3.1 Superposition, Boundary Conditions, and Modes

Let's step back into the field view and see how guided waves form, what boundary conditions are, how modes arise, and how planar transmission lines like microstrip and stripline channel energy. This is the bridge between Maxwell's equations and the transmission-line models we've been using.

Let's ask ourselves a fundamental question, what *are* boundary conditions and modes?

Boundary conditions are the physical or electromagnetic constraints at the edges or interfaces of a structure where the electric and magnetic field must satisfy (imposed by material properties and geometry). These conditions dictate how fields behave at the surfaces of waveguides, resonators, and antennas. They restrict the possible field configurations that can exist inside of a structure. My brother, CJ, is a musician and is super good at guitar, so I'm going to dedicate this analogy to him. Imagine a guitar string stretched tightly between two fixed points (the ends of the fret board). The fact that the string is nailed down at both ends is a *boundary condition*. No matter how the string vibrates, it must be motionless at both ends. Those endpoints in and of themselves constrain how the string is allowed to move. This is exactly what boundary conditions due in electromagnetics. They define how the fields behave at the edges of a region. Essentially, they're rules the fields must obey at those borders. In order for the string to vibrate, the ends must be stationary at either end. They can't move. It's a condition that must be satisfied in order to play the guitar.

Modes on the other hand are distinct field patterns that satisfy Maxwell's equations **and** the boundary conditions of the structure. Think modes like the "natural vibration shapes" of EM fields in a structure, just like a guitar string has natural vibration modes. They tell you how energy flows as waves.

Now, let's combine the two with this guitar analogy. The frets and string tension set the boundary condition and the possible vibrations are the modes - each with its own pitch and shape.

Why does this matter? Without boundary conditions, you'd have no control over where the energy goes, how the signal reflects, or how efficiently a system works. Modes are important, because they are the allowed field patterns that can exist in a structure - very similar to how musical notes are allowed vibrations on a guitar string.

Together, boundary conditions and modes determine which frequencies can propagate, control signal integrity and impedance matching which are all essential for RF component design such as filters, antennas, and transmission lines.

3.2. Guided Waves and Planar Geometries

While plane waves are great in terms of explaining wave propagation in free space and through different general mediums such as a vacuum, water, and copper. What plane waves don't do a great job explaining is how to characterize these waves while they are propagating through RF PCB substrates and microstrip/stripline configurations. Superposition's of plane waves do. Let's first outline the most typical RF PCB planar geometries - stripline and microstrip.

3.2.1 Stripline

Stripline is one of the most common RF PCB (printed circuit board) geometries. Striplines can be miniaturized and these circuits can be fabricated/manufactured using very accurate photolithographic/etching processes. For those who aren't familiar, photolithography is the process of printing an image onto a material (substrate) using some sort of resistive film and then electroplating copper with the resistive photo printed film. Take away this film using some sort of chemistry and you have a perfect copper circuit based on whatever the image was before it was stripped away. Etching on the other hand takes away any unwanted copper and can be accurately controlled based on the chemistry being dispensed onto the PCB. Since the electrical wavelength is on the order of the circuit due to the high frequencies, these circuits need to be exceptionally accurate to reflect the design (certain linewidths, stub length, etc.). It's safe to say that a lot of designs and advances in modern RF Engineering and design would not be possible if these processes did not exist and/or produced crude results.

Stripline is a conducting strip such as copper of width, w, and is centered between two conductive ground planes and is surrounded/filled with a dielectric medium. In other words, the actual signal stripline is embedded and the signal transmission line is not exposed to multiple dielectric mediums - air and whatever the substrate the circuit has been printed on. This means the entire electric field is encapsulated in the dielectric medium and stays in the region around the center conductor. Since the signal trace is embedded and surrounded by a singular dielectric medium (in basic cases), the guided wave mode of propagation is purely TEM (transverse electromagnetic). Also, stripline geometries can introduce higher-order modes of propagation which isn't desirable. To mitigate this, a spacing of $\lambda_g/2$ is applied to suppress parallel-plate higher-order modes between the ground planes. This isn't a strict design rule - it's a guideline to suppress parallel-plate higher-order modes. Also, shorting vias can be added to mitigate these higher-order modes which can lead to negative effects on the signal. These examples utilize an electrostatic, curve-fit approximation approach and are very accurate (accurate to a couple percent). So the reader is aware, stripline impedance follows the Wheeler approximation for symmetric stripline [Wadell, Ch. 4]. Attenuation is estimated using first-order closed-form expressions suitable for trend comparison [Pozar, Ch. 3; Wadell, Ch. 6]. Laplace's equations can be used to paint a more accurate picture, but we are not looking to create an EMI solver utilizing Laplace's equations. Just looking to get an accurate approximation.