Chapter 2
Basic Physical Principles

‘If we knew what it was we were doing, it would not be called research, would it?’.
Albert Einstein

Abstract. In this chapter, the basic concepts behind broadband microwave reflectometry (BMR) are recalled. First, a brief overview of the transmission line theory is provided, and the most common electromagnetic structures are introduced. Secondly, the major parameters that are used to characterize electrical networks are introduced, and the related theoretical background is briefly discussed. Finally, a short overview on dielectric spectroscopy is provided, thus anticipating its connection with reflectometric measurements.

2.1 Transmission Line Basics

In electric circuits, when the wavelength of the propagating signal is large compared to the physical dimensions of the system, the electrical characteristics of the system, at a given time, can be assumed to be the same at all points (lumped-element model). On the other hand, when the physical dimensions of the system are comparable to the wavelength of the propagating signal, the dimensions of the cables, connectors and other components cannot be ignored: in such cases, it is particularly useful to model the system through transmission line (TL) segments.

TLs are typically used to transfer a signal from the generator to the load, by guiding the electromagnetic (EM) signal between two conductors [5]. A TL is a distributed-parameter network and must be described by circuit parameters that are distributed throughout its length. For the purposes of analysis, a TL can be modeled as a two-port network. The model represents the transmission line as an infinite series of two-port elementary components, each representing an infinitesimal segment of the transmission line. The elementary section of a TL can be modeled as shown in Fig. 2.1. This model includes four parameters, referred to as primary line constants, which are generally defined ‘per unit length’. The primary line constants are the series resistance ($R$), the series inductance ($L$), the shunt conductance ($G$), and the shunt capacitance ($C$). For a uniform transmission line, the primary line constants do not change with distance along the line. These constants are used to
For an infinitely long line, the characteristic impedance $Z_0$ (which is defined as the ratio of voltage $V$ to current $I$ in any position) can be written as

$$Z_0 = \sqrt{\frac{R + i\omega L}{G + i\omega C}} \quad (2.1)$$

where $\omega = 2\pi f$ is the angular frequency and $i^2 = -1$.

The propagation coefficient is given by

$$\gamma = \sqrt{(R + i\omega L)(G + i\omega C)} \quad (2.2)$$

It is useful to separate the imaginary part ($\beta$), which gives the phase-shift coefficient, from the real part ($\alpha$), which gives the attenuation coefficient:

$$\alpha \approx \frac{R}{2Z_0} + \frac{GZ_0}{2} \quad (2.3)$$

$$\beta \approx \omega \sqrt{LC} \quad (2.4)$$

For a lossless TL (i.e., when $R \approx 0$ and $G \approx 0$), $Z_0$ can be written simply as

$$Z_0 \approx \sqrt{\frac{L}{C}} \quad (2.5)$$

From (2.5), it can be seen that for a lossless TL, the characteristic impedance is purely resistive, although given by reactive elements ($C$ and $L$). It is important to point out that this does not mean that the line is a resistance.

In the following subsections, the most common types of TLs are considered, namely coaxial, two-wire, and microstrip.

### 2.1.1 Coaxial Transmission Line

Coaxial lines are made of a central conductor with diameter $a$ and a hollow outer conductor with inner diameter $b$. The space between the conductors is usually filled with a dielectric material: the electric and magnetic fields are confined within the