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UHF and Microwave Phase-Shift Measurements

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Abstract—**A phase-shift standard, a measurement system, and the techniques for determining the corresponding limit of uncertainty are all required for obtaining the phase-shift characteristics of UHF and microwave components.**

Differential phase-shift standards, measurement techniques, and measurement uncertainties are all discussed in a general sense and a comprehensive bibliography is included to supplement the general discussion.

I. INTRODUCTION

PHASE-SHIFT calibration of UHF and microwave components can be accomplished provided that the following three ingredients are available: a phase-shift standard or components that can be assembled to serve this purpose, a measurement system, and the techniques for determining the corresponding measurement uncertainty.

Many different phase-shift standards and many different measurement techniques exist today and the development of most of them has been reported in the literature. The results of careful analysis of particular standards and particular measurement systems have been reported and a number of general review papers have also been published [1]–[12]. The limits of uncertainty are discussed to some extent in practically every measurements publication; however, there has been no general discussion of the uncertainties involved in the measurement of phase shift.

The prime objective in this paper is to report on the state-of-the-art of differential phase-shift measurements at UHF and microwave frequencies. Differential phase-shift standards, measurement techniques, and measurement uncertainties are discussed. Technical criteria that should be considered when selecting a standard or a measurement system are given and techniques for minimizing the limits of uncertainty are included. All the discussion is of a general nature; a bibliography is included to supplement the general discussion.

II. DIFFERENTIAL PHASE-SHIFT STANDARDS

Differential phase shift is defined in this paper as "the magnitude of the change in phase of a field quantity at the output of a two-port network which is produced by an adjustment of the characteristics of the two-port network." A differential phase-shift standard is then a network, or device, whose phase-shift characteristics are known, within a limit of uncertainty.

The uncertainty associated with a differential phase-shift standard is usually of major significance; therefore the choice of a phase shifter as a standard is governed primarily by the limit of uncertainty that is prescribed for the measurement. Other technical criteria that must be considered when selecting a standard include the phase shifter's loss characteristics, its operational frequency bandwidth, its maximum differential phase shift and its ease of operation.

Each differential phase shifter is designed to operate in either the analog (continuous) or the digital (stepped) mode. The discussion here is centered on analog phase shifters because digital phase shifters have found little application to date as standards. The design and performance of digital phase shifters have been discussed in several articles [33], [35], [38].

The class of analog phase shifters can be subdivided in several different ways. In this discussion they are subdivided into four general groups entitled reflection-type phase shifters, line-stretcher phase shifters, dielectric phase shifters, and electrically controlled phase shifters.

A brief discussion of the principles of operation for a number of devices in each group follows. Each phase shifter is examined with respect to the selection criteria outlined above and the factors which limit the uncertainty are pointed out.

A. Reflection-Type Phase Shifters

Reflection-type differential phase shifters can be quickly constructed in the laboratory from multiport components and sliding short-circuit terminations [35]. Three different arrangements are shown in Fig. 1. In all three arrangements,

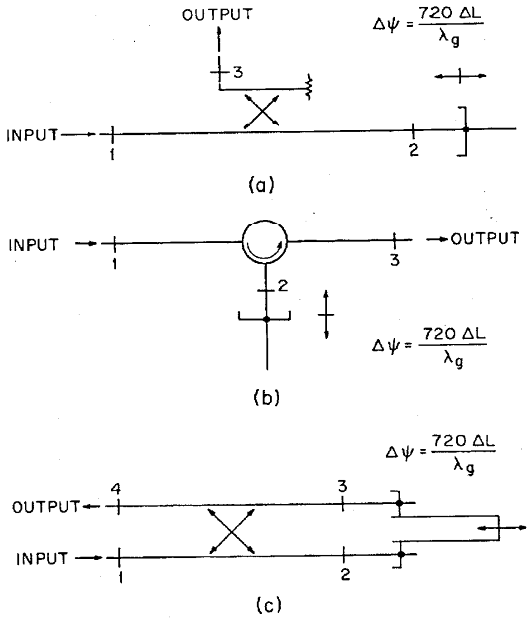

Fig. 1. Reflection-type phase shifters. The differential phase shift $\Delta\psi$ is a function of the displacement of the movable portion ΔL and the waveguide wavelength λg. (a) Directional coupler arrangement. (b) Circulator arrangement. (c) Three-dB symmetric hybrid arrangement.

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the output signal is derived from the reflected signal. A differential phase shift is produced when the positions of the short circuits are changed. Ideally, the amount of differential phase shift is determined only by the displacement of the short circuits and the waveguide wavelength.

A directional coupler is illustrated in Fig. 1(a). Considerable mismatch exists at the input (port 1) of this arrangement because port 2 is terminated in a short circuit. Assuming that a 10-dB directional coupler is used, the theoretical return loss as seen at the input is 0.92 dB, which corresponds to an input reflection coefficient of approximately 0.9. Analysis shows that both ports must be connected to a well-matched system in order to minimize the uncertainty caused by the mismatch.

The tolerance involved in the measurement of short-circuit displacement, the dimensional tolerance of the waveguide, and the frequency instability of the UHF or the microwave signal each cause various amounts of measurement uncertainty. Analysis shows that a limit of uncertainty of ±1.0 degree is typical at 10 GHz if commercial components are used. A limit of uncertainty on the order of ±0.1 degree is possible if matching transformers, a precision waveguide section, and other special equipment are properly used.

The phase shifter's input reflection coefficient is reduced if a circulator is used in place of the directional coupler, as shown in Fig. 1(b). It is necessary to use this phase shifter in a well-matched system in order to maintain a minimum limit of uncertainty. The limit of uncertainty with the circulator arrangement is, in principle, the same as that for a directional coupler arrangement. However, circulators are not widely used in this application because they are not available for all frequencies; those in existence are relatively narrowband devices, and they are not found in as many measurement laboratories as are directional couplers.

A variety of hybrid junctions, such as E-H tees, magic tees [18], 3-dB directional couplers, rat races [20], and ring circuits [20], are suited for use in reflection-type phase shifters. The 3-dB symmetric hybrid, shown in Fig. 1(c), is especially convenient because it is easy to couple together the sliding short ciruits in waveguides which have parallel axes [24].

The signal incident on port 1 is divided equally between ports 2 and 3 and the characteristics of the hybrid cause the signal components emerging from those ports to be in phase quadrature. These signal components travel paths of equal length and are reflected by a pair of short circuits. The reflected signal from each short circuit is divided equally between ports 1 and 4, resulting in two signal components emerging from both ports 1 and 4. The reflected signal components emerging from port 1 cancel while the reflected signal components emerging from port 4 add. Therefore, a reflected signal emerges from port 4 only and the phase shifter is, in principle, matched at its input (port 1).

The uncertainties in this arrangement are caused by superposition of the residual reflections from the phase shifter and from the system to which it is attached, the uncertainty in measuring the displacement of the short circuits, and the frequency instability of the UHF or the microwave signal source. The limit of uncertainty for the hybrid arrangement has a range of ±(0.25–3.0) degrees, depending upon the components used and the frequency of the UHF or the microwave signal.

Typical insertion losses of the devices in Fig. 1 are approximately 6, 10.5, or 20 dB for the directional coupler (corresponding to the use of either a 3-, 10-, or 20-dB directional coupler, respectively), 1 dB for the circulator, and 0.1 dB for the hybrid junction. Typically, the change of insertion loss that occurs when the phase shifter is adjusted will be less than 0.05 dB at frequencies up to 12 GHz.

The phase shifters shown in Fig. 1 can be constructed from either coaxial or rectangular waveguide components. The maximum differential phase shift that can be produced with any of the arrangements is determined by the waveguide wavelength and the maximum displacement of the short circuits. For example, a differential phase shift of 360 degrees will be produced in a coaxial waveguide arrangement if the short-circuit position is changed 15 cm when the frequency is 1 GHz and a displacement of 1.5 cm will produce a differential phase shift of 360 degrees if the frequency is 10 GHz.

B. Line-Stretcher Phase Shifters

Line stretchers operate by changing the length of waveguide in a portion of the circuit, which results in a change in the electrical length of that circuit [17], [19], [20], [28]. This change of length is accomplished by sliding together two waveguides of slightly different sizes, as illustrated in Fig. 2.

In the telescoping type, shown in Fig. 2(a), the change in electrical length is proportional to the displacement of the

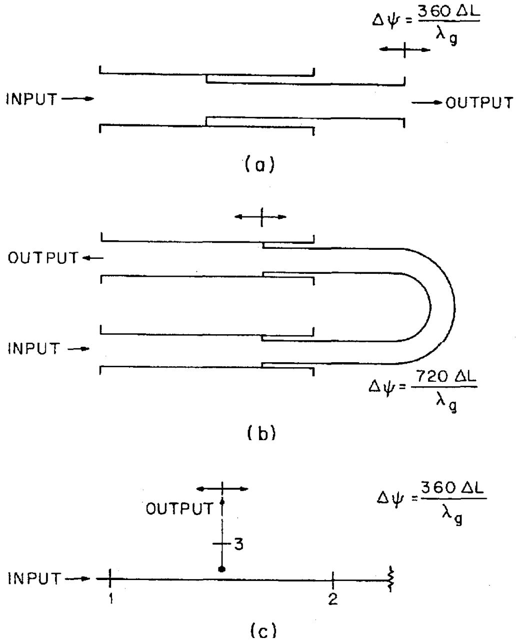


Fig. 2. Line-stretcher phase shifters. The differential phase shift $\Delta\psi$ is a function of the short-circuit displacement ΔL and the waveguide wavelength λg. (a) Telescoping-type line stretcher. (b) Trombone-type line stretcher. (c) Slotted-line-type line stretcher.

movable portion, while in the trombone type, shown in Fig. 2(b), the change in electrical length is proportional to twice the displacement of the movable portion. This is significant in that the telescoping type must have a displacement capability of twice that for the trombone type in order to produce an identical differential phase shift, assuming that the waveguide wavelength is the same in both configurations. But for a given uncertainty in displacement measurement, the phase-shift uncertainty of the trombone type is twice that for the telescoping type. However, the trombone type is usually used because of its convenience of installation and operation.

It is ordinarily required that a line stretcher be capable of producing a differential phase shift of at least 180 degrees if it is to be useful. Thus, the maximum change of length of a line stretcher usually limits the lower frequency of operation. If a telescoping line stretcher of coaxial waveguide has a maximum length variation of 15 cm, for example, the lower frequency limit would be 1 GHz. It would still operate satisfactorily at lower frequencies, but it would produce less than 180 degrees of phase shift. For rectangular waveguide line stretchers, the practical lower frequency limit is that recommended for the waveguide, but it would still operate at frequencies down to the cutoff frequency of the waveguide.

The upper frequency limit of a line stretcher is usually determined by its deterioration of performance due to reflections whose effects increase with frequency. These reflections arise from unavoidable discontinuities which occur at the steps where a telescoping tube slides over another tube of slightly smaller dimensions. Usually attempts are made to compensate for these discontinuities, but as the frequency increases the compensation will eventually become ineffective. In the case of a rectangular waveguide line stretcher, the practical upper frequency limit may be that recommended for the waveguide so that higher modes are not excited.

In addition to the need to compensate for unavoidable discontinuities, there are several other considerations which are important in the design of line stretchers: 1) it is desirable to maintain a constant impedance as the line is lengthened, even though waveguide dimensions must be different in the movable portion than in the fixed portion, 2) it is desirable to have no "noise" or variation of impedance caused by sliding contacts or the transition from the fixed portion to the movable portion, 3) leakage from the unavoidable joint between fixed and movable portions of the line stretcher should be minimized, 4) the waveguide of which the line stretcher is made should have uniform dimensions, and 5) the drive mechanism (if used) for the movable portion should operate smoothly.

The limit of uncertainty of commercial coaxial and rectangular waveguide line stretchers ranges from ±(0.1–1.0) degree for the frequency range of 1–12.4 GHz, the uncertainty increasing with frequency. The bulk of the uncertainty is caused by interaction between the residual reflections from the line stretcher and the system where it is attached, the uncertainty in measuring the displacement of the movable section, and the frequency instability of the UHF or the microwave signal source.

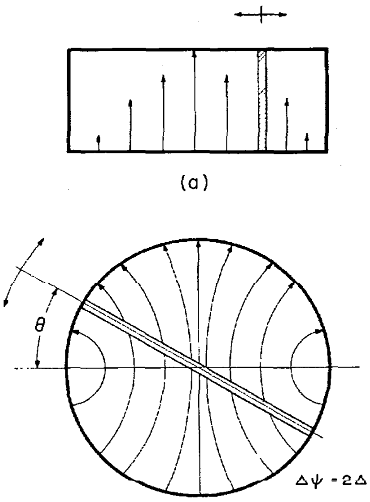
The insertion loss for both the telescoping and the trombone line stretcher is low, 0.5 dB or less. The change of insertion loss caused by changes in line length is less than 0.05 dB at frequencies up to 12.4 GHz. The maximum differential phase shift that can be produced with either the telescoping or the trombone type is dependent upon the maximum displacement of the movable portion and the waveguide wavelength.

Another arrangement which is classified as a line stretcher in this discussion is shown in Fig. 2(c). The slotted section is terminated in a matched load. A small portion of the UHF or the microwave signal is coupled out of the slotted section with a probe, and a differential phase shift is produced by changing the probe position. A major uncertainty is caused by the mismatch of the terminating element. As an example, if the terminating element has a VSWR of 1.10, uncertainty in the phase shift is on the order of ±2.5 degrees, while a VSWR of 1.50 could result in an uncertainty of ±12.0 degrees. The maximum differential phase shift that can be produced with this arrangement is dependent upon the maximum displacement of the probe and the waveguide wavelength.

The insertion loss of the slotted-line device is typically 20 dB and the typical change of insertion loss over the range of phase shifts is less than 0.05 dB.

C. Dielectric Phase Shifters

A differential phase shift is produced when a strip of dielectric material is placed within a waveguide as shown in Fig. 3(a). The change is small if the dielectric strip is placed in the weakest portion of the electric field and a larger change is produced if the dielectric strip is placed in a



(a)

(b)

Fig. 3. Dielectric-vane phase shifters. The differential phase shift $\Delta\psi$ of the rotary-vane phase shifter is a function of the vane rotation $\Delta\theta$. (a) Dielectric vane in rectangular waveguide (TE_{10} mode). (b) Rotary-vane phase shifter in circular waveguide (TE_{11} mode). The differential phase shift $\Delta\psi$ is a function of the differential rotation angle $\Delta\theta$.

stronger portion of the electric field. Hence, a differential phase shifter can be constructed by mounting a movable dielectric vane [17], [19] in rectangular waveguide (TE_{10} mode). Vane-type attenuators can be converted into differential phase shifters by replacing the lossy vane with a dielectric vane. Dielectric materials such as polystyrene and glass have been used in that conversion.

The maximum differential phase shift that can be produced with the arrangement shown in Fig. 3(a) is a function of the vane dimensions, the vane material, and the microwave frequency. Usually a differential phase shift of at least 90 degrees can be produced with a repeatability ranging from a few tenths of a degree to ±3.0 degrees. These phase shifters are not direct reading devices; they must be calibrated at each frequency of use because their characteristics are not accurately predictable.

In the rotary-vane phase shifter [16], [21], a differential phase shift is produced when the angular position of a dielectric vane is changed, as shown in Fig. 3(b). Because the principle of operation of the rotary-vane phase shifter cannot be briefly summarized, it is not discussed here. In practice, circular waveguide operating in the circularly polarized dominant (TE_{11}) mode is used. Fortunately, the differential phase shift of the device is nearly independent of the microwave frequency so that the phase shifter's dial can be marked in degrees and this same scale can be used for any frequency recommended for that waveguide size.

Rotary-vane phase shifters are commercially available for the frequency range 5.0–110 GHz. They are manufactured with rectangular waveguide inputs and outputs. Their specified limits of uncertainty range between ±(2–5) degrees, depending upon the waveguide size and the frequency of operation. A differential phase shift of unlimited magnitude can be produced if one continues to rotate the dielectric vane. The insertion loss for these devices ranges from 1.0 to 2.0 dB for any frequency and for any dielectric vane angle.

D. *Electrically Controlled Phase Shifters*

A number of electrically controlled differential phase shifters have been developed in recent years and the most prominent in this category are the ferrite phase shifters [22], [32], [34], [35].

The ferrite phase shifter consists of a ferrite material placed in a homogeneous dc magnetic field within a waveguide and an arrangement for controlling the intensity of the magnetic field. The maximum differential phase shift for these devices is typically 500 degrees at 10 GHz. The greatest difficulty with the ferrite phase shifter is its sensitivity to temperature variations.

Other electrically controlled phase-shifter arrangements are possible [25], [35], such as the use of varactors with 3-dB hybrids, with directional couplers, or with circulators; however, the difficulties of these arrangements limit their use as standards. The difficulties include 1) nonlinearity of bias voltage vs. phase-shift characteristics, 2) generation of harmonics at high power drive levels due to the inherent nonlinearities, 3) self-biasing which changes the phase-shift characteristics with respect to biasing current, and 4) insertion-loss variation which is a function of the bias level and the level of the UHF or the microwave signal.

III. Differential Phase-Shift Measurement Systems

The technical criteria that govern the selection of a measurement system are nearly those given for a phase-shift standard. Still of prime importance is the limit of uncertainty that is prescribed for the measurement; however, the operational bandwidth of the system, its ease of operation, and the effect that an attenuation change has upon system performance must also be considered.

In this paper three general groups of measurement systems are considered: single-channel systems, dual-channel systems, and IF systems. The discussion for the systems in each group is based upon basic block diagrams which show only the essentials of the system; matching devices, power supplies, wavemeters, etc., are not shown.

This discussion is centered upon fixed-frequency measurement systems but it should be noted that equipment has been developed so that most of the systems are adaptable to swept-frequency and pulsed-signal operation. References to articles which treat measurement under swept-frequency or pulse-signal operation are included in the bibliography [50], [63], [74].

A. *Single-Channel System*

Simple arrangements for measuring the differential phase shift of low-loss, reciprocal components are shown in Fig. 4. In Fig. 4(a), a slotted section serves as a null position detector. A minimum of the standing wave pattern is used as a reference to position the probe when the device under test

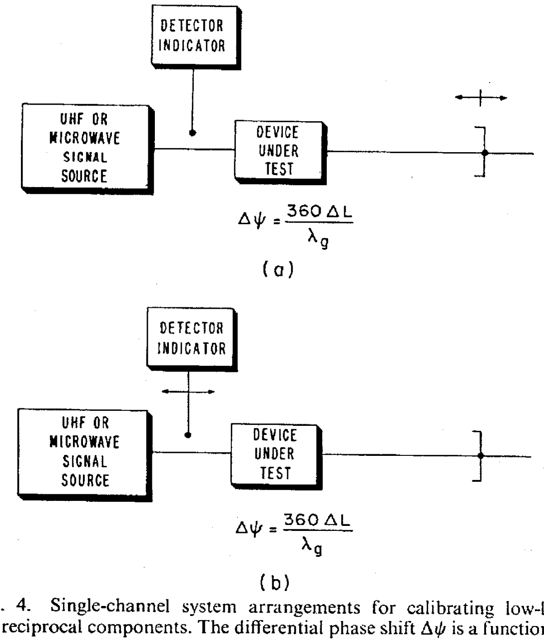


Fig. 4. Single-channel system arrangements for calibrating low-loss reciprocal components. The differential phase shift $\Delta\psi$ is a function of the short-circuit (or probe) displacement ΔL and the waveguide wavelength λg. (a) Single-channel system using a calibrated short circuit as the phase-shift standard. (b) Single-channel system using a slotted section as the phase-shift standard.

is adjusted to its initial dial setting. After the device under test is adjusted to a new dial setting, the minimum of the standing wave pattern is restored to the reference position of the probe by moving the calibrated short circuit [39], [40]. The calibrated short circuit is, in this arrangement, the differential phase-shift standard.

In Fig. 4(b), the position of the probe is adjusted to restore the minimum of the standing wave pattern to its reference position [39]. The slotted section in this arrangement serves as both the detector and the phase-shift standard.

An accurate calibration cannot be obtained with the measurement systems of Fig. 4 unless the device under test has very low reflections (mismatch). Considering the maximum mismatch for a commercial reciprocal phase shifter (VSWR = 1.35), the limit of uncertainty is on the order of ±17.0 degrees when calibrated with either of the arrangements of Fig. 4. If the device under test has an input VSWR of 1.15, the limit of uncertainty is reduced to ±8.0 degrees.

B. Basic Two-Channel System

If the measurement system shown in Fig. 5(a) is used, the mismatch uncertainty present in the single-channel systems can be reduced because the device under test is isolated from the phase-shift standard. For theoretical purposes, the isolation between the standard and the device under test is assumed infinite and in the practical situation it must be high (60 dB or more). A high isolation eliminates the mismatch interaction between the device under test and the standard. Furthermore, tuners can be used for minimizing the uncertainty caused by the superposition of residual reflections.

The two-channel terminology is used in this paper when the UHF or the microwave energy in both channels is derived from a common signal generator. The signal which propagates through the phase-shift standard is called the reference signal, while the signal which propagates through the device under test is called the test signal.

A null occurs at the detector of Fig. 5(a) when the reference and test signals have equal amplitudes and their phase angles differ by 180 degrees. With the device under test adjusted to its initial dial setting, a null is established in the detector by adjusting both the phase-shift standard and the variable attenuator. The device under test is then adjusted to its next dial setting and, assuming that the levels of the reference and test signals remain constant, the null is restored in the detector by readjustment of the phase-shift standard. The differential phase shift of the device under test is then equal to the differential phase shift required of the standard for restoring the null.

If the device under test or the standard should introduce amplitude variations along with the differential phase changes, a minimum signal rather than a null will be established at the output of the detector. The phase resolution of the system is seriously degraded if the amplitude of one of the signals differs from the amplitude of the other by 3 dB or more. If their amplitudes differ by 10 dB, it may be difficult to locate a minimum signal.

A null can be restored at each calibration point with the additional adjustment of a variable attenuator. If the amplitudes of the reference and test signals are equalized at each calibration point, maximum phase resolution is maintained in the measurement system. However, the attenuator itself may introduce small phase changes along with the amplitude changes. In precise measurements the phase changes caused by the attenuator should be taken into consideration in order to obtain a suitable measurement uncertainty.

Considerable effort has been spent to reduce the uncertainty of this system since it was originally developed. An uncertainty on the order of ±0.3 degree is possible if a system is carefully constructed and a precise differential phase shift standard is used [42].

The instrumentation used to indicate the null, or minimum signal condition, in this two-channel system can have a wide variety of configurations. A simple arrangement consists of connecting a standing wave indicator to the crystal video detector, provided that the UHF or microwave signal

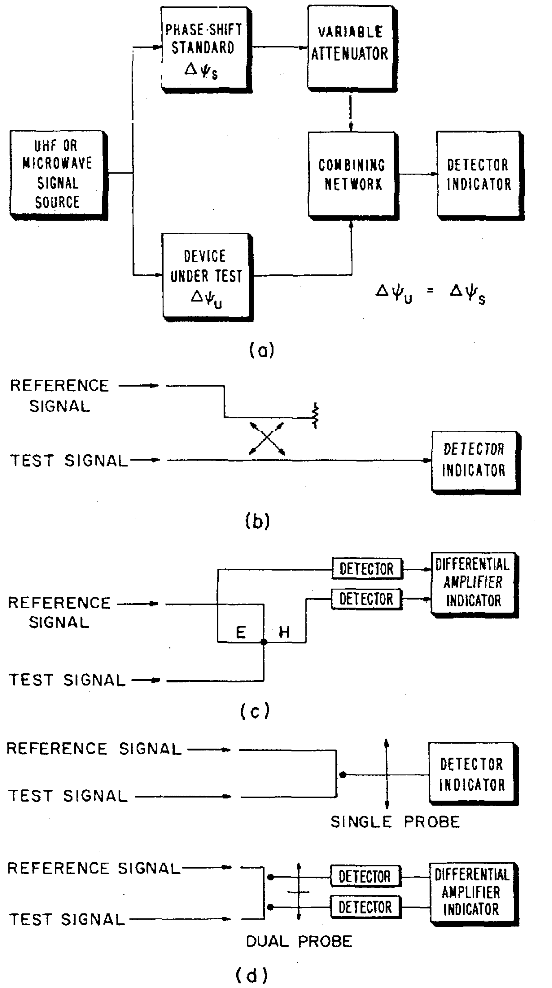


Fig. 5. Block diagram of a basic two-channel phase-shift measurement system and various signal-combining networks. (a) Block diagram of a basic two-channel system. (b) A directional coupler is the combining network. (c) A magic tee is the combining network. (d) Slotted sections are the combining networks.

is amplitude-modulated at its source. Usually the UHF or the microwave signal is amplitude-modulated at its source for instrumentation purposes; however, modulation is not essential for operation of the system.

Other instrumentation techniques are shown in Fig. 5. The signals from the two channels can be recombined with a directional coupler [Fig. 5(b)] magic tee [Fig. 5(c)], or slotted section [Fig. 5(d)]. The magic tee of Fig. 5(c) is particularly useful because it is arranged so that a null is established at each calibration point regardless of any attenuation changes that may occur [41], [53], [58]. Thus the necessity of establishing a null with an auxiliary variable attenuator is eliminated.

By injecting reference and test signals into opposite ends of the slotted section, as shown in Fig. 5(d), a standing wave pattern is set up. The probe is manually positioned so as to obtain a null at the detector output (or a minimum signal is observed at the detector output if the reference and test signals are not of equal amplitude). A phase change caused by adjustment of the device under test will cause the position of the null (or minimum) to shift from its initial position within the slotted section, and the differential phase change produced by adjustment of the device under test is proportional to the distance that the null (or minimum) has shifted. (The proportionality constant is 2β in the ideal case, where β is the phase constant of the slotted section.) A single-probe arrangement can be used to measure the distance that the null (or minimum) of the standing wave pattern has shifted; however, a dual-probe arrangement has also been used [44]. The slotted section serves as both a signal recombiner and a phase-shift standard.

C. *Two-Channel Systems Which Use Amplitude Modulation in One Channel Only*

The two-channel systems described here utilize amplitude modulation in only one channel, as shown in Fig. 6. The test signal is amplitude-modulated at some convenient frequency (usually between 1 and 10 kHz). The modulated test signal is combined with the reference signal and their resultant goes into the detector.

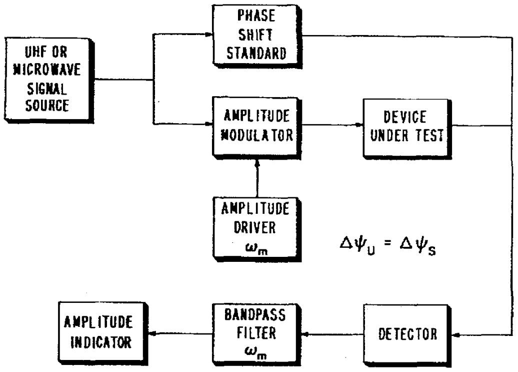


Fig. 6. Block diagram of a two-channel phase-shift measurement system which requires amplitude modulation in only one channel. The differential phase shift $\Delta\psi_u$ produced by the device under test is equal to the differential phase shift $\Delta\psi_s$ required from the standard to restore a null.

The bandpass filter is tuned to the modulation frequency. The amplitude of the detected signal is dependent upon the amplitudes of the reference and test signals and the difference between their phase angles. If the amplitudes of both signals are held constant but the phase angle of one is adjusted, the amplitude of the modulation-frequency signal from the filter will vary between a null and a maximum, provided the amplitude of the test signal is smaller than that of the reference signal. In contrast with the case of a standing wave in a slotted line, here it is not necessary to maintain reference and test signals of equal amplitude to establish a null at the indicator. A null will be established in this system for any relative-amplitude relationship.

Two different types of amplitude modulation have been used in this system. The original arrangement used a double-sideband-suppressed-carrier modulator (usually called a balanced modulator) [61]. If a balanced modulator is used, a null occurs at the indicator when the difference between the phase angles of the reference and test signals at the detector input is 90 degrees. Since the phase-angle difference at the null condition (hereafter called the null angle) is independent of the amplitudes of the reference and test signals, the balanced-modulator arrangement is very useful for measuring the differential phase-shift characteristics of lossy devices such as variable attenuators.

One difficulty with a balanced-modulator arrangement lies in trying to locate one which completely suppresses the carrier signal. Usually a residual signal at the carrier frequency is present at the output of the balanced modulator. This is undesirable because the null angle is no longer 90 degrees but is now dependent upon the amplitudes of the test signal and the residual carrier signal.

A system that uses an amplitude modulator which does not suppress the carrier has been developed [62], [64]. In this system, called the modulated-subcarrier system, a change of attenuation in one of the channels will cause the null angle to change. It is common practice to arrange for the magnitude of the test signal to be much smaller (by 40 dB or more) than the magnitude of the reference signal. Then amplitude changes of the test signal will cause the null angle to change only an insignificant amount. In addition, a technique has been developed [62] for canceling the effect of attenuation changes. With that technique, the modulated-subcarrier system can also be used to measure the differential phase-shift characteristics of lossy devices, such as variable attenuators.

Differential phase shifters are usually calibrated in the systems of Fig. 6 by means of the nulling technique described for the basic two-channel system. It is possible, however, to indicate the phase change in other ways, such as with an oscilloscope [65] or with a ratio detector [63], [66].

D. *IF Systems*

Differential phase-shift measurement systems whose operation depends on the generation of a suitable intermediate frequency (IF) are distinguished from two-channel systems in that two UHF or two microwave signal sources are required to generate the IF signal. Differential phase-shift information can be transferred from a UHF or a microwave signal to a signal of lower frequency by two different methods. In both, a differential phase change in the UHF or the microwave signal appears as a differential phase change of equal magnitude in the lower frequency (IF) signal. The actual phase measurement is done at the IF.

Consider first the heterodyne arrangement shown in Fig. 7(a). Mixer 1 develops an IF signal which is used as a reference signal in the phase meter. Mixer 2 develops an IF signal whose phase angle tracks the change of phase angle of the UHF or the microwave test signal. An IF phase meter, or other devices such as a resolver, can be used to measure the difference between the phase angles of the two IF signals.

In the system which uses a single-sideband (SSB) modulator, shown in Fig. 7(b), the UHF or the microwave signal in the modulated arm is offset in frequency (the frequency can be either increased or decreased) by an amount equal to the modulation frequency. Normally the carrier is suppressed in these systems; however, the theory of measurement for the system where the carrier is unsuppressed has also been developed [69].

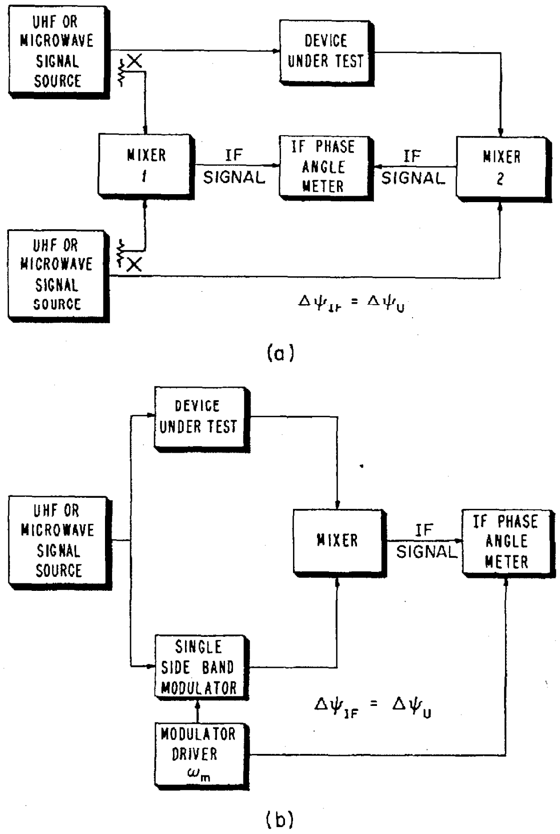


Fig. 7. Block diagrams for phase-shift measurement systems whose operation depends upon the generation of IF signals. The differential phase shift $\Delta\psi_u$ produced by the device under test is equal to the differential phase shift of the intermediate frequency signal $\Delta\psi_{IF}$. (a) Heterodyne phase-shift measurement system which uses two UHF or microwave oscillators. (b) Heterodyne phase-shift measurement system which uses one UHF or microwave oscillator and a single-sideband modulator.

The modulator in the arrangement shown in Fig. 7(b) is considered to be the second UHF or microwave signal source. The reference and test signals are combined in the mixer and the frequency of the signal out of the mixer is then the same as the modulation frequency. The differential phase shift of the device under test is determined by measuring the difference between the phase angles of the two IF signals.

The major disadvantage with the SSB arrangement is the unavailability of suitable SSB modulators. Usually SSB modulation is accomplished by applying sawtooth modulation to the helix of a traveling wave tube [71], [73]; this is often referred to as the serrodyne process.

IV. The Limits of Uncertainty

The limit of uncertainty for each measurement system is a function of the measurement technique and the quality of the components used to instrument that technique. Although each measurement system must be analyzed in relation to its own measurement uncertainties, some uncertainties are common to all systems. The purpose of this section is to point out these common uncertainties and to offer techniques for minimizing their magnitudes.

A. Measurement Uncertainty Caused by Mismatch

This uncertainty is usually the most significant of all those present in a measurement system. It has been carefully analyzed [83]–[85] and the results cannot be easily summarized. Therefore, only the results of sample calculations will be given here to demonstrate the magnitude of this uncertainty.

Basically the uncertainty is caused by the superposition of reflections from the phase-shift standard and reflections from the measurement system as seen at the insertion-point terminals. Another measurement uncertainty is caused by the superposition of reflections from the device under test and reflections from the measurement system at its insertion-point terminals [82]. Both of these uncertainties are eliminated if the system is reflectionless at the insertion-point terminals.

For an example, assume that the device under test has a maximum VSWR of 1.35 at both ports and it is connected into a system whose insertion-point VSWR's are both 1.10. The limit of uncertainty caused by the superposition of these reflections is ±2.0 degrees. If the system VSWR's are both reduced to 1.05, the limit of uncertainty is reduced to ±0.90 degree. If the system VSWR's are both reduced to 1.006 and the device under test has VSWR's of 1.15 at both ports, the limit of uncertainty is ±0.05 degree. Tuners are generally used to reduce these uncertainties to a tolerable level by reducing the reflections caused by a mismatched generator or detector in the system.

B. Measurement Uncertainty Caused by Frequency Instability

Most differential phase-shift measurement systems are two-channel systems and thus contain two propagation paths between the generator and the detector. Because the electrical lengths of the two channels are seldom equal, a differential phase shift between the reference and test signals may be produced at the detector as the frequency of the UHF or the microwave signal varies. This uncertainty is related to the frequency instability of the signal source, the propagation constants of the components in those paths, and the differential path length [68]. It can be minimized by equalizing the electrical path lengths between the generator and the detector. Stabilizing the frequency of the UHF or the microwave signal source is another means of minimizing this uncertainty.

The magnitude of this uncertainty is usually negligible when compared with some of the other uncertainties. As an example, assume that the frequency in a rectangular waveguide system is 10 GHz, that the frequency stability is 1 part in 10^6, and that the electrical path-length differential is 61 cm. For these conditions, the limit of uncertainty is approximately ± 0.01 degree. If the frequency is stabilized to 1 part in 10^8, the limit of uncertainty is reduced to approximately $\pm 10^{-4}$ degrees.

C. Measurement Uncertainty Caused by Laboratory Environmental Changes

Even though the environment within many calibration laboratories is closely controlled, inhomogeneous temperature variation may still occur. These temperature variations may be of sufficient magnitude to cause changes in length and cross-sectional dimensions of the waveguide. In general, these dimensional fluctuations will cause a differential phase shift between the reference and the test signal. In practice this problem is minimized by allowing sufficient equipment warm-up time and by collecting the calibration data as rapidly as possible.

D. Measurement Uncertainty Caused by Detector Nonlinearities, IF Amplifier Characteristics, and IF Phase Meters

This measurement uncertainty is that associated with the UHF or the microwave detectors and with the circuitry following detection. In some measurement systems, such as the heterodyne system, this uncertainty can be appreciable because tuned amplifiers and tuned phase meters are usually used. In other systems a linear-detector characteristic or a pair of matched detectors are required for the correct indication of the differential phase shift.

Each component used in each system must be selected and evaluated for the specific situation. For example, an amplifier used in the basic two-channel system need not be considered as carefully as an amplifier used in the heterodyne measurement system.

As an example of the limits of the uncertainty considered here, signal-input-level variations will produce a differential phase shift of less than ± 1.0 degree in some IF amplifiers [87] if the amplifier is not saturated. Frequency instability may also produce an appreciable differential phase shift because IF amplifiers contain tuned circuits.

A variety of direct-reading phase-shift meters now exist. The limit of uncertainty for these devices ranges from a few tenths of a degree to ± 5.0 degrees. Phase-shift resolvers which operate at the IF can also be used as the phase-shift standard and their limit of uncertainty can be as low as ± 0.30 degree [81].

E. Measurement Uncertainties Caused by Leakage Signals

The RF energies that reach the UHF or the microwave detector through spurious paths are called leakage signals. Undesired or spurious IF signals are also called leakage signals. Leakage signals may occur from connector junctions, from components in the system, from interconnecting cables, or from imperfectly shielded signal sources.

An RF or an IF leakage signal of any magnitude will introduce a measurement uncertainty. This uncertainty is minimized when the magnitude of the leakage signal is minimized. Proper shielding of leaky components and the use of RF seals at connector junctions are the most effective means of reducing RF leakage signals. The IF leakage signals can be minimized by proper shielding, by proper filtering, and by assuring that all IF equipment operates from a common ground.

The limit of uncertainty caused by a leakage signal is given (in radians) by the ratio of the amplitudes of the leakage signal voltage to the desired signal voltage, where the leakage-signal amplitude is much smaller than that of the desired signal. A limit of uncertainty of ± 0.006 degree is possible if the amplitude of either an RF or an IF leakage signal is known to be 80 dB below the amplitude of the desired signal. A leakage signal whose amplitude is known to be 60 dB below the amplitude of the desired signal has a limit of uncertainty of ± 0.057 degree, while a leakage signal level that is 40 dB below the level of the desired signal has a limit of uncertainty of ± 0.57 degree.

F. Measurement Uncertainty Caused by the Phase-Shift Standard

A major uncertainty in a differential phase-shift measurement is the uncertainty associated with the phase-shift standard. In order to arrive at a conservative limit of uncertainty for the standard, one should fully understand the theory and the operation of the device. With that knowledge, one will be able to evaluate it in terms of the UHF or the microwave frequency instability, the change in laboratory environment, the mechanical limitations, etc. Some differential phase shifters have already been evaluated and their limits of uncertainty established [79], [80]–[82].

V. CONCLUSIONS

A variety of differential phase-shift standards and phase-shift measurement techniques have been described. Usually the limit of uncertainty required by the application determines which of those standards and measurement systems are suitable for a particular measurement; however, other criteria such as the operational frequency bandwidth and the ease of operation must also be considered.

Even though the limit of uncertainty for any standard or measurement system is a function of many error sources, the major portion is usually contributed by the interactions between the reflections from the standard (or the device under test) and from the measurement system. A limit of uncertainty on the order of ±5.0 degrees can be expected with a rather crude arrangement; however, highly refined equipment and measurement procedures are required to achieve a limit of uncertainty of ±0.20 degree or less.

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