Chapter 4&5: Passive and Active Microwave Devices and Networks

Outline

- **Basic principles of passive and active microwave devices**
- **Types of passive and active microwave devices**
- **Matching network design**

Passive Devices

- Maxwell's equations govern all types of electromagnetic behavior at all frequencies.
- At lower frequencies (below about 500 MHz) where lumped components are less than $\lambda/8$ in length, it is convenient to define the component as a frequency-independent R, L,or C.
- As the frequency increases, the component will have distributed effects or added phase shift which must be accounted for in the analysis.
- As electrical engineers, we first learn to analyze lumped-element circuits consisting of R, L, and C components, which are independent of frequency; the impedance or admittance of the components is linearly dependent on frequency.
- Then we learn that at high frequencies additional parasitic effects must be included in the model of the component.

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- For lumped components at low frequencies signals travel at essentially the speed of light instantaneously through points in space where the component is located.
- At microwaves (defined as 300 MHz to 30 GHz, with above 30 GHz also called **millimeter wave),** the electrical component used to generate and process signals has a size similar to an eighth of a wavelength.
- Then we must back up to Maxwell’s equations subject to the appropriate boundary conditions.

Chip Resistor Versus Size and Typical Parasitic *C* and *L*

Resistor Size	Length (mm)	Width (mm)	Capacitance (pF)	Inductance (nH)
1206	3.2	1.6	0.05	2
0805	2.0	1.25	0.09	1
0603	1.6	0.8	0.05	0.4
0402	0.5	0.5		

Active Devices

- The majority of microwave circuits use active devices one way or another.
- While some applications operate the devices in a linear range, many applications need to understand the behavior under large-signal conditions.
- Typical examples for large signal operations are mixer and oscillator circuits as well as power amplifiers.

- The basic nonlinearities are frequency independent, and yet because the nonlinear capacitance of the device starts playing a major role at higher frequencies, their effect has to be considered.

- ✓ This chapter will provide some high-frequency insight into the commonly used **microwave active devices** and prepare the reader for large-signal considerations.
- ✓ This chapter begins with a detailed discussion of diode nonlinear performance, including: the pn junction, the Schottky diode, the pin diode, and the varactor diode (variable reactance).
- ✓ The basic nonlinearities are the capacitance and the forward bias current.
- ✓ Next the many forms of three-terminal transistors will be covered:

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- **BJT** A current controlled transistor which is a minority carrier device in the base region; this a bipolar device because there are **two junctions**, the **emitter–base junction**, which is forward biased to inject the minority carriers into the **base**, and the **collector–base junction**, which is reverse biased to collect all of the base minority carriers into the **collector.**
- **MOSFET** Modern metal–oxide–semiconductor field-effect transistors (MOSFETs) have become important at frequencies below 2.5 GHz.
- ✓ The nonlinear models come from SPICE developments, including bipolar CMOS nonlinear (Bi-CMOS) models among others.
- ✓ Bi-CMOS implies that BJTs, n-channel MOSFETs, and p-channel MOSFETs are on the same silicon chip.

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- **MESFET:** This transistor came about in 1965 with the development of Schottky diodes and ohmic contacts simultaneously on GaAs.
- ✓ It is a majority-carrier device which is voltage controlled at the gate. The name means metal–semiconductor field-effect transistor.

- **HEMT:** (PHEMT and MHEMT) This is replacing MESFETs in many applications due to superior performance.
- ✓ It is a high-electron-mobility transistor first introduced about 1980 by Fujitsu. It has progressed to PHEMT and MHEMT structures, with even better performance.
- ✓ A PHEMT is a lattice-matched pseudo morphic HEMT, while a MHEMT is a metamorphic HEMT, a newer development with great promise, where graded layers of doping are employed.

- **HBT:** The hetero junction bipolar transistor (HBT) was originally developed to improve emitter injection efficiency in GaAs BJTs, which has been a longstanding problem (since 1965).

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Six Active Device Types

BJT	MOSFET	MESFET	PHEMT	MHEMT	HBT
Ge Si	CMOS DMOS LDMOS	Si GaAs	Al_2O_3GaAs InGaAs	InAlAs/InGaAs	InGaP/InGaAs SiGe

- ❖ Some recent developments include the enhancement- as well as depletion-mode PHEMTs, which are serious contenders for 2-GHz wireless amplifiers.
- ❖ The newer materials being developed today offer even further improvements in the near future, such as SiC and GaN, very promising high-power FETs.
- ❖ In addition n-channel MOSFETs have shown considerable promise at 60 GHz.

- In designing a **microwave circuit**, which will be built on a material such as GaAs, one needs to go to a GaAs alternative silicon or silicon germanium foundry.
- The foundries seem to be very secretive about their information, and the first experience with a foundry is a shock because one needs to sign a nondisclosure agreement and pay up to $5000 to obtain a foundry manual.
- These foundry manuals are somewhat unique to each foundry and vary.
- The foundry supplies information about **passive** and **active** structures as well as interconnect information.

- The following is an example of foundry manual which was put together from information from various foundries.
- It does not apply to a particular foundry but is generic in its contents. In the area of passive components, typically a variety of inductor cells are recommended: the same applies to spiral inductors/rectangular inductors and interconnect components such as bends, tees, crosses, and other components as outlined.

Active Versus Passive Devices

An ***active* device** is any type of circuit component with the ability to electrically control electron flow (electricity, controlling electricity).

- A circuit to be properly called *electronic*, it must contain at least one active device.
- Active devices include, but are not limited to, vacuum tubes, transistors, silicon-controlled rectifiers (SCRs
- Components incapable of controlling current by means of another electrical signal are called ***passive* devices**. Resistors, capacitors, inductors, transformers, and even diodes are all considered passive devices.

- All active devices control the flow of electrons through them.
- Some active devices allow a voltage to control this current while other active devices allow another current to do the job.
- Devices utilizing a static voltage as the controlling signal are, not surprisingly, called *voltage-controlled* devices.
- Devices working on the principle of one current controlling another current are known as *current-controlled* devices.
- For the record, vacuum tubes are voltage-controlled devices while transistors are made as either voltage-controlled or current controlled types.
- The first type of transistor successfully demonstrated was a current-controlled device.

- Basic and vague difference is active devices are made of active elements like OPAMPS, CMOS,BJTs etc. while passive devices are made of passive elements like resistors etc.
- Passive elements looses power like resistor provides a voltage drop across it whereas active elements have low power dissipiation like current mirrors.
- Active Elements have low dynamic and static power losses and are highly efficient than passive elements.
- Passive devices never provide gain. You cannot get an amplified wave after passing through a passive network.
- Active Devices are more superior and efficient than Passive Devices.
- Active device is one which doesn't required external energy to perform prescribed task while Passive device required external energy.
- Active devices are self generating devices.

Active Components

- Any component that is capable of providing a power gain is called an active component.
- They inject power to the circuit, and can control the current (or energy) flow within the circuit.
- Any electronic circuit should contain at least one active component to operate.
- Some examples for active devices are battery, vacuum tubes, transistor and SCR (silicon controlled rectifier / thyristor).
- Controlling the current flow in circuit may be helped by another small current or voltage.
- They are called current controlled devices (ex: Bipolar Junction Transistor) and voltage controlled devices (example Field Effect Transistor).

Passive Components

- Components that cannot provide any power gain to the circuit are called passive devices.
- These devices are incapable of controlling the current (energy) flow in the circuit and need the help of active devices to operate.
- Some examples for passive devices are resistors, inductors and capacitors.
- Although passive components cannot amplify a signal with a gain more than one, they can multiply a signal by a value less than one.
- They also can oscillate, phase shift and filter signals.
- Some passive components also have the capability to store energy (drawn from an active element) and release later.
- Example: capacitors and inductors.

Impedance Matching

- Impedance matching is a vitally important part of **amplifier design**. There are **four main** reasons for impedance matching:
  - ✓ To match an impedance to the conjugate impedance of a source or load for **maximum power transfer**
  - ✓ To match an amplifier to a certain load value to provide a required **transistor gain**
  - ✓ To match an amplifier to a load that does **not cause transistor instability.**
  - ✓ To provide a load for an oscillator that will **cause instability and hence oscillations.**

Matching methods

There are many means of impedance matching. These include:

- **Quarter wave transmission line matching**
- **Capacitive matching**
- **Single stub matching**
- **L- network matching**
- **Double stub matching**
- **Pi- network matching**
- **Transformer matching**
- **T- network matching**
- **Auto-transformer matching**

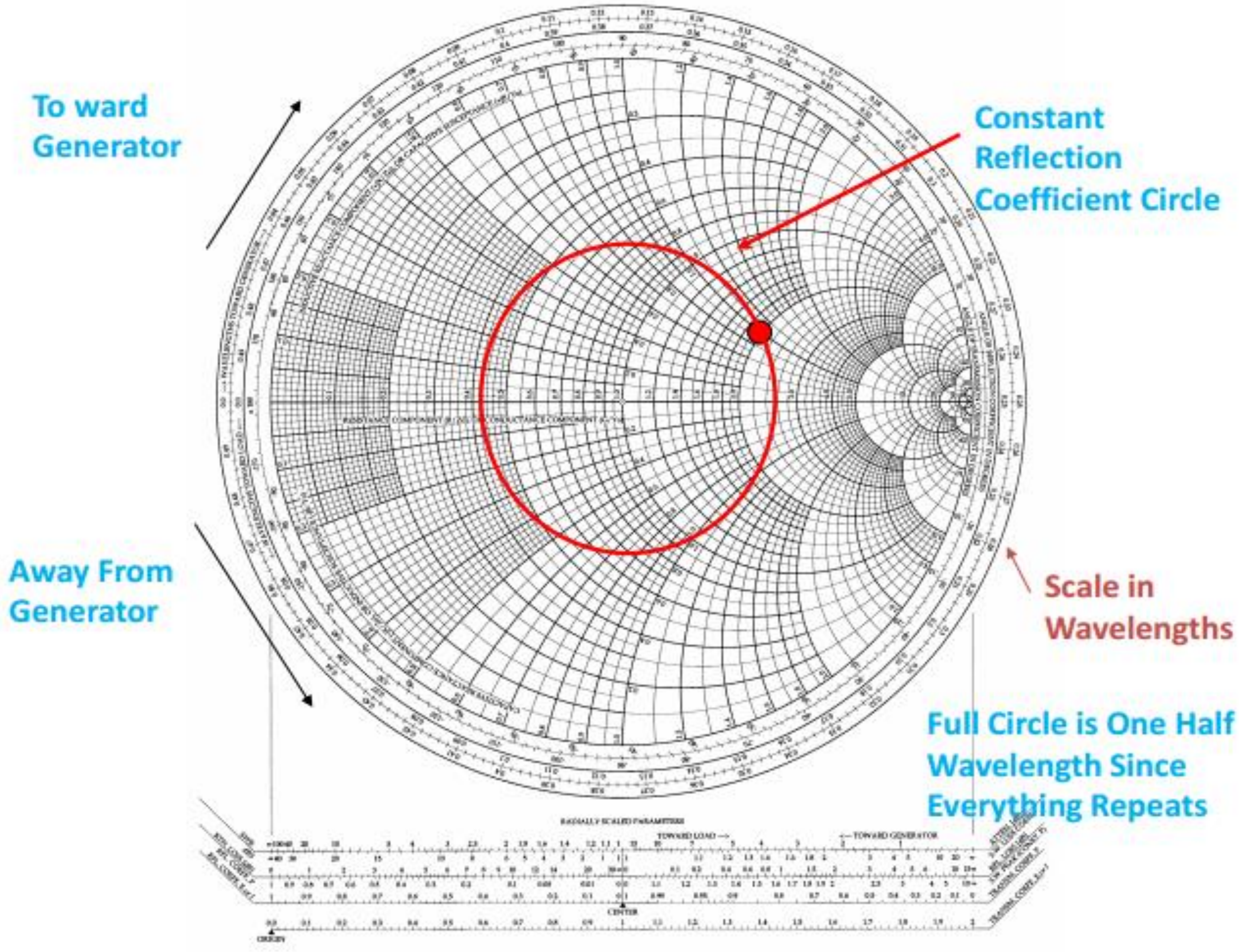
Objectives of Smith charts

- Evaluate impedance and admittance networks;
- Design impedance and admittance networks;
- Design matching networks.
- Understand scattering parameters;
- Use two port scattering parameters efficiently;
- Design two port scattering networks;
- Evaluate two port scattering networks;
- Calculate the frequency response of networks;
- Calculate the gain of two port networks or an amplifier;
- Calculate the input impedance of two port networks or an amplifier,
- Manipulate two port data into other types of parameter data.

Smith Chart

- The Smith Chart is a clever tool for analyzing transmission lines
- The outside of the chart shows location on the line in wave lengths.
- The combination of intersecting circles inside the chart allow us to locate the normalized impedance and then to find the impedance anywhere on the line.
- Thus, the first step in analyzing a transmission line is to locate the normalized load impedance on the chart.
- Next, a circle is drawn that represents the reflection coefficient or Standing wave ratio (SWR).

- The center of the circle is the center of the chart.
- The circle passes through the normalized load impedance
- Any point on the line is found on this circle.
- Rotate clockwise to move toward the generator (away from the load)
- The distance moved on the line is indicated on the outside of the chart in wavelengths

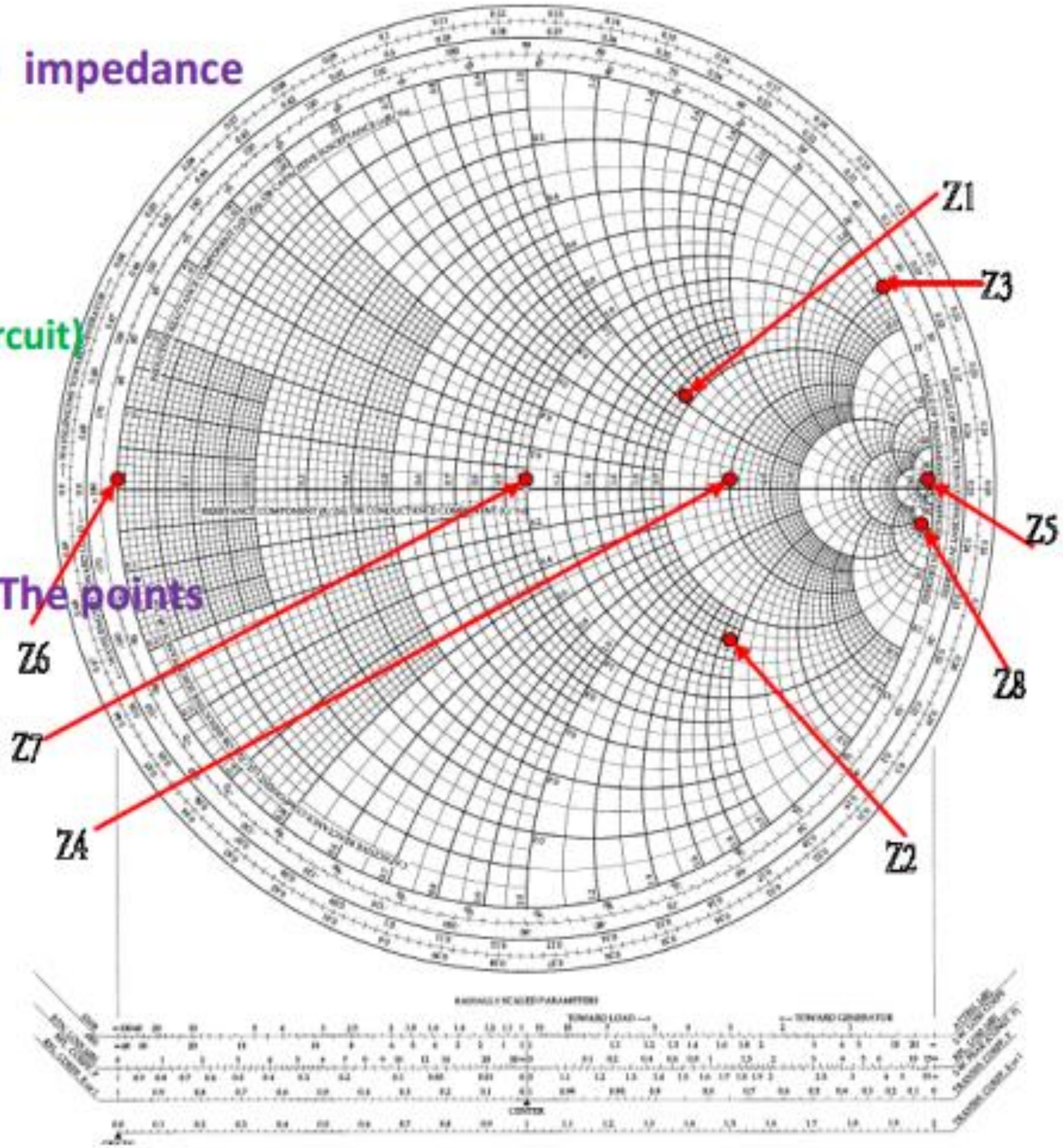

To ward Generator
Away From Generator
Constant Reflection Coefficient Circle
Scale in Wavelengths
Full Circle is One Half Wavelength Since Everything Repeats
RADIALLY SCALED PARAMETERS
TOWARD LOAD →
← TOWARD GENERATOR
CENTER
ORIGIN

Impedance divided by line impedance (50 Ohms)

- Z1 = 100 + j50
- Z2 = 75 -j100
- Z3 = j200
- Z4 = 150
- Z5 = infinity (an open circuit)
- Z6 = 0 (a short circuit)
- Z7 = 50
- Z8 = 184 -j900

Then, normalize and plot. The points are plotted as follows:

- Z1 = 2 + j
- Z2 = 1.5 -j2
- Z3 = j4
- Z4 = 3
- Z5 = infinity
- Z6 = 0
- Z7 = 1
- Z8 = 3.68 -j18



The Smith chart is the representation in the reflection coefficient plane, called the Γ *plane*, of the relation

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

for all values of Z, such that Re $[Z] \geq 0$. Z_o is the characteristic impedance of the transmission line or a reference impedance value. Defining the normalized impedance z as $z = Z/Z_o$,

$$\Gamma = \frac{z - 1}{z + 1}$$

Impedances having a negative real part will have a reflection coefficient whose magnitude is greater than 1. These impedances, therefore, map outside the Smith chart.

An alternative way of handling negative resistances (i.e., $|\Gamma| > 1$) is to plot in the Smith chart $1/\Gamma^*$ and take the values of the resistance circles as being negative and the reactance circles as labeled.

Example

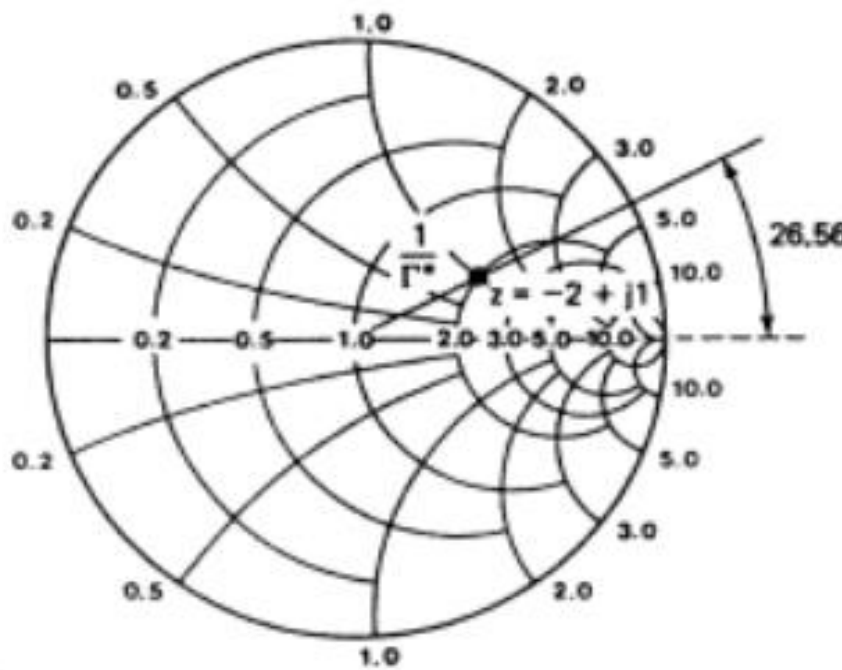
Find the impedance whose reflection coefficient is $2.236e^{j26.56^\circ}$.

Solution. we plot in the Smith chart

$$\frac{1}{\Gamma^*} = 0.447e^{j26.56^\circ}$$

the resulting z is $-2 + j1$.

$$\Gamma = \frac{-2 + j1 - 1}{-2 + j1 + 1} = 2.236e^{j26.56^\circ}$$



For a lossless transmission line,

$$\Gamma_0 = \frac{z - 1}{z + 1}$$

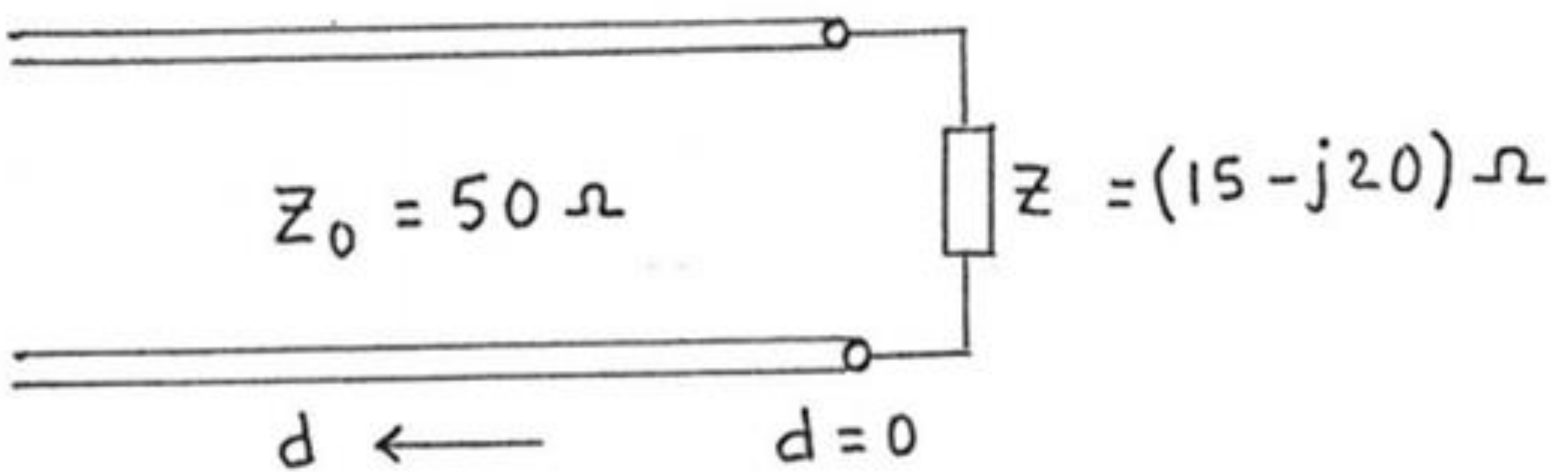
$$\Gamma_{IN}(d) = \Gamma_0 e^{-j2\beta d}$$

$$z_{IN}(d) = \frac{1 + \Gamma_{IN}(d)}{1 - \Gamma_{IN}(d)}$$

A typical transmission-line input impedance calculation involves the following steps:

1. Locate Γ_0 in the Z Smith chart for a given $z = Z_L/Z_o$.
2. Rotate Γ_0 by $-2\beta d$ to obtain $\Gamma_{IN}(d)$ Observe that the rotation is along a vector of constant magnitude, namely $|\Gamma_0| = |\Gamma_{IN}(d)|$.
3. Read the value of the normalized $z_{IN}(d)$ associated with $\Gamma_{IN}(d)$

Determination of Standing Wave Parameters



$$\bar{z} = \frac{Z}{Z_0} = \frac{15 - j20}{50} = 0.3 - j0.4$$

1) Locate $\bar{z}$ $(= 0.3 - j0.4)$ at point A.

2) Measure $|OA|$ relative to the radius of the chart, and $\angle OA$.

$\bar{\Gamma} = 0.6\angle{-133^\circ}$

3) Draw constant SWR circle through point A and locate V_{max} point at point B.

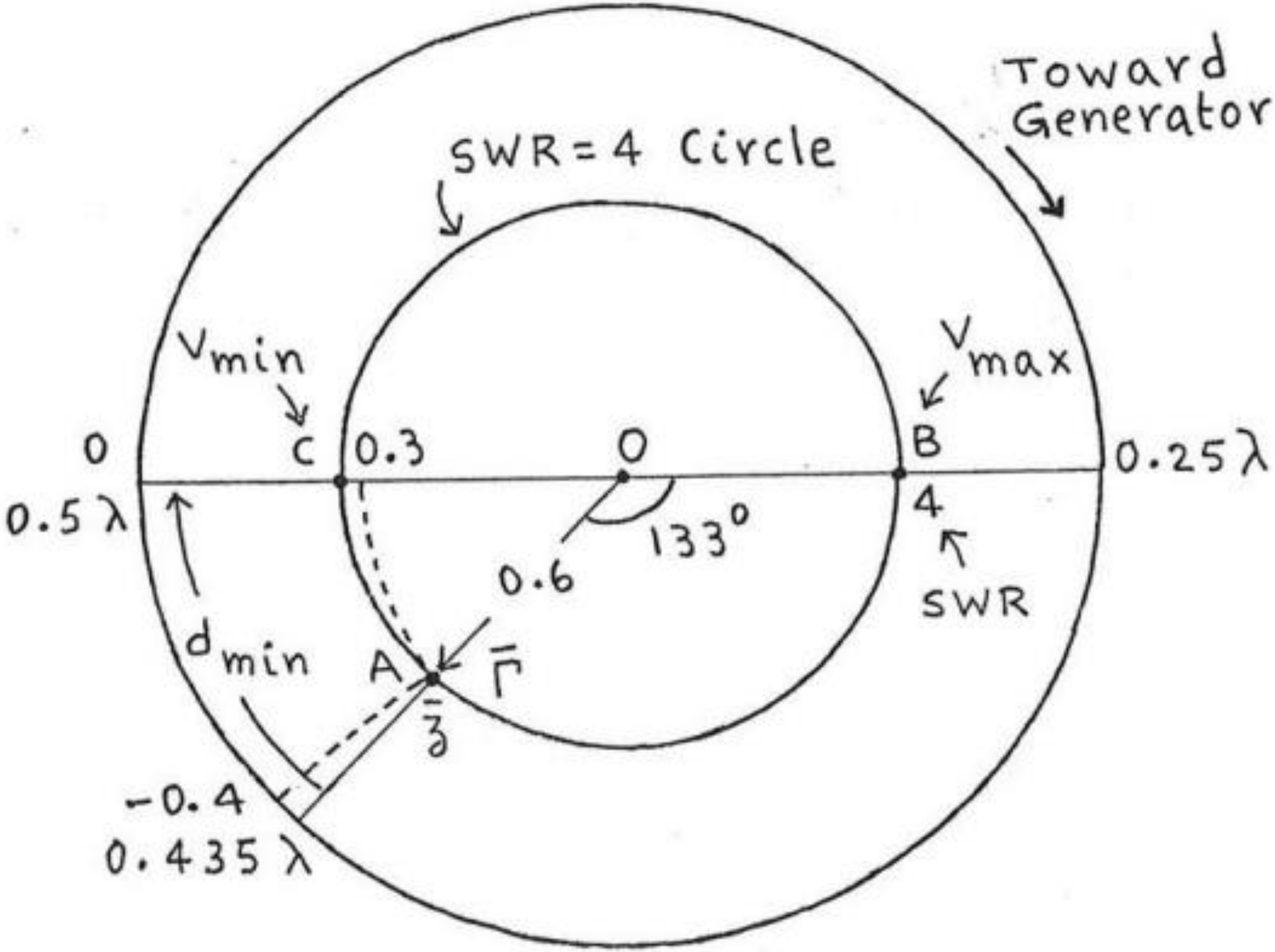
4) Read r value at point B.

$SWR = r_{max} = 4.0$

5) Locate V_{min} point at point C on the constant SWR circle.

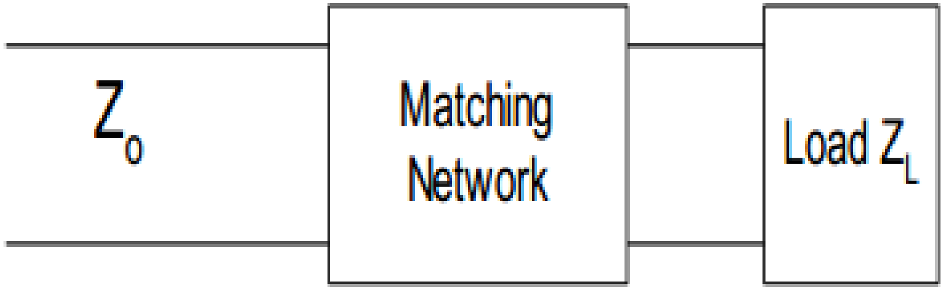
6) Find distance from A to C toward generator.

$$d_{min} = (0.5 - 0.435)\lambda$$
$$= 0.065\lambda$$


Toward
Generator
SWR = 4 Circle
V_{min}
V_{max}
0
C
0.3
O
B
0.25 λ
0.5 λ
4
133°
0.6
SWR
d_{min}
A
$\bar{\Gamma}$
$\bar{z}$
-0.4
0.435 λ

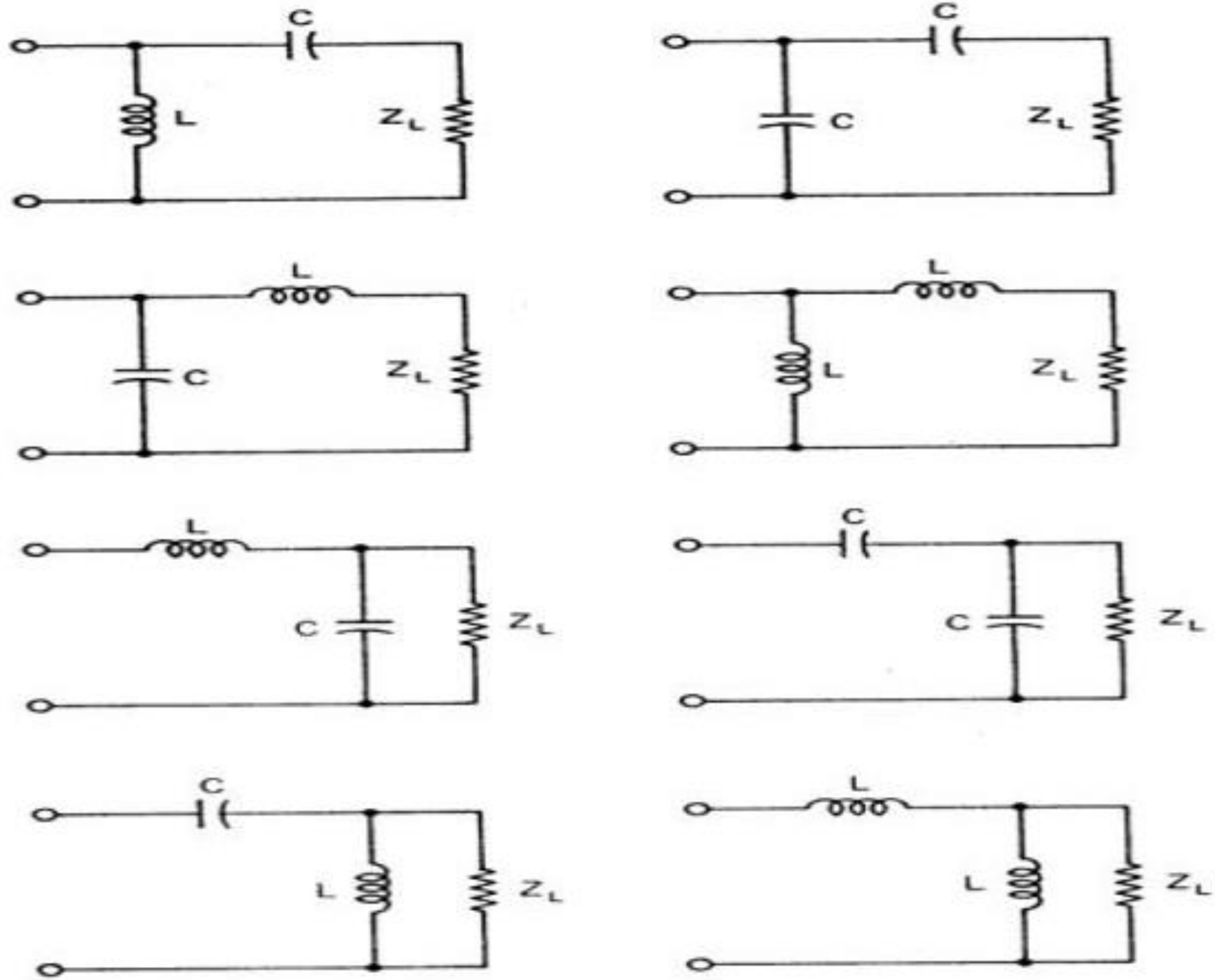
Why matching is important?

- To maximize power delivery and minimize power loss
- To improve signal to noise ratio as in sensitive receiver components
- To reduce amplitude and phase error



Factors in selecting matching network

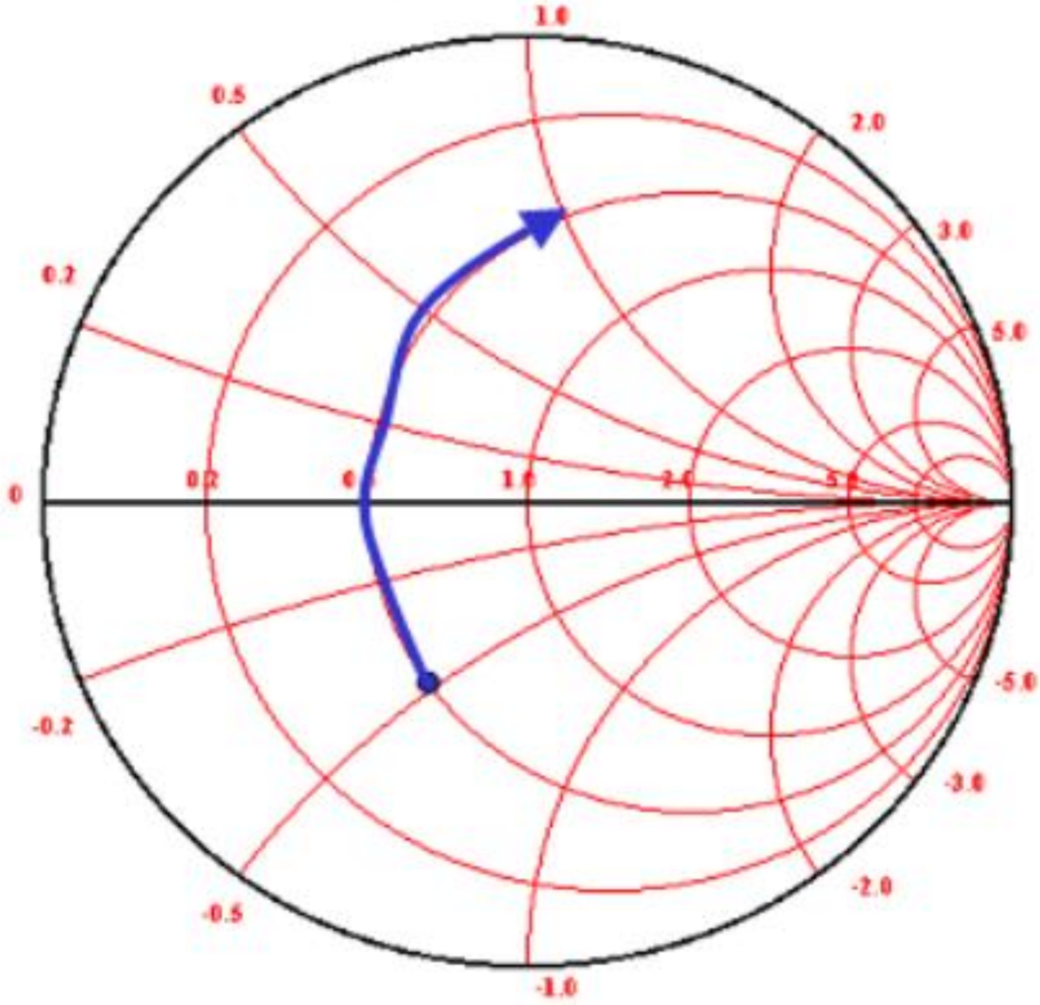
- **Complexity:** simpler, cheaper, more reliable and low loss circuit is preferred.
- **Bandwidth:** match over a desirable bandwidth.
- **Implementation:** depend on types of transmission line either cable, stripline, microstripline, waveguide, lump circuit etc.
- **Adjustability:** some network may need adjustment to match a variable load.
- The **Smith Chart** can be used to design a lumped (L-C) matching network to match one impedance to another
- Each LC element behaves in a certain way on the chart



Matching networks.

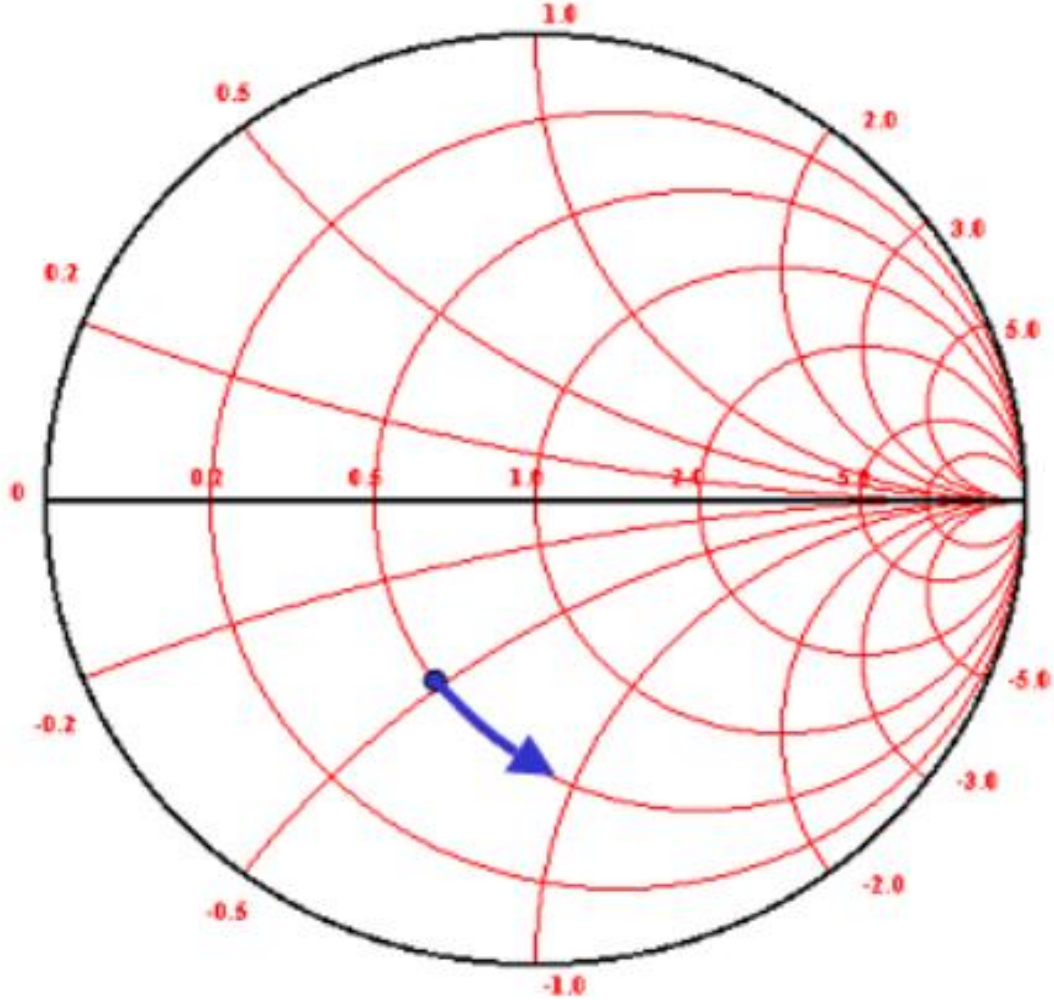
1. Series Inductors

❖ Moves clockwise along circles of constant resistance



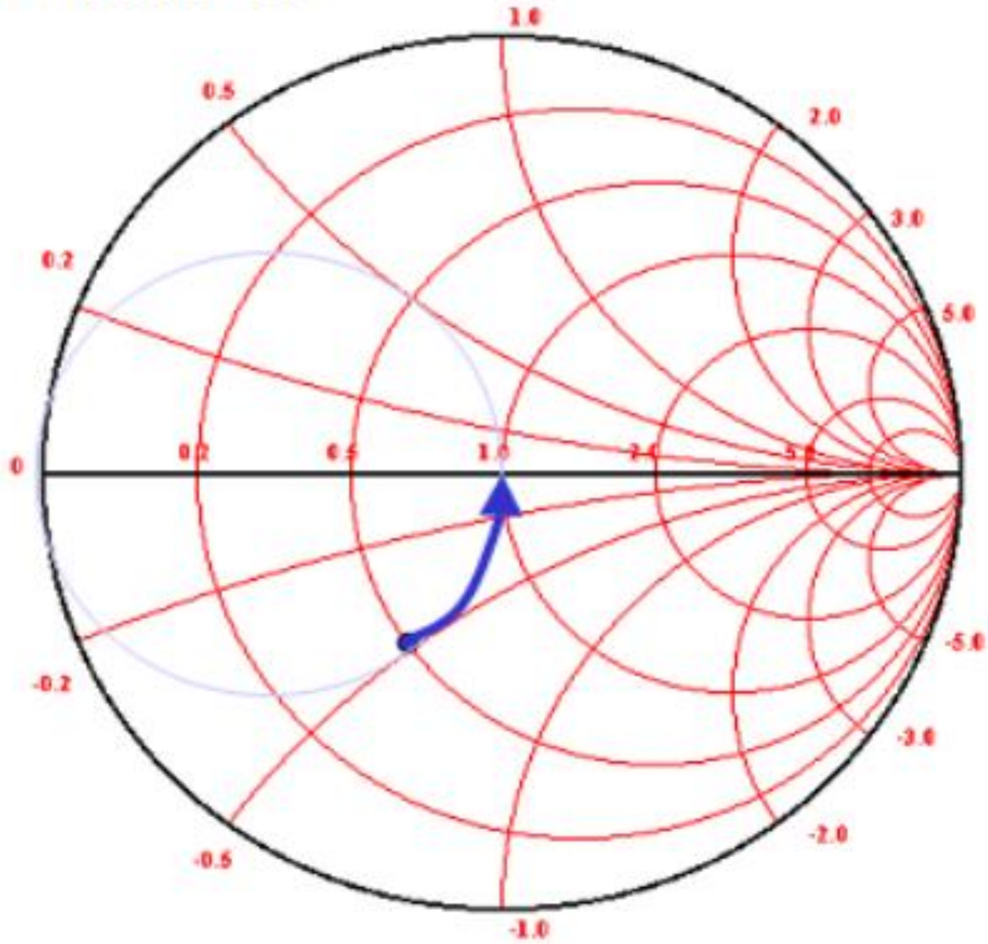
2. Series Capacitors

❖ **Moves counter-clockwise along circles of constant resistance**



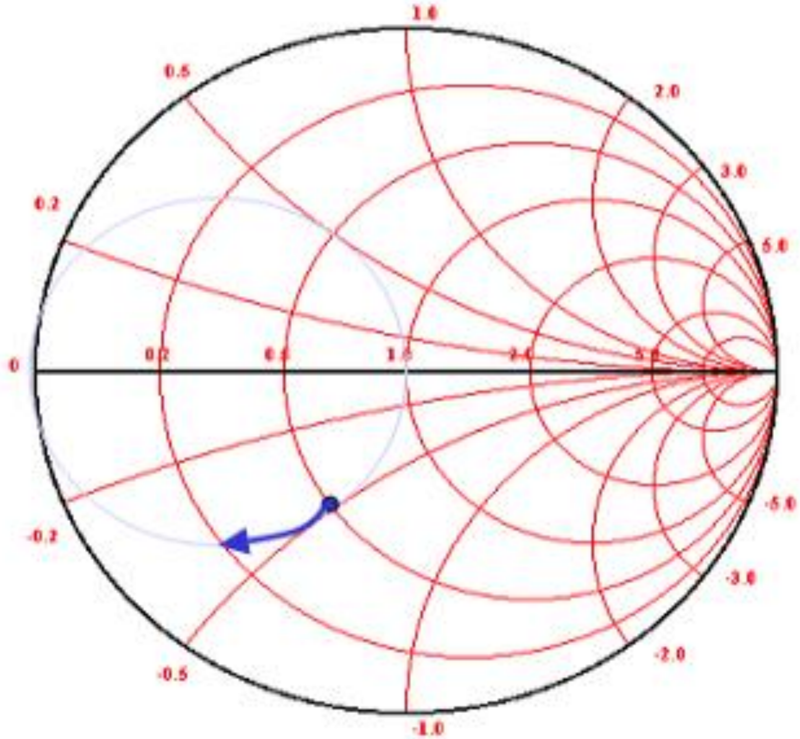
3. Shunt Inductors

- ❖ Moves counter-clockwise along circles of constant conductance



4. Shunt Capacitors

❖ Moves clockwise along circles of constant conductance



Smith chart applications

- To find reflection coefficients and
- Impedances of networks.

Questions ?

Thanks !!!