A Simplified Calibration of Two-Port Transmission Line Devices

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Summary—**During the evaluation measurements of several two-port junction devices over a wide band of frequencies the authors found that the method of shorts as described in three previous papers was too laborious to be practical. By reinterpreting and combining the ideas of earlier authors[1,2] a valuable simplification was obtained. Since this paper is based upon the previous articles, no fundamental proofs will be given except to show the necessary extensions involved.**

Introduction

G. A. DESCHAMPS originally described a graphical method of measuring impedances through an unknown junction. For example, these junctions may be step or tapered transitions between two physical line sizes of the same impedance or between lines of different impedances or a combination of both. They may be baluns which convert from unbalanced lines to balanced lines or junctions which convert from coaxial to waveguide. In fact, measurements through almost any two-port junction between the measuring device (normally a slotted line) and the unknown load are possible without detailed knowledge of the junction.

The literature describes what is called a "calibration of the junction," which is a long and involved procedure in most cases. The simplest method of accomplishing the calibration is to plot on a Smith chart the measured results of a matched load and a reference short placed at the output of the junction. Its major difficulty is that matched loads are not available for most cases.

One of the methods described by Deschamps simulates a perfect matched load, regardless of the line impedance, by using a series of shorts at discrete positions along the uniform transmission line out of the unknown junction. At least four different short positions are used with the specification that they be used alternately in pairs a quarter wavelength apart. These points may be plotted on a Smith chart (Fig. 1). If straight lines are constructed between points of the pair, then the intersection of these lines is the crossover point.

The construction given by Deschamps and illustrated in Fig. 2 converts the crossover point into the iconocenter. The iconocenter is the same point that would have been found on a Smith chart had a matched load been used to terminate the junction. The difficulty with this method is that four new short positions must be made for each frequency. This becomes exceedingly difficult and time consuming when working with dielectric filled line or with line in which a movable short cannot be placed. It is also difficult to make each cut of the line under test to the exact electrical length desired.

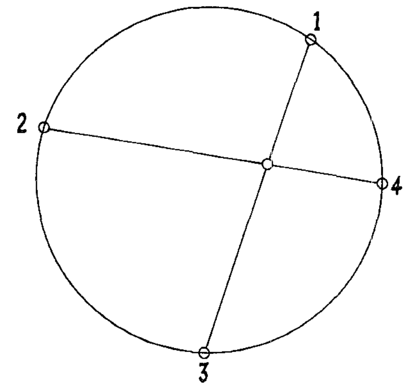

Fig. 1—Position of four shorts and location of crossover point.

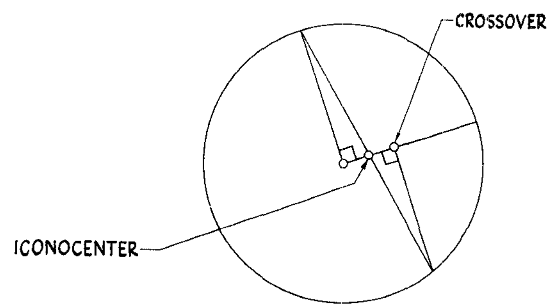

Fig. 2—Construction of iconocenter from crossover point.

The use of a matched output load locates the iconocenter, and the use of four $\lambda/8$ shorts locates the crossover point. The method described by this paper will locate the iconocenter directly where matched loads are unavailable.

In the interest of clarity, the following terms are defined, althought the definitions may not coincide with the work of other authors:

1) The test plane includes those measurements, plots, and graphs involving no transforming network. All standard impedance measurements fall into this category.
2) The transformation plane is the result of transforming all points and measurements in the test plane by the network transformation junction. Measurements performed between the generator and the two-port junction fall in the transformation plane.

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[1] G. A. Deschamps, "A hyperbolic protractor for microwave impedance measurements and other purposes," Fed. Telecommun. Labs.; 1953, and "Determination of reflection coefficients and insertion loss of a waveguide junction," *J. Appl. Phys.*, vol. 24, pp. 1046–1050; August, 1953.

[2] J. E. Storer, L. S. Sheingold, and S. Stein, "A simple graphical analysis of a two-port waveguide junction," Proc. IRE, vol. 41, pp. 1004–1013; August, 1953.

3) The projective plane is the result of transforming all points in the transformation plane by the projective construction described by Deschamps and shown in Fig. 2.
4) The iconocenter is the center of a Smith chart after it has been transformed into the transformation plane.
5) The crossover point is the iconocenter after it has been transformed into the projective plane.
6) The elliptic angle is a construction in the projection plane drawn with straight lines from two points to a vertex which is usually the crossover point.

Simplified Graphical Construction

Analytically, the junction can be described by a transformation matrix.[2] All points measured through the junction when plotted on a Smith chart will be in the transformation plane described by this matrix. The transformation is bilinear and conformal. Therefore, circular arcs are transformed into circular arcs, and angles and sense preserved. In the transformation plane, one cannot read directly the phase angle of an unknown load. However, in the projective plane straight lines may be drawn to describe an elliptic angle, which also may not be read directly. However, Deschamps gives the relationship of the elliptic angle to the angle in the test plane. This is illustrated in Fig. 3, which also shows the center of the Smith chart in the test plane, transformation plane, and projective plane. Fig. 3 shows too that if points 1, 1′, 2, and 2′ are known, then the iconocenter is defined.

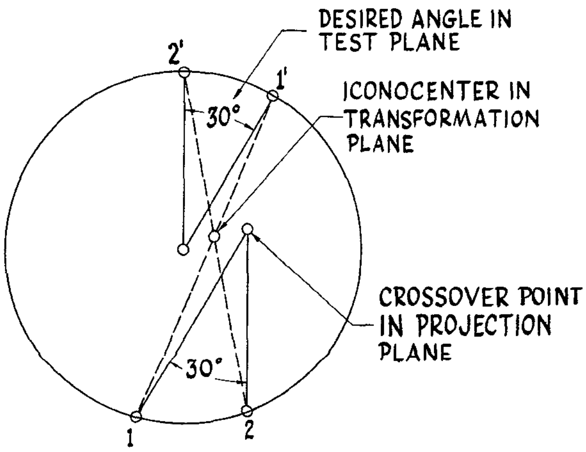

Fig. 3—Evaluation of an elliptic angle.

Fig. 4 demonstrates the measurements necessary to make the calibration. A short is placed at point 1′, and the null is read on the slotted line at point 1. The short is moved along the line an arbitrary distance (in this case, 30 degrees) to point 2′, and the null is read at point 2. The short is moved again (35 degrees this time) to point 3′, and the null read at point 3.

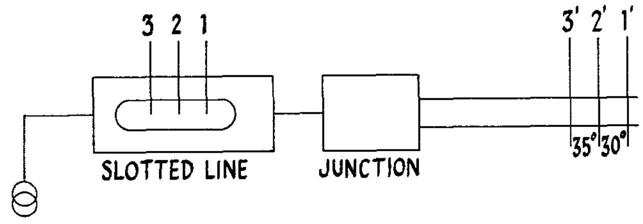

Fig. 4—Typical measurement.

Using the nulls of a reference short at the end of the slotted line, points 1, 2, and 3 are plotted on a Smith chart (Fig. 5) in the transformation plane. An arbitrary line is drawn from 1 to a point on the opposite side of the circle and the intersection is designated at point 1′. Knowing the real angle between 1′ and 2′ point 2′ is now constructed in the test plane. The intersection of 1′-1 and 2′-2 at "a" and the points 1 and 2 define a circle. It can be readily shown by similar construction that as the position of line 1′-1 is varied the point "a" describes a circle, and that the locus of the circle described by point "a" passes through points 1 and 2.

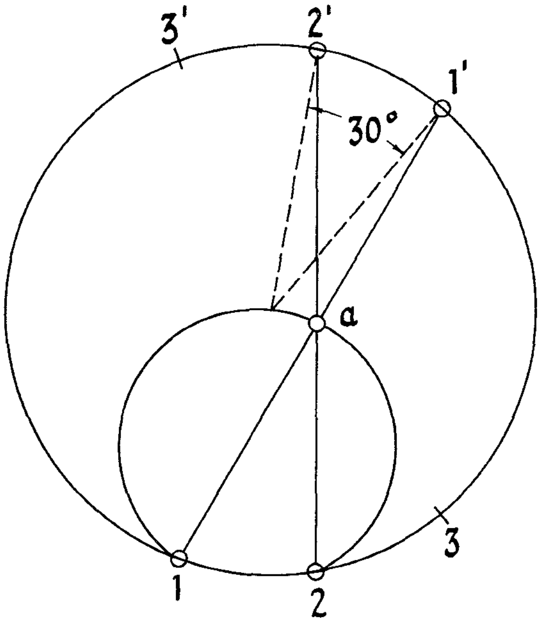

Fig. 5—Locus circle for points 1 and 2.

This circle is the locus of possible iconocenters for the junction under test. Using the points 2 and 3 and the real angle between 2′ and 3′ in a like manner, a second locus circle may be constructed (Fig. 6). Since the iconocenter must lie on both circles, then their intersection within the Smith chart locates the desired iconocenter.

It should be noted that no requirements are imposed upon the location of the shorts except that their separation be accurately known. The same three short positions may be used for calibration of the junction over a

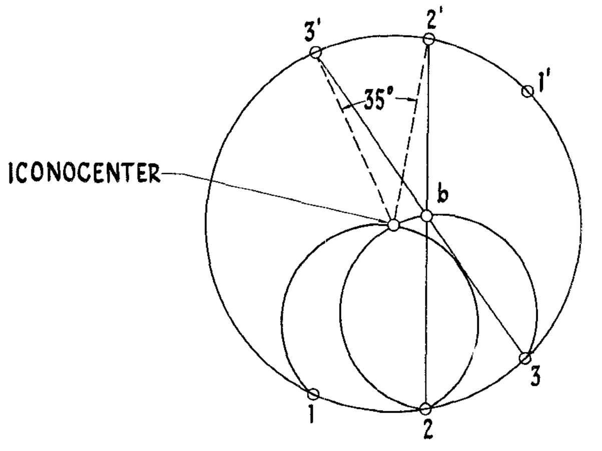

Fig. 6—Locus circle for 2 and 3. Intersection of the two circles locates the iconocenter.

wide band of frequencies and thereby provide a considerable simplification over the original calibration method.

The procedure to follow in the wide band case is to make 3 sets of impedance measurements over the frequency band, one for each short position. It is most important that the frequencies be repeated accurately in the second and third sets. However, with modern equipment this is easily accomplished.

Up to this point, the main concern was to calibrate an unknown junction for purposes of measuring impedances through this junction. However, the same method also is capable of evaluating a junction which is being designed. For instance, in designing a tapered transition, one of the requirements would be a maximum allowable reflection. In general, this test would be made simply by placing a matched load at the output and examining the reflection of the input.

For cases where a matched load is not available, the method of shorts would provide an evaluation of the junction. The iconocenter, when plotted on the Smith chart, will be a parallel combination of the equivalent reactance of the junction and the matched impedance of the output line. Since the output impedance is known, then the equivalent impedance of the junction is also known. In order to measure an impedance with a standing wave machine, one requires a reference short, where the impedance measured is said to exist. In design work one would then want to make the reference short at a point where a design correction or a matching section would be made if necessary.

Several items of accuracy that are necessary for satisfactory results are: frequency, velocity of propagation, distance between shorts, and null positions on standing wave machines. Also the transmission line used to make the shorts should be uniform, and the quality of the short circuit should be better than 50:1 vswr. If the quality of the shorts is not that good, but is fairly uniform for all three positions, then the error introduced by assuming infinite vswr is proportional to the magnification of the Γ' circle (Fig. 7). Where the quality of the short is good, but the measured vswr is not uniform, then the junction is lossy.

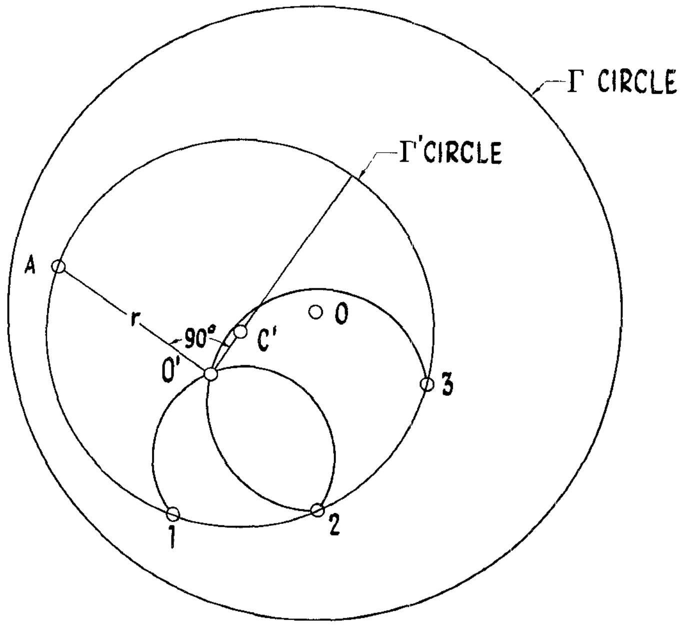

Fig. 7—Effect of a lossy junction

The procedure for lossy junctions is to plot the actual impedance measured on the Smith chart and to fit a circle to the results to form the Γ' circle. Within the Γ' circle one proceeds as before to find the iconocenter. The input reflection coefficient of the junction is $O'O$. The output reflection coefficient is $O'C'/r$. The transmission coefficient is $O'A/\sqrt{r}$ as described very nicely by Storer, Sheingold, and Stein.[2]