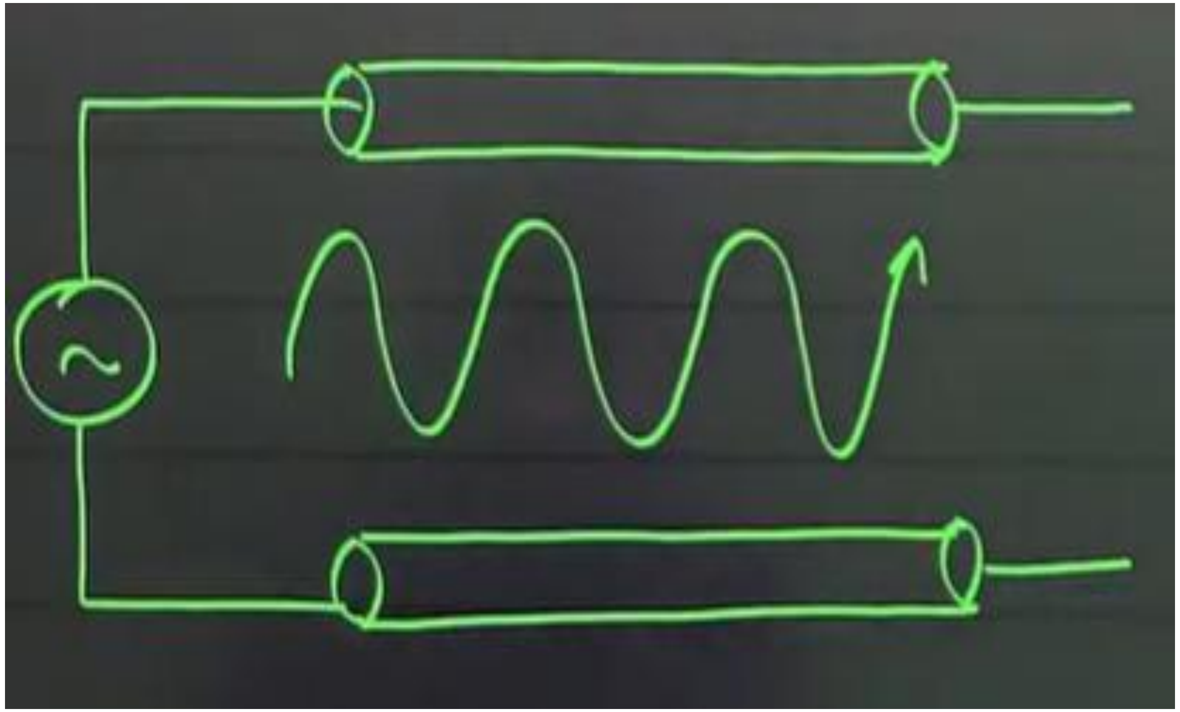
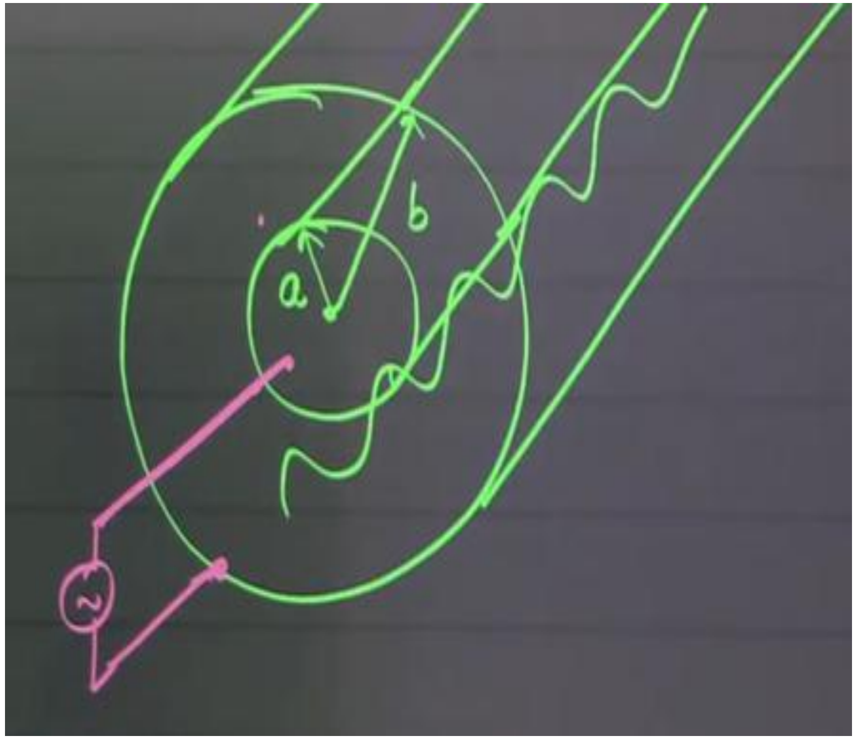
Lecture 11

RF Sensor

Transmission Lines

- A transmission line is a two-conductor structure used to transmit electrical signals or power over a distance, especially at high frequencies where the wavelength of the signal becomes comparable to the physical length of the line. In such cases, wave phenomena like reflections, standing waves, and impedance matching become important, and the line must be analyzed using electromagnetic field theory.



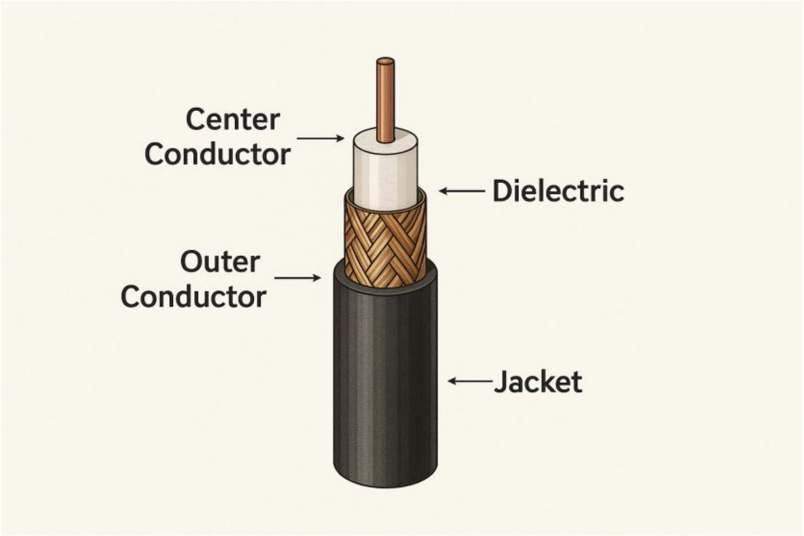


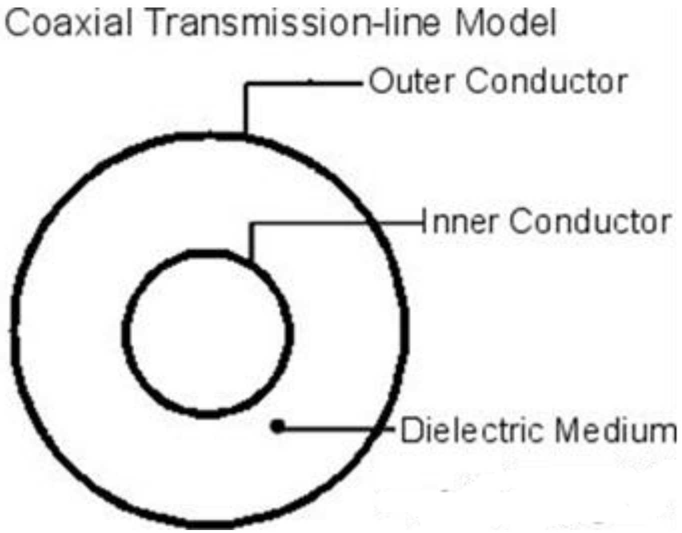
(a) wave propagation between two conductors (b) cross-sectional view of a coaxial cable with signal propagation

Common Types of Transmission Lines

1.Coaxial Cable (Coax)

1. Inner conductor, dielectric insulator, outer conductor/shield.
2. Good shielding from external noise.
3. Used in cable TV, RF test equipment, and antennas.



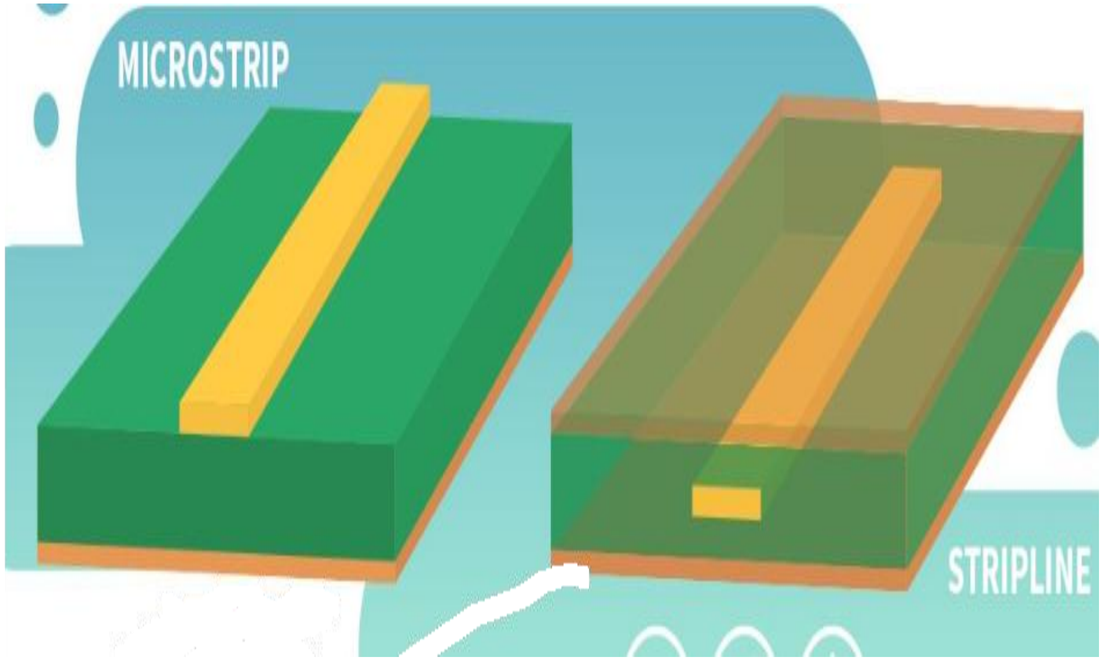


2.Microstrip Line

1. Conductive strip over a dielectric substrate with a ground plane underneath.
2. Common in PCB (printed circuit board) RF design.
3. Easy to integrate but subject to radiation losses.

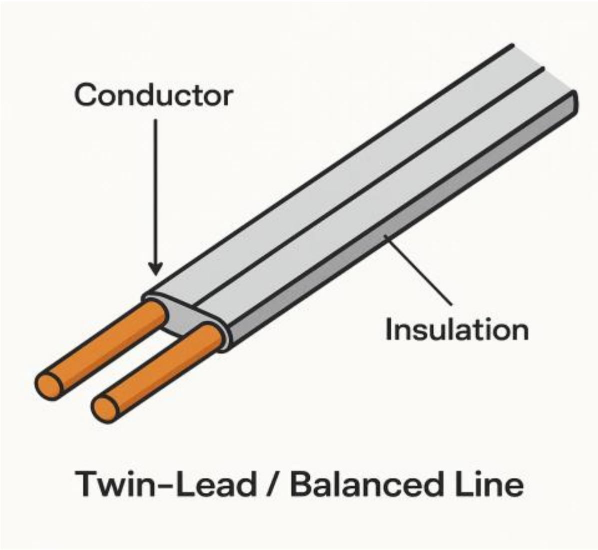
3.Stripline

1. A conductor between two ground planes inside a PCB.
2. Less radiation loss than microstrip.
3. Used in high-speed and high-frequency circuits.



4. Twin-lead / Balanced Lines

Two Parallel Conductors: The conductors are usually arranged in parallel, separated by a consistent dielectric material, such as air or plastic, which helps in maintaining a controlled impedance. The symmetry of the design ensures that the signal is balanced between the two conductors.



5. Twisted Pair

Two conductors (wires) are twisted together, and each conductor carries an opposite signal (like a balanced line).

6. Waveguides

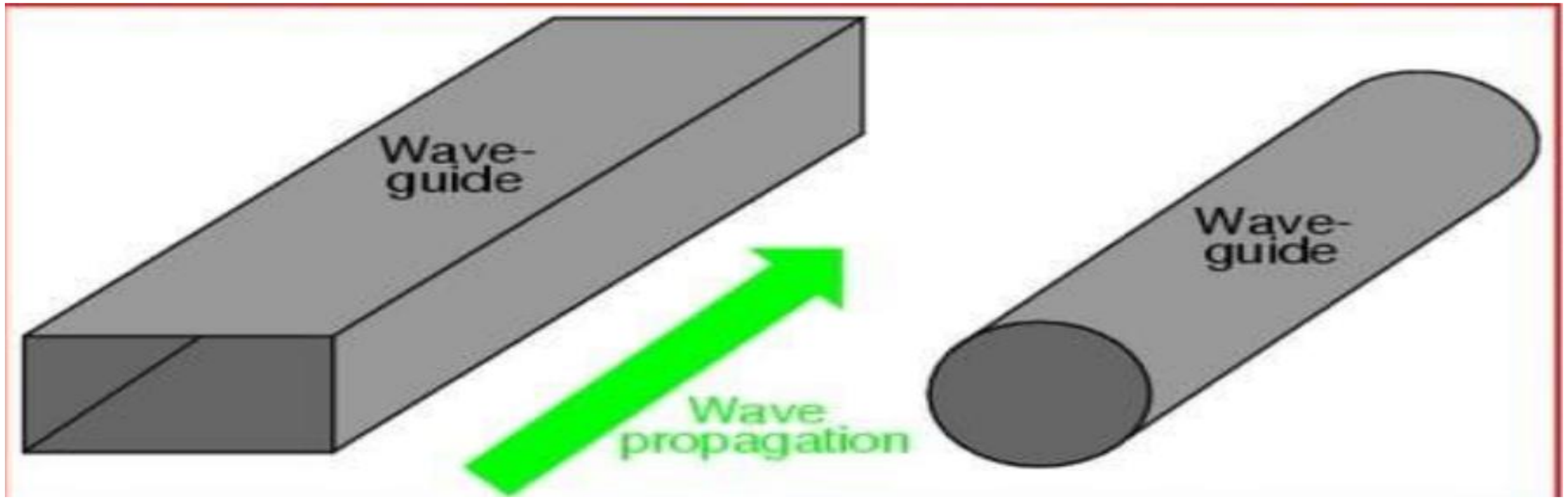
Waveguides are **hollow metallic structures** (typically tubes) used to guide **electromagnetic waves** from one point to another. Instead of using conductors like coaxial cables, waveguides rely on **internal reflections** to direct wave propagation.

- **Key Characteristics:**
- Operate primarily at **microwave and millimeter-wave frequencies** (typically above 1 GHz).
- Utilize the **principle of total internal reflection** to confine and direct waves within the tube.
- Only support **certain modes** of propagation (e.g., TE and TM modes), depending on frequency and geometry.

- **Advantages:**
- **Extremely low loss** at high frequencies compared to coaxial cables.
- **High power-handling capacity**.

Disadvantages:

- **Bulky and rigid**, making installation more complex.
- **Expensive** due to precision manufacturing requirements.
- Limited to **high-frequency applications** due to size constraints at lower frequencies.



Types of Waveguides (as shown in the image):

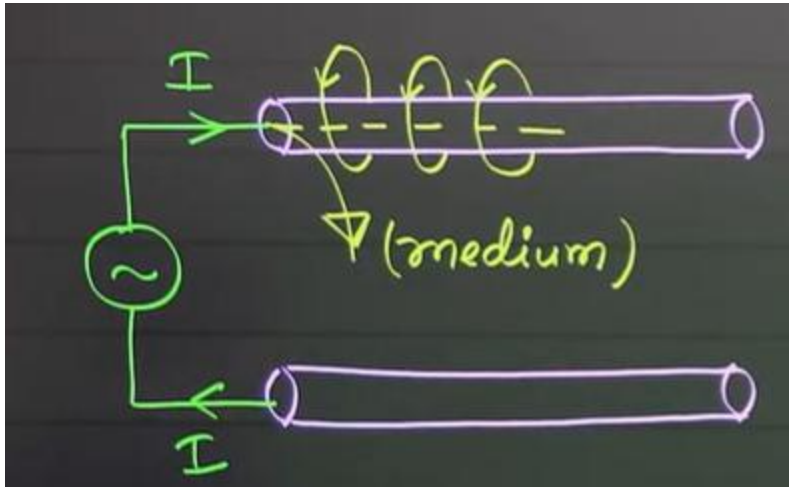
Rectangular Waveguide:

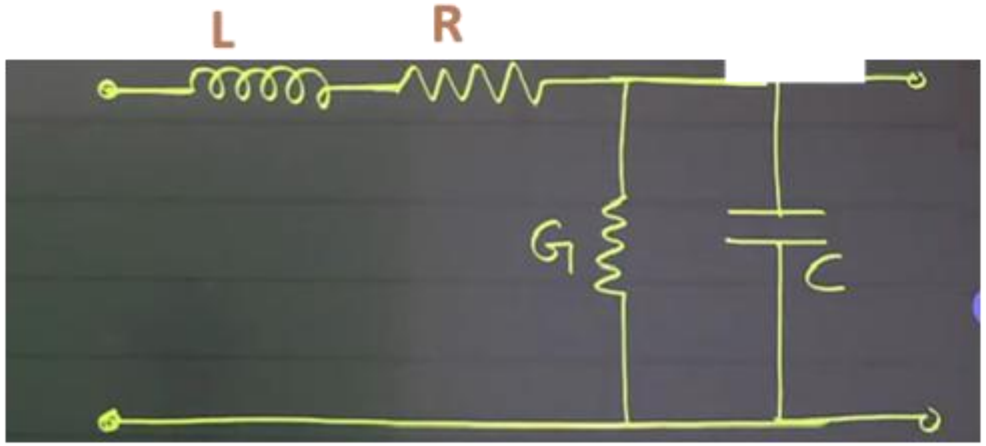
- Most commonly used type.
- Preferred for simpler manufacturing and mode analysis.
- Dominant propagation mode is **TE_{10} (Transverse Electric)**.
- Used in radar systems, satellite communication, and microwave ovens.

Circular Waveguide:

- Supports both **TE** and **TM (Transverse Magnetic)** modes.
- Slightly more complex mode structure.
- Often used in applications where rotation or bending is required, like satellite antenna feeds.

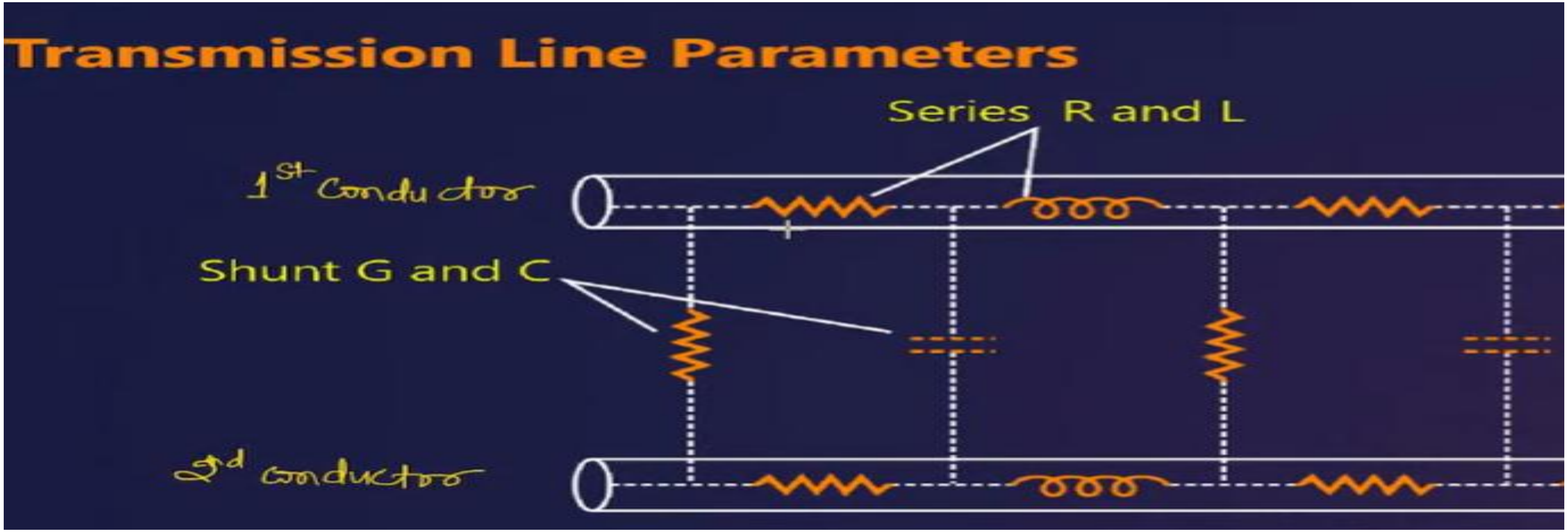
Equivalent Circuit model of transmission line





Primary Constant:

- R = resistance per unit length (Ω/m)
- L = inductance per unit length (H/m)
- G = conductance per unit length ($\mho/m$ or S/m)
- C = capacitance per unit length (F/m)

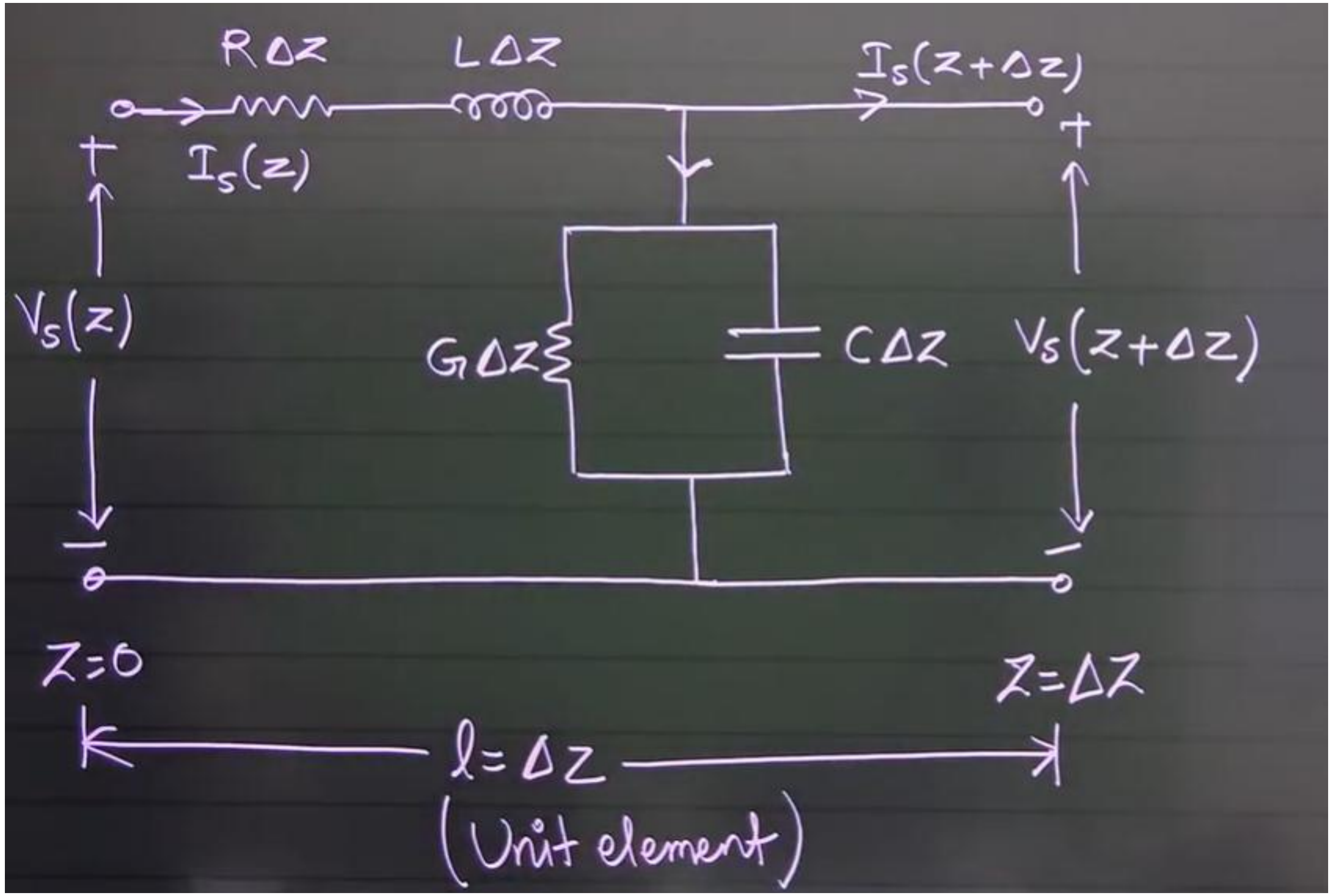


G ≠ 1/R?

Even though it **looks like** G and R might be inverses of each other (like conductance and resistance normally), in the context of transmission lines:

•**R** is the **series resistance per unit length** (due to the conductor).

•**G** is the **shunt conductance per unit length** (due to the dielectric leakage between conductors). Both are for different things so G ≠ 1/R here.



RΔz
LΔz
$I_s(z+\Delta z)$
$I_s(z)$
+
$V_s(z)$
−
GΔz
CΔz
+
$V_s(z+\Delta z)$
−
z=0
z=Δz
l=Δz
(Unit element)

$$\boxed{\frac{d^2 V_s(z)}{dz^2} - \gamma^2 V_s(z) = 0}$$

Transmission Line Equation
(voltage wave)

$$\boxed{\frac{d^2 I_s(z)}{dz^2} - \gamma^2 I_s(z) = 0}$$

Transmission line equation
(Current wave)

γ = propagation constant (m^{-1})

$$\gamma = \alpha + j\beta = \sqrt{(R + j\omega L)(G + j\omega C)}$$

Where:

α = **attenuation constant** (in **nepers per meter**, Np/m)

Describes **signal loss** per unit length.

β = **phase constant** (in **radians per meter**, rad/m)

Describes how the **phase** of the signal changes as it moves along the line.

$$\frac{d^2 V_s}{dz^2} - \gamma^2 V_s = 0$$

$$\frac{d^2 I_s}{dz^2} - \gamma^2 I_s = 0$$

$z=0 \rightarrow z=\infty$

$z=0 \rightarrow z=-\infty$ ✓

$$(D^2-\gamma^2)V_s = 0$$

$$D = \pm\gamma$$

$$(D^2-\gamma^2)I_s = 0$$

$$D = \pm\gamma$$

$$\boxed{V_s(z) = V_0^+ e^{-\gamma z} + V_0^- e^{\gamma z}}$$

V_0^+: Forward Travelling

V_0^-: Reverse Travelling

$$\boxed{I_s(z) = I_0^+ e^{-\gamma z} + I_0^- e^{\gamma z}}$$

I_0^+: Forward Travelling

I_0^-: Backward travelling

$$\gamma = \sqrt{(R+j\omega L)(G+j\omega C)} = \alpha + j\beta$$

Voltage Standing Wave Ratio (VSWR)

When a signal is sent down a transmission line and encounters an **impedance mismatch**, some of it is **reflected back**.

This creates **standing waves**, and the **Voltage Standing Wave Ratio (VSWR)** is a measure of how bad the mismatch is.

Formula:

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

Where:

- Γ = Reflection coefficient
- V_{max}, V_{min} = Maximum and minimum voltages along the line

- **Ideal:** 1:1
- **Good:** ≤ 1.5:1
- **Acceptable:** 1.5:1 to 2:1
- **Poor:** > 2:1

Lossless Transmission Line

A **lossless** transmission line is an *ideal* line where **no energy is lost** as the signal travels through it.

Assumptions:

- Resistance (R) = 0 → no power loss due to resistance.
- Conductance (G) = 0 → no leakage through the dielectric.

What it means:

- Signal strength stays the same over distance.
- Only reactive elements exist: inductance (L) and capacitance (C).
- Signal *shape* is preserved (no distortion), but only if it starts undistorted.

Example Use:

- Idealized coaxial cables in RF simulations.
- Short, high-quality cables at high frequencies.

G represents how much leakage current flows through the insulating material between the wires. Ideally, in a lossless transmission line, G = 0, meaning no current leaks through the dielectric—perfect insulation.

Distortionless Transmission Line

A **distortionless** line allows the signal to travel **without changing shape**, but it may still **lose power**.

Condition for distortionless line (called Heaviside Condition):

$$\frac{R}{L} = \frac{G}{C}$$

- Resistance (R) $\neq 0$ → some power loss.
- Conductance (G) $\neq 0$ → some leakage.
- But the **signal waveform** is preserved.

What it means:

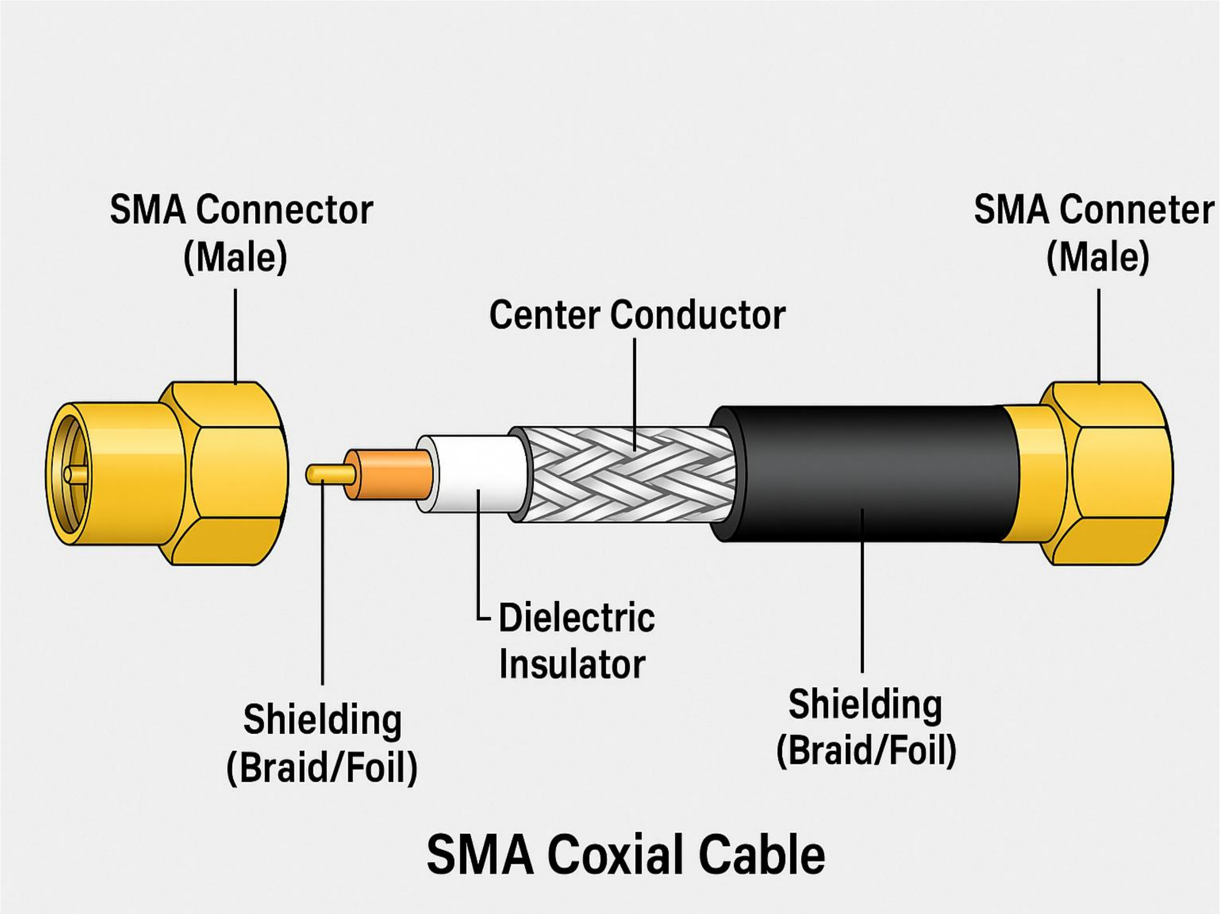
- The signal gets **weaker** but keeps the **same shape**.
- Important for analog and digital communication where waveform fidelity matters.

Example Use:

- Long telephone lines or DSL systems.

SMA Cabel

- An **SMA (Subminiature version A)** cable is a coaxial cable with an SMA connector used for transmitting radio-frequency signals. It's specifically designed for high-frequency communication in compact systems. The **SMA connector** itself is a precision RF connector that is widely used in systems requiring good signal integrity and reliable connection in a small form factor.
- **Conductors:** SMA cables typically use copper or tinned copper as the center conductor. This allows them to conduct RF signals efficiently with minimal loss.
- **Insulation:** The dielectric (insulation) material is usually made of PTFE (Teflon), PE (Polyethylene), or FEP (Fluorinated Ethylene Propylene), which helps in maintaining signal integrity and preventing signal loss.
- **Shielding:** SMA cables are shielded to reduce electromagnetic interference (EMI). The shielding is often made of braided copper or aluminum foil.
- **Jacket:** The outer jacket of the cable is typically made of PVC (Polyvinyl Chloride) or TPE (Thermoplastic Elastomer) for protection.


SMA Connector
(Male)
Center Conductor
SMA Conneter
(Male)
Dielectric
Insulator
Shielding
(Braid/Foil)
Shielding
(Braid/Foil)
SMA Coxial Cable

Applications of SMA Cables:

- **Antenna Connections:** SMA cables are commonly used to connect antennas to devices like radios, GPS receivers, or wireless communication equipment.
- **Testing and Measurement:** SMA cables are commonly used in signal generators, oscilloscopes, and network analyzers in RF testing and measurement setups.
- **Wireless Communication:** They're often used in wireless communication devices like cell phones, Wi-Fi routers, and satellite systems due to their ability to carry high-frequency signals with minimal interference.
- **Microwave Systems:** SMA cables are critical in microwave systems, used in radar, satellite communication, and military applications due to their ability to handle high-frequency signals.
- **RF Systems:** From RF amplifiers to transceivers, SMA cables ensure reliable signal transmission between components.

Advantages of SMA Cables:

1. **High-Frequency Performance**
   - Can operate effectively up to **18 GHz** (some variants up to 26.5 GHz or more).
2. **Excellent Signal Integrity**
   - Low reflection and consistent impedance (typically **50 ohms**), which ensures minimal signal loss.
3. **Compact Size**
   - Small and lightweight, ideal for **dense RF circuitry** and **portable devices**.
4. **Durability**
   - **Threaded coupling** ensures a secure connection, making it resistant to vibration and mechanical stress.
5. **Wide Availability**
   - Common and standardized, making replacement and integration easy.
6. **Precision Engineering**
   - Designed for **repeatable performance** in lab and field environments.
7. **Versatile Applications**
   - Used in test equipment, antennas, microwave systems, GPS, satellite, aerospace, and military communications.

Common Challenges and Limitations:

- **Signal Loss at High Frequencies**: While SMA cables are great for high-frequency applications, at extremely high frequencies (above 18 GHz), signal loss can become more significant, requiring more advanced cables or connectors.
- **Mechanical Stress**: Although SMA cables are robust, excessive bending or physical stress on the cables can lead to signal degradation or damage to the connectors.
- **Cost**: Compared to other types of connectors like **BNC** or **RCA**, SMA cables and connectors can be a bit more expensive due to their precision and performance characteristics.

SMA vs Other RF Connectors:

1. BNC (Bayonet Neill–Concelman):
    - **Usage:** Lower-frequency signals (typically up to 4 GHz)
    - **Connector Type:** Bayonet
    - **Comparison:** SMA is better for high-frequency use (up to 26.5 GHz).
2. N-Type Connectors:
    - **Usage:** Designed for low signal loss, can handle high power.
    - **Size:** Larger than SMA.
    - **Comparison:** SMA is more compact and suitable for space-constrained, high-frequency systems.
3. TNC (Threaded Neill–Concelman):
    - **Usage:** Threaded version of BNC, handles higher frequencies than BNC.
    - **Comparison:** SMA offers **better impedance matching** and is favored for **precise RF applications**.

Connector	Frequency Range	Size	Impedance	Common Use
SMA	Up to 26.5 GHz	Small	50 ohms	High-frequency, low-power RF
BNC	Up to 4 GHz	Medium	50 ohms	Standard RF, surveillance, audio
N-Type	Up to 11 GHz	Larger	50 ohms	High-power RF, base stations
TNC	Up to 11 GHz	Medium	50 ohms	Military, industrial RF systems
F-Type	Up to 1 GHz	Small	75 ohms	TV and satellite communications

Choosing the Right SMA Cable:

- **Frequency Range**: Make sure the cable you choose can handle the frequency of your application.
- **Flexibility**: If the cable needs to be routed around corners or through tight spaces, go for a flexible version.
- **Attenuation**: For longer distances, choose cables with low attenuation to minimize signal loss.
- **Durability**: If you're working in a harsh environment, look for SMA cables with robust shielding and durable jackets.

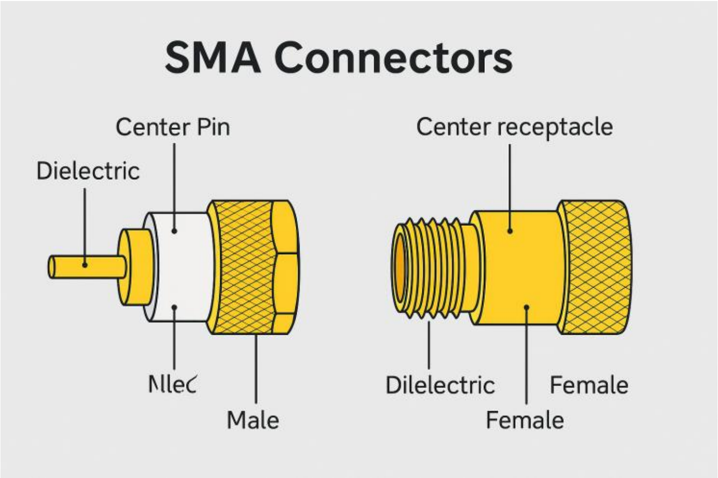
Specifications and Features of SMA Cables

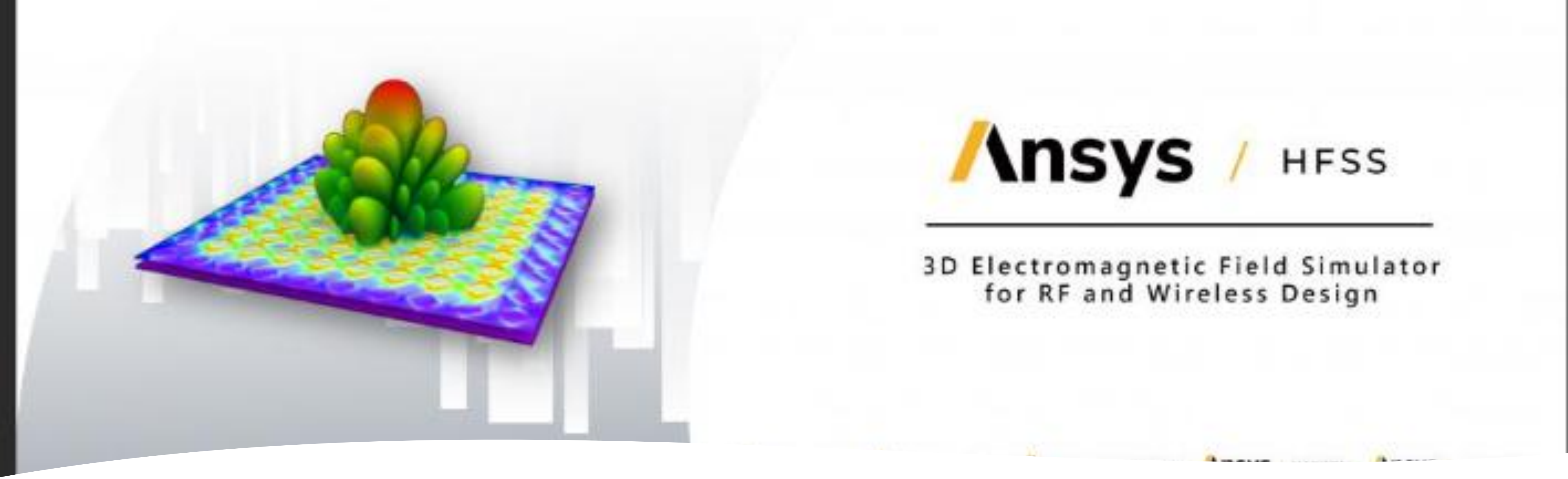
Performance Characteristics

- **Frequency Range**: SMA cables are suitable for frequencies from DC to 18 GHz, with certain variations extending up to 26.5 GHz or higher, depending on the design and material quality.
- **Return Loss**: SMA connectors have a low return loss (good impedance matching), which reduces signal reflections and power loss.
- **Insertion Loss**: SMA cables typically have low insertion loss, meaning the signal that travels through them suffers minimal attenuation, preserving signal quality.
- **VSWR (Voltage Standing Wave Ratio)**: A low **VSWR** is critical in RF applications, as it indicates minimal signal reflection. The ideal VSWR is 1:1, though practical SMA cables often show a VSWR of **1.1 to 1.3**.

SMA connectors

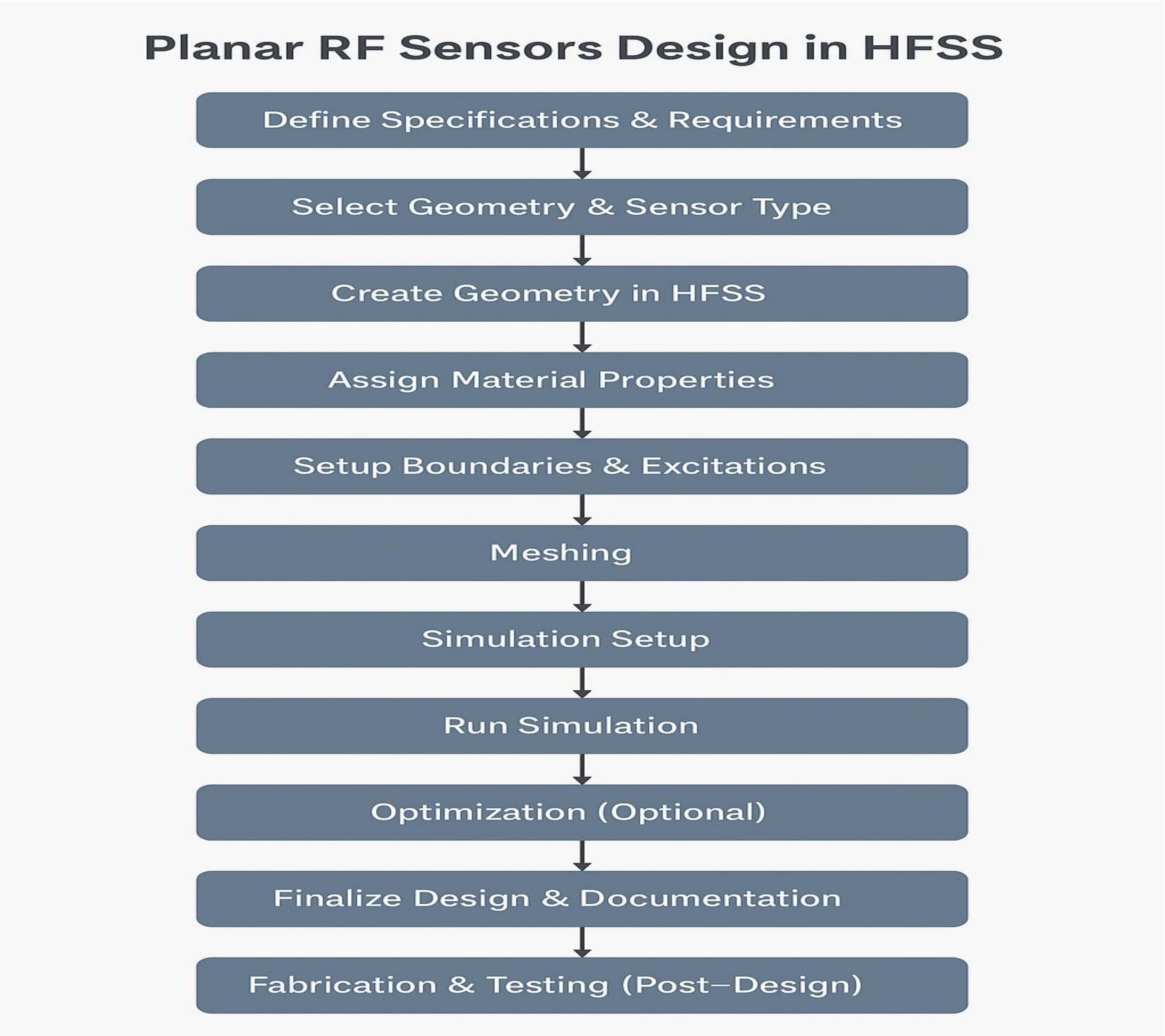
- **SMA connectors** are precision RF (Radio Frequency) connectors designed for coaxial cables.
- It's widely used in microwave systems, antennas, test equipment, and high-frequency communications due to its excellent electrical performance. It comes in pin and socket versions. This allows for a reliable and secure connection.
- Impedance Matching: SMA connectors are designed to maintain a 50-ohm impedance, which is standard for most RF systems. Proper impedance matching is crucial in RF systems to minimize signal reflections and power loss.

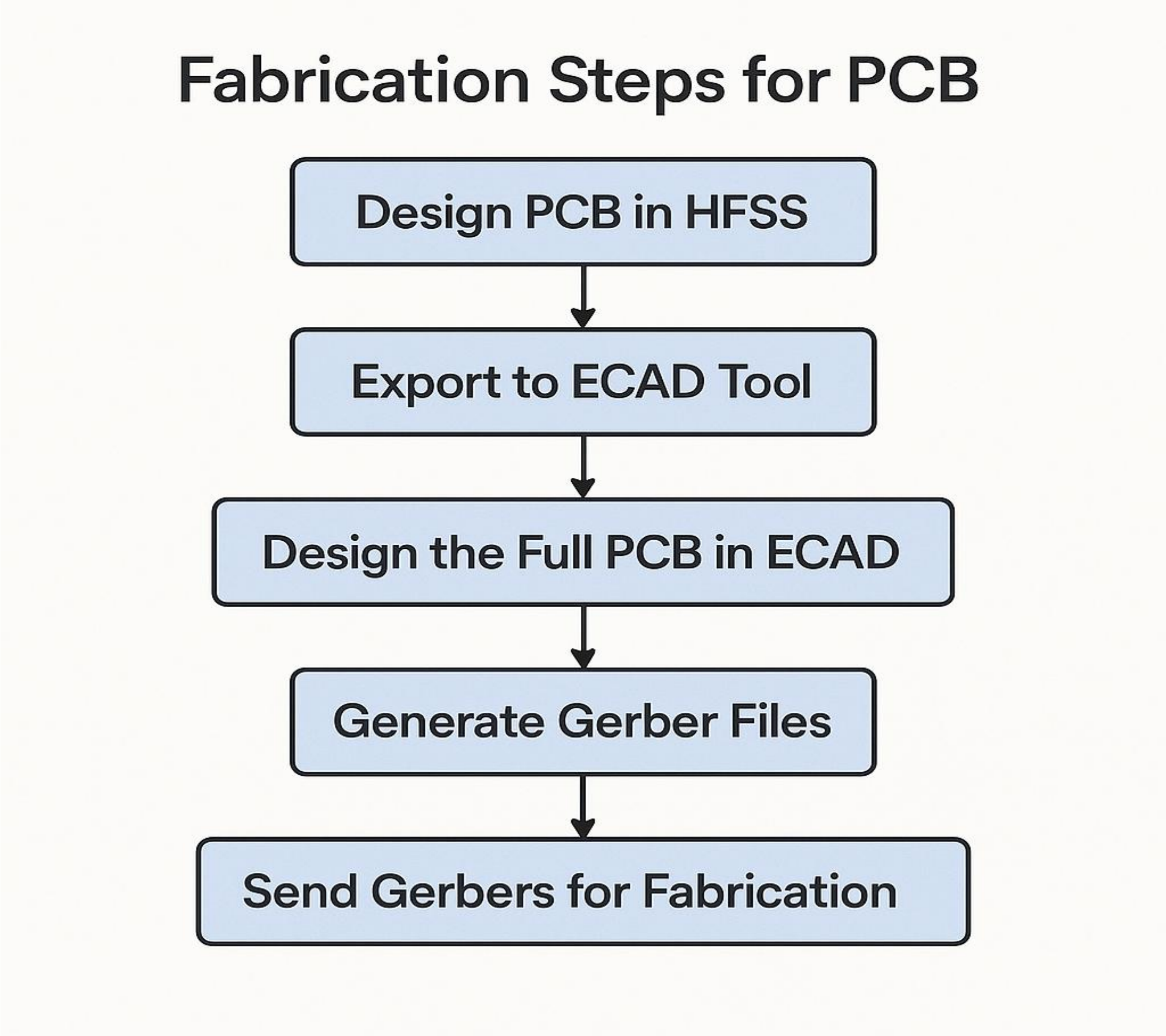




High-Frequency Structure Simulator (HFSS)

- HFSS is a 3D full-wave electromagnetic field simulator developed by Ansys Inc. It uses advanced numerical methods to solve Maxwell's equations, which govern how electric and magnetic fields behave.


Planar RF Sensors Design in HFSS
Define Specifications & Requirements
Select Geometry & Sensor Type
Create Geometry in HFSS
Assign Material Properties
Setup Boundaries & Excitations
Meshing
Simulation Setup
Run Simulation
Optimization (Optional)
Finalize Design & Documentation
Fabrication & Testing (Post–Design)



ECAD tool (Electronic Computer-Aided Design tool)

Final PCB ready for experiment

These two images specifically depict interdigitated capacitor (IDC) sensors after the fabrication process.