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IEEE Standard for
**Waveguide and Waveguide
Component Measurements**



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IEEE Standard for Waveguide and Waveguide Component Measurements

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1.1 Introduction

THIS STANDARD is concerned with measurements of the quantities which characterize a waveguide or waveguide component and the associated electromagnetic fields. The term "waveguide," as used here, is a generic term which includes transmission lines and uniconductor waveguides as special cases.

The measurements are described in general terms. For the specific details of procedure and equipment, the reader is directed to numerous references (Sec. 6), which form an indispensable part of this Standard.

Definitions of terms employed in this Standard are given in Sec. 5. These definitions are presented both to insure precision of meaning with regard to the measured quantities and to clarify possible conceptual differences in the usage of terms common to both microwave and low-frequency circuit practice. As an example of the latter, the term "match" has different significance in the two usages.

Section 2 is concerned with measurements in a waveguide having uniform characteristics. Sections 3 and 4 are concerned with components which are connected to or located in waveguides.

This Standard is limited to measurements in linear, reciprocal systems, and unless otherwise stated to single frequency sources. For example, it does not apply to special devices such as nonreciprocal ferrite components and crystal detectors.

1.2 Measurement Techniques

In general, the equipment required for waveguide measurements includes a signal source of the appropriate frequency and a suitable detector. In addition depending on the nature of the measurement being made, equipment such as attenuators, slotted lines, impedance bridges, sampling devices, and terminations may also be required. The exact form of this equipment will vary depending upon the nature of the waveguide, the frequency range, and the particular method used for the measurement.

Regardless of the equipment used, there are certain basic precautions which must be taken if the measurements are to be meaningful. The signal supplied by the source should be stable and free of harmonics and other spurious components and should be free of undesired modulation. In many cases, this requirement may be relaxed if the detector is selective enough so as not to respond to the undesired signals. Leakage into a detector either directly from the signal source, through undesired paths in the component, or from external sources should be guarded against. If the detector is used at other than a constant level, it is often necessary to know accurately the response law of the detector. In connecting the measuring equipment to the device being measured, care should be taken to minimize

unwanted discontinuities or reflections. If high precision is required, such discontinuities as do exist must be separately determined and accounted for in the data reduction. In certain kinds of measurements, it is desirable that the impedance of the source be matched to the characteristic impedance of the waveguide being used. For the case of balanced transmission line systems, care must be taken that the probe and detector respond only to the balanced component of the existing fields. This is a special case of the more general problem involving measurements in waveguides which can support multimode transmission, and it is obvious for such cases that the detector should respond only to the mode of interest.

SECTION 2—MEASUREMENTS IN WAVEGUIDES [1], [2]

2.1 Measurement of Voltage

(a) In transmission lines carrying a TEM mode, it is possible to measure the total voltage across the line (*i.e.*, the line integral, in the transverse plane, of the electric field strength) at frequencies below a few hundred mc with a reasonable degree of accuracy by using vacuum tube voltmeters or crystal diode voltmeters which are available commercially. In making this type of measurement, care should be taken to insure that the voltmeter does not unduly load the line. In addition, the voltmeter leads should not couple to any field other than that being measured.

(b) In a balanced transmission line system it is necessary that a balanced type of voltmeter be used. This may consist of an unbalanced voltmeter with a balance-to-unbalance transformer of known ratio. A second method of measuring a balanced voltage is to use a quarter-wave shunt stub of balanced transmission line with an ammeter shorting the line at the far end. The voltage across the line is equal to the current times the characteristic impedance of the stub line.

(c) In uniconductor waveguides, total voltage is not usually of interest. However, measurement of electric field strength is frequently of interest (see Sec. 2.3).

2.2 Measurement of Current [1], [3]

(a) In a transmission line carrying a TEM mode, the total current flowing in either conductor can be measured with a reasonable degree of accuracy at frequencies below several hundred mc with a thermo-couple type ammeter. At frequencies much lower than this, a thermo-ammeter is sometimes used.

(b) In a balanced transmission line system, the total current may be measured by inserting ammeters in series with each conductor or by using a single ammeter and a suitable coupling loop such that the loop couples only to the balanced component of the current [4]. If unbalanced currents are present, as may be evidenced by a difference in the meter readings on the two sides of the line or by other methods (see Sec. 2.12), it will be necessary to locate and remove the sources of the unbalance before proceeding with the measurement.

(c) In a uniconductor waveguide, the definition of total current has no practical importance. However, the local current density at a point on the surface can be determined by measuring the magnetic field strength at that point (see Sec. 2.4).

2.3 Measurement of Electric Field Strength [5]

The component of the electric field in a specified direction at a point in space is usually obtained by measuring the voltage induced in a small linear probe oriented in the specified direction. Care must be taken that the transmission line leading to the probe does not itself affect the field nor the probe pickup. It is important that the amount of power absorbed or scattered by the probe be small compared to the total power in the guide.

Although it is possible to make absolute electric field strength measurements by calibrating the probe, relative measurements are usually of most interest.

2.4 Measurement of Magnetic Field Strength [5]

The component of the magnetic field in a specified direction at a point in space is usually obtained by measuring the voltage induced in a small loop type probe oriented in the specified direction. Care must be taken that the transmission line leading to the probe does not itself affect the field nor the probe pickup. It is important that the amount of power absorbed or scattered by the probe be small compared to the total power in the guide.

It should be noted that a loop type probe will always have a certain amount of response to the electric field as well as to the magnetic field. This response can be minimized by keeping the loop and the associated meter balanced and by keeping sizes as small as possible. Balance can be checked by physically reversing the loop.

When measuring the magnetic field strength on a metallic surface, a small rectangular slot in the surface is sometimes used as the probing device. For this case, the voltage across the slot is measured.

Although it is possible to make absolute magnetic field strength measurements by calibrating the probe, relative measurements are usually of most interest.

2.5 Power Measurements [6]–[9]

(a) In a matched lossless transmission line carrying a TEM mode, the power absorbed by the load (which is equal to the incident power) can be determined from the characteristic impedance (Z_0) of the line and either the total voltage (V) or the total current (I). If the line is mismatched, the power (P) absorbed by the load can be computed from the value of either of these quantities at both a maximum and minimum.

$$P = \frac{V_{\max} V_{\min}}{Z_0} = I_{\max} I_{\min} Z_0.$$

The absorbed power is sometimes measured by the three meter method in which either voltage or current

readings are taken along a line at three appropriately spaced points [10].

(b) In a matched lossless waveguide, the incident power can be determined by measuring the power dissipated in the matched load or by extracting and measuring a known fraction of that power. If the waveguide is mismatched, the incident power can be determined by extracting, and measuring a known small fraction of the forward traveling wave by means of a directional coupler.

(c) There are several common methods of measuring the power in a matched load.

1. Measurement of resistance change. This method includes the use of devices such as bolometers and thermistors [7].
2. Calorimetric methods [7].
3. Thermo-electric (e.g., thermo-couple) methods [7].

2.6 Measurement of Waveguide Wavelength [11]–[13]

A common means of measuring waveguide wavelength employs a movable probe for observing the standing wave along a length of the waveguide which is terminated by a mismatched load. The use of a short-circuit termination as the mismatched load will improve the accuracy of the measurement. A half wavelength in the waveguide is equal to the distance between adjacent minima of the standing wave. In the case of completely enclosed waveguides it is necessary to provide a non-radiating longitudinal slot for the movable probe. Commercial slotted sections are available for most standard waveguides.

An equivalent procedure uses a fixed probe and a movable short circuit to position successive minima of the standing wave at the probe.

An alternate method employs a cavity arrangement wherein the waveguide under measurement is terminated at both ends by short circuits, one of which is adjusted for two successive resonances of the cavity.

For waveguides of simple cross section it is possible to compute the waveguide wavelength from a measurement of the frequency and a knowledge of the dimensions of the waveguide cross-section.

2.7 Measurement of Attenuation Constant [14]

The attenuation constant is the real part of the propagation constant and is the attenuation per unit length, expressed in nepers/unit length.

(a) The methods of measuring attenuation constant fall into two main groups, one based on transmission and one on reflection procedures.

(b) Transmission type procedures involve the measurement of the insertion loss of a known length of the waveguide under test by the methods of Sec. 3.1.

(c) Reflection type measurements require a knowledge of the magnitude of the input reflection coefficient of a known length of waveguide terminated in a load of known reflection coefficient [15].

(d) A variation on the reflection type measurement, particularly useful for waveguides of

section, employs the measurement of the Q of a cavity consisting of the length of waveguide under test, short-circuited at both ends (see Sec. 3.8) [16]. The end losses must be small or separable.

2.8 Measurement of Input Impedance [17], [18]

It is necessary to distinguish between input impedance and normalized input impedance. Input impedance is generally significant in transmission lines carrying a TEM mode; in uniconductor waveguides it is practicable to measure normalized input impedance. Input admittance is the reciprocal of input impedance.

At frequencies below several hundred mc, lumped constant bridges are useful in determining impedance [17]. At higher frequencies, impedance may be found by measuring the normalized impedance in a transmission line of known characteristic impedance carrying a TEM mode.

2.9 Measurement of Normalized Input Impedance [18]–[21]

The quantities Z' , the normalized input impedance, Y' , the normalized input admittance, and ρ , the complex voltage reflection coefficient, are simply related in the following manner

$$Z' = \frac{1}{Y'} = \frac{1 + \rho}{1 - \rho}.$$

Another associated quantity, the standing wave ratio (S) is related to the magnitude of ρ as

$$S = \frac{1 + |\rho|}{1 - |\rho|}.$$

Methods of measuring normalized input impedance may be classified under distributed constant bridge methods, standing wave ratio techniques, and procedures involving the separation of incident and reflected traveling waves.

(a) One class of distributed constant bridges consists of comparison devices which either directly compare the unknown with a known normalized impedance, or which effect the comparison through variable ratios [18], [21]–[24]. Another type of distributed constant bridge determines the complex ratio of the electric and magnetic field strengths [25], [26]. A number of commercially available bridges fall into these categories.

(b) Standing wave ratio techniques include a number of methods based upon the sampling of the field variation in a waveguide terminated by the unknown impedance. The most common of these procedures employs a sliding probe [20]. Other methods include the use of multiple fixed probes [27], or sweep methods such as frequency sweeping or the Chipman line procedure [28], [29].

(c) Procedures involving the separation of incident and reflected traveling waves, such as those employing directional couplers, yield directly the reflection coefficient magnitude only [30]. Phase information is some-

times obtained by the introduction of a known (usually capacitive) susceptance in a known location [31], [32].

2.10 Measurement of Dielectric Voltage Breakdown [33], [34]

(a) In a waveguide, it is possible to measure the dielectric breakdown of a particular region if its power-handling ability is less than that of the remainder of the line under test. Conditions affecting the lowest power level at which corona or arcing (breakdown) first appears include pressure, temperature, frequency, ionization, extraneous material, and magnitude of standing wave at the location of the breakdown.

(b) To measure power capacity, breakdown is induced by raising the applied power or lowering the ambient pressure, whichever is more convenient, and noting the pressure, temperature, and load conditions at breakdown. Breakdown may be observed by various methods including sight, sound, increased reflection, change in generator output, changes in transmission properties, or heating effects. Power capacity under most other conditions of pressure, temperature, and load reflection may then be computed. If an accurate measurement of the applied peak power is not available, due to irregular waveform, etc., a comparison may be made between a component of known breakdown, and the part under test [35]. Repeatability of results may be improved by irradiation.

(c) The variation of high-frequency breakdown with pressure and distance may be computed by a simple rule [33], [36] except under conditions of relatively low pressure and small distances, where the observed power capacity will be significantly greater than the computed value [33].

(d) Under short-pulse high-power conditions, it is possible to obtain stable states of “breakdown probability” less than unity, in which only a certain percentage of applied pulses break down. The peak power for zero probability of breakdown is known as the “threshold” and is generally computed by extrapolation from observed percentages of pulses breaking down at higher powers. The entire range between the threshold and unity breakdown probability is known as the “over-voltage” region. For convenience in testing, a point within the over-voltage region corresponding to a fairly low probability (one or two arcs per minute) is commonly chosen as indicating failure, or alternatively a point approaching 100 per cent arcing may be so designated.

There are various methods for increasing the gradient available from a particular generator, such as decreasing electrode spacing, decreasing radius of curvature of an electrode, establishing a standing wave with a voltage maximum at the region of interest, or setting up a resonance condition with an electric field maximum at the region of interest [36a], [36b].

(e) Corona

Corona is a particular type of high-voltage discharge differing from arcing principally in the magnitude and

continuity of current involved. At low frequencies and high pressures, the difference is clearly evident: corona is a relatively low-current, often stable, discharge originating at a point of high gradient and diffusing into space; as the gradient is increased, there is a rapid transition to breakdown by arcing, which is a high-current cumulative discharge between two points, generally resulting in complete failure of the system during the arc. At high frequencies, however, electron oscillation within the region of high gradient can reduce the cumulative action of an arc to such a degree that the transition region between corona and arcing becomes entirely obscured, particularly at reduced pressures. For this reason, high-frequency breakdown is often considered to comprise all detectable discharges, including corona.

2.11 Measurement of Mode Purity

In recent years, especially for the higher frequencies, increasing use is being made of waveguides which may propagate several modes simultaneously. Generally, however, only one of these modes is of interest; the remainder are referred to as undesired or spurious modes. Two quantities are of interest in this connection: mode purity and spurious mode level. Mode purity generally refers to the desired mode and is defined as the ratio of power present in the forward-traveling wave of the desired mode to the total power present in the forward-traveling waves of all modes. Spurious mode level involves a ratio of the power present in the forward-traveling wave of a particular undesired mode to that in the desired mode; this ratio is commonly expressed in decibels.

(a) The amount of power present in the forward-traveling wave of any given mode is best measured by the use of a mode-selective device such as a coupled line transducer [37], [38]. In general, a separate device of this type is required for each mode of interest. Such a procedure enables one to completely determine the spurious mode level or to find the numerator of the mode-purity expression. The denominator of the mode-purity expression, the total power present in the forward-traveling wave of all modes, can be measured by any of the means indicated in Sec. 2.5 which are not mode-dependent; e.g., a calorimetric method.

(b) The proportion of power in the forward-traveling waves of each of the propagating modes present may be measured directly by terminating the line in a mode-independent match and by appropriately probing the field distribution in the cross section. Such a probing procedure is rather difficult, however, and is feasible only for simple, stable field configurations and for a few modes present. Since at any given cross-section plane an arbitrary but constant time phase between the modes may exist, it is generally necessary to take measurements at more than one cross-section plane. In view of these difficulties, the probing is considered useful only for qualitative analyses.

(c) In the specific but valuable case of the TE_{01} mode

in circular waveguide in which the TE_{02} mode is beyond cutoff, the radial resistive card mode filter [37] is sufficiently selective to permit the transmitted power to be regarded as being in the TE_{01} mode only and, therefore, to permit a direct measurement of the power in that mode.

(d) If the TE_{11} mode in a particular orientation in circular waveguide is designated as the desired mode, the orthogonal TE_{11} mode may be considered as a spurious mode. This latter mode may be excited by ellipticities or irregularities in the waveguide. The resulting polarization will, in general, be elliptical and may vary with location along the waveguide. Elliptical polarization may be completely described by the axial ratio and the orientation of the major axis of the ellipse of polarization. Mode purity may be determined at any particular cross section by noting the ratio of minimum to maximum field strength (axial ratio) and the angular position of the minimum with respect to the desired reference direction [39]. This measurement may be made by circumferential rotation of a radial detecting probe.

If the axial ratio is designated as $\tan \alpha$, and the angle between the direction of the maximum and the reference direction of the desired TE_{11} component is β , the level of the undesired TE_{11} component, $\tan^2 \gamma$, and the mode purity, $\cos^2 \gamma$, can be obtained from

$$\cos 2\gamma = \cos 2\alpha \cos 2\beta.$$

2.12 Measurement of Transmission Line Unbalance

(a) In the case of uniconductor waveguides or coaxial transmission lines, the question of unbalance does not usually arise. For a coaxial line, the total current on the inner conductor must always be equal and opposite to the total current on the inner surface of the outer conductor. The only balance problem which commonly occurs with a coaxial line is for the case when the generator or load is connected to the line in such a way that currents are caused to flow on the outer surface of the outer conductor. For this case, the presence of current on the outer conductor can be detected by a measurement of the magnetic field strength on the outer surface as outlined in Sec. 2.4.

(b) For a balanced transmission line system operating properly, the voltages (relative to ground) on the conductors are push-pull voltages, and the currents in the conductors are push-pull currents. When the system becomes unbalanced, this is evidenced by the presence of push-push voltages and currents in addition to the push-pull voltages and currents. The amount of the system unbalance is measured by the ratio of the push-push voltage component to the push-pull voltage component or by the ratio of the push-push current to the push-pull current (Sec. 2.1).

(c) One excellent method for measuring the ratio of unbalanced to balanced currents involves the use of a transmission line arrangement and shielded loop pickup