CHAPTER 1

INTRODUCTION TO BALANCED TRANSMISSION LINES, CIRCUITS, AND NETWORKS

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1.1 INTRODUCTION

This chapter is an introduction to the topic of balanced lines, circuits, and networks. The main objectives are (i) to point out the advantages and limitations of balanced versus unbalanced systems; (ii) to analyze the origin and effects of the main source of noise in differential systems, that is, the common-mode noise; (iii) to provide the fundamentals of

Balanced Microwave Filters, First Edition. Edited by Ferran Martín, Lei Zhu, Jiasheng Hong, and Francisco Medina.

differential transmission lines, with special emphasis on microstrip lines (the most common), including the main topologies and fundamental propagating modes; and (iv) to present the mixed-mode scattering parameters, suitable for microwave differential circuit characterization. We will also point out the two main approaches for the implementation of balanced microwave filters with common-mode noise suppression (end of Section 1.3), which will be further discussed along this book.

1.2 BALANCED VERSUS SINGLE-ENDED TRANSMISSION LINES AND CIRCUITS

Unbalanced systems transmit single-ended signals. In such systems, one of the two conductors is connected to the common ground, being the signal referenced to ground. Alternatively, signal propagation can be made on the basis of balanced or differential systems, where each wire (or conductor) has the same impedance to the circuit common, which is typically grounded. Differential signals are transmitted as complementary pairs, driving a positive voltage on one wire and an equal but opposite voltage on the other wire. The signal of interest is the potential difference between the two conductors, called differential-mode signal, which is no longer referenced to ground [1].

The main advantages of differential over single-ended signals are lower electromagnetic interference (EMI) and higher immunity to electromagnetic noise and crosstalk. Due to the previous advantages, a better signal integrity and a higher signal-to-noise ratio (SNR) can be achieved in differential systems [2, 3]. The cancelation of the fields, resulting from opposite current flowing, is the reason for the low EMI in differential systems [4]. The high noise immunity is related to the fact that voltages and currents induced from interfering sources (noise) tend to be identical on both conductors, and hence this noise couples to the differential line as a common-mode signal (to be discussed later in this chapter) [1, 3, 5]. The main drawback of differential systems is the need for balanced circuits and interconnects (transmission lines),[1] representing further complexity in terms of layout and number of elements [6].

Traditionally, differential circuits have been used in low-frequency analog and digital systems. In radio-frequency (RF) and microwave applications, unbalanced structures have dominated the designs for decades and are still more common than differential circuits. Nevertheless,

[1] Note that a complete differential system involves a differential transmitter, a differential interconnect, and a differential receiver.

recent technological advances are pushing differential circuits into the RF and microwave frequency domain [7]. Thus, balanced lines and devices are becoming increasingly common in high-speed digital circuits, as well as in modern balanced communication systems [8, 9].

1.3 COMMON-MODE NOISE

In differential transmission lines and circuits, the main contribution to noise is the so-called common-mode noise [1]. Common-mode noise is originated from electromagnetic radiation (through crosstalk or through an external source) and from the ground terminal [3, 10, 11]. Moreover, common-mode signals (also viewed as noise for the differential signals) can also be generated as consequence of time skew, amplitude unbalance, and/or different rising/falling times of the differential signals. These latter effects are ultimately caused by imperfect balance, resulting in conversion from the differential mode to the common mode. Similarly, in practice, conversion from the common mode to the differential mode always exists. Therefore, a perfect balance of the two signal conductors with respect to the reference conductor is necessary to avoid (or minimize) the conversion from common-mode noise to differential-mode noise (always representing a degradation in signal integrity).

Although, ideally, the differential mode is fully independent of the common mode, in actual differential systems, the circuits are sensitive to the common mode (e.g., in differential-mode receivers, the common-mode noise is rejected up to a certain limit that defines the ability of the receiver to work properly up to a defined amount of common-mode noise) [3]. The presence of common-mode signals in differential lines and circuits may also cause radiated emission [3]. The reason is that common-mode currents flow in the same direction (contrary to differential-mode currents, which flow in opposite directions, thus preventing far-field radiation, provided the two conductors are closely spaced). A method to reduce dramatically common-mode radiated emission is to place a metallic plane beneath and parallel to the differential line pair [3]. Such metallic plane produces image currents flowing in opposite direction to the original common-mode currents, generating fields that tend to cancel the fields resulting from the original wires. Nevertheless, due to the limited dimensions of the ground plane, a perfect image is not achieved, causing the ground plane to radiate.

Due to the negative effects of common-mode noise in differential systems (mainly signal integrity degradation and common-mode radiation), it must be reduced as much as possible. Traditionally, solutions that use common-mode chokes with high permeability ferrite cores have been proposed [12–14], but chokes represent a penalty in terms of size and frequency operating range, not being useful for high-speed, high-density, and microwave systems. Recently, many approaches fully compatible with planar fabrication technology for the design of differential lines able to suppress the common mode in the range of interest, and simultaneously preserving the integrity of the differential signals, have been reported. These common-mode filters are exhaustively reviewed in Chapter 2. Such filters may be used not only for differential-mode interconnects but also to improve the common-mode rejection of balanced bandpass filters by cascading both components, as will be pointed out in Chapter 3. Nevertheless, the design of balanced filters with inherent (and efficient) common-mode suppression without the need to cascade common-mode filters is by far the optimum solution for common-mode suppressed microwave filters, the main objective of this book (Parts III and IV of this book are dedicated to this topic).

1.4 FUNDAMENTALS OF DIFFERENTIAL TRANSMISSION LINES

Since most of the balanced filters and circuits studied in this book are implemented in microstrip technology, the present analysis is entirely focused on microstrip differential lines. Such lines are able to propagate both differential- and common-mode signals. Therefore, a comprehensive analysis of both modes is carried out in this section. The first part of the section is devoted to the topology of these lines.

1.4.1 Topology

Transmission lines may be classified according to the currents flowing on it. For comparative purposes let us first consider a two-wire unbalanced transmission line (see Figure 1.1a). In such lines, the conductors have different impedance to ground, and they are fed by single-ended ports

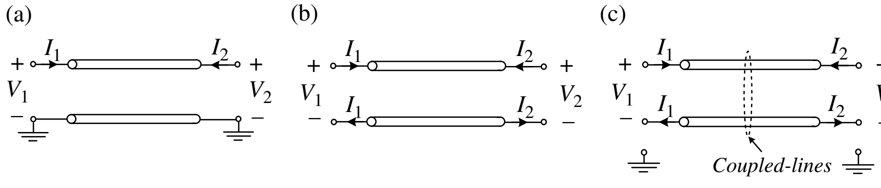

Figure 1.1 Schematic of two-port transmission lines. (a) Two-wire unbalanced line; (b) two-wire balanced line; (c) three-wire balanced line.

in which there are an active terminal and a ground terminal (or, equivalently, one of the conductors is fed, whereas the other one is tied to ground potential) [15]. One conductor is used for transporting signal current and the other one is the return current path. By contrast, in a two-wire balanced line (Figure 1.1b), the conductors have equal potential respect to ground with 180° phase shift [16]. The signal on one line is referenced to the other, which means that each conductor provides the signal return path for the other and the currents flowing on the conductors have the same magnitude but opposite direction. Such lines are fed by differential ports consisting of two terminals, neither of which is explicitly tied to ground. In a balanced line, also called differential line, the conductors have the same impedance to ground, if it exists. It is important to highlight that the nature (balanced or unbalanced) of a transmission line is determined by the currents, not only by the physical structure. Essentially, a balanced line carries balanced currents. Microstrip lines (Figure 1.2a), coplanar waveguides (CPW), and coaxial lines are well-known examples of two-wire unbalanced lines. Conversely, coplanar strips (CPS), such as those depicted in Figure 1.2(b), or slotlines are balanced structures by nature. Nevertheless, these balanced lines can be regarded as either balanced or unbalanced depending on whether the feeding is either balanced or unbalanced, respectively [15].

Most practical implementations of balanced lines incorporate a third conductor acting as a ground plane. Such three-wire line is composed of

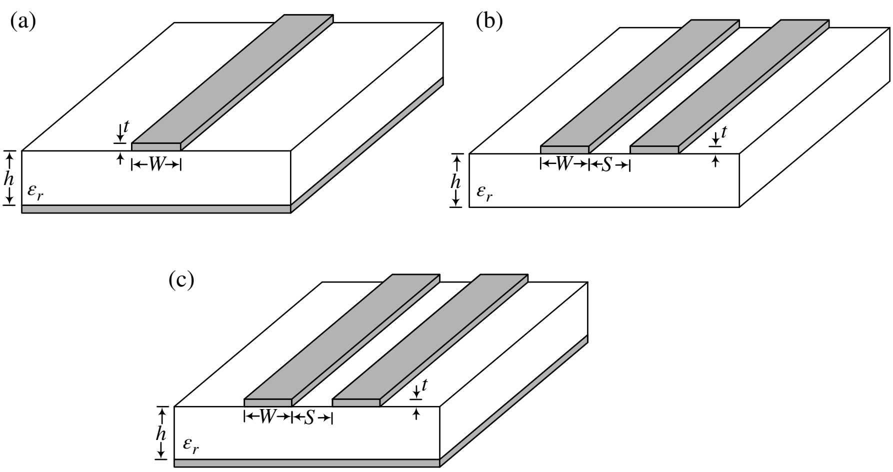

Figure 1.2 Examples of two-port transmission lines. (a) Microstrip line as an example of a two-wire unbalanced line; (b) coplanar strips (CPS) as an example of a two-wire balanced line; (c) symmetric microstrip coupled lines as an example of a three-wire balanced line.

a pair of coupled lines over a ground plane (Figure 1.1c). If this is not perfectly balanced due to the presence of the ground plane, currents flowing on it can unbalance the currents on the wires. Conversely, if the three-wire structure is perfectly balanced, the active wires carry equal and opposite currents because the impedances of each line to ground are identical. Figure 1.2(c) is an example of a three-wire balanced line, implemented by means of a pair of coupled microstrip lines. It can also be seen as a CPS transmission line with a ground plane.

1.4.2 Propagating Modes

Three-wire balanced transmission lines support two fundamental propagation modes: the balanced mode and the unbalanced mode.[2] The balanced or differential mode is the fundamental mode, equivalent to the so-called odd mode, in which the line is driven differentially. The unbalanced mode, also called common mode, is equivalent to the so-called even mode. In the common mode, equal signals (in magnitude and phase) propagate at both individual lines. For the balanced structure of Figure 1.2(c), all these modes are quasi-TEM modes [16], provided the separation between the ground plane and the lines (substrate thickness) is very small as compared with the wavelength. Let us now discuss the subtle differences between the even/odd modes and the common/differential modes, which are indeed related to signal definitions.

1.4.2.1 Even and Odd Mode Differential microstrip lines support two quasi-TEM modes, that is, the even and odd modes. These modes may be present in the differential line simultaneously, which means that these lines propagate hybrid even- and odd-mode waves. The resulting wave is hence a superposition of the even and odd modes [8], both generally with different amplitudes. From linearity assumptions, it follows that an arbitrary excitation in microstrip differential lines can be decomposed into the fundamental modes or treated as a superposition of appropriate amplitudes of such even and odd modes.

The differential microstrip line of Figure 1.2(c) can be considered to be composed of four single-ended ports. Therefore, a single-ended, or unbalanced, signal referenced to the ground potential can be generated at each of these ports. Figure 1.3 illustrates the single-ended voltages and currents for the even and odd modes in a differential microstrip line. Let us assume that the lines are appropriately terminated by a source/load single-ended reference (matched) impedance, Z_0, such that no reflections exist. Under

[2] Contrarily, two-wire balanced transmission lines support only the balanced mode.

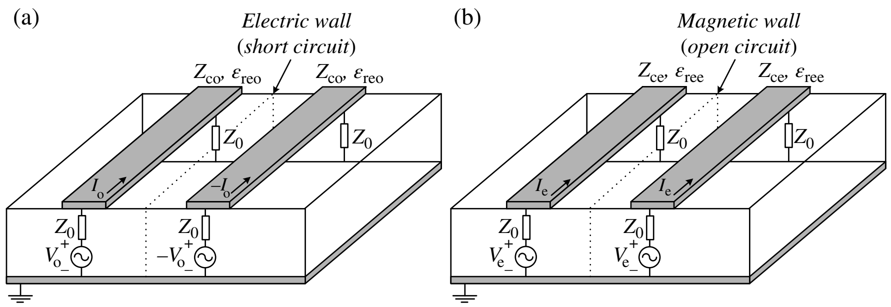

Figure 1.3 Voltages and currents in a differential microstrip line and generation of the odd (a) and even (b) modes.

these conditions, we can consider only the propagation of forward waves. The odd and even voltages are defined, respectively, as [17]

$$V_\mathrm{o} = \frac{1}{2}(V_1 - V_2) \tag{1.1a}$$

$$V_\mathrm{e} = \frac{1}{2}(V_1 + V_2) \tag{1.1b}$$

whereas the odd and even currents are given by

$$I_\mathrm{o} = \frac{1}{2}(I_1 - I_2) \tag{1.2a}$$

$$I_\mathrm{e} = \frac{1}{2}(I_1 + I_2) \tag{1.2b}$$

In the previous expressions, V_1 (V_2) and I_1 (I_2) are the voltage and current, respectively, in line 1 (line 2) of the differential pair. Note that for the pure fundamental modes, it follows that $V_\mathrm{o} = V_1 = -V_2$ and $V_\mathrm{e} = 0$ for the odd mode and $V_\mathrm{o} = 0$ and $V_\mathrm{e} = V_1 = V_2$ for the even mode. Similar results are obtained for the currents.

The characteristic impedance of each mode can be computed as the ratio between voltage and the current on each line. The odd-mode characteristic impedance is defined as the impedance from one line to ground when both lines are driven out of phase from identical sources of equal impedances and voltages (or currents), that is, odd-mode excitation, as shown in Figure 1.3(a):

$$Z_\mathrm{co} = \frac{V_\mathrm{o}}{I_\mathrm{o}} \tag{1.3a}$$

Similarly, the even-mode characteristic impedance is the impedance from one line to ground when both lines are driven in phase with identical sources and impedances, as depicted in Figure 1.3(b):

$$Z_{\mathrm{ce}} = \frac{V_{\mathrm{e}}}{I_{\mathrm{e}}} \tag{1.3b}$$

These odd- and even-mode characteristic impedances can be expressed as [16]

$$Z_{\mathrm{co}} = \frac{1}{v_{\mathrm{po}} C_{\mathrm{o}}} = \frac{1}{c\sqrt{C_{\mathrm{o}} C_{0\mathrm{o}}}} \tag{1.4a}$$

$$Z_{\mathrm{ce}} = \frac{1}{v_{\mathrm{pe}} C_{\mathrm{e}}} = \frac{1}{c\sqrt{C_{\mathrm{e}} C_{0\mathrm{e}}}} \tag{1.4b}$$

where c is the speed of light in vacuum; C_{o} and C_{e} are the per-unit-length odd- and even-mode capacitances, respectively; $C_{0\mathrm{o}}$ and $C_{0\mathrm{e}}$ denote the per-unit-length odd- and even-mode capacitance, respectively, of each line by replacing the relative dielectric constant of the substrate by unity; and v_{po} and v_{pe} are the odd- and even-mode phase velocities, given by

$$v_{\mathrm{po}} = \frac{c}{\sqrt{\varepsilon_{\mathrm{re,o}}}} \tag{1.5a}$$

$$v_{\mathrm{pe}} = \frac{c}{\sqrt{\varepsilon_{\mathrm{re,e}}}} \tag{1.5b}$$

where the effective dielectric constants for the odd and even mode are, respectively [16],

$$\varepsilon_{\mathrm{re,o}} = \frac{C_{\mathrm{o}}}{C_{0\mathrm{o}}} \tag{1.6a}$$

$$\varepsilon_{\mathrm{re,e}} = \frac{C_{\mathrm{e}}}{C_{0\mathrm{e}}} \tag{1.6b}$$

In general, the even and odd modes exhibit different characteristic impedances and effective dielectric constants. However, the values are identical if the lines are uncoupled. In this case (uncoupled lines), the characteristic impedance is the same than the one of the individual (isolated) line.[3]

1.4.2.2 Common and Differential Mode

The differential and common modes are quasi-TEM modes equivalent to the odd and even mode, respectively. The difference between such modes comes just from signal definitions. In the differential and common modes, two single-ended ports are driven as a pair that is called composite port [8]. Any single-ended signal pair applied to a composite port can be decomposed into its differential- and common-mode portions [7], which are equivalent (but not equal) to the odd and even portions, respectively.

The decomposition of hybrid differential- and common-mode voltages and currents into its differential and common-mode portions is depicted in Figure 1.4. Let us assume that the lines are appropriately terminated (so that only forward waves are present in the lines) by a differential source/load reference impedance Z_{0d} (for the differential mode) and by a common source/load reference impedance Z_{0c} (for the common mode). The differential voltage is defined as the difference between the voltages in the pair of lines [7]:

$$V_d = V_1 - V_2 \tag{1.7}$$

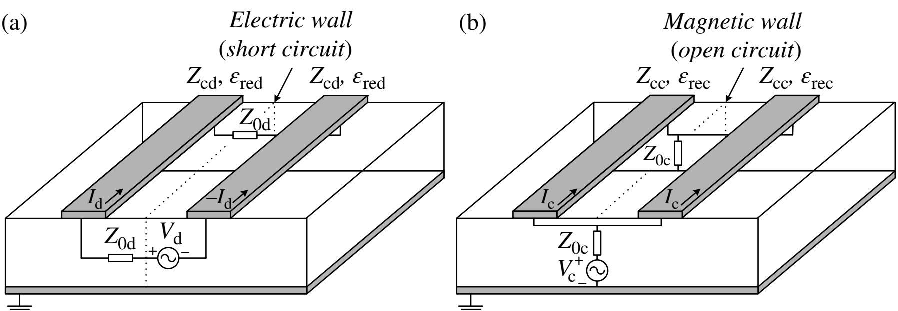

Figure 1.4 Voltages and currents in a differential microstrip line and generation of the differential (a) and common (b) modes.

[3] Note that the definition of Z_0 in Figure 1.3 corresponds to Z_{co} (Figure 1.3a) and Z_{ce} (Figure 1.3b), not to the characteristic impedance of the isolated line. Z_{co} and Z_{ce} are indeed the characteristic impedances of the isolated line with the presence of an electric wall and magnetic wall, respectively, in the symmetry plane of the lines. Unless the lines are uncoupled, there is not a single-ended impedance, Z_0, that guarantees lack of reflections at the output ports (i.e., matching), regardless of the single-ended signals injected at the input ports. To this end, a π-network is necessary, and such network is composed by the impedance Z_{ce} in the shunt branches and by the impedance $2Z_{ce}Z_{co}/(Z_{ce} - Z_{co})$ in the series branch.

With this definition, the signal is no longer referenced to ground potential. Rather than this, the signal on one line is referenced to the other. The magnitude of the current entering a single-ended port is expected to be the same than the one leaving the other single-ended port. Hence, the differential-mode current is defined as one half the difference between currents entering the single-ended ports [7]:

$$I_{\mathrm{d}} = \frac{1}{2}(I_1 - I_2) \tag{1.8}$$

The common-mode voltage is defined as the average between the voltages at each line, whereas the common-mode current is given by the total current flowing on the lines,[4] that is,

$$V_{\mathrm{c}} = \frac{1}{2}(V_1 + V_2) \tag{1.9}$$

$$I_{\mathrm{c}} = I_1 + I_2 \tag{1.10}$$

According to the previous definitions, the voltages and currents for the differential and common mode are related to those for the odd and even mode as follows:

$$V_{\mathrm{d}} = 2V_{\mathrm{o}} \tag{1.11a}$$

$$I_{\mathrm{d}} = I_{\mathrm{o}} \tag{1.11b}$$

$$V_{\mathrm{c}} = V_{\mathrm{e}} \tag{1.11c}$$

$$I_{\mathrm{c}} = 2I_{\mathrm{e}} \tag{1.11d}$$

The differential-mode characteristic impedance is defined as the impedance between the pair of lines when both lines are driven out of phase from equal sources of equal impedances and voltages (or currents). The common-mode characteristic impedance is defined as the impedance seen from both lines to ground. The characteristic impedances for the differential and common mode can be expressed in terms

[4] Note that the return current for the common-mode signal flows through the ground plane. Ideally, in a pure differential signal, $V_1 = -V_2$ and $I_1 = -I_2$, and the common mode is canceled.

of the characteristic impedances for the even and odd modes (ground referenced) according to [7]

$$Z_{\mathrm{cd}} = 2Z_{\mathrm{co}} \tag{1.12a}$$

$$Z_{\mathrm{cc}} = \frac{Z_{\mathrm{ce}}}{2} \tag{1.12b}$$

Note that the differential- and common-mode reference impedances of Figure 1.4 are indeed those given by 1.12(a) and 1.12(b), respectively.

1.5 SCATTERING PARAMETERS

The scattering parameters (*S*-parameters), or scattering matrix (*S*-matrix), are typically used for the characterization of microwave networks. These parameters give relative information of the amplitude and phase of the transmitted and reflected wave with reference to incident wave, at least in the small-signal limit (linear regime). Let us first present the single-ended *S*-parameters, applicable to any arbitrary network, and then the mixed-mode *S*-parameters, specific of differential networks. The relation between these sets of parameters will be given at the end of this section.

1.5.1 Single-Ended *S*-Parameters

Single-ended *S*-parameters provide characterization for networks driven by single-ended or unbalanced signals. A conceptual diagram of single-ended *S*-parameters, providing the so-called single-ended *S*-matrix, $\mathbf{S_{se}}$, for a four-port structure is depicted in Figure 1.5. Such parameters satisfy

$$\mathbf{b_{se}} = \mathbf{S_{se}} \cdot \mathbf{a_{se}} \rightarrow \begin{pmatrix} b_1 \\ b_2 \\ b_3 \\ b_4 \end{pmatrix} = \begin{pmatrix} S_{11} & S_{12} & S_{13} & S_{14} \\ S_{21} & S_{22} & S_{23} & S_{24} \\ S_{31} & S_{32} & S_{33} & S_{34} \\ S_{41} & S_{42} & S_{43} & S_{44} \end{pmatrix} \begin{pmatrix} a_1 \\ a_2 \\ a_3 \\ a_4 \end{pmatrix} \tag{1.13}$$

where a_i and b_i are the normalized voltages corresponding to waves entering $\left(V_i^+\right)$ or being reflected $\left(V_i^-\right)$ from the different ports, respectively, that is,

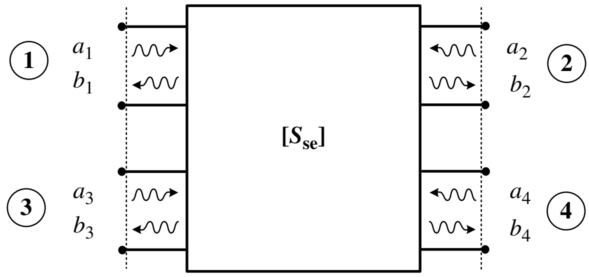

Figure 1.5 Single-ended four-port circuit described by the single-ended *S*-parameter matrix and indication of the normalized voltages (a_i, b_i) at device ports.

$$a_i = \frac{V_i^+}{\sqrt{Z_0}};\ b_i = \frac{V_i^-}{\sqrt{Z_0}} \tag{1.14}$$

For the calculation of the *S*-parameters, all ports except the stimulus port must be terminated with the port reference impedance Z_0 (matched port).[5]

If the considered network is symmetric, it can be bisected into two identical halves with respect to the symmetry plane. Using the symmetry properties [16, 18], the analysis of the *N*-port network is reduced to the analysis of two *N*/2-port networks. Particularly, the analysis of symmetric differential lines driven by single-ended four ports is reduced to the analysis of two single-ended two-port networks. As indicated in Figure 1.6(a), when an odd excitation is applied to the network, the symmetry plane is an electric wall (short circuit), and the two halves become the same two-port network, namely, the odd-mode network, with *S*-matrix defined as

$$\mathbf{S_o} = \begin{pmatrix} S_{11}^{\mathrm{o}} & S_{21}^{\mathrm{o}} \\ S_{12}^{\mathrm{o}} & S_{22}^{\mathrm{o}} \end{pmatrix} \tag{1.15}$$

Similarly, under an even excitation (Figure 1.6b), the symmetry plane is a magnetic wall (open circuit), and the two identical halves constitute the even-mode network, with scattering matrix given by

$$\mathbf{S_e} = \begin{pmatrix} S_{11}^{\mathrm{e}} & S_{21}^{\mathrm{e}} \\ S_{12}^{\mathrm{e}} & S_{22}^{\mathrm{e}} \end{pmatrix} \tag{1.16}$$

[5] We assume that the reference impedance is identical in all ports.

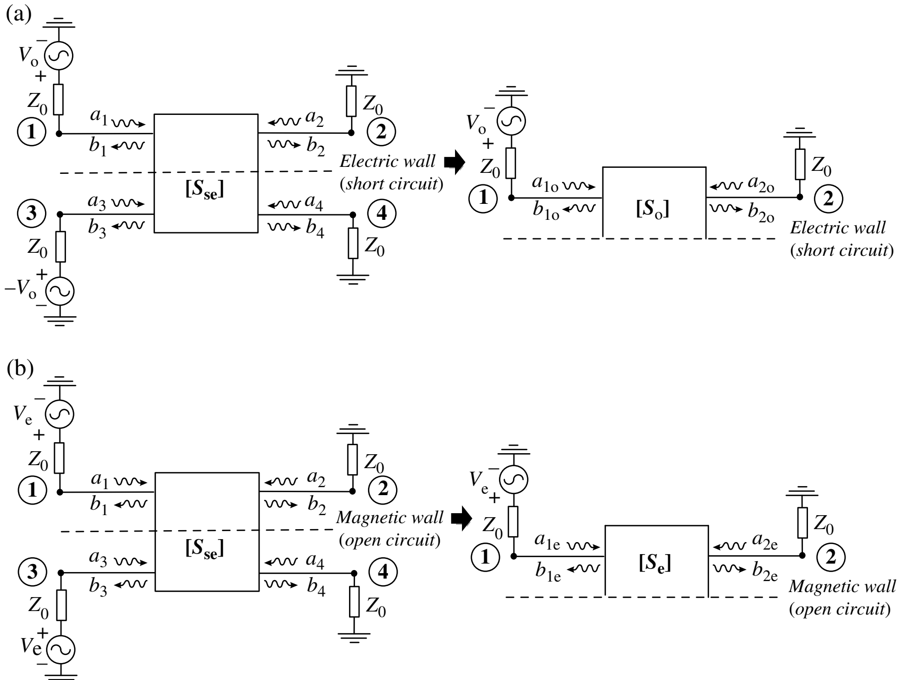

Figure 1.6 Single-ended *S*-parameters in a symmetric single-ended four-port network under (a) odd- and (b) even-mode excitations. The four-port circuit is reduced to two two-port circuits.

On the other hand, from symmetry considerations, it follows that the four-port *S*-matrix of the symmetric differential lines can be expressed as [16]

$$\mathbf{S_{se}} = \begin{pmatrix} \mathbf{S_A} & \mathbf{S_B} \\ \mathbf{S_B} & \mathbf{S_A} \end{pmatrix} \tag{1.17}$$

where $\mathbf{S_A}$ and $\mathbf{S_B}$ are order-2 matrices. For odd-mode excitation, the normalized voltages at both sides of the symmetry plane are identical in magnitude and have different sign. The resulting order-4 matrix equation can be reduced to an order-2 matrix equation. By comparing $\mathbf{S_o}$ with the such matrix, it follows that

$$\mathbf{S_o} = \mathbf{S_A} - \mathbf{S_B} \tag{1.18}$$

For even-mode excitation, it follows that

$$\mathbf{S_e} = \mathbf{S_A} + \mathbf{S_B} \tag{1.19}$$

From (1.18) and (1.19), one obtains

$$\mathbf{S_A} = \frac{1}{2}(\mathbf{S_e} + \mathbf{S_o}) \tag{1.20a}$$

$$\mathbf{S_B} = \frac{1}{2}(\mathbf{S_e} - \mathbf{S_o}) \tag{1.20b}$$

and the single-ended S-matrix can be expressed as [16]

$$\mathbf{S_{se}} = \frac{1}{2}\begin{pmatrix} S_{11}^{e} + S_{11}^{o} & S_{12}^{e} + S_{12}^{o} & S_{11}^{e} - S_{11}^{o} & S_{12}^{e} - S_{12}^{o} \\ S_{21}^{e} + S_{21}^{o} & S_{22}^{e} + S_{22}^{o} & S_{21}^{e} - S_{21}^{o} & S_{22}^{e} - S_{22}^{o} \\ S_{11}^{e} - S_{11}^{o} & S_{12}^{e} - S_{12}^{o} & S_{11}^{e} + S_{11}^{o} & S_{12}^{e} + S_{12}^{o} \\ S_{21}^{e} - S_{21}^{o} & S_{22}^{e} - S_{22}^{o} & S_{21}^{e} + S_{21}^{o} & S_{22}^{e} + S_{22}^{o} \end{pmatrix} \tag{1.21}$$

The single-ended reference impedance is usually $Z_0 = 50\,\Omega$. Since in a differential microstrip line the characteristic impedances of the even and odd modes are in general different, it follows that both modes cannot be, in general, matched simultaneously to that reference impedance.

1.5.2 Mixed-Mode *S*-Parameters

A differential microwave network consists of and can be analyzed by an even number of N single-ended ports or $N/2$ composite ports (i.e., two single-ended ports driven as a pair [19, 20]). While standard S-parameters (1.13) or (1.21) for a symmetric network can be used to characterize the network, they do not provide information about the propagation properties for the differential and common modes. The simultaneous propagation of differential and common mode is referred to as mixed-mode propagation [7]. Mixed-mode S-parameters are convenient for microwave differential circuit characterization. In this chapter, the mixed-mode S-parameters are limited to the two-port case, but the generalized theory for N-port circuits can be found in Ref. [19].

A conceptual diagram of mixed-mode S-parameters in a differential two-port circuit is shown in Figure 1.7. These mixed-mode S-parameters can be seen as corresponding to a traditional four-port network where two single-ended ports are driven as a pair. However, these four ports

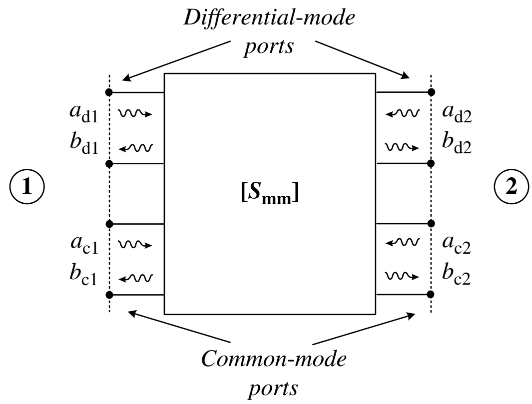

Figure 1.7 Conceptual diagram of mixed-mode S-parameters in a differential two-port network.

are conceptual tools only, rather than physically separated ports. Mixed-mode S-parameters can be arranged in matrix form as [7, 8, 20]

$$\mathbf{b_{mm}} = \mathbf{S_{mm}} \cdot \mathbf{a_{mm}} \rightarrow \begin{pmatrix} b_{d1} \\ b_{d2} \\ b_{c1} \\ b_{c2} \end{pmatrix} = \begin{pmatrix} S_{11}^{dd} & S_{12}^{dd} & S_{11}^{dc} & S_{12}^{dc} \\ S_{21}^{dd} & S_{22}^{dd} & S_{21}^{dc} & S_{22}^{dc} \\ S_{11}^{cd} & S_{12}^{cd} & S_{11}^{cc} & S_{12}^{cc} \\ S_{21}^{cd} & S_{22}^{cd} & S_{21}^{cc} & S_{22}^{cc} \end{pmatrix} \begin{pmatrix} a_{d1} \\ a_{d2} \\ a_{c1} \\ a_{c2} \end{pmatrix} \tag{1.22}$$

where b_{di} and b_{ci} are the normalized differential- and common-mode voltages corresponding to waves reflected from the two-port differential network ($i = 1,2$) and a_{di} and a_{ci} are the same variables but for waves impinging the network. In order to calculate the S-parameters, all ports except the stimulus port must be terminated with the port reference impedance, Z_{0d} (for the differential mode), or Z_{0c} (for the common mode). The mixed-mode S-matrix can be expressed as [7, 8]

$$\mathbf{S_{mm}} = \begin{pmatrix} \mathbf{S^{dd}} & \mathbf{S^{dc}} \\ \mathbf{S^{cd}} & \mathbf{S^{cc}} \end{pmatrix} \tag{1.23}$$

where $\mathbf{S^{dd}}$ is the differential-mode S-parameter matrix (Figure 1.8a), $\mathbf{S^{cc}}$ is the common-mode S-matrix (Figure 1.8b), and $\mathbf{S^{dc}}$ and $\mathbf{S^{cd}}$ are the mode-conversion or cross-mode S-matrices. The interpretation of the previous matrices is very clear: $\mathbf{S^{dd}}/\mathbf{S^{cc}}$ determine the differential-/common-mode responses to differential-/common-mode inputs,

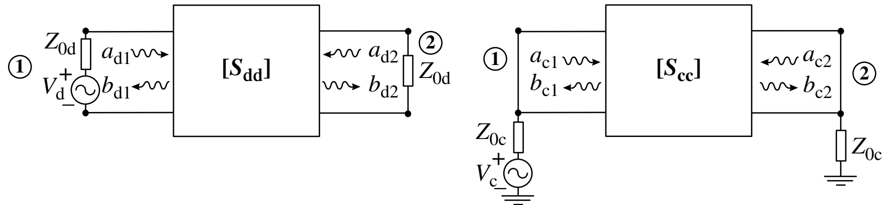

Figure 1.8 Mixed-mode S-parameters in a differential two-port circuit. (a) Differential-mode parameters; (b) common-mode parameters.

$\mathbf{S^{dc}}$ describes the conversion of common-mode inputs into differential-mode outputs, and $\mathbf{S^{cd}}$ describes the conversion of differential-mode inputs into common-mode outputs. Mode conversion occurs as consequence of imbalances in the circuit. An ideal balanced device is characterized by perfect (ideal) symmetry. Actual devices are not perfectly balanced, in part due to manufacturing imperfections, and energy transfer between the differential and common modes is unavoidable.

The relationship between the single-ended S-parameters and the mixed-mode S-parameters is given by [8][6]

$$\mathbf{S^{dd}} = \frac{1}{2}\begin{pmatrix} S_{11}-S_{13}-S_{31}+S_{33} & S_{12}-S_{14}-S_{32}+S_{34} \\ S_{21}-S_{23}-S_{41}+S_{43} & S_{22}-S_{24}-S_{42}+S_{44} \end{pmatrix} \tag{1.24a}$$

$$\mathbf{S^{cc}} = \frac{1}{2}\begin{pmatrix} S_{11}+S_{13}+S_{31}+S_{33} & S_{12}+S_{14}+S_{32}+S_{34} \\ S_{21}+S_{23}+S_{41}+S_{43} & S_{22}+S_{24}+S_{42}+S_{44} \end{pmatrix} \tag{1.24b}$$

$$\mathbf{S^{dc}} = \frac{1}{2}\begin{pmatrix} S_{11}+S_{13}-S_{31}-S_{33} & S_{12}+S_{14}-S_{32}-S_{34} \\ S_{21}+S_{23}-S_{41}-S_{43} & S_{22}+S_{24}-S_{42}-S_{44} \end{pmatrix} \tag{1.24c}$$

$$\mathbf{S^{cd}} = \frac{1}{2}\begin{pmatrix} S_{11}-S_{13}+S_{31}-S_{33} & S_{12}-S_{14}+S_{32}-S_{34} \\ S_{21}-S_{23}+S_{41}-S_{43} & S_{22}-S_{24}+S_{42}-S_{44} \end{pmatrix} \tag{1.24d}$$

It is important to mention that if a differential two-port network is symmetric, the single-ended S-parameters for the odd and even networks are identical to the S-parameters for the differential and common mode, that is,

[6] The derivation of the mixed-mode S-parameters can be found in Chapter 6 as well. However, note that the ports' designation in that chapter is different than in Figure 1.6.

$$\mathbf{S^{dd}} = \mathbf{S_o} \tag{1.25a}$$

$$\mathbf{S^{cc}} = \mathbf{S_e} \tag{1.25b}$$

Thus, from (1.24) and (1.25), the *S*-parameters for the even and odd modes, of special interest along this book, can be easily obtained by measuring the single-ended *S*-parameters of the complete network.

1.6 SUMMARY

In this introductory chapter, the advantages of differential circuits over their single-ended counterparts have been reviewed, and the need to suppress the common mode as much as possible has been justified. Moreover, this chapter has dealt with the fundamentals of differential-mode transmission lines, including the main topologies and propagating modes. The chapter ends with the mixed-mode *S*-parameters, useful for the analysis and characterization of differential circuits, and their relation to the single-mode *S*-parameters.

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