A Review of the Six-Port Measurement Technique

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Abstract

The six-port measurement technique has found wide acceptance, and played a major role in microwave metrology, particularly within the community of national standards laboratories. This paper will review this development and technology.

Summary

A basic problem, which underlies much of microwave metrology, is the measurement of the *complex* wave amplitudes (usually denoted by a and b) at some terminal surface or plane. The determination of reflection coefficient, for example, is obtained from the ratio between these wave amplitudes. The "fundamental" equation, upon which most measuring instruments is based, may be written,

$$b_1 = Aa + Bb \tag{1}$$

where b_1 is the signal delivered to some sensing device, and A, and B are complex constants which characterize the measuring instrument. In order to utilize this result one typically requires a second sensor and equation,

$$b_2 = Ca + Db \tag{2}$$

If the $A \cdot\cdot\cdot D$ are known (which generally requires a suitable calibration procedure), and the b_1 and b_2 may be measured, one has a determinate system of equations which may be solved for a and b. (As a practical matter, the measurement of reflection coefficient requires only the ratio between b_1 and b_2, and the ratios $A/D \cdot\cdot\cdot$.) Although conceptually very simple, the requirement for the phase difference puts a substantial burden on the detection system. The field of microwave metrology is dominated, today, by the vector automatic network analyzer (VANA). In their typical form, these are highly developed instruments which include a heterodyne detection system which provides both amplitude and phase response as required to implement this technique. This, in turn, calls for frequency conversion (possibly multiple) and the attendant local oscillators, etc. These components make a substantial contribution to the complexity of the device, and their realization becomes increasingly difficult in the millimeter region.

The six-port reflectometer (including the dual version) provides an alternative method of implementing a VANA. In common with the usual designs, the deviations of the hardware, from the design objectives, are taken care of via a suitable calibration and software. In contrast with eqn. 1, the basic equation is now,

$$P_1 = |Aa + Bb|^2 \tag{3}$$

and the requirement for phase response has been eliminated. The distinguishing feature is thus the use a much simpler detection system, based on power or amplitude only. In order to have a determinant system of equations, however, it is now necessary to add a third, and preferably a fourth detector as well, which then leads to the "six-port." The six-port network (from which the technique derives its name) can be assembled from a suitably interconnected collection of directional couplers or power dividers. Four of the ports are terminated by power detectors which may, for example, be of the diode or bolometric type. One of the remaining ports is connected to the generator, the other becomes the "test port," to which the items to be measured are connected.

Although the hardware is much easier to implement, the converse is true of the associated theory and software. First, it will be noted that the basic equations are quadratic rather than linear. In addition to the complex A/D, B/D, and C/D, which suffice to describe the conventional VANA, there are an additional five real parameters to be determined in the calibration phase. However these may be determined by exploiting the redundancy in the system.

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Thus, this added requirement represents only a minimal additional burden on the system and its user.

The details of the solution of the system of four equations, which are based on eqn. 3, for the ratio *a/b* or reflection coefficient, is rather involved, and beyond the

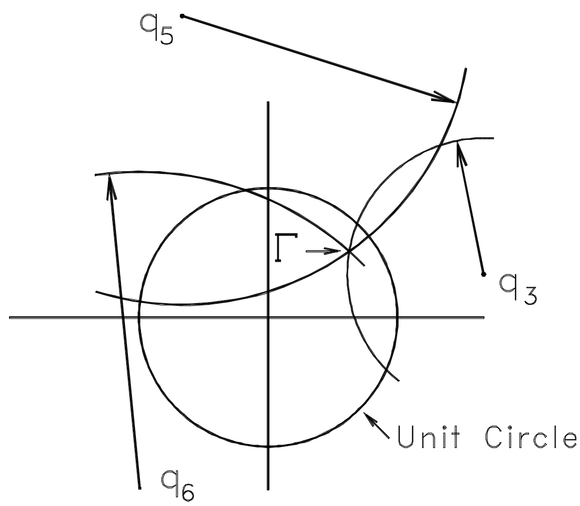

Figure 1. The reflection coefficient is determined from the intersection of three circles.

scope of this paper. As shown in Fig. 1, however, it is possible to represent the solution and operation graphically as that of finding a number (reflection coefficient) in the complex plane from the intersection of three circles, whose centers (q_3, q_5, q_6) are determined (approximately) by the parameters of the six-port network. The radii are determined from the ratio of three of the power meter readings to the fourth. This simple picture has made a substantial contribution to the intuitive understanding of the device.

In order to measure two-port devices, the *dual* six-port may be used. As shown in Fig. 2, this is implemented by a pair of six-ports which are fed from a common source and dividing network. The latter includes a provision for adjusting the phase difference between the signal inputs to the two six-ports. In operation, the "reflection coefficient" as observed by six-port 1, at terminal 1, is augmented by the signal which is fed through the device under test (DUT) via six-port 2. This measurement is repeated for several different phase differences which makes it possible to distinguish between the transmitted signal and the actual reflection from the DUT. For a 40 dB attenuator, the transmitted signal is of the same amplitude as that provided by a reflection from the DUT of 0.01. The dynamic range in an attenuation measurement is thus limited by the resolution of the power detectors in use rather than their dynamic range. For these reasons, the detectors of choice are of the bolometric type, although extensive use has also been made of diode types in less demanding applications.

Although this technology is more than a decade old, it continues to provide the mainstay for a substantial portion of the calibration services offered by NIST.

The level of interest in this technique is indicated by a bibliography of more than 150 items.

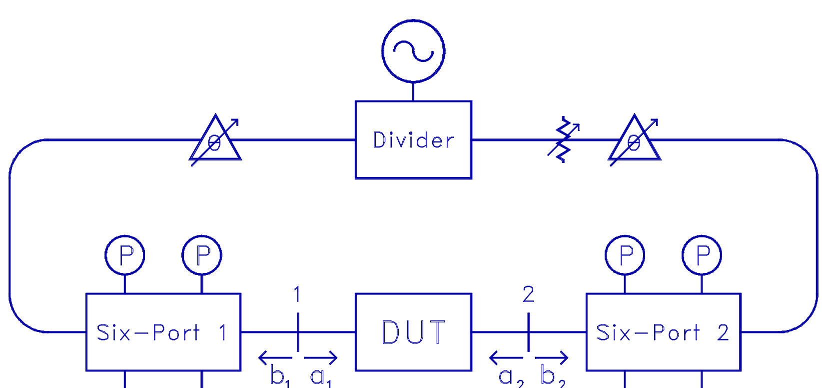

Figure 2. The dual six-port may be used to measure two-port devices.

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The reason for this is that with the use of four detectors, the system is "over-determined" in that the response of three of the detectors determines that of the fourth to the extent of a choice between two possible values. To be more explicit, the ratios of three of the (power) detector readings to the fourth all lie on a three dimensional surface in "P-space." This surface is a paraboloid, and since the powers are non-negative, this surface lies entirely in the first octant. The parameters which describe it are just the five which are required by the calibration. It is thus possible to determine these five constants by observing the system response to a suitably chosen set of terminations but for which the actual value of reflection need not be known, other than as required to obtain a well conditioned solution, or distribution over the surface of interest.

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