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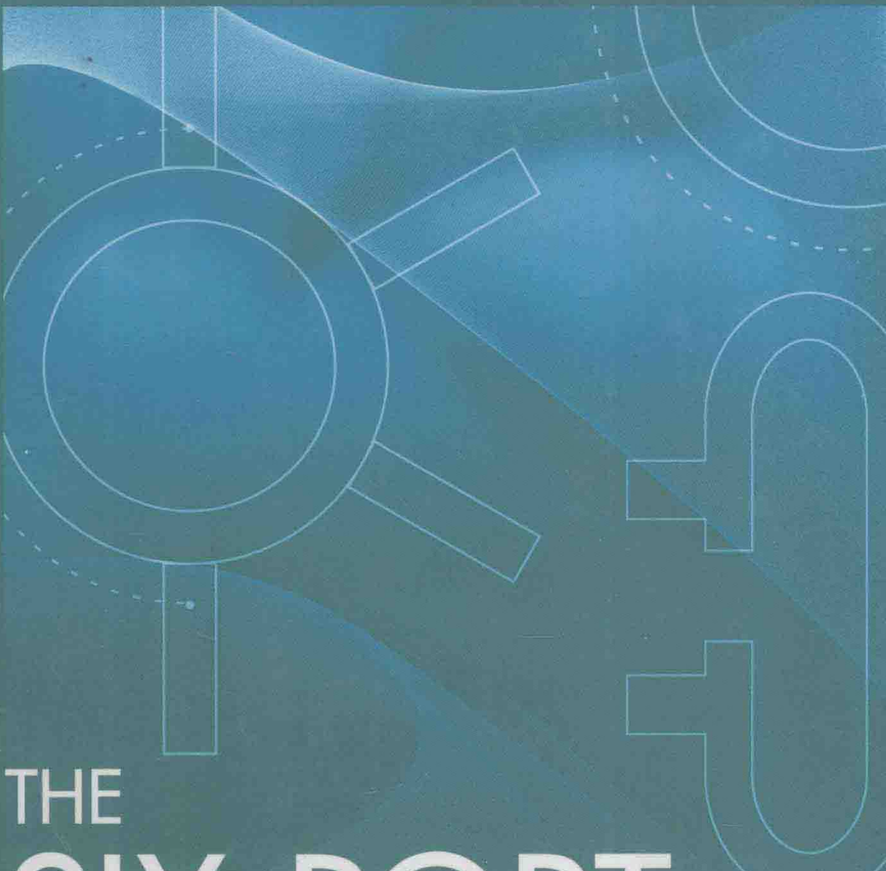

# THE SIX-PORT TECHNIQUE

**WITH MICROWAVE AND WIRELESS APPLICATIONS**

# The Six-Port Technique with Microwave and Wireless Applications

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# Contents

# Chapter 1

# Introduction to the Six-Port Technique

This chapter is an introductory chapter to the book and it briefly reports the basic concepts and principles related to transmissions lines, modeling of linear networks, defining S parameters, and some elements relevant to microwave metrology and the design of network analyzers.

## 1.1 MICROWAVE NETWORK THEORY

The definition of voltages and currents for non-TEM lines is not straightforward [1]. Moreover, there are some practical limitations when one tries to measure voltages and currents in microwave frequencies. To solve these problems, the incident and reflected powers and their parameters are measured in microwave frequencies. The scattering parameters, which indeed are the parameters that can be directly related to power measurements, are used to characterize microwave circuits and networks.

### 1.1.1 Power and Reflection

Figure 1.1 shows a one-port network with input impedance $Z$ that is connected to the generator $V_g$ with generator impedance $Z_g$. Power is transmitted from the generator to the one-port network. The current and voltage at terminal are

$$i = \frac{V_g}{Z_g + Z} \tag{1.1}$$

and

$$v = \frac{ZV_g}{Z_g + Z} \tag{1.2}$$

In order to receive the maximum available power from generator in the load, the conjugate matched, $Z = Z_g^*$, conditions must be realized. Let $Z_g = R_g + jX_g$; then, under this condition, the incident current and voltage are defined as [2]

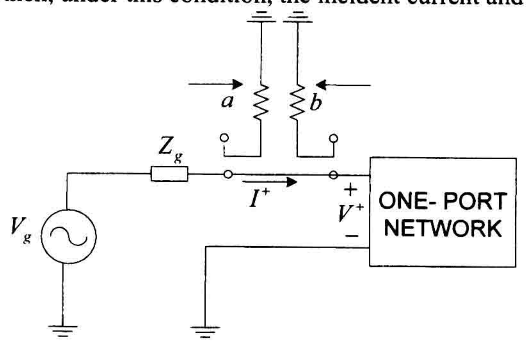


**Figure 1.1** One-port network and extraction of incident and reflected waves using a directional coupler.

$$I^+ = \frac{V_g}{Z_g^* + Z_g} = \frac{V_g}{2R_g} \tag{1.3}$$

and

$$V^+ = \frac{Z_g^* V_g}{Z_g^* + Z_g} = \frac{Z_g^* V_g}{2R_g} \tag{1.4}$$

The relationship between incident voltage and incident current is given by

$$V^+ = Z_g^* I^+ \tag{1.5}$$

The maximum available power is

$$P_A = \mathrm{Re}(VI^*) = \frac{|V_g|^2}{4R_g} \tag{1.6}$$

where current and voltage are RMS values. As may be seen from (1.4) and (1.5), incident voltage and incident current are independent of the impedance of the one-port network. The terminal voltage and current according to Figure 1.1 are obtained as

$$V = V^+ + V^- \tag{1.7a}$$

$$I = I^{+} - I^{-} \tag{1.7b}$$

From (1.6), the incident power is defined as the maximum available power from a given generator as

$$P_{inc} = \mathrm{Re}\left[V^{+}(I^{+})^{*}\right] = \frac{\left|V_g\right|^2}{4R_g} \tag{1.8}$$

By using (1.4), the incident power (1.8) can be written as

$$P_{inc} = \frac{\left|V^{+}\right|^2 R_g}{\left|Z_g^{*}\right|^2} \tag{1.9}$$

The magnitude of the normalized incident wave, *a,* and reflected wave, *b,* are defined as the square root of the incident and reflected powers as

$$|a| = \sqrt{P_{inc}} = \frac{V^{+}\sqrt{R_g}}{Z_g^{*}} = I^{+}\sqrt{R_g} \tag{1.10a}$$

$$|b| = \sqrt{P_r} = \frac{V^{-}\sqrt{R_g}}{Z_g^{*}} = I^{-}\sqrt{R_g} \tag{1.10b}$$

The dimensions of *a* and *b* are the square root of power. They are directly related to power flow. The ratio of the normalized reflection wave to normalized incident wave is called reflection coefficient

$$\Gamma = \frac{b}{a} \tag{1.11}$$

### 1.1.2 Scattering Parameters

The normalized incident and reflected waves are related by scattering matrix. The scattering matrix characterizes a microwave network at a given frequency and operating conditions. Let the characteristics impedance of the transmission lines in Figure 1.2 be equal to Z0; then the scattering matrix of a two-port network can be represented as

$$\begin{bmatrix} b_1 \\ b_2 \end{bmatrix} = \begin{bmatrix} s_{11} & s_{12} \\ s_{21} & s_{22} \end{bmatrix} \begin{bmatrix} a_1 \\ a_2 \end{bmatrix} \tag{1.12}$$

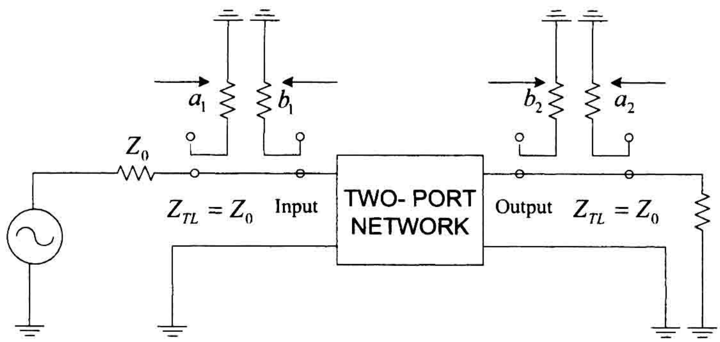


**Figure 1.2** Two-port network and extraction of incident and reflected waves using directional coupler.

where $s_{11} = b_1 / a_1 \big|_{a_2=0}$ is the input reflection coefficient while the output is terminated with $Z_0$,

$s_{21} = b_2 / a_1 \big|_{a_2=0}$ is the forward transmission coefficient between $Z_0$ terminations,

$s_{12} = b_1 / a_2 \big|_{a_1=0}$ is the reverse transmission coefficient between $Z_0$ terminations,

and $s_{22} = b_2 / a_2 \big|_{a_1=0}$ is the output reflection coefficient while the input is terminated with $Z_0$.

If we have a lossless passive two-port, the power applied to the input port is either reflected or transmitted. Accordingly,

$$|s_{11}|^2 + |s_{21}|^2 = 1 \tag{1.13}$$

The advantage of scattering parameters is that they can be evaluated by attaching direction couplers to all of the network ports. The directional couplers separate incident and reflected power waves directly, simplifying the measurement procedure. The fact to remember is that the conditions required for determining the individual s-parameter value need properly terminated transmission lines at the various ports [3].

The scattering matrix may be expanded to define any N-port network, where $N$ is any positive integers. The characteristic impedance of the different port can be the same. This is the case in the many practical applications. However, the scattering matrix can be generalized to include the different characteristic impedances in various ports [1]. An N-port network is shown in Figure 1.3, where $a_n$ is the incident wave in port $n$ and $b_n$ is the reflected wave in port $n$.

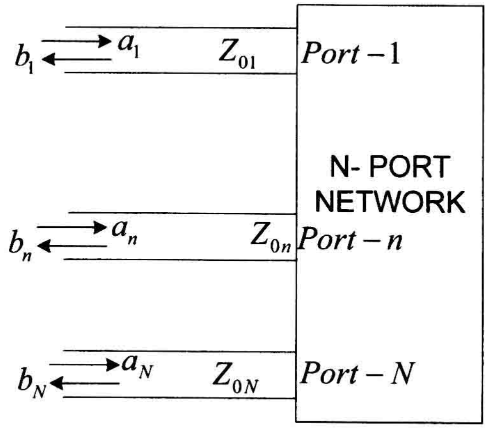


**Figure 1.3** An arbitrary N-port microwave network.

The scattering matrix, or [S] matrix, is defined in relation to these incident and reflected waves as

$$\begin{bmatrix} b_1 \\ b_2 \\ \vdots \\ b_N \end{bmatrix} = \begin{bmatrix} s_{11} & s_{12} & \cdots & s_{1N} \\ s_{21} & & & \vdots \\ \vdots & & & \\ s_{N1} & \cdots & & s_{NN} \end{bmatrix} \begin{bmatrix} a_1 \\ a_2 \\ \\ a_N \end{bmatrix} \tag{1.14}$$

A specific element of [S] matrix is defined as

$$s_{i,j} = b_i / a_j \Big|_{a_k = 0 \ for \quad k \neq j} \tag{1.15}$$

A vector network analyzer is mostly used to measure the scattering parameters. A vector network analyzer is basically a four-channel microwave receiver that processes the amplitude and phase of the transmitted and reflected waves from a microwave network.

A vector network analyzer generally includes three sections: RF source and test set, IF processing, and digital processing. To measure the scattering parameters of a DUT, RF source sweep over a specific bandwidth, the four-port reflectometer samples the incident, reflected and transmitted RF waves, and a switch allows the network to be driven from either ports of DUT.