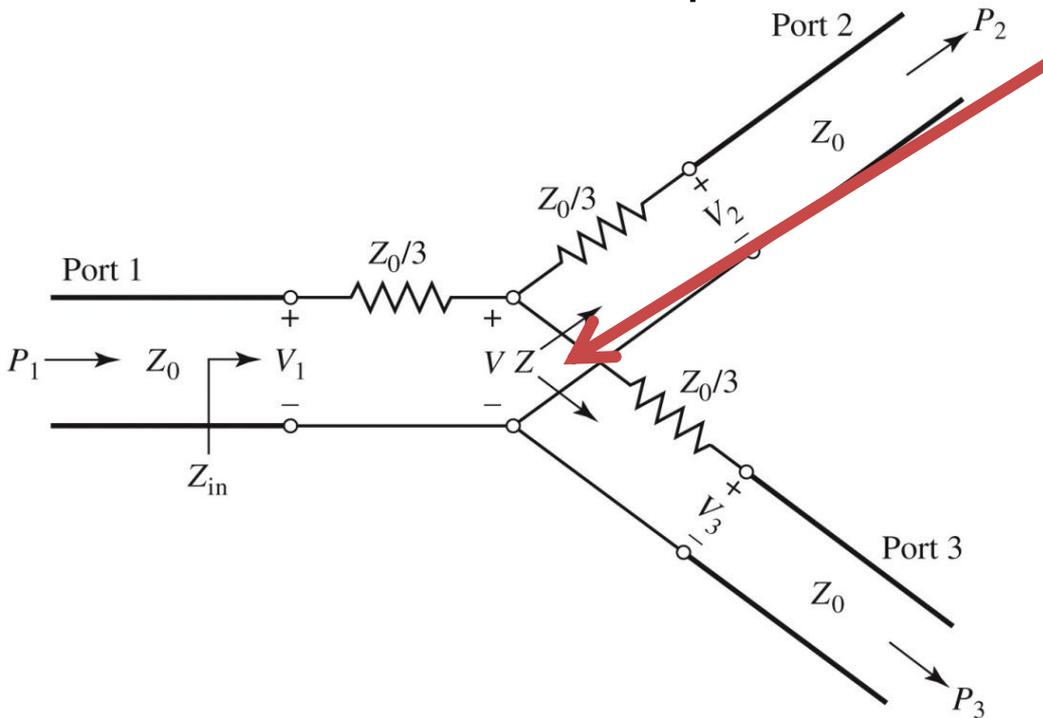
Power division of the T-junction

- consists in splitting an input line into two separate output lines
- available in various technologies for the lines



Resistive Divider

- If a three-port divider contains lossy components, it can be made to be :
 - reciprocal
 - matched at all ports



The impedance Z , seen looking into the $Z_0/3$ resistor followed by a terminated output line:

$$Z = \frac{Z_0}{3} + Z_0 = \frac{4Z_0}{3}$$

The input line will be terminated with a $Z_0/3$ resistor in series with two such lines Z in parallel

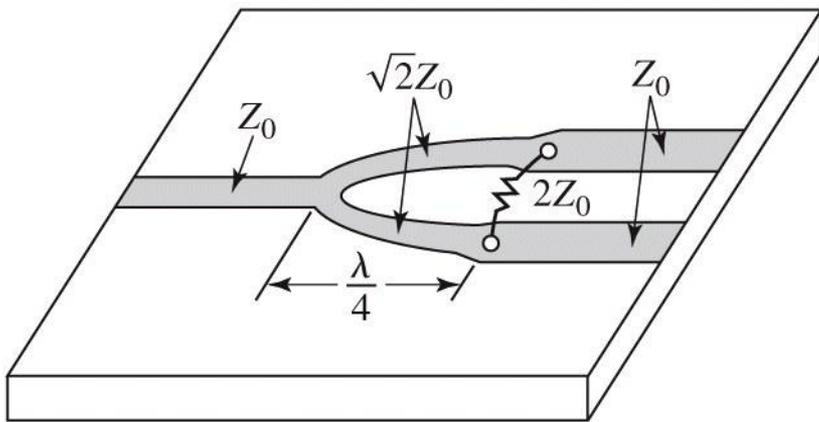
$$Z_{in} = \frac{Z_0}{3} + \frac{1}{2} \cdot \frac{4Z_0}{3} = Z_0$$

so it will be matched: $S_{11} = 0$

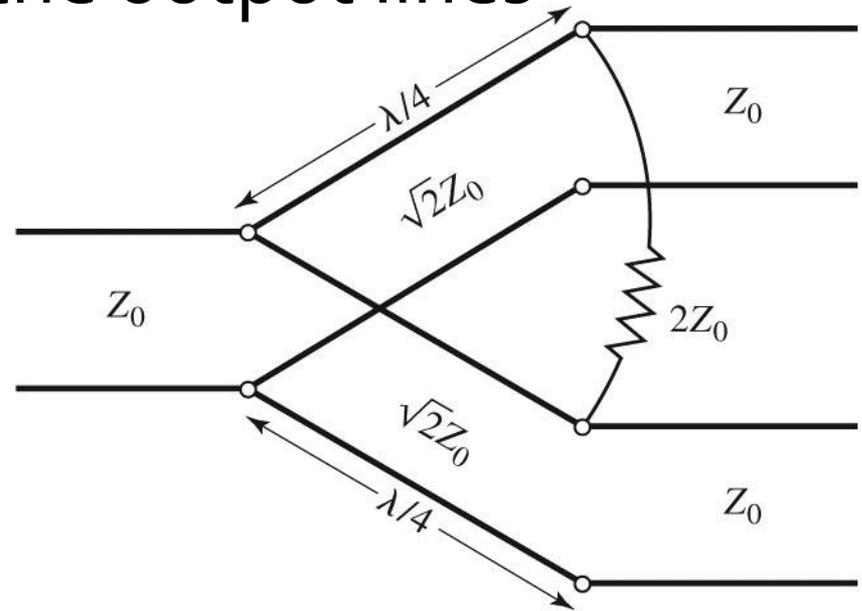
from symmetry: $S_{11} = S_{22} = S_{33} = 0$

The Wilkinson power divider

- one input line
- two $\lambda/4$ transformers
- one resistor between the output lines

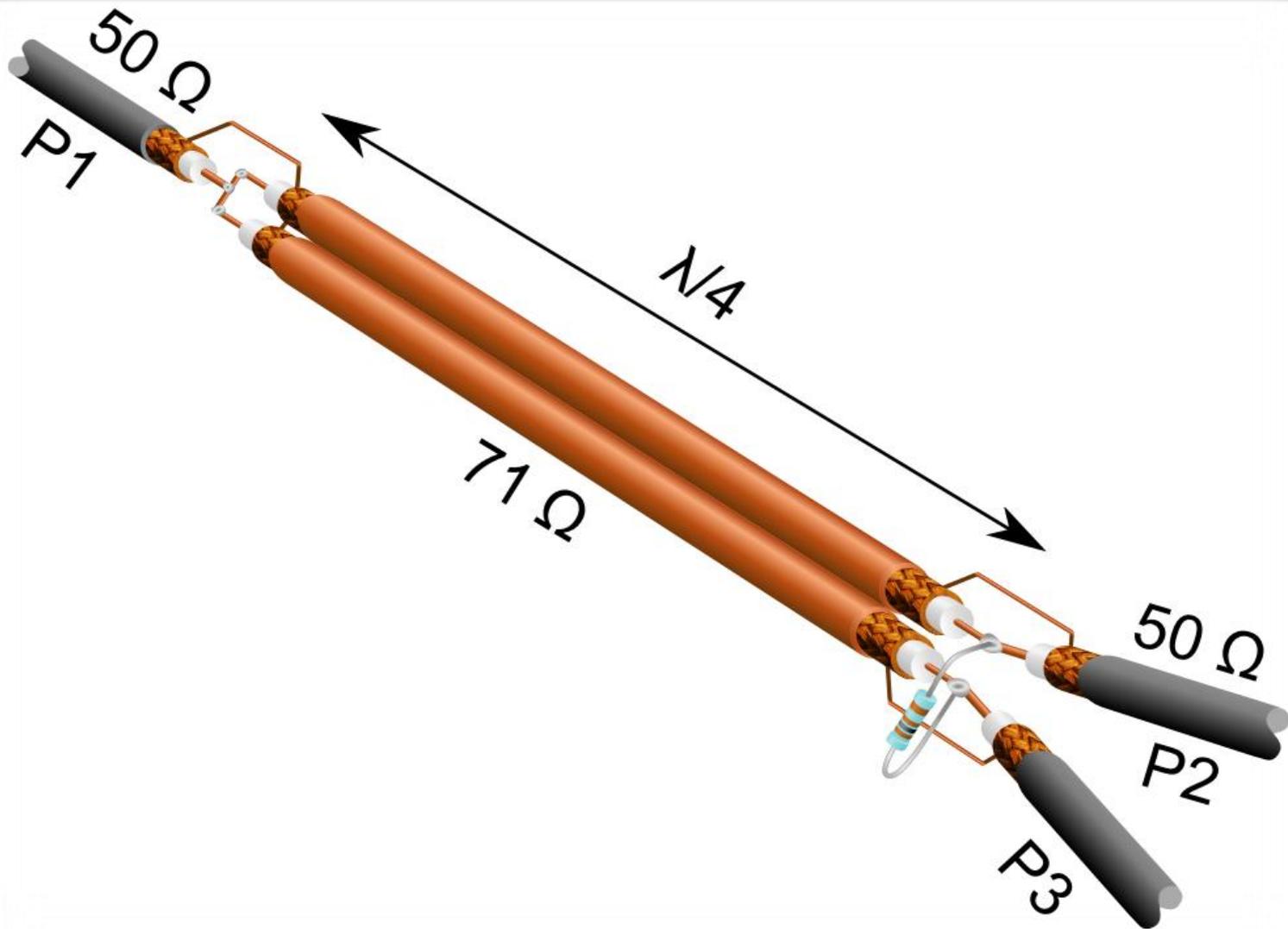


(a)



(b)

The Wilkinson power divider



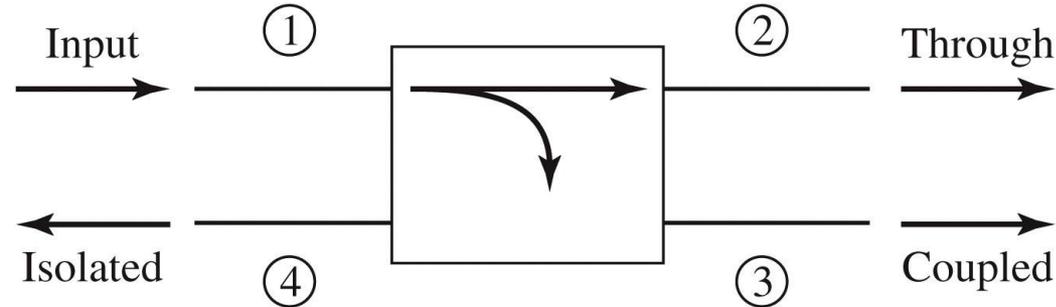
Directional couplers

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

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

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

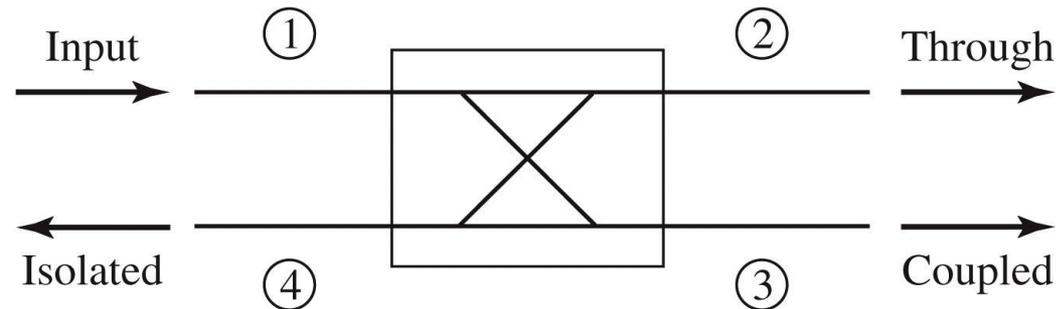


Figure 7.4
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Directional Couplers

Laboratory no. 2

The quadrature (90°) hybrid

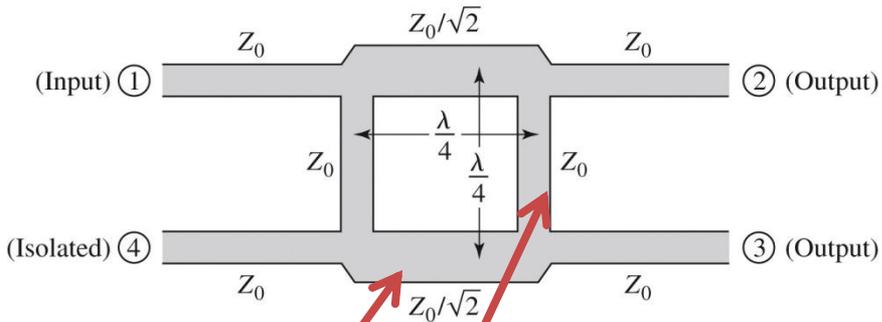


Figure 7.21
© John Wiley & Sons, Inc. All rights reserved.

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

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

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

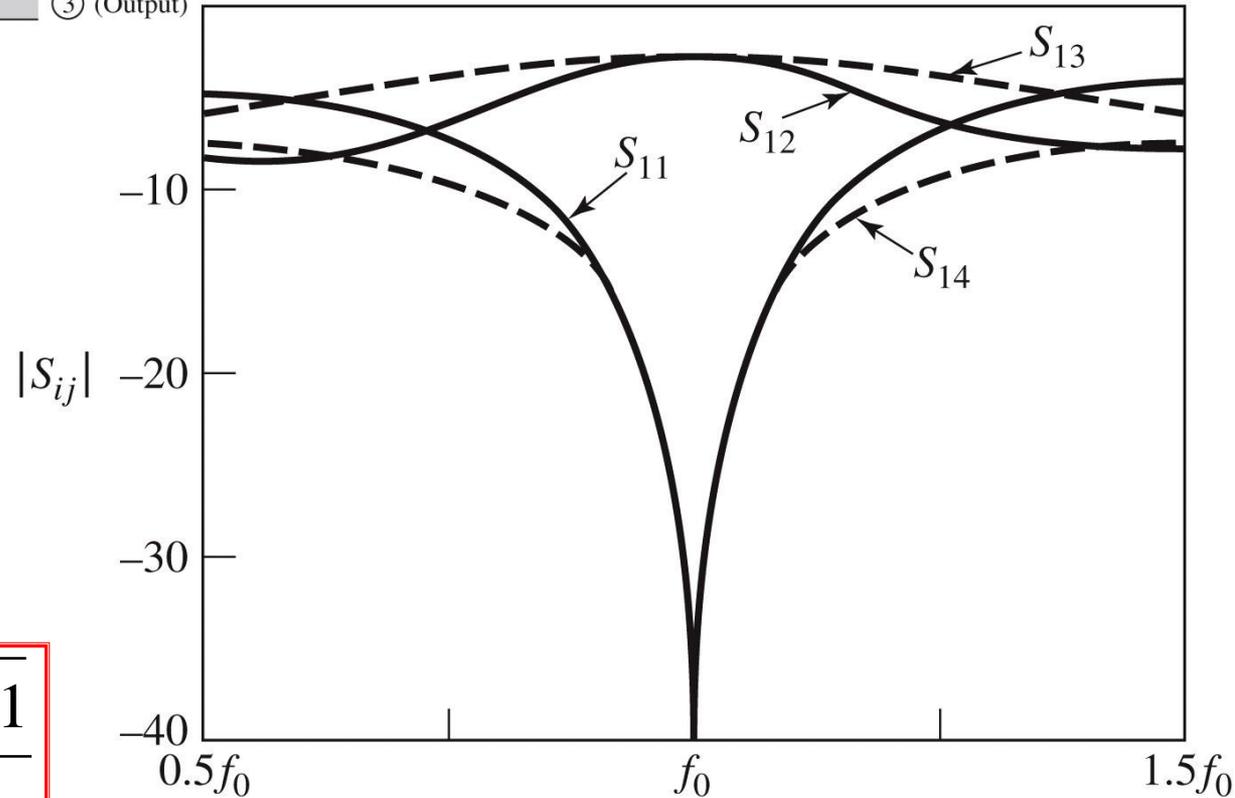
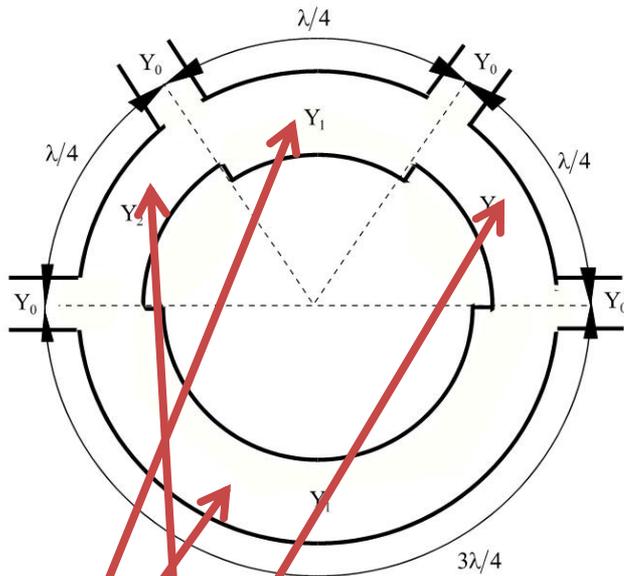


Figure 7.25
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The 180° ring hybrid



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

$$|\beta| = y_1$$

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

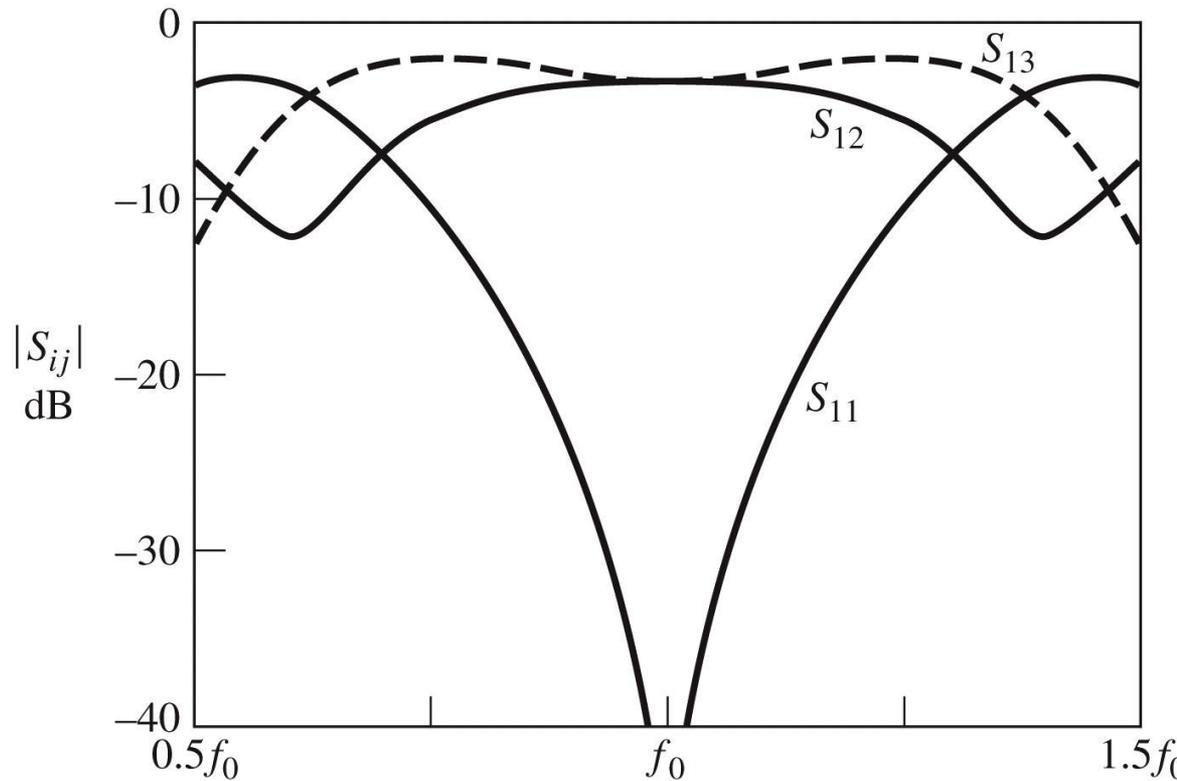
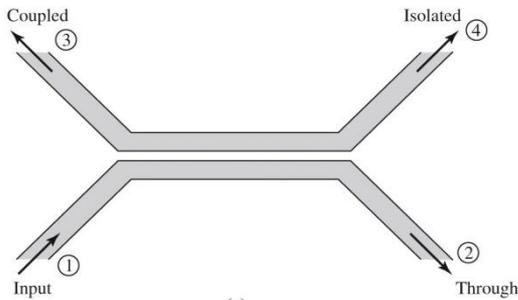


Figure 7.46
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Coupled Line Coupler



Coupling, Directivity (dB)

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

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

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

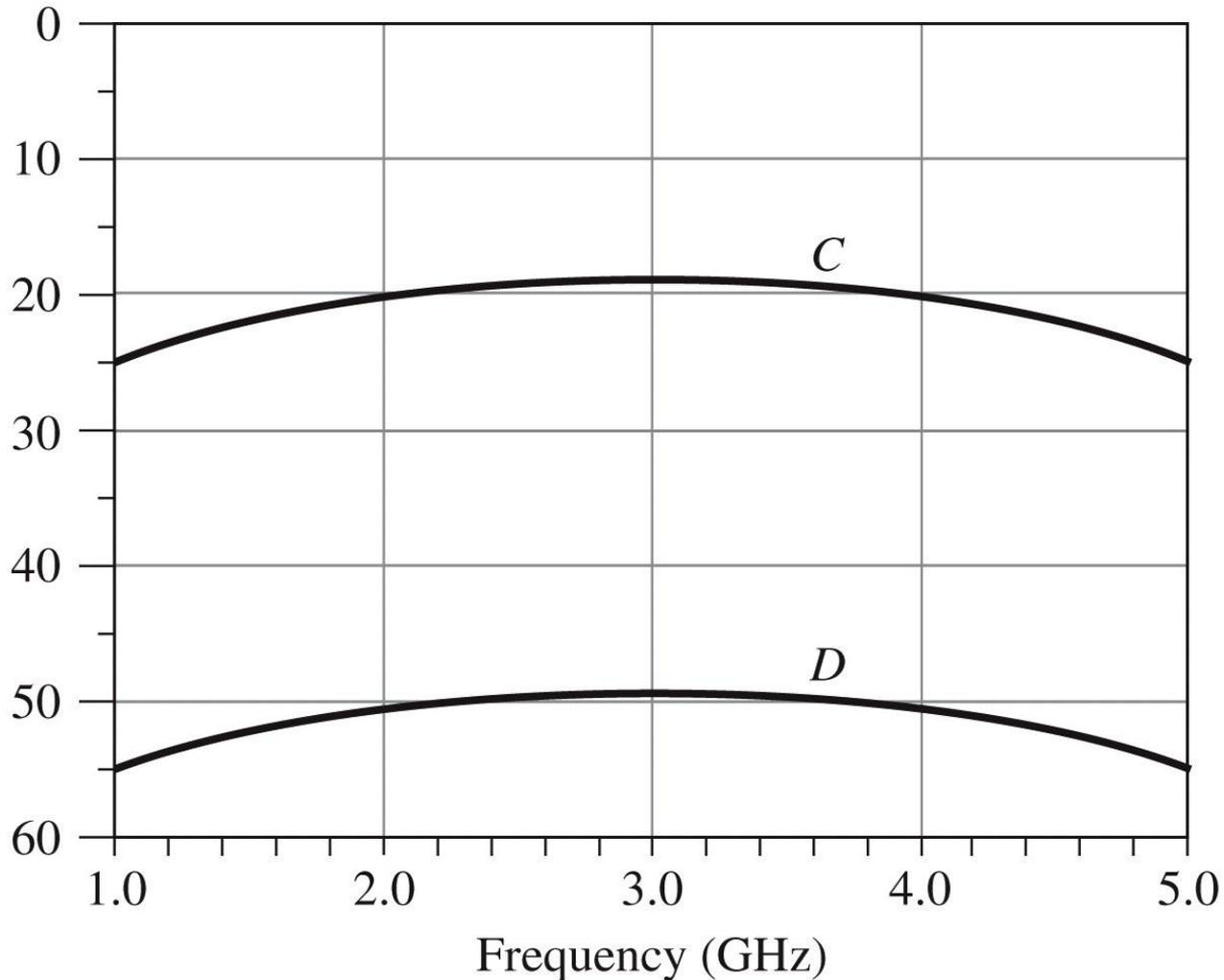


Figure 7.34
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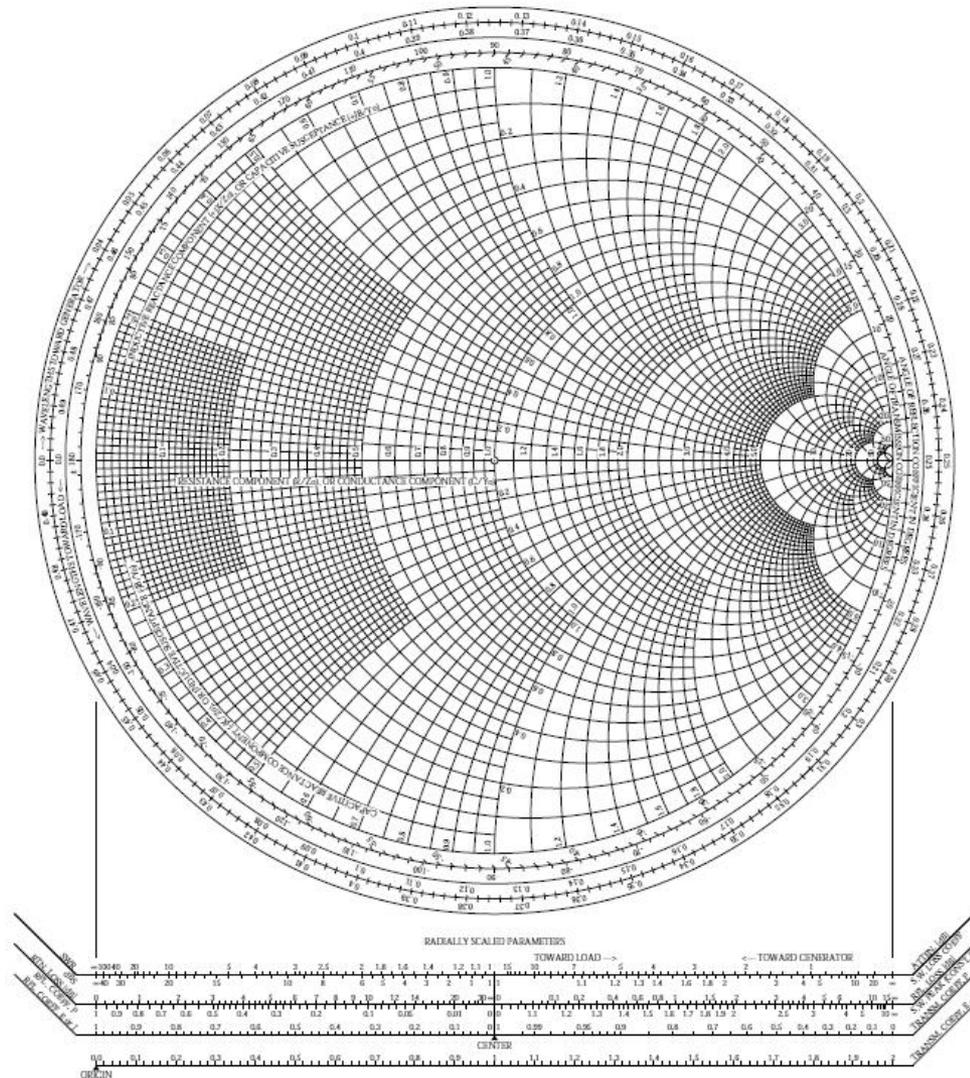
Impedance Matching

The Smith Chart

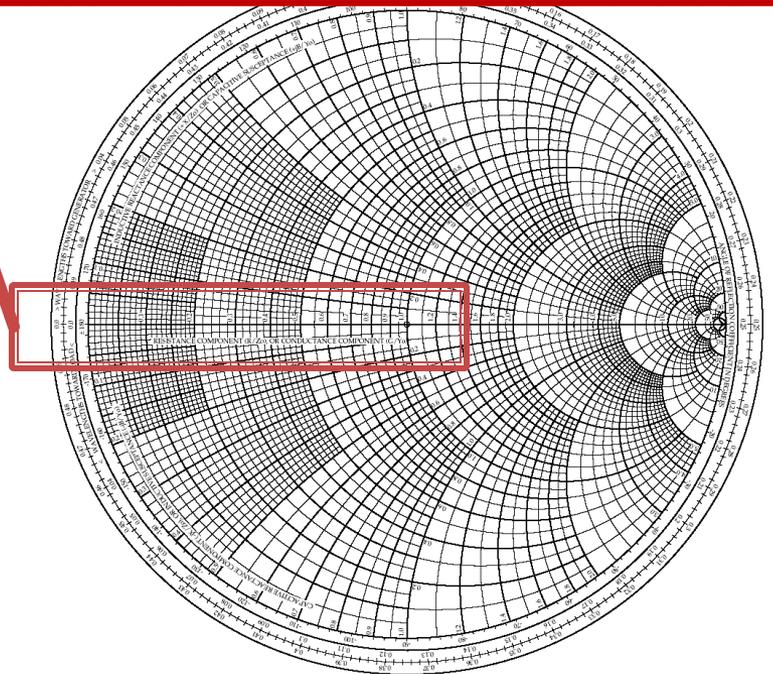
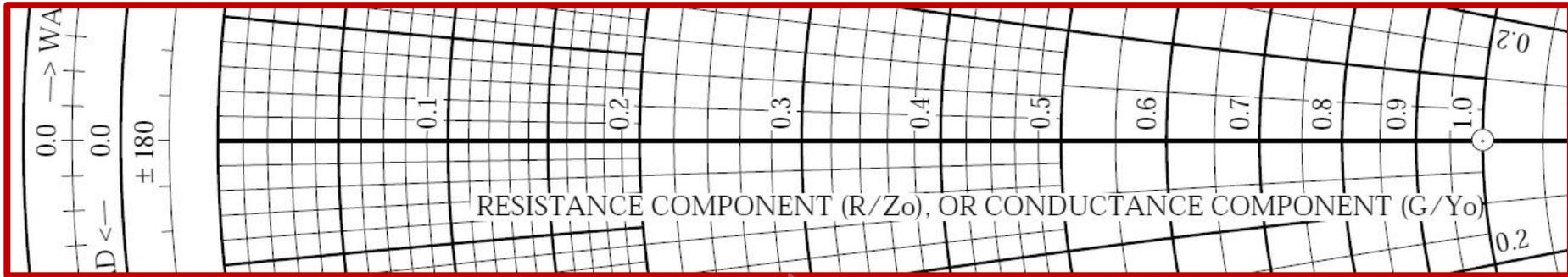
Course Topics

- Transmission lines
 - Impedance matching and tuning
 - Directional couplers
 - Power dividers
 - Microwave amplifier design
 - Microwave filters
 - ~~Oscillators and mixers?~~
- 

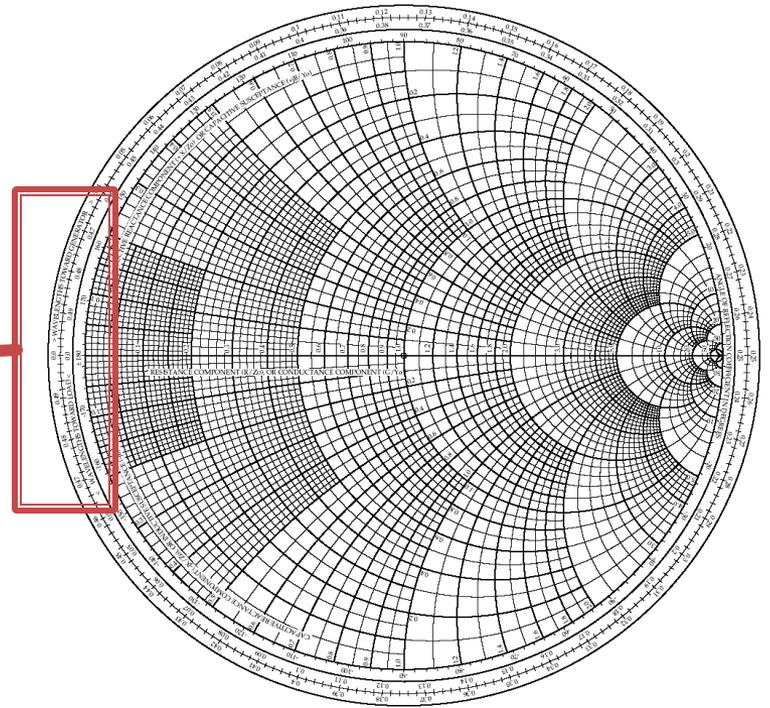
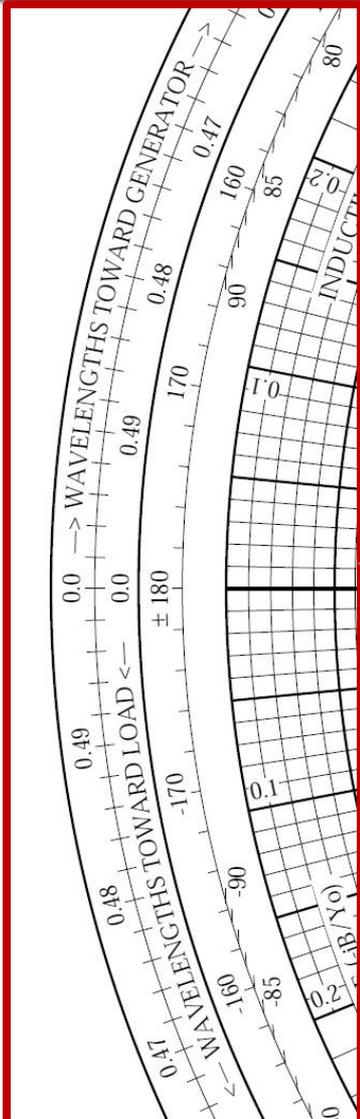
The Smith Chart



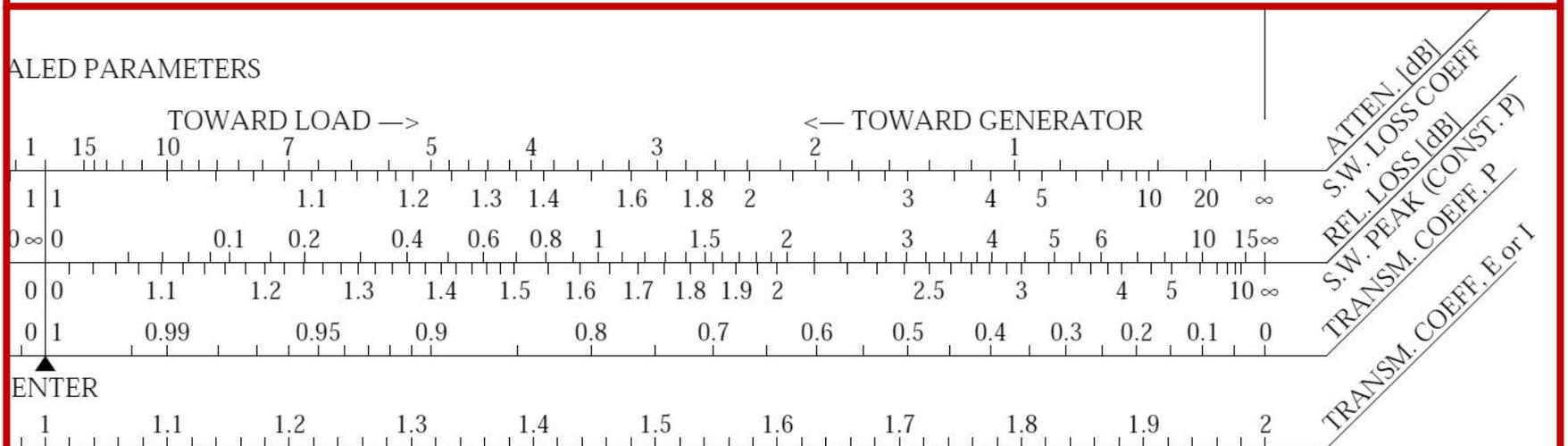
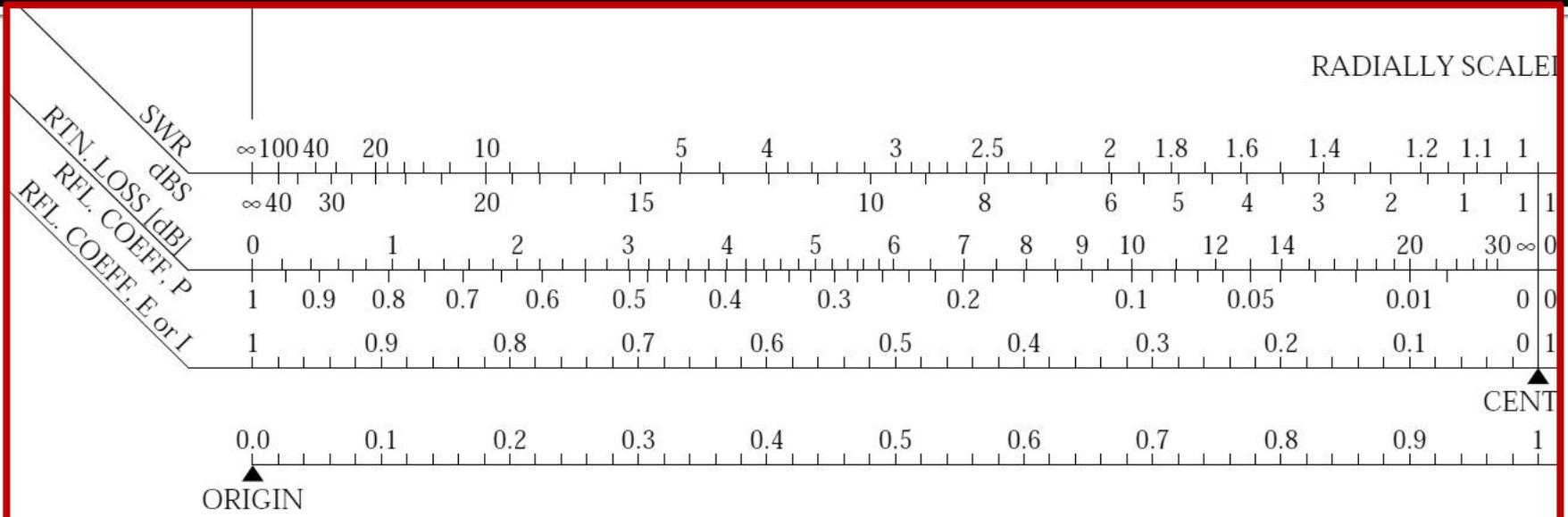
The Smith Chart



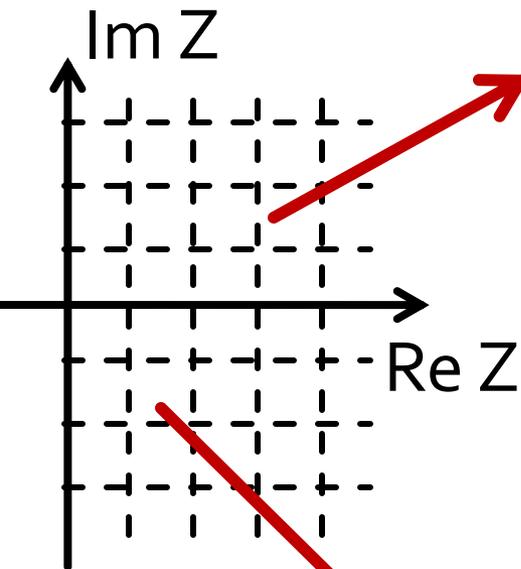
The Smith Chart



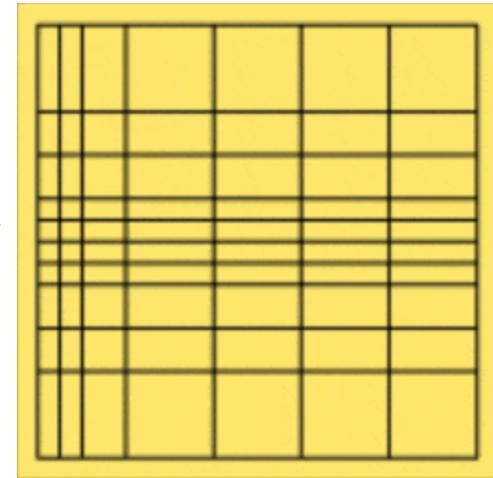
The Smith Chart



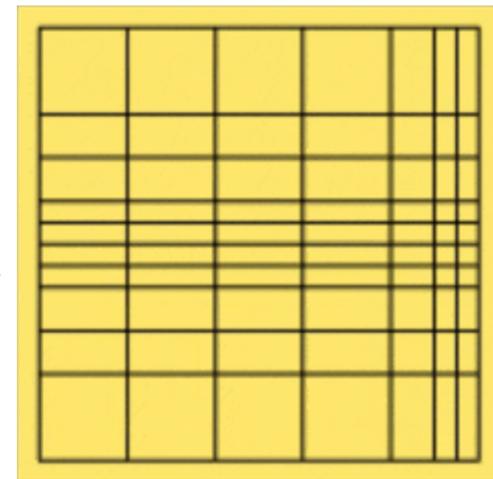
The Smith Chart



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

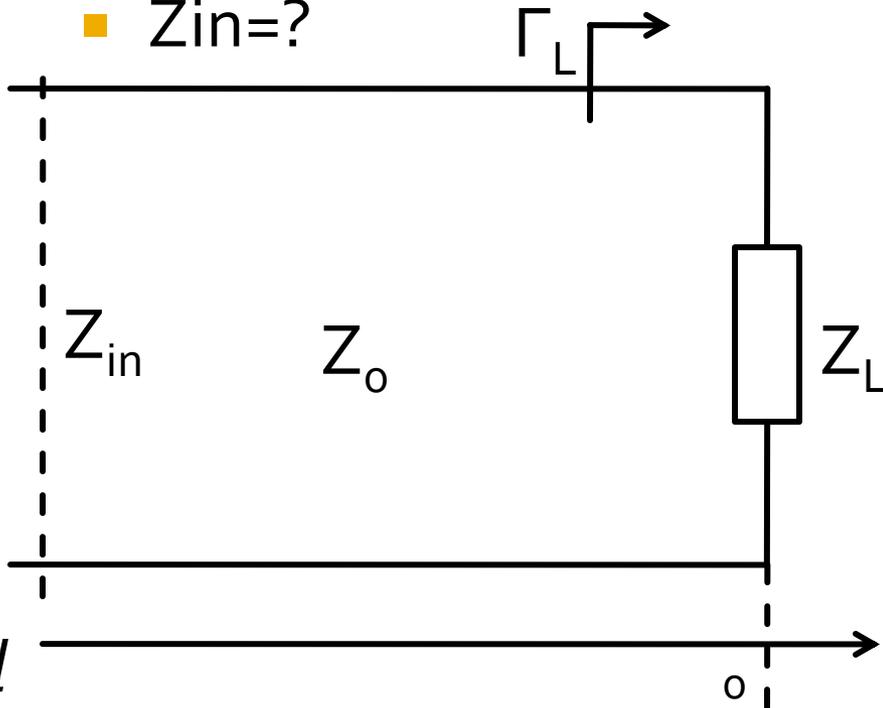


$$\Gamma = \frac{Z_L - Z_0}{Z_L + Z_0} = \frac{Y_0 - Y_L}{Y_0 + Y_L} = \frac{1 - y_L}{1 + y_L}$$



Traditional usage

- transmission line
 - 100Ω characteristic impedance
 - 0.3λ length
 - $Z_L = 40\Omega + j \cdot 70\Omega$ load
- $Z_{in} = ?$



$$Z_{in} = Z_0 \cdot \frac{Z_L + j \cdot Z_0 \cdot \tan \beta \cdot l}{Z_0 + j \cdot Z_L \cdot \tan \beta \cdot l}$$

$$Z_{in} = 36.5340\Omega - j \cdot 61.1190\Omega$$

Traditional usage

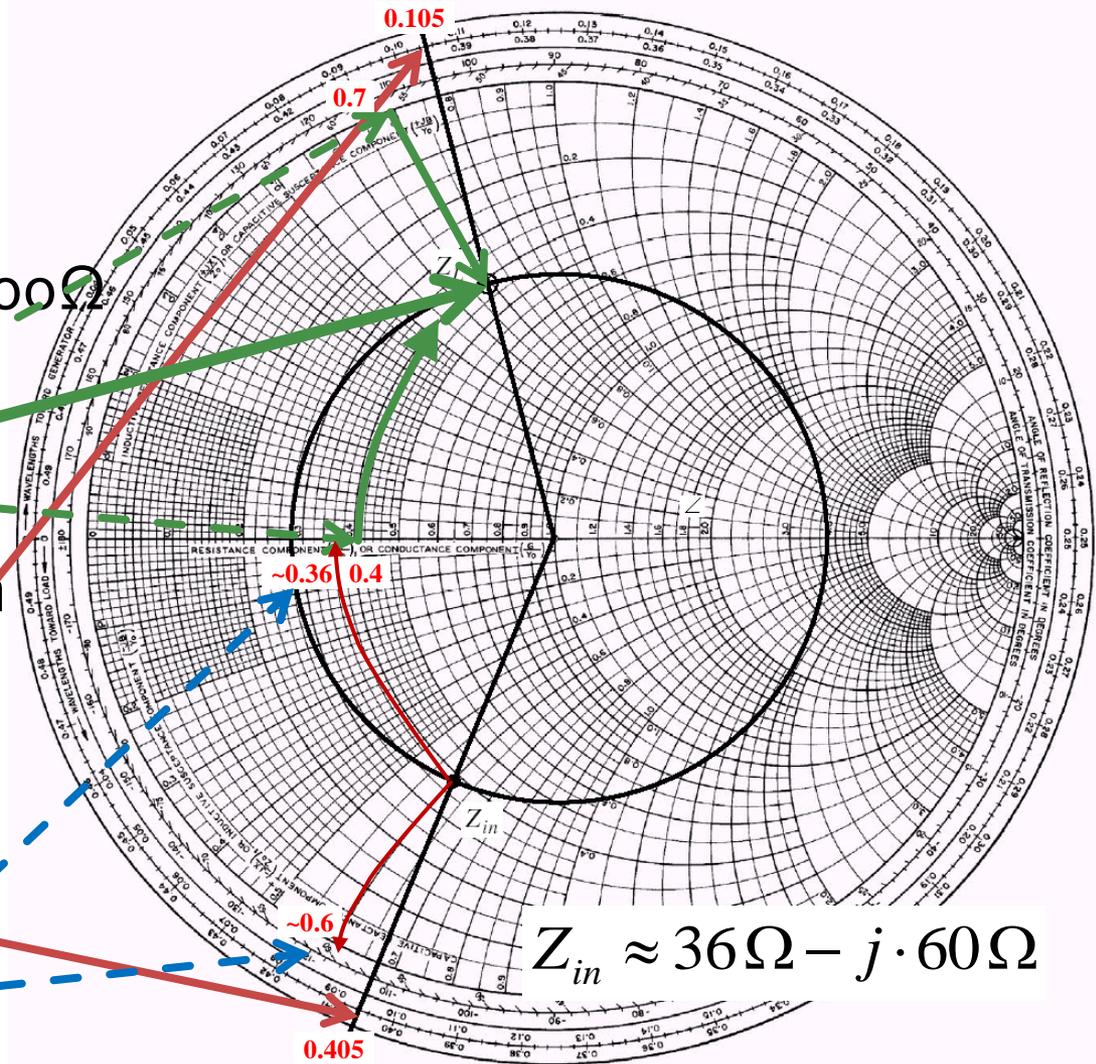
- transmission line
 - 100Ω impedance
 - 0.3λ length
 - $Z_L = 40\Omega + j \cdot 70\Omega$ load
- normalization with $Z_0 = 100\Omega$

$$z_L = \frac{Z_L}{Z_0} = 0.4 + j \cdot 0.7$$

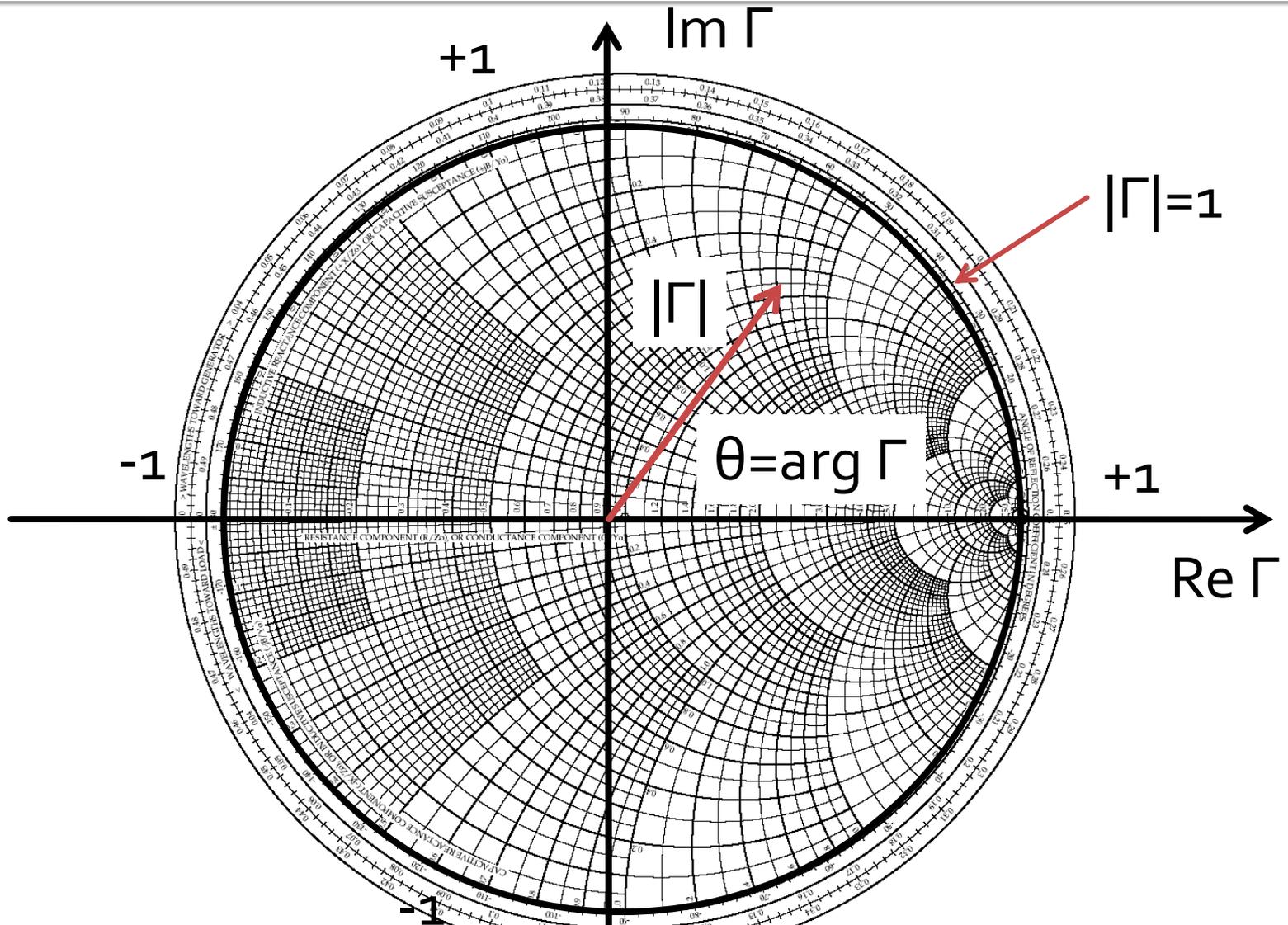
- movement with 0.3λ on a line with $Z_0 = 100\Omega$ (**circle**)

- from z_L (0.105λ)
- to z_{in} (0.405λ)

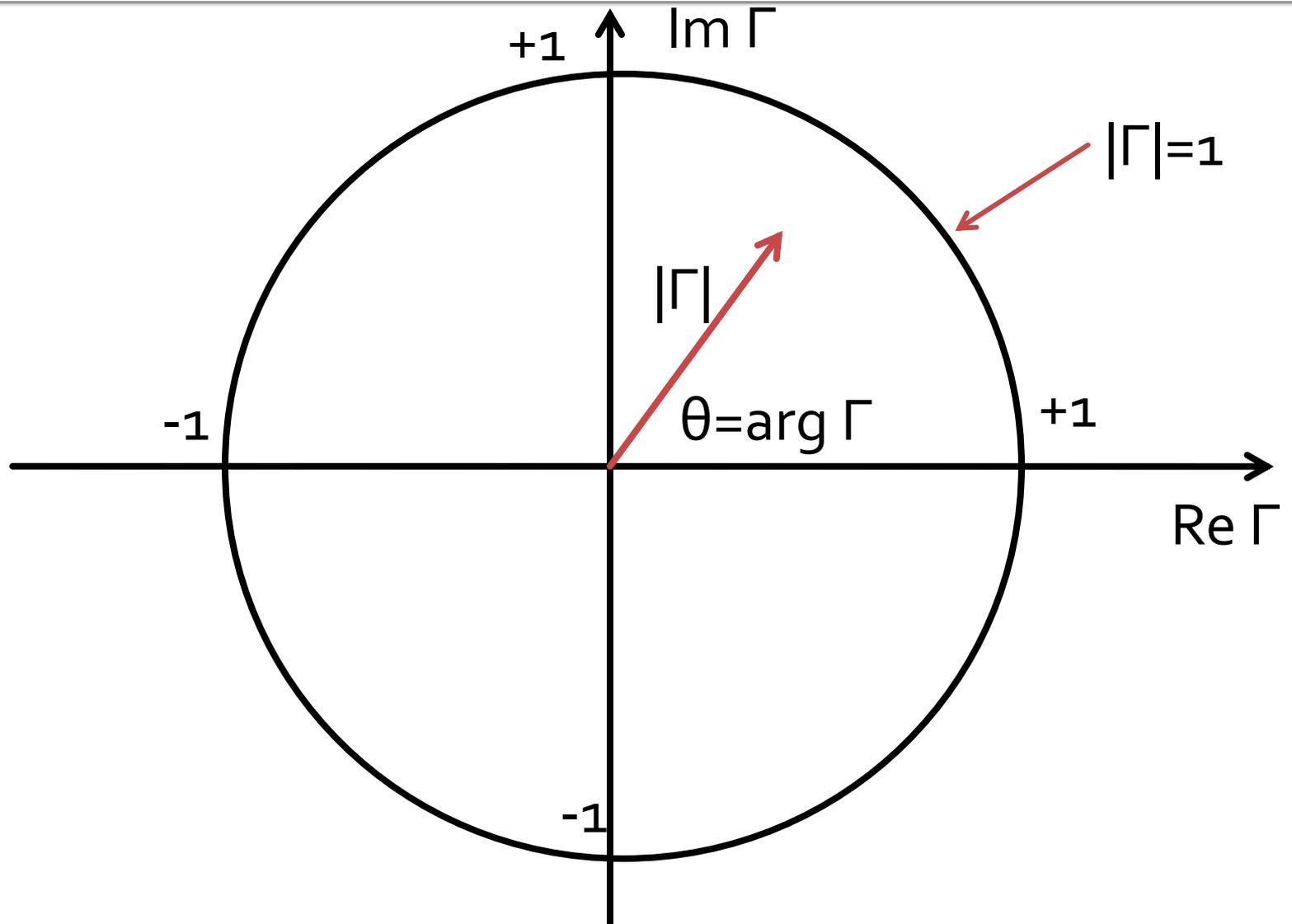
$$z_{in} \approx 0.36 - j \cdot 0.6 = \frac{Z_{in}}{Z_0}$$



The Smith Chart



The Smith Chart



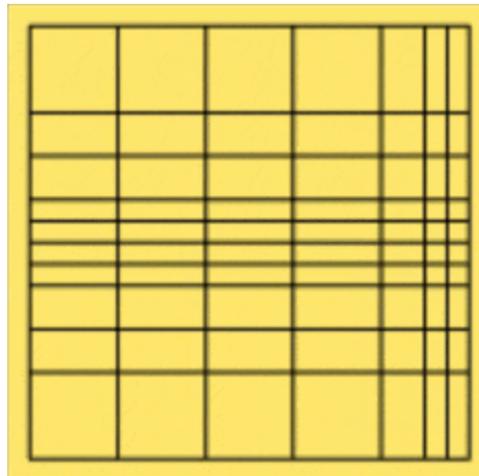
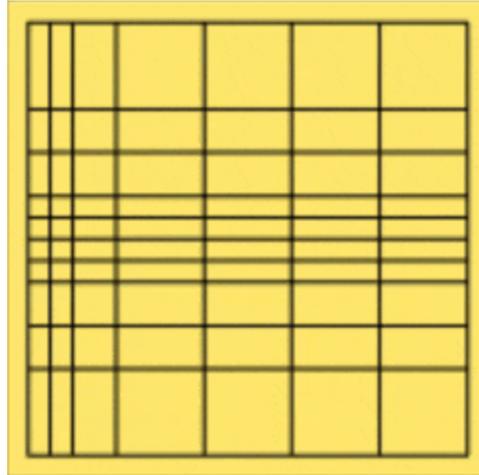
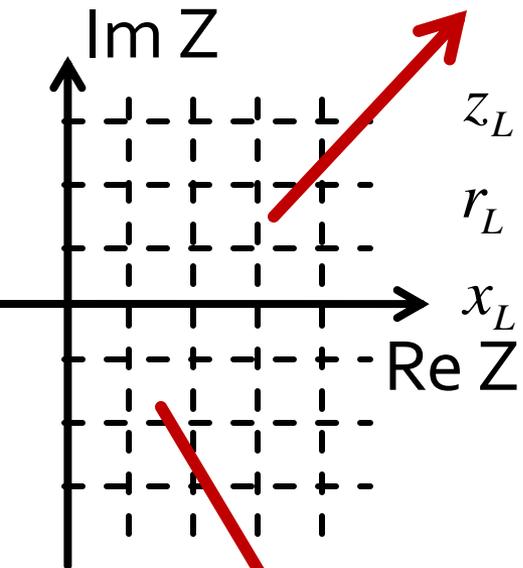
The Smith Chart

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

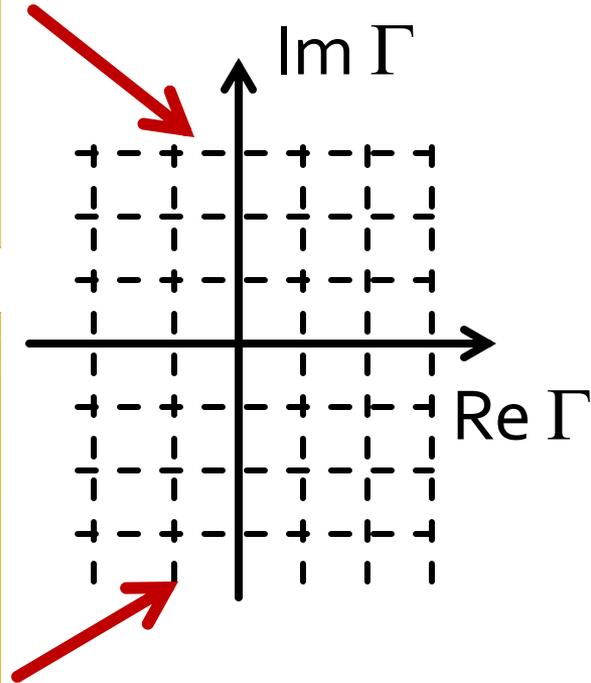
$$z_L = r_L + j \cdot x_L$$

$$r_L = ct.$$

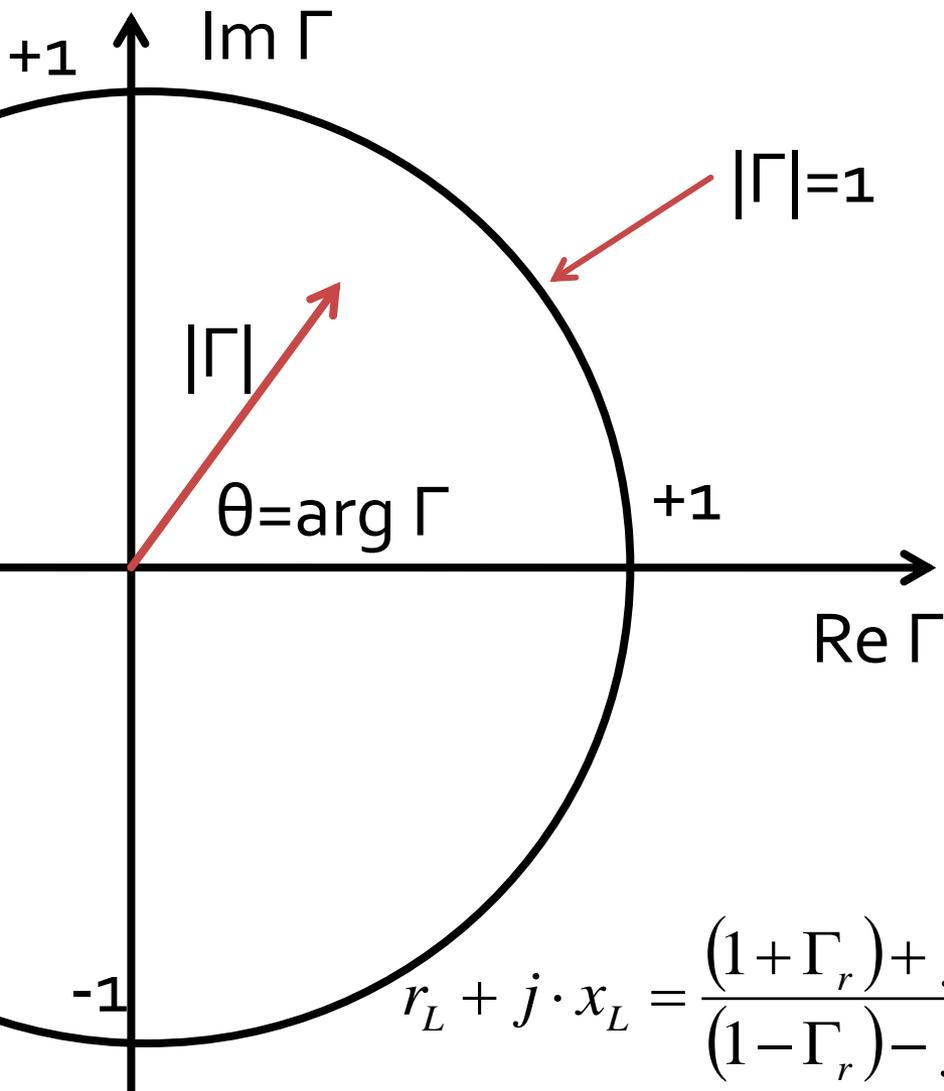
$$x_L = ct.$$



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



The Smith Chart



$$\Gamma = \frac{Z_L - Z_0}{Z_L + Z_0} = \frac{z_L - 1}{z_L + 1} = |\Gamma| \cdot e^{j\theta}$$

$$z_L = \frac{Z_L}{Z_0} \quad y_L = \frac{Y_L}{Y_0} = \frac{Z_0}{Z_L}$$

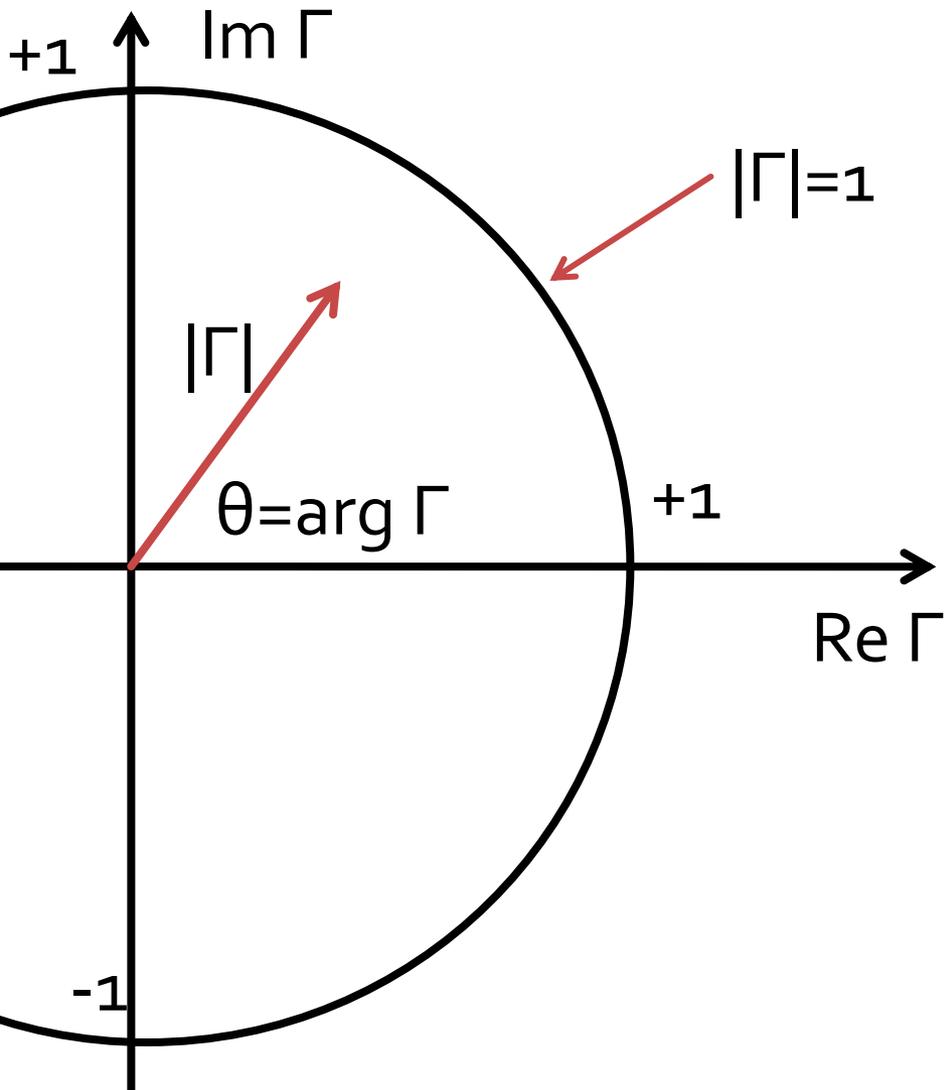
normalization $Z_L \rightarrow z_L$ allows using the same chart for any reference impedance Z_0 (the plot becomes independent of the chosen Z_0)

$$\Gamma = \Gamma_r + j \cdot \Gamma_i$$

$$z_L = \frac{1 + |\Gamma| \cdot e^{j\theta}}{1 - |\Gamma| \cdot e^{j\theta}} = r_L + j \cdot x_L$$

$$r_L + j \cdot x_L = \frac{(1 + \Gamma_r) + j \cdot \Gamma_i}{(1 - \Gamma_r) - j \cdot \Gamma_i} = \frac{1 - \Gamma_r^2 - \Gamma_i^2}{(1 - \Gamma_r)^2 + \Gamma_i^2} + j \cdot \frac{2 \cdot \Gamma_i}{(1 - \Gamma_r)^2 + \Gamma_i^2}$$

The Smith Chart



$$r_L = \frac{1 - \Gamma_r^2 - \Gamma_i^2}{(1 - \Gamma_r)^2 + \Gamma_i^2}$$

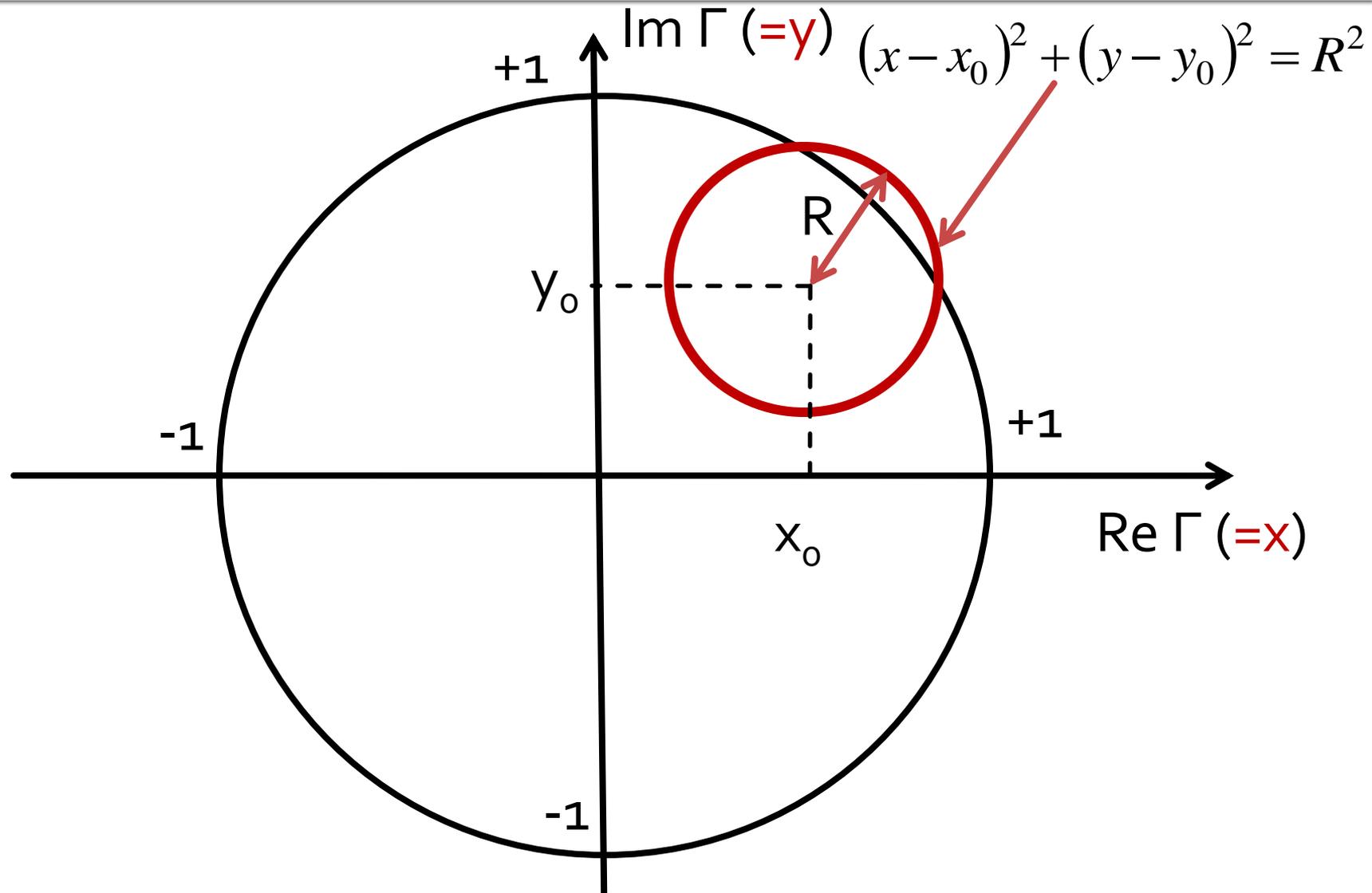
$$x_L = \frac{2 \cdot \Gamma_i}{(1 - \Gamma_r)^2 + \Gamma_i^2}$$

■ Rearranged

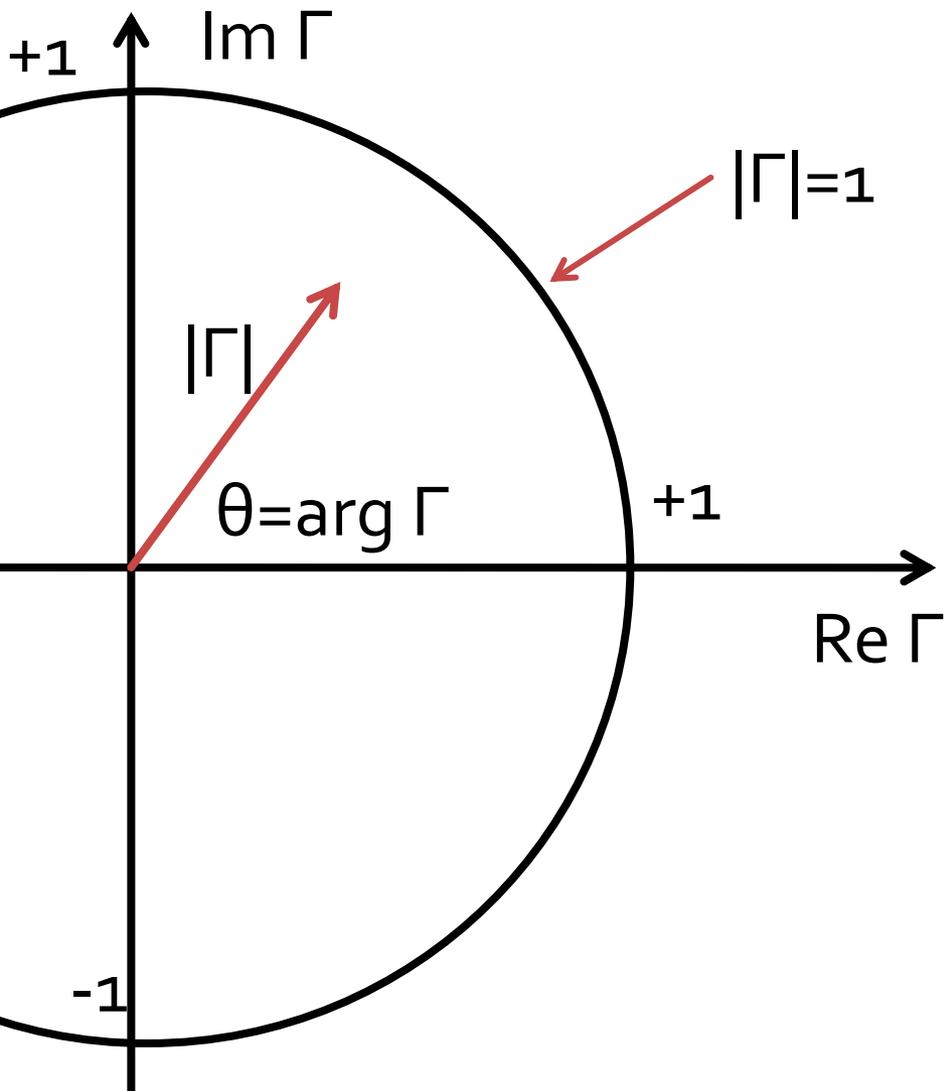
$$\left(\Gamma_r - \frac{r_L}{1 + r_L} \right)^2 + \Gamma_i^2 = \left(\frac{1}{1 + r_L} \right)^2$$

$$(\Gamma_r - 1)^2 + \left(\Gamma_i - \frac{1}{x_L} \right)^2 = \left(\frac{1}{x_L} \right)^2$$

The Smith Chart



The Smith Chart



$$\left(\Gamma_r - \frac{r_L}{1+r_L} \right)^2 + \Gamma_i^2 = \left(\frac{1}{1+r_L} \right)^2$$

$$(\Gamma_r - 1)^2 + \left(\Gamma_i - \frac{1}{x_L} \right)^2 = \left(\frac{1}{x_L} \right)^2$$

- **Circles** in the (Γ_r, Γ_i) complex plane

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

The Smith Chart, resistance

$$\left(\Gamma_r - \frac{r_L}{1+r_L} \right)^2 + \Gamma_i^2 = \left(\frac{1}{1+r_L} \right)^2$$

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

$$\begin{cases} x_0 = \frac{r_L}{1+r_L} \\ y_0 = 0 \\ R = \frac{1}{1+r_L} \end{cases}$$

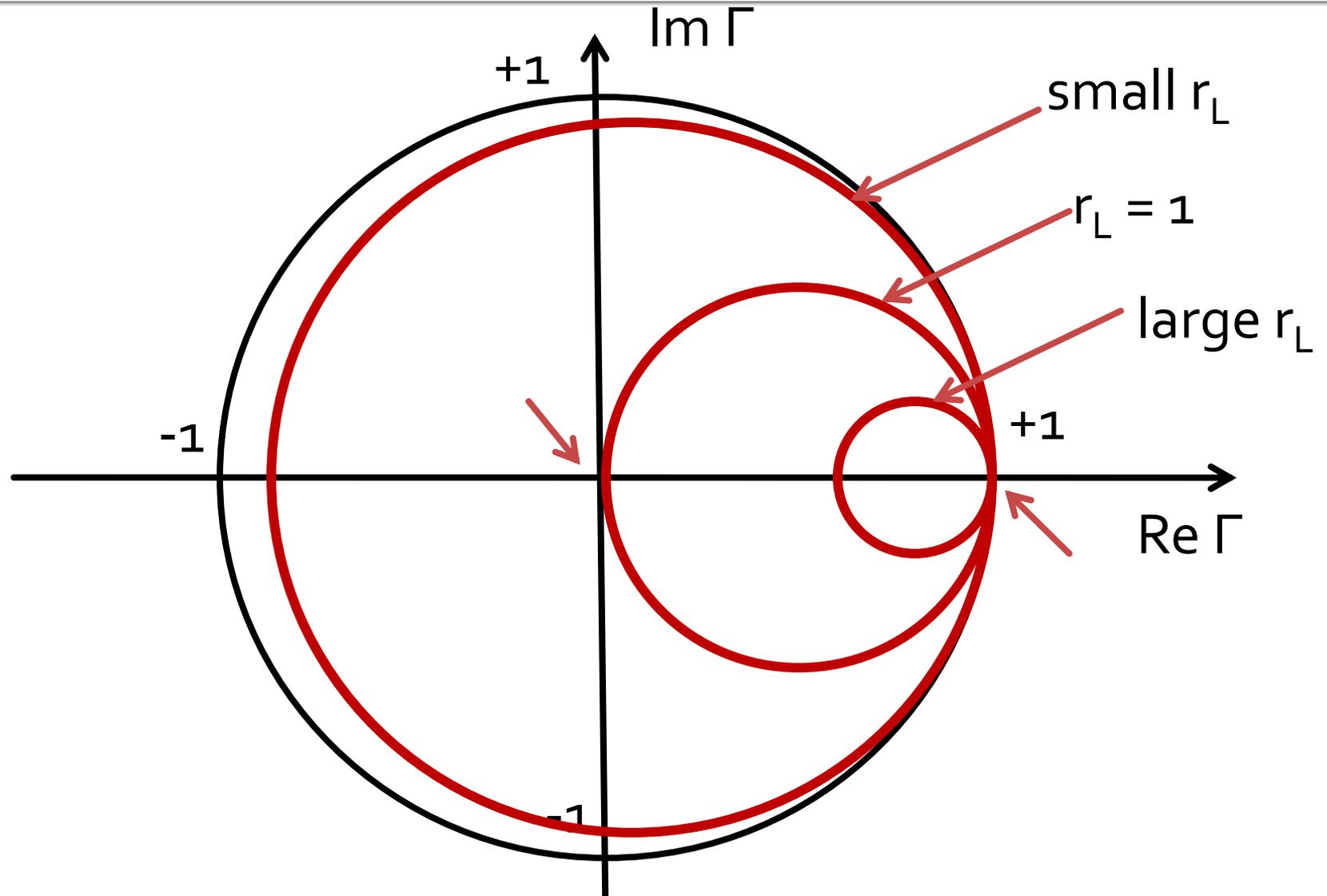
- The locus (the set of all points whose location satisfies one or more specified conditions) of the points generated by all impedances having normalized resistance r_L is a circle which:

- have its **center on the horizontal axis** ($y_0=0$)
- passes through **$x=1, y=0$** point, whatever x_0, r_L
- have its radius between 0 and 1
 - tends to 0 for large r_L
 - tends to 1 for small r_L
- when r_L is **1** passes also through **origin**
- for any **positive** r_L radius is **<1**

$$\left(1 - \frac{r_L}{1+r_L} \right)^2 + 0 = \left(\frac{1}{1+r_L} \right)^2$$

$$\left(0 - \frac{r_L}{1+r_L} \right)^2 = \left(\frac{1}{1+r_L} \right)^2 \leftrightarrow r_L = 1$$

The Smith Chart, resistance



The Smith Chart, reactance

$$(\Gamma_r - 1)^2 + \left(\Gamma_i - \frac{1}{x_L}\right)^2 = \left(\frac{1}{x_L}\right)^2$$

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

$$\left\{ \begin{array}{l} x_0 = 1 \\ y_0 = \frac{1}{x_L} \\ R = \frac{1}{|x_L|} \end{array} \right.$$

- The locus of the points generated by all impedances having normalized resistance x_L is a circle which:

- have its **center on a line parallel with the vertical axis** ($x_0=1$)

- passes through **$x=1, y=0$** point, whatever x_0, x_L

- have its radius between 0 and ∞

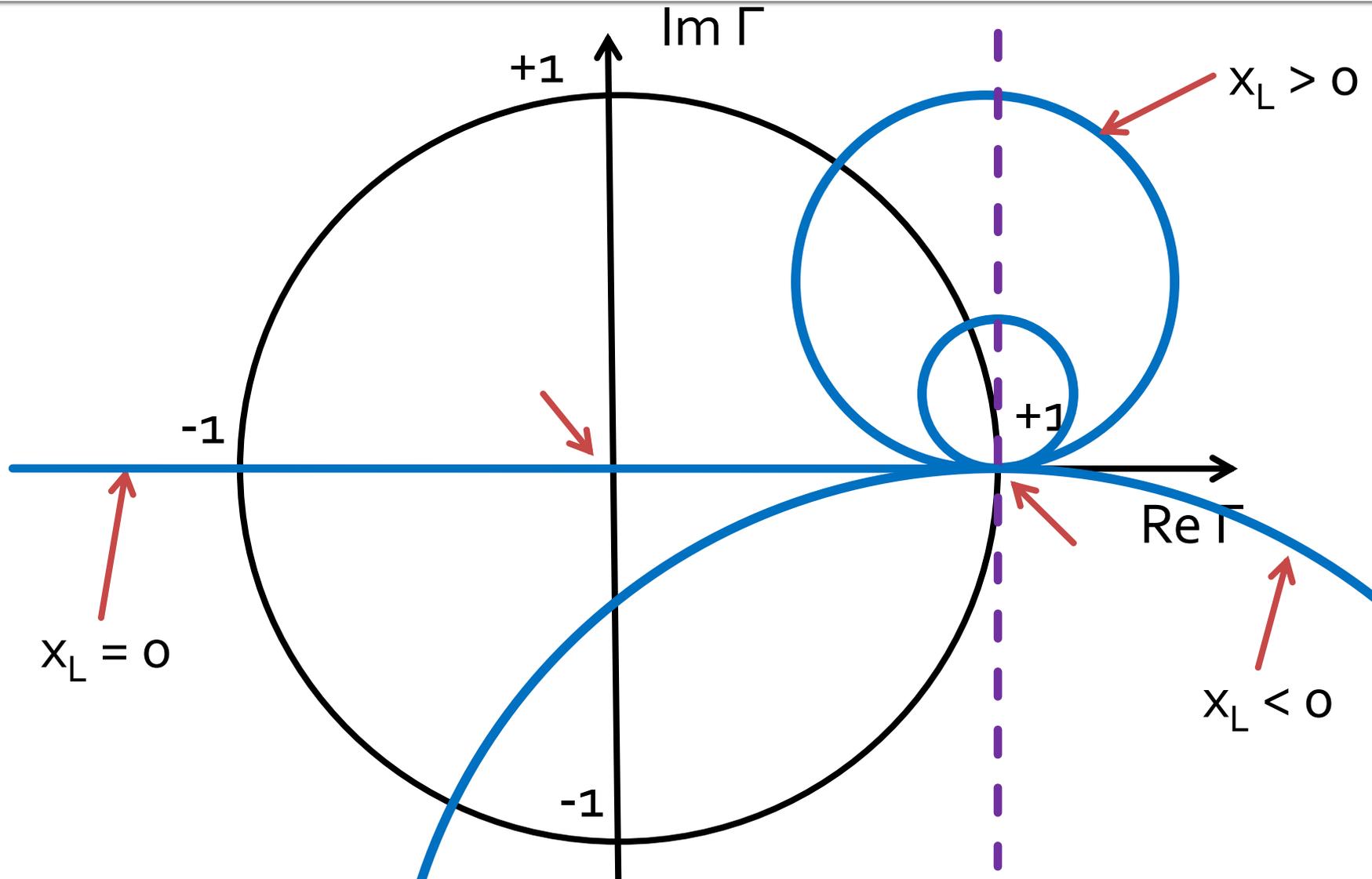
- tends to 0 for large $|x_L|$
- tends to ∞ for small $|x_L|$

$$(1-1)^2 + \left(0 - \frac{1}{x_L}\right)^2 = \left(\frac{1}{x_L}\right)^2$$

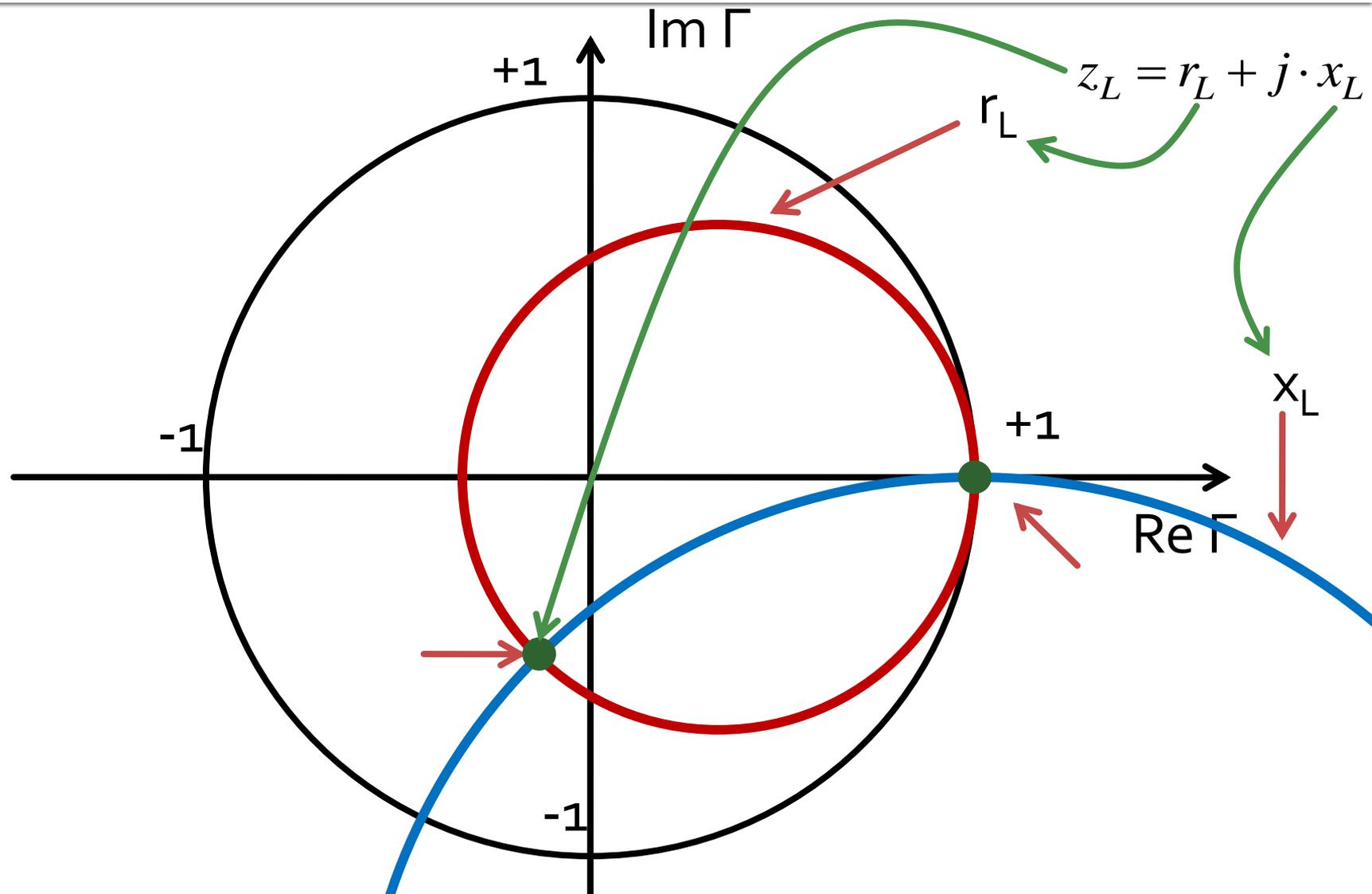
- when x_L is **o** transforms itself in the **horizontal axis**

- if $x_L > 0$ the circle is above the horizontal axis, otherwise is below it

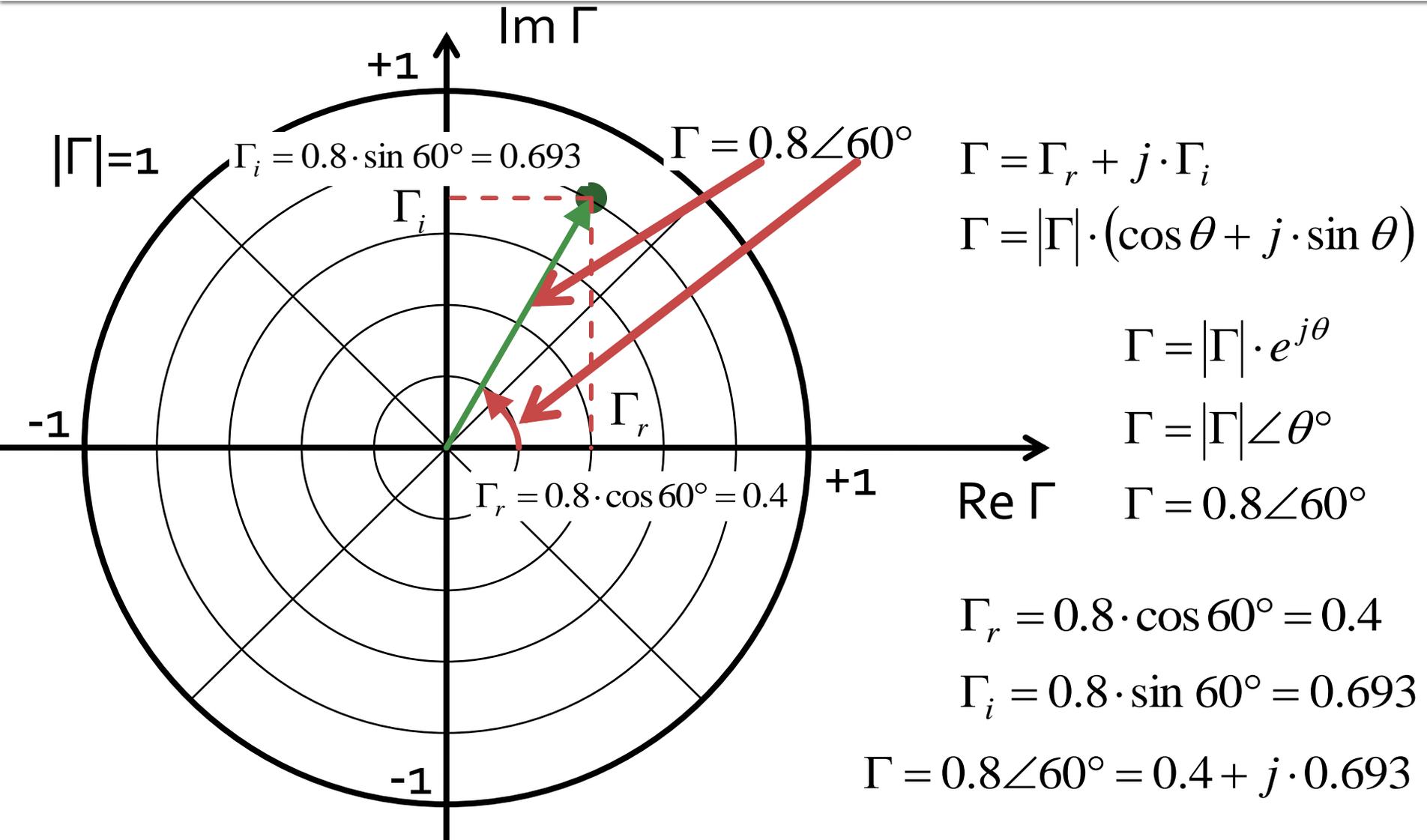
The Smith Chart, reactance



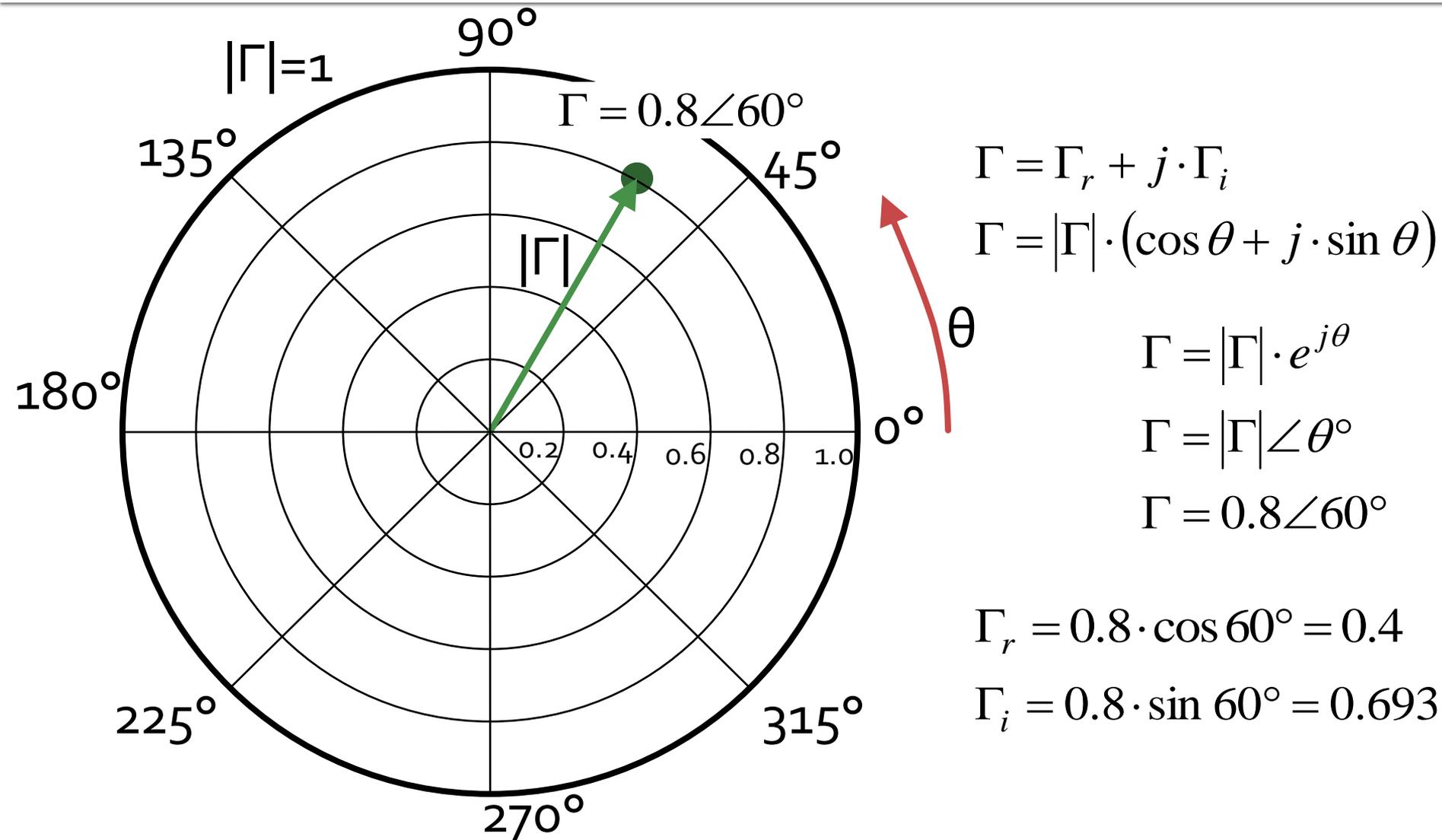
The Smith Chart, impedance



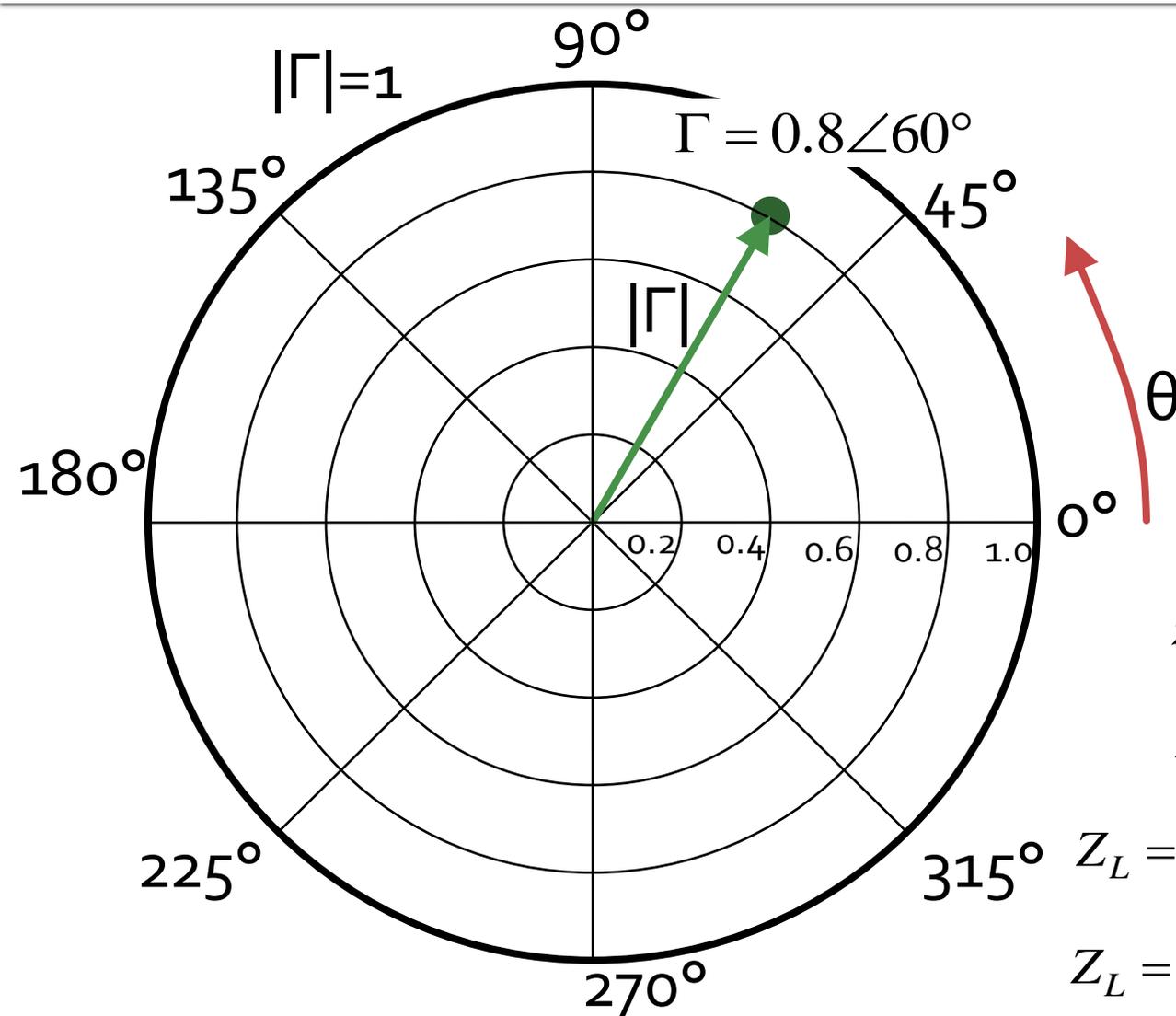
The Smith Chart, reflection coefficient, Cartesian coordinate system



The Smith Chart, reflection coefficient, Polar coordinate system



The Smith Chart, reflection coefficient, impedance



$$\Gamma = |\Gamma| \cdot e^{j\theta}$$

$$\Gamma = |\Gamma| \angle \theta^\circ$$

$$\Gamma = 0.8 \angle 60^\circ$$

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

$$z_L = \frac{1 + \Gamma}{1 - \Gamma} = \frac{1 + 0.8 \angle 60^\circ}{1 - 0.8 \angle 60^\circ}$$

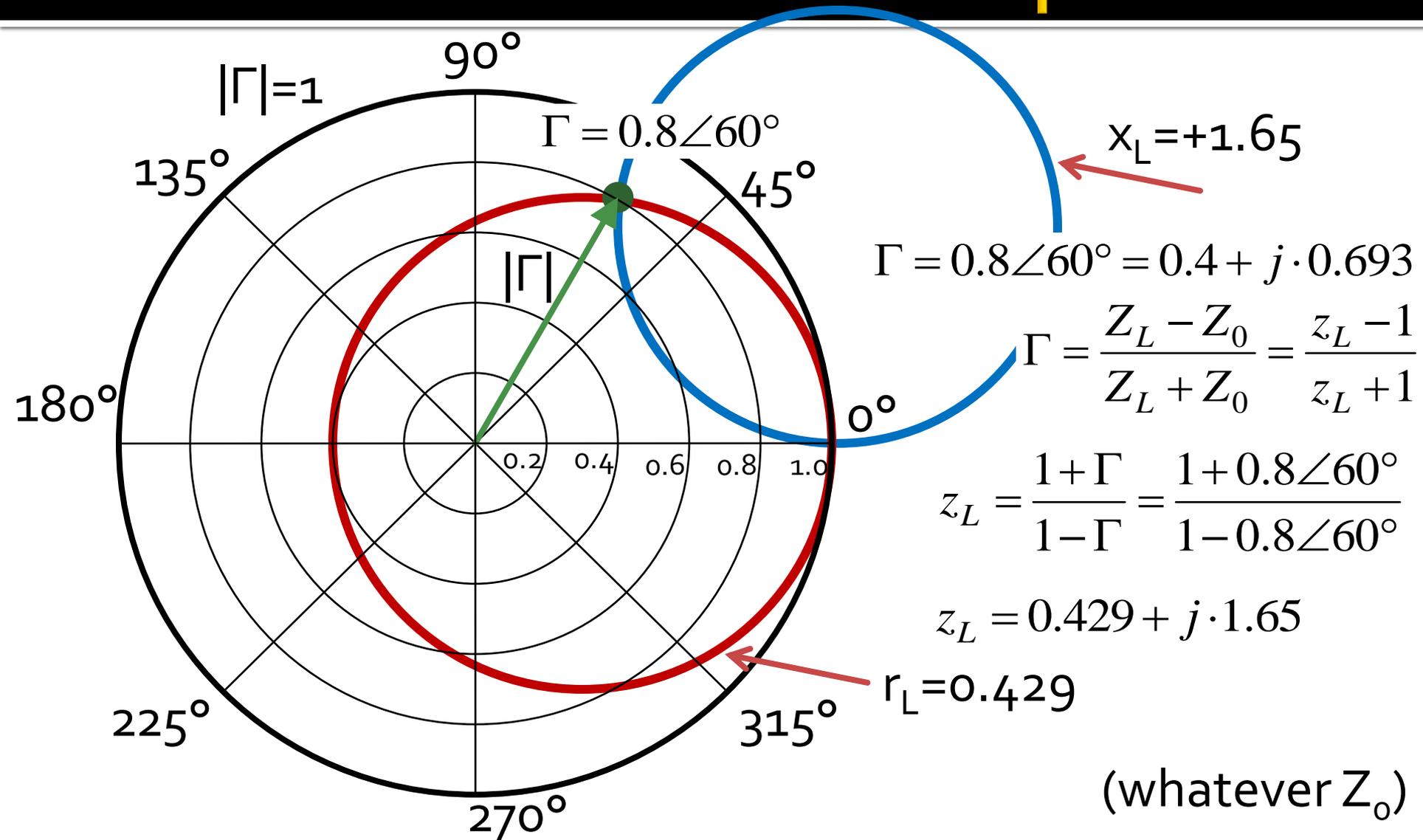
$$z_L = 0.429 + j \cdot 1.65$$

$$Z_L = Z_0 \cdot \frac{1 + \Gamma}{1 - \Gamma} = 50\Omega \cdot \frac{1 + 0.8 \angle 60^\circ}{1 - 0.8 \angle 60^\circ}$$

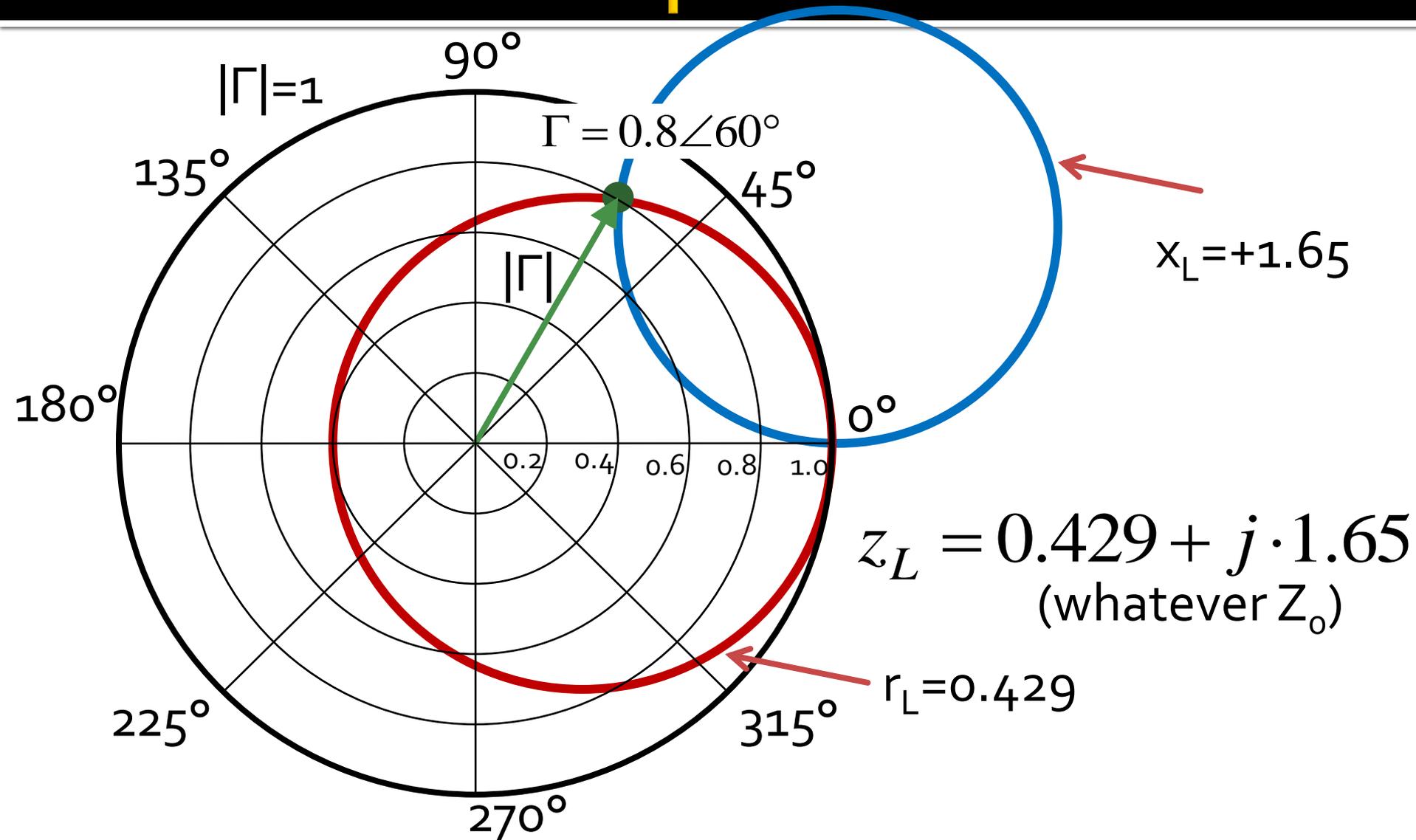
$$Z_L = 21.429\Omega + j \cdot 82.479\Omega$$

Equivalence

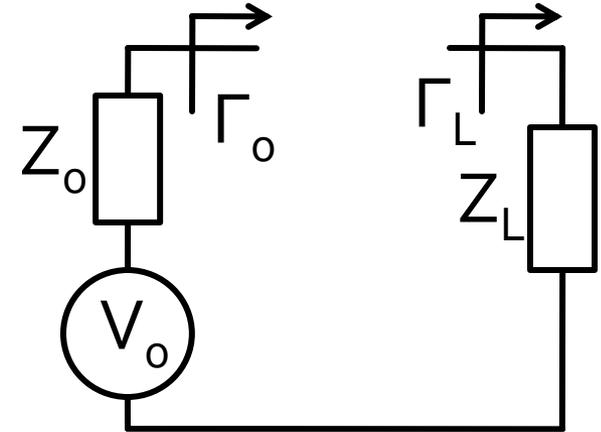
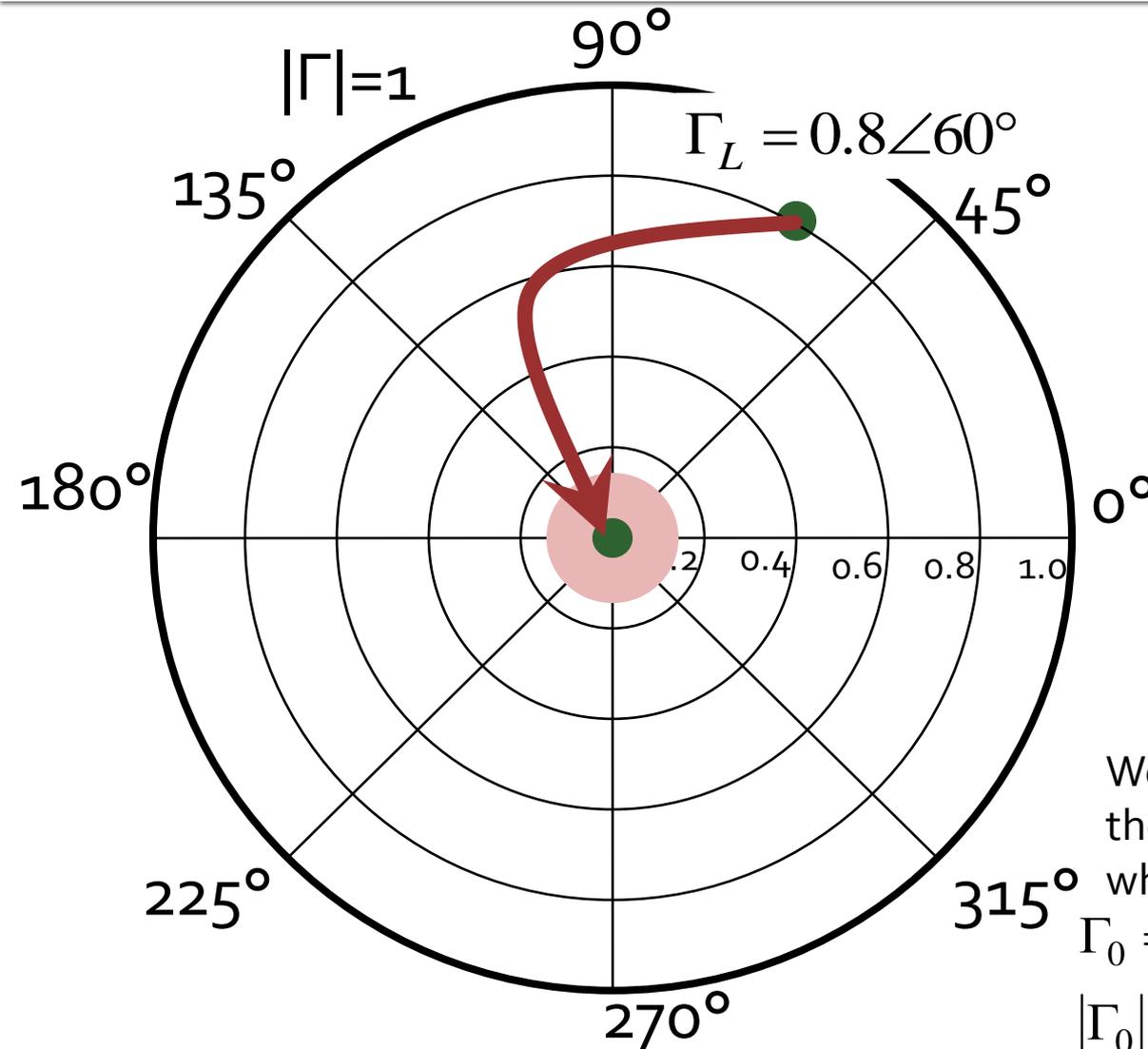
reflection coefficient \Leftrightarrow impedance



The Smith Chart, reflection coefficient \Leftrightarrow impedance



The Smith Chart, reflection coefficient, matching



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

$$Z_L = 21.429\Omega + j \cdot 82.479\Omega$$

$$z_L = 0.429 + j \cdot 1.65$$

$$\Gamma_L = 0.8 \angle 60^\circ$$

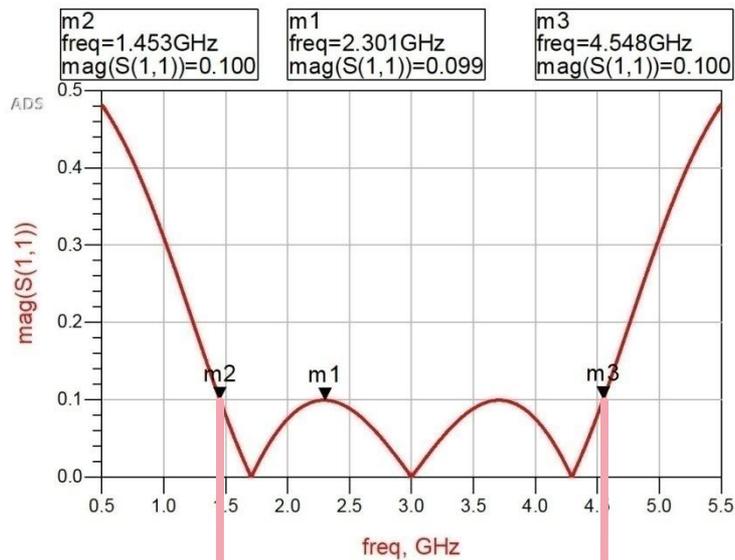
We must move the point denoting the reflection coefficient in the area where with a Z_o source we have:

$\Gamma_o = 0$ perfect match ●

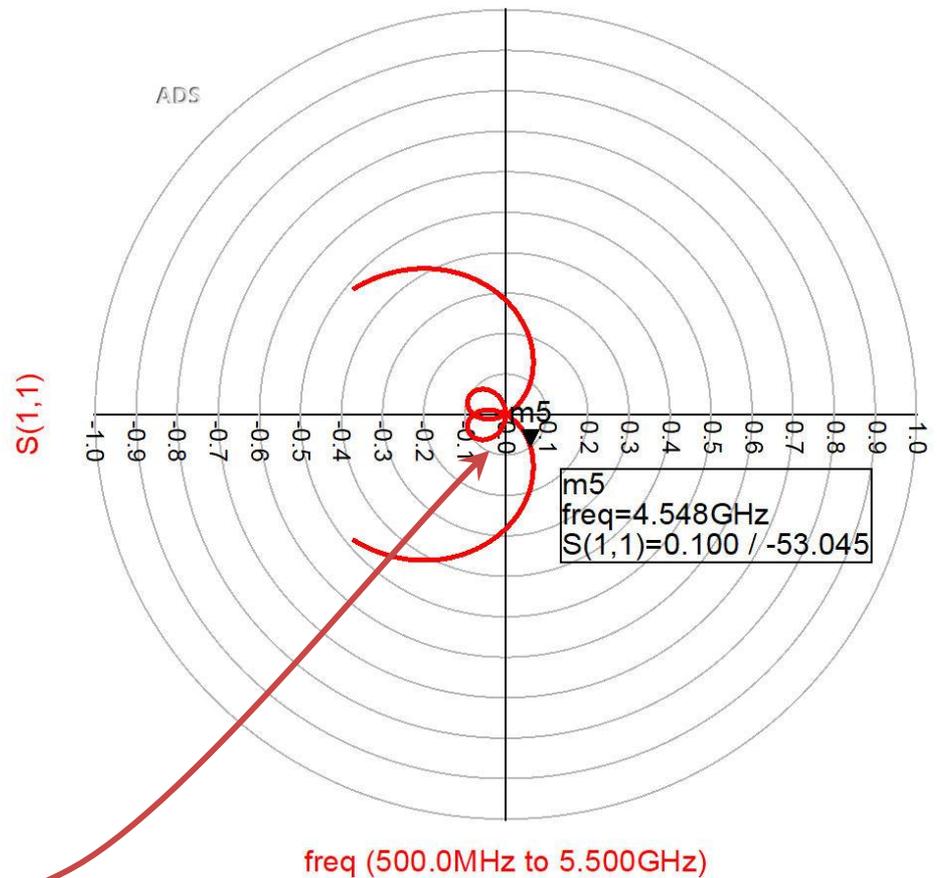
$|\Gamma_o| \leq \Gamma_m$ "good enough" match ●

Example

■ Laboratory 1

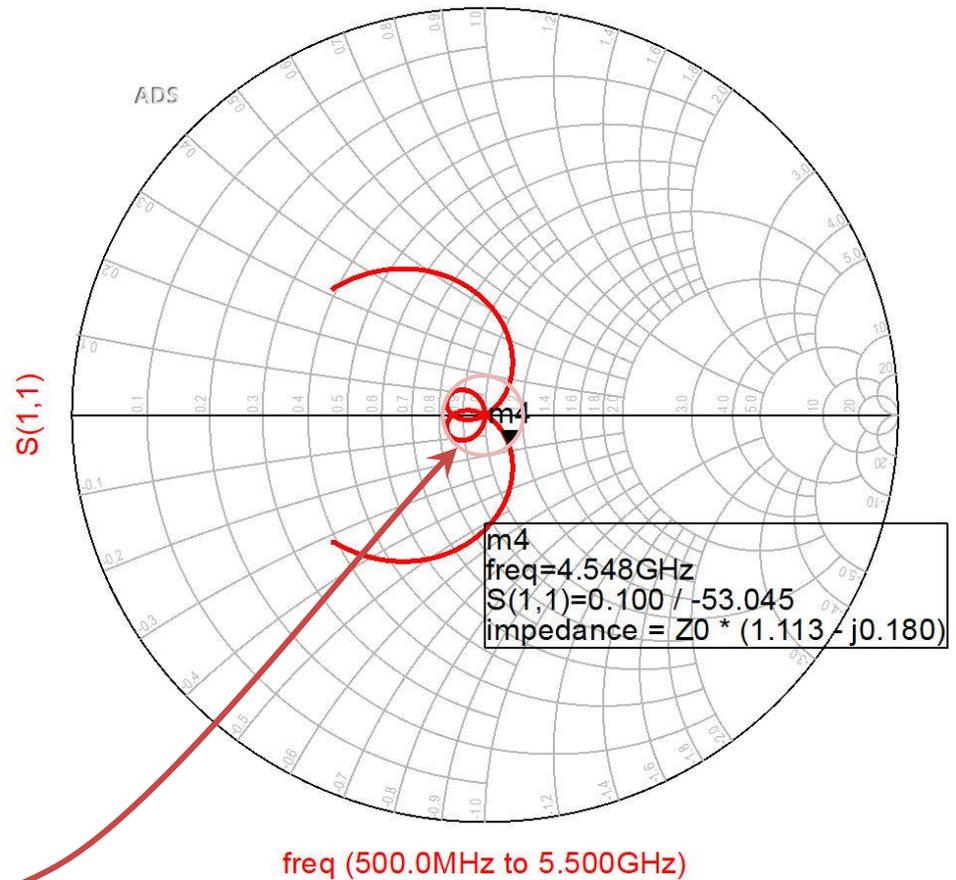
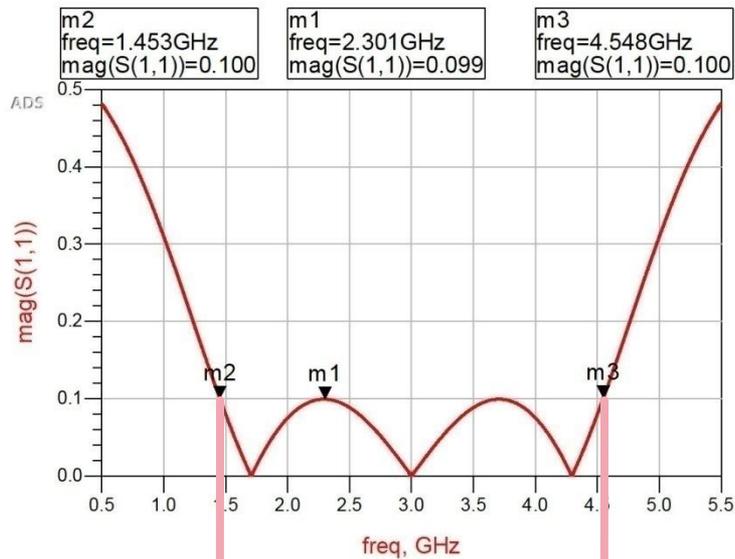


$$|\Gamma_0| \leq \Gamma_m$$



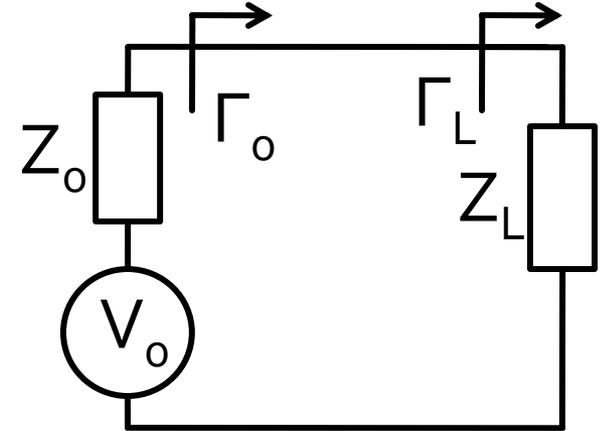
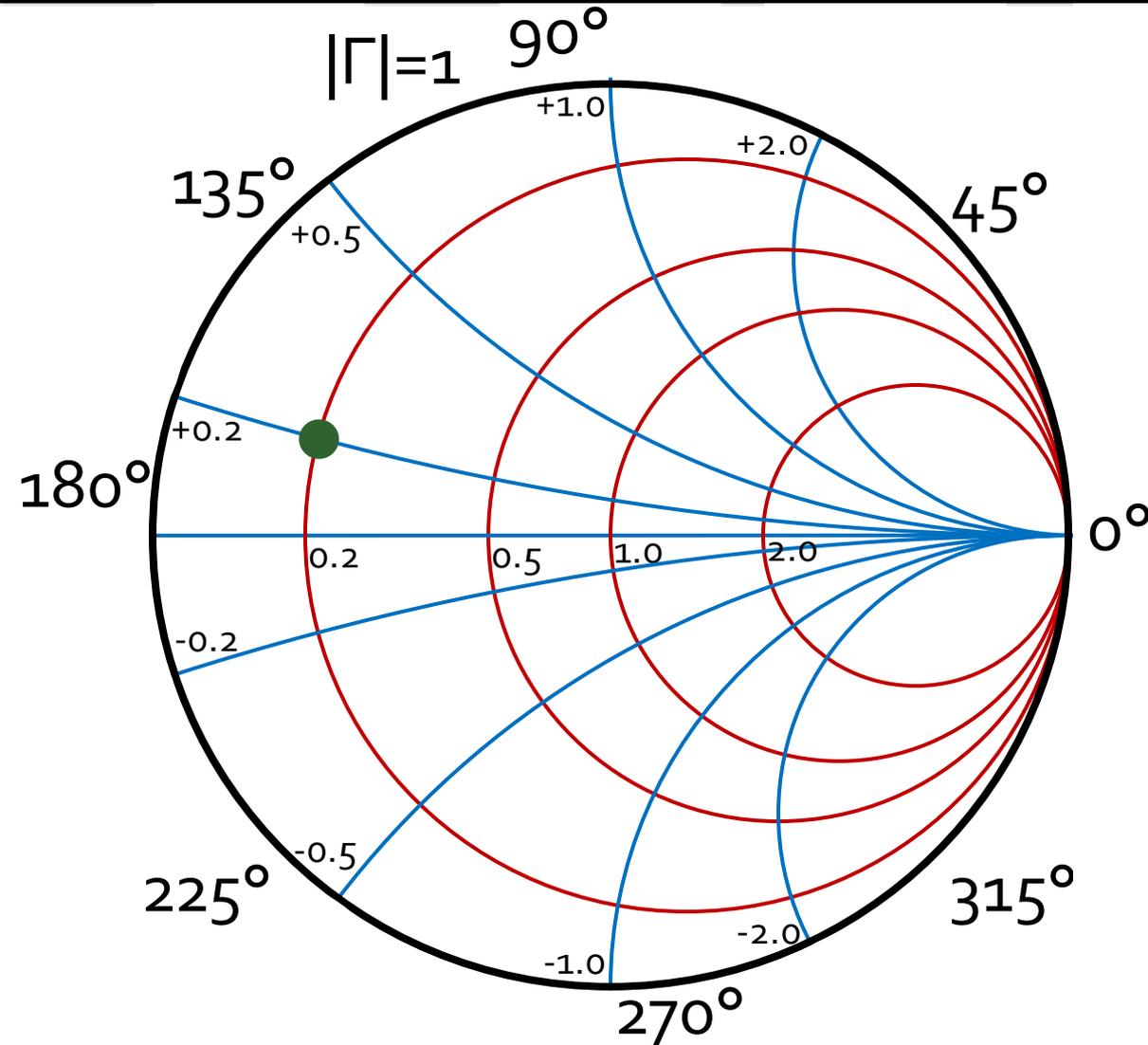
Example

■ Laboratory 1



$$|\Gamma_0| \leq \Gamma_m$$

The Smith Chart, impedance/reflection coefficient



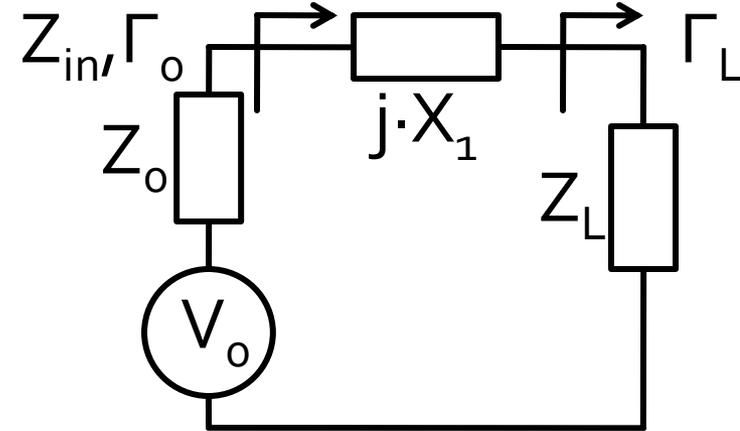
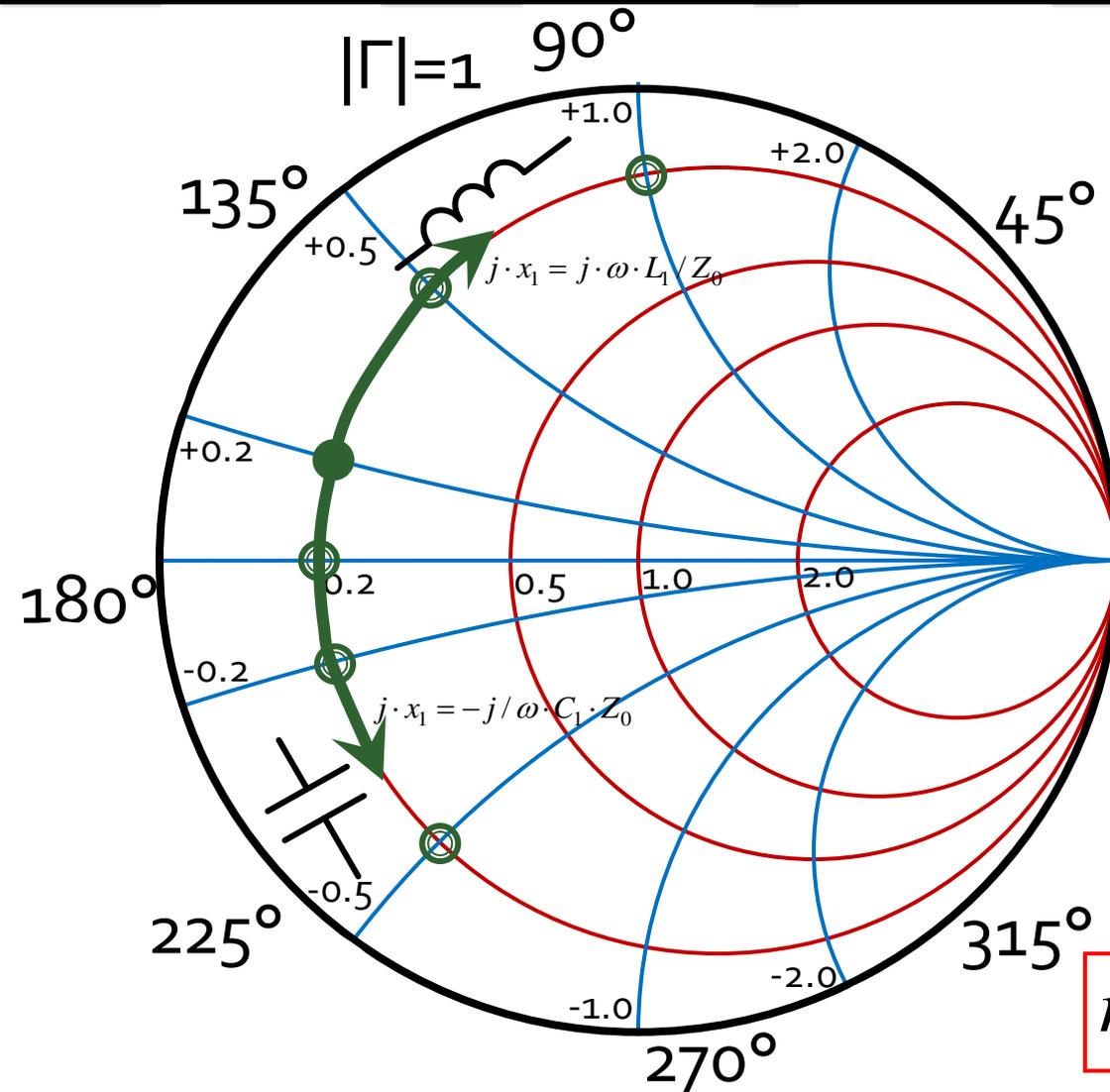
$$Z_0 = 50\Omega$$

$$Z_L = 10\Omega + j \cdot 10\Omega$$

$$z_L = 0.2 + j \cdot 0.2$$

$$\Gamma_L = \Gamma_0 = 0.678 \angle 156.5^\circ$$

The Smith Chart, series reactance



$$Z_0 = 50\Omega$$

$$Z_L = R_L + j \cdot X_L = 10\Omega + j \cdot 10\Omega$$

$$z_L = r_L + j \cdot x_L = 0.2 + j \cdot 0.2$$

$$\Gamma_L = 0.678 \angle 156.5^\circ$$

$$Z_{in} = Z_L + j \cdot X_1 = R_L + j \cdot (X_L + X_1)$$

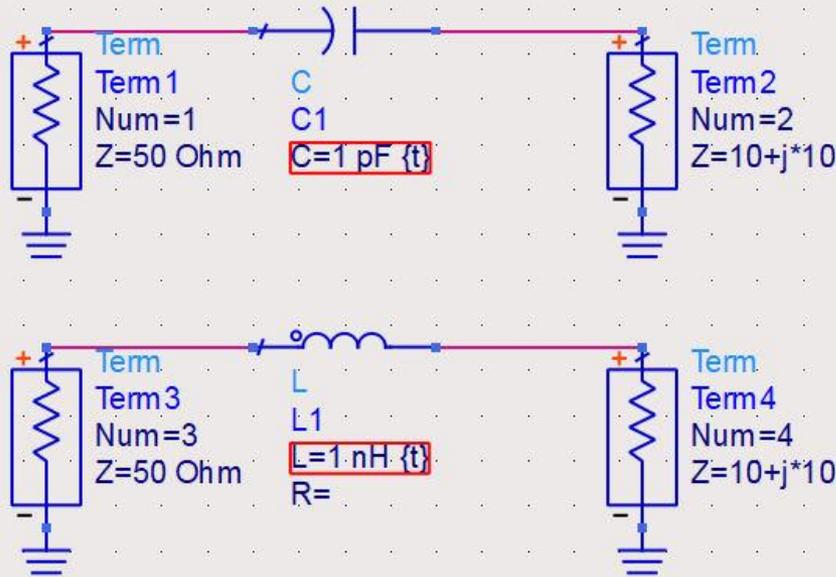
$$z_{in} = r_L + j \cdot (x_L + x_1)$$

$$r_{in} = r_L$$

$$j \cdot x_1 = j \cdot \omega \cdot L_1 / Z_0 > 0$$

$$j \cdot x_1 = -j / \omega \cdot C_1 \cdot Z_0 < 0$$

ADS, Smith Chart, series reactance



Tune Parameters

Simulate: While Slider Moves

Tune

Parameters: Include Opt Params, Enable/Disable..., Display Full Name

Snap Slider to Step

Traces and Values: Store..., Recall..., Trace Visibility..., Reset Values

Close Unassociated Data Displays

Update Schematic

Close Help

adaptare_LC_lib:X_S:schematic

Component	Value	Max	Min	Step	Scale
C1.C (pF)	39.605	50	0.5	0.1	Lin
L1.L (nH)	0.895	40	0.5	0.1	Lin

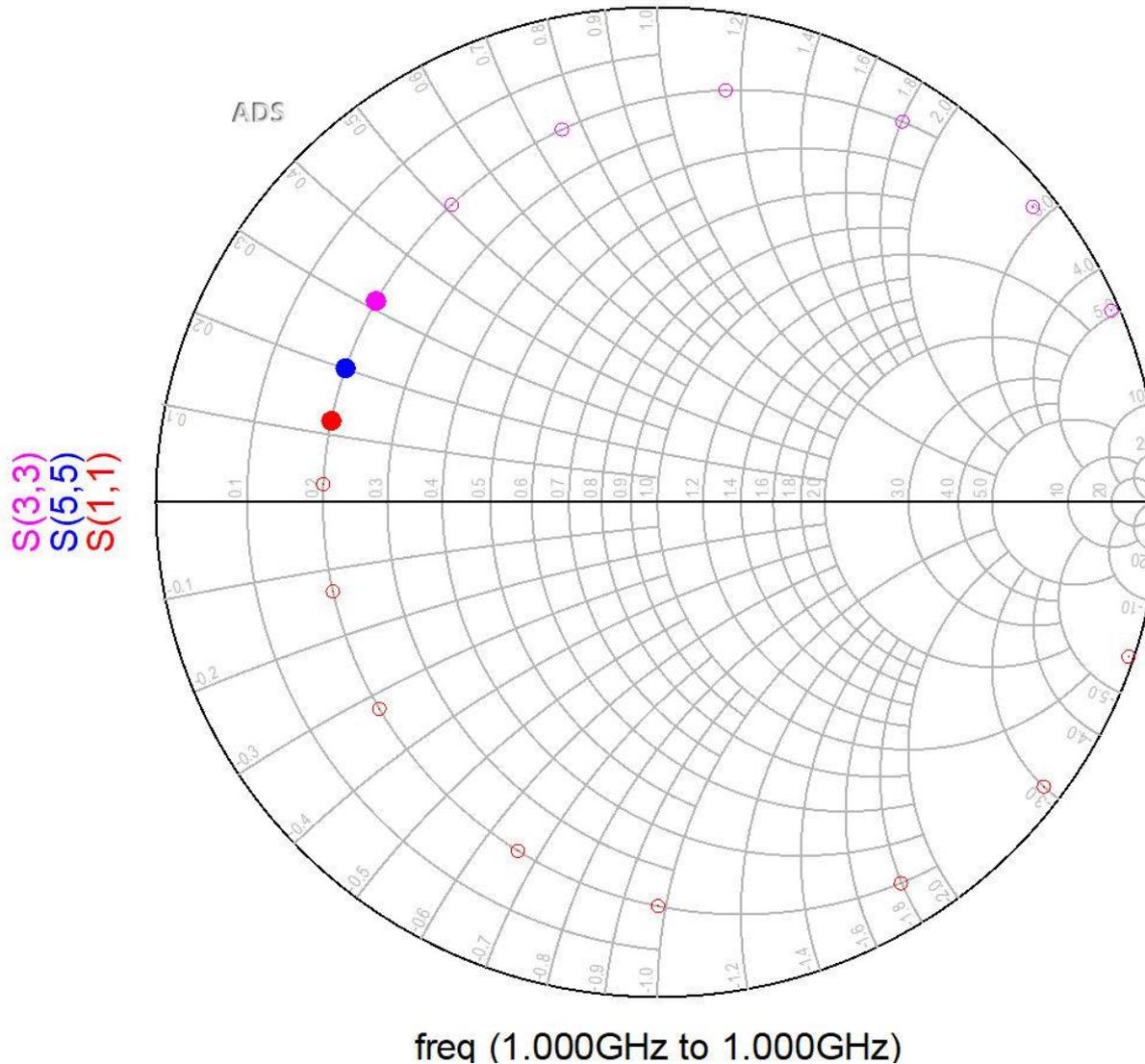


S-PARAMETERS

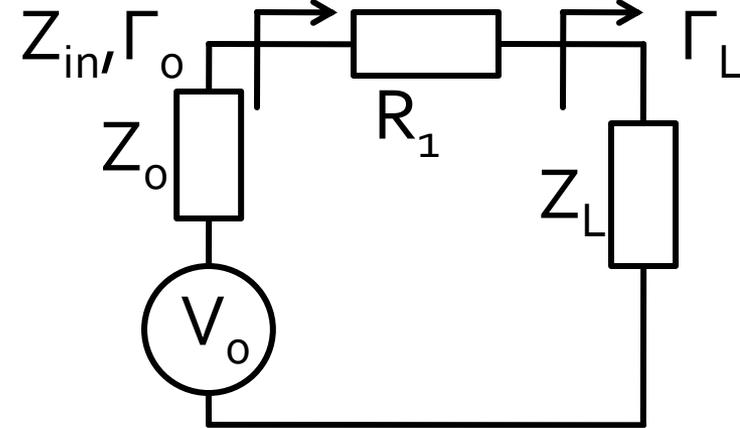
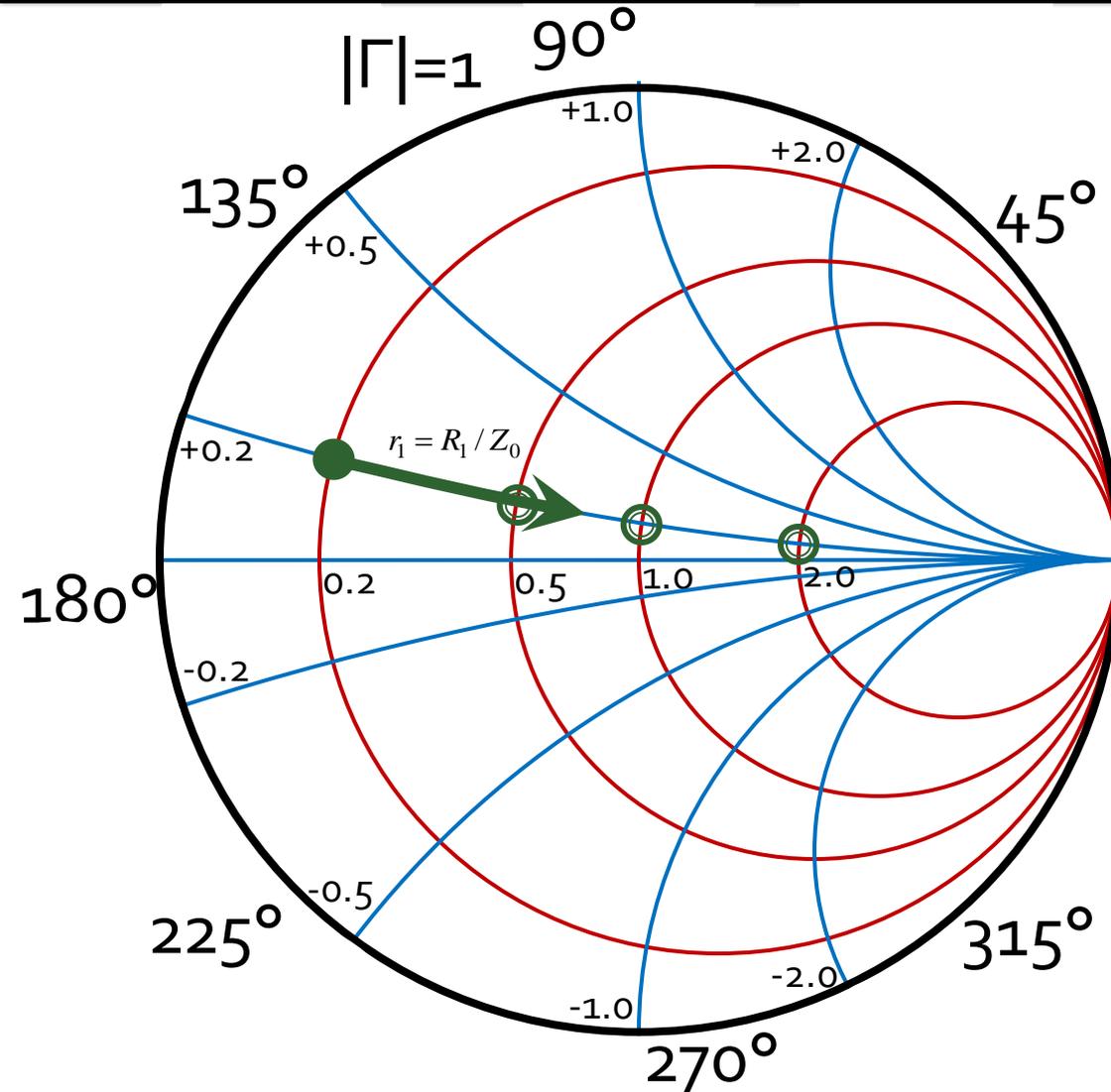
S_Param
SP1

Freq=1.0 GHz

ADS, Smith Chart, series reactance



The Smith Chart, series resistance



$$Z_0 = 50\Omega$$

$$Z_L = R_L + j \cdot X_L = 10\Omega + j \cdot 10\Omega$$

$$z_L = r_L + j \cdot x_L = 0.2 + j \cdot 0.2$$

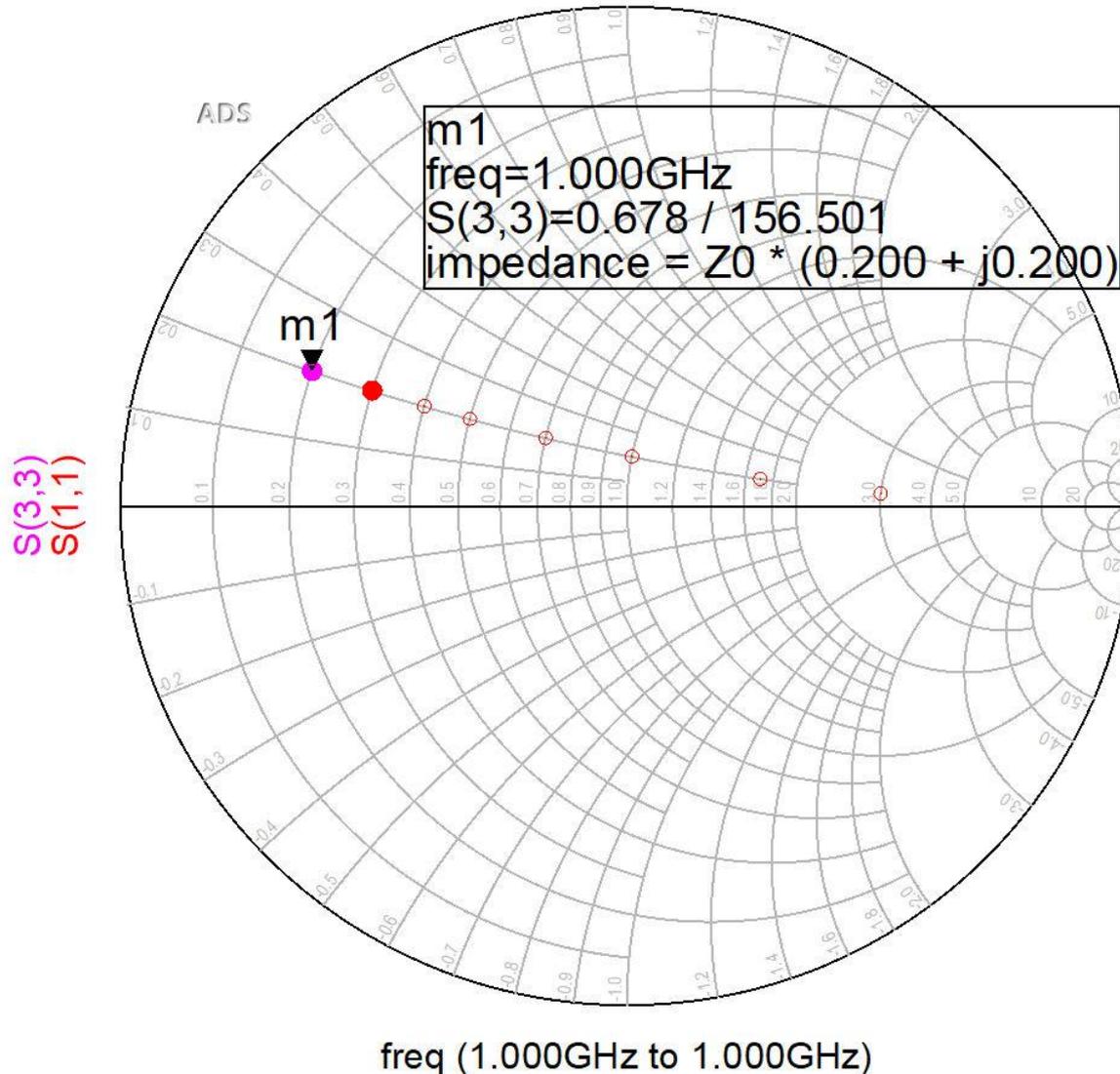
$$\Gamma_L = 0.678 \angle 156.5^\circ$$

$$Z_{in} = Z_L + R_1 = (R_L + R_1) + j \cdot X_L$$

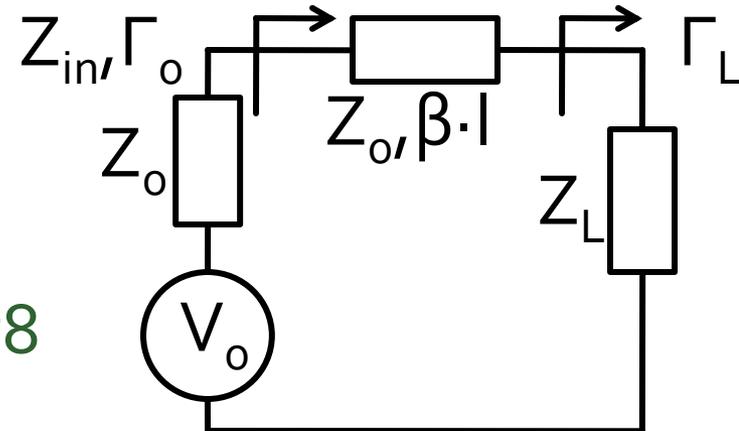
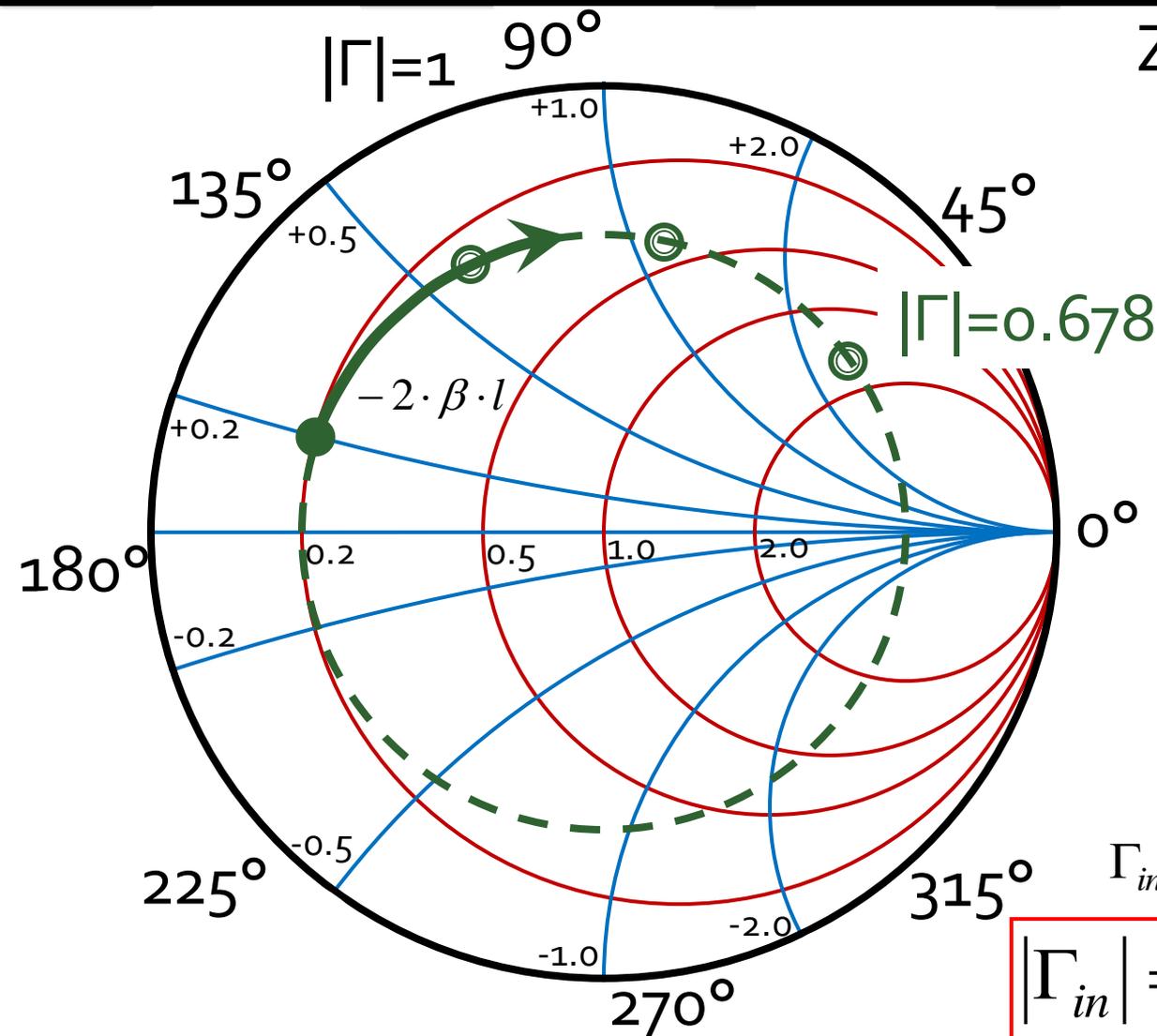
$$z_{in} = z_L + r_1 = (r_L + r_1) + j \cdot x_L$$

$$x_{in} = x_L \quad r_{in} = r_L + R_1 / Z_0$$

ADS, Smith Chart, series resistance



The Smith Chart, series transmission line, Z_0



$$Z_0 = 50\Omega$$

$$Z_L = R_L + j \cdot X_L = 10\Omega + j \cdot 10\Omega$$

$$z_L = r_L + j \cdot x_L = 0.2 + j \cdot 0.2$$

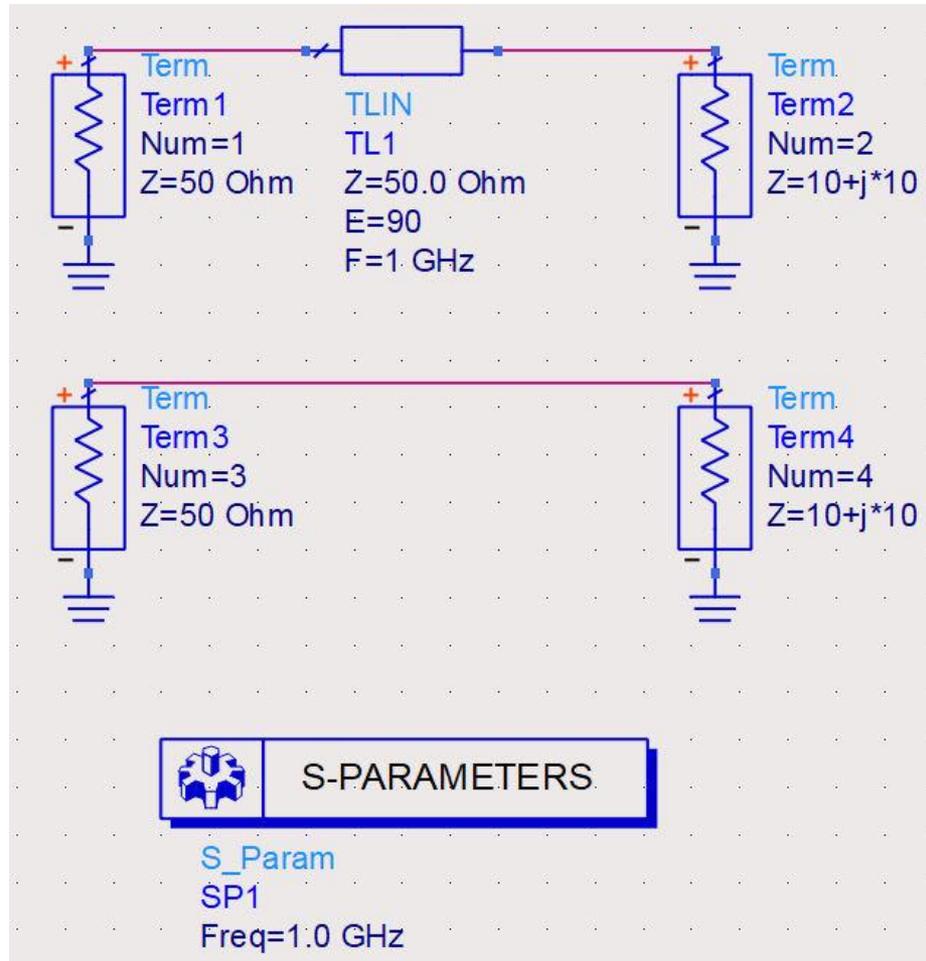
$$\Gamma_L = 0.678 \angle 156.5^\circ$$

$$Z_{in} = Z_0 \cdot \frac{1 + \Gamma_L \cdot e^{-2j \cdot \beta \cdot l}}{1 - \Gamma_L \cdot e^{-2j \cdot \beta \cdot l}}$$

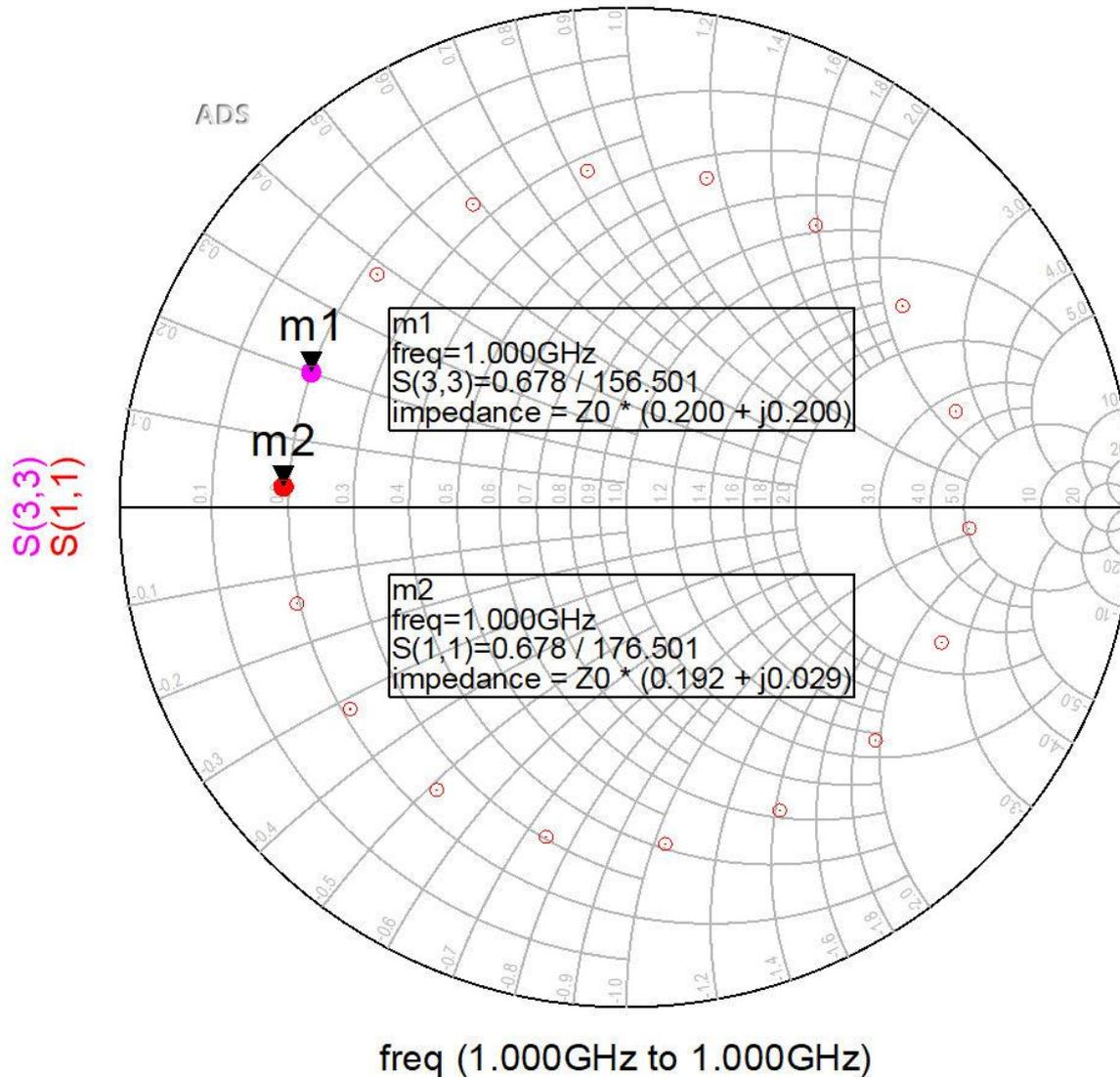
$$\Gamma_{in} = \Gamma_L \cdot e^{-2j \cdot \beta \cdot l}$$

$$|\Gamma_{in}| = |\Gamma_L| \quad \arg(\Gamma_{in}) = \arg(\Gamma_L) - 2 \cdot \beta \cdot l$$

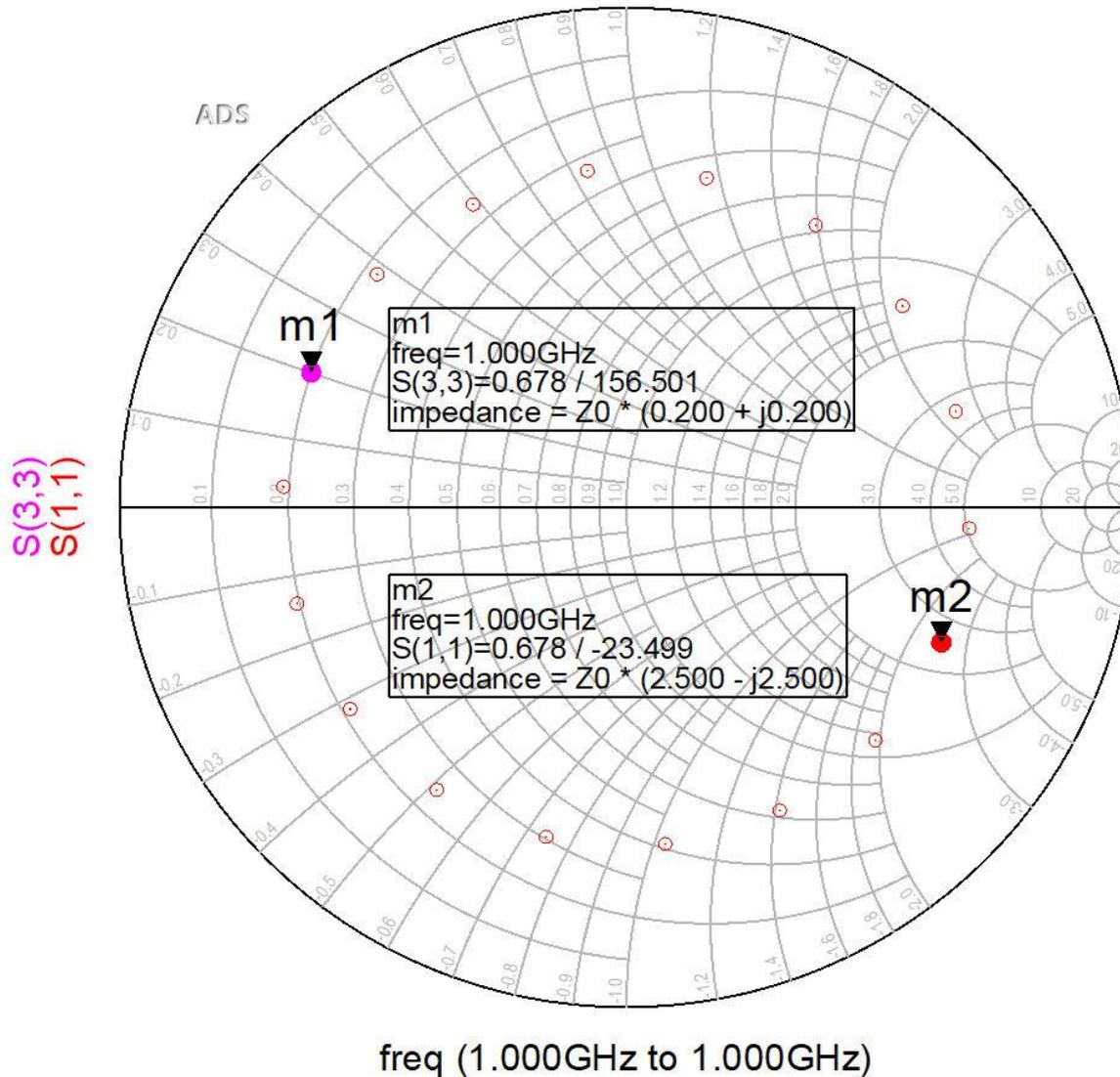
ADS, Smith Chart, series transmission line



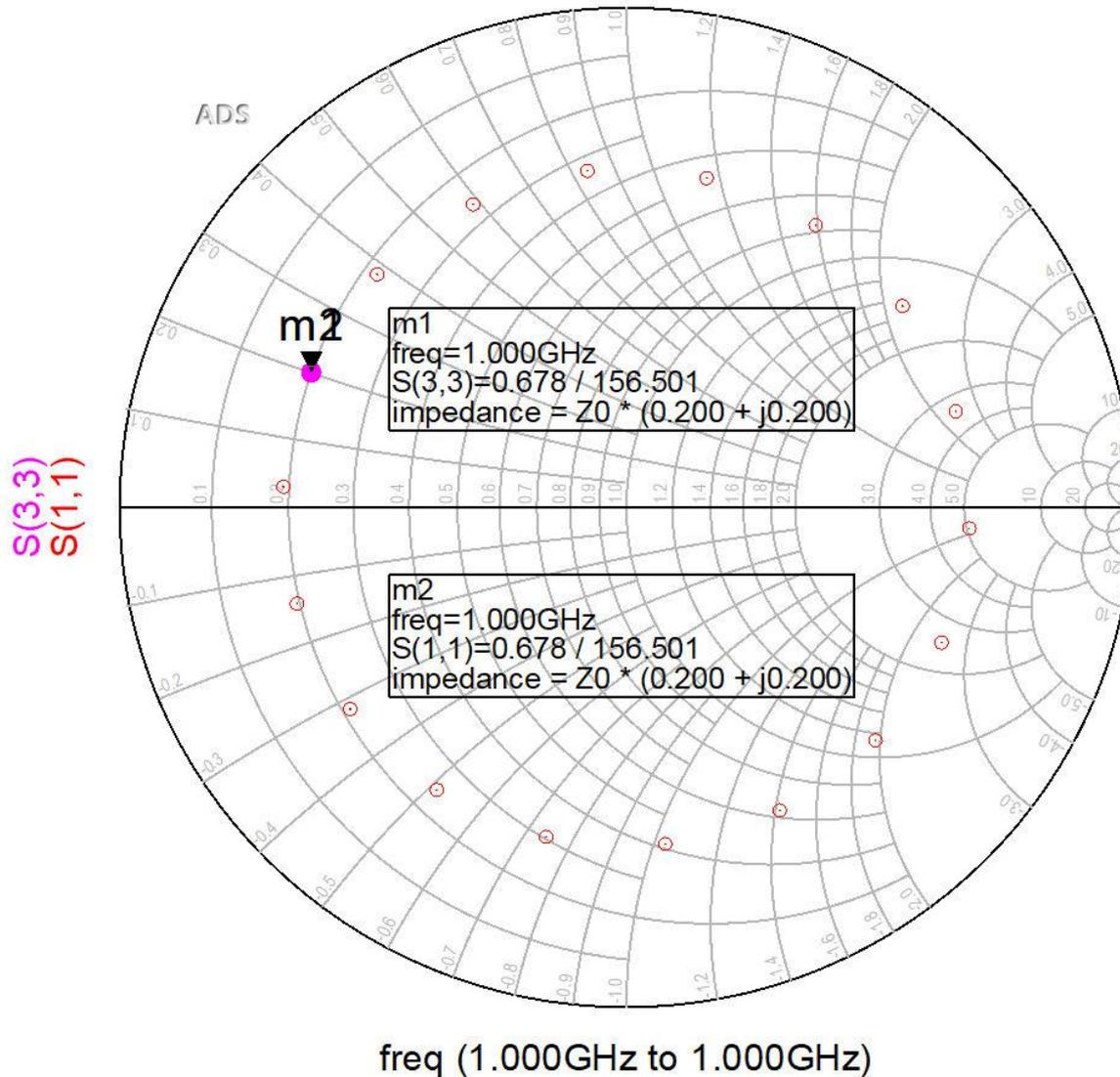
ADS, Smith Chart, series transmission line



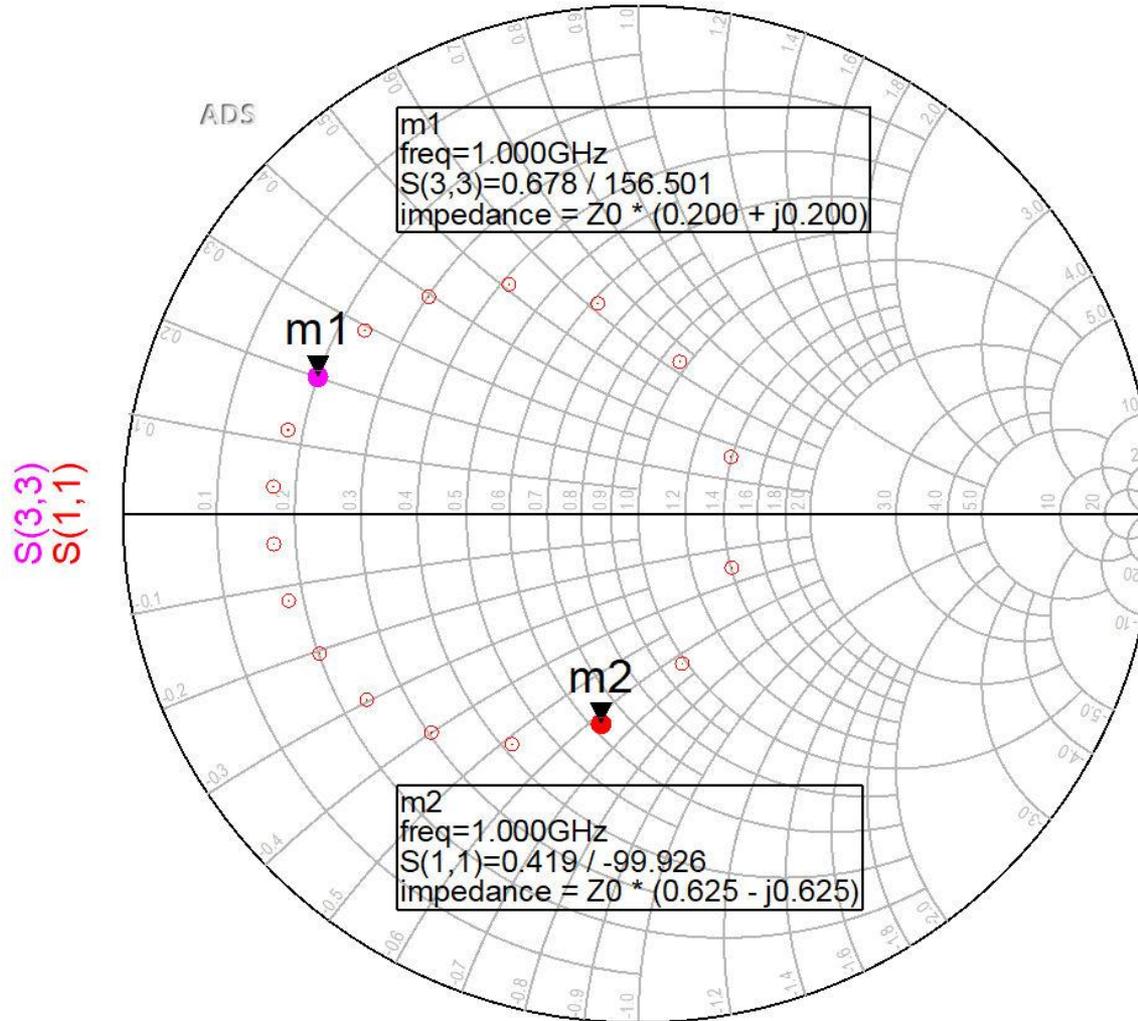
ADS, Smith Chart, series transmission line, $E=90^\circ$



ADS, Smith Chart, series transmission line, $E=180^\circ$

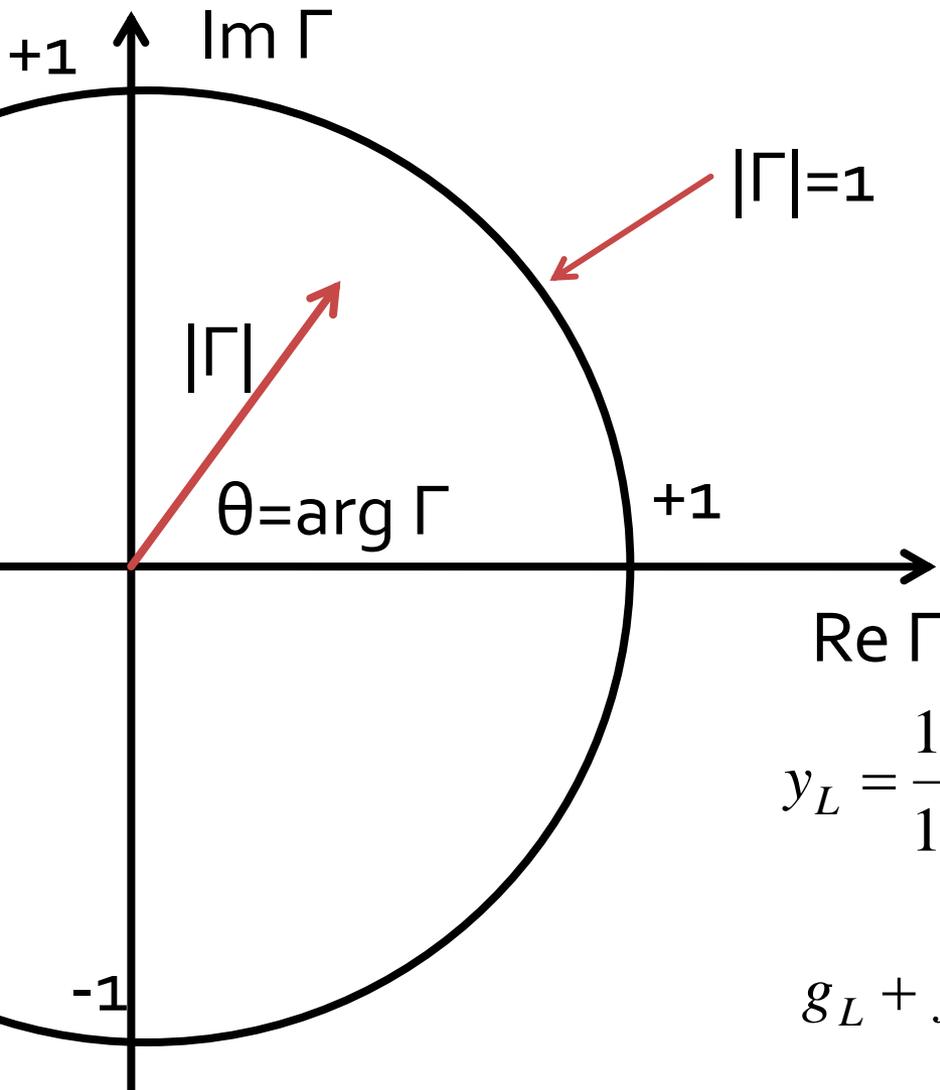


ADS, Smith Chart, series transmission line, $Z=25\Omega \neq Z_0$



freq (1.000GHz to 1.000GHz)

The Admittance Smith Chart



$$\Gamma = \frac{Z_L - Z_0}{Z_L + Z_0} = \frac{z_L - 1}{z_L + 1} = |\Gamma| \cdot e^{j\theta}$$

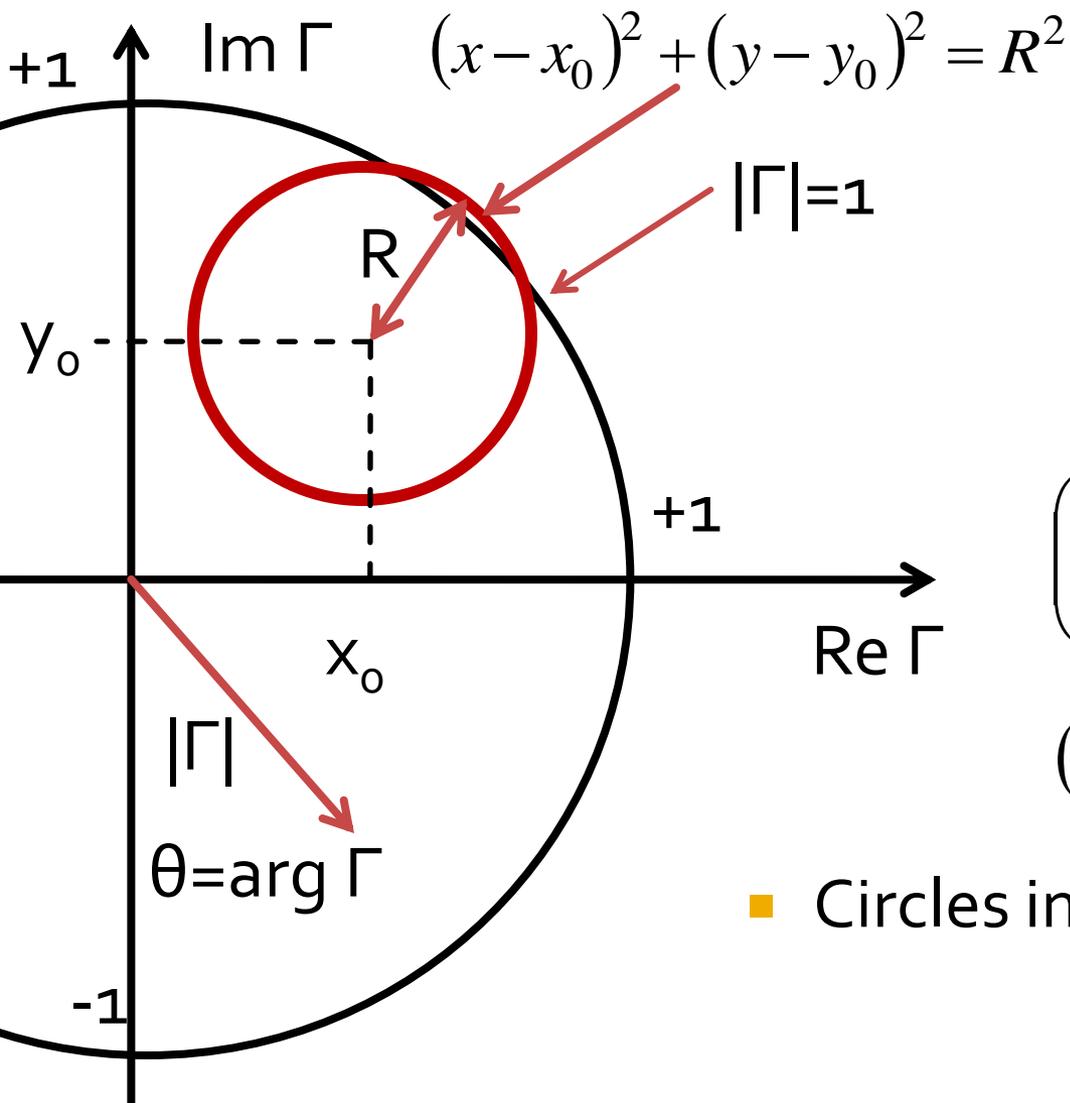
$$\Gamma = \Gamma_r + j \cdot \Gamma_i$$

$$z_L = \frac{1 + |\Gamma| \cdot e^{j\theta}}{1 - |\Gamma| \cdot e^{j\theta}} = r_L + j \cdot x_L$$

$$y_L = \frac{1 - |\Gamma| \cdot e^{j\theta}}{1 + |\Gamma| \cdot e^{j\theta}} = \frac{1}{r_L + j \cdot x_L} = g_L + j \cdot b_L$$

$$g_L + j \cdot b_L = \frac{(1 - \Gamma_r) - j \cdot \Gamma_i}{(1 + \Gamma_r) + j \cdot \Gamma_i}$$

The Admittance Smith Chart



$$g_L = \frac{1 - \Gamma_r^2 - \Gamma_i^2}{(1 + \Gamma_r)^2 + \Gamma_i^2}$$

$$b_L = \frac{-2 \cdot \Gamma_i}{(1 + \Gamma_r)^2 + \Gamma_i^2}$$

■ Rearranged

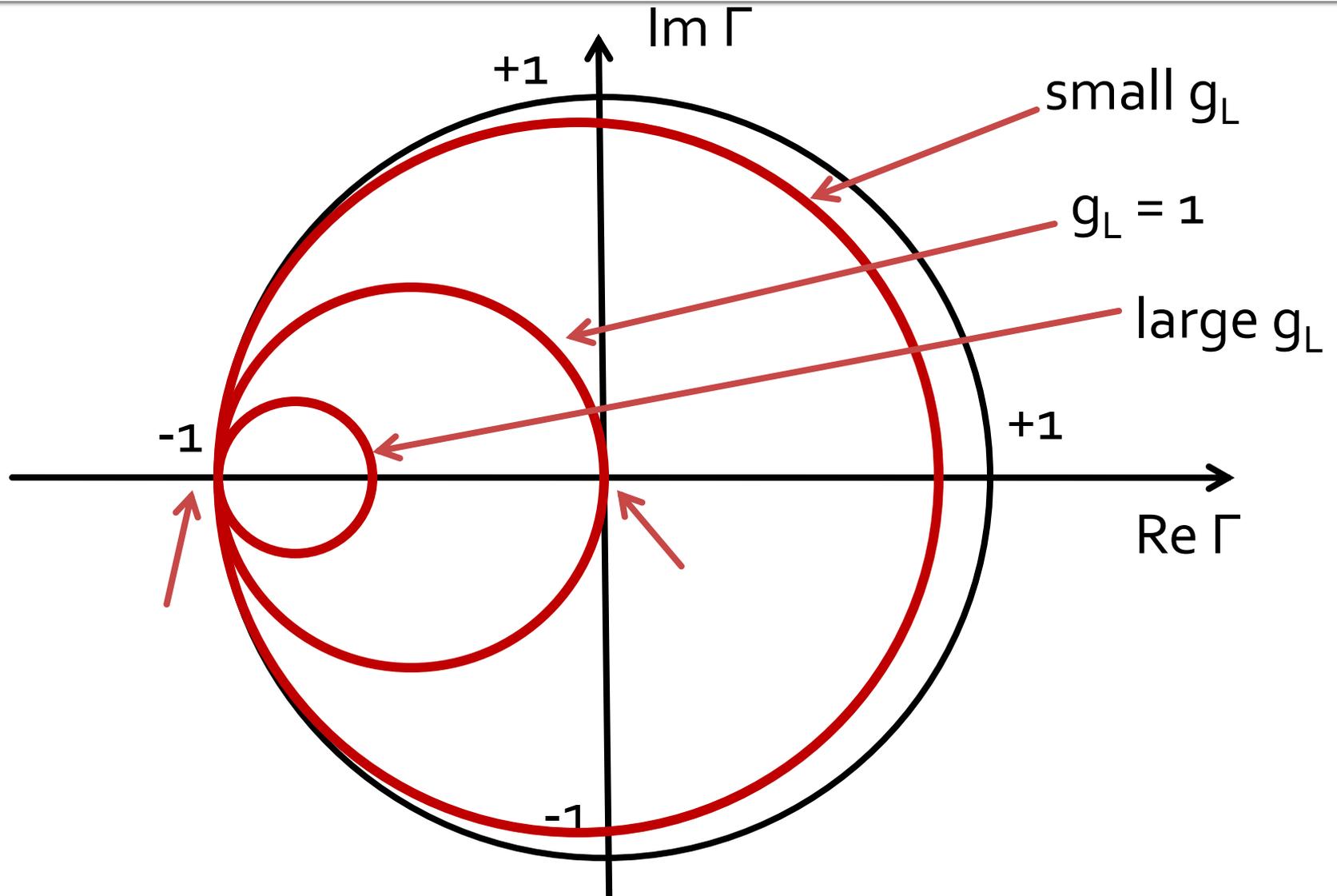
$$\left(\Gamma_r + \frac{g_L}{1 + g_L} \right)^2 + \Gamma_i^2 = \left(\frac{1}{1 + g_L} \right)^2$$

$$(\Gamma_r + 1)^2 + \left(\Gamma_i + \frac{1}{b_L} \right)^2 = \left(\frac{1}{b_L} \right)^2$$

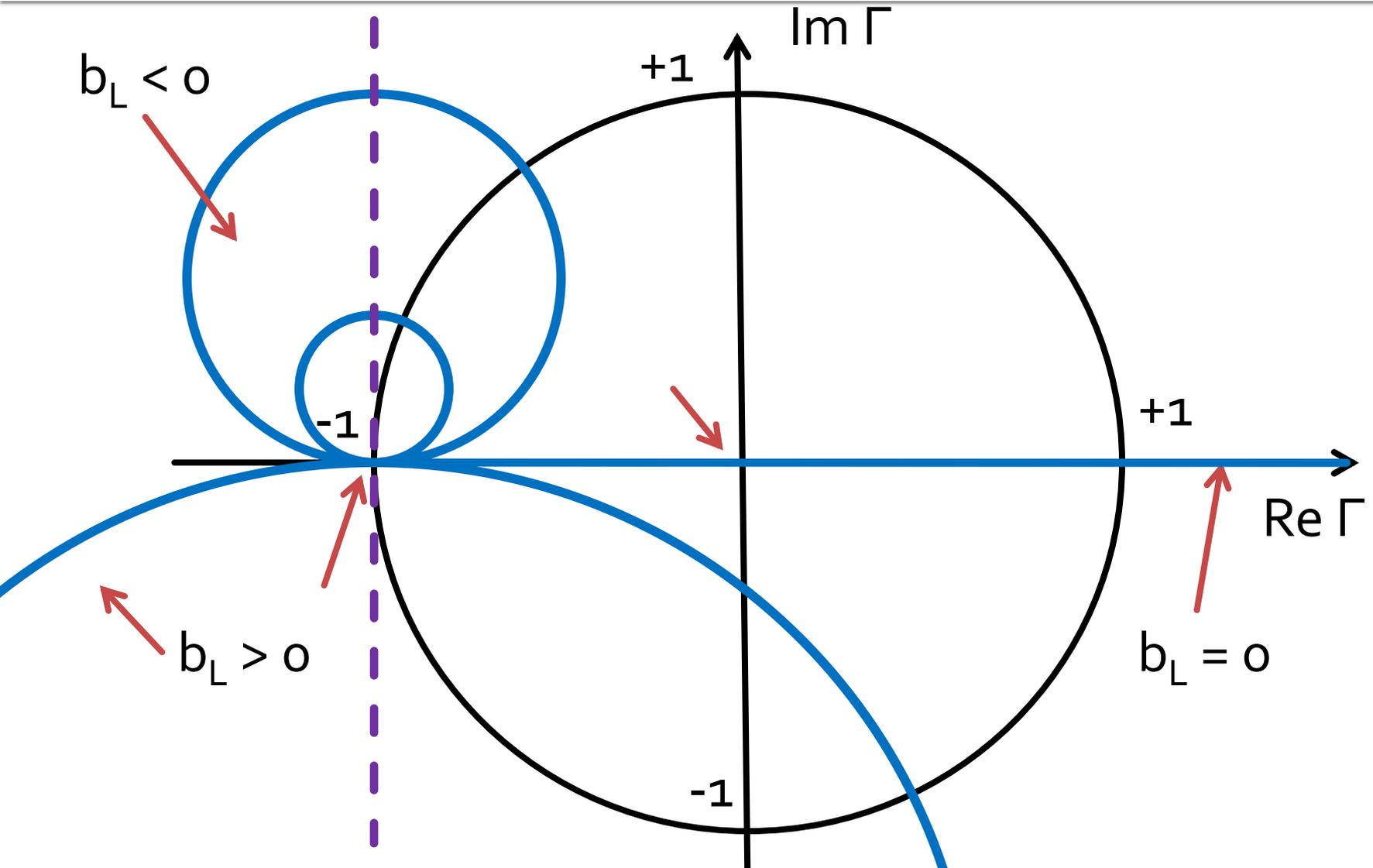
- Circles in the (Γ_r, Γ_i) complex plane

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

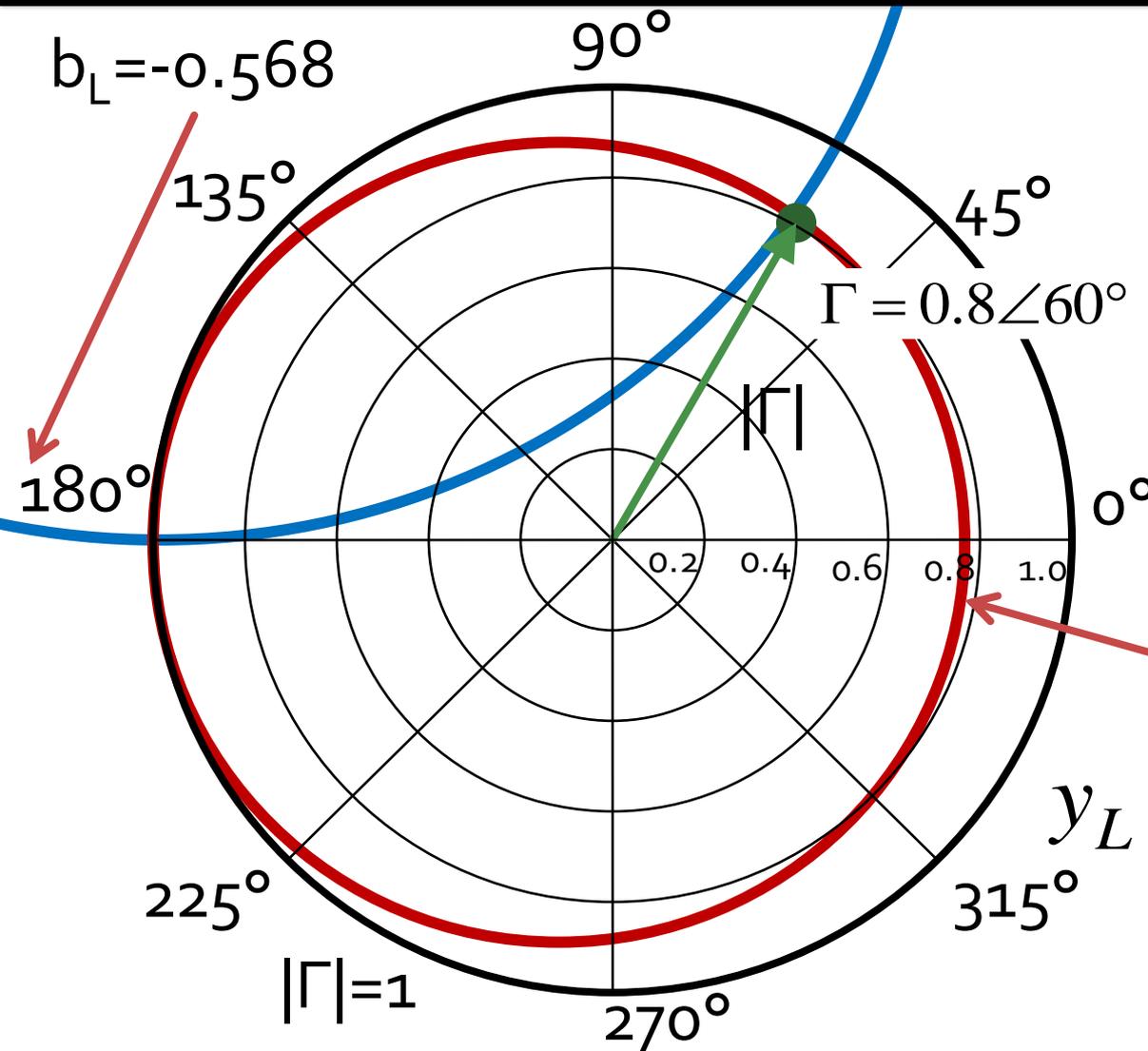
The Smith Chart, conductance



The Smith Chart, susceptance



The Smith Chart, reflection coefficient \Leftrightarrow admittance



$$\Gamma = 0.8 \angle 60^\circ$$

$$Z_L = 21.429\Omega + j \cdot 82.479\Omega$$

$$z_L = 0.429 + j \cdot 1.65$$

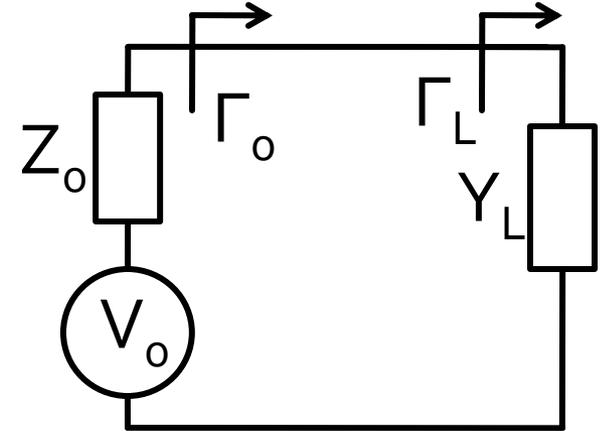
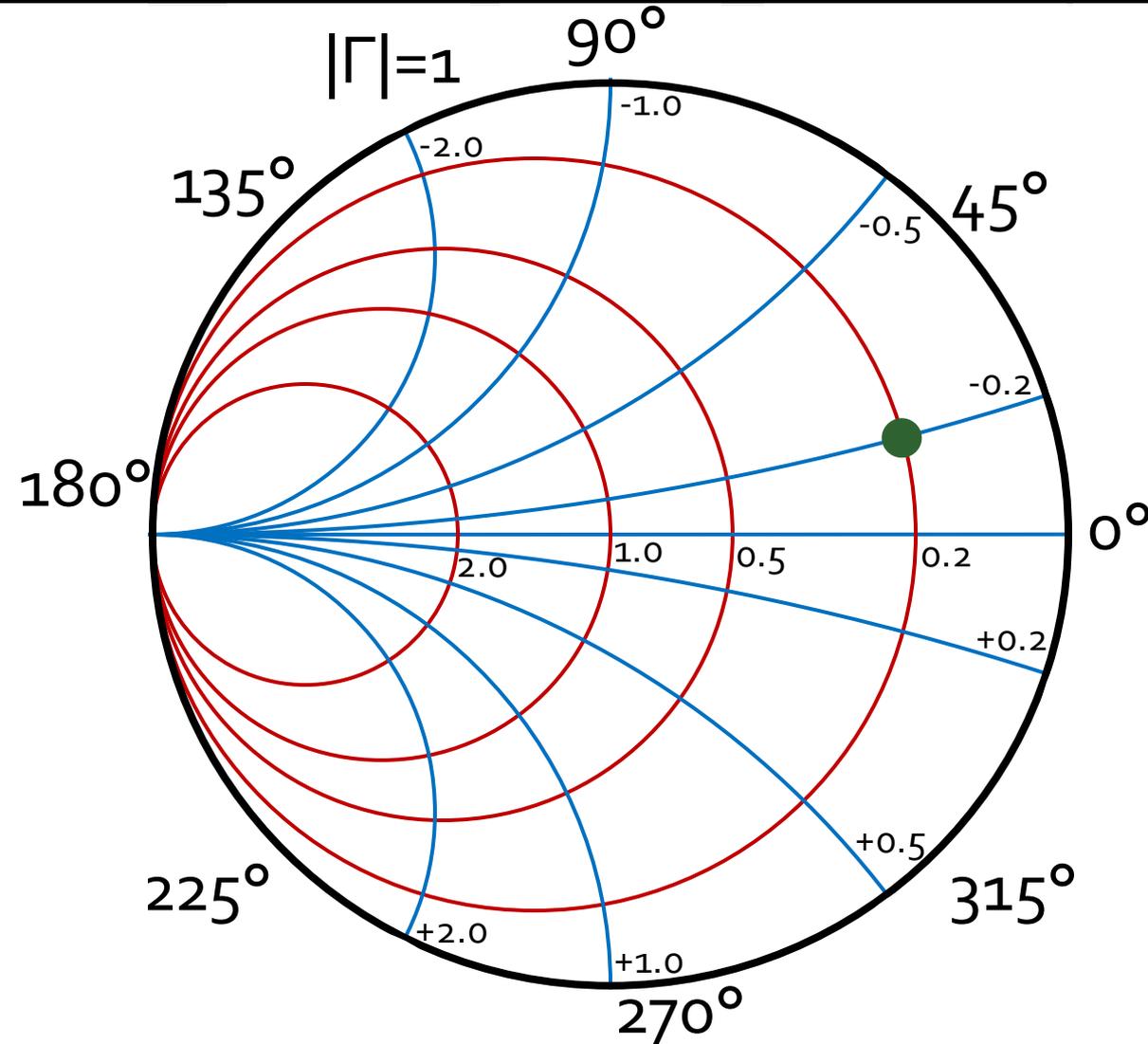
$$y_L = \frac{1}{z_L} = 0.148 - j \cdot 0.568$$

$$g_L = 0.148$$

$$y_L = 0.148 + j \cdot 0.568$$

(whatever Z_0)

The Smith Chart, reflection coefficient \Leftrightarrow admittance



$$Z_0 = 50\Omega, Y_0 = 0.02S$$

$$Z_L = 125\Omega + j \cdot 125\Omega$$

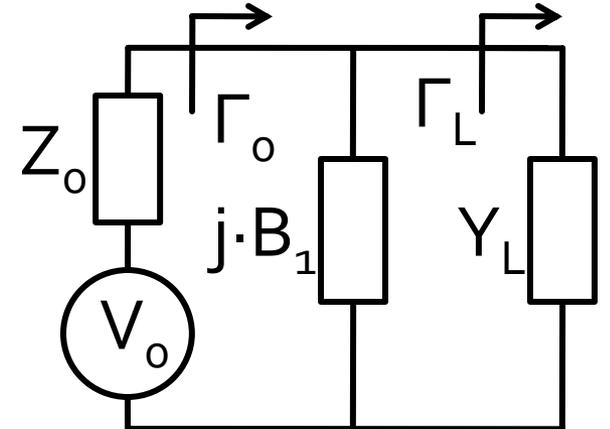
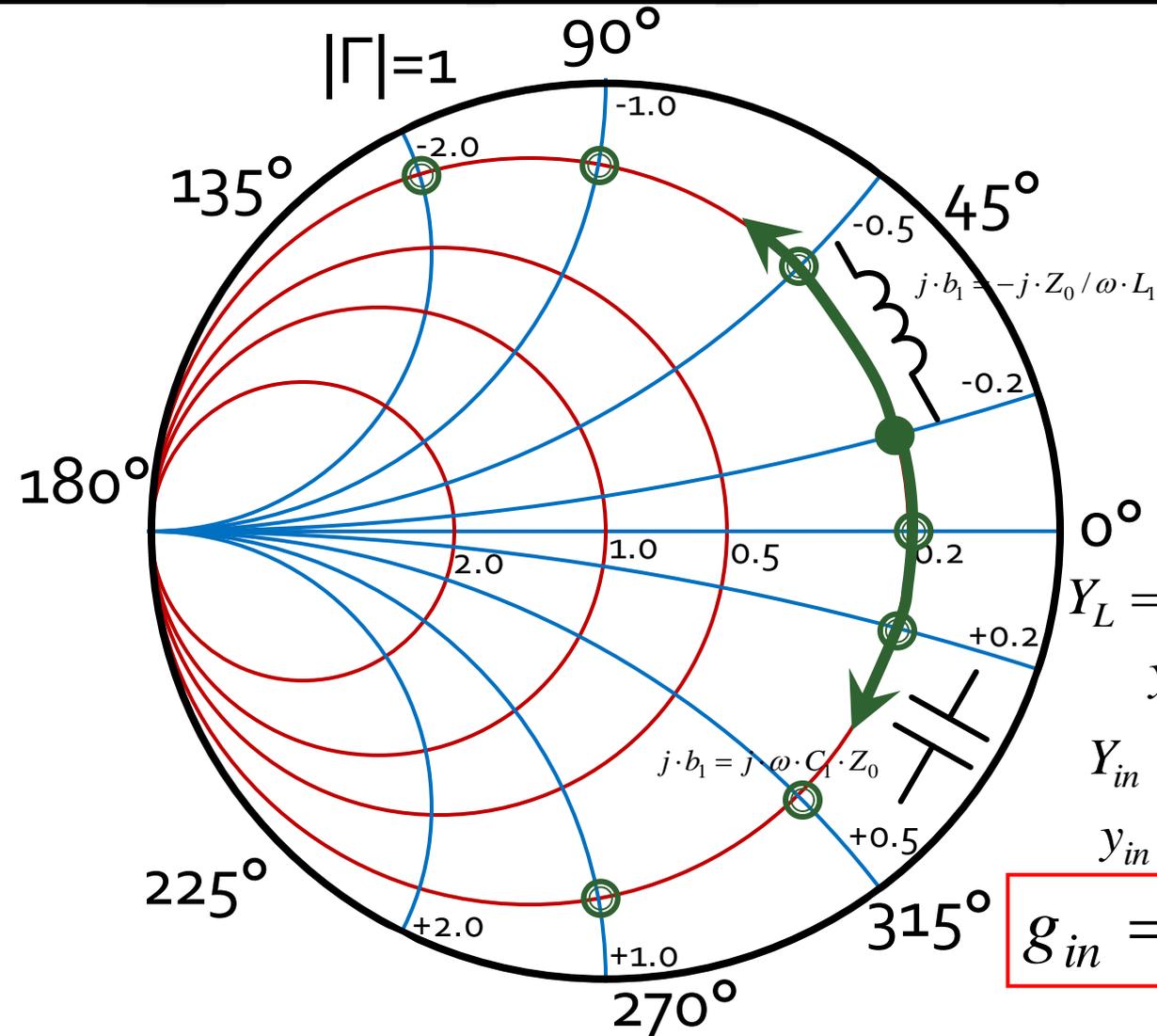
$$z_L = 2.5 + j \cdot 2.5$$

$$\Gamma_L = \Gamma_0 = 0.678 \angle 23.5^\circ$$

$$Y_L = \frac{1}{Z_L} = 0.004S - j \cdot 0.004S$$

$$y_L = \frac{1}{z_L} = \frac{Y_L}{Y_0} = 0.2 - j \cdot 0.2$$

The Smith Chart, shunt susceptance



$$Z_0 = 50\Omega, Y_0 = 0.02S$$

$$\Gamma_L = 0.678 \angle 23.5^\circ$$

$$Y_L = G_L + j \cdot B_L = 0.004S + j \cdot 0.004$$

$$y_L = g_L + j \cdot b_L = 0.2 - j \cdot 0.2$$

$$Y_{in} = Y_L + j \cdot B_1 = G_L + j \cdot (B_L + B_1)$$

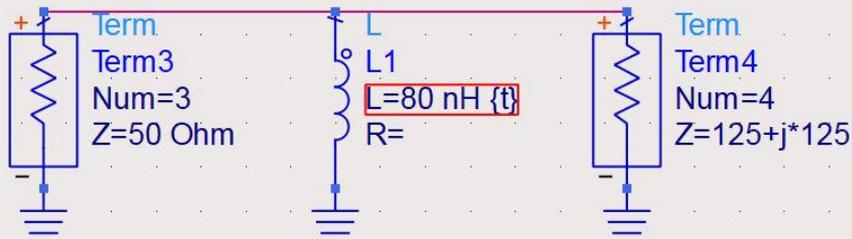
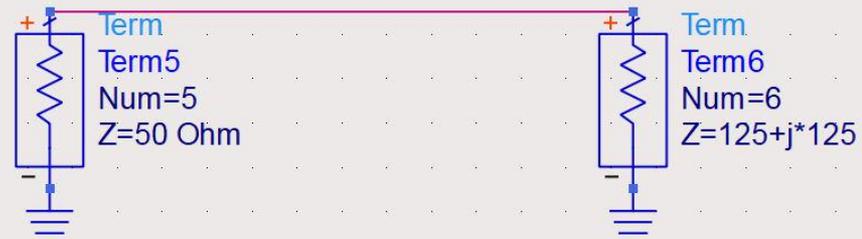
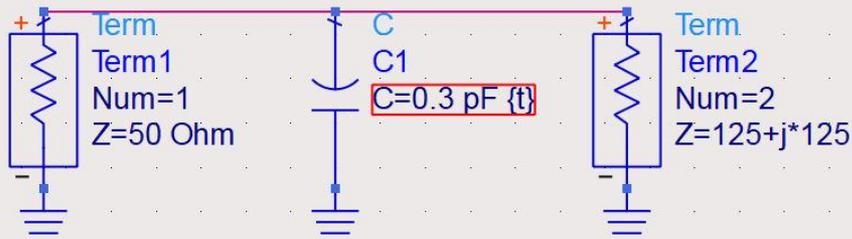
$$y_{in} = g_L + j \cdot (b_L + b_1)$$

$$g_{in} = g_L$$

$$j \cdot b_1 = j \cdot \omega \cdot C_1 \cdot Z_0 > 0$$

$$j \cdot b_1 = -j \cdot Z_0 / \omega \cdot L_1 < 0$$

ADS, shunt susceptance



S-PARAMETERS

S_Param

SP1

Freq=1.0 GHz

Tune Parameters

Simulate
While Slider Moves
Tune

Parameters
Include Opt Params
Enable/Disable...
 Display Full Name
 Snap Slider to Step

Traces and Values
Store... Recall...
Trace Visibility...
Reset Values
Close Unassociated Data Displays

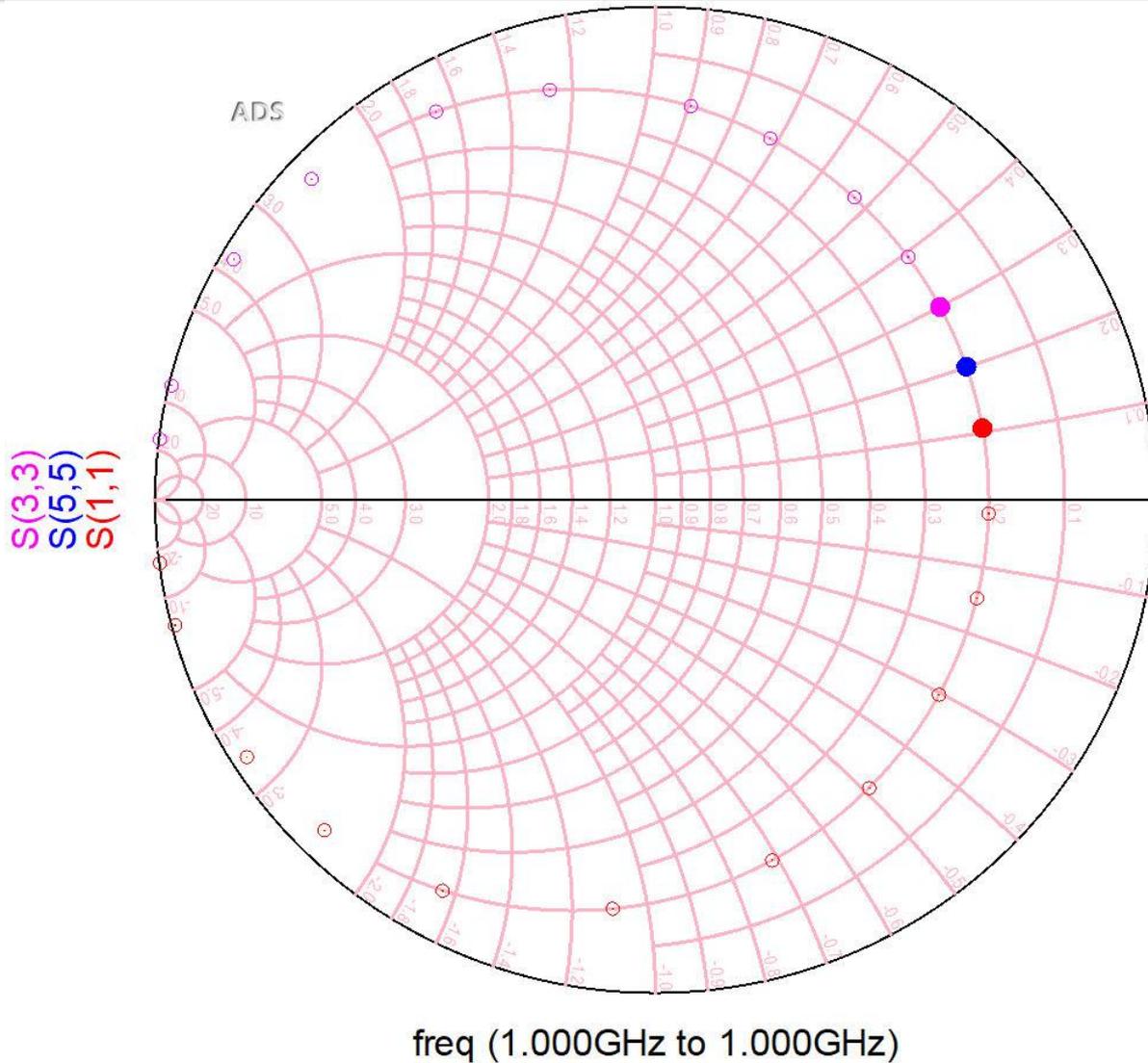
Update Schematic
Close Help

adaptare_IC_lib:X:schematic

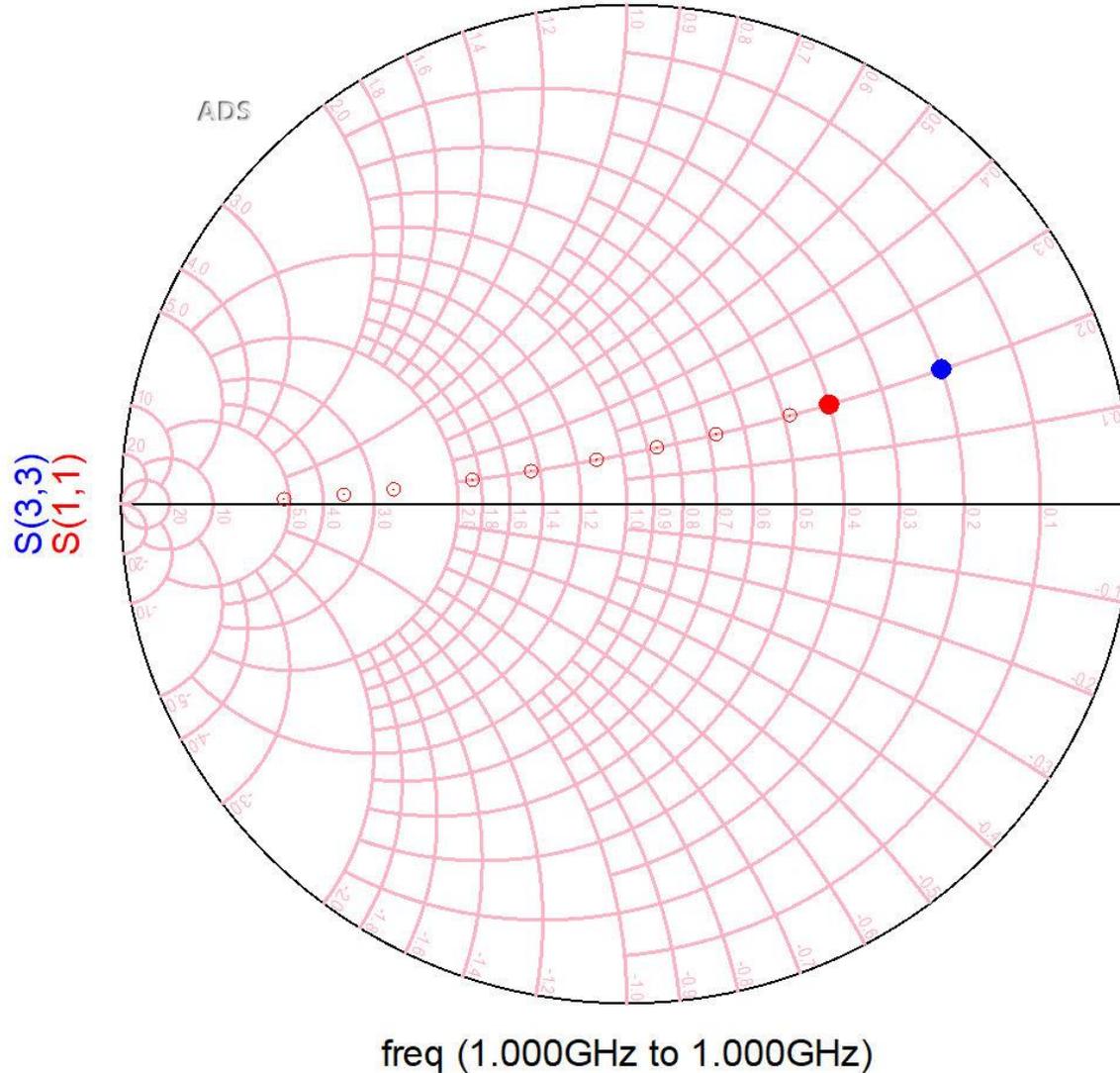
L1.L (nH)
Value: 80
Max: 100
Min: 0.5
Step: 0.1
Scale: Lin

C1.C (pF)
Value: 0.3
Max: 50
Min: 0.1
Step: 0.1
Scale: Lin

ADS, shunt susceptance



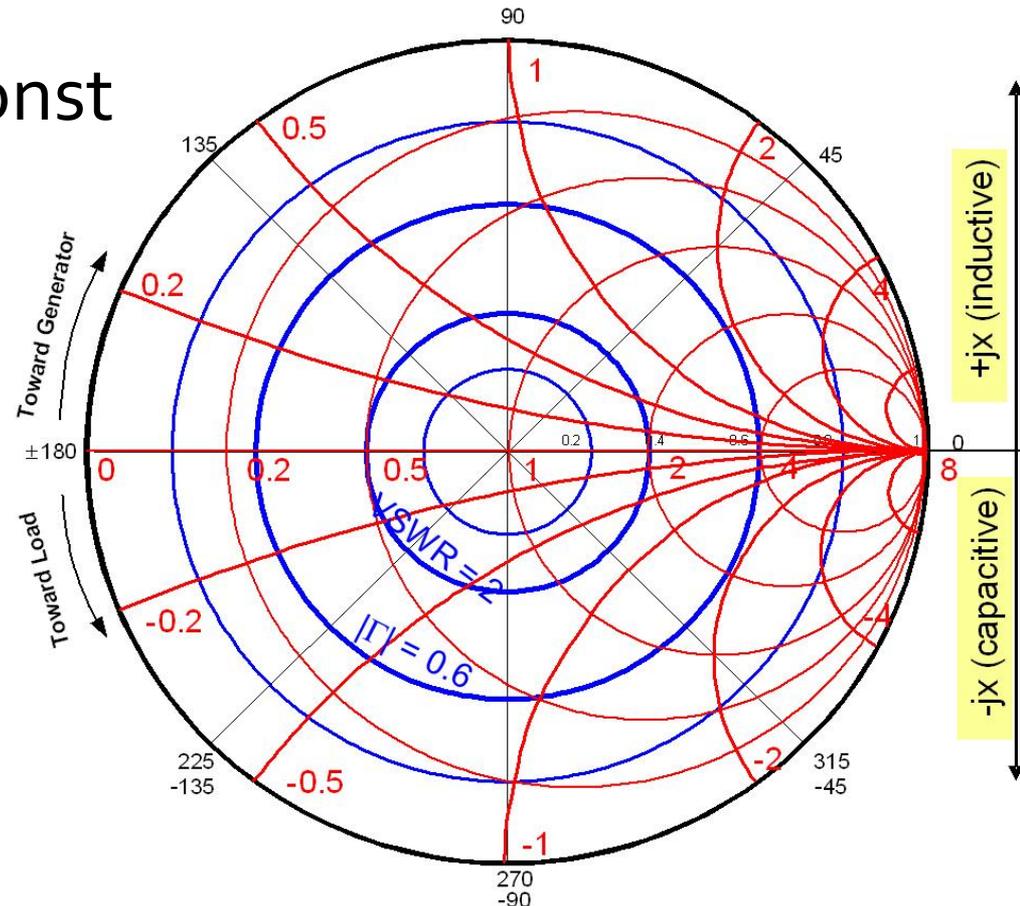
ADS, shunt conductance



Constant VSWR circles

- Certain applications may require a certain ratio between maximum / minimum line voltage
- $VSWR = \text{const} \rightarrow \Gamma = \text{const}$

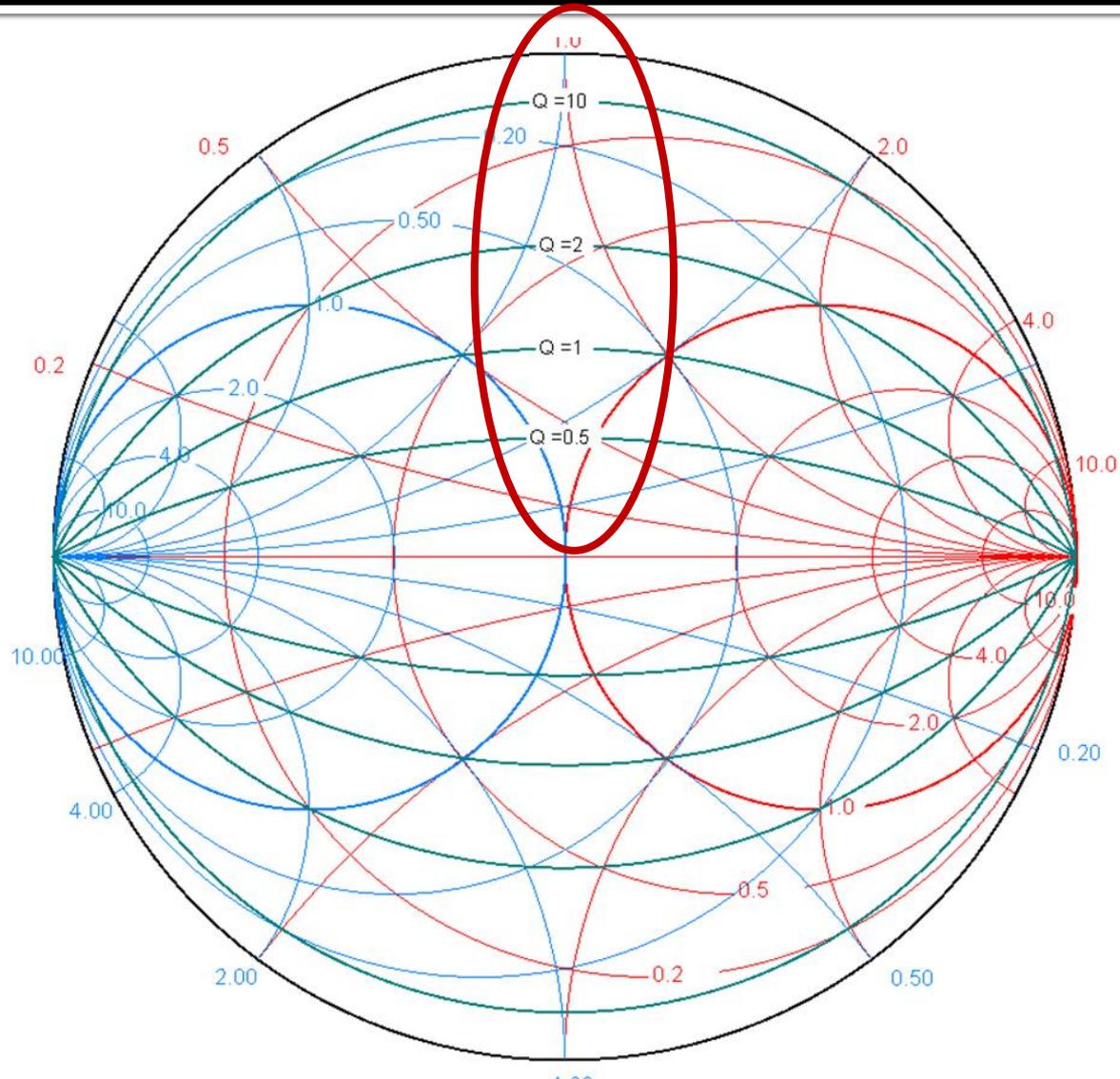
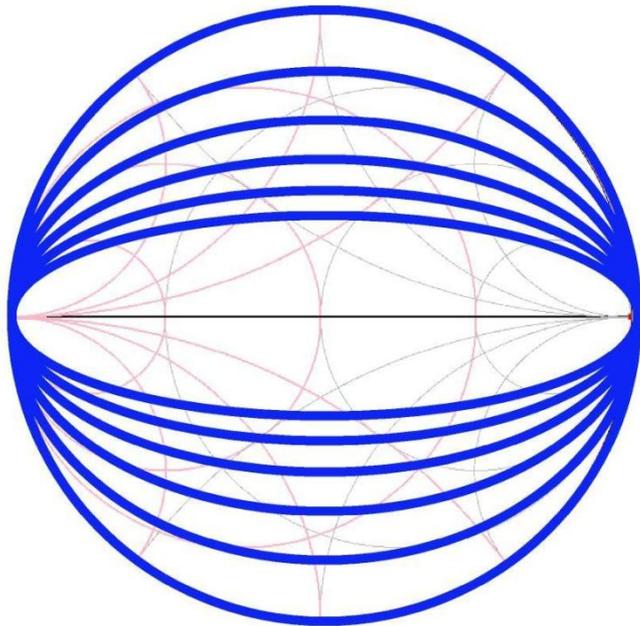
$$VSWR = \frac{V_{\max}}{V_{\min}} = \frac{1 + |\Gamma|}{1 - |\Gamma|}$$



Constant Q circles

- Quality factor Q

$$Q = \frac{X}{R} = \frac{G}{B} = \text{const}$$



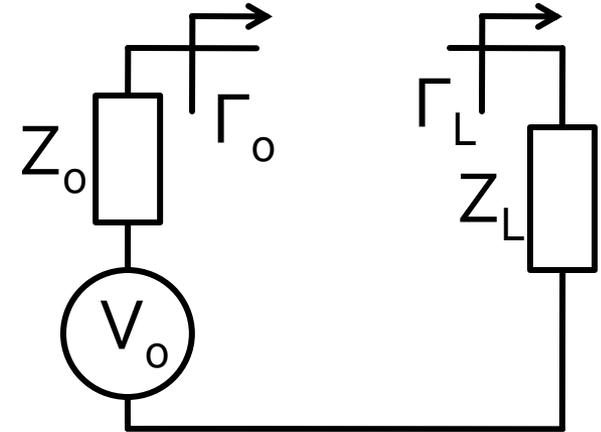
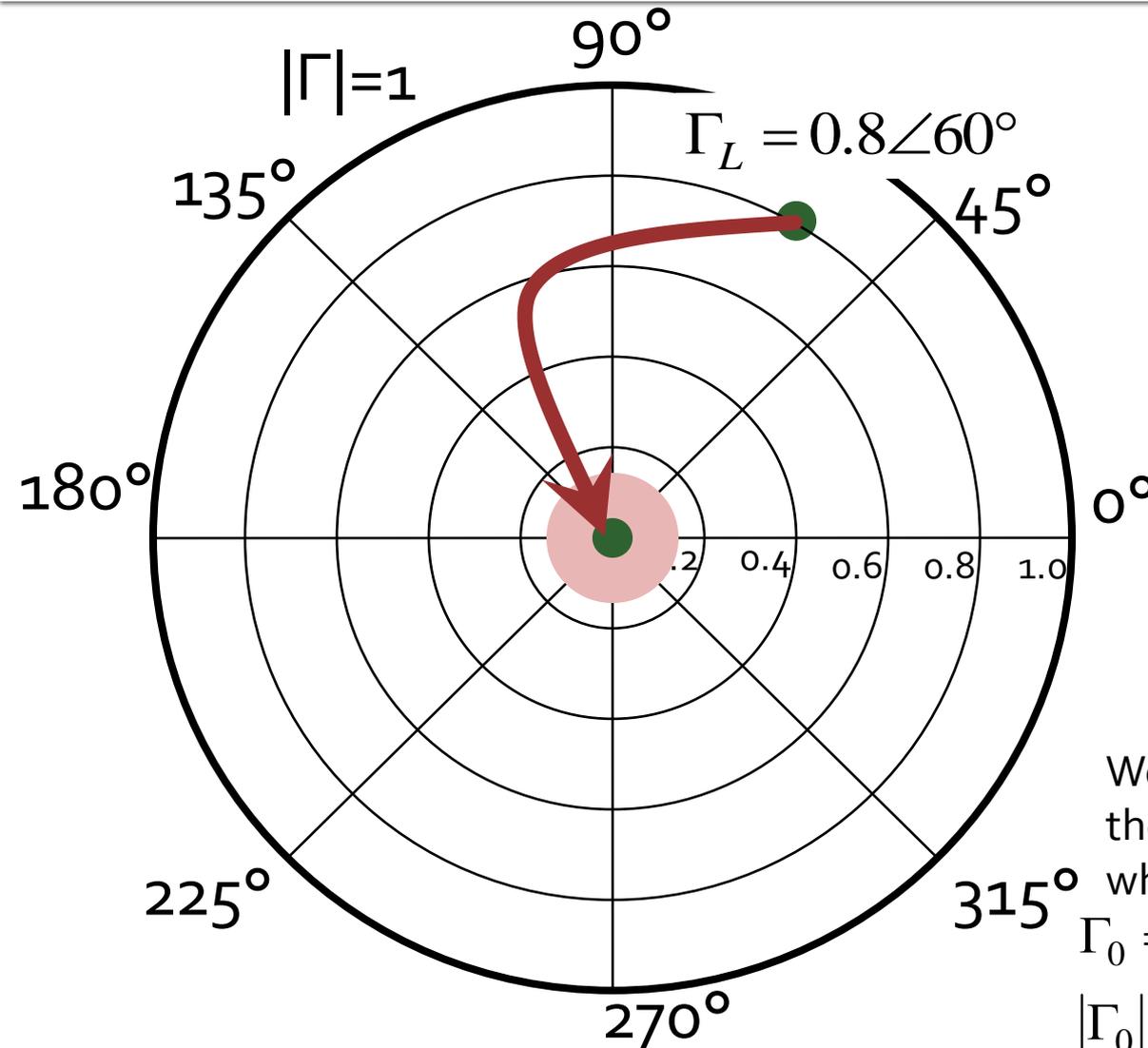
Impedance matching

Impedance Matching with lumped elements (L Networks)

Course Topics

- Transmission lines
- **Impedance matching and tuning**
- Directional couplers
- Power dividers
- Microwave amplifier design
- Microwave filters
- ~~Oscillators and mixers?~~

The Smith Chart, reflection coefficient, impedance matching



Matching Z_L load to Z_0 source.
We normalize Z_L over Z_0

$$Z_L = 21.429\Omega + j \cdot 82.479\Omega$$

$$z_L = 0.429 + j \cdot 1.65$$

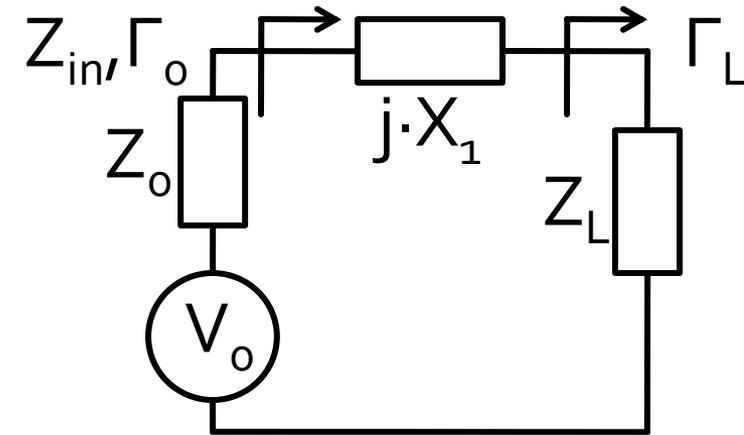
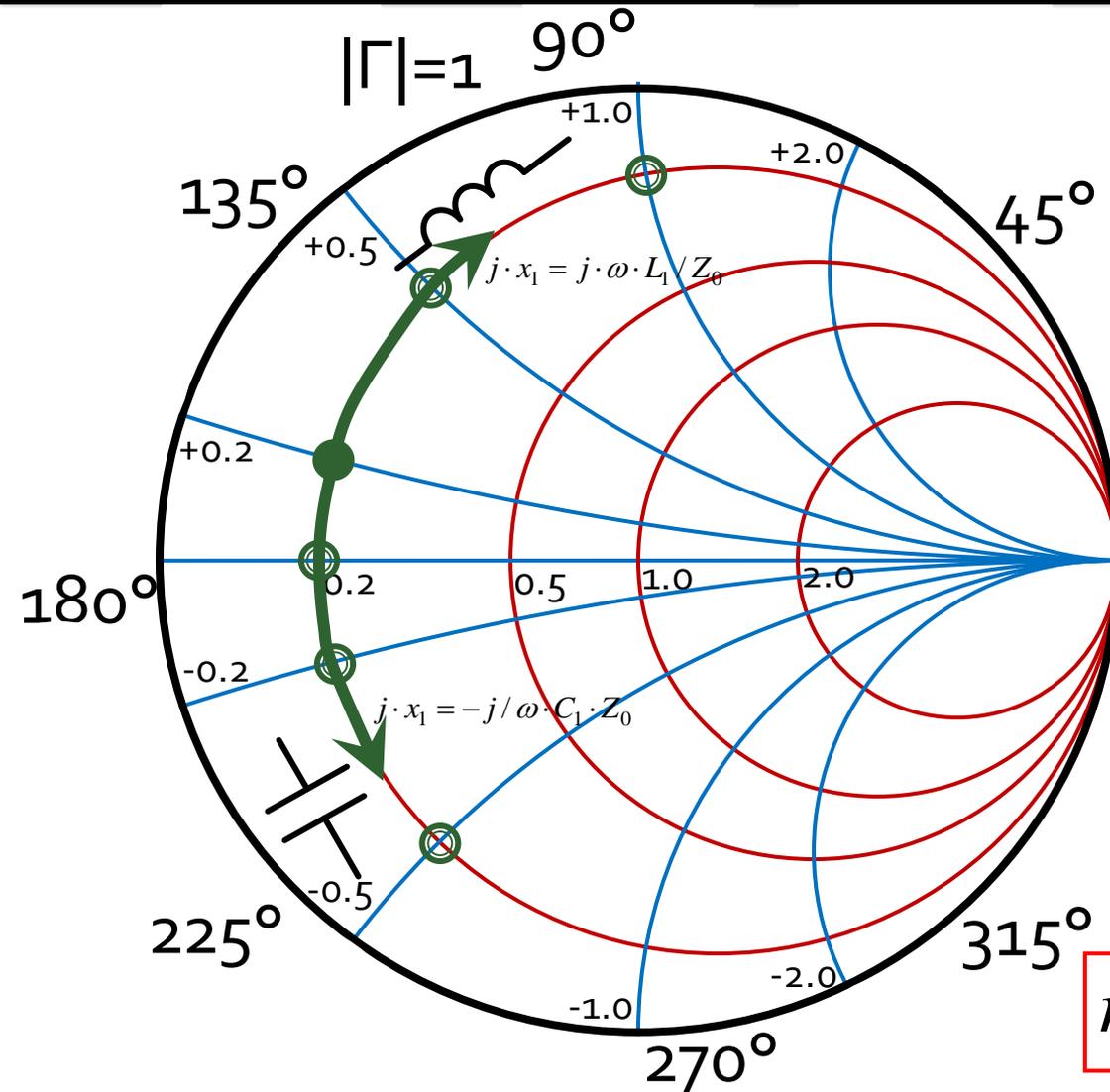
$$\Gamma_L = 0.8 \angle 60^\circ$$

We must move the point denoting the reflection coefficient in the area where with a Z_0 source we have:

$$\Gamma_0 = 0 \text{ perfect match } \bullet$$

$$|\Gamma_0| \leq \Gamma_m \text{ "good enough" match } \bullet$$

The Smith Chart, series reactance



$$Z_0 = 50\Omega$$

$$Z_L = R_L + j \cdot X_L = 10\Omega + j \cdot 10\Omega$$

$$z_L = r_L + j \cdot x_L = 0.2 + j \cdot 0.2$$

$$\Gamma_L = 0.678 \angle 156.5^\circ$$

$$Z_{in} = Z_L + j \cdot X_1 = R_L + j \cdot (X_L + X_1)$$

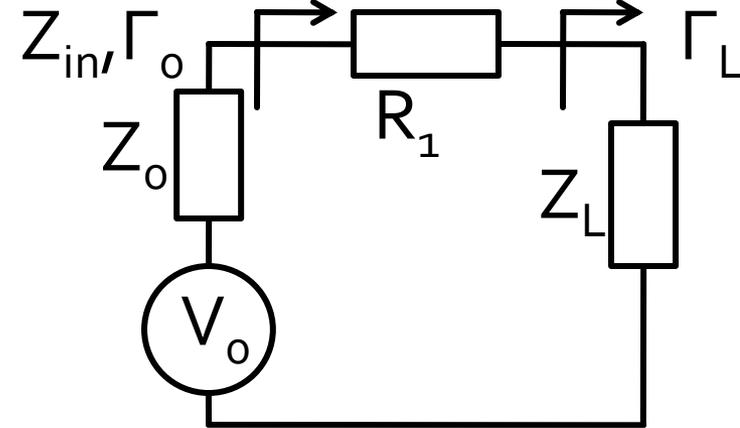
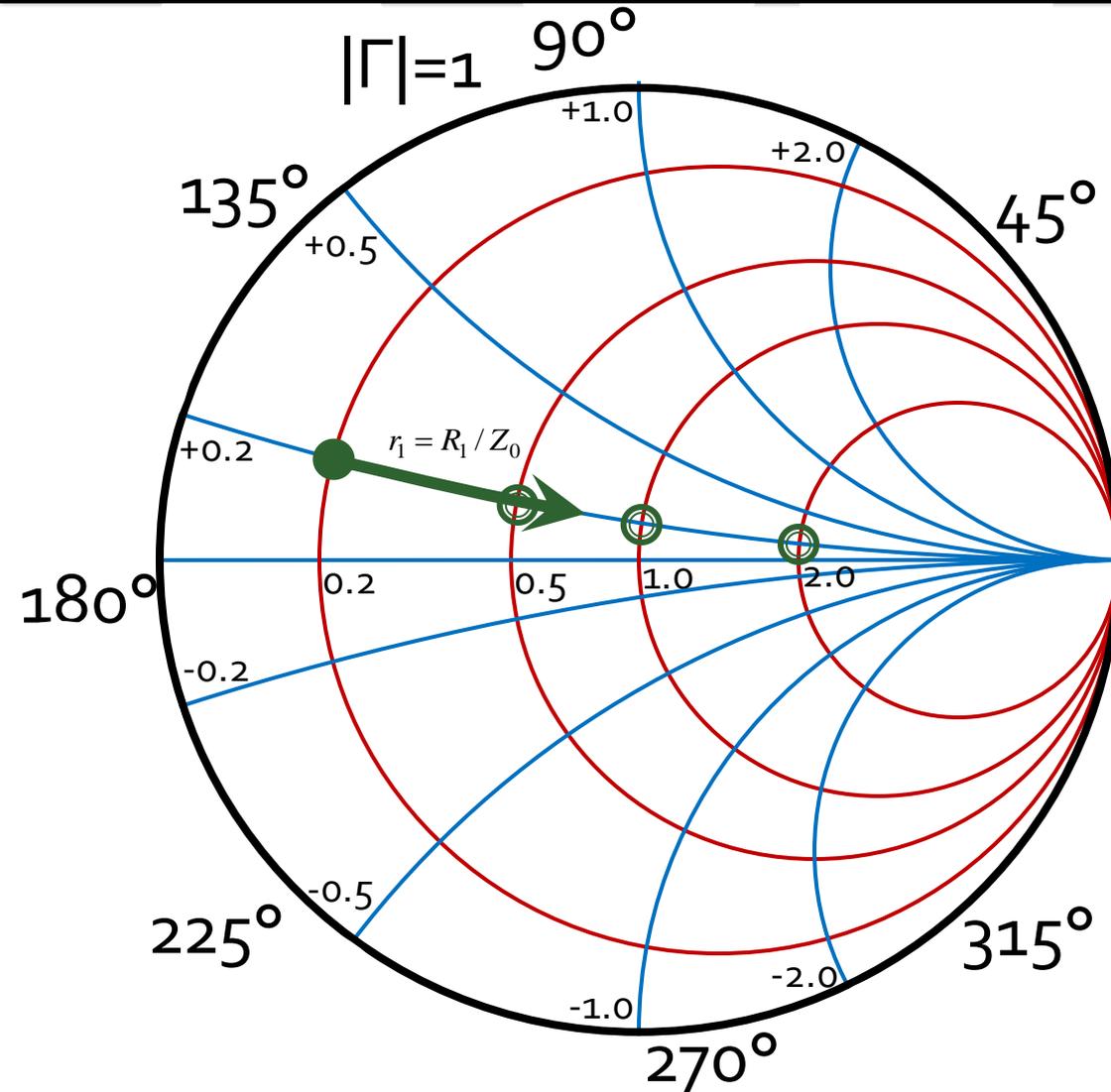
$$z_{in} = r_L + j \cdot (x_L + x_1)$$

$$r_{in} = r_L$$

$$j \cdot x_1 = j \cdot \omega \cdot L_1 / Z_0 > 0$$

$$j \cdot x_1 = -j / \omega \cdot C_1 \cdot Z_0 < 0$$

The Smith Chart, series resistance



$$Z_0 = 50\Omega$$

$$Z_L = R_L + j \cdot X_L = 10\Omega + j \cdot 10\Omega$$

$$z_L = r_L + j \cdot x_L = 0.2 + j \cdot 0.2$$

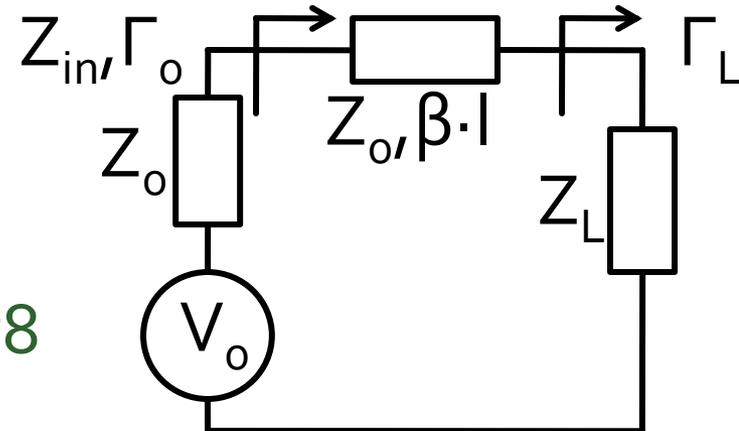
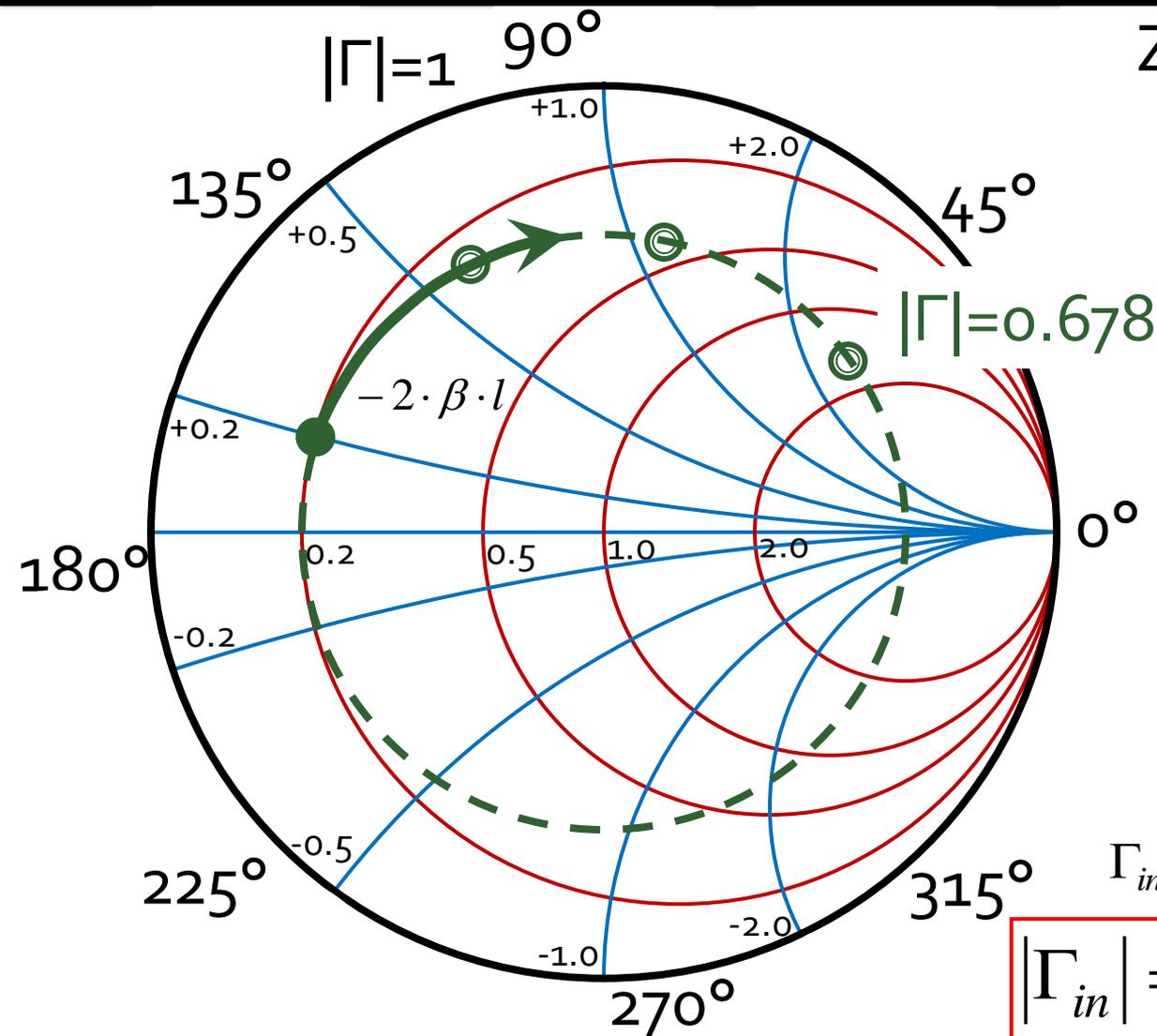
$$\Gamma_L = 0.678 \angle 156.5^\circ$$

$$Z_{in} = Z_L + R_1 = (R_L + R_1) + j \cdot X_L$$

$$z_{in} = z_L + r_1 = (r_L + r_1) + j \cdot x_L$$

$$x_{in} = x_L \quad r_{in} = r_L + R_1 / Z_0$$

The Smith Chart, series transmission line, Z_0



$$Z_0 = 50\Omega$$

$$Z_L = R_L + j \cdot X_L = 10\Omega + j \cdot 10\Omega$$

$$z_L = r_L + j \cdot x_L = 0.2 + j \cdot 0.2$$

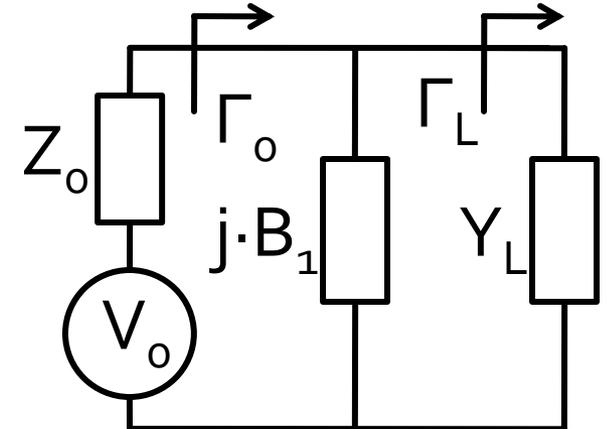
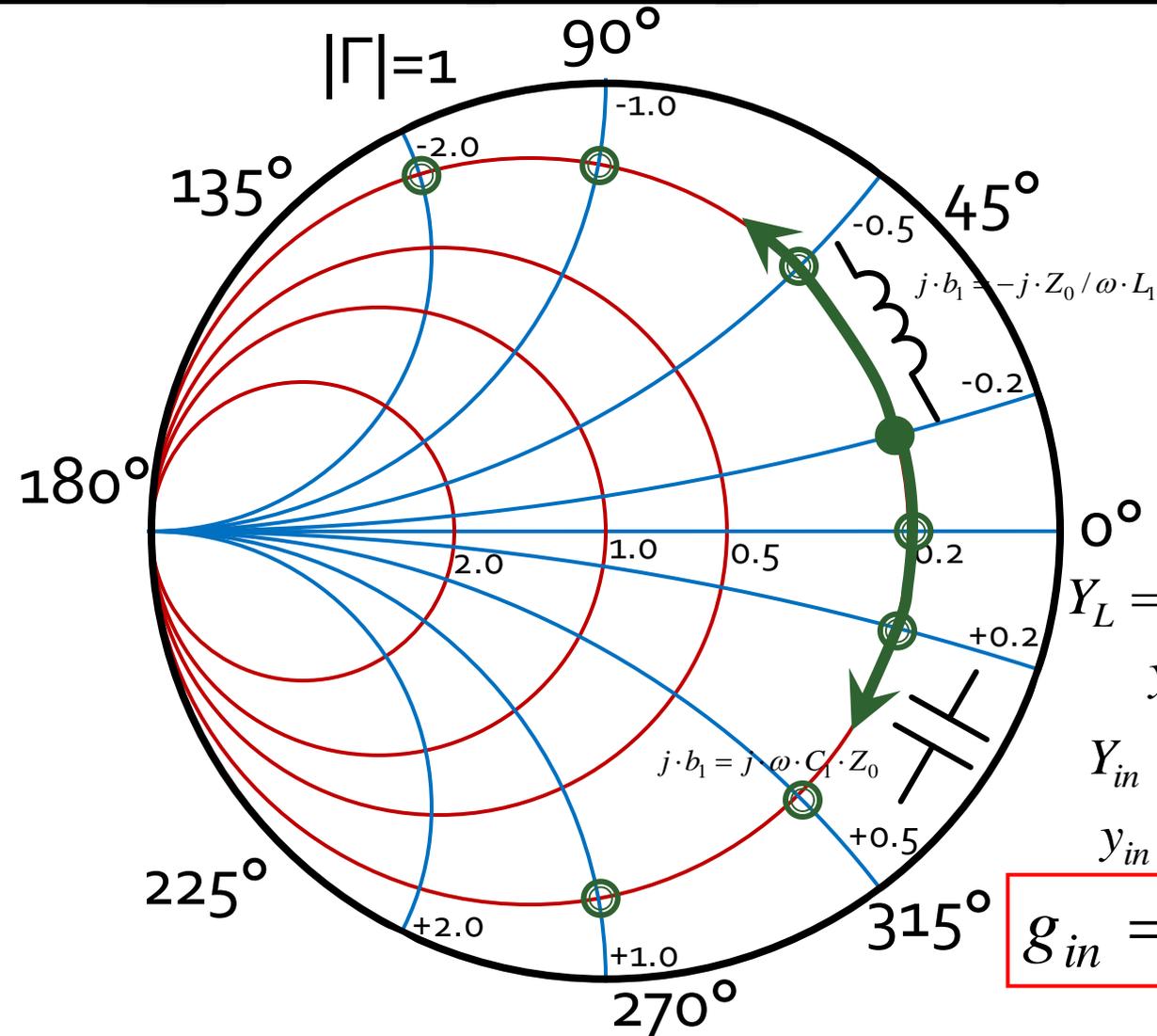
$$\Gamma_L = 0.678 \angle 156.5^\circ$$

$$Z_{in} = Z_0 \cdot \frac{1 + \Gamma_L \cdot e^{-2j \cdot \beta \cdot l}}{1 - \Gamma_L \cdot e^{-2j \cdot \beta \cdot l}}$$

$$\Gamma_{in} = \Gamma_L \cdot e^{-2j \cdot \beta \cdot l}$$

$$|\Gamma_{in}| = |\Gamma_L| \quad \arg(\Gamma_{in}) = \arg(\Gamma_L) - 2 \cdot \beta \cdot l$$

The Smith Chart, shunt susceptance



$$Z_0 = 50\Omega, Y_0 = 0.02S$$

$$\Gamma_L = 0.678 \angle 23.5^\circ$$

$$Y_L = G_L + j \cdot B_L = 0.004S + j \cdot 0.004$$

$$y_L = g_L + j \cdot b_L = 0.2 - j \cdot 0.2$$

$$Y_{in} = Y_L + j \cdot B_1 = G_L + j \cdot (B_L + B_1)$$

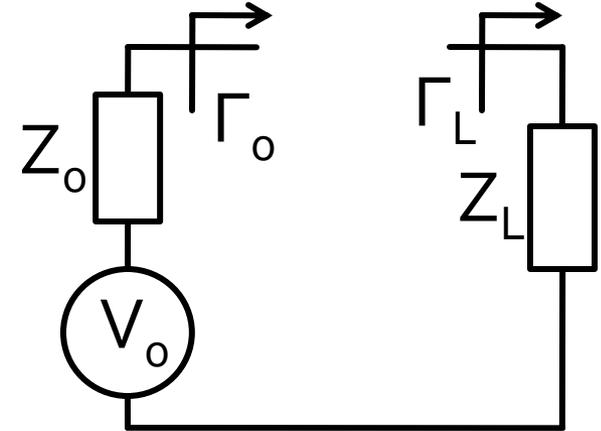
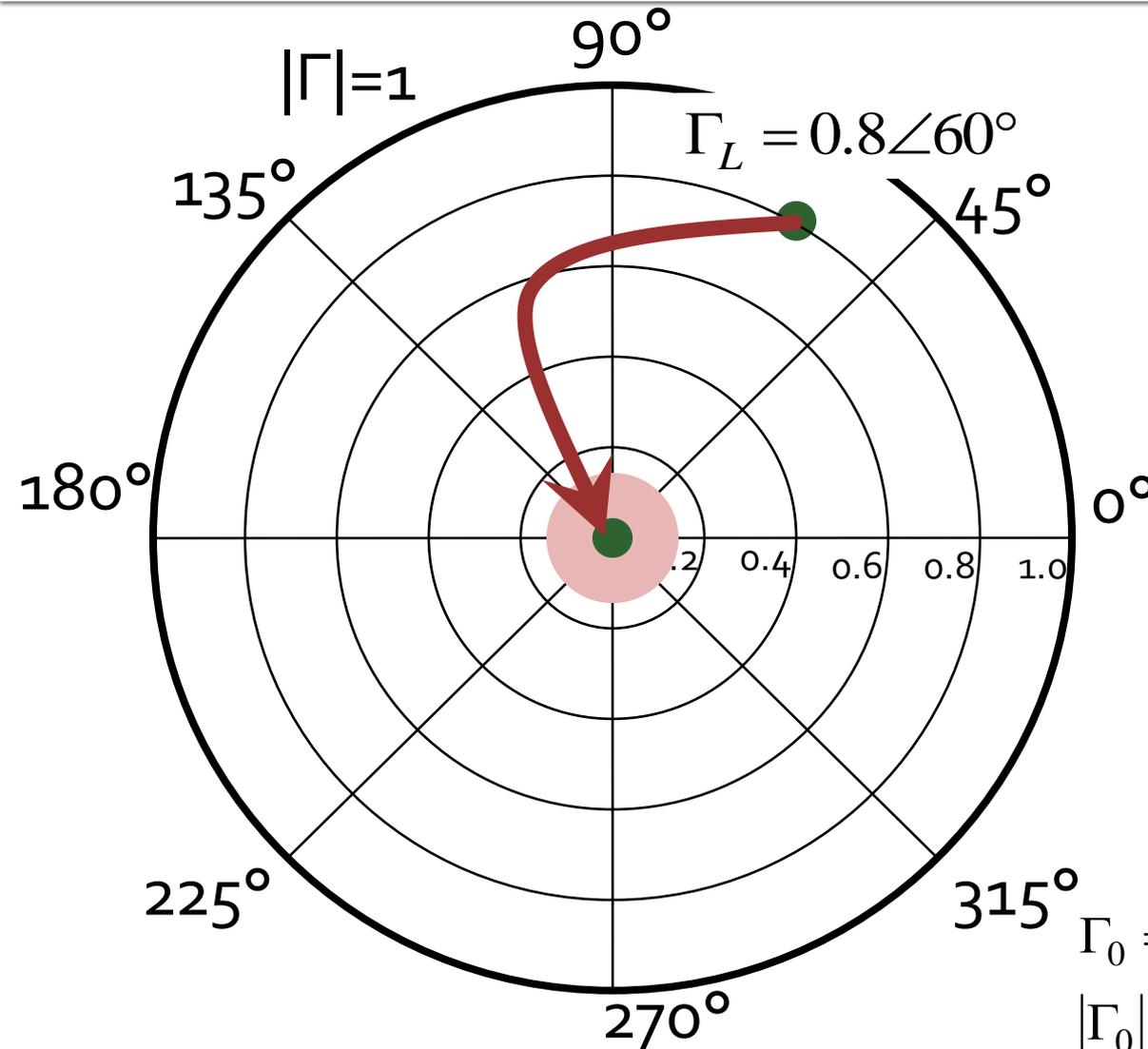
$$y_{in} = g_L + j \cdot (b_L + b_1)$$

$$g_{in} = g_L$$

$$j \cdot b_1 = j \cdot \omega \cdot C_1 \cdot Z_0 > 0$$

$$j \cdot b_1 = -j \cdot Z_0 / \omega \cdot L_1 < 0$$

Impedance matching

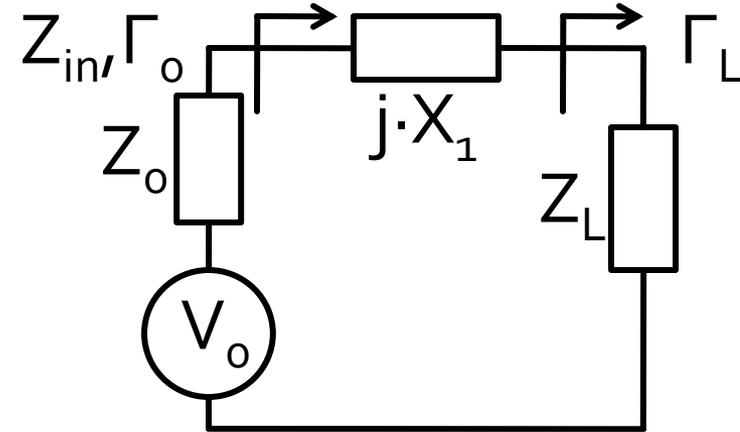
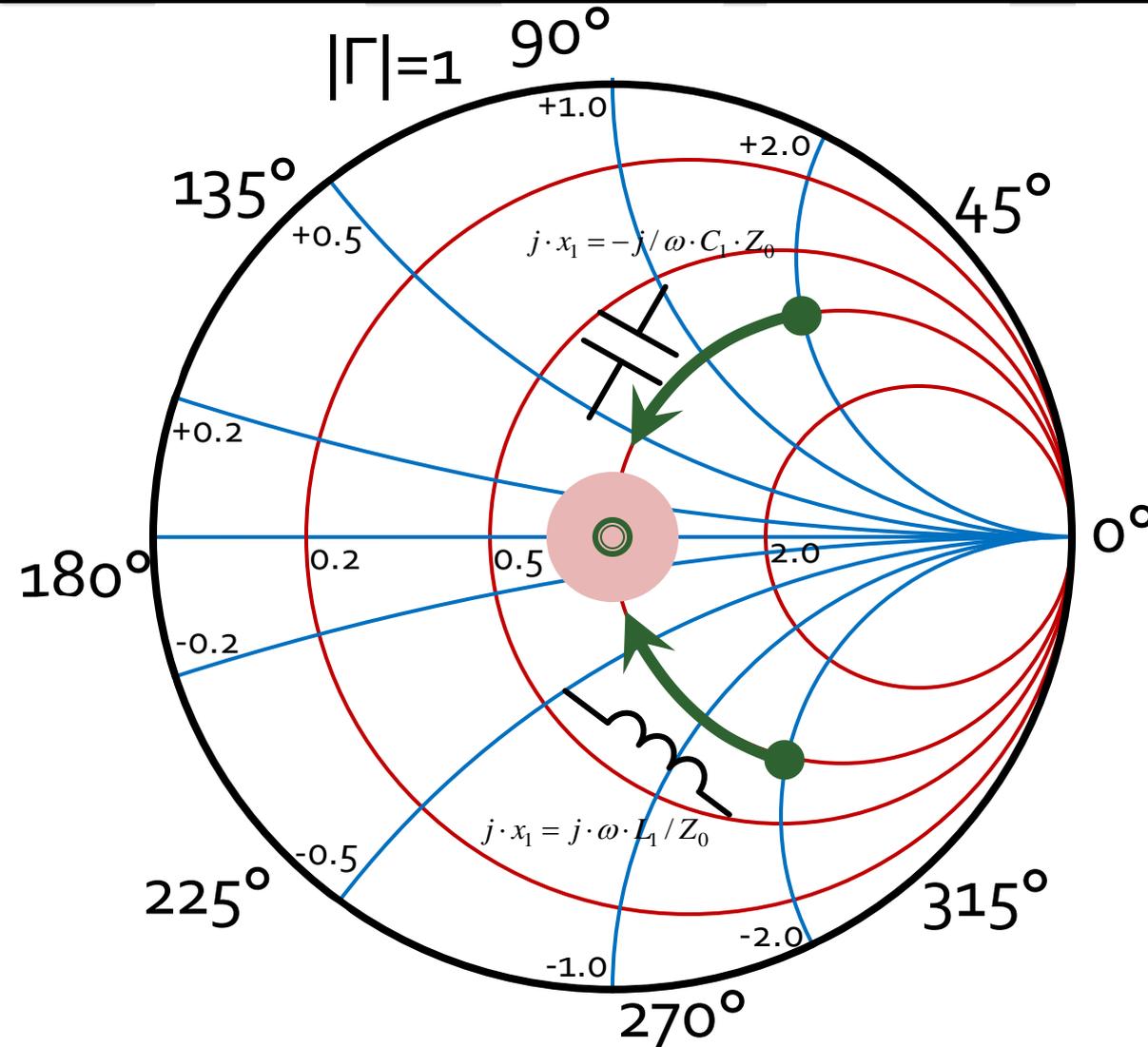


How?

$\Gamma_0 = 0$ perfect match ●

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

Matching, series reactance



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

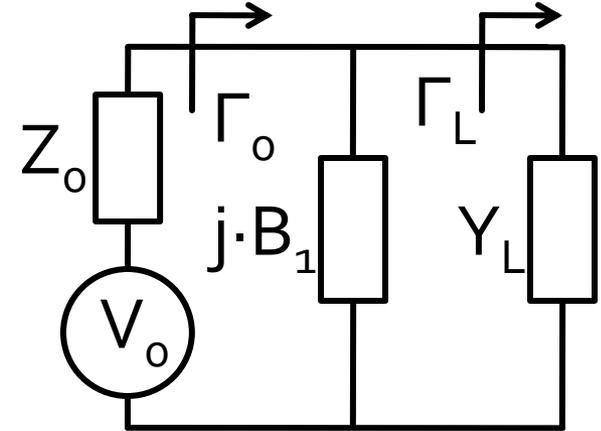
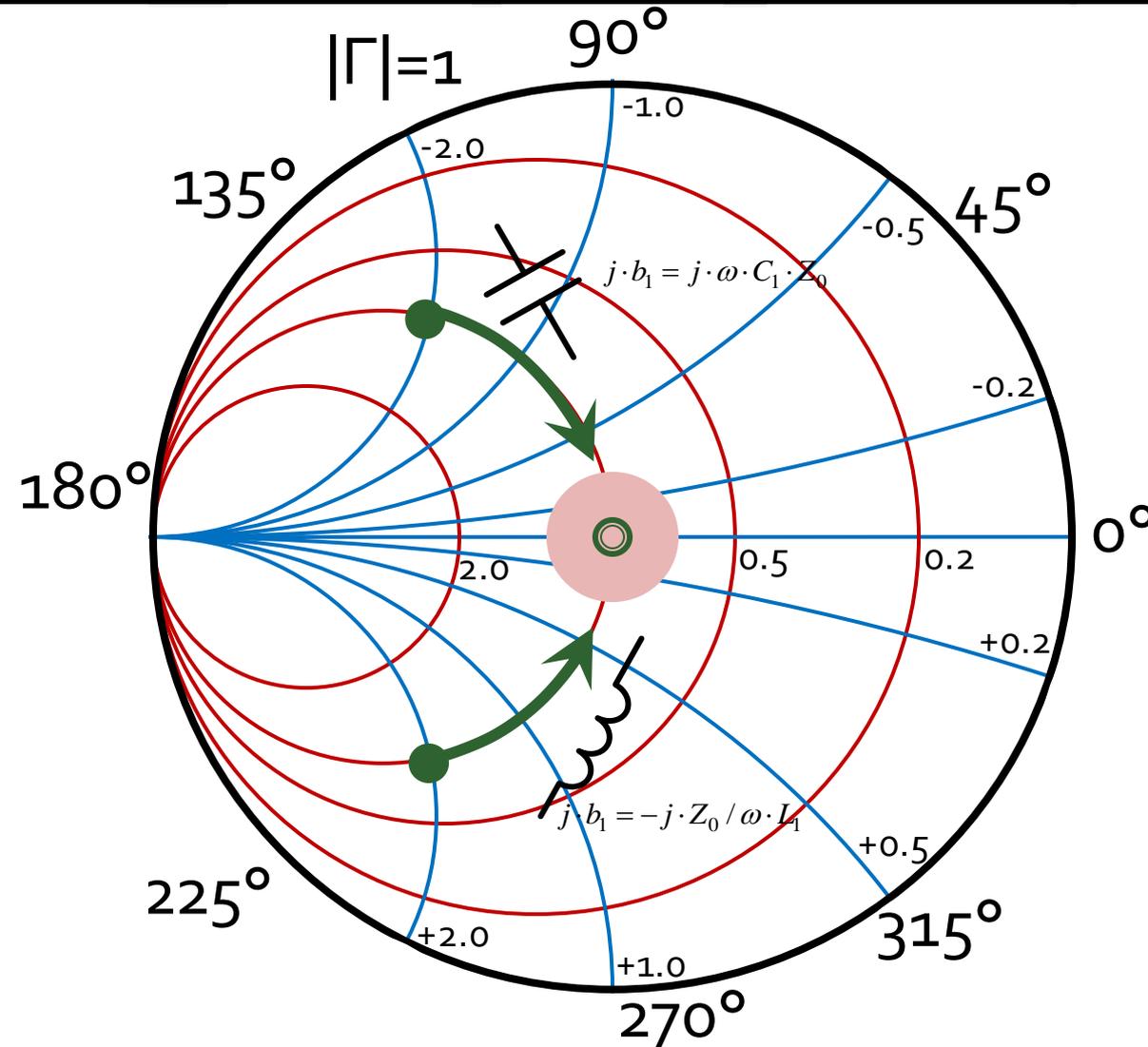
$$z_{in} = r_L + j \cdot (x_L + x_1)$$

$$r_{in} = r_L$$

- 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



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

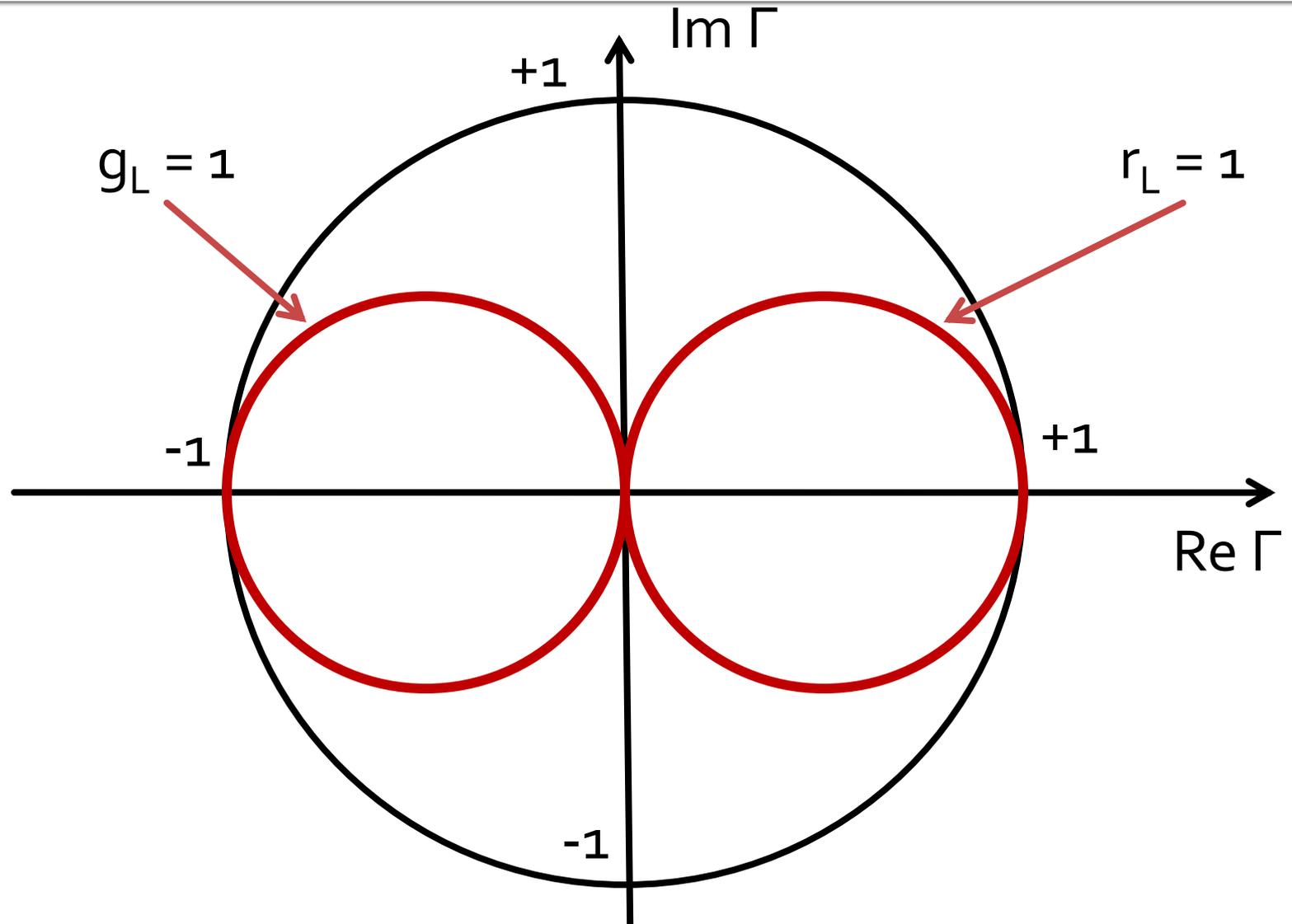
$$y_{in} = g_L + j \cdot (b_L + b_1)$$

$$g_{in} = g_L$$

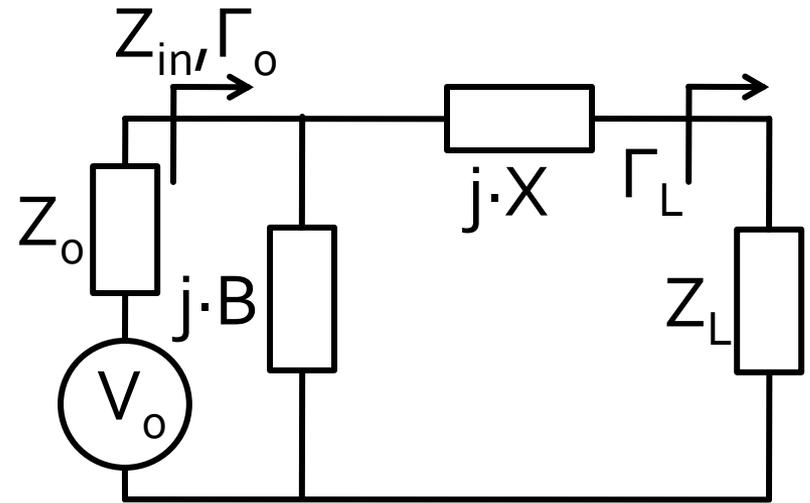
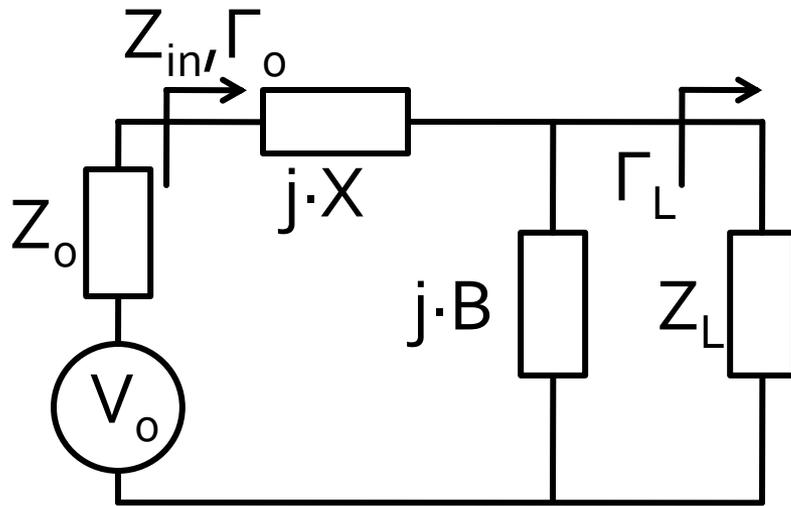
- Match can be obtained **if and only if** $g_L = 1$
- we compensate the reactive part of the load

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

Smith chart, $r=1$ and $g=1$

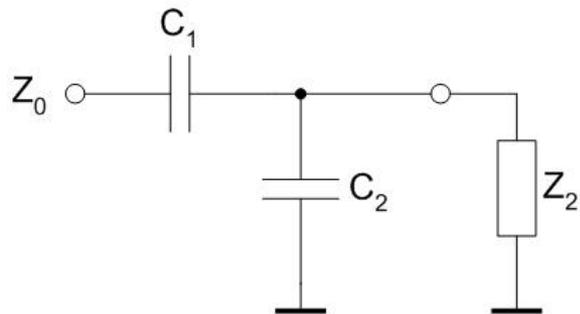
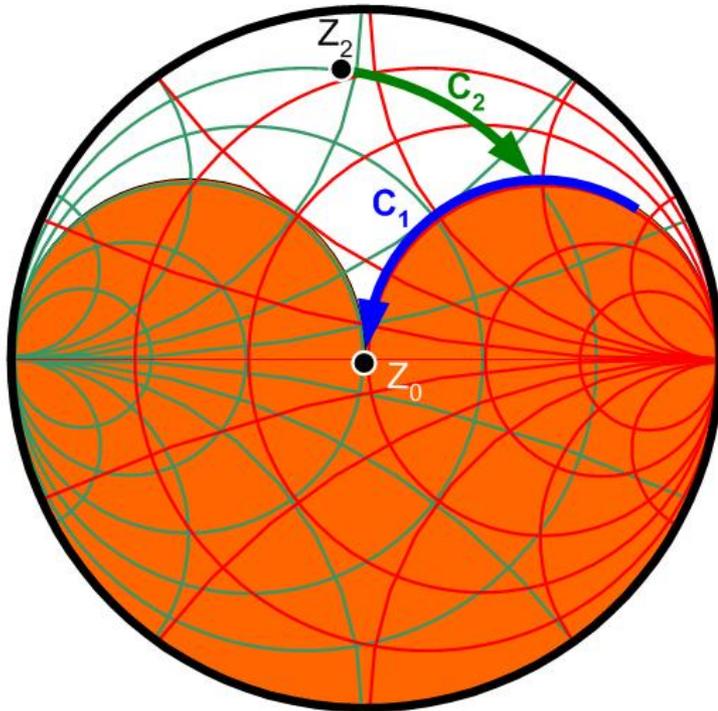


Matching with 2 reactive elements (L Networks)

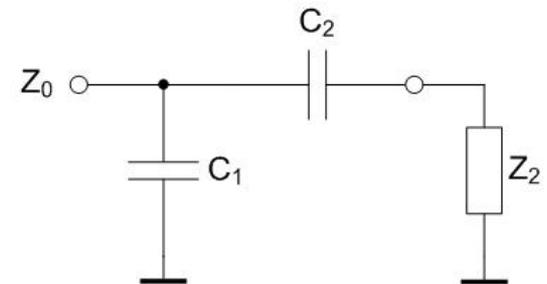
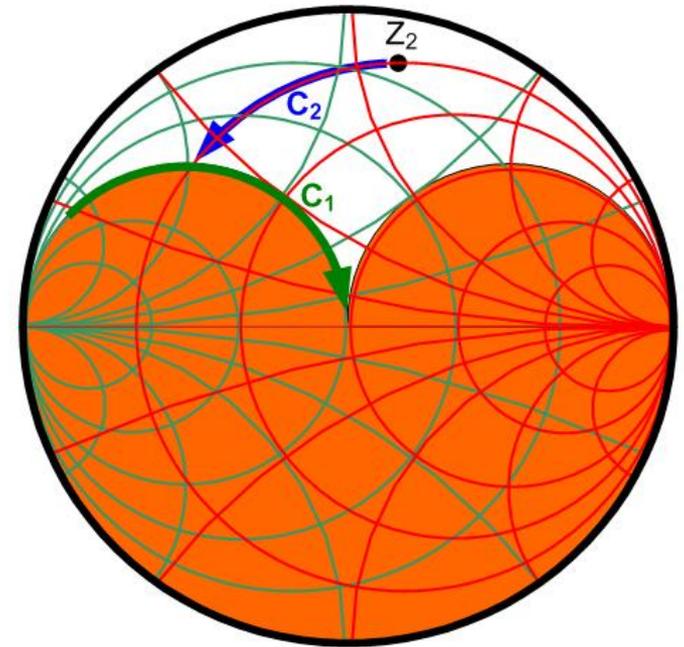


- Two steps matching
 - first reactive element moves the reflection coefficient **on the circle** $r_L = 1/g_L = 1$
 - second element compensates the remaining reactance and achieves the impedance match

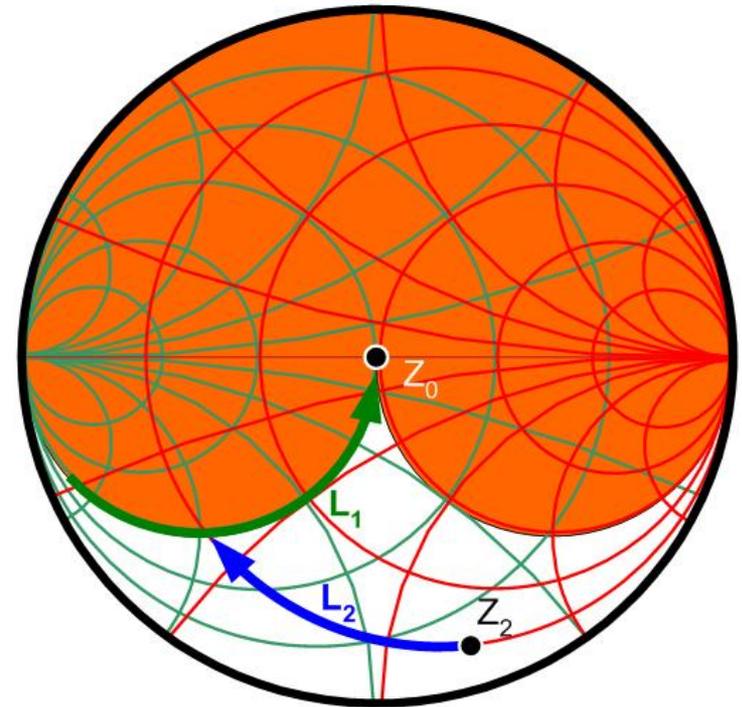
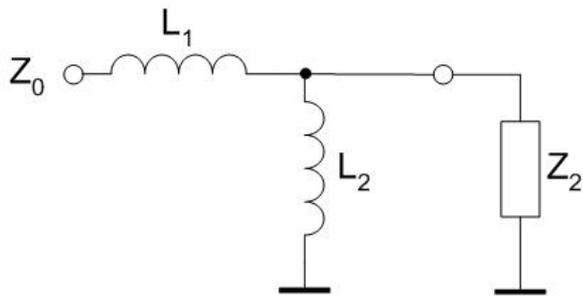
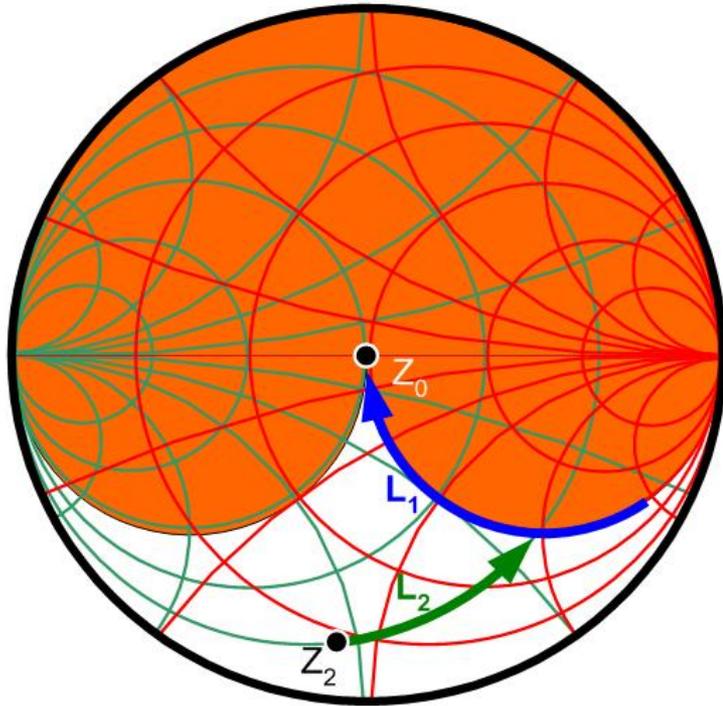
series C, shunt C / shunt C, series C



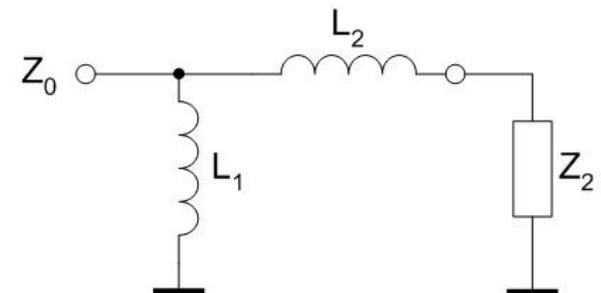
Forbidden area for current network



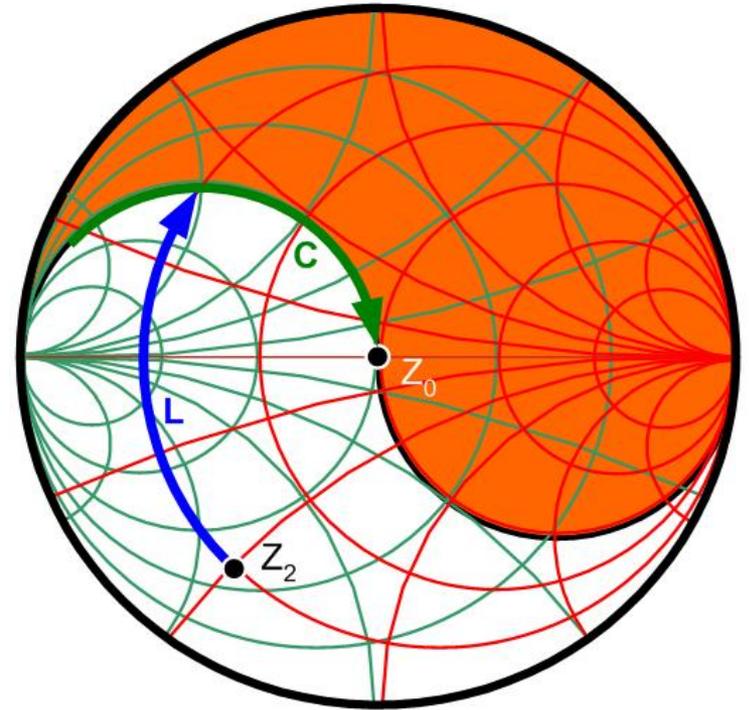
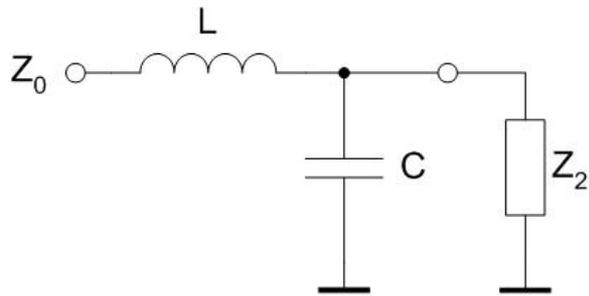
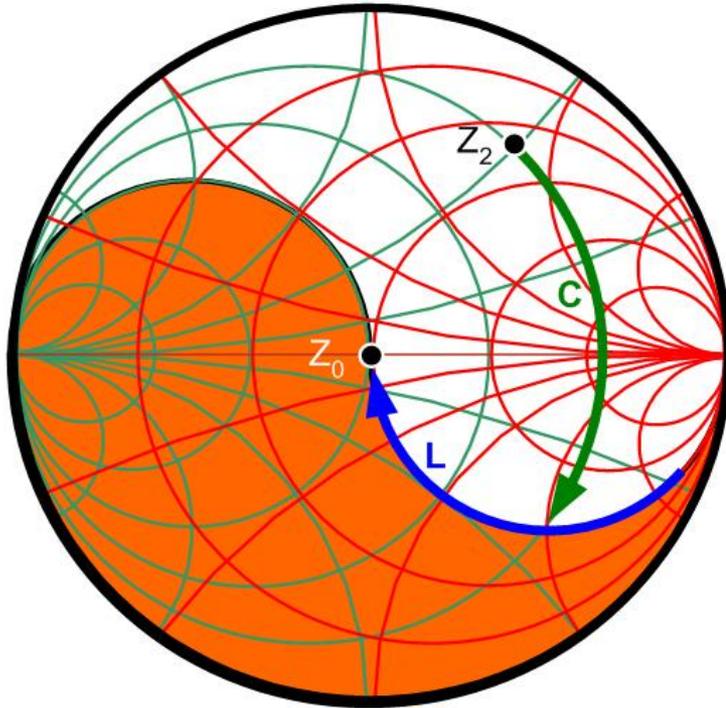
series L, shunt L / shunt L, series L



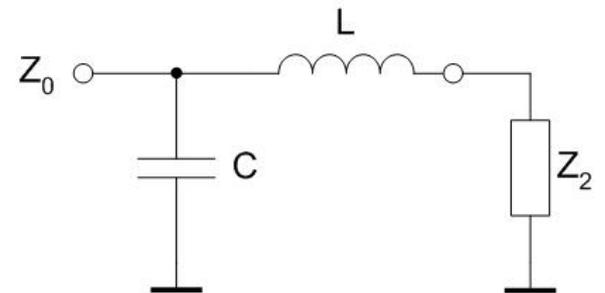
Forbidden area for current network



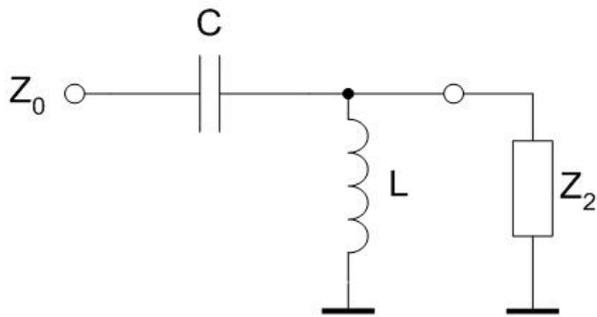
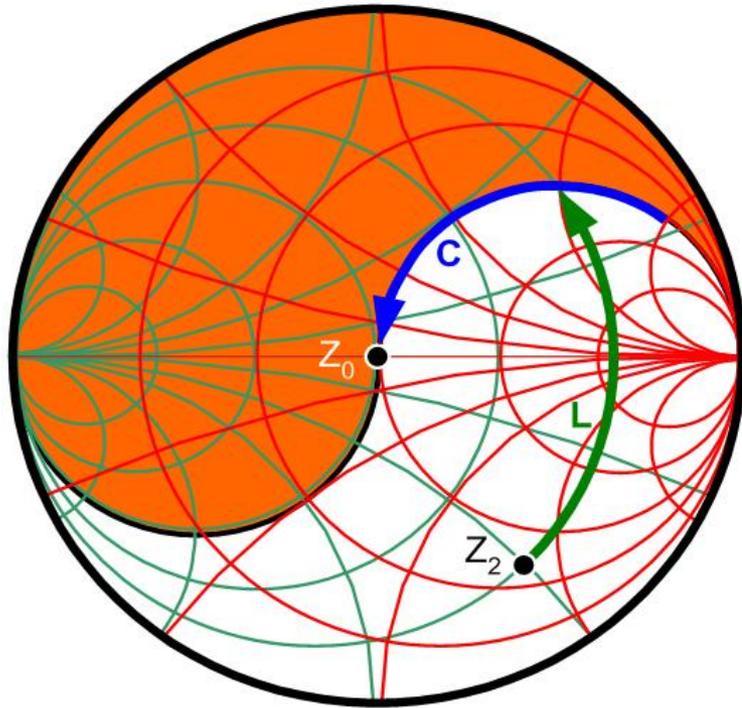
series L, shunt C / shunt C, series L



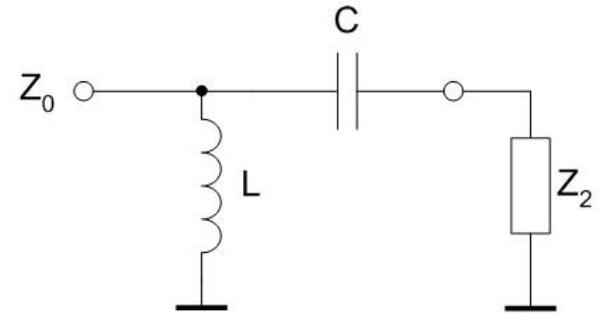
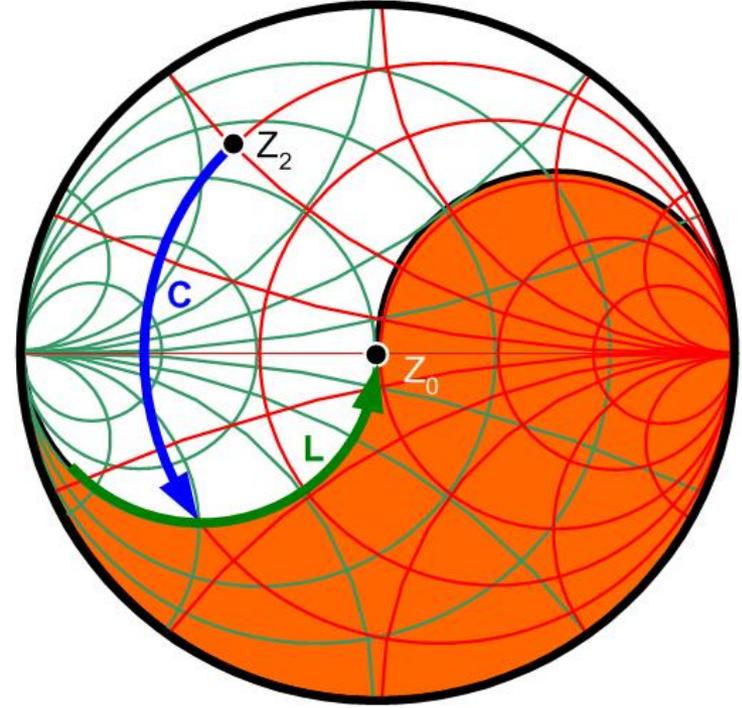
Forbidden area for current network



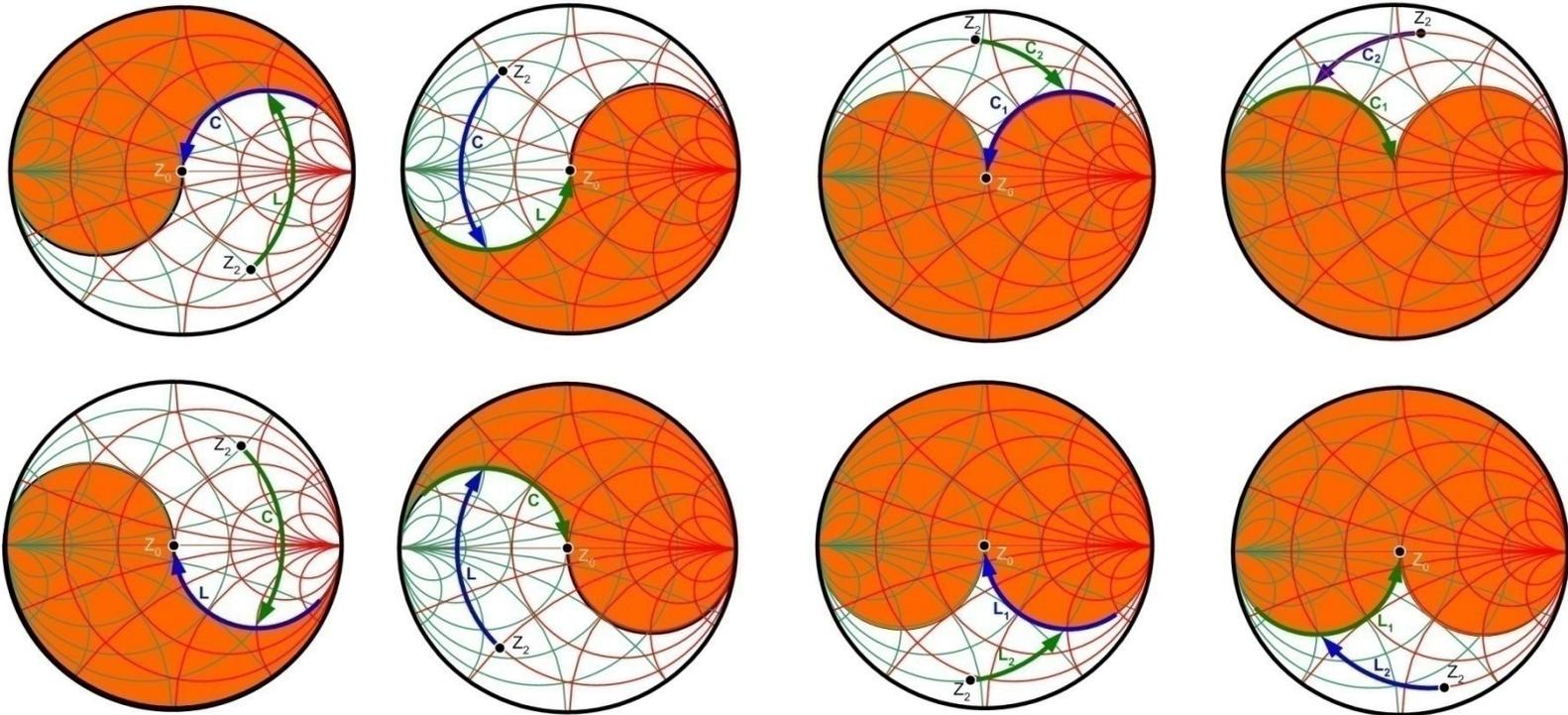
series C, shunt L / shunt L, series C



 Forbidden area for current network



Matching with 2 reactive elements (L Networks)



Forbidden area for
current network

Matching with 2 reactive elements (L Networks)

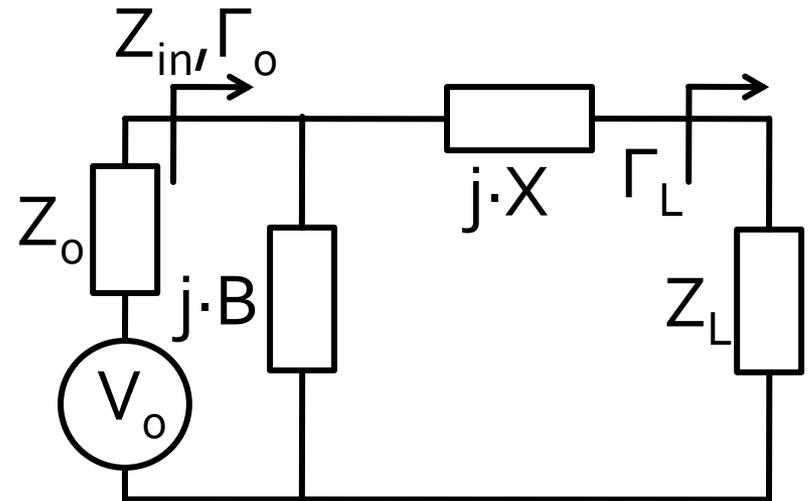
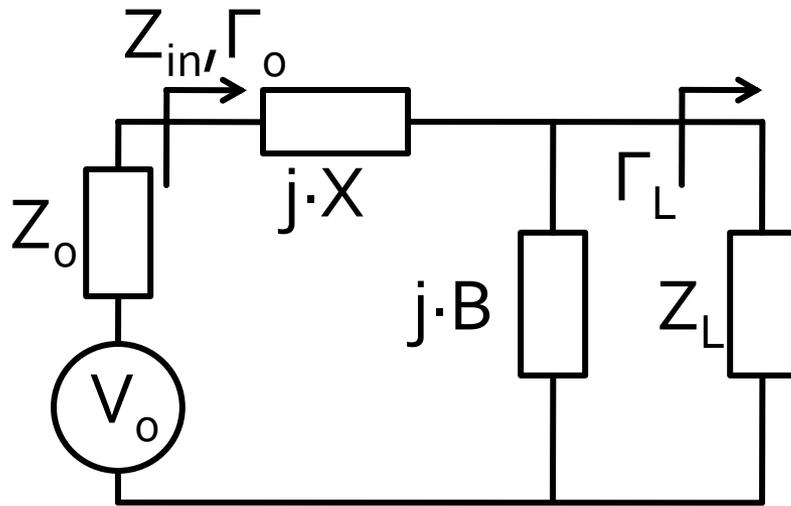
- For any Γ_L there are at least 2 possible L networks to achieve match (L+C)
- For some starting areas on the Smith Chart there are 4 possibilities (+2 C+C/L+L networks)
- We choose the network that requires components with existent/practically realizable values
- By adding the resistive elements, we can supplement the number of networks but with **loss of signal power (not recommended)**

Matching with resistive elements

- In microwave frequencies active circuits work very near to the transition frequency f_T
- Any “waste” of signal power **is not recommended**
- Sometimes such an action might be **necessary** to insure device stability

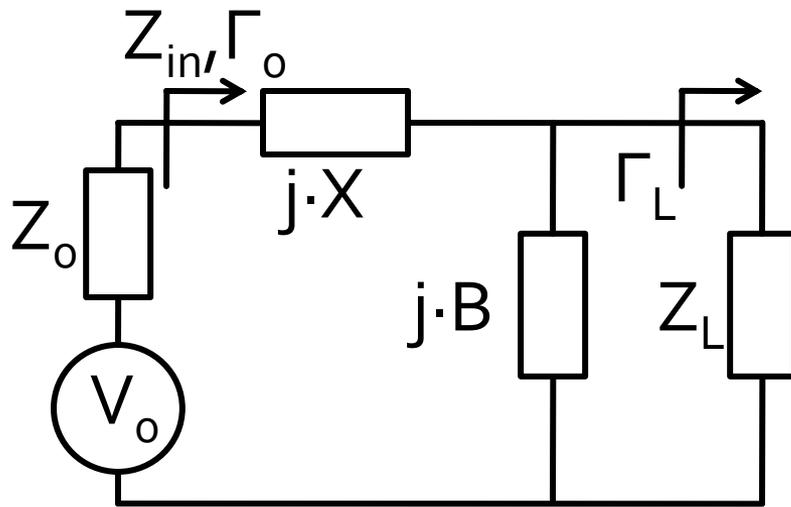


Matching with 2 reactive elements (L Networks)



- Two steps matching
 - for starting reflection coefficient inside the $r_L = 1$ circle we must use first schematic
 - for starting reflection coefficient outside the $r_L = 1$ circle we must use second schematic

Matching with 2 reactive elements (L Networks)



$$Z_L = R_L + j \cdot X_L \quad R_L > Z_0 \quad Z_{in} = Z_0$$

$$Z_0 = j \cdot X + \frac{1}{j \cdot B + 1/(R_L + j \cdot X_L)}$$

$$\begin{cases} B \cdot (X \cdot R_L - X_L \cdot Z_0) = R_L - Z_0 \\ X \cdot (1 - B \cdot X_L) = B \cdot Z_0 \cdot R_L - X_L \end{cases}$$

$$B = \frac{X_L \pm \sqrt{R_L/Z_0} \cdot \sqrt{R_L^2 + X_L^2 - Z_0 \cdot R_L}}{R_L^2 + X_L^2}$$

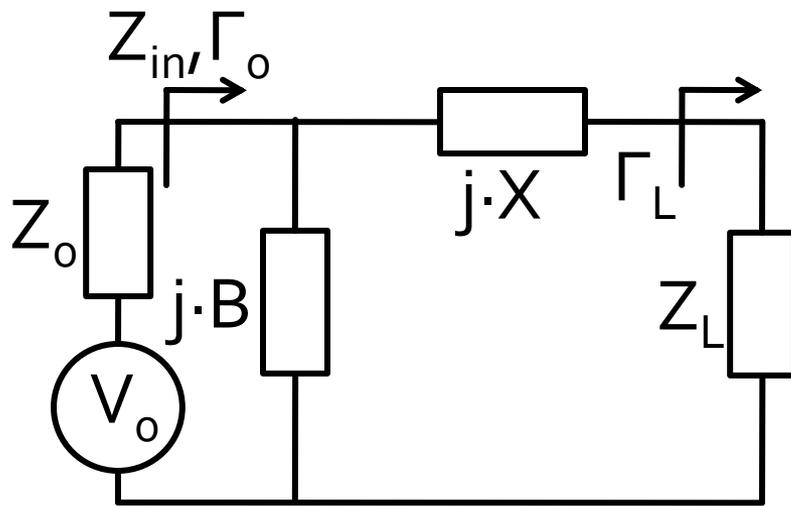
$$X = \frac{1}{B} + \frac{X_L \cdot Z_0}{R_L} - \frac{Z_0}{B \cdot R_L}$$

- the argument of the second square root is always positive for:

$$R_L > Z_0$$

- two physically realizable solutions are possible for B and X

Matching with 2 reactive elements (L Networks)



$$Z_L = R_L + j \cdot X_L \quad R_L < Z_0 \quad Y_{in} = Y_0 = \frac{1}{Z_0}$$

$$\frac{1}{Z_0} = j \cdot B + \frac{1}{R_L + j \cdot (X + X_L)}$$

$$\begin{cases} B \cdot Z_0 \cdot (X + X_L) = Z_0 - R_L \\ (X + X_L) = B \cdot Z_0 \cdot R_L \end{cases}$$

$$X = \pm \sqrt{R_L \cdot (Z_0 - R_L)} - X_L$$

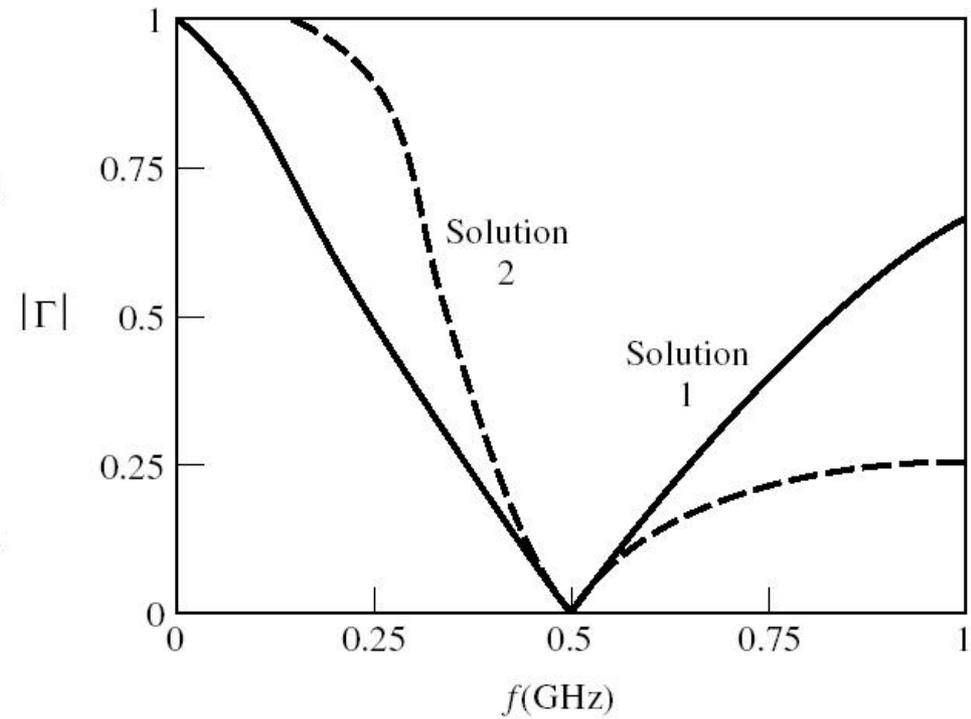
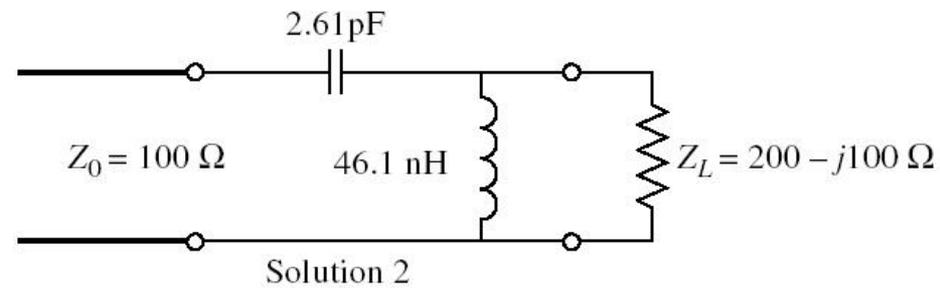
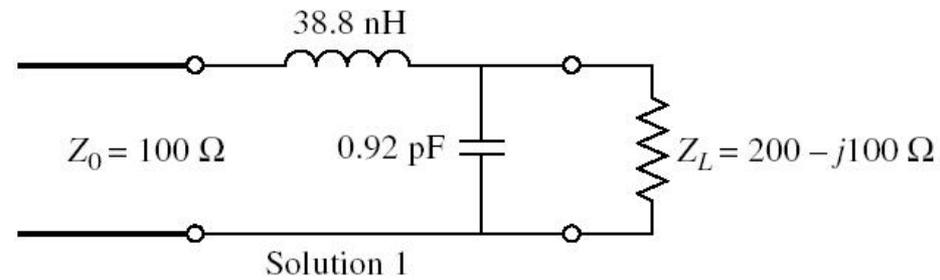
$$B = \pm \frac{\sqrt{(Z_0 - R_L)/R_L}}{Z_0}$$

- the argument of the square root is always positive for:

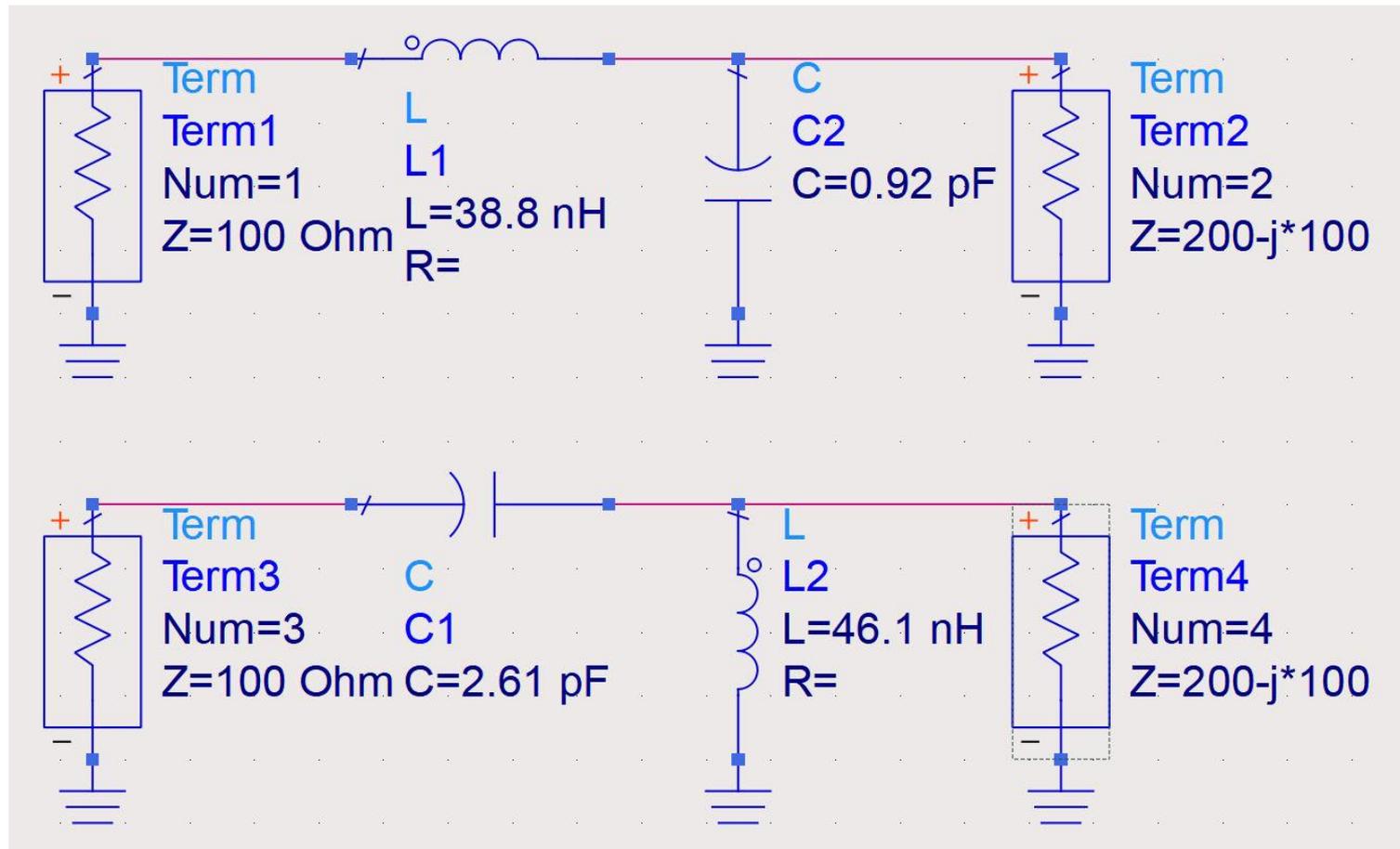
$$R_L < Z_0$$

- two physically realizable solutions are possible for B and X

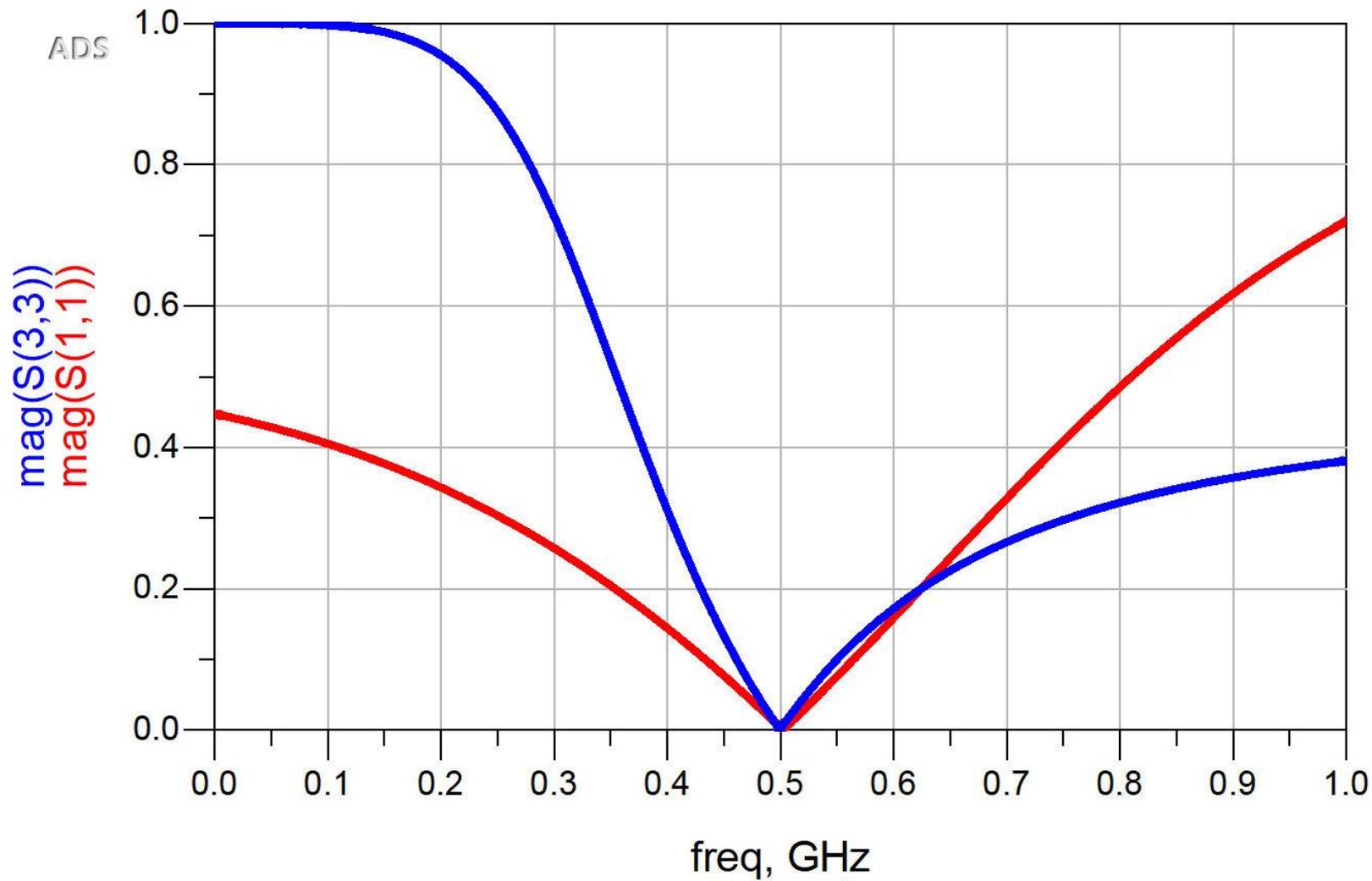
Example



Example



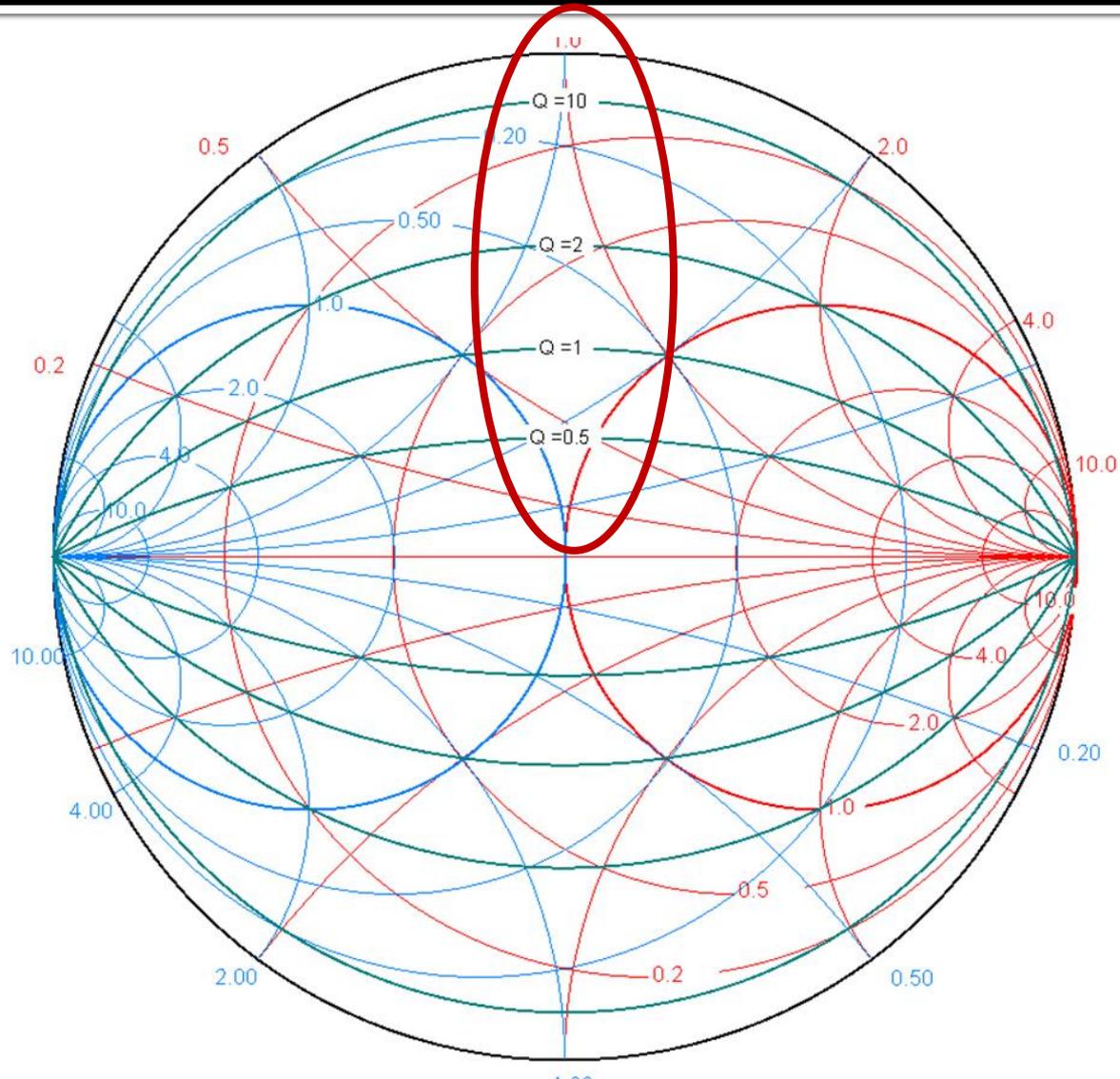
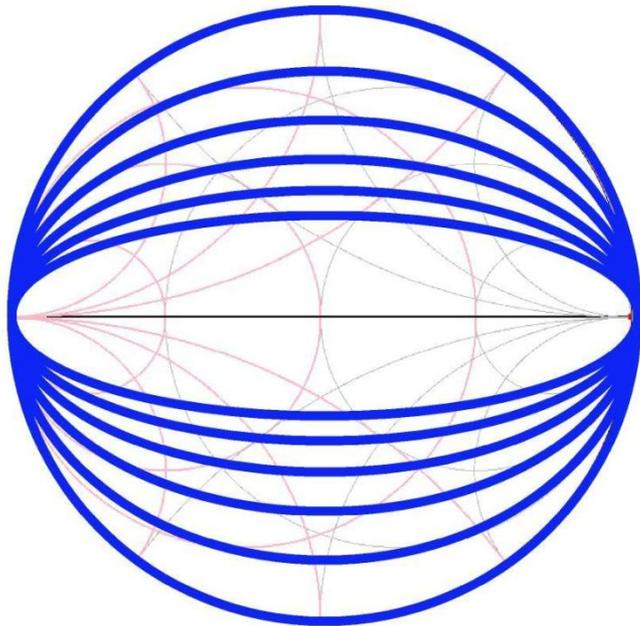
Example



Constant Q circles

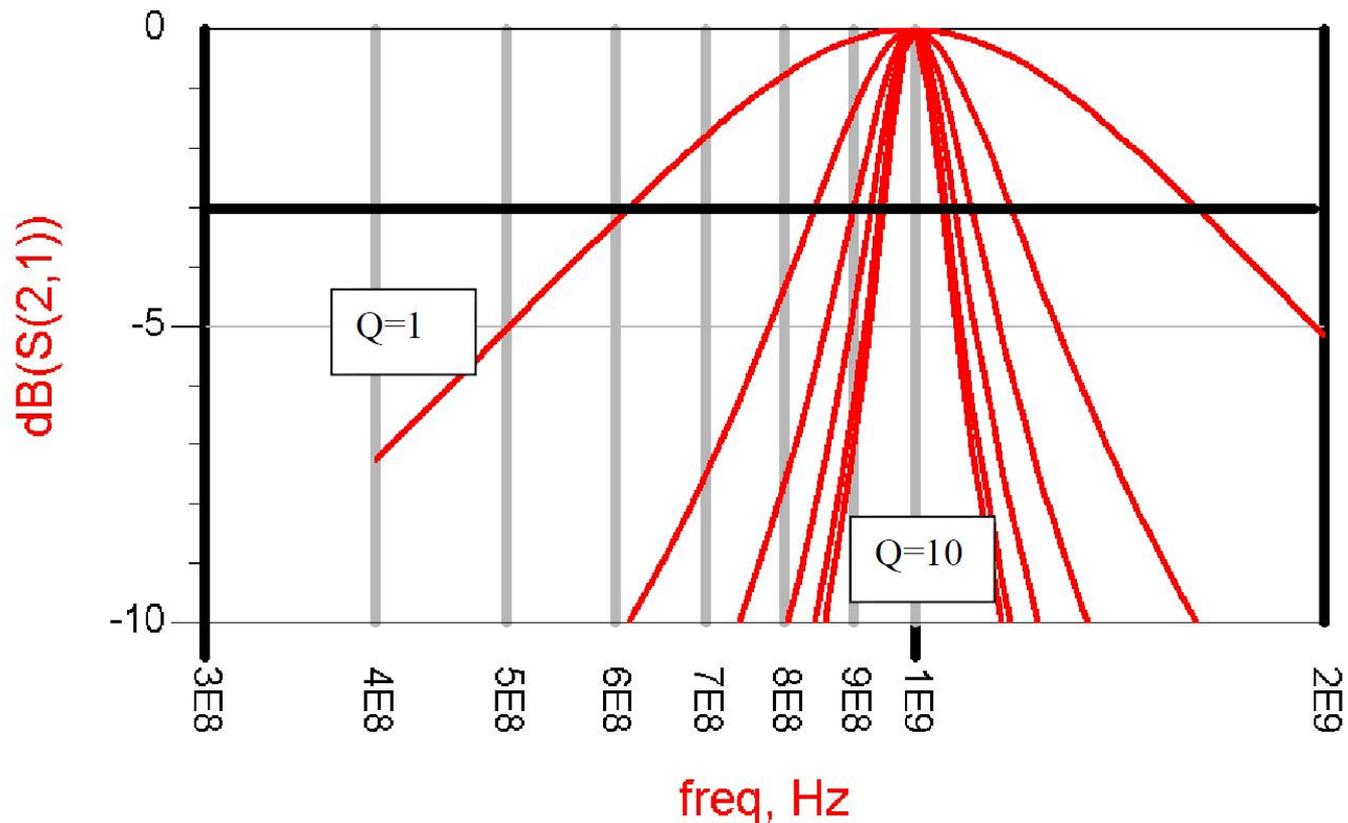
- Quality factor Q

$$Q = \frac{X}{R} = \frac{G}{B} = \text{const}$$

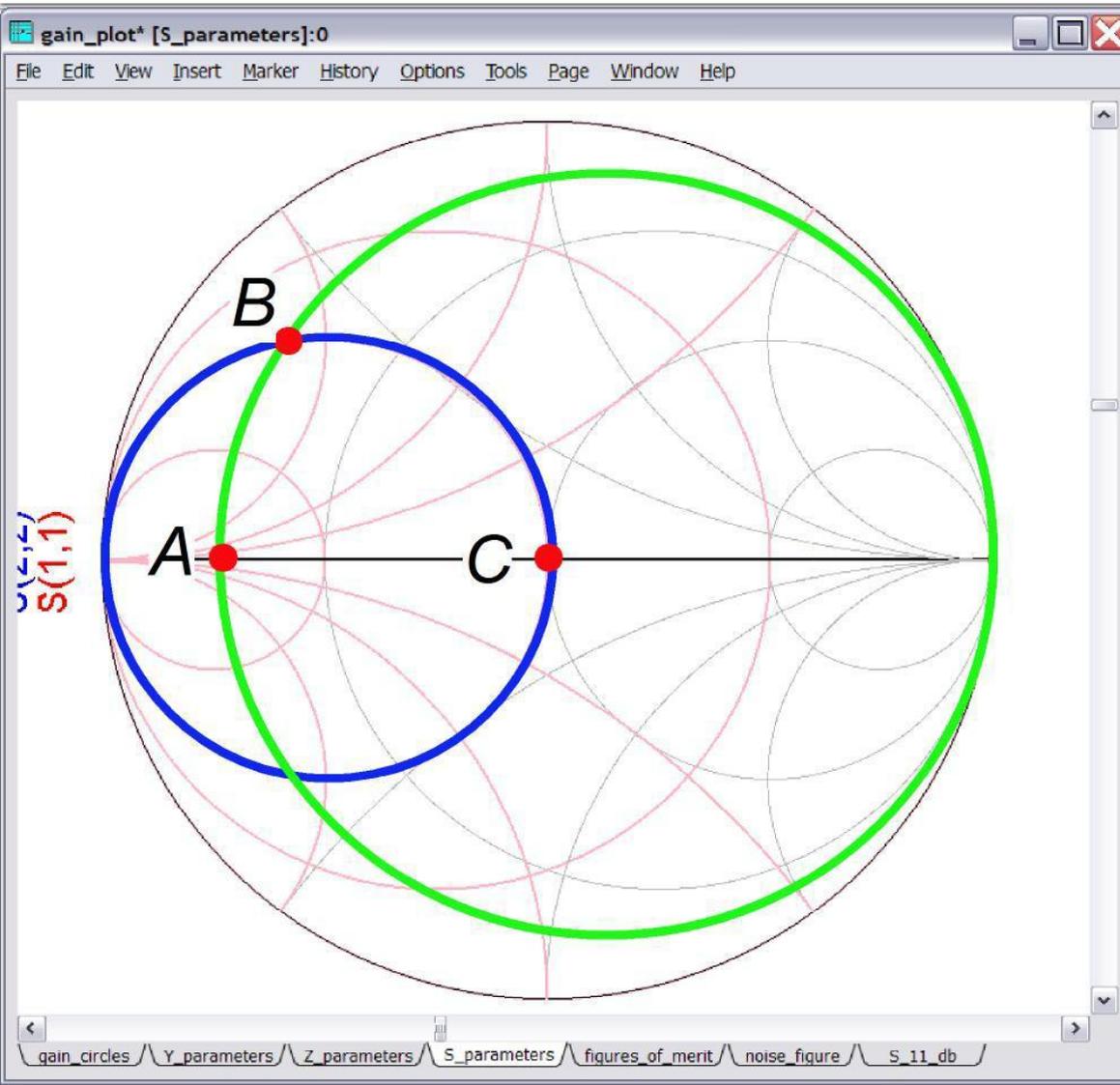


Quality factor - bandwidth

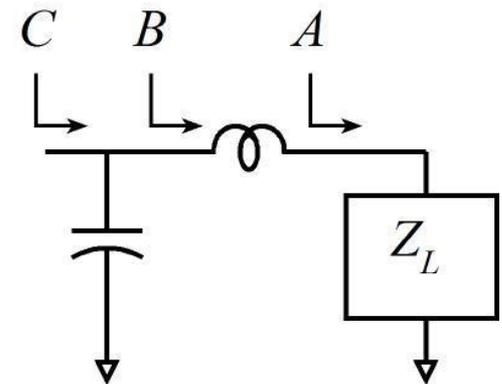
- High quality factor is equivalent with narrow bandwidth



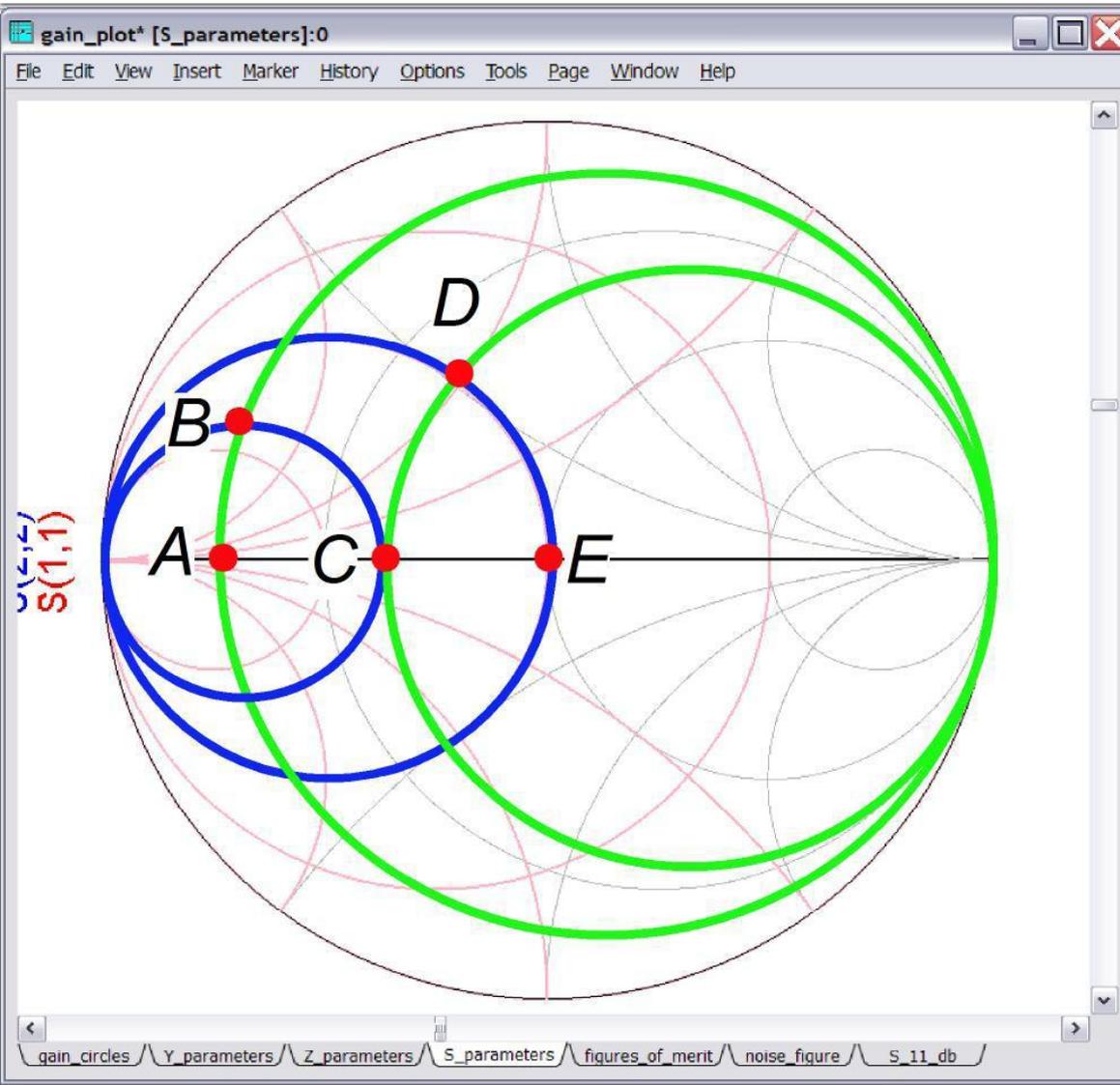
Match bandwidth



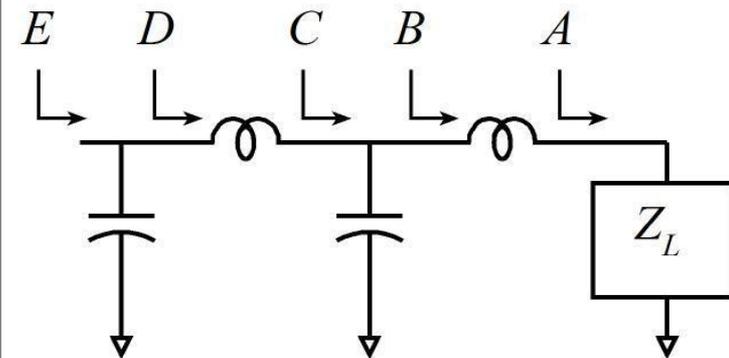
- The position with highest Q for intermediate reflection coefficients (B) imposes the match bandwidth



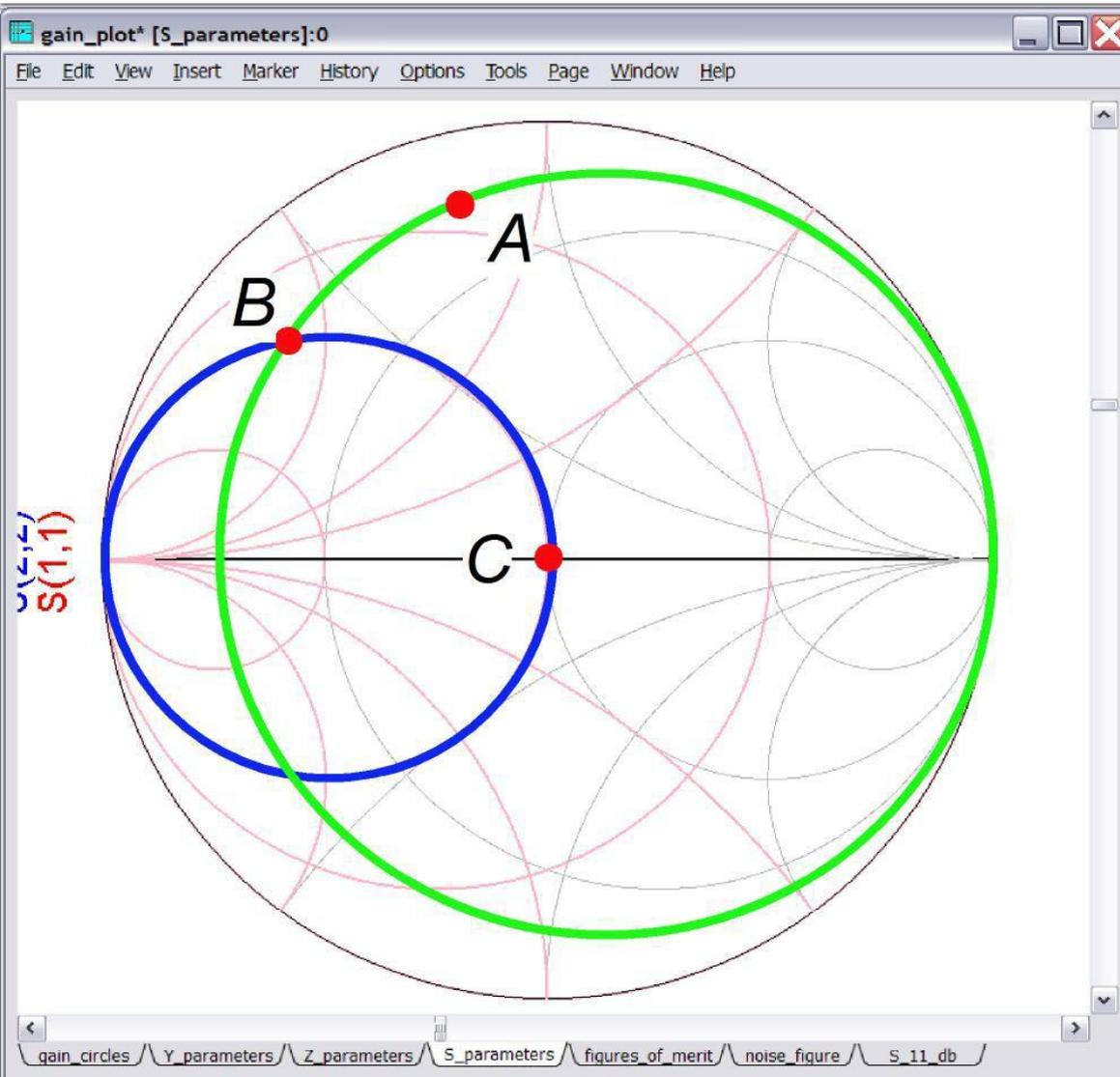
Match bandwidth



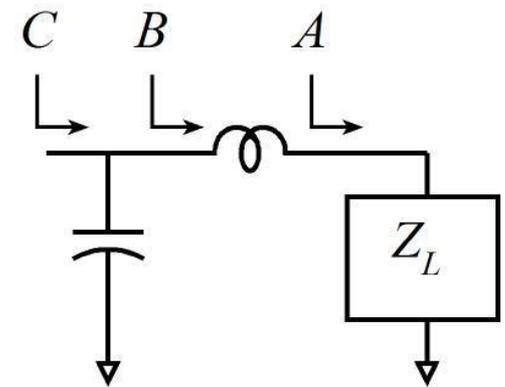
- Wider matching bandwidth can be obtained with multiple, smaller steps, insuring that all intermediate reflection coefficients (B, D) correspond to smaller Q



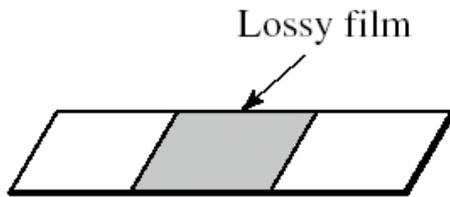
Match bandwidth



- For high Q starting reflection coefficients (A) narrow bandwidth match is unavoidable



Practical realization of lumped elements for microwave frequencies

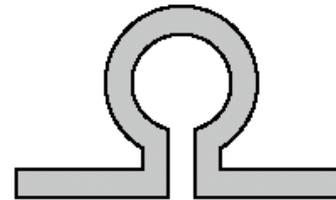


Planar resistor

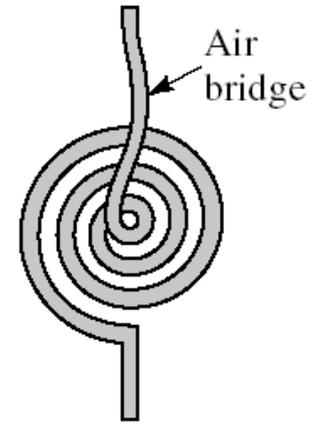
Lossy film



Chip resistor



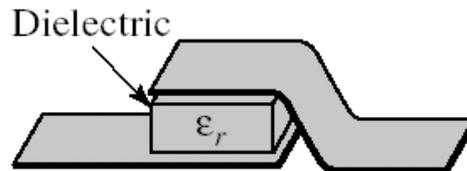
Loop inductor



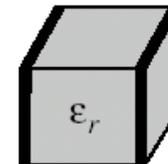
Spiral inductor



Interdigital gap capacitor



Metal-insulator-metal capacitor



Chip capacitor

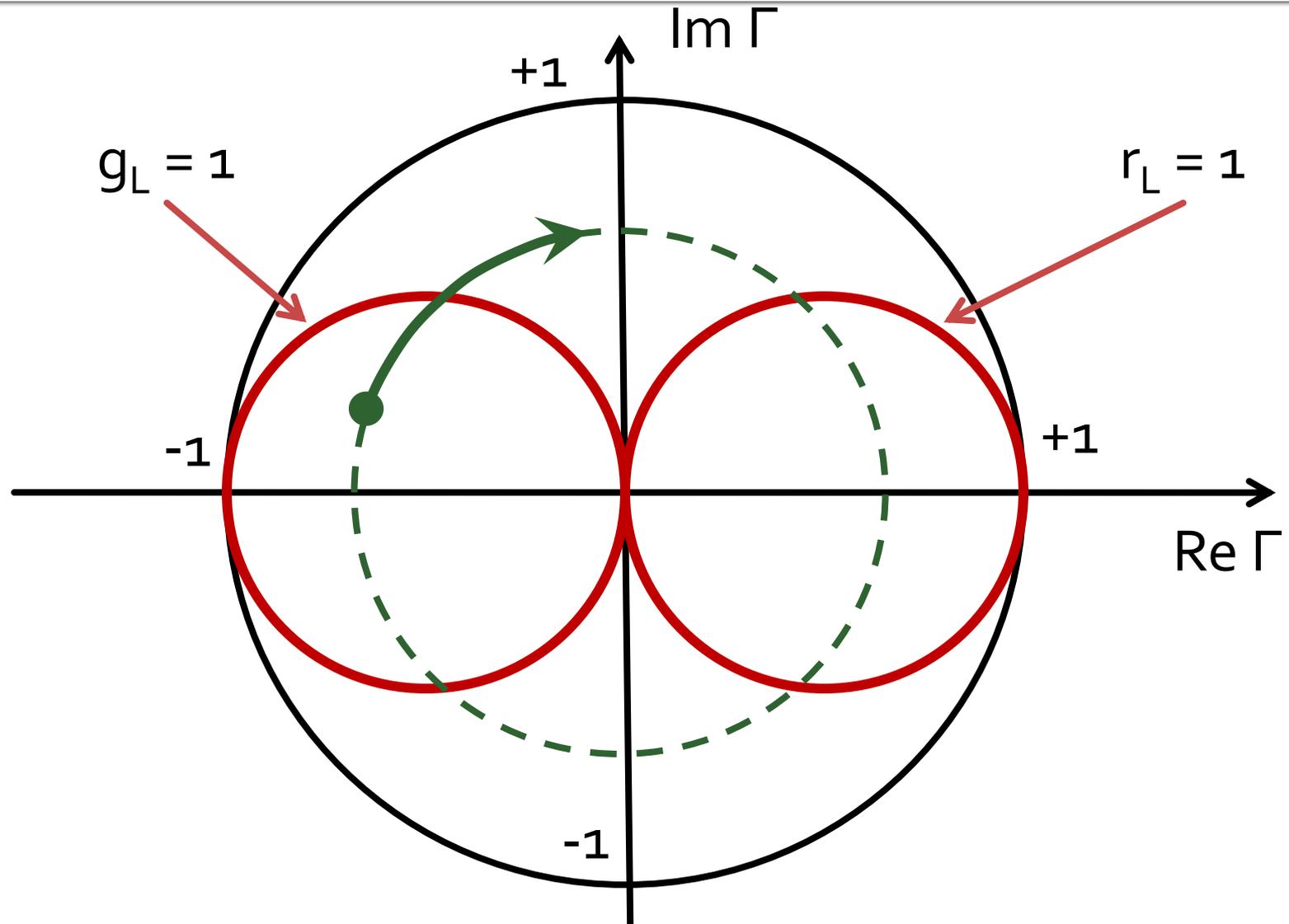
Impedance Matching

Impedance Matching with Stubs

Stub

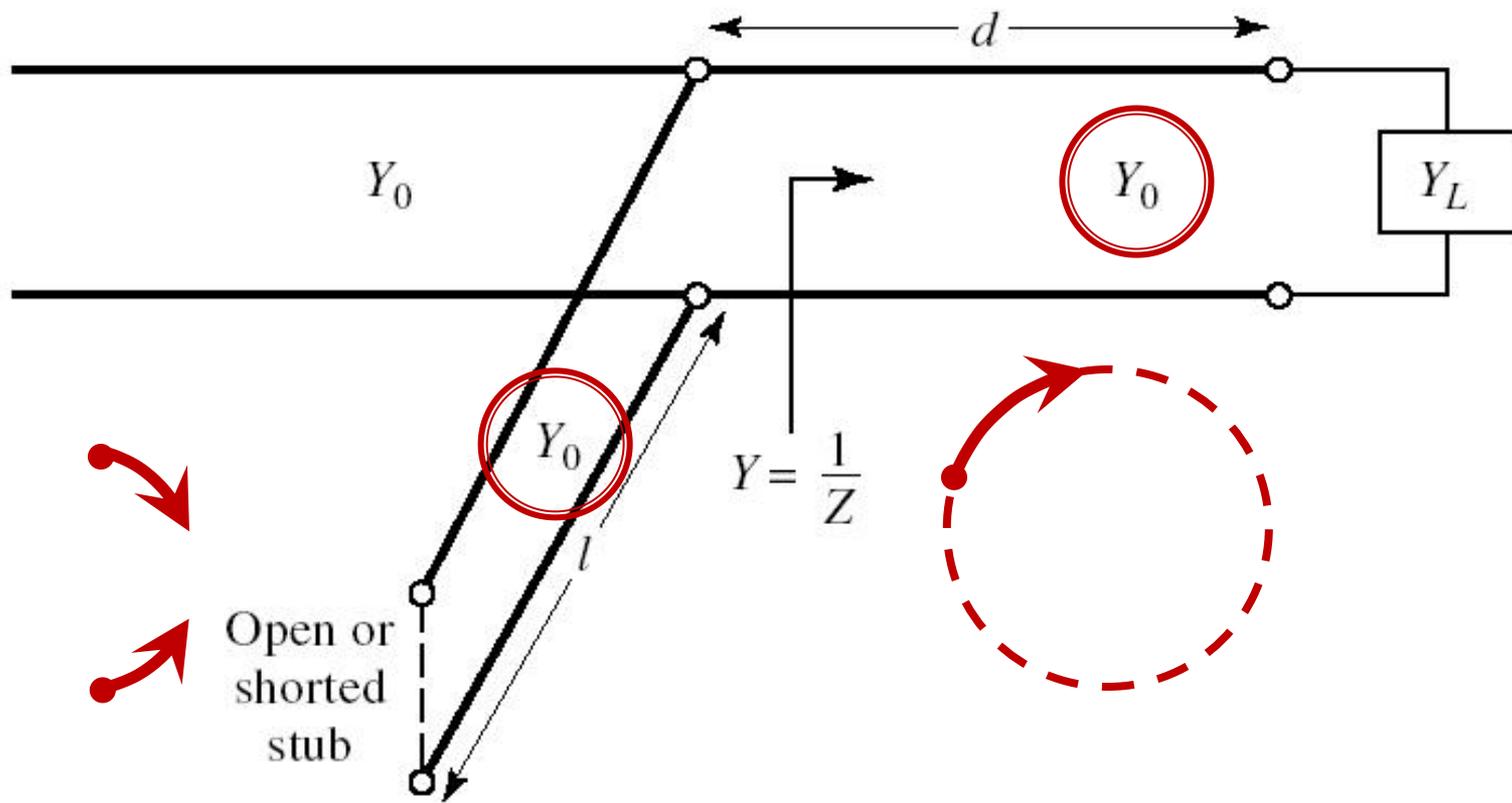
- **Stub** (en) = "rest, ciot, cotor, capăt" (ro)
- We avoid the necessity to use lumped elements
- Matching is achieved (with higher accuracy) using usual Z_0 transmission lines of the circuit
- We use one or more lengths of transmission line (stub) connected either in parallel or in series with the transmission feed line :
 - open-circuited
 - short-circuited
- Usually open-circuited transmission lines are easier to implement and are preferred

Smith chart, $r=1$ and $g=1$



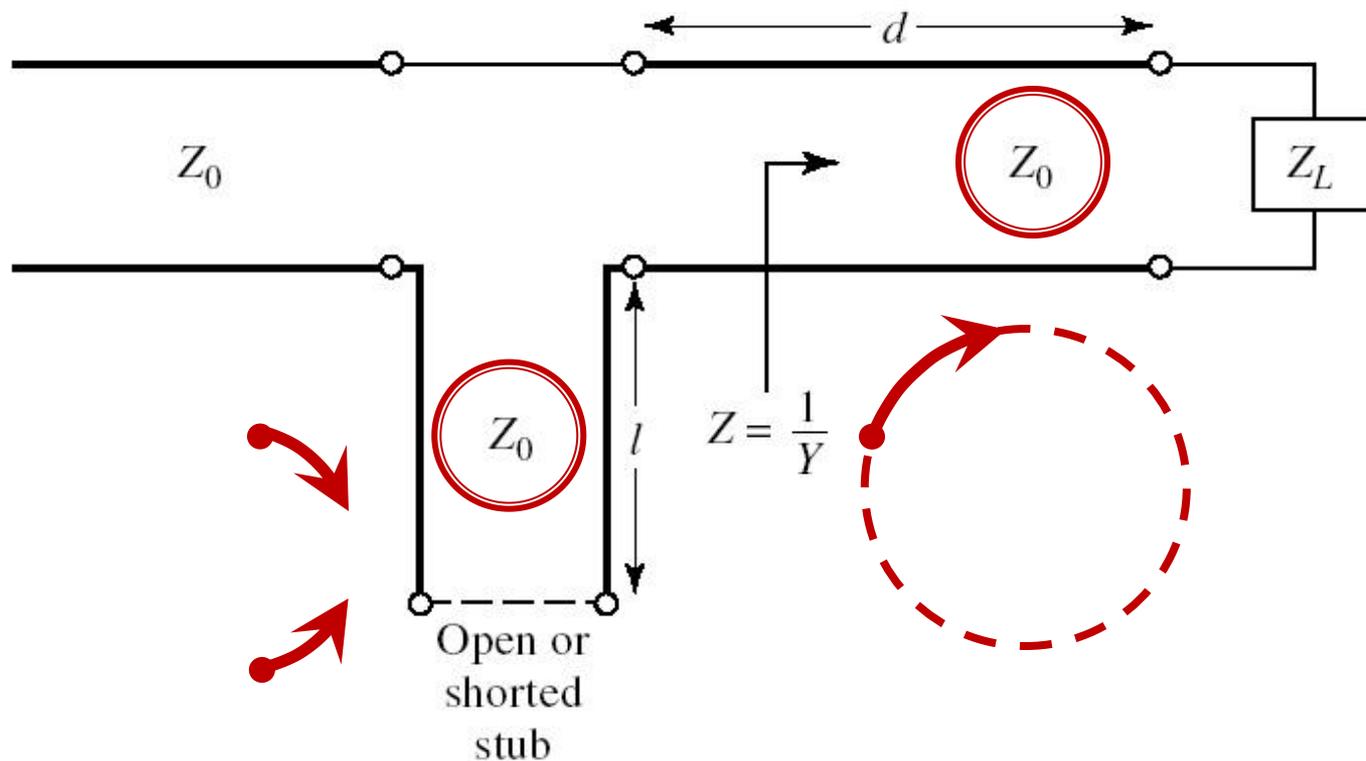
Single stub tuning

- Shunt Stub



Single stub tuning

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



Shunt Stub

Sectiune de linie paralel

Case 1, Shunt Stub

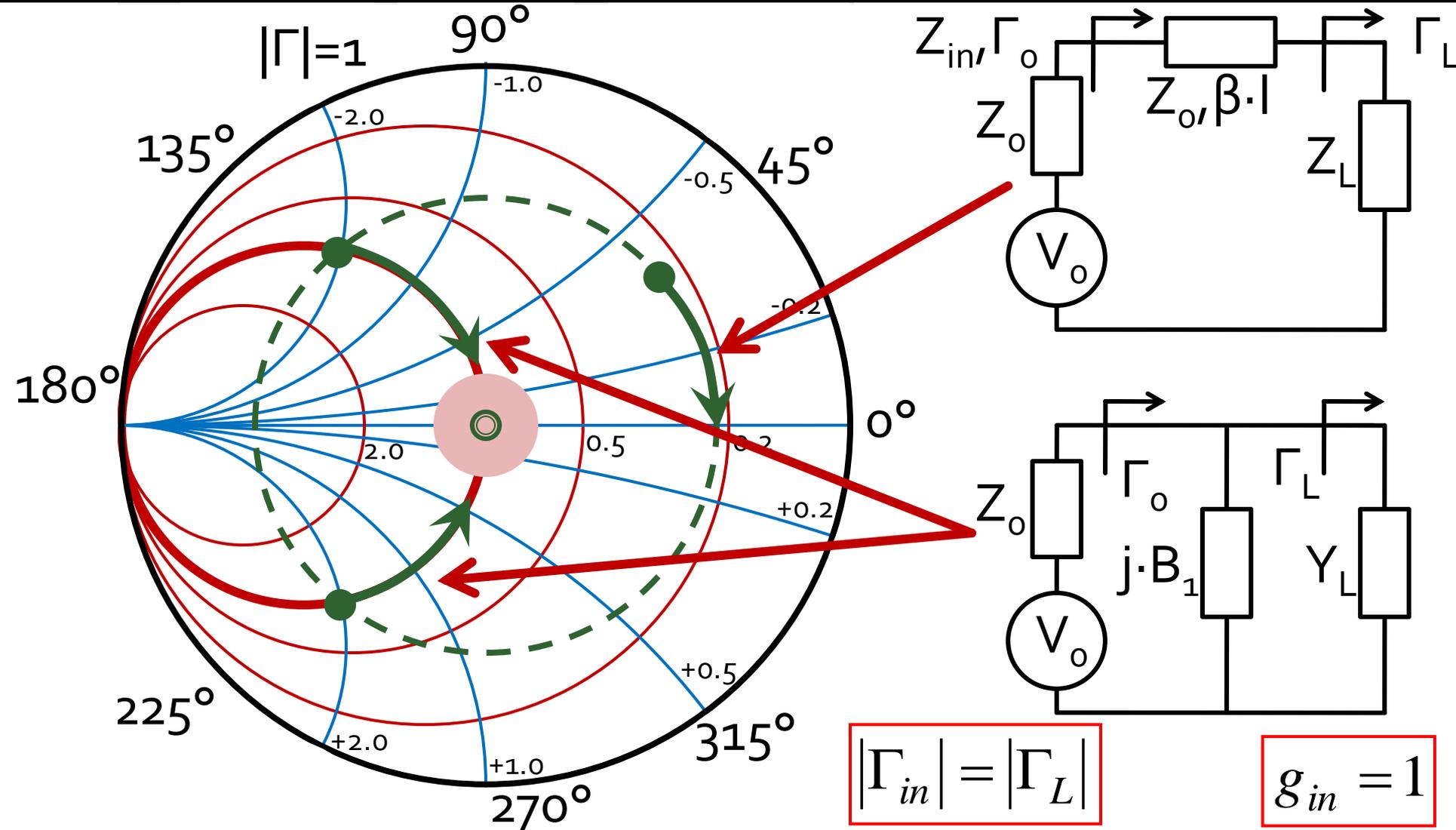
- We use a series transmission line to move the reflection coefficient **on the circle** $g_L = 1$
- We compensate the remaining reactive part of the load with a shunt reactance to achieve match
- The shunt reactance is made with a stub which can be,
as needed:
 - open-circuited
 - short-circuited

$$Z_{in} = Z_0 \cdot \frac{Z_L + j \cdot Z_0 \cdot \tan \beta \cdot l}{Z_0 + j \cdot Z_L \cdot \tan \beta \cdot l}$$

$$Z_{in,sc} = j \cdot Z_0 \cdot \tan \beta \cdot l$$

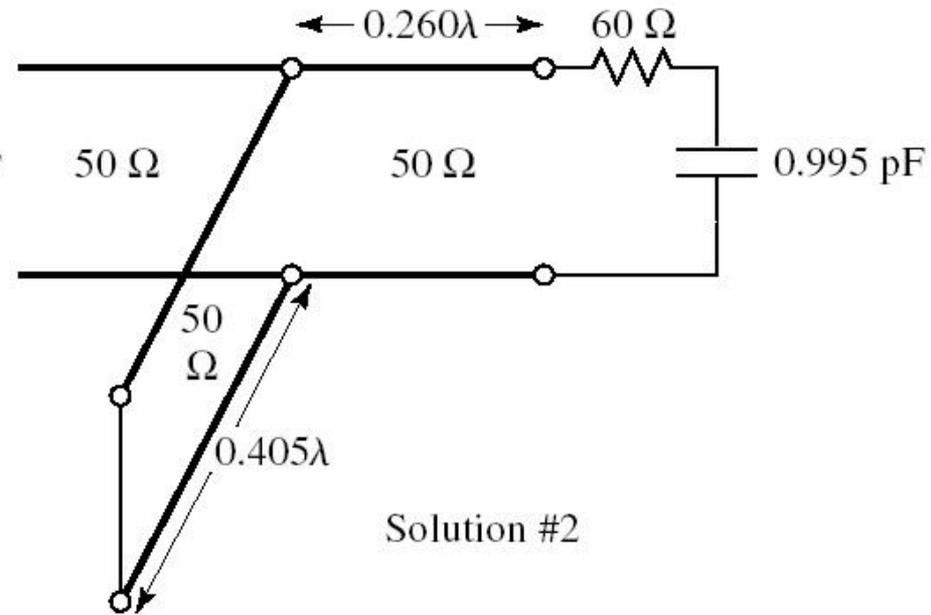
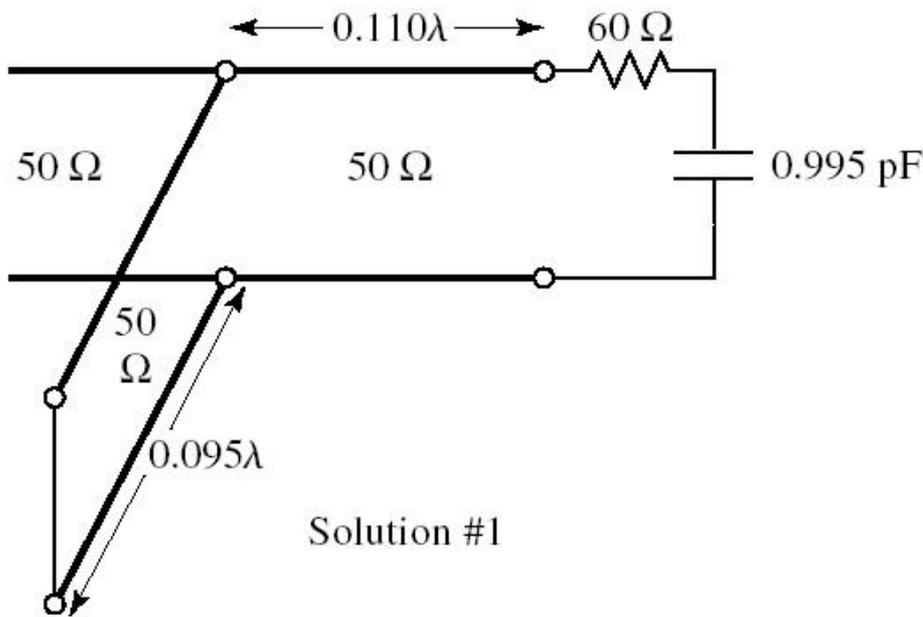
$$Z_{in,oc} = -j \cdot Z_0 \cdot \cot \beta \cdot l$$

Matching, series line + shunt susceptance

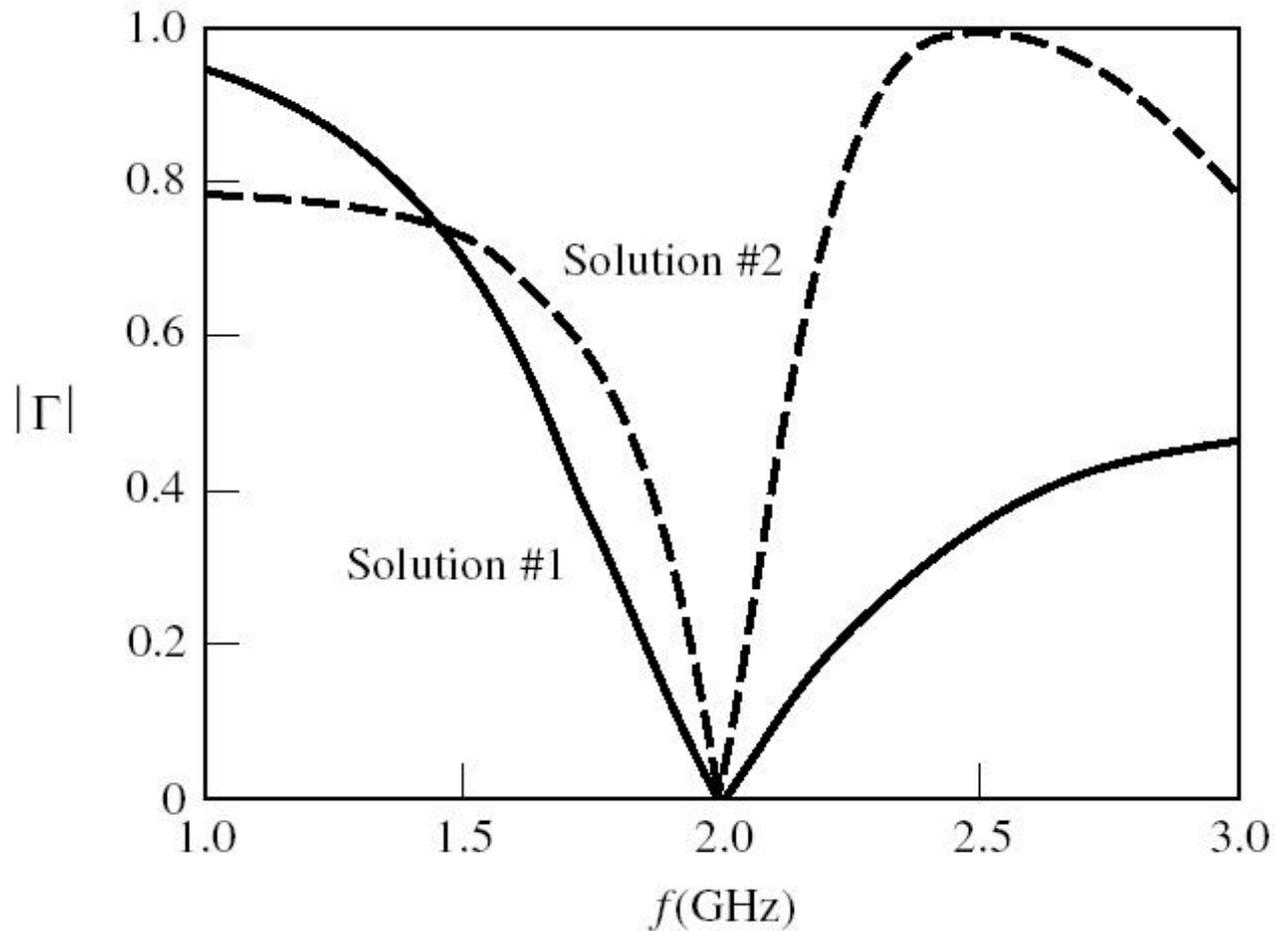


Example, Shunt Stub, sc.

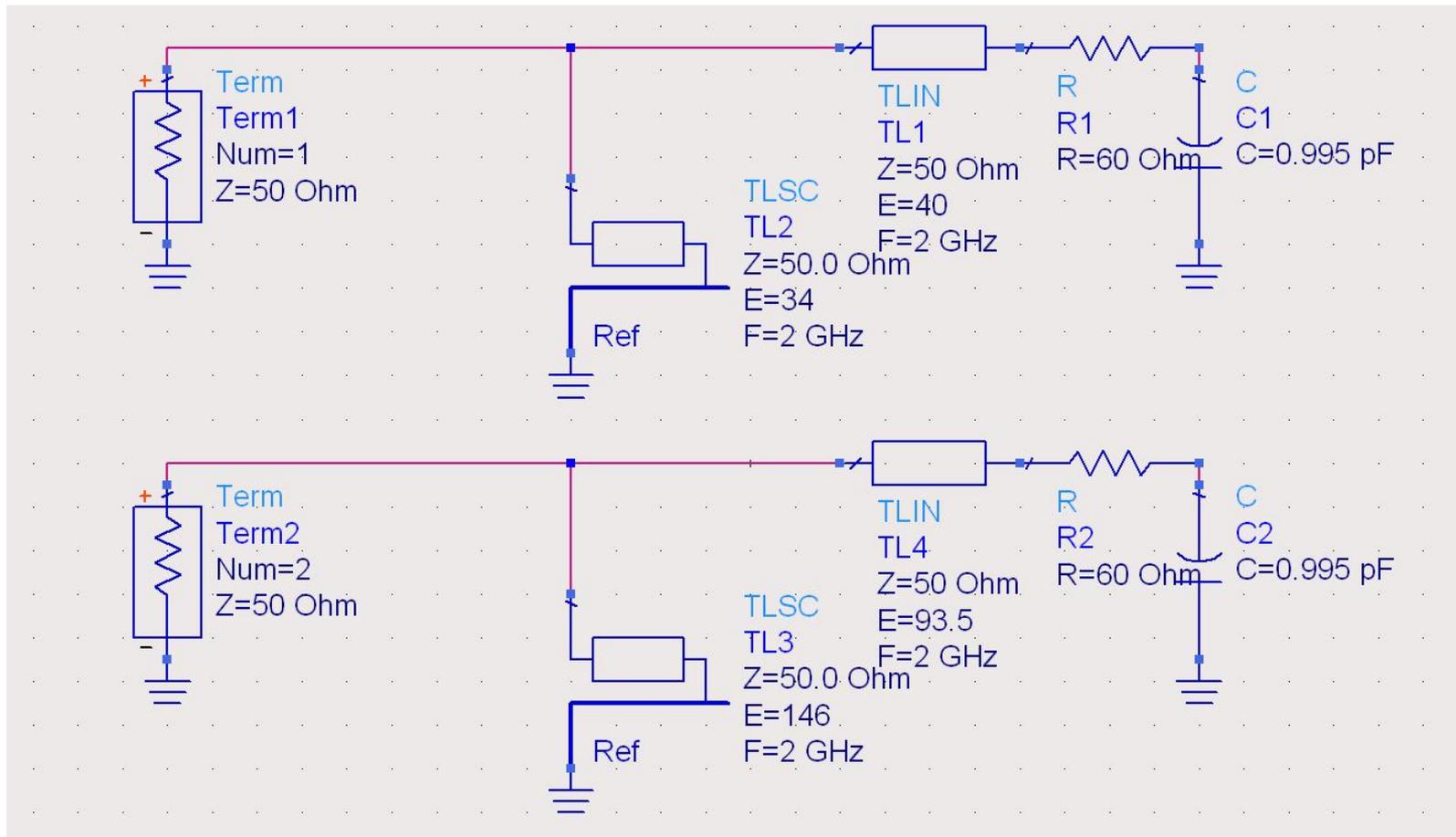
- load: $60\ \Omega$ series with $0.995\ \text{pF}$ at $2\ \text{GHz}$
- two possible solutions



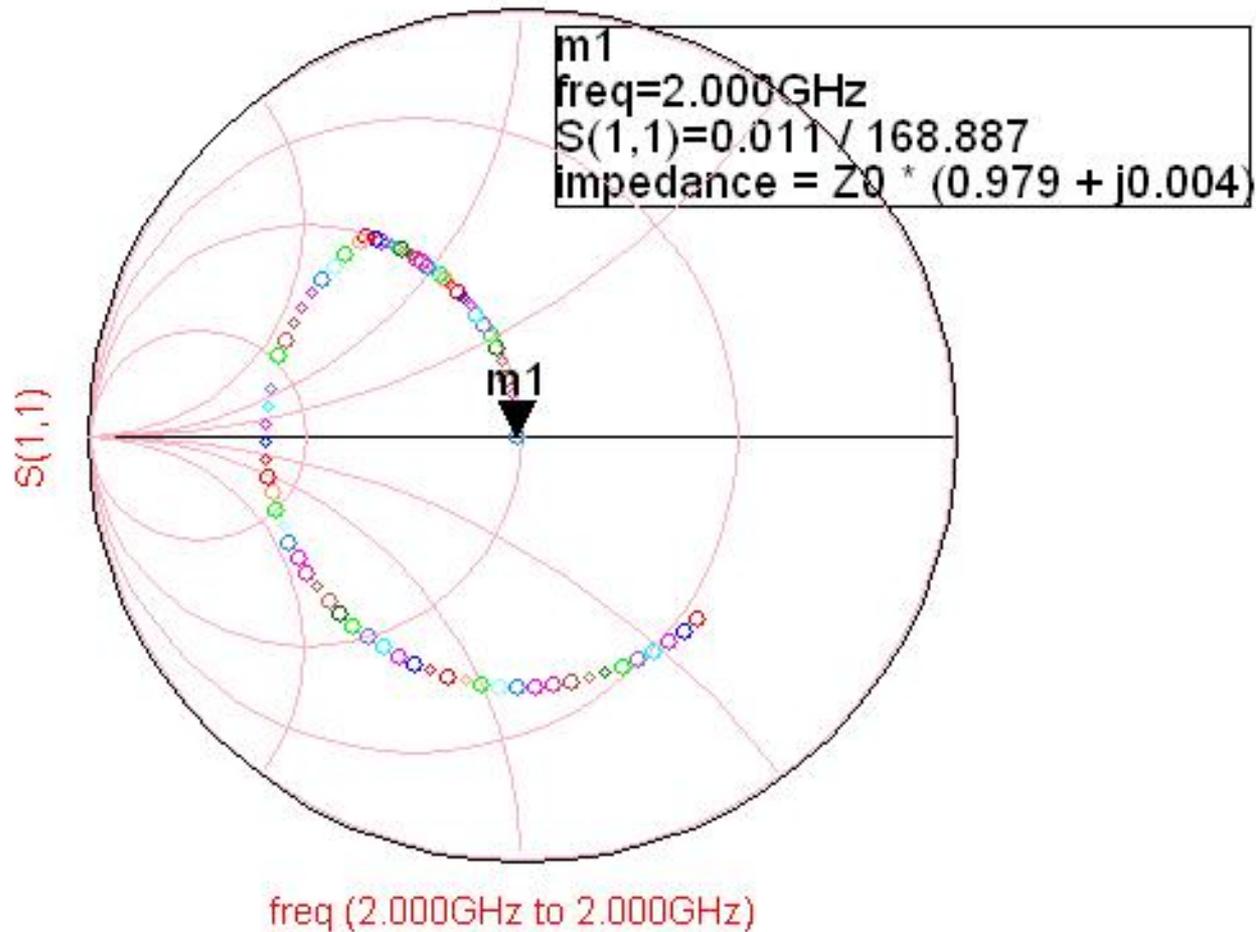
Example, Shunt Stub, sc.



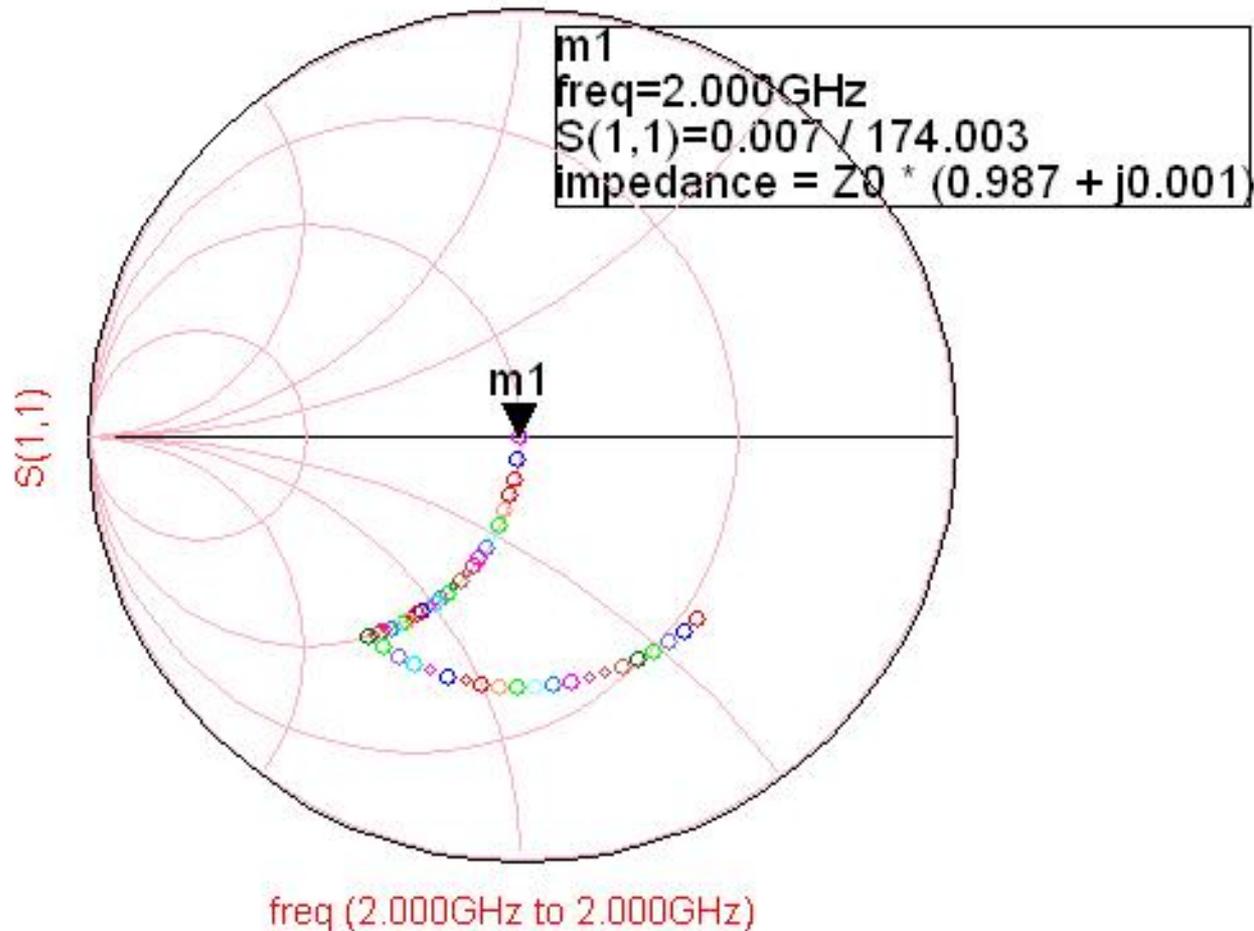
Example, Shunt Stub, sc.



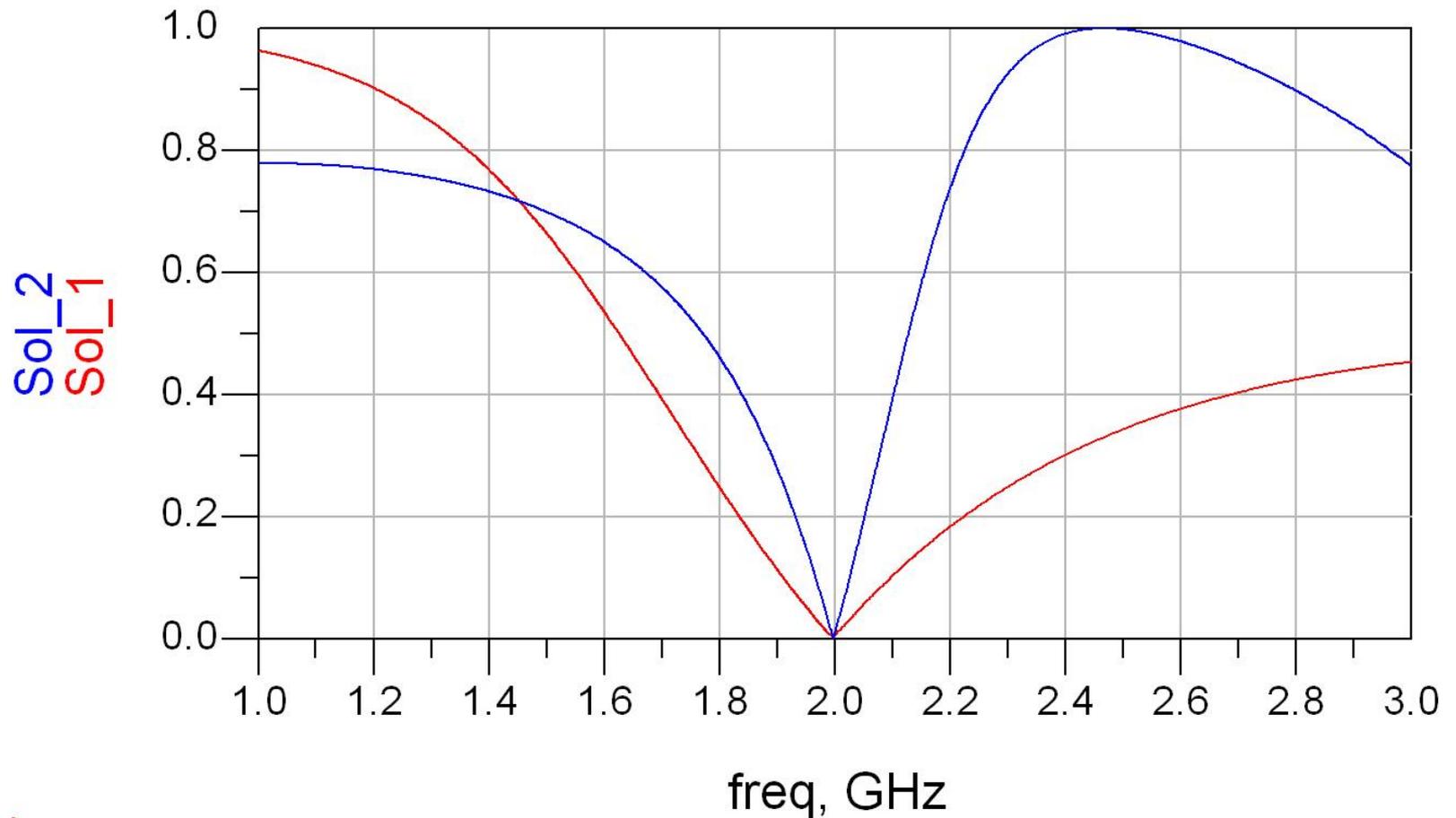
Example, Shunt Stub, sc.



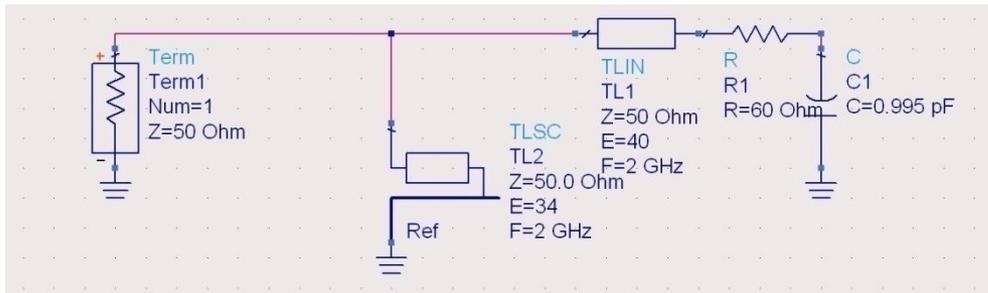
Example, Shunt Stub, sc.



Example, Shunt Stub, sc.



Example, Shunt Stub, sc.

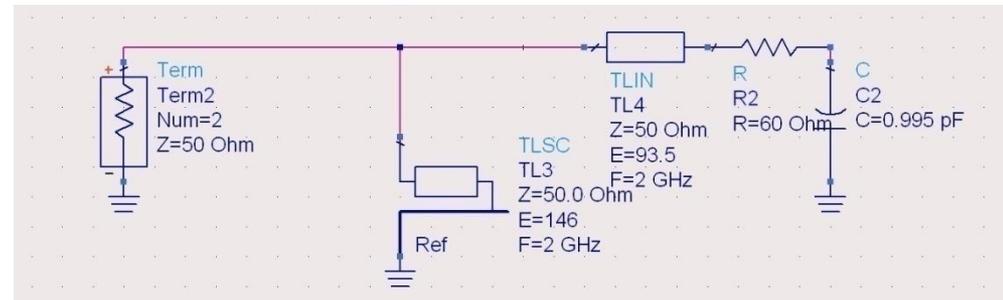


$$l_1 = \frac{40^\circ}{360^\circ} \cdot \lambda = 0.111 \cdot \lambda$$

$$l_2 = \frac{34^\circ}{360^\circ} \cdot \lambda = 0.094 \cdot \lambda$$

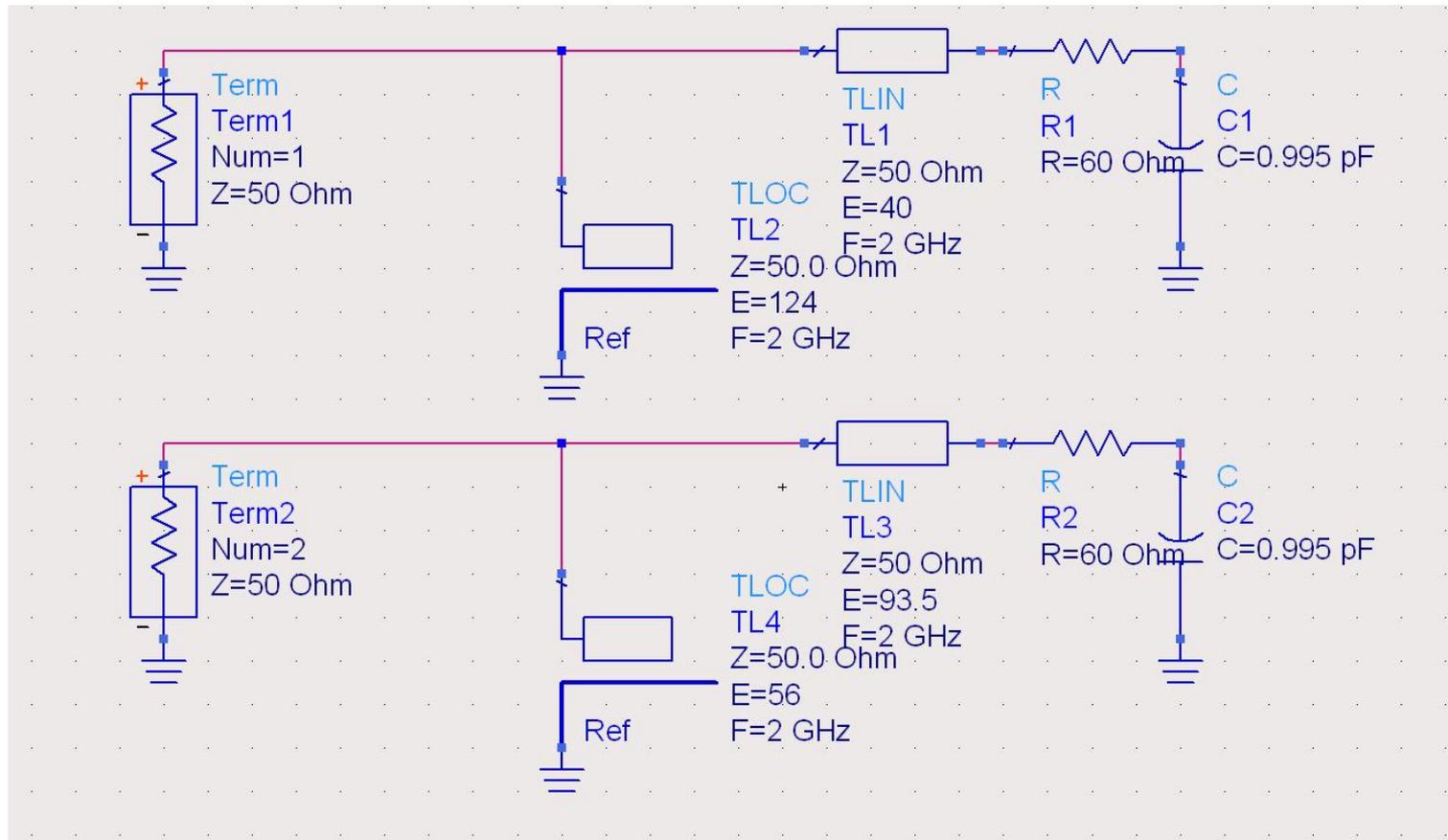
$$l_1 = \frac{93.5^\circ}{360^\circ} \cdot \lambda = 0.260 \cdot \lambda$$

$$l_2 = \frac{146^\circ}{360^\circ} \cdot \lambda = 0.406 \cdot \lambda$$

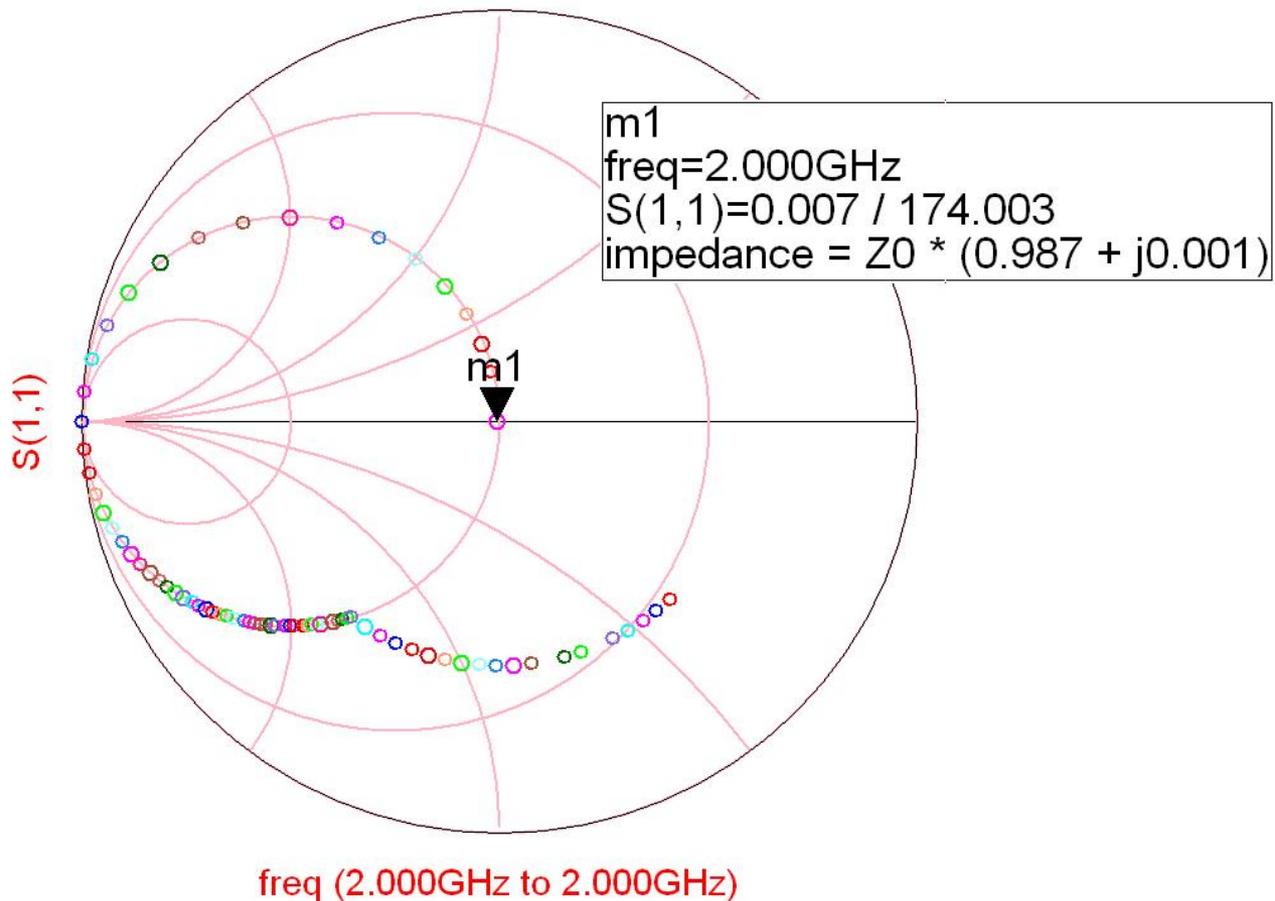


Example, Shunt Stub, oc.

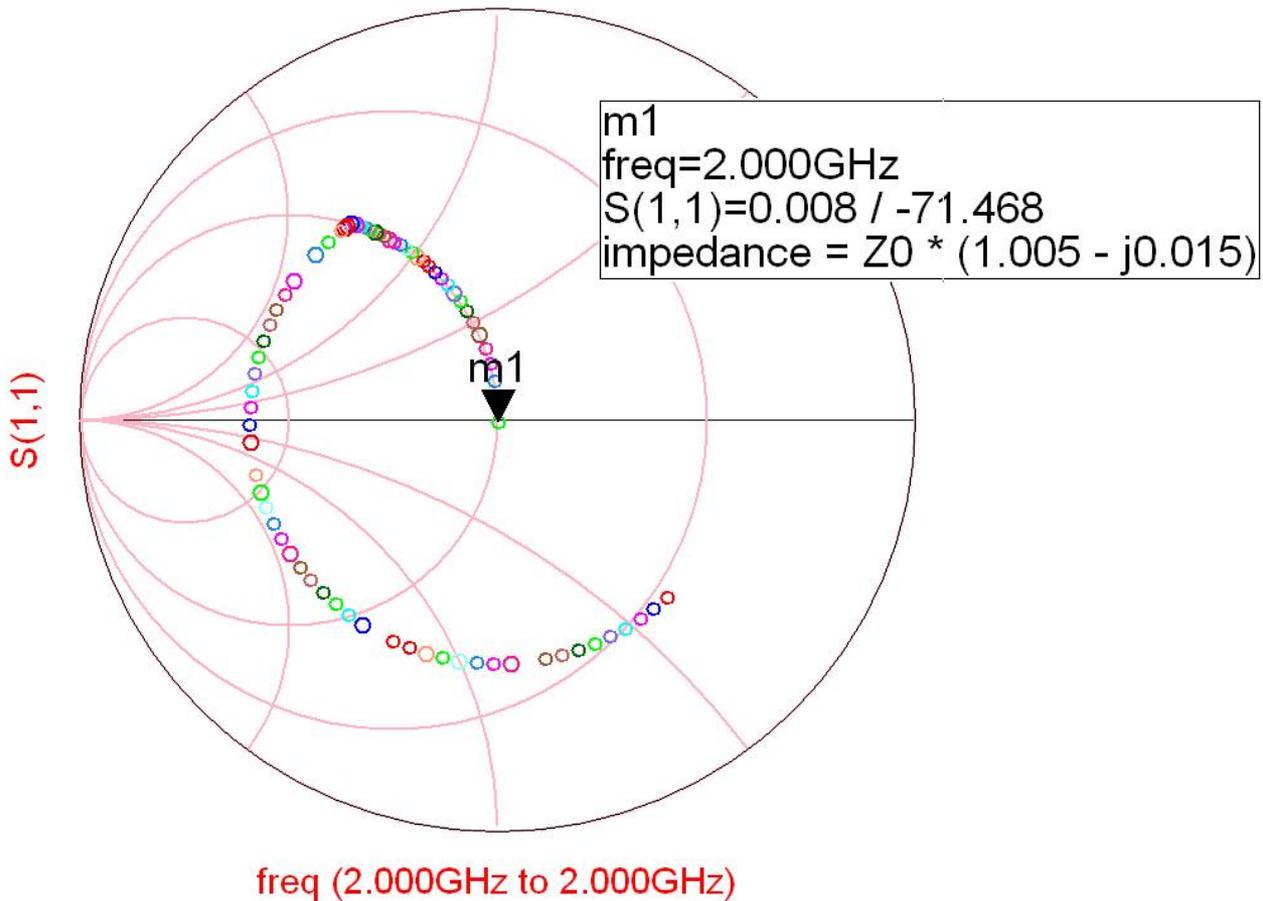
- load: $60\ \Omega$ series with $0.995\ \text{pF}$ at $2\ \text{GHz}$
- two possible solutions



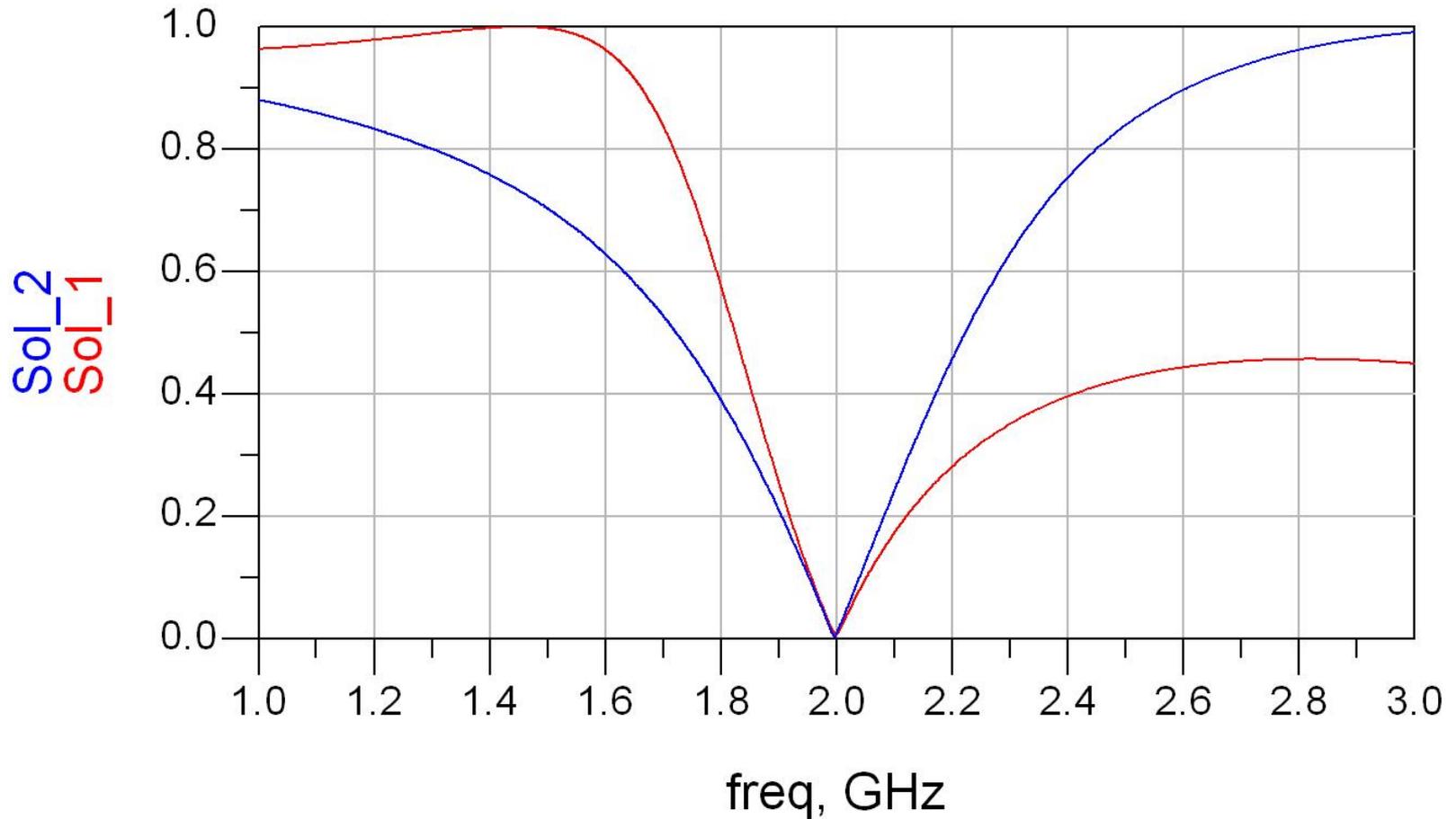
Example, Shunt Stub, oc.



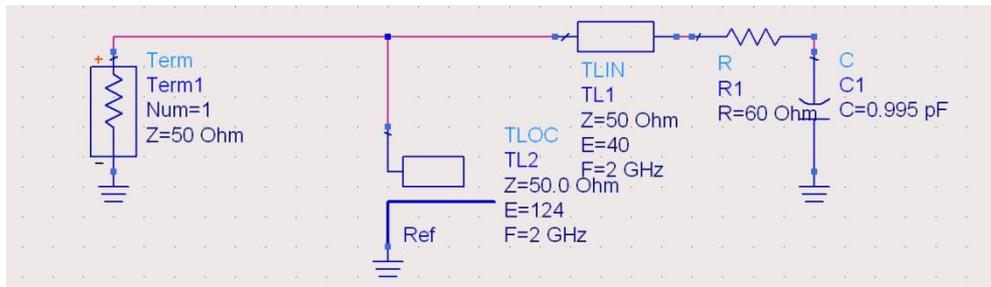
Example, Shunt Stub, oc.



Example, Shunt Stub, oc.



Example, Shunt Stub, oc.

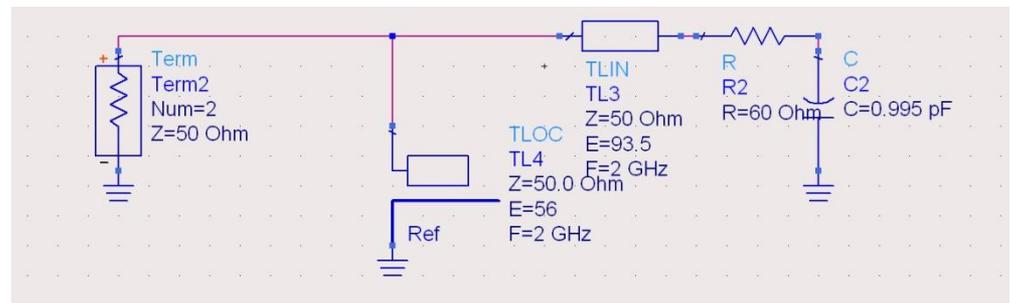


$$l_1 = \frac{40^\circ}{360^\circ} \cdot \lambda = 0.111 \cdot \lambda$$



$$l_2 = \frac{124^\circ}{360^\circ} \cdot \lambda = 0.344 \cdot \lambda = 0.094 \cdot \lambda + \frac{\lambda}{4}$$

$$l_1 = \frac{93.5^\circ}{360^\circ} \cdot \lambda = 0.260 \cdot \lambda$$



$$l_2 = \frac{56^\circ}{360^\circ} \cdot \lambda = 0.156 \cdot \lambda = 0.406 \cdot \lambda - \frac{\lambda}{4}$$



Shunt Stub, some notes

- mathematical functions which offer the input impedance in a stub are periodic functions of l , tan/cot based functions

$$Z_{in,sc} = j \cdot Z_0 \cdot \tan \beta \cdot l$$

$$Z_{in,oc} = -j \cdot Z_0 \cdot \cot \beta \cdot l$$

- adding or subtracting

$$E = \beta \cdot l = \pi = 180^\circ \quad l = k \cdot \frac{\lambda}{2}, \forall k \in \mathbf{N}$$

doesn't change the result (full rotation around the Smith Chart – hence the 0.5λ gradation of the circumference of the diagram)

Shunt Stub, some notes

- adding or subtracting $\lambda/4$ transforms the impedance:

$$Z_{in,sc} = j \cdot Z_0 \cdot \tan \beta \cdot l$$

$$Z_{in,oc} = -j \cdot Z_0 \cdot \cot \beta \cdot l$$

$$\tan \beta \cdot \left(l + \frac{\lambda}{4} \right) = \tan \left(\beta \cdot l + \frac{\pi}{2} \right) = \frac{\sin(\beta \cdot l + \pi/2)}{\cos(\beta \cdot l + \pi/2)} = \frac{\cos \beta \cdot l}{-\sin \beta \cdot l} = -\cot \beta \cdot l$$

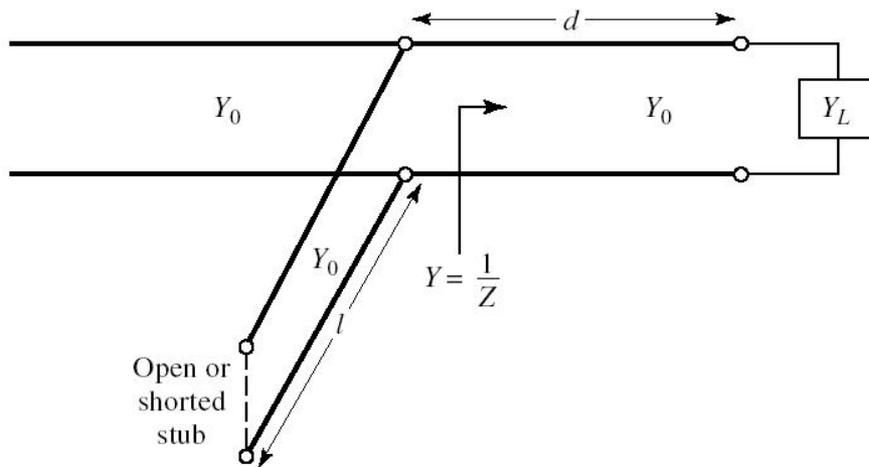
from the open-circuited value to the short-circuited one and vice versa

- For tuning in ADS it's better to start from the neutral point (value of the electrical length of the line which doesn't influence the circuit)
 - series line: $E = \beta \cdot l = 0$
 - shunt stub: $Z_{in} \rightarrow \infty, \tan \beta \cdot l / \cot \beta \cdot l \rightarrow \infty, E = 90^\circ / 0^\circ$

Analytical solution

Shunt Stub

Analytical solution, impedances



$$Z_L = \frac{1}{Y_L} = R_L + j \cdot X_L$$

$$Z = Z_0 \cdot \frac{(R_L + j \cdot X_L) + j \cdot Z_0 \cdot t}{Z_0 + j \cdot (R_L + j \cdot X_L) \cdot t}$$

$$\overset{\text{not}}{t} = \tan \beta \cdot d \quad Y = G + j \cdot B = \frac{1}{Z}$$

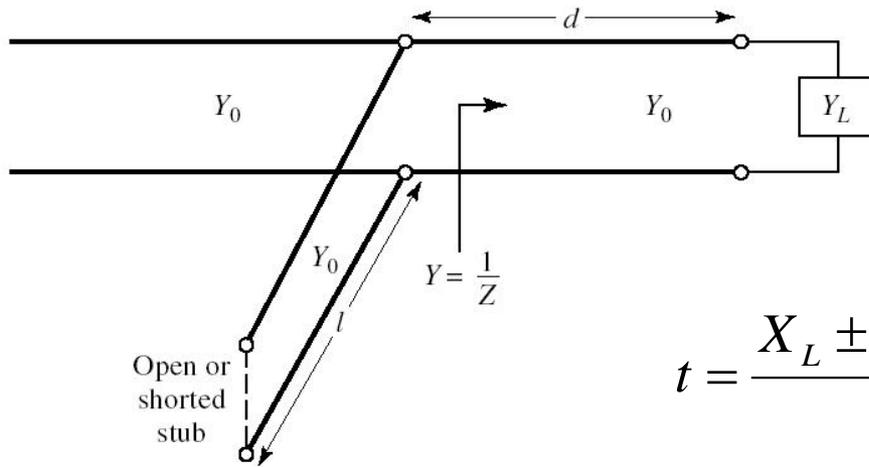
$$G = \frac{R_L \cdot (1 + t^2)}{R_L^2 + (X_L + Z_0 \cdot t)^2}$$

$$B = \frac{R_L^2 \cdot t - (Z_0 - X_L \cdot t) \cdot (X_L + Z_0 \cdot t)}{Z_0 \cdot [R_L^2 + (X_L + Z_0 \cdot t)^2]}$$

- d (which implies t) is chosen so that: $G = Y_0 = \frac{1}{Z_0}$

$$Z_0 \cdot (R_L - Z_0) \cdot t^2 - 2 \cdot X_L \cdot Z_0 \cdot t + (R_L \cdot Z_0 - R_L^2 - X_L^2) = 0$$

Analytical solution



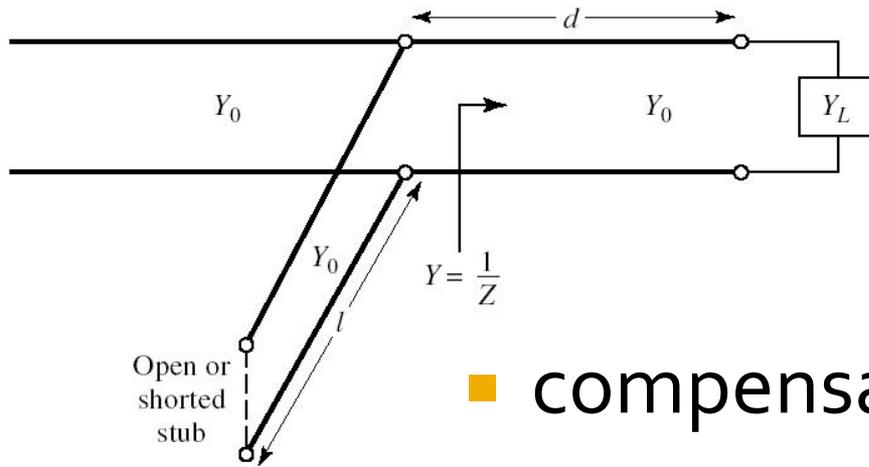
$$t = -\frac{X_L}{2 \cdot Z_0}, \quad R_L = Z_0$$

$$t = \frac{X_L \pm \sqrt{R_L \cdot [(Z_0 - R_L)^2 + X_L^2]} / Z_0}{R_L - Z_0} \quad R_L \neq Z_0$$

- second grade equation, 2 solutions possible
- d computed from t

$$\frac{d}{\lambda} = \begin{cases} \frac{1}{2\pi} \cdot \arctan t & t \geq 0 \\ \frac{1}{2\pi} \cdot (\pi + \arctan t) & t < 0 \end{cases}$$

Analytical solution



$$B_S = -B$$

$$B = \frac{R_L^2 \cdot t - (Z_0 - X_L \cdot t) \cdot (X_L + Z_0 \cdot t)}{Z_0 \cdot [R_L^2 + (X_L + Z_0 \cdot t)^2]}$$

- compensating susceptance is:

$$\frac{l_{oc}}{\lambda} = \frac{1}{2\pi} \cdot \arctan\left(\frac{B_S}{Y_0}\right) = \frac{-1}{2\pi} \cdot \arctan\left(\frac{B}{Y_0}\right)$$

$$\frac{l_{sc}}{\lambda} = \frac{-1}{2\pi} \cdot \arctan\left(\frac{Y_0}{B_S}\right) = \frac{1}{2\pi} \cdot \arctan\left(\frac{Y_0}{B}\right)$$

- for **negative lengths** we add $\lambda/2$

Contact

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