JEDEC STANDARD

Measurement of Small-Signal Transistor Scattering Parameters

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JEDEC SOLID STATE TECHNOLOGY ASSOCIATION

Electronic Industries Alliance

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JEDEC STANDARD No. 25

MEASUREMENT

OF

SMALL-SIGNAL TRANSISTOR SCATTERING PARAMETERS

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Prepared by

JEDEC JC-25 Committee on Low Frequency Power Transistors

FOREWORD

The material herein was developed by the JEDEC JC-25 Committee on Low Frequency Power Transistors of the JEDEC Solid State Products Council. It has been approved for publication by the JEDEC Council as a JEDEC Standard.

MEASUREMENT
OF
SMALL-SIGNAL TRANSISTOR SCATTERING PARAMETERS

1. DEFINITIONS

1.1 Definition of the Scattering Parameters

Given a two-port network as shown in Figure 1, the scattering parameters may be defined as the elements of the matrix

$$S = \begin{vmatrix} s_{11} & s_{12} \\ s_{21} & s_{22} \end{vmatrix} \quad (1)$$

associated with the linear equations

$$b_1 = s_{11}\, a_1 + s_{12}\, a_2 \quad (2)$$

$$b_2 = s_{21}\, a_1 + s_{22}\, a_2 \quad (3)$$

where

$$a_i = \frac{1}{2\sqrt{Z_0}} \; (V_i + Z_0\, I_i) \quad (4)$$

$$b_i = \frac{1}{2\sqrt{Z_0}} \; (V_i - Z_0\, I_i) \quad (5)$$

$$i = 1,\ 2$$

Here Z_0 is defined as a real impedance called the normalizing (or reference) impedance, usually taken to be 50 ohms. When other values are used, the value must be specified along with other conditions such as frequency, bias, temperature, etc.

Each of the scattering parameters may be individually defined as follows:

s_{11} is the voltage (or current) reflection coefficient (with respect to Z_0) at port one with port two terminated in Z_0; i.e.,

$$s_{11} = \left.\frac{b_1}{a_1}\right|_{a_2=0} = \left.\frac{(V_1/I_1) - Z_0}{(V_1/I_1) + Z_0}\right|_{Z_2=Z_0} \tag{6}$$

s_{12} is the reverse transmission coefficient with port one terminated in Z_0 and port two driven with a generator of impedance Z_0; i.e.,

$$s_{12} = \left.\frac{b_1}{a_2}\right|_{a_1=0} = \left.\frac{V_1}{(V_o/2)}\right|_{Z_1=Z_2=Z_0} \tag{7}$$

where V_o is the open-circuit generator voltage.

s_{21} is the forward transmission coefficient with port two terminated in Z_0 and port one driven with a generator of impedance Z_0; i.e.,

$$s_{21} = \left.\frac{b_2}{a_1}\right|_{a_2=0} = \left.\frac{V_2}{(V_o/2)}\right|_{Z_1=Z_2=Z_0} \tag{8}$$

s_{22} is the reflection coefficient (with respect to Z_0) at port two with port one terminated in Z_0; i.e.,

$$s_{22} = \left.\frac{b_2}{a_2}\right|_{a_1=0} = \left.\frac{(V_2/I_2) - Z_0}{(V_2/I_2 + Z_0}\right|_{Z_1=Z_0} \tag{9}$$

The scattering parameters of transistors are also represented by the following symbols:

$$s_{11} \longrightarrow s_{ix}$$

$$s_{12} \longrightarrow s_{rx}$$

$$s_{21} \longrightarrow s_{fx}$$

$$s_{22} \longrightarrow s_{ox}$$

where x is replaced by e, b, or c for bi-polar transistors in common-emitter, common-base, or common-collector configuration, respectively; and by s, g, or d for field-effect transistors in common-source, common-gate, or common-drain configuration, respectively.

1.2 Definition of Small-Signal Conditions

Transistors are essentially non-linear devices which for sufficiently small applied signals behave as linear two-ports. Small-signal conditions may, therefore, be defined as the values of the voltage and current at ports one and two below which values the transistor may be considered a linear two-port.

For practical applications the following definition will be used: small-signal conditions are satisfied when a reduction of 50% in the amplitudes of V_1, I_1, V_2 or I_2 will not result in a variation of the ratio defined by (6), (7), (8), or (9) of more than 1%.*

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*All asterisks in this document refer to the following footnote:

The numerical values quoted have been agreed upon by the JC-24 JEDEC committee as those representing a practical compromise between the usual requirements of circuit design applications of scattering parameters and the measurement technology at the time of writing this document. (See Appendix I)

1.3 Definition of the Transistor Terminal Reference Planes

1.3.1 Single-Ended Axial Lead Package --

The reference plane defined by points on the transistor leads at a distance of 1.5 mm (0.06") from the seating plane of the transistor package (see Figure 2a).

1.3.2 Strip-Line Packages+ --

The reference planes (or plane) transverse to the input and (or) output leads defined by the point (or points) on the transistor lead (or leads) at a distance from the package body equal to or less than the dimensional tolerance range of the package body at the lead-body interface (see Figure 2b).

1.3.3 Coaxial Packages+ --

A reference transverse plane whose distance from the centerline of the seating flange is equal to the maximum dimension from the centerline of the seating flange to the body end of the input or output terminal (see Figure 2c).

For other packages not defined here, the transistor terminal reference planes must be specifically defined for each particular package.

+Stripline -- any transistor package with its leads in the same plane (this includes beam leads).

Coaxial -- any transistor package designed to mount directly into coaxial lines.

2. MOUNTS

The transistor mount must satisfy the following requirements:

2.1 It shall have well-designed terminals to which ports one and two of the transistor-under-test are connected. It shall also have well-designed ground connections to which the common terminal of the transistor package is connected. The SWR introduced by the transistor mount with the 50-ohm feedthrough shall be less than $(1.02 + 0.02\ f_{GHz})^{*}$, with respect to the defining reference to which the "s" parameters are referred. The expression f_{GHz} represents the test frequency in gigahertz.

2.2 The magnitude of the transfer scattering parameter between the input-output terminals (when no device is inserted in the mount) shall be less than 5% (-26 dB)* of the magnitude of the reverse transfer of the transistor under test.

2.3 The input-output terminals shall be designed to eliminate the high-frequency effects of that part of each lead extending from the transistor terminal defined in 1.3 to the physical extremity of said lead. This is normally achieved by the use of tubular inputs in the case of axial- or coaxial-leaded transistors; for stripline transistors the width of the center or stripline conductor of the fixture shall be equal to or greater than that of the transistor lead.

2.4 The location of the reference plane(s) of the input-output terminals shall be known within less than ± one thousandth* of the wave length at the test frequency or 0.003 inches*, whichever is greater.

2.5 Repeatable low-resistance electrical contact between the transistor leads and the terminals of the mount shall be made within 0.5 mm(0.02")* of the specified reference planes and should have low enough resistance to assure repeatability of the intended measurement.

2.6 For axial-leaded transistors,no portion of the input shall extend beyond the reference plane defined in clause 2.5 above and no insulating materials shall be placed in the air-gap between the seating plane of the transistor package and the reference plane of the transistor mount (see Figure 2a).

2.7 The mount insertion loss with its feedthrough shall be equal to or less than (0.3 dB + 0.05 dB/GHz)*.

2.8 The following suggested feedthrough comments are useful in minimizing losses and electrical discontinuities.

a) Approximately the same material and geometry should be used as in the transmission line of the fixture.

b) In case of stripline packages the physical dimensions should be the same as that of the space which the transistor will occupy.

c) Feedthrough leads should have sufficient length and should have widths slightly narrower than both the fixture and feedthrough transmission lines.

3. THE MEASURING SYSTEMS FOR SCATTERING PARAMETERS

3.1 General

The measuring system must provide a means for applying bias to the transistor under test. The bias system must be such as not to influence the accuracy of the measurements.

The signal applied by the measuring system to the transistor must be sufficiently small to satisfy the small-signal conditions defined in 1.2. In addition, any spurious signals which might appear at the transistor terminals and, in particular, the local oscillator feed-through when a superheterodyne receiver is used, must be kept at least 30 dB* below the applied desired signal.

3.2 Input & Output Source Match

Ideally, the measurement of scattering parameters would require that system source and load impedances at the two-port-reference planes be precisely equal to Z_0, the defining reference impedance. In practice, these impedances must satisfy the following conditions:

Input Source Match:

$$\left|\Gamma_1\right| = \left|\frac{Z_1-Z_0}{Z_1+Z_0}\right| < 0.1 + 0.02f_{GHz}$$

Output Source Match:

$$\left|\Gamma_2\right| = \left|\frac{Z_2-Z_0}{Z_2+Z_0}\right| < 0.1 + 0.02f_{GHz}$$

3.3 Directivity

In reflectometer systems used for the measurement of s_{11} and s_{22}, the directivity, D, of the directional couplers used must meet the following conditions:

$$\left|D\right| > 40\ \text{dB}^*$$

3.4 Transmission lines may be used to make connection between the transistor mount and the measuring system. These lines may include adjustable-length sections for phase compensation. However, the SWR created by residual reflections in the lines must not exceed $(1.01 + 0.01f_{GHz})^*$ where f_{GHz} represents the test frequency expressed in gigahertz. Also, the errors in the measured parameters caused by losses in the lines must be less than 3%*. If these errors exceed 3%*, appropriate corrections should be made.

APPENDIX I

Instrument Accuracy, Dynamic Range, and Sensitivity for Transistor Scattering Parameter Measurements from 100 MHz to 12 GHz Outside Test Fixture

Three basic types of instruments are used for transistor measurements above 100 MHz:

1. Bridge circuits, where the unknown is compared to standard impedances using impedance ratios but no directional devices;
2. Slotted sections where the unknown is compared to a characteristic impedance using voltage ratios; and
3. Reflectometers, including network analyzers, where power levels and phase are compared to a reference signal assuming an impedance reference.

In general, over the range of concern, reflection coefficients can be measured[1] to 0.01 and phase angles to $1°/s_{mm}$ using typical equipment and techniques (see figures 3 and 4). Using the best equipment and technique this can be improved[1] to 0.001 and $0.1°/s_{mm}$ (see figures 5 and 6). Using either typical or the best equipment, attenuation or gain can be measured to 0.2 dB + $0.01s_{mn}$ (in dB). The phase angle of attenuation can be measured to $1°+(0.1°/\mathrm{dB})s_{mn}$ (in dB) (see figures 7 and 8). For low power levels these are degraded as shown in Table I. A summary of error versus power level using optimum and typical equipment and techniques is shown in this table.

The effect of power level on the test terminals can be estimated as follows. Noise and detector sensitivity will be the primary limiting factors on the measurement at low power levels. While detectors can be improved in sensitivity at the expense of response time and cost, typical detectors used for measurements have sensitivities of about -80 dBm. The slotted line or reflectometer has about 20 dB decoupling in the probe or directional coupler giving roughly -60 dBm sensitivity. A typical generator will have about 10 dBm output decoupled by pads or power splitters by around 10 dB providing roughly 1 mW to the test terminals. The 60 dB difference then allows a sensitivity of 60 dB in return loss or 0.0003 in Γ, which is about the best found in practice. This is subject to considerable variation but can serve as a general limitation. Not all of the error at low reflection coefficients is due to noise limitation so the power level can probably be reduced by 10 dB before the general 0.01 limit given above is exceeded. The bridge circuit is usually limited by errors other than noise at low reflections but a similar treatment will show that for 0.01 error in Γ, the bridge will require about -10 dBm on the test terminals.

At lower signal levels, the slotted line with the generator feeding the probe appears most practical.[2] With such a system it is possible to obtain errors as low as 0.003 in Γ and 0.1° in phase angle at 8 GHz using -50 dBm on the test terminals.

A rigorous error analysis would not be feasible for the following reasons.

1. Insufficient data is available on the various instruments, particularly the interaction of phase and magnitude values and errors.
2. Some instruments measure the parameters of two ports under matched conditions, others under open- and short-circuit conditions, and others approximate these conditions to different degrees. Thus, they cannot be directly compared.

3. For comparison, errors should be given for the same quantity while different instruments measure variously: impedances, scattering parameters, reflection coefficients, or standing wave ratios.

4. While the above quantities are mathematically related, four independent measurements are required to describe the two port device. These four complex measured values and their errors interact in the transformation.

The input reflection coefficient of a two-port, Γ_1, is related to the scattering parameters by[3]

$$\Gamma_1 = s_{11} + \frac{s_{12}s_{21}\Gamma_L}{1 - s_{22}\Gamma_L} \quad ,$$

where Γ_L is the reflection coefficient of the load.

Therefore, if the two port is terminated in a matched impedance

$$\Gamma_L = 0 \quad ,$$

and

$$\Gamma_1 = s_{11} \quad ,$$

then the power incident on a two-port, P_1, is

$$P_1 = \frac{|a_1|^2}{Z_{01}} \left(1 - |\Gamma_1|^2\right) ,$$

where Z_{01} is the input impedance of the two-port.

The transmitted power, P_2, is

$$P_2 = \frac{|b_2|^2}{Z_{02}} (1 - |\Gamma_L|^2) \quad ,$$

where Z_{02} is the output impedance of the two-port.

The ratio of P_2/P_1 as would be measured by a reflectometer or ratio meter is

$$\frac{P_2}{P_1} = \frac{Z_{01}}{Z_{02}} \frac{|b_2|^2}{|a_1|^2} \frac{(1 - |\Gamma_L|^2)}{(1 - |\Gamma_1|^2)} \quad .$$

For the case where the input and output are matched and the terminal planes are at the same impedance

$$\frac{P_2}{P_1} = \frac{|b_2|^2}{|a_1|^2} = |s_{21}|^2 \quad .$$

Approximate comparison of the methods can be obtained by letting

$$S_{mm} = \Gamma_{mm} = \frac{r - 1}{r + 1} = \left[\frac{R_N - 1}{R_N + 1}\right]_{R>R_0} \quad \text{or} \quad \left[\frac{1 - R_N}{1 + R_N}\right]_{R<R_0} \quad ,$$

where r is the SWR and R_N is the normalized resistance, R/R_0.

This is true only if the two-port is terminated in a matched load which is purely resistive.[4] Then

$$\Delta s = \Delta\Gamma = \frac{2\Delta r}{(r + 1)^2} = \left[\frac{2\Delta R_N}{(R_N + 1)^2}\right]_{R>R_0} \quad \text{or} \quad \left[\frac{-2\Delta R_N}{(R_N + 1)^2}\right]_{R<R_0}$$

INSTRUMENT ERRORS AS A FUNCTION OF TEST TERMINAL POWER LEVEL OVER THE FREQUENCY RANGE 0.1 to 12 GHz

TABLE I

USING OPTIMUM EQUIPMENT AND TECHNIQUE

Test Power	s_{mm} Error Magnitude	s_{mm} Error Phase	s_{mn} Error Magnitude ††	s_{mn} Error Phase
10^{-3} W	0.001	$0.1°/s_{mm}$	0.2 dB + $0.01 s_{mn}$ dB	$1° + (0.1°/dB) s_{mn}$ (in dB)
10^{-4} W	0.001	$0.1°/s_{mm}$ #	0.2 dB + $0.1 s_{mn}$ dB	$1° + (1°/dB) s_{mn}$ (in dB)
10^{-5} W †	0.003	$0.1°/s_{mm}$		
10^{-6} W †	0.003	$0.1°/s_{mm}$		
10^{-7} W †	0.003	$0.1°/s_{mm}$		
10^{-8} W †	0.003	$0.1°/s_{mm}$ #		

TABLE II

USING TYPICAL EQUIPMENT AND TECHNIQUE

Test Power	s_{mm} Error Magnitude	s_{mm} Error Phase	s_{mn} Error Magnitude ††	s_{mn} Error Phase
10^{-3} W	0.01	$1°/s_{mm}$	0.2 dB + $0.01 s_{mn}$ dB	$1° + (0.1°/dB) s_{mn}$ (in dB)
10^{-4} W	0.01	$1°/s_{mm}$	0.2 dB + $0.1 s_{mn}$ dB	$1° + (1°/dB) s_{mn}$ (in dB)
10^{-5} W †	0.01	$1°/s_{mm}$		
10^{-6} W †	0.01	$1°/s_{mm}$		
10^{-7} W †	0.01	$1°/s_{mm}$		
10^{-8} W †	0.01	$1°/s_{mm}$		

\# Requires detector sensitivity better than -90 dBm.

† For power levels below 10^{-4} W, the reverse slotted line technique is required.

†† Range of s_{mn} 0 to ± 60 dB.

REFERENCES

1. "IEEE Standards Report on The State of the Art of Measuring Unbalanced Transmission Line Impedance"
IEEE Standard #314, IEEE Trans. On Instrumentation and Measurement, May 1971, Vol. IM-20, #2, p. 129

2. "Precision Slotted-Line Impedance Measurements Using Computer Simulation for Data Correction" B. J. Clifton, IEEE Trans. On Instrumentation and Measurement, Nov. 1970, Vol. IM-19, No. 4, p. 358-364.

3. "Basic Theory of Waveguide Junctions and Introductory Microwave Network Analysis" D. M. Kerns, and R. W. Beatty, Pergamon Press, 1967, pp. 42,49.

4. "Microwave Measurements" E. L. Ginzton, p. 223, McGraw-Hill Book Company, Inc. 1957.

The numerical values shown which have no referenced footnote are based upon measurement technology at the time of writing this document.

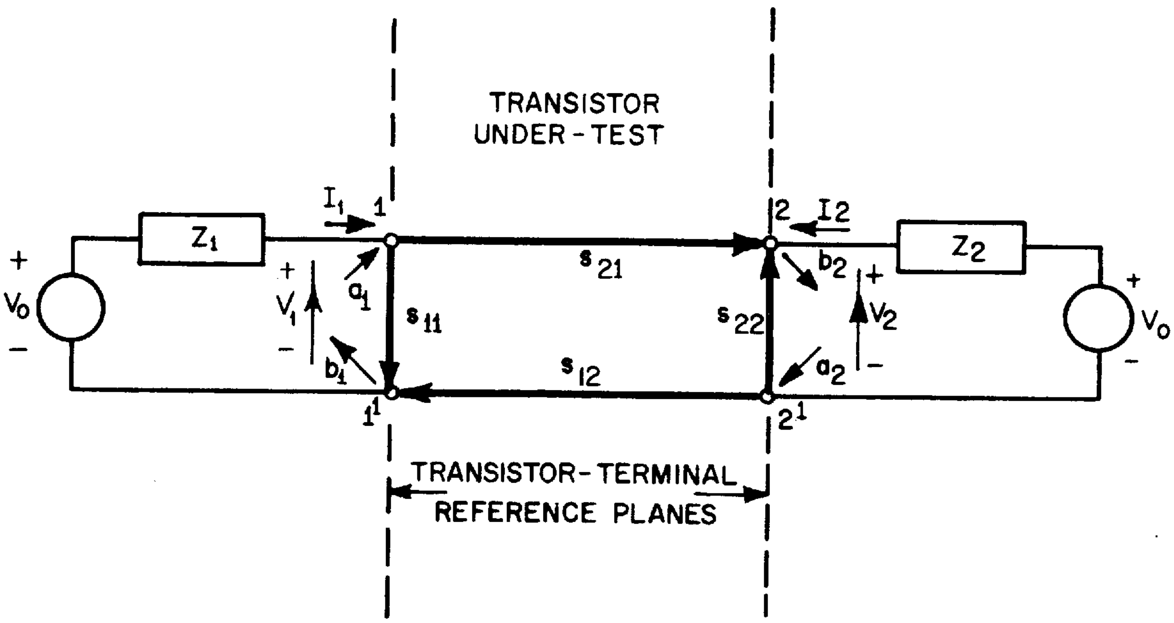
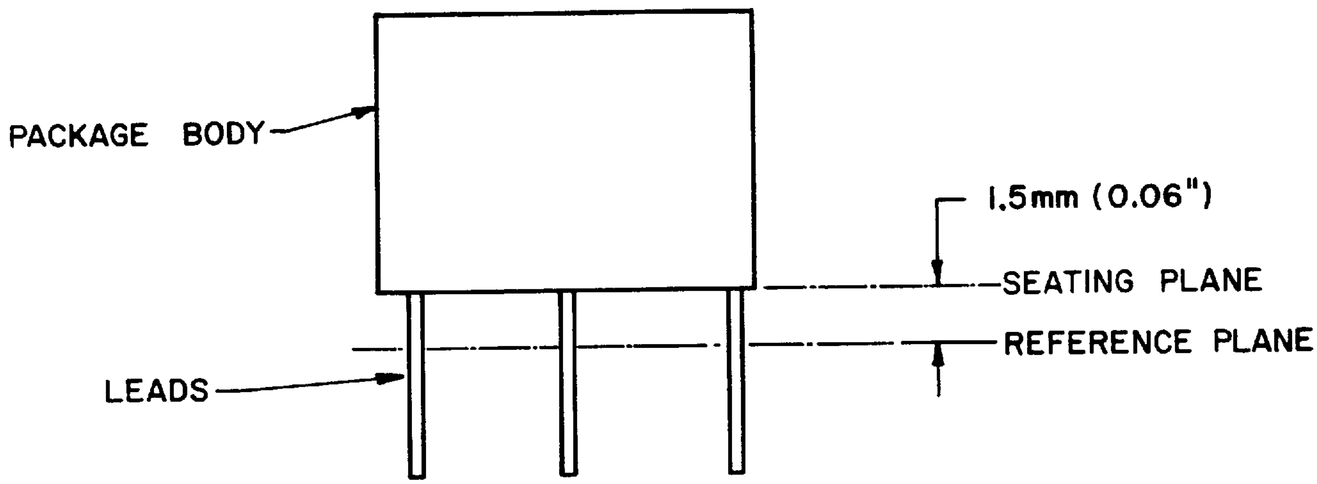
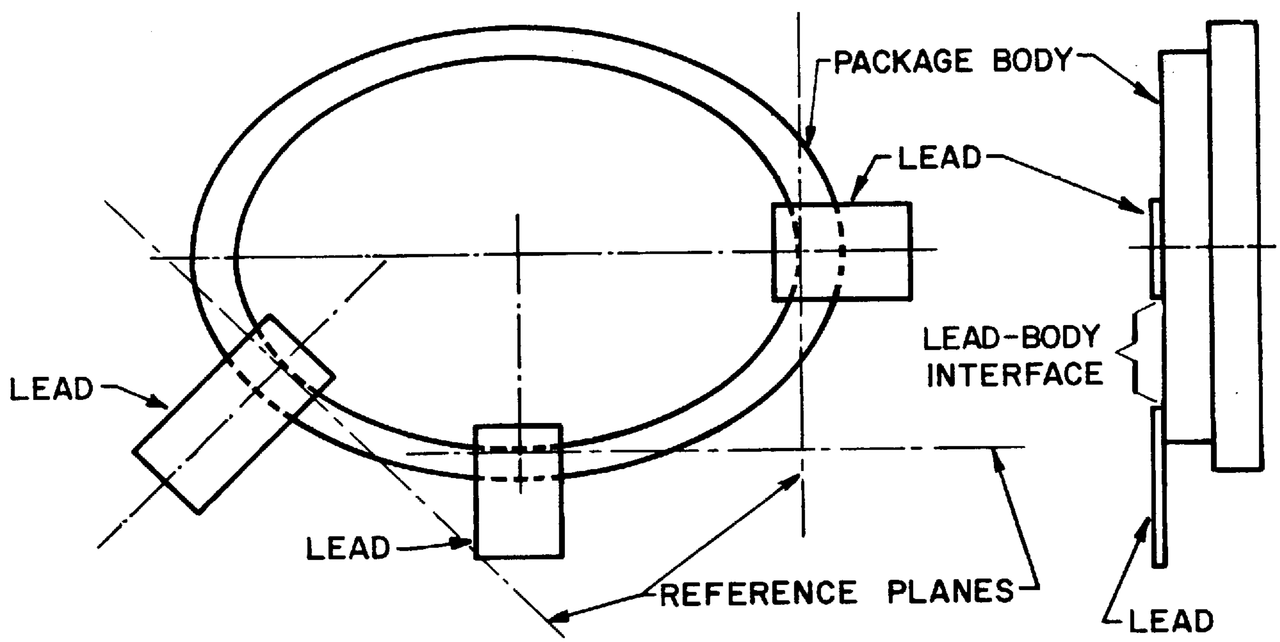


FIG. 1 — SCATTERING PARAMETER DEFINITION SCHEMATIC

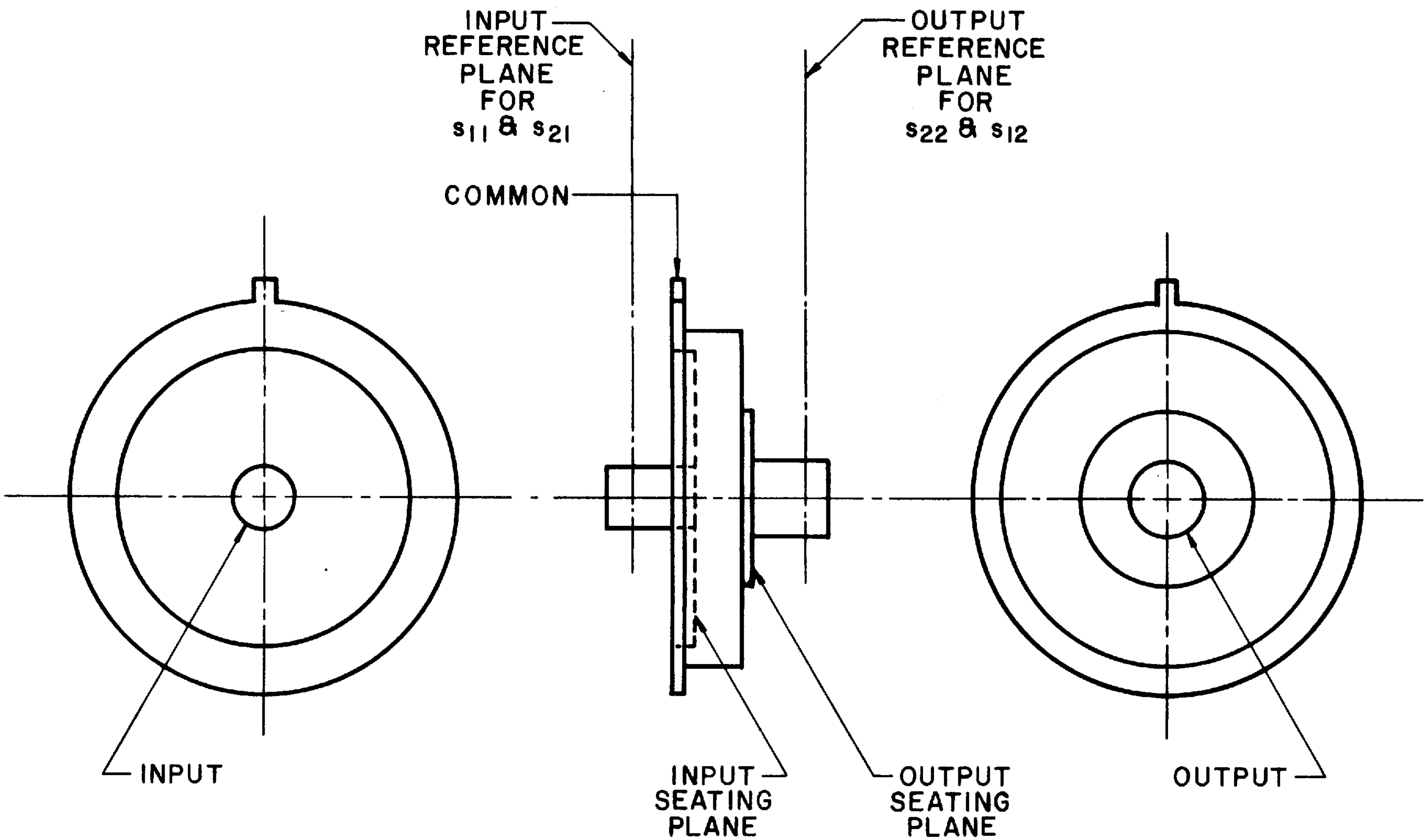


(a) SINGLE-ENDED AXIAL-LEAD PACKAGE



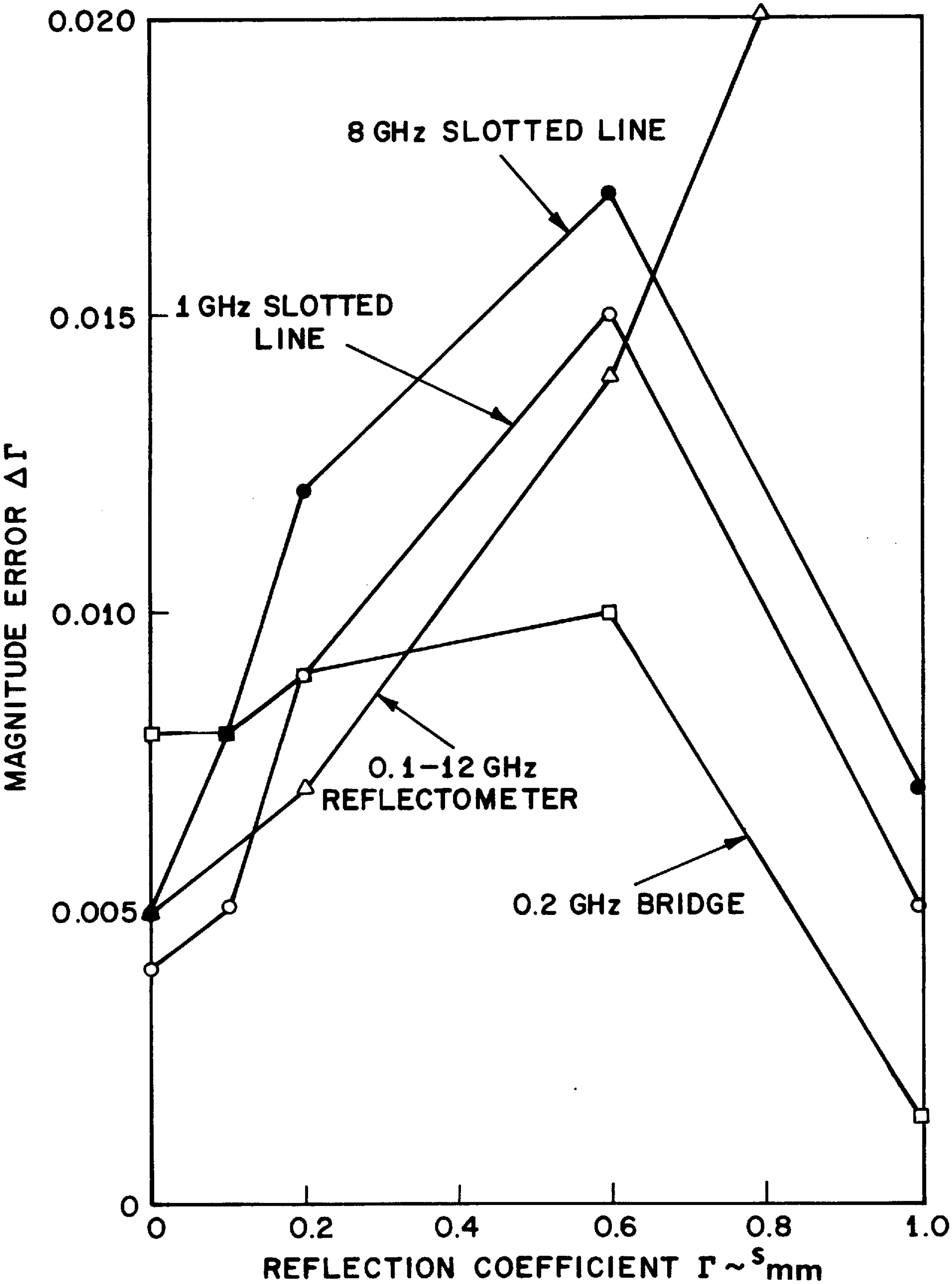
(b) STRIP-LINE PACKAGE

FIG. 2 - TRANSISTOR TERMINAL REFERENCE PLANES



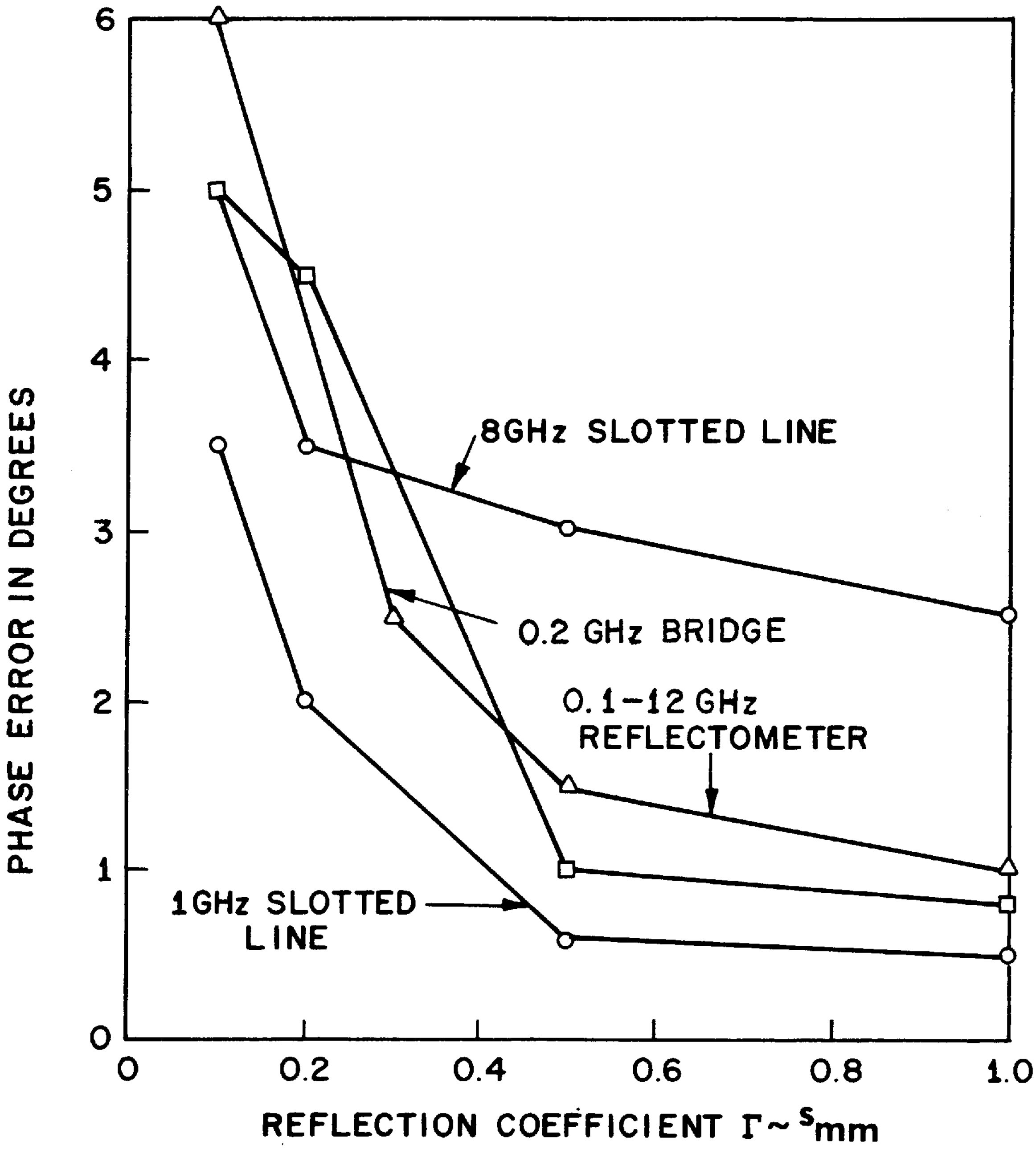
(c) COAXIAL PACKAGE

FIG.2—TRANSISTOR TERMINAL REFERENCE PLANES



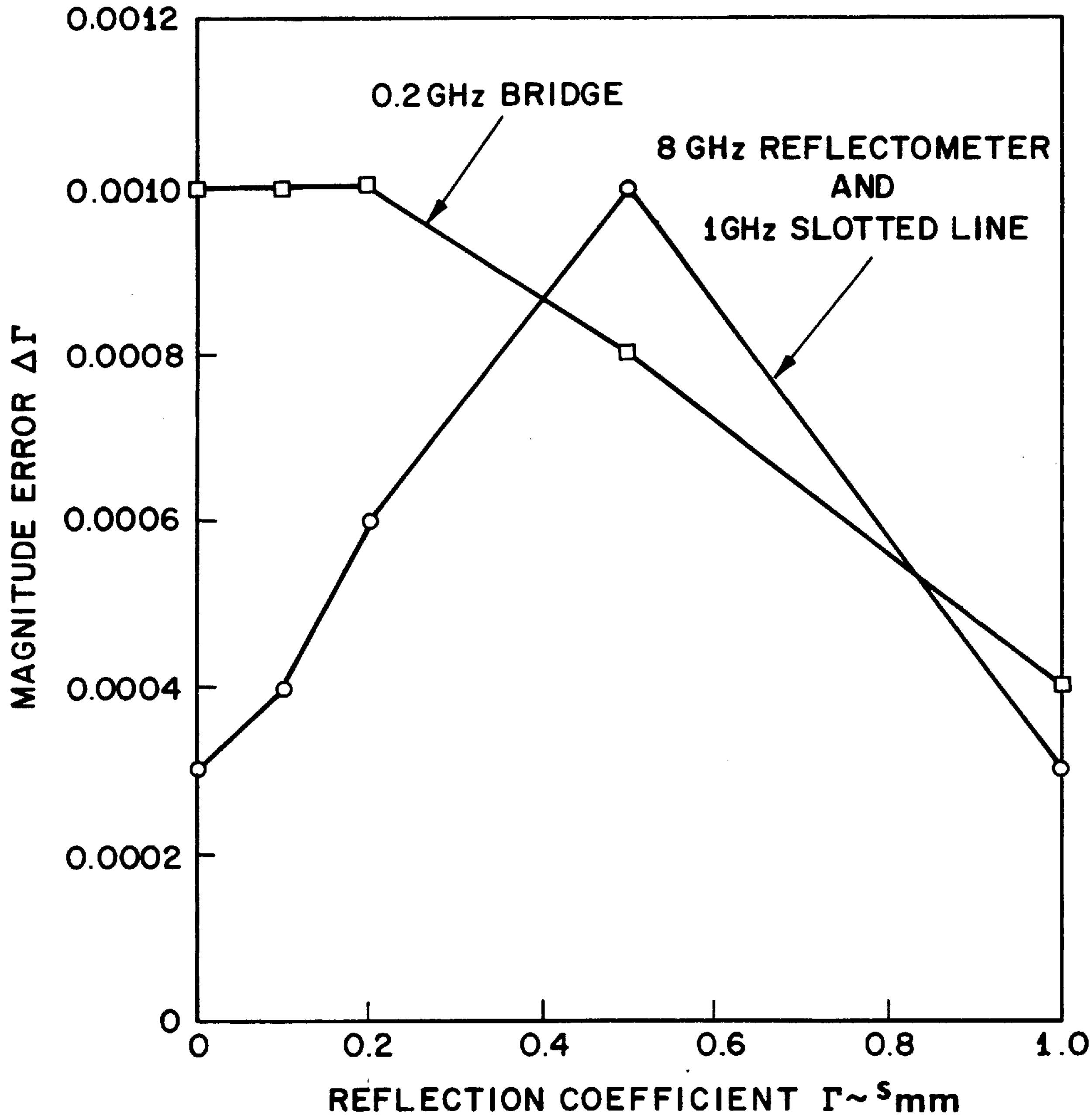
TYPICAL MEASUREMENT ERROR
MAGNITUDE ERROR

FIGURE 3



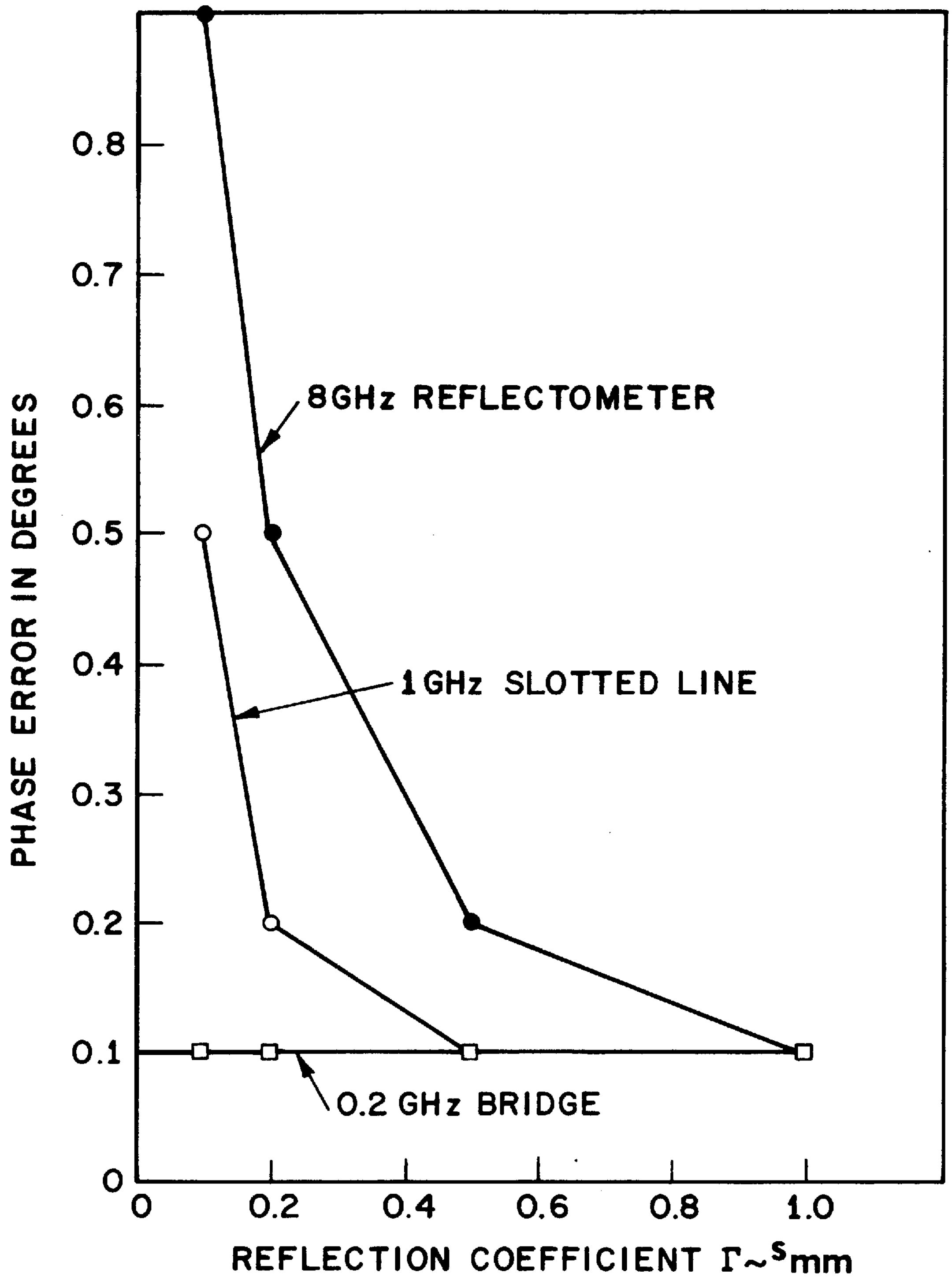
TYPICAL MEASUREMENT ERROR
PHASE ERROR

FIGURE 4



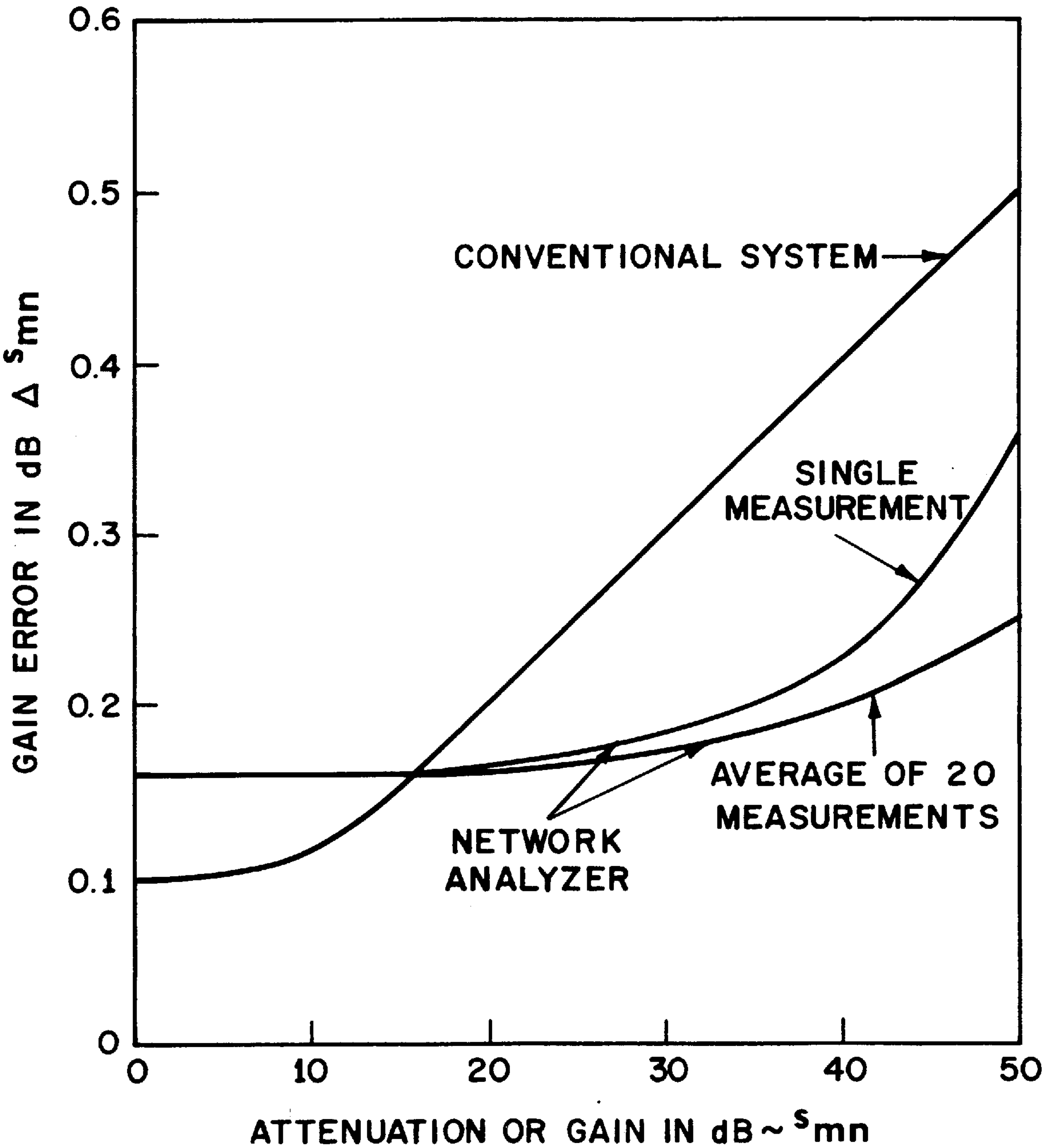
MINIMUM MEASUREMENT ERROR
MAGNITUDE ERROR

FIGURE 5



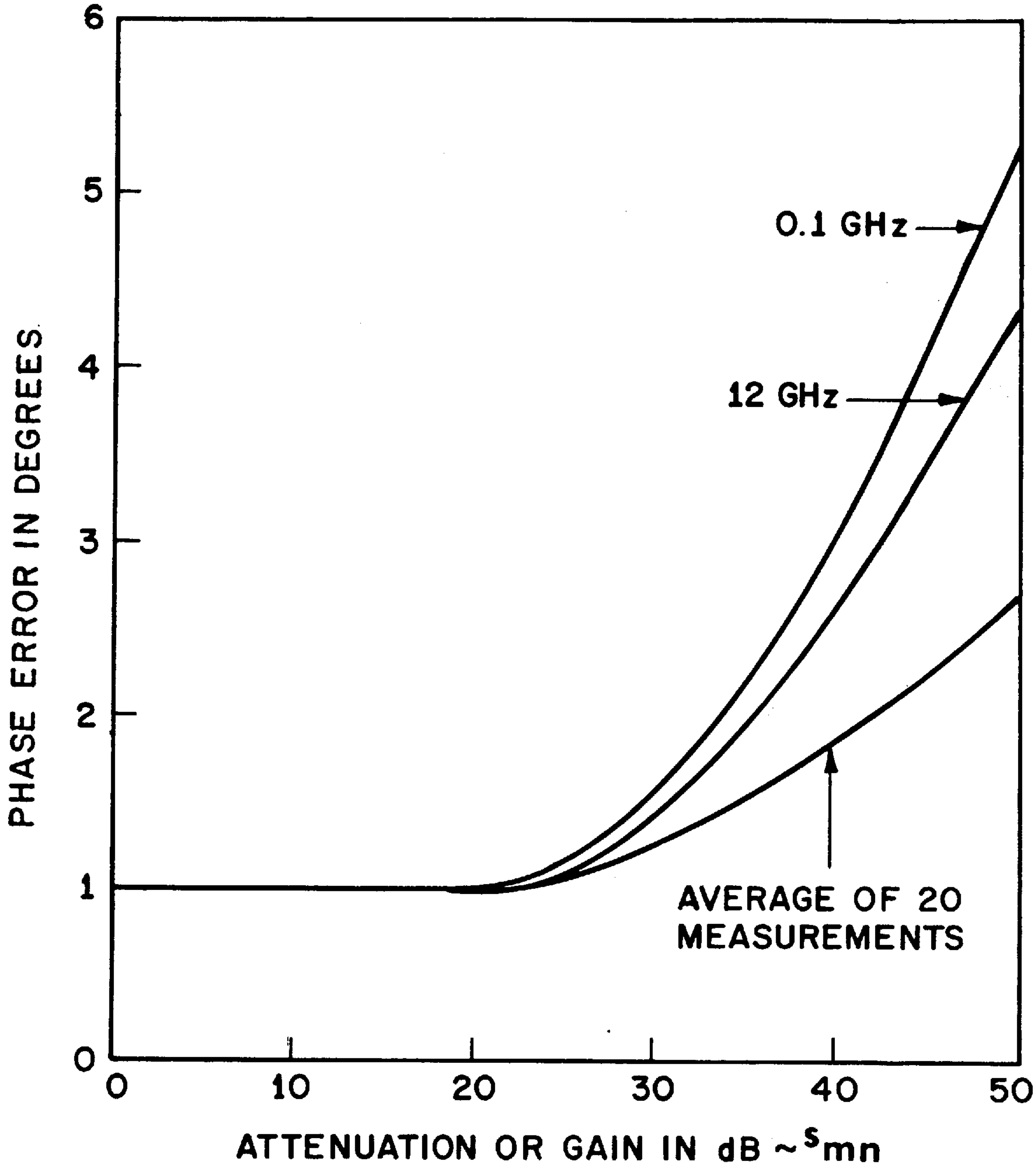
MINIMUM MEASUREMENT ERROR
PHASE ERROR

FIGURE 6



MEASUREMENT ERROR
AMPLITUDE OF ATTENUATION

FIGURE 7



MEASUREMENT ERROR
PHASE OF ATTENUATION

FIGURE 8

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