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APPLICATION NOTE 46

(hp)

INTRODUCTION

TO

MICROWAVE MEASUREMENTS

CONTENTS

PREFACE

Introduction to Microwave Measurements has been prepared to meet a continuing and increasing demand in the microwave industry for basic information on microwave theory and microwave measurements.

Introduction to Microwave Measurements provides basic information on microwave theory, microwave instrumentation, and microwave measurement techniques. The material is presented so that any person with a fundamental engineering background can obtain a general understanding of the specialized field of microwaves. Undergraduate or graduate students can use this publication as a supplement to other classroom or laboratory texts. Practicing engineers charged with establishing a microwave facility or training others in microwave theory and techniques can use it as the basis for their planning and training activities.

Introduction to Microwave measurements includes four major sections. Section I is an introduction which describes the importance and fundamental behavior of microwaves. Section II covers microwave theory. Section II-1 describes basic microwaves, explains the difference between microwave and low frequency circuits, and discusses voltages and currents in a transmission line. Section II-2 extends these considerations to waveguide systems.

The heart of the manual and the material most often requested is contained in Sections III and IV which deal with microwave measurements. Section III has information on the basic types of microwave measurements; Section IV contains a set of eight experiments designed to acquaint the user with microwave equipment and with the techniques employed in making microwave measurements.

Since microwave equipment must be compatible, and since maximum compatibility is usually derived when equipment is purchased from one manufacturer, Section IV is based on the use of a specially selected group of microwave instruments currently available from Hewlett-Packard. The group contains instruments needed to make the measurements described in Section III.

Appendix I is a glossary of microwave terms. Appendix II contains literature describing the individual microwave instruments. Appendix III is a bibliography listing several reference books as well as other Hewlett-Packard publications on microwave subjects.

If you are working or expect to be working in the microwave field and would like further information about anything contained in Introduction to Microwave Measurements, get in touch with the Hewlett-Packard Company or your (hp) Field Engineer who is listed in the (hp) catalog. Additional copies of Introduction to Microwave Measurements may be obtained from your Field Engineer, or by writing directly to Hewlett-Packard.

SECTION I
INTRODUCTION

Microwaves have a broad range of applications in modern technology. In the field of entertainment, for example, television programs are transmitted from coast to coast via a transcontinental microwave network. The same network also carries hundreds of telephone and telegraph circuits. Microwaves are also used for inter-city communications and for local transmission of television between studios and remote transmitters.

Microwaves are also an important element in local and national security programs. Microwave applications in radar, guidance systems and communications are of major importance in our overall national defense. At the level of local security, microwave is used extensively for police and fire department communications.

There are also many strictly commercial uses of microwaves. These include private communication systems within large organizations such as railroads, pipeline companies and public utility organizations. Microwave techniques are being utilized to develop improved methods of air navigation and airport control.

Most of the areas of microwave application involve "communication" in the broadest sense of the word. The reasons why microwaves are so important to communications are, in general, related to the manner in which they are generated and transmitted.

1-1   BACKGROUND MATERIAL

Electromagnetic Waves

Electromagnetic waves are wave motions produced by electric and magnetic fields whose intensity and orientation are varying as a function of time. Neglecting the manner in which these fields are produced, and considering only that their existence produces an electromagnetic wave, the rate at which these fields vary with time can range over a tremendous magnitude. They extend from the extremely slow rates due to the rotation of a coil in a magnetic field, to the tremendously high rates due to molecular and atomic disturbances.

Included in this wide spectrum are the various rates of variation (frequencies) at which electromagnetic waves produce such tangible and well known effects as visible light, radiant heat, and, at much lower rates, our well known radio waves.

Except for the manner of production of their fields, all electromagnetic waves obey the same physical laws. For this reason the microwave engineer can borrow considerably from the techniques of both the optical engineer and the communications engineer who works with the more familiar lower radio frequencies.

It can be demonstrated both analytically and experimentally that wherever electromagnetic waves are propagated they inherently carry energy in the direction of propagation. The manner of production of the time varying fields, and the manner of launching the resultant electromagnetic wave into free space, is the concern of the microwave engineer. Also, the accuracy and dependability of communication is very closely related to the quantity of energy that is propagated, and therefore the matter of efficiency in handling this energy is of as much importance to the microwave engineer as it is, for example, to the power engineer.

Optics

Many familiar examples of how light may be focused into beams and reflected or refracted have their counterpart in microwave engineering. In fact, the extensive knowledge of optics has lent very considerably to advancements in the microwave field. Behavior of optical waves and microwaves becomes increasingly similar as frequency of the microwaves increases. The similarities are particularly important when considering the transmission of microwaves in free space (between antennas).

Wavelength and Frequency

The characteristics of electromagnetic waves, and the manner in which they physically behave, are a function of the rate at which the electric and magnetic fields vary. In the single frequency case these variations are periodic and sinusoidal, and therefore can be considered in terms of frequency in cycles (complete alternations) per second.

The wave motions produced by electromagnetic fields propagate and carry energy. In microwave communications the medium of propagation is usually the "free space" surrounding the earth. Regardless of the frequency of the wave, the velocity of propagation is constant within any one medium, and for the most usual case (free space) the propagation velocity is the speed of light.

Wavelength is the measure of how far a wave travels during one alternation of the producing field. This relation is written in the form:

$$\text{Wavelength} = \frac{\text{Velocity of Propagation}}{\text{Frequency}}$$

Note that for a given medium, wavelength is inversely proportional to frequency. A typical example of long wavelength is that of the field produced by 60 cycle current in power transmission lines. This is in the order of 3100 miles. On the other hand, the center of the amplitude modulation broadcasting band involves wavelength of the order of 300 meters. The frequencies generally considered to be microwaves involve wavelengths on the order of 30 centimeters to a fraction of a centimeter. (The light used for viewing this page involves wavelengths averaging 60 millionths of a centimeter.) The lower limit of the microwave frequency spectrum is not well defined. Some communications companies refer to all frequencies above 890 mc (about 30 cm wavelength) as microwaves. Other engineering authorities say the microwave region begins at about 2000 mc. Waveguide, the most convenient closed microwave transmission system, is commonly used for frequencies above 2.6 kmc, although some extremely high power systems utilize waveguide for delivering power at frequencies in the range of 500 mc.

History

Much of the analytical work for microwave development is derived from the basic equations formulated by James Clerk Maxwell in 1864. Even at that early date Maxwell was able to predict that if radio waves could be produced, they would act in the same manner as light waves. It was not until some 25 years later that Heinrich Hertz produced electromagnetic waves having a wavelength of around 60 centimeters, and was able to demonstrate that the effects anticipated by Maxwell did, in fact, obtain.

In 1897 (still before the days of radio communications as known today) Lord Rayleigh, making use of Maxwell's Equations, was able to show that electromagnetic waves may be propagated in hollow tubes or, in fact, in any medium having specified boundaries between two electrically different media. Finally, at the turn of the century, Marconi demonstrated the first practical radio communication. The story of radio in the ensuing sixty years is well known.

Generation

As mentioned earlier, electromagnetic fields can be generated by widely divergent physical phenomena. This is the aspect in which there are major differences between light and radio waves. At the wavelengths of light, energy is produced by disturbances in the chemical or physical structure of material itself. A natural result is that frequencies produced are dispersed over a narrow spectrum and are not, in general, coherent. This means that visible light does not consist of single frequencies of constant amplitude but rather a dispersion of frequency, amplitude and phase.

In the early spark gap experiments, at the time of Hertz, radio waves were incoherent in this same sense. However, thanks to the vacuum tube and other devices, essentially single frequency and constant amplitude, or coherent waves can now be produced easily.

In the early days the vacuum tube served merely as a method for supplying the necessary electrical energy to maintain constancy of amplitude of the electrical oscillation. However, the physical dimensions of vacuum tubes became excessively large compared to the wavelengths encountered as the communications art worked up toward the microwave range. As a result, it became necessary to lump these parameters into the basic structure of the tube. This technique gave rise to such microwave sources as the klystron and the magnetron. Detailed knowledge of operation of these tubes is not necessary to the consideration of microwave systems. It is, however, important to note that these sources are generally of rather low efficiency, and therefore maximum efficiency in transmitting the energy is a matter of prime importance.

Transmission of Microwaves

Microwaves travel through free space when transmitted between antennas. The transmission system extending from the microwave generator to the antenna usually consists of either coaxial lines or hollow metal pipes (rectangular or circular) called waveguide. Coaxial lines have higher losses than waveguides. They are usually limited in application to very short distances or to special situations where the wider bandwidth of a coaxial system is needed.

Design and construction of appropriate waveguide transmission systems is now a major field of engineering. Most of the material in this publication is meant to help the reader understand waveguide systems so that he may use them for any specific application in the microwave field.

1-2   WHY USE MICROWAVES?

Bandwidth Considerations

There is a direct relationship between bandwidth and information carrying capacity of a microwave system. The more information one wishes to communicate, the wider the bandwidth that is required in the transmission system. A single frequency source of electromagnetic energy can transmit intelligence only with some form of modulation.

Regardless of the method of modulation, its effect is to produce sideband frequencies with respect to the original carrier. The extent to which these sideband frequencies deviate from the carrier is directly proportional to the information transmitted. Consider, for example, a typical amplitude modulated broadcasting system, operating at 1 megacycle, which carries a radio program having frequency components of, say, 10,000 cycles. Then, that station requires exclusive use of a range of frequencies

approximately 20,000 cycles wide, centered around the carrier frequency. The allotted frequency range for commercial AM broadcasting is only from 0.5 to 1.5 megacycles. Accordingly, there is a limit to the number of stations that can operate in the same geographical area without interfering with one another.

As a further example consider that a television station requires a bandwidth of about 5 megacycles to handle all the information necessary to the production of a good TV picture. Obviously 1 megacycle cannot, in the normal sense, be used as the carrier. However, a center frequency of 100 MC can easily be used. A major reason for the importance of microwaves in communications is that it is possible to place a large number of information channels in a frequency range which is only a small percentage of the carrier frequency.

Antenna Directivity

If electromagnetic energy can be radiated in such a manner that the outward energy flow from the radiating source is increased in a particular direction instead of being equal in all directions, the result is equivalent to an increase in power. At microwave frequencies such radiation can be made very highly directive. In fact, a good antenna arrangement can effectively produce a beam in much the same sense that a spotlight is beamed. Also, as a result of this high directivity of radiation, a certain amount of information security is obtained. This can provide security in terms of military needs or, probably more important, security from interference by other transmitting systems in the same area. Finally, the very fact that microwave beams can be made sharp is used to give directional information in applications such as radar.

Waveguides as Transmission Systems

Both coaxial lines and waveguide are used to transmit microwaves up to 12.4 kmc. The choice depends on several factors such as bandwidth to be transmitted, length of the system, and ease of setting up and changing the system. Coaxial systems have wider bandwidth and are easier to handle; waveguide has lower loss and greater power handling capacity. As a generality, coaxial systems predominate below about 2 kmc, and waveguide systems are more widely used at higher frequencies.

1-3   SOME BASIC CONSIDERATIONS

Because generation of power at microwave frequencies is not a particularly efficient process, every effort is made within the transmission and radiation systems to obtain high efficiency in order to conserve the power available. To do this the microwave engineer pays considerable attention to the problem of reducing any electrical defects which waste power in the system.

There are two important causes of power loss in a transmission system. Some power is lost because of inherent imperfections in the conductors. This loss, which can be considered as power dissipation, can be reduced to almost negligible amounts in waveguide by means of modern manufacturing techniques. The most common practice is to plate the interior waveguide surface with a thin coating of high conductivity material such as silver.

In many cases the power lost through reflection of transmitted energy is more significant than the power lost through attenuation or dissipation. Power is reflected whenever the impedances of connected sections of the transmission system are not perfectly matched. A major part of microwave engineering is the measurement and minimization of reflections.

Luckily, the nature of electromagnetic waves is such that reflection can easily be detected by measuring the standing wave pattern in the system. This pattern is essentially an interference effect caused by power flowing in both directions. A comparable physical phenomena occurs when a wave is introduced by means of a transverse motion on a rope with one end tied to a fixed point. Most of the power in the wave is reflected from the fixed end to form nodes or standing waves along the rope.

Impedance Matching

If a transmission system were infinitely long and there were no impedance discontinuities, there would be no reflections. In a waveguide system any abrupt variation in the transmission path appears as an impedance discontinuity and causes a reflection. Note that abrupt changes in the transmission path, rather than gradual changes, are the cause of discontinuities. Where changes in physical dimensions or electrical characteristics must be made, one way of avoiding reflections is by making the changes gradually.

Characteristic Impedance and Normalized Impedance

Every transmission system has a characteristic impedance. If the system were terminated by a load whose impedance is equivalent to the characteristic impedance there would be no reflections. Further, every condition of reflection is caused by an impedance which can be related to the characteristic impedance. Thus, by determining the nature of the reflection, the nature of the impedance irregularity can also be determined. With this knowledge, corrective measures can be taken to compensate for the irregularity and obtain increased transmission efficiency.

Most waveguide impedance calculations are made on the basis of what is called "normalized" impedance. This is simply the actual impedance divided by the characteristic impedance. The normalized impedance is always unity (1) for a system in which there are no reflections since this condition exists only when the system is terminated with its characteristic impedance.

SECTION II
MICROWAVE TRANSMISSION THEORY

2-1 TRANSMISSION LINES

Circuit Constants

At low frequencies circuit elements are lumped. This means that there is no variation of parameters with position. Another way of expressing the same concept is to say that low frequency circuits are electrically short compared to the wavelength of the signals transmitted.

Microwave frequencies, on the other hand, have much shorter wavelengths (60 cm and less). The result is that circuits have electrical lengths either comparable to or greater than the wavelength of the signals under consideration. Because of this the various circuit parameters vary with position- a fact which must be taken into account in microwave work.

In general all the well known low frequency circuit concepts apply to microwave circuits. In addition, however, the basic concept of distributed circuits must be considered.

A distributed circuit is simply a transmission path in which the basic elements of the circuit (resistance, inductance and capacity) are spread evenly over the entire length of the path. The importance of the distributed circuit concept can be demonstrated by comparing equivalent circuits for low frequency and microwave work. First consider a section of ordinary transmission line as shown in Figure 2-1. This shows a generator feeding a load through a section of transmission line. We want to find out how this section of line affects the transmission from the generator to the load, first at a representative low frequency, and then at higher or microwave frequencies.

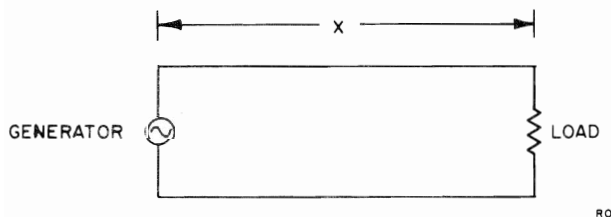Current flowing in the conductors sets up a magnetic field encircling the conductors. Hence the transmission line has inductance. Furthermore the conductors making up the transmission line will have resistance associated with them. For a unit length of this line the resistance and inductance can be calculated. Let this resistance be R ohms per unit length and this inductance be L henries per unit length. Since all other sections of the transmission line are in series for these basic elements the total line resistance will be Rx ohms, and the total line inductance will be Lx henries.

There also will be voltage between, and charges on the conductors, so there will be a capacity between the conductors. Furthermore, in the general case, the lines may be embedded in a lossy dielectric material so that a conductive element must be assumed between the lines to account for this loss. Here again a unit length can be used to calculate the capacity and conductance. Let the capacity be C farads per unit length and the conductance be G ohms per unit length. Now for this capacity and conductance all sections of the line can be considered to be in parallel. Hence the total capacity is Cx farads and the total conductance is Gx mhos.

At very low frequencies the effect of the inductance, capacity, resistance and conductance of the line can be taken into effect by means of either equivalent circuit shown in Figure 2-2.

The circuits shown in Figure 2-2 obviously incorporate the correct amount of series inductance and

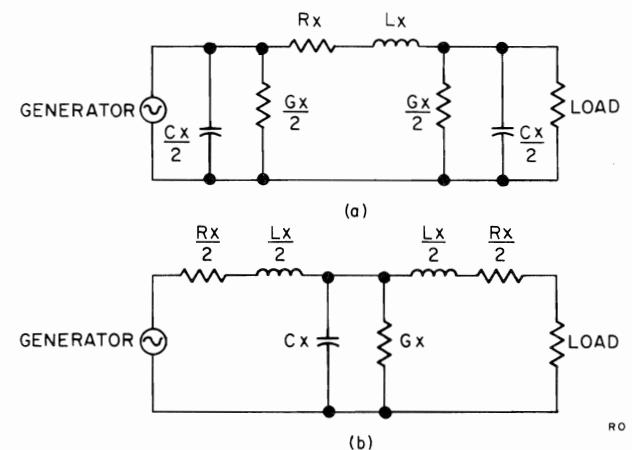Figure 2-1. Transmission Line Section

Figure 2-2. Low Frequency Equivalent
Circuit of Transmission Line

resistance as well as the proper amount of shunt capacity and conductance. This produces a temptation to treat them as exact equivalent circuits. If this were true their effects should be the same under all conditions. Further investigation shows that this simple assumption is not true. At very high frequencies the circuits of Figures 2-2a and 2-2b present different impedances to the generator. In the case of Figure 2-2a the impedance presented to the generator at sufficiently high frequencies is $2/j\omega Cx$. In the case of Figure 2-2b this impedance is $j\omega Lx/2$. Obviously these are not the same, as the impedance presented to the generator in Figure 2-2a goes to 0 as the frequency becomes very high, and the impedance in Figure 2-2b goes to infinity as the frequency becomes very high.

A simple means of making the impedances more nearly alike is to split up the total inductance, resistance, capacity and conductance into more sections. In the ultimate case these basic elements could be divided into an infinite number of sections. When this is done the two circuits shown in Figure 2-2 do indeed become one and the same. This ultimate equivalent circuit, shown in Figure 2-3, is the essence of distributed constant circuits.

Characteristic Impedance and Propagation Constant

Many circuit concepts apply to microwave circuits in essentially the same manner as they are used in low frequency work. Perhaps the most important of these are (1) characteristic impedance and (2) propagation constant.

1) Characteristic Impedance, Z, is the input impedance of an infinitely long line. In terms of the inductance, resistance, capacity and conductance, per unit length of the line, it is given by:

$$Z_o = \sqrt{\frac{R + j\omega L}{G + j\omega C}} \quad \text{ohms} \qquad (1)$$
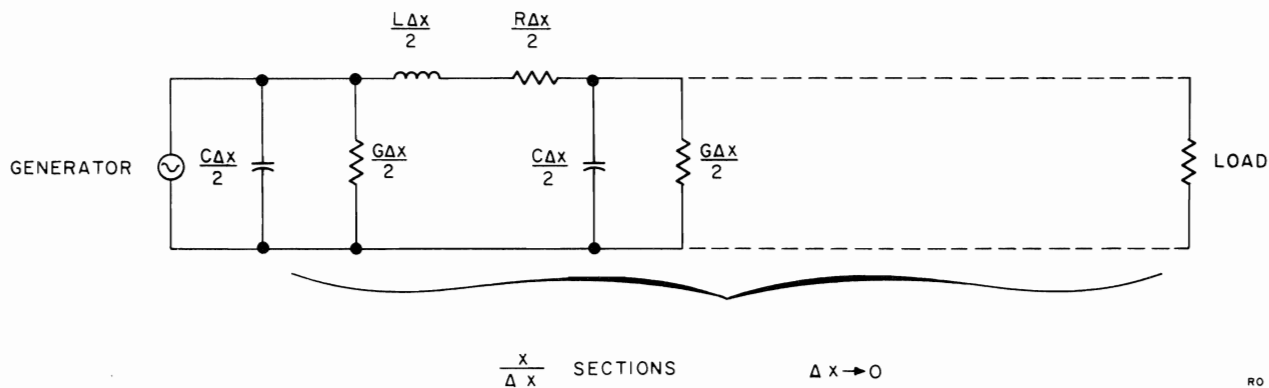
2) Propagation Constant, γ, is a measure of the

Figure 2-4. Section of Infinite Transmission Line

phase shift and attenuation along the line. It is a complex quantity given by:

$$\gamma = \alpha + j\beta = \sqrt{(R + j\omega L)(G + j\omega C)}$$
$$\text{per unit length} \qquad (2)$$

There are two units for propagation constant. Attenuation, α, is expressed in nepers per unit length; Phase shift, β, in radians per unit length.

As in low frequency circuits γ is the exponent of an exponential function which relates the amplitude and phase of a voltage or current at two different points in a system. Consider, for example, a section of an infinitely long transmission line as shown in Figure 2-4. In this figure let a signal E_1 be imposed at the left hand terminal. Let E_x be the voltage a distance x down the line.

Now E_x is related to E_1 by the propagation constant in the following manner:

$$\frac{E_x}{E_1} = e^{-\gamma x} = e^{-\alpha x - j\beta x} = e^{-\alpha x} \cdot e^{-j\beta x} \qquad (3)$$

The first term in this expression, $e^{-\alpha x}$ is a real quantity and gets smaller as x increases. It tells us how much the signal is attenuated. The second term $e^{-j\beta x}$ is an imaginary exponential quantity. It represents a vector of unit amplitude with a phase angle of βx radians. Thus this quantity tells us how much the phase of the voltage E_x lags the phase of the voltage E_1.

Figure 2-3. Exact Equivalent Circuit of Transmission Line

Hence these two terms together completely define the phase and amplitude relations existing between voltages E_x and E_1. The propagation constant can be applied similarly to the current.

3) Guide Wavelength and Velocity of Propagation. The lag in phase down the line is characteristic of distributed constant circuits and comes about because there is a finite velocity with which a signal travels down the transmission line. If a signal such as E_1 in Figure 2-4 is impressed upon a transmission line, this signal does not appear instantaneously along the whole line but will appear at a point a distance x from the sending end after a time t_x given by:

$$t_x = \frac{x}{v} \tag{4}$$

where v = velocity of propagation

Now if x is of such length, say x_0, that t_x is equal to one period of the applied signal E_1 then it is obvious that the phase of the signal at x_0 lags the phase of E_1 by 360^0 or 2π radians. Thus the signal at x_0, having suffered a 360^0 phase shift, is for all intents in phase with the applied signal E_1. This distance x_0 is called a guide wavelength and can be related to velocity of propagation and phase shift as follows:

Let λ_g = guide wavelength

Then the period of the signal is $\tag{5}$

$$\frac{1}{f} = \frac{x_0}{v} = \frac{\lambda_g}{v}$$

Furthermore $\tag{6}$

$$\beta x_0 = \beta \lambda_g = 2\pi$$

Hence $\tag{7}$

$$\lambda_g = \frac{v}{f} = \frac{2\pi}{\beta}$$

and $\tag{8}$

$$\beta = \frac{2\pi}{\lambda_g} = \frac{2\pi f}{v}$$

Velocity of Propagation is the speed with which a signal is transmitted along a transmission line. This velocity of propagation depends upon such factors as the mode of transmission in the line and the values of the elements of its equivalent circuit. For normal lossless two wire lines, such as coaxial, with air dielectric between the lines, and transmitting in its lowest order mode (the normal mode used for two wire lines) the velocity of propagation is equal to the velocity of light. If the velocity of light is represented by v_c then from equation 7 we have:

$$\lambda_g = \frac{v_c}{f} = \text{free space wavelength } \lambda \tag{9}$$

In normal coaxial transmission systems the loss is small so that R and G can be neglected in determining β. Hence from equation 2, for an air dielectric coaxial line

$$j\beta = j\omega \sqrt{LC_a} \tag{10}$$

and from equation 10 and 8

$$\beta = \omega \sqrt{LC_a} = \frac{2\pi f}{v_c}$$

or

$$v_c = \frac{1}{\sqrt{LC_a}} \quad \text{(air dielectric line)} \tag{11}$$

and if there were a dielectric in the line having a dielectric constant k, then the capacity would be

$$C = k C_a$$

and

$$v = \frac{1}{\sqrt{L k C_a}} = \frac{v_c}{\sqrt{k}} \tag{12}$$

also from 7 and 9

$$\lambda_g = \frac{v}{f} = \frac{v_c}{f\sqrt{k}} = \frac{\lambda}{\sqrt{k}} \tag{13}$$

Infinitely Long Line

Some of the properties of an infinitely long line are discussed in the previous section. The infinitely long line, while never encountered in practice, may be used to develop an understanding of the basic concepts of microwave circuits. Refer back to Figure 2-4 in which a voltage E_1 was impressed on the sending end of an infinitely long line. At a distance x from the sending end we have a voltage E_x given by

$$E_x = E_1 e^{-\gamma x} \tag{3}$$

Also, we know from the definition of characteristic impedance that the impedance looking into the sending end of this infinitely long line is Z_0. Hence

$$I_1 = \frac{E_1}{Z_0} \tag{14}$$

and

$$I_x = I_1 e^{-\gamma x} \tag{15}$$

and

$$\frac{E_x}{I_x} = \frac{E_1 e^{-\gamma x}}{I_1 e^{-\gamma x}} = Z_0 \tag{16}$$

Voltage and current at any position along an infinitely long line are related to the characteristic impedance and the propagation constant by equation (16).

In almost all practical cases the line can be considered lossless, so that R = G = O and (from equations 1 and 2)

$$Z_0 = \sqrt{\frac{L}{C}} \quad \text{a purely real quantity}$$

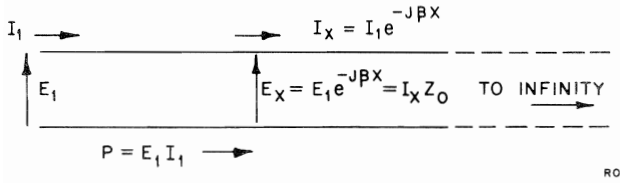and $\quad \gamma = j\omega\sqrt{LC}$ a purely imaginary quantity (no attenuation)

Figure 2-5. Voltage, Currents, and Power in Infinitely Long Transmission Line

Figure 2-7. Finite Matched Transmission Line

and hence in the lossless case

$$E_x = E_1 e^{-j\beta x}$$

$$I_x = I_1 e^{-j\beta x}$$

$$\frac{E_x}{I_x} = Z_o \quad \text{a pure resistance}$$

and power being transmitted from left to right in the line is:

$$P = E_x I_x = E_1 I_1 = \frac{E_1^2}{Z_o} = I_1^2 Z_o \qquad (17)$$

These relations for the lossless case are shown in Figure 2-5.

Matched Finite Line

With the concept of the infinite line firmly in mind, lines of finite length can be considered. Start with an infinitely long line and split it into two sections as shown in Figure 2-6.
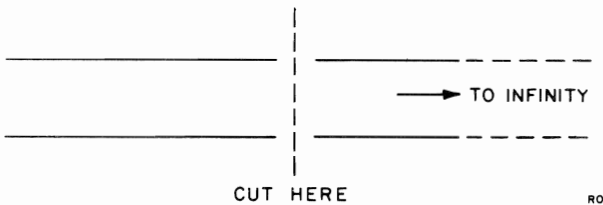

Figure 2-6. Infinitely Long Line Split into Two Sections

This action produces a line of finite length on the left terminated by a line infinitely long on the right. Insofar as the finite section on the left is concerned there would be no difference in the voltages and currents existing on it if the infinite section to the right could be replaced by its exact equivalent impedance. This can be done. The input impedance of an infinitely long line is Z_o. Hence if the section of infinite line in Figure 2-6 is replaced by Z_o none of the conditions existing on the left hand section of
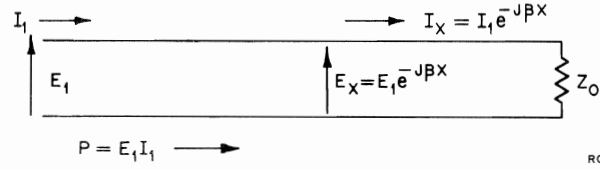
finite length will be affected. If the line is considered to be lossless, the conditions shown in Figure 2-7 are obtained by placing Z_o in the position of the infinitely long line section of Figure 2-6. This is known as matched operation.

Finite Line With Arbitrary Load

In the above section we made the transition from an infinitely long line to one of finite length. This produced a rather special case in which the finite line section is terminated in its characteristic impedance. Of considerably more practical importance is a finite line with an arbitrary load. Note that in the special case of a finite line terminated in its characteristic impedance, the ratio of voltage to current at any point in the line was equal to Z_o, and that all the power the generator delivered into the line was absorbed in the load. Furthermore in this special case the voltages and currents were being propagated only from the generator to the load. In other words there was no signal traveling from right to left.

There is only one more condition to be added to permit handling of arbitrary loads. Since the forward wave at all points on the transmission line maintains the ratio between E_i and I_i as Z_o, the wave meeting an impedance not equal to Z_o can no longer support the same ratio between E_i and I_i. However, the addition of a signal traveling from right to left permits the resulting voltage and current at that point to have the proper ratio which is the impedance of the load. There are then two current and voltage waves on the line which are defined as follows:

Incident wave –
The voltage or current wave being propagated from the generator towards the load. These waves will be denoted by the subscript i.

Reflected wave –
The voltage or current wave being propagated from the load towards the generator. These waves will be denoted by the subscript r.

The general case of a finite line with arbitrary load is shown in Figure 2-8.

Since the relation between the reflected and incident waves is completely determined by the load and the line we will measure distance from right to left with zero distance at the load. Voltages and currents at the load will be denoted by the subscript o, and voltages and currents at other points will be denoted by the subscript x.
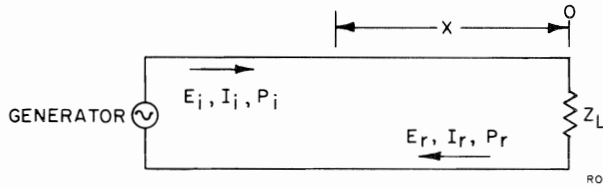
Figure 2-8. Finite Line Terminated
in Arbitrary Load

Reflection Coefficient

There is a definite relation between the reflected and incident waves. It is determined by the load and characteristic impedance of the line. Called voltage reflection coefficient ρ_v and current reflection coefficient ρ_i the relations are defined as follows:

$$\frac{E_{ro}}{E_{io}} = \frac{Z_L - Z_o}{Z_L + Z_o} = \rho_v \quad \text{voltage reflection coef.} \quad (18)$$

$$\frac{I_{ro}}{I_{io}} = \frac{Z_o - Z_L}{Z_o + Z_L} = \rho_i = -\rho_v \quad \begin{array}{l}\text{current} \\ \text{reflection coef.}\end{array} \quad (19)$$

Furthermore, at any point in the line the incident and reflected voltages and currents add vectorially to give the total voltage and current. Thus, at the load or position o the total or load voltage and current is given by:

$$E_L = E_{ro} + E_{io}$$

$$I_L = I_{ro} + I_{io}$$

Voltages and Currents Along Line

Knowing the voltages and currents at the load or position zero, the basic concepts of propagation constant and characteristic impedance may be applied to see how the voltage, currents and impedances vary at other positions in the line. At a distance x from the load toward the generator we have a voltage E_x composed of the incident and reflected wave given by:

$$E_x = E_{rx} + E_{ix} = E_{io}e^{\gamma x} + E_{ro}e^{-\gamma x}$$

$$= E_{io}e^{\gamma x} + \rho_v E_{io}e^{-\gamma x}$$

$$= E_{io}e^{\gamma x} (1 + \rho_v e^{-2\gamma x}) \quad (20)$$

Similarly I_x is given by:

$$I_x = I_{rx} + I_{ix} = I_{io}e^{\gamma x} + I_{ro}e^{-\gamma x}$$

$$= I_{io}e^{\gamma x} + \rho_i I_{io}e^{-\gamma x}$$

$$= I_{io}e^{\gamma x} (1 + \rho_i e^{-2\gamma x})$$

$$= I_{io}e^{\gamma x} (1 - \rho_v e^{-2\gamma x}) \quad (21)$$

Don't let the sign of the exponent used for the propagation constant confuse you. Just remember that when we move along a line in the direction of propagation of a particular wave then the wave must get smaller (if the line has loss) and suffer a lag in phase. When we move in a direction opposite to the direction of propagation then the wave must get larger and have a leading component of phase.

Standing Wave Ratios

Now let us look at the voltage at an arbitrary position x along the line. The value of this voltage, given in equation 20, becomes in the lossless case, ($\alpha = o$),

$$E_x = E_{io} e^{j\beta x} (1 + \rho_v e^{-2j\beta x}) \quad (20)$$

The term $E_{io}e^{j\beta x}$ is a multiplying term and denotes signal level. The amplitude variation with position is determined by the term within the brackets, so this term should be examined more closely. The term in brackets can be represented vectorially as shown in Figure 2-9.
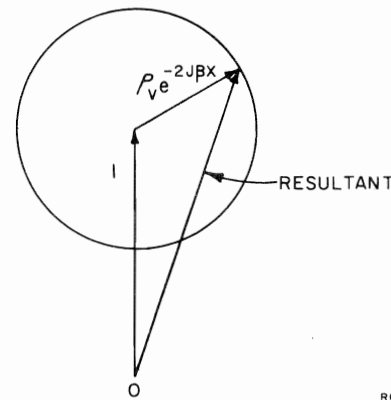
Figure 2-9. Vector Relations of Voltage
in Transmission Line

As position x is varied, the small vector $\rho_v e^{-j2\beta x}$ will rotate around the end of the unit vector and the distance from 0 to this circle will represent the magnitude and phase of the resultant vector. The maximum of this resultant vector will be $1 + \rho_v$ and the minimum will be $1 - |\rho_v|$.

Hence $E_{max} = E_{io}e^{j\beta x} (1 + |\rho_v|)$

$$E_{min} = E_{io}e^{j\beta x} (1 - |\rho_v|)$$

The relation between maximum and minimum voltage is called the voltage standing wave ratio σ which is:

$$\sigma = \frac{E_{max}}{E_{min}} = \frac{1 + |\rho_v|}{1 - |\rho_v|} \quad (22)$$

Also $2\beta x$ has to change by 180° or π radians between a maximum and minimum. The distance between maximum and minimum can be determined from equation 8 as follows:

$$2\beta\,(X_{max} - X_{min}) = \pi$$

But

$$\beta = \frac{2\pi}{\lambda_g}$$

Hence

$$\frac{4\pi}{\lambda_g}\,(X_{max} - X_{min}) = \pi$$

or

$$X_{max} - X_{min} = \frac{\lambda_g}{4} \qquad (23)$$

A similar process can be applied to the current to show that the current standing wave ratio is the same as the voltage standing wave ratio. However, since there is a 180° phase difference between the current and voltage standing wave ratio ($\rho_i = -\rho_v$) the current maximum will occur where the voltage is a minimum and vice versa. Typical current and voltage patterns are shown in Figure 2-10.

Impedance at Voltage Maximum and Minimums
At a voltage maximum we have

$$E_{max} = E_{io}e^{j\beta x}(1 + |\rho_v|)$$

$$I_{min} = I_{io}e^{j\beta x}(1 - |\rho_v|)$$

or the line Z_{max} is given by

$$Z_{max} = \frac{E_{max}}{I_{min}} = \frac{E_{io}}{I_{io}}\,\frac{1 + |\rho_v|}{1 - |\rho_v|}$$

$$= Z_o\,\sigma \qquad (24)$$

and similiarly at a voltage minimum

$$E_{min} = E_{io}e^{j\beta x}(1 - |\rho_v|)$$

$$I_{max} = I_{io}e^{j\beta x}(1 + |\rho_v|)$$

$$Z_{min} = \frac{Z_o}{\sigma} \qquad (25)$$

Note that in these last 2 special cases, and with a lossless transmission line, the impedances are purely resistive.

Impedance at any Point Along a Line
The only other factor to be determined is the impedance at any point a distance x from the load. Voltage and current at a point x are:

$$E_x = E_{io}e^{\gamma x} + \rho_v\,E_{io}e^{-\gamma x} \qquad (20)$$

$$I_x = I_{io}e^{\gamma x} - \rho_v\,I_{io}e^{-\gamma x} \qquad (21)$$

Hence

$$Z_x = \frac{E_{io}}{I_{io}}\,\frac{e^{\gamma x} + \rho_v e^{-\gamma x}}{e^{\gamma x} - \rho_v e^{-\gamma x}}$$

$$= Z_o\,\frac{e^{\gamma x} + \dfrac{Z_L - Z_o}{Z_L + Z_o}\,e^{-\gamma x}}{e^{\gamma x} - \dfrac{Z_L - Z_o}{Z_L + Z_o}\,e^{-\gamma x}}$$

$$= Z_o\,\frac{(Z_L + Z_o)\,e^{\gamma x} + (Z_L - Z_o)\,e^{-\gamma x}}{(Z_L + Z_o)\,e^{\gamma x} - (Z_L - Z_o)\,e^{-\gamma x}}$$

$$= Z_o\,\frac{Z_L\cosh\gamma x + Z_o\sinh\gamma x}{Z_o\cosh\gamma x + Z_L\sinh\gamma x} \qquad (26)$$
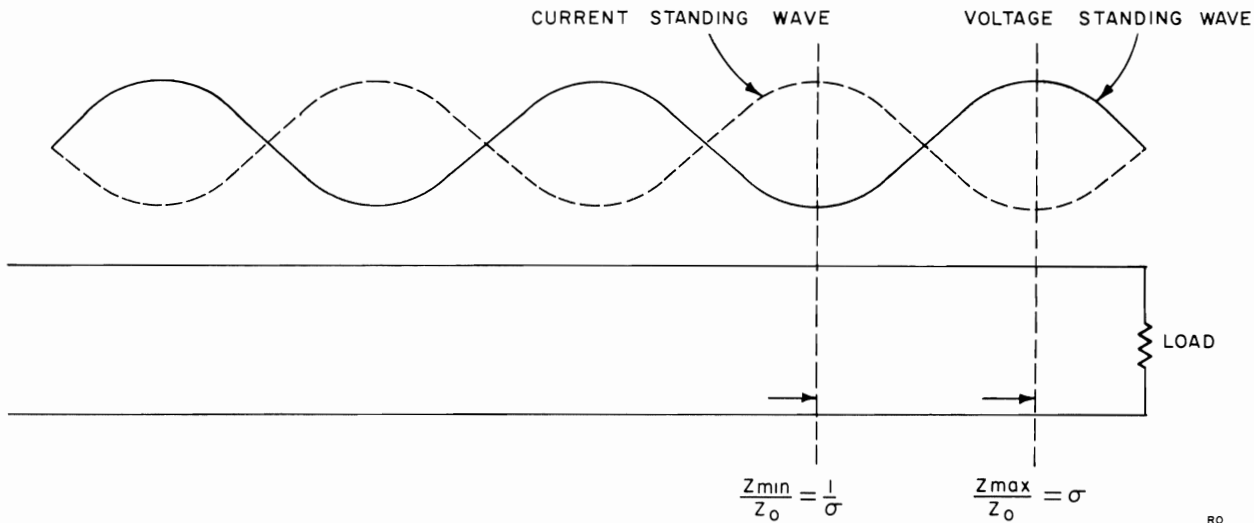

Figure 2-10. Current and Voltage Standing Wave on Transmission Line

Where

$$\cosh \gamma x = \frac{e^{\gamma x} + e^{-\gamma x}}{2}$$

$$\sinh \gamma x = \frac{e^{\gamma x} - e^{-\gamma x}}{2}$$

For the lossless case the equation 26 reduces to

$$Z_x = Z_o \frac{Z_L \cos \beta x + j Z_o \sin \beta x}{Z_o \cos \beta x + j Z_L \sin \beta x} \quad (27)$$

Impedances for Short and Open Circuited Lines
A lossless transmission line has been assumed in most of the work done so far. This is usually justifiable in practice except in certain specific cases. One of these important exceptions is when the line is terminated in an open or short circuit. Since an open circuit is the same as a short circuit a quarter of a wavelength further down the line the two conditions can be handled in a similar fashion.

For a short circuited line the impedance Z_x is given by

$$Z_x = Z_o \tanh \gamma x$$

$$= Z_o \tanh (\alpha x + j \beta x)$$

$$= Z_o \frac{\tanh \alpha x + \tanh j \beta x}{1 + \tanh \alpha x \tanh j \beta x}$$

$$= Z_o \frac{\tanh \alpha x + j \tan \beta x}{1 + j \tanh \alpha x \tan \beta x} \quad (28)$$

The voltage will be zero at a short and hence will be a maximum when $x = \frac{\lambda g}{4}$ so that

$$\tan \beta x = \tan \frac{2\pi}{\lambda g} \cdot \frac{\lambda g}{4} = \tan \frac{\pi}{2} = \infty$$

and here $Z_{\frac{\lambda g}{4}} = \frac{Z_o}{\tanh \alpha x} \quad (29)$

at a distance $\frac{\lambda g}{2}$ from the short

$$\tan \beta x = \tan \frac{2\pi}{\lambda g} \cdot \frac{\lambda g}{2} = \tan \pi = 0$$

and $Z_{\frac{\lambda g}{2}} = Z_o \tanh \alpha x \quad (30)$

Equations (29) and (30) serve as the basis of a very useful way for measuring attenuation of transmission lines. The term "$\tanh \alpha x$" (and thus attenuation per unit length) can be determined by measuring impedance at a quarter wavelength from the short. The measured value is then substituted in equation (30).

This procedure provides very accurate determination of small attenuation values.

Normalization
The process of normalization refers all transmission line equations to unity characteristic impedance. This is done to simplify equations so that they are the same for a line of any characteristic impedance. Various engineering aids such as Smith Charts are much easier to use when working with normalized impedances. True impedance values are obtained by multiplying the normalized answers by the characteristic impedances.

Note that in the various equations in which impedance has appeared we could have divided each impedance by Z_o. Thus each impedance would have been expressed as a ratio of that impedance to Z_o. For instance consider equation 18

$$\rho_v = \frac{Z_L - Z_o}{Z_L + Z_o} = \frac{\frac{Z_L}{Z_o} - 1}{\frac{Z_L}{Z_o} + 1} \quad (18)$$

or equation 24 and 25 which can be rewritten

$$\frac{Z_{max}}{Z_o} = \sigma \quad (24)$$

$$\frac{Z_{min}}{Z_o} = \frac{1}{\sigma} \quad (25)$$

or equation 26 which can also be rewritten

$$\frac{Z_x}{Z_o} = \frac{\frac{Z_L}{Z_o} \cosh \gamma x + \sinh \gamma x}{\cosh \gamma x + \frac{Z_L}{Z_o} \sinh \gamma x} \quad (26)$$

In each case any particular impedance appears as the ratio of itself to Z_o. These ratios are called normalized impedances and are normally written as small z. Using this notation the above equations would become

$$\rho_v = \frac{z_L - 1}{z_L + 1} \quad (31)$$

$$z \, max = \sigma \quad (32)$$

$$z \, min = \frac{1}{\sigma} \quad (33)$$

$$Z_x = \frac{z_L \cosh \gamma x + \sinh \gamma x}{\cosh \gamma x + z_L \sinh \gamma x} \quad (34)$$

Characteristic impedance does not have to be known in many microwave measurements. Thus the concept of normalized impedance is particularly useful when working with waveguide which does not have the well defined concept of impedance that coaxial systems have.

Power Relations

Impedance relations in a transmission system are primarily important because of their effect on transmitted power. By knowing the reflection coefficient for a particular system, the percentage of power transmitted to the load can be determined.

Equation 17 showed that the power being transmitted by the incident wave from the generator towards the load is given by P_i where

$$P_i = E_i I_i = \frac{E_i^2}{Z_o} \tag{31}$$

Furthermore the power being transmitted by the reflected wave from the load towards the generator is given by

$$P_r = E_r I_r = \frac{E_r^2}{Z_o^2} \tag{32}$$

Hence power transmitted to the load is

$$P_L = P_i - P_r \tag{33}$$

$$= \frac{E_i^2}{Z_o} - \frac{E_r^2}{Z_o}$$

$$\frac{P_L}{P_i} = \frac{E_i^2 - E_r^2}{E_i^2} = \frac{1 - |\rho_v|^2}{1} = \frac{4\sigma}{(1 + \sigma)^2} \tag{34}$$

$$\frac{P_r}{P_i} = \frac{E_r^2}{E_i^2} = |\rho_v|^2 = \left(\frac{1 - \sigma}{1 + \sigma}\right)^2 \tag{35}$$

2-2 WAVEGUIDE

A waveguide is a single conductor transmission system. Coaxial systems are two conductor. The basic difference between coaxial lines and waveguides is the mode in which they propagate energy. There are an infinite number of modes by which energy can be propagated down a transmission system. These various modes of propagation in waveguide are all characterized by having a cut-off frequency below which they cannot propagate energy. The higher order the mode the higher is this cut-off frequency. All waveguide transmission systems act like a high pass filter.

Modes in transmission systems are described as TE (Transverse Electric Field) or TM (Transverse Magnetic Field). A TE mode has no component of electrical field in the direction of propagation while a TM mode has no component of magnetic field in the direction of propagation.

A coaxial line or any two wire system also has the property of being able to propagate in a mode having neither electric nor magnetic field components in the direction of propagation. In this mode, called TEM, the low frequency cut-off is at 0 frequency. In other words all frequencies down to DC can be transmitted by a 2 conductor system operating in the TEM mode. The field configurations in a coaxial system are shown in Figure 2-11.

The field configurations in a rectangular guide transmitting in the commonly used TE_{10} mode are shown in Figure 2-12.

In all types of transmission systems it is desirable to select sizes so that only one mode of propagation is possible. This means that the physical size of the guide is related to the frequency band under consideration. Because of the possibility of higher order modes it has become common to operate waveguides
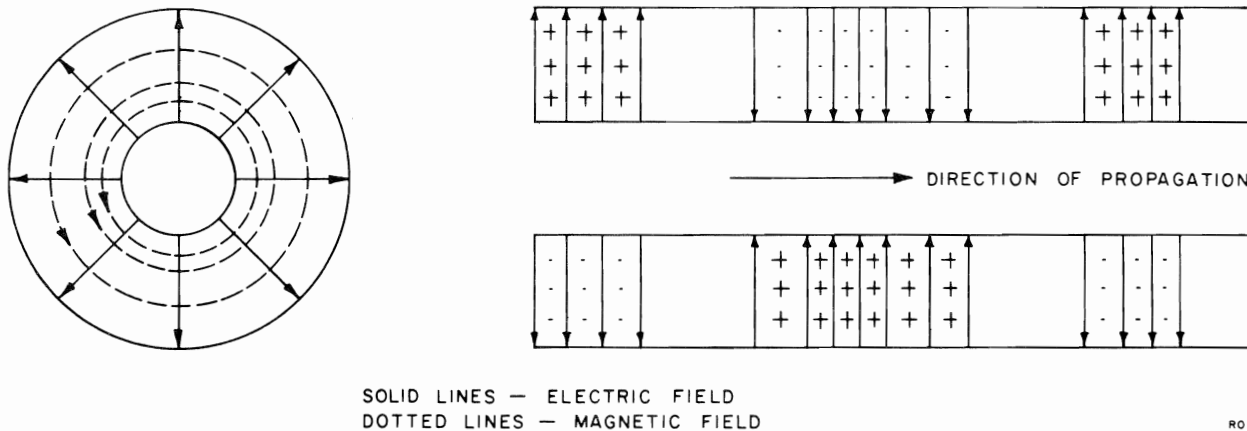

SOLID LINES — ELECTRIC FIELD
DOTTED LINES — MAGNETIC FIELD

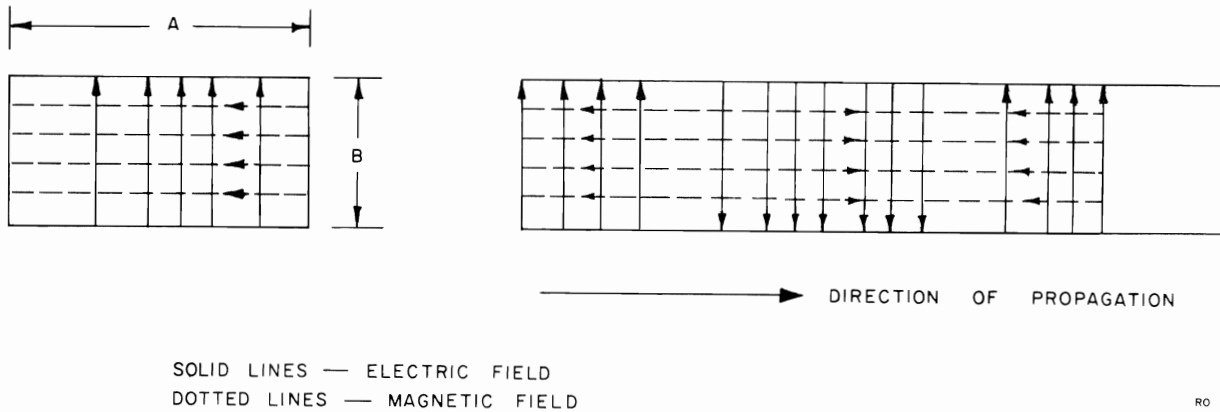Figure 2-11. Fields in a Coaxial line (TEM mode)

Figure 2-12. Fields in a Rectangular Guide (TE$_{10}$ mode)

only over approximately 1.5 to 1 frequency range. By properly selecting this frequency range it is possible to operate far enough from cutoff that the guide parameters do not vary too rapidly and also avoid the frequency region where other modes are possible.

For the guide shown in Figure 2-12 the low frequency cut-off f_c or cut-off wavelength λ_c is given by

$$\lambda_c \;=\; 2a \;=\; \frac{V_c}{f_c} \tag{36}$$

where, as previously, V_c = velocity of light

Although most of the basic concepts for coaxial systems also apply for waveguide, small modifications are necessary. Two areas of difference are velocity of propagation and determination of characteristic impedance.

For any coaxial system the velocity of propagation is constant for all frequencies. In waveguide systems the velocity of propagation changes with frequency. For normal waveguides with no dielectric inside the guide the velocity of propagation V is given by

$$V \;=\; V_c \frac{\lambda_c}{\sqrt{\lambda_c^2 - \lambda_o^2}} \tag{37}$$

A more common notation is

$$V \;=\; \frac{V_c}{\sqrt{1 - \left(\dfrac{F_c}{F_o}\right)^2}} \tag{38}$$

Then using equation 8 and 9 we find

$$\lambda_g \;=\; \frac{V}{f} \;=\; \frac{V_c}{f} \cdot \frac{\lambda_c}{\sqrt{\lambda_c^2 - \lambda_o^2}} \;=\; \frac{\lambda_o}{\sqrt{1 - \left(\dfrac{F_c}{F_o}\right)^2}} \tag{39}$$

Here

λ_g = guide wavelength

λ_c and F_c = cut-off wavelength and frequency

λ_o and F_o = free space wavelength and frequency

Now

$$\beta \;=\; \frac{2\pi}{\lambda_g} \;=\; \frac{2\pi}{\lambda_o} \sqrt{1 - \left(\frac{F_c}{F_o}\right)^2} \tag{40}$$

Characteristic impedance cannot be determined as easily for waveguide as for a coaxial line because there are no unique currents and voltages. But this is not really a problem since the process of normalization eliminates characteristic impedance as a requirement for calculations. The basic quantities for waveguide work are reflection coefficient, standing wave ratio, and propagation constant. From these the normalized impedance at any point can be determined, and the complete waveguide system can be described in terms of its performance and characteristics.

For coaxial systems the reflection coefficient was defined as the ratio of the reflected signal to the incident signal. This holds true for waveguide also. Starting from these facts, and using propagation constant as defined in equation (40), all the equations developed above are applicable to waveguide.

SECTION III
MICROWAVE MEASUREMENTS

3-1 MICROWAVE EQUIPMENT

Microwave parameters such as power, impedance, noise figure, attenuation and frequency can be measured with commercially available test and measurement instruments. Also available are a wide variety of accessories and waveguide fittings such as slotted lines, detectors, mounts, attenuators, phase shifters, directional couplers, etc. Instrumentation and accessory equipment manufactured by Hewlett-Packard is available for making all normal measurements in all microwave frequency bands to 40 kmc. The specific equipment types referred to in this publication are fully described in ⓗ catalogs and technical literature.

Equipment Designations

Each item of ⓗ equipment is identified by a model number. For waveguide components, the model numbers are normally prefixed by a letter which designates the waveguide size and frequency band. Each ⓗ waveguide instrument for a given band will have the same prefix to its model number. All instruments with a given prefix are compatible.

Nine band-designation prefixes are used:

BAND	FITS WAVEGUIDE SIZE (In.)	FREQ. RANGE
S	3 x 1-1/2	2.6 to 3.95 kmc
G	2 x 1	3.95 to 5.85 kmc
J	1-1/2 x 3/4	5.3 to 8.2 kmc
H	1-1/4 x 5/8	7.05 to 10.0 kmc
X	1 x 1/2	8.2 to 12.4 kmc
M	.850 x .475	10.0 to 15.0 kmc
P	.702 x .391	12.4 to 18.0 kmc
K	.500 x .250	18.0 to 26.5 kmc
R	.360 x .220	26.5 to 40 kmc

For example, an ⓗ 370 Fixed Waveguide Attenuator designed for use with 3 x 1-1/2 in. waveguide is designated Model S370. The same instrument for use with .702 x .391 in. waveguide is designated Model P370.

Many Hewlett-Packard instruments also have suffix letters as part of the model number. In many cases an "A" suffix will identify the original design of an instrument, while "B", "C", and other letters indicate a revised, modified or special version of the basic model.

However, in the case of certain ⓗ microwave items, the suffix letter indicates specific attenuation or coupling factors. Six designator letters are used:

"A"	3 db
"B"	6 db
"C"	10 db
"D"	20 db
"E"	30 db
"F"	40 db

For example, the 20 db coupling version of the ⓗ Model 750 Cross-Guide Coupler is designated the Model 750D.

Flanges

All ⓗ waveguide equipment items have plain cover flanges which mate with standard UG-( ) flanges. Model 290 Cover to Choke Flange Adapters may be used to connect between individual instruments and a choke flange system under actual operating conditions.

Types of Measurements

In general, the measurements made in research, design, test and check out of microwave equipment can be divided into five types: frequency, attenuation, impedance, power and noise figure.

Frequency measurement is made in a straightforward manner with wavemeters[1]. This technique is described in experiment 1. The other measurements are described below.

3-2 ATTENUATION MEASUREMENT

Attenuation measurements are usually made by a substitution or modified substitution method. In this method the signal source is connected to a detector mount through a length of transmission system into which the unknown device may be inserted. A reference reading is first obtained on the output indicator. The device under test is then inserted between the signal source and the detector. The power attenuation at the output indicator is a measure of the attenuation. This measurement requires that the detection law of the detector be known over the complete

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1   Frequency counting techniques may be used for greater accuracy. These are described in other Hewlett-Packard publications.

frequency range of the measurement, and that re-
flection effects in the system be negligible both with
and without the test device.

The type of detecting equipment used will depend on
the range of the attenuation measurement. A power
monitoring combination such as the ⓗ 430C Micro-
wave Power Meter and a bolometer mount will allow
attenuation measurement over approximately 20 db.
A wider range of attenuation measurement, up to 30
or 40 db, can be achieved with a detector mount em-
ploying a barretter, and an ⓗ 415B Standing Wave
Indicator (high sensitivity tuned voltmeter). In this
case, the signal source must be modulated, and the
rf power level must be kept below 200 microwatts for
square law detector characteristics. The attenua-
tion in decibels may be read directly from the Mod-
el 415B.

To eliminate effects of reflections between genera-
tor and attenuator, and attenuator and load, it is
desirable to use attenuation pads. Pads should be
well matched to the transmission system.

Another method of measuring attenuation is appli-
cable when the signal generator has an accurately
calibrated attenuator. When using this method the
output of the signal generator is fed into the detector
and a reading is obtained on the 415B. The setting of
the signal generator attenuator is noted. The attenua-
tor is then inserted, and the signal generator output
is adjusted to obtain the same output reading as be-
fore. The difference between the signal generator
attenuator settings is the attenuation of the attenua-
tor in db. Since the detector is always operated at
the same level, detector law is no problem.

3-3 IMPEDANCE MEASUREMENTS

Of all the possible measurements to be made in de-
sign and production, probably the most important is
impedance. With distributed parameters, impedance
varies with the position of measurement. Hence all
impedance measurements must be referred to some
reference plane. Since impedance determines ener-
gy reflected by the load, information concerning a
load can often be obtained by determining the magni-
tude of the reflection coefficient.

The value of the reflection coefficient can be deter-
mined by using a slotted section of transmission line
and measuring the standing wave ratio, (ratio of maxi-
mum to minimum voltage in the system feeding the
load). In many cases it is only necessary to know the
magnitude of the reflection coefficient. This can be
measured directly with a reflectometer by sampling
the incident and reflected waves and obtaining their
ratio which is equal to the reflection coefficient.
The reflectometer method will be explained following
the discussion of the slotted line.

Slotted Line Measurements

A typical setup for making slotted line measurements
is shown in Figure 3-1. The transmission system
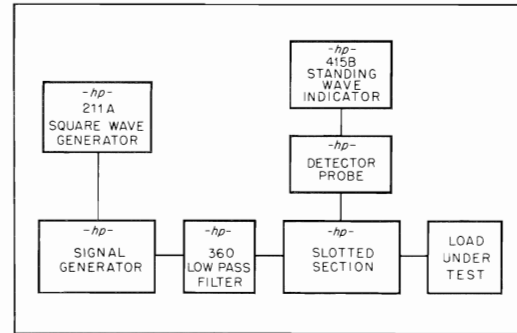contains the incident wave and a reflected wave

Figure 3-1. Typical Setup for
Impedance Measurements

which depends on the mismatch of the load. These
two waves will alternately cancel and add, setting up
a standing wave pattern along the line. By inserting
a probe into the slotted section and sliding it along
the line, the resultant voltage pattern can be meas-
ured. The usual practice is to amplitude modulate
the signal source and to use a crystal or bolometer
to detect the probe output. The detected output of the
probe is connected to a high sensitivity, tuned volt-
meter, such as the ⓗ 415B Standing Wave Indicator.
Using this procedure, the swr and the position of
maximum and minimum of the load can be deter-
mined. The load is then replaced by a short circuit
and the shift of the minimum is recorded. A proper
transformation of this information can be entered on
a Smith Chart from which the point of measurement
can be referred back to the load or point of interest.
In this way, one can quickly determine the value of
the impedance and the reflection coefficient in mag-
nitude and phase.

Slotted Line Techniques

In measuring with slotted lines there are several
places where errors may occur. A proper operating
technique will eliminate or minimize these errors.
Among the sources of error are: probe loading,
detector characteristics, harmonics, fm, and other
spurious signals.

Harmonics and spurious signals can be minimized by
use of low pass filters such as the ⓗ 360 series. Of
special importance is the fact that modulation should
not be attempted by very short pulses or poor quality
square waves. When modulating klystrons in such a
manner the resulting fm tends to obscure the nulls
of the standing waves. To avoid fm, modulation of
klystron signal sources should be by square wave.

Since the ratios of different voltage levels are being
measured with slotted lines, it is essential that the
detector follow the same law for all levels. If bar-
retters are operated at levels less than 200 micro-
watts and crystals at power levels of less than 20
microwatts, the characteristics are essentially square
law. It is for this condition that the ⓗ 415B
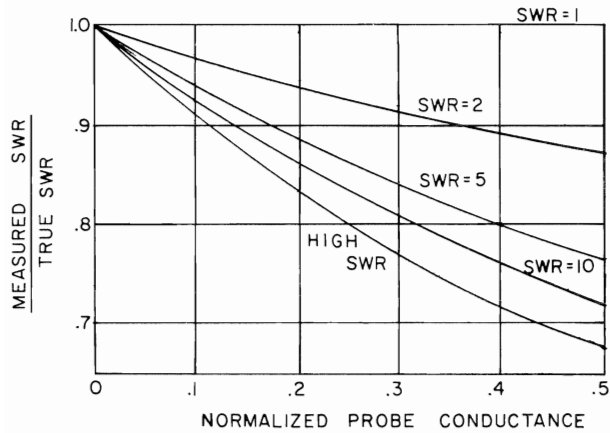meter scale is calibrated. This condition will be

Figure 3-2.   Effect of Probe Penetration on
Measured SWR

adequately met in the setup shown in Figure 1-1 (for standing wave ratios of 10 to 1 or less) if the probe coupling is reduced to a point where the minimum is 5 to 10 db above the system noise level.

The sampling probe will extract some power from the line to supply the indicating devices and in addition will set up reflections in the line from the probe itself. Both errors become greater as the probe insertion is increased. It is therefore important in a slotted line measurement to keep the probe penetration at a minimum.

The power extraction by the probe can be explained by considering the probe as admittance shunting the line. This admittance is kept small by coupling as loosely as possible (small penetrations) and by using a high sensitivity detector in conjunction with a source output of one milliwatt or more. If the coupling between the probe and the line is not small, shunt admittance introduced by the probe will cause the measured swr to be lower than the true swr (as shown in Figure 3-2) and will shift both the maximum and the minimum from their natural position. An exception to this minimum penetration rule occurs when it is desired to examine in detail the minimum point on the standing wave ratio pattern. For this work a greater probe penetration can be tolerated because the minimum corresponds to the lowest impedance point on the line.

In addition to extracting power from the line, the penetration of the sampling probe into the slotted section gives rise to reflections from the probe itself. These reflections travel back towards the generator. If the generator is mismatched, these reflections are re-reflected. When the probe is moved under these conditions, the phase of the reflection is changed and errors result. However, reflections from the generator are a second-order effect, important only when measuring low standing wave ratios (2 to 1 or less). In this case, a moderately good match between the generator and load is

desirable. In general, the match of an ⓗⓟ signal generator is sufficient for this purpose, providing the cables and connectors do not introduce spurious reflection. However, when klystrons are used directly to feed a waveguide network, the match is poor. Therefore, the klystron should always be followed by a pad or an isolator.

Various methods of measuring swr's have specific advantages for different swr ranges. Straight-forward measurement of swr by conventional methods is generally preferred when measuring swr's in the range of 10 to 1 or less. But, when the swr is high, coupling to the probe must also be high in order to obtain readings at the minimum. This may result in deformation of pattern when the maximum is measured. There is also a possibility of error due to a change in detector characteristics because of rf level changes.

To measure swr's greater than 10 to 1 within 1% accuracy, the twice-minimum-power method is recommended. Here it is only necessary to establish the electrical distance between the points that are twice the amplitude of the minimum. The swr can be obtained by substituting this distance into the following expression as shown in Figure 3-3:

$$\sigma_L = \frac{\lambda_g}{\pi \, \Delta x}$$

σ_L = Voltage Standing Wave Ratio of Load.

λ_g = Guide wavelength

Δx = Distance between "twice-minimum-power" points

The value referred to in this method is the twice-power value. Therefore, if a linear voltage indicator is used with a square-law detector, the voltage indication of the twice-power point will be twice that of the minimum. If a standing wave indicator (calibrated for use on a square-law detector such as the ⓗⓟ 415B or a linear receiver) is used, the voltage ratio of the two readings will be 1.4 to 1 (a 3 db difference in reading).
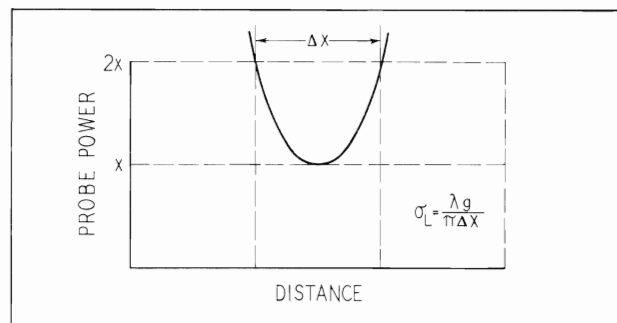

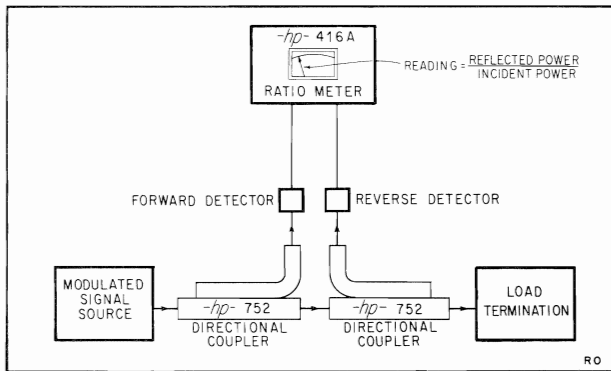Figure 3-3.   Twice Minimum Power Method for
Measuring SWR

Figure 3-4.   Typical Reflectometer Setup

Reflectometer Measurements

An additional method of making impedance measurements conveniently is by use of a reflectometer. The reflectometer will indicate magnitude of the impedance but will not provide phase angle information as does the slotted line. The reflectometer is most useful for fast, swept frequency, production measurements.

A typical reflectometer setup is shown in Figure 3-4. This arrangement determines the magnitude of the reflection coefficient by use of directional couplers which sample the input wave and the reflected wave. The couplers feed to detectors and then to a ratio meter (such as the ⓗ 416A) where a direct comparison is made. The resultant ratio of the two sampled powers is read directly on the ratio meter. For best results in reflectometer operation, the input power should be kept to a low level by means of input attenuators so that the power at the forward detector is in the order of -20 dbm. At the reverse detector it should be in the order of -10 dbm at the calibration point. This will more nearly insure square-law operation of the crystal.

ⓗ reflectometers are available to measure the magnitude of reflection coefficients rapidly and with good accuracy in the popular waveguide frequencies. This method is most practical for measuring reflection coefficients up to approximately 0.5 (swr of 3.0). When the reflectometer is used with swept frequencies, and is calibrated with a short, accuracies of approximately ±0.02 can be obtained for reflection coefficients of 0.1 (swr of 1.22). For reflection coefficients of 0.4 (swr of 2.3) accuracies of approximately ±0.04 can be obtained. The potential accuracy of the reflectometer is greatest at low swr's when using a fixed frequency, a sliding short for calibration, a slide screw tuner, and a moving load. Under ideal conditions errors of less than ±0.005 in reflection coefficient, equal to a residual swr of 1.01, are attainable.

Impedance Measurements with VHF Bridge

Below 500 mc, slotted sections become exceedingly long and other techniques for impedance measurements
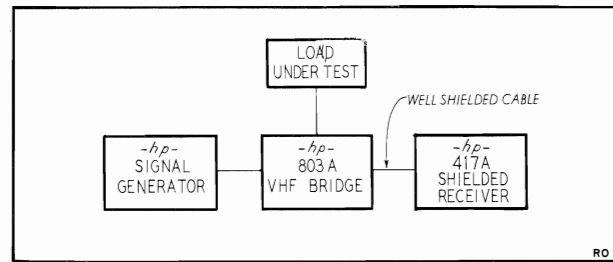
Figure 3-5.   Impedance Measurements for
Frequencies Below 500 MC

are more desirable. For these frequencies, the ⓗ Model 803A VHF Bridge is ideal. (See Figure 3-5.)

The VHF bridge provides a convenient means of measuring impedances, reading both magnitude and phase angle. The bridge is operated simply by tuning two controls until a sharp null is obtained. At the null, one dial reads unknown impedance in ohms and the other dial shows phase angle.

Because of the nulling nature of the measurement, the voltages measured are very small. Therefore, to avoid any effects from extraneous voltages, lines connected to the bridge should be adequately shielded. The signal source supplying the bridge should be capable of delivering several milliwatts of power for a well defined sharp null to be observed. The detecting equipment should have high sensitivity, as does the ⓗ 417A VHF Detector which is designed primarily to be used with the Model 803A Bridge.

The bridge is basically an unbalanced device. Measurements can be made in balanced systems by the use of a balun, a simple form of which is shown in Figure 3-6.

This structure is equivalent to a 4 to 1 impedance transformer. Hence, impedances measured at the input of the balun should be multiplied by 4 to obtain the actual impedance.

Figure 3-6.   Measurement Setup Using
Balun with Balanced Load

Figure 3-7.   Arrangement for Using Four Instrument Fuses in Series Parallel Combination in ⓗ 476A

Figure 3-8.   Diagram of Tunable Bolometer Mount (ⓗ 475B)

3-4   POWER MEASUREMENT

In the microwave region, power measurements are considered to be more basic than current or voltage measurements. This is because power is invariant with position of measurement, while current and voltage (because of the distributed nature of the transmission system at these frequencies) are not.

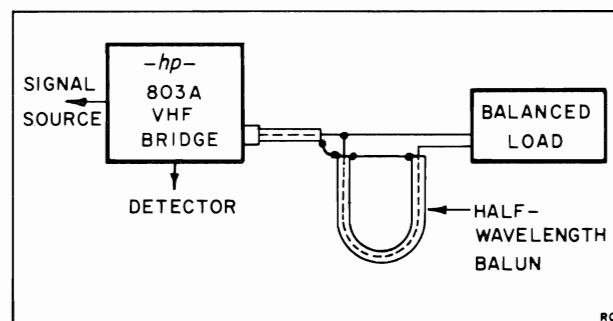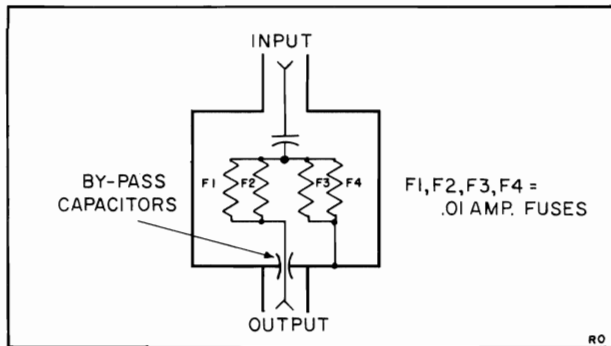In the range 0.1 to 10 milliwatts, power measurements are customarily made with a bolometer which operates in a bridge circuit and changes rf energy into heat energy. This causes the resistance of the bolometer to change, unbalancing the bridge. The audio power which is substituted to rebalance the bridge and keep the bolometer resistance constant is then measured. Typical bolometer arrangements are shown in Figures 3-7 and 3-8.

In the range 10 watts and above, power measurements are generally made directly, using conventional calorimeters.

The ⓗ 434A Calorimetric Power Meter is a convenient measuring device in the range 10 mw to 10 watts. A discussion of power measurements below 10 milliwatts follows. The discussion then takes up the precision and convenience of power measurements between 10 mw and 10' watts using proper techniques and the high accuracy 434A.

0.1 to 10 Milliwatts

Bolometers used for microwave measurements are of two general types--metallic wire or film in which the temperature coefficient of resistance is positive, and thermistors in which it is negative. Both barretters and instrument fuses are used as positive temperature coefficient bolometers. Barretters consist of a short length of very fine platinum wire suitably capsulated. Negative temperature coefficient bolometers (thermistors) consist of a small bit of semi-conductive material suspended between two fine wires.

In general, barretters are delicate and readily burned out by too much power.   Even if the overload is insufficient to burn out a barretter, it may still increase its cold resistance to the point where a self-balancing bridge meter cannot be zero set. Thermistors are much more rugged.   Although they are rated at 25 mw maximum, they generally burn out at about 400 mw or more, and their characteristics change only slightly, if at all, upon overload.
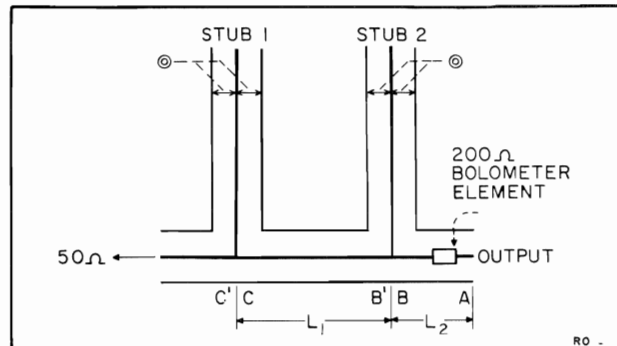
The bolometer element is used in conjunction with a power meter such as the ⓗ Model 430C. This power meter is designed to operate with bolometer impedances of either 100 or 200 ohms.

The bolometer element itself must be mounted and well matched to the transmission system used and to the power meter. ⓗ bolometer mounts with low swr through their operating range are available for coaxial and waveguide systems.   Barretters are usually operated at 200 ohms, while thermistors usually operate at 100 or 200 ohm levels. Series-parallel combinations of the bolometer element are used in ⓗ coaxial mounts.   The ⓗ 477B Coaxial Thermistor Mount, for example, uses two thermistor elements biased to 100 ohms each which present 200 ohms to a microwave power meter but present 50 ohms to the rf energy.

The power measured by a bolometer mount also depends upon the relationship between the load and the source impedance.   To obtain maximum available power the load should present a conjugate match to the source impedance.   This can be achieved by properly adjusting a double-stub tuner, a stub-line stretcher, an E-H tuner, or a slide-screw tuner. These tuners transform the magnitude and phase of the source impedance in order to conjugate match it to the load impedance. The ⓗ Model 475B Tunable Bolometer Mount operates on this principle.

The ⓗ 430C Microwave Power Meter will give direct instantaneous readings of microwave power when connected with a suitable bolometer mount. The bias current necessary to bring the bolometer to the correct operating resistance is furnished by the 430C Power Meter. This power meter circuit includes a self-balancing bridge and an audio voltmeter to indicate the magnitude of the bridge amplifier output

Figure 3-9. Basic Circuit of Power Meter

(Figure 3-9). The self-balancing bridge uses the external bolometer element (a non-linear resistor) as one of the bridge arms. A h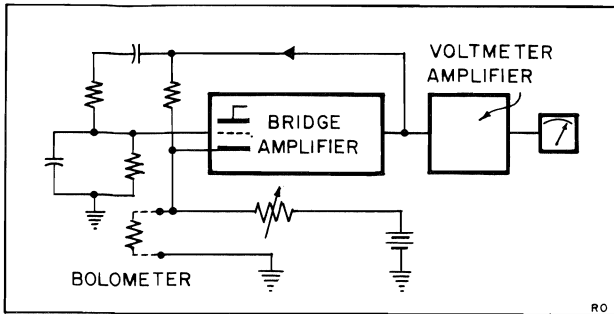igh gain amplifier is connected across the bridge as a detector, and the output of the same amplifier is connected as the driving source for the bridge. Then, assuming sufficient gain, the circuit oscillates at an amplitude such that the bridge is almost balanced. When the rf power is applied to the element, the amplitude of oscillation decreases the amount necessary to maintain the element's resistance constant. This power decrease is equal to that power added by the rf source and can be read on the voltmeter which is calibrated in power units.

⑩ bolometer mounts have been designed for both coaxial and waveguide systems at frequencies between 10 mc and 40.0 kmc. These mounts are extremely simple to use, have low swr, and may be used with the ⑩ 430C Power Meter to provide direct reading measurements. ⑩ bolometer mounts may be classified according to the type of bolometer element employed--thermistor, or barretter--and whether the mount is untuned (broadbanded) or tunable.

⑩ fixed tuned thermistor mounts are exceptionally broad band bolometers. Model 477B Coaxial Thermistor Mount covers the frequency range of 10 mc to 10 kmc, while ⑩ 487B (waveguide series) are available from 3.95 to 40.0 kmc. No tuning is required and an extremely low swr is maintained throughout all frequency bands.

Model 485B Detector Mounts employ a single tuning control to match the applicable waveguide to a detector element (barretter or crystal). In general, their swr is less than 1.25 over the rated frequency range when using barretters.

⑩ 476A Universal Bolometer Mount is a fixed tuned bolometer in the frequency range from 10 to 1,000 mc. The bolometer element consists of 1/100 ampere fuses. ⑩ 475B is a double stub tuner matching 50 ohm coaxial systems into 100 or 200 ohm bolometers. It covers a frequency range of 1,000 to 4,000 mc, for more accurate microwave power measurements.

In general, square wave or pulse modulated power can be measured accurately with either a barretter, fuse, or thermistor, subject to certain limitations

which depend upon the characteristics of the bolometer elements in conjunction with the bridge oscillator. However, in the ⑩ 430C Power Meter, these limitations are not serious.

When using barretters or fuses, precautions should be taken if the modulation frequency is below about 200 cps since the heating time constant allows the element resistance to follow the modulation. For sine and square wave modulated power, the meter reading will tend to increase at such low modulated frequencies. For use with thermistors, precautions should be taken for frequencies less than 100 cps.

Furthermore, with barretters or fuses, care should be taken to avoid modulating frequencies approaching the bridge frequency (10.6 kc) or its sub-multiples. At pulse frequencies, near sub-multiples of 10.6 kc beats are produced which show on the meter. At modulation frequencies which are exact sub-multiples of the oscillator frequency, the oscillator may lock in with the modulation frequency causing the meter pointer to dip to a low value. In either case, the effect can be avoided by changing the repetition frequency slightly. This solution can be used down to frequencies at least as low as 200 cps.

A tabulation of ⑩ equipment to be used with Model 430C Power Meter for a specific transmission system, frequency range and power level is given in Figure 3-10. Power levels greater than the highest range of the 430C Power Meter can be measured by attenuating the power by pads or by directional couplers to the range of the Model 430C.
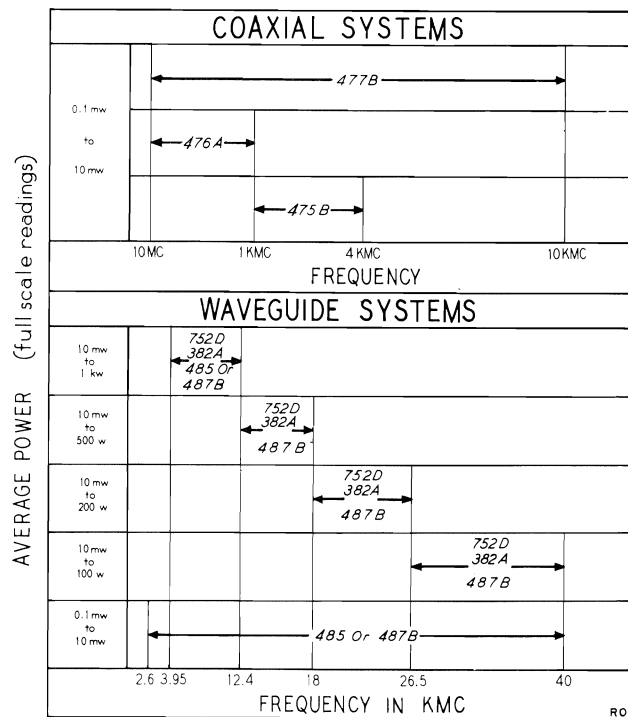

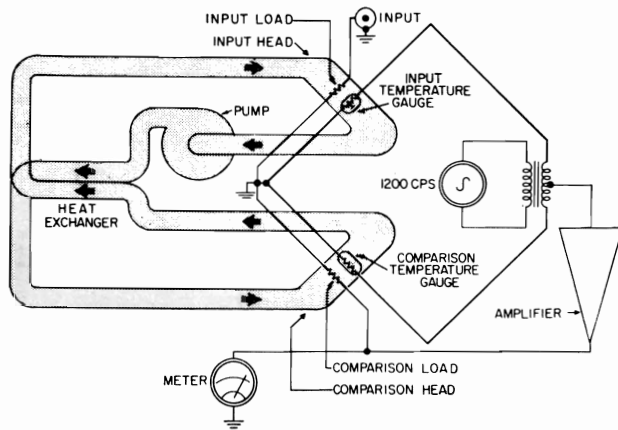Figure 3-10. ⑩ Equipment for use with ⑩ 430C Microwave Power Meter

Figure 3-11.   Simplified Diagram, ⓗ 434A
Calorimetric Power Meter

10 mw to 10 watts

The Model 434A Calorimetric Power Meter automat-
ically measures average power from 10 milliwatts to
10 watts.   The instrument operates from dc to
12.4 kmc.   The operator simply connects the source
to the 434A and reads the power.   Power above 10
watts may be measured by reducing it to the range
acceptable to the 434A with calibrated attenuators
or directional couplers.

The Model 434A, shown simplified in Figure 3-11,
consists of a self-balancing bridge which has identi-
cal temperature-sensitive resistors (gauges) in two
legs, an indicating meter and two load resistors, one
for the unknown input power and one for the compari-
son power.   The input load resistor and one gauge
are in close thermal proximity so that heat generated
in the input load resistor heats the gauge and unbal-
ances the bridge.   The unbalance signal is amplified
and applied to the comparison load resistor which is
in close thermal proximity to the other gauge so that
the heat generated in the comparison load resistor
is transferred to its gauge and nearly rebalances
the bridge.

The meter measures the power supplied to the com-
parison load to rebalance the bridge.   The charac-
teristics of the gauges are the same and heat trans-
fer characteristics from each load are the same, so
the power dissipated in each load is the same, and
the meter may be calibrated directly in input power.

An efficient (and fast) heat transfer from the loads to
the temperature gauges is accomplished by immersing
the components in an oil stream.

The power measurement is accurate because the flow
rates through the two heads and head characteristics
are the same.   To insure constant temperature, and
to bring the streams to nearly the same temperature,
they are passed through a parallel-flow heat ex-
changer just prior to entering the heads.   Identical

flow rates are obtained by placing all elements of
the oil system in series as shown in Figure 3-11.

Accuracy of the Model 434A is one of its unique
attributes. Since the new power meter represents the
most accurate method available for measuring high-
frequency power, the 434A may find much use as a
laboratory standard power meter. Nominal accuracy
is 5%.   However, higher accuracies can be achieved
by employing techniques to minimize frequency and
impedance mismatch effects.

For example, accuracy can be improved by applying
an efficiency correction to compensate for the inter-
nal power loss in the rf termination. Also, accuracy
can be improved by accurately matching the 434A to
the source.   For this purpose it is desirable that the
power be carried in a waveguid rather than a coaxial
cable.   This not only reduces line loss but permits a
waveguide slide-screw tuner to be used ahead of the
waveguide-coax transition at the instrument connector.
Such waveguide tuners normally give less loss than
coaxial tuners.

3-5 NOISE FIGURE

In microwave communications, the weakest signal
that can be used is usually determined by the amount
of noise added by the receiving system. Thus, any
decrease in the amount of noise generated in the
receiving system will produce an increase in the
output signal-to-noise ratio equivalent to a corre-
sponding increase in received signal.   From a per-
formance standpoint, an increase in the signal-to-
noise ratio by reducing the amount of noise in the
receiver is more economical than increasing the
received signal level by raising the power of the
transmitter.   For example, a 5 db improvement in
receiver noise figure is equivalent to increasing the
transmitter power by 3:1.

The noise appearing at the output of a receiver or an
amplifier is the sum of the noise arising from the in-
put termination (antenna) and the noise contributed by
the receiver or amplifier itself. The noise factor is
the ratio of the actual output noise power of the device
to the noise power which would be available if the
device were perfect and merely amplified the thermal
noise of a load at temperature T_0 rather than con-
tributing any noise of its own.   Noise figure is that
power ratio expressed in db.

The noise factor (F) of a device (amplifier or mixer,
for example) can be defined as:

$$F = \frac{N}{kT_0 B \ \times \ G} \qquad (1)$$

where:

N = the noise output of the device
k = Boltzman's constant
T_0 = 290°K (standard temperature)
B = Bandwidth of the device in mc
G = Power gain of the device

kT_O is equivalent to the available thermal noise per mc from the input resistor or resistive network. A theoretically perfect device adds no noise to the signal passing through it and thus the noise output equals the noise input per mc from the source resistor, times the bandwidth in mc, times the gain. Substituting this value for N in (1), the noise factor of a perfect device would be:

$$F = \frac{kT_O B \times G}{kT_O B \times G} = 1 \qquad (2)$$

and the noise figure (power ratio expressed in db) would be 0 db.

The noise figure of a receiver may be measured using a signal generator and an output power (square law) detector. However, this method is time-consuming and has the added disadvantage that the effective power gain-bandwidth product must be determined. Moreover, the available signal power may be difficult to determine accurately at the low levels involved.

Another method which overcomes these drawbacks is used in the Hewlett-Packard Noise Figure Meters to provide a continuous display of noise figure. In place of a signal generator, this method uses a standard white noise source to supply a noise spectrum of known power which is flat with frequency. At intermediate and low radio frequencies temperature-limited diodes are suitable sources, while at microwave frequencies argon gas discharge tubes, in suitable waveguide or coaxial sections, are both accurate and reliable.

Hewlett-Packard Models 340B and 342A Noise Figure Meters measure noise figure as a function of the ratio between the noise output of the device under test when a known amount of noise is introduced at the input, to the noise output when the device is terminated in its normal load.

To make noise figure measurements, the 340B or 342A, the appropriate noise source and the receiver or amplifier under test are connected as shown in Figure 3-12. The noise figure meter square wave modulates the noise source at about a 500 cps rate and measures noise figure by comparing the noise output of the device under test when the noise source is off to the noise output when the noise source is on.

The input circuitry of the 340B consists of a gated-tuned amplifier which operates at two frequencies, 30 or 60 mc, selected by a front panel switch. The input circuitry of the 342A consists of a 30 mc gated-tuned amplifier preceded by a four channel mixer-local oscillator combination which, depending upon the position of the front panel switch, will convert four frequencies--60, 70, 105 and 200 mc--to 30 mc. The output from the 340B/342A tuned amplifier is detected, amplified, and alternately applied to two gated inte-
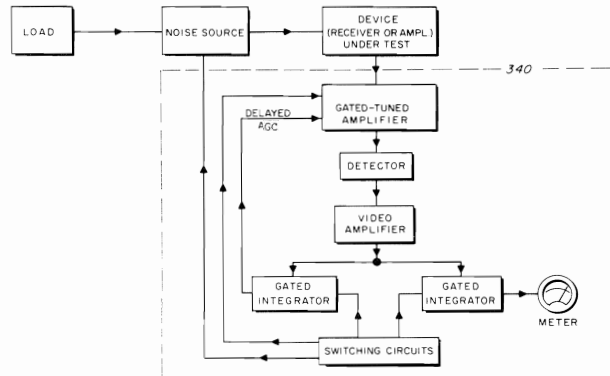
Figure 3-12. Simplified Block Diagram of
ⓗⓟ Model 340B

grators. When the noise source is on, the combined noise power from the noise source and the device under test is amplified by the tuned amplifier, detected, and passed through the AGC integrator. The time constant of the AGC voltage applied to the amplifier is long enough to hold the gain of the amplifier the same whether the noise source is on or off.

When the noise source is turned off, the combined noise power from the source impedance (load) and the device under test is amplified, detected, and passed through the meter integrator and displayed on the meter. Because of the AGC action, the meter deflection is proportional to the ratio of the noise powers, (source on and source off) and, since the additional noise from the noise source (excess noise) is accurately known, the meter face is calibrated directly in db of noise figure.

The AGC action, in addition to establishing a reference against which noise figure measurements can be made, provides a wide (50 db) input operating range and also eliminates the necessity for periodic recalibration of the Noise Figure Meter. AGC voltages appear on a pair of terminals at the rear of the instrument to facilitate measurements which require an indication of the gain of the system in relation to changes in noise figure.

The meter face is provided with two noise figure scales--a "Noise Diode" scale for use with the ⓗⓟ 343A VHF Noise Source and 345B IF noise source and a "Gas Tube" scale for use with 347A Waveguide Noise Sources. Current scales indicate the current supplied to the noise sources. Special circuitry is included to enable offsetting the Noise Figure Meter scale so that low values of noise figure can be read on a more sensitive external meter. A phone jack is provided on the rear of the Noise Figure Meter to drive a remote meter or galvanometer recorder.

SECTION IV
MICROWAVE EXPERIMENTS

The series of eight experiments on the following pages has been planned to accomplish two objectives. First, to gain experience in making the various types of measurements required in microwave work; second, to become familiar with the more common types of waveguide and test equipment as they are used in making these measurements.

Equipment for Experiments

The degree to which the experiments can be utilized will depend, of course, on the equipment available for making them. Basic measurements of frequency, attenuation and swr can be made with a minimum investment in specialized test apparatus. Some additional equipment is needed for making basic power measurements. Where considerable work is to be done, an even greater investment can be justified for other equipment which simplifies the experimental setup or extends the range of measurement possible.

All experiments utilize Hewlett-Packard "X" band (8.2 - 12.4 kmc) equipment. These instruments are of convenient size and are more economical than other bands. The specific items required are listed in each experiment and summarized in Table I. They are described in more detail in Appendix II, Microwave Equipment Data Sheets.   Recognizing that training operations often have budget limitations, the equipment required for the experiments has been divided into a basic group and two optional groups. Only the basic group is needed for the majority of the experiments. Individual equipment items in each group can be ordered from Hewlett-Packard as necessary to meet individual training needs.

The experimenter is encouraged to exercise ingenuity, both in substitution of equipment items to utilize test equipment which might be available without further purchases, and in modification of the experiments to achieve specific training objectives.

TABLE I.   EQUIPMENT FOR MICROWAVE EXPERIMENTS

Equipment	QTY	Model No.	Description	Unit Price	Experiments in which used							
					1	2	3	4	5	6	7	8
	4	24	Waveguide Stands	3.00	x	x	x	x				
	4	X25	Waveguide Clamps	2.50	x	x	x	x				
	1	X375A	Variable Flap Attenuator	90.00		x	x					
GROUP I	1	X382A	Broadband Attenuator	275.00	x	x				x	x	
Basic Equipment for	1	415B	Standing Wave Indicator	200.00	x	x	x				x	x
Measuring Frequency,	1	X421A	Crystal Detector	75.00	x	x						
Attenuation, and SWR	1	X532B	Frequency Meter	150.00	x						x	
	1	X715A	Klystron Power Supply	300.00	x	x	x				x	
	1	809B	Universal Probe Carriage	160.00			x			x	x	x
	1	X810B	Waveguide Slotted Section	90.00			x			x	x	x
	1	X-13	Klystron	*	x	x	x				x	
	1	444A	Untuned Probe	40.00			x			x	x	x
GROUP II												
Additional Basic												
Equipment for Power	1	430C	Microwave Power Meter	250.00				x		x	x	
Measurement	1	X487B	Detector Mount	75.00				x		x	x	x
GROUP III												
Optional Equipment for	1	X281A	Waveguide-Coax Adapter	25.00						x		x
more Detailed Measure-	1	620A	Signal Generator**	2250.00						x		x
ments of Attenuation,	1	X485B	Thermistor Mount	75.00							x	x
Impedance, and Power	1	X870A	Slide Screw Tuner	125.00							x	

*   Varian Associates $295.00
**   The X-13 Klystron and 715A Power Supply included in Group I can be substituted for the
      620A Signal Generator.

Experiment 1
Frequency Measurement

OBJECT

To measure frequency of a microwave source and to become familiar with the equipment used for frequency measurement.

INTRODUCTION

Resonant cavity wavemeters are the most commonly used microwave frequency measuring devices. They can measure to a high degree of accuracy, are simple and easy to use, and are physically large in proportion to the wavelength being measured. Precision wavemeters are widely used to measure frequency in microwave laboratories, on production lines, and on operating microwave systems. Wavemeters also are incorporated as the frequency measuring element in general purpose microwave test sets. Direct reading wavemeters such as the ⓗ Model X532B can measure frequencies with accuracy better than 1 part in 1000 (0.1%). By using calibrating charts to correct for temperature and humidity, accuracies of 1 part in 10,000 can be achieved.

A direct reading resonant cavity wavemeter is used to measure frequency in this experiment.

PROCEDURE

1) Set up the equipment as shown. A fan should be used to keep the klystron cool.

2) Review the data sheets and/or instruction books for each equipment item.

3) Turn on the klystron in accordance with the procedure in the instruction manual for the Model 715A Klystron Power Supply.

4) With the klystron tuned for approximately the middle of its range, and the klystron modulated with 1000 cycles from the 715A, adjust the repeller voltage until the klystron is oscillating. The condition of oscillation is determined by an indication on the 415A Standing Wave Indicator. Adjust the X382A Attenuator and the range selector on the 415A for a midscale reading on the 415A. Adjust 1000 cycle modulation frequency on the 715A power supply to peak the 415A.

5) Tune the klystron for the strongest indication on the 415A.

6) Slowly change the repeller voltage and observe the 415A to note the different modes of oscillation of the klystron.

7) Retune the klystron and readjust repeller voltage for the strongest indication on the 415A.

8) Tune the 532 wavemeter while observing the 415A. Watch for a dip on the 415A. The frequency at which the klystron is oscillating can then be read directly from the dial of the wavemeter.

9) Repeat the frequency measurement for other settings of the klystron tuning screw and the repeller voltage.

QUESTIONS

1) What is the effect on klystron frequency of increasing the reflector voltage?

2) How would you use a wavemeter to tune a klystron to some desired frequency?

3) Why must wavemeter cavities be free of spurious responses?

4) How would you present a swept frequency display of the klystron modes with wavemeter dip on an oscilloscope?

5) After a frequency reading, why should the wavemeter always be turned off frequency?
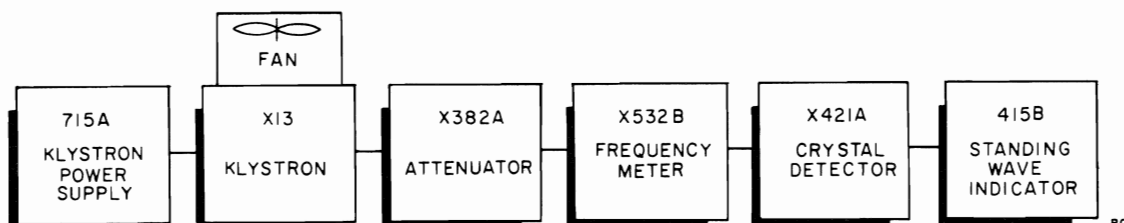
Experiment 2
Attenuation Measurement

OBJECT

To demonstrate the techniques of measuring attenuation of a component part of a waveguide system.

INTRODUCTION

Attenuation of any part of a waveguide system can be measured by the "power ratio" or the "substitution" method. In the power ratio method, the output of the system is measured first with the unknown part in place, and then with it removed. The ratio of the two output powers is the attenuation in db of the part. An inherent disadvantage of the power ratio method is that the detector operates at different power levels so any variation of the detection law will be reflected in the attenuation value determined.

The substitution method eliminates the inherent error of the power ratio procedure. In this method the output power is held constant by replacing the part to be measured by a precisely calibrated variable attenuator. The unknown attenuation is then equal to the value of attenuation which must be inserted to obtain the original reading on the power indicator.

In this experiment attenuation is measured by both the power ratio and substitution methods.

PROCEDURE

1) Set up the equipment as shown.

2) Review the data sheets and/or instruction books for each equipment item not used in experiment 1.

3) Turn on the klystron and adjust for any convenient frequency following the procedure used in experiment 1.

Power Ratio Method of Attenuation Measurement

4) Set the X375A dial to 0 db attenuation. The detector must operate within its square-law detection range. Since the X-13 klystron can put out more than 100 mw at points in its band, it is necessary to reduce this power to about 0.1 mw into the crystal detector by setting the X382A to bring the 415B reading down to the 30 db range. Adjust the range switch and gain control of the 415B, and the X382A Attenuator dial for a zero db reading on the 415B.

5) Increase attenuation of the X375A in 5 db steps. Record the reading of the 415B for each step.

X375A Dial Setting	415B Reading
0 db	_____ db
5 db	_____ db
10 db	_____ db
15 db	_____ db
20 db	_____ db

Note: Rated accuracy of the X375A dial is ±1 db to 10 db, and ±2 db to 20 db; rated accuracy of the 415B is ±0.1 db over each 10 db range with ±0.2 db cumulative error. Thus, the dial of the X375A can be calibrated by measuring actual attenuation with the more accurate 415B as done here by the power ratio method.

Substitution Method

6) Set the X375A dial to 10 db. Set the X382A to provide a zero indication on the 415B (30 db range). Record the reading on the X382A.

_____ db

7) Set the X375A to 15 db. Reset the 415B to zero by decreasing the attenuation of the X382A. Record the reading on the X382A.

_____ db

8) The actual attenuation is the difference between the two readings of the X382A.

Note: Since both readings were taken with the same power level at the detector and the 415B, the only source of error is the X382A Attenuator, and it would not be necessary to be within the square law detection range.

715A KLYSTRON POWER SUPPLY	X13 KLYSTRON	X375A ATTENUATOR	X382A ATTENUATOR	X421A CRYSTAL DETECTOR	415B STANDING WAVE INDICATOR

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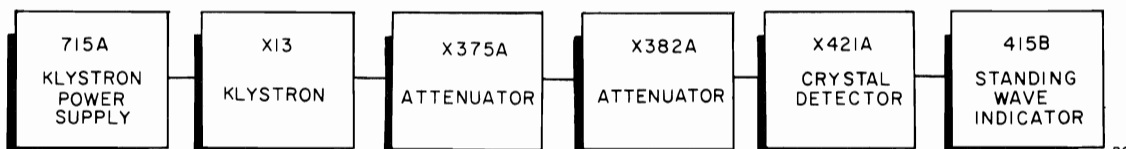
Experiment 3
Measuring SWR

OBJECT

To become familiar with the basic techniques for measuring Voltage Standing Wave Ratio.

INTRODUCTION

Measurement of Voltage Standing Wave Ratio (commonly abbreviated to swr) is a basic requirement for determining impedance at any point in a waveguide system.   By measuring the swr of a load with a slotted section of waveguide, and determining the distance between the maximum and minimum points of the standing wave, both impedance and reflection coefficient of the load can be determined. Relatively simple techniques can then be used to determine the impedance at points in the waveguide system other than the load.

There are several methods for measuring swr with a slotted waveguide.   In the most straightforward method the swr can be read directly on the ⓗⓟ Model 415B Standing Wave Indicator.   For swr's higher than about 10, the straightforward method of measurement can result in erroneous readings. Two other techniques, the double minimum method, and the calibrated attenuator method can be used to obtain greater accuracy.   These methods are briefly described in the Model 415B Operating and Servicing Manual; a more complete description is included in the article "Good Practice in Slotted Line Measurements" in the Hewlett-Packard Journal, Volume 3, Nos. 1 and 2, Sept. and October, 1951.

In this experiment the most simple and straightforward method is used to measure Voltage Standing Wave Ratio on a line terminated in a typical load.

PROCEDURE

1) Set up the equipment as shown.

2) Turn on the klystron and adjust for any convenient frequency.

3) Move the probe in the slotted waveguide until the 415B indicates a voltage maximum. Adjust the range switch and gain of the 415B until the meter indicates an swr of 1 (full scale).

4) Move the probe until the 415B indicates a minimum.

5) Read the SWR on the 415B.

Note: Detailed procedures for using the 415B to measure swr are included in the Operating and Servicing Manual.

6) Make additional measurements of swr for other oscillator frequencies and, if desired, other loads.

7) Loosen the X421A load and misalign the flanges until an swr over 10:1 is obtained. Then make a double minimum measurement as described in the 415B manual.
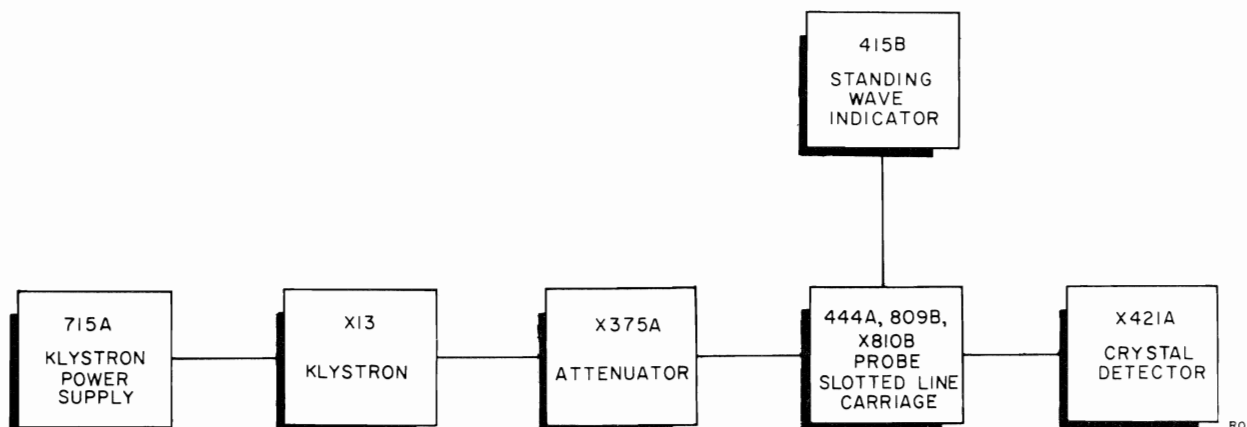
Experiment 4
Power Measurement

OBJECT

To become familiar with the bolometer method of measuring power at microwave frequencies.

INTRODUCTION

At low levels, power in a microwave system is normally measured by means of a bolometer connected into a bridge circuit. DC bias and audio power are supplied to the element to bring it to the correct operating resistance and thus balance the bridge. The unknown rf power absorbed in a resistive bolometer element unbalances the bridge. A known amount of audio power is then removed from the bridge to restore balance.

In this experiment, microwave power is measured by using an ⓗ Model 430C Microwave Power Meter and an external bolometer element inserted into the waveguide system.

PROCEDURE

1) Set up the equipment as shown.

Note: A suitable bolometer element must be inserted into the X487B Thermistor Mount.

2) Review the Operating and Servicing Manual for the ⓗ Model 430C Microwave Power Meter.

3) Energize the klystron and measure power as detected by the bolometer element in the X485B Detector Mount.

4) Repeat the power measurement for other klystron frequencies and for various settings of the X375A Attenuator.

715A	X13	X375A	X487B	430C
KLYSTRON POWER SUPPLY	KLYSTRON	ATTENUATOR	THERMISTER MOUNT	MICROWAVE POWER METER

RO
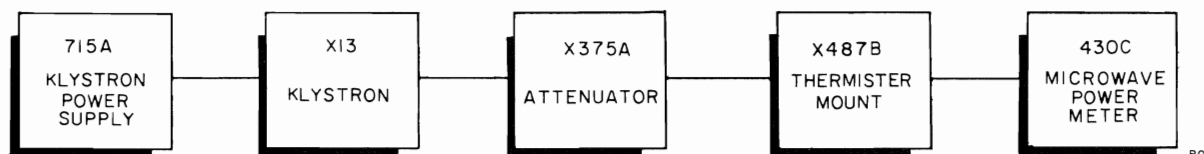
Experiment 5
The Smith Chart

OBJECT

To become familiar with the use of the Smith Chart for determining impedance characteristics from measurements of swr.

INTRODUCTION

The Smith Chart is just as important a tool for determining characteristics of a waveguide system as are the various equipment items used to measure frequency, attenuation and standing wave ratio. In fact, because impedance cannot be measured directly, it is only by using the Smith Chart that measurements of Standing Wave Ratio made with a slotted section can be translated into needed information on impedance without resorting to lengthy and laborious calculations.

Developed in the late 1930's by P. H. Smith, the chart is a special kind of impedance co-ordinate system mechanically arranged so that the relationships of impedances can be determined at any point along a transmission line. Only the swr and the positions of the voltage maximum and voltage minimum need be known to make use of the Smith Chart.

All values of resistance and reactance on a Smith Chart are normalized. Multiplication by the characteristic impedance of the line will convert these normalized values to actual values.

All of the figures in this experiment are illustrations of the Smith Chart.

Circles tangent to the bottom of the chart are circles of constant resistance. The constant resistance circles for normalized resistances of 0, 0.3, 1.0, 3.0 and 10.0 are emphasized in Figure 4-1. Note that the resistance values are given along the center line of the chart.

Curved lines starting from the bottom of the chart and going to the right and left of center are the reactance co-ordinates. The vertical center line represents zero reactance. Curved lines going to the right of center represent positive reactance; lines going to the left represent negative reactance. Note that the normalized reactance values are given along the outer limits of the reactance lines. Positive and negative reactance co-ordinates are emphasized in Figure 4-2 for values of 0.3, 1.0, 3.0, and 10.0.

Any specific value of impedance can be located on the Smith Chart by locating the proper co-ordinate positions. For example, the normalized impedance of a line terminated in its characteristic impedance would be 1.0 + j0. On the Smith Chart this would be at 1.0 on the vertical center line. A normalized impedance of 0.1 + j0.5 is shown at point A in Figure 4-2.

In addition to the resistance and reactance co-ordinates, the Smith Chart has two circular scales. One is calibrated in wavelength; the other in degrees.

The wavelength scale shows that a complete revolution of the chart is equivalent to a half wavelength. The degree scale shows that in a complete revolution of the chart the reflection coefficient goes through a complete cycle of 180° positive and 180° negative. These scales are important because the impedance varies cyclically along a line terminated in other than its characteristic impedance. They are used to determine the impedance at various points along a line after the impedance is determined for any one specific point. The entire variation in impedance on a line is repeated cyclically in each half wavelength along the line.

As an example, consider that point A in Figure 4-2 (0.1 + j0.5) represents the impedance of the load and impedance information is desired for a point one-tenth wavelength away from that load. This can be done by swinging an arc from the center of the chart (1.0 on the center line) through point A in a clockwise direction. Radius of the arc is the distance from the center to point A. A line is then drawn from the center to the point on the outer scale 0.1 wavelength away from point A. The intersection of this line and the arc, point B in Figure 4-2, represents the desired impedance. It can be read from the chart as 0.4 + j1.9.

The arc drawn in this example illustrates another fundamental and important property of the Smith Chart. Any circle drawn around the chart center is a circle of constant swr. The value of the swr is determined by the point at which the circle crosses the center line. SWR can be read directly on the lower half of the line, or reciprocal of swr can be read on the upper half. Extension of the arc in Figure 4-2 shows an swr of about 12:1 on the line.

Another useful feature of the Smith Chart is that admittance can be determined at any point for which the impedance is known. It is only necessary to locate the point on the swr circle 1/4 wavelength away from the impedance position. The normalized admittance can then be read directly from the resistance and reactance co-ordinates.
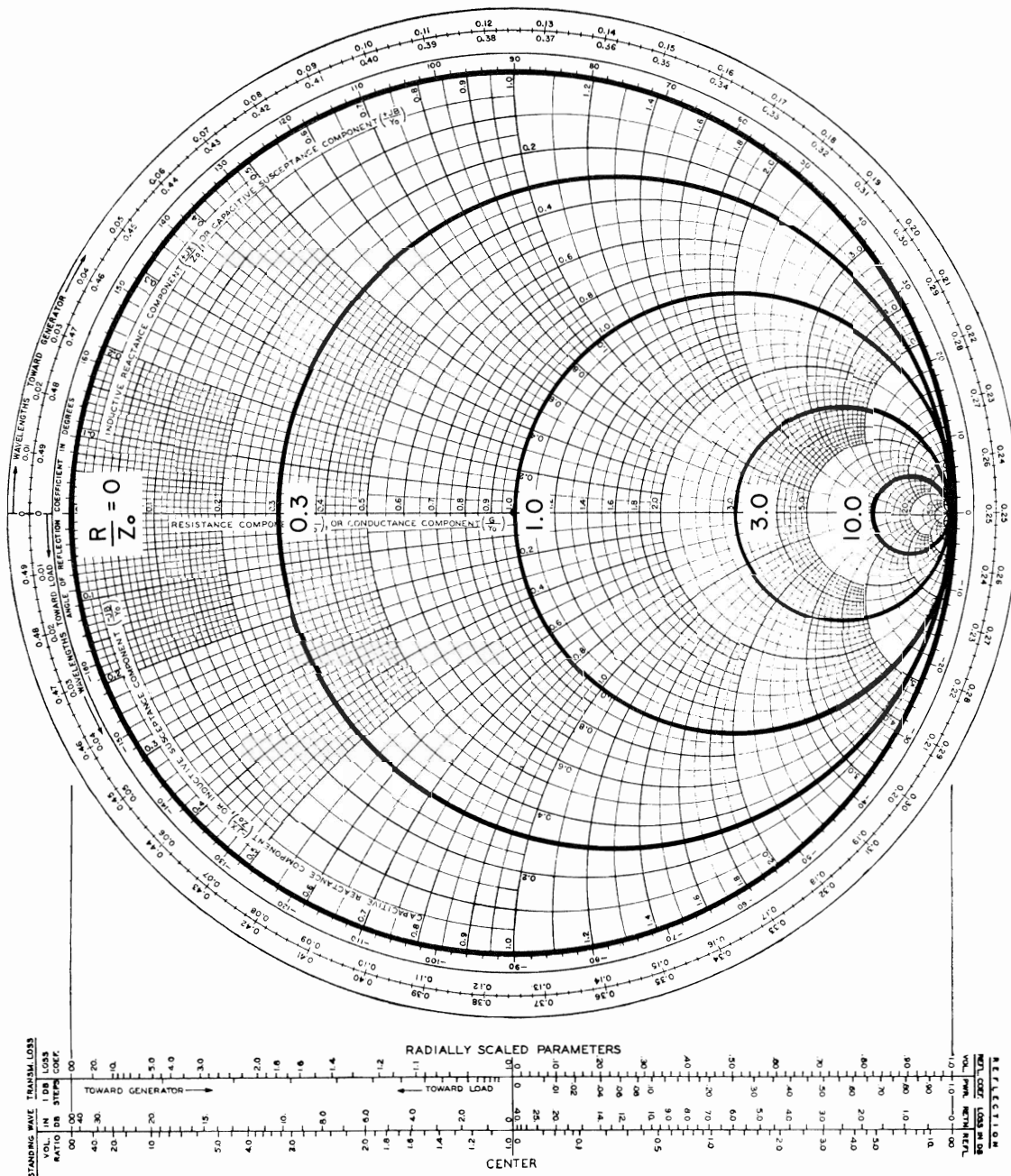
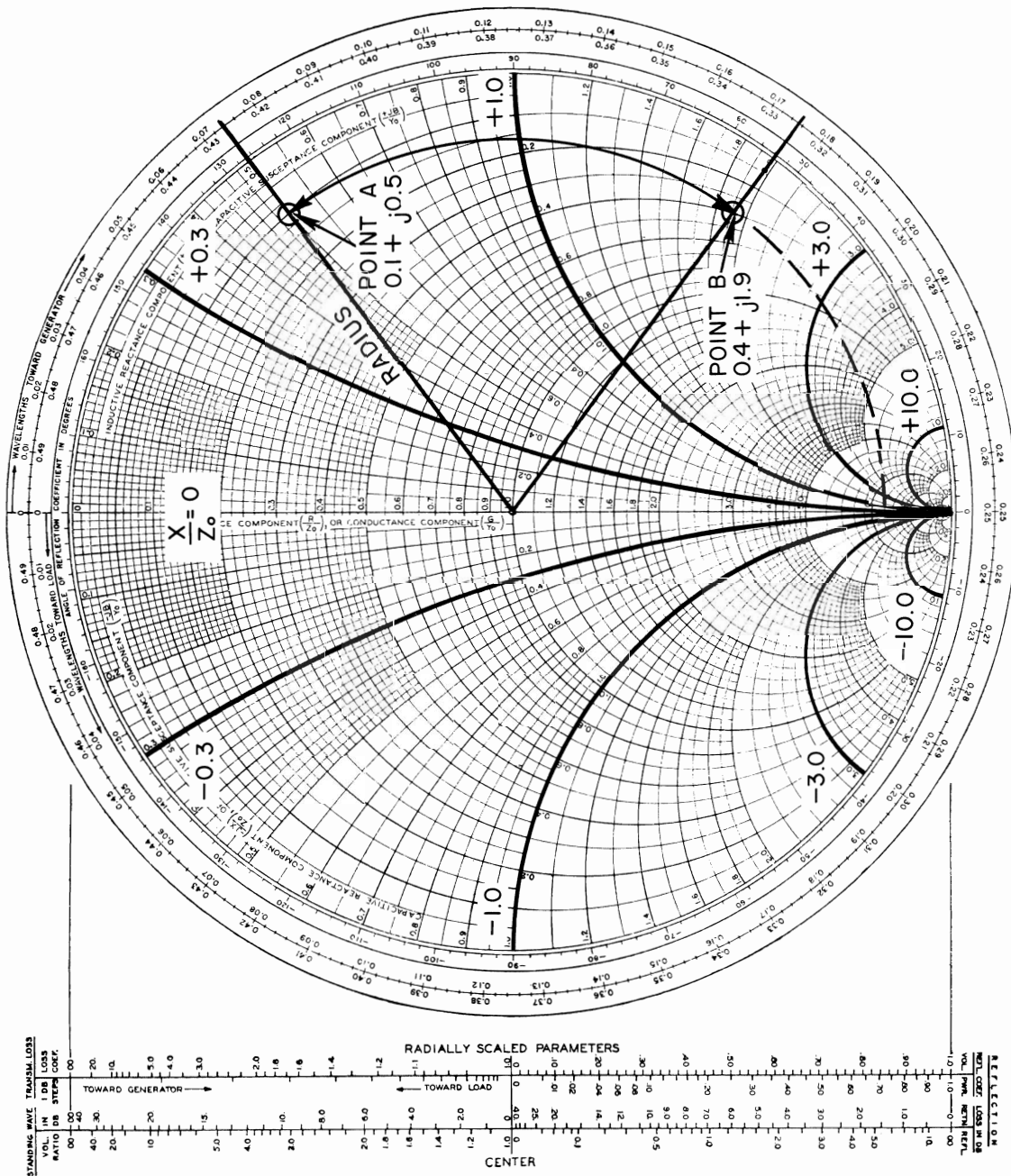Figure 4-1. Circles of Constant Resistance
(Experiment 5)

Figure 4-2. Arcs of Constant Reactance
(Experiement 5)

PROBLEM

Given:
1) The normalized impedance at a point on a lossless transmission line is 0.1 + j0.5.

2) Frequency of the source is 1000 mc.

Find:
1) Impedance of the transmission line 3.8 centimeters toward the source.

2) Admittance at the same point

3) SWR on the line

Solution: (Refer to Figure 4-3)
1) Locate the impedance point 0.1 + j0.5 on the Smith Chart. This is point A in Figure 4-3.

2) Determine the number of wavelengths corresponding to 3.8 cm at 1000 mc. Since wavelength at 1000 mc is 30 cm, 3.8 cm represents .126 wavelengths. (This assumes that the velocity of propagation in the line is equal to that in air. i.e. coaxial line.)

3) Draw lines from the chart center through point A and through a point .126 wavelengths towards the generator from point A.

4) Draw a constant swr circle through point A.

5) Read the desired impedance 0.8 + j2.9 at point B.

6) Read desired admittance .085 + j0.32 at point C.

7) Read the swr where the swr circle crosses the center line. This can be determined most accurately by reading the upper half of the scale and taking the reciprocal to obtain an swr of 13.1.

PROBLEM

Given:
1) A transmission line with a slotted section an undetermined distance from the load.

2) Frequency of the source is 3000 mc.

3) SWR = 3.3

4) Replacing load with short causes voltage minimum point to move 1.0 cm towards the generator.

Find:
1) Impedance of the load

Discussion:
Solution of problems of this type requires measuring the distance between voltage minima, first with the load connected and then with the plane of the load shorted. The sketch below shows the standing waves which exist on a line for the conditions of (1) normal load and (2) a short in place of the load. The voltage minimum point for the shorted condition is moved from the minimum with load by a specific fraction of a wavelength. Since the distance from the load to the voltage minimum is always an integral number of half wavelengths when the load is replaced by a short, the distance between the two minimums is all the information necessary to determine the angular or reactive component of the load impedance.

Solution: (Refer to Figure 4-4)
1) Draw the swr circle (swr = 3.3)

2) Determine the number of fractional wavelengths represented by 1 cm. (Wavelength at 3000 mc is 10 cm assuming coaxial line; hence 1 cm = 0.1 wavelength.)

3) Draw a line from the chart center to the point on the outer scale representing 0.1 wavelength towards the generator.

4) Read the impedance of the load as 0.44 + j.63.

Note: There are a number of rules which are helpful in interpreting slotted line measurements and in using the measured data in Smith Chart plots. The rules are stated below and summarized in Figure 4-5.

1) The shift in the minimum after the load has been shorted is never more than $\pm \frac{\lambda}{4}$.

2) If shorting the load causes the minimum to move toward the load a capacitive component exists in the load.

STANDING WAVE PATTERN
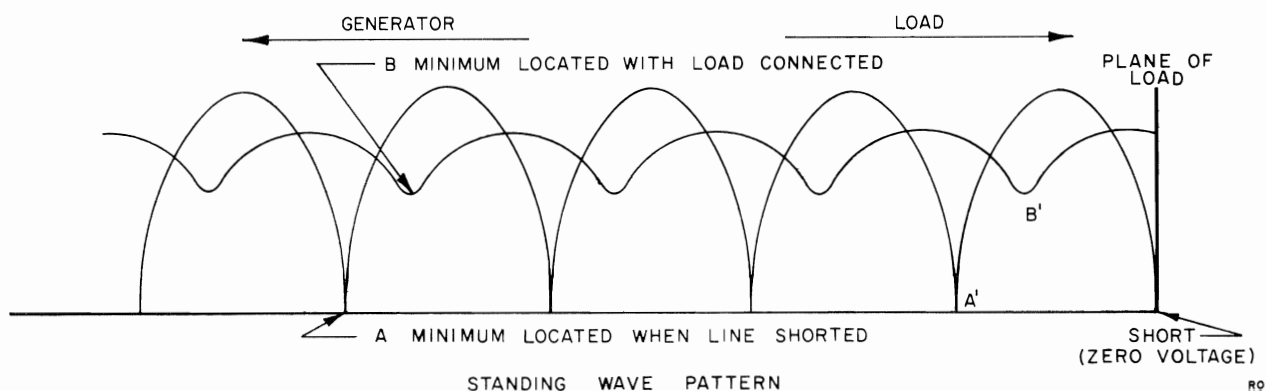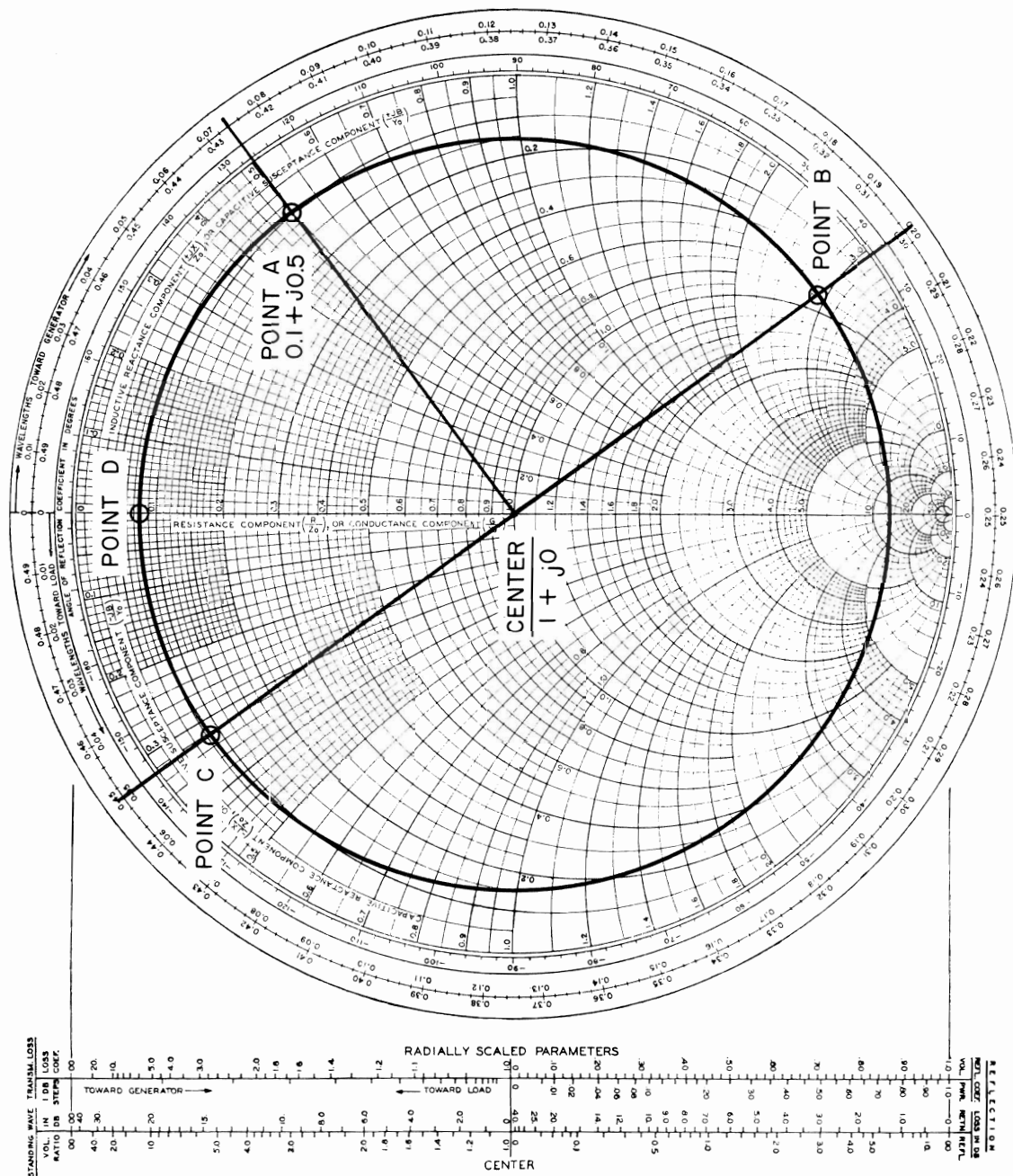
Figure 4-3.   Problem I
(Experiment 5)
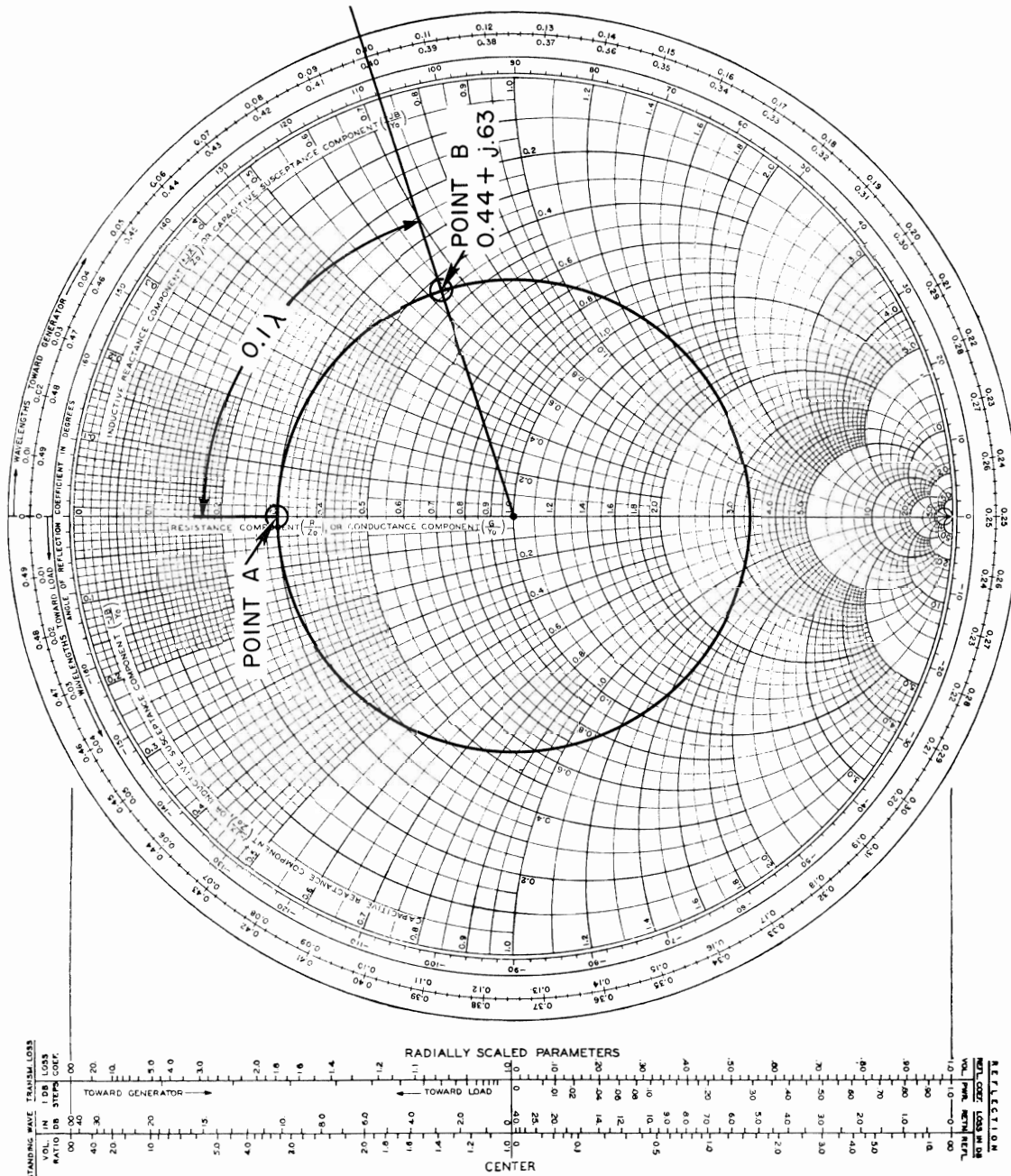
Figure 4-4.   Problem II
(Experiment 5)

3) If shorting the load causes the minimum to shift toward the generator an inductive component exists in the load.

4) If shorting the load causes no shift in the minimum a completely resistive load exists equal to Z_o/SWR.

5) If shorting the load causes the minimum to shift exactly $\dfrac{\lambda}{4}$ the load is completely resistive and has a value of (Z_o) (SWR).

6) When the load is shorted the minimum will always be a multiple of $\dfrac{\lambda}{2}$ from the load.

QUESTIONS

1) When measuring swr in waveguide slotted sections, the guide wavelength does not equal that in free space.

How do you measure guide wavelength for use on the Smith Chart?

2) Find the impedance of a load $(0.5 + j0.2)$ at a point 0.65λ towards the generator if the line has 1 db of attenuation between the load and the point desired. (Hint: find swr as for lossless line, then change radius of swr circle according to transfer loss scale at bottom of chart--see Figure 4-6. The answer is $1.4 + j0.6$.)

ADDITIONAL MATERIAL

An interesting application of the Smith Chart is illustrated in the Hewlett-Packard Journal, Volume 1, No. 9, May, 1950. Operation of a double-stub tuner is explained by means of a Smith Chart.
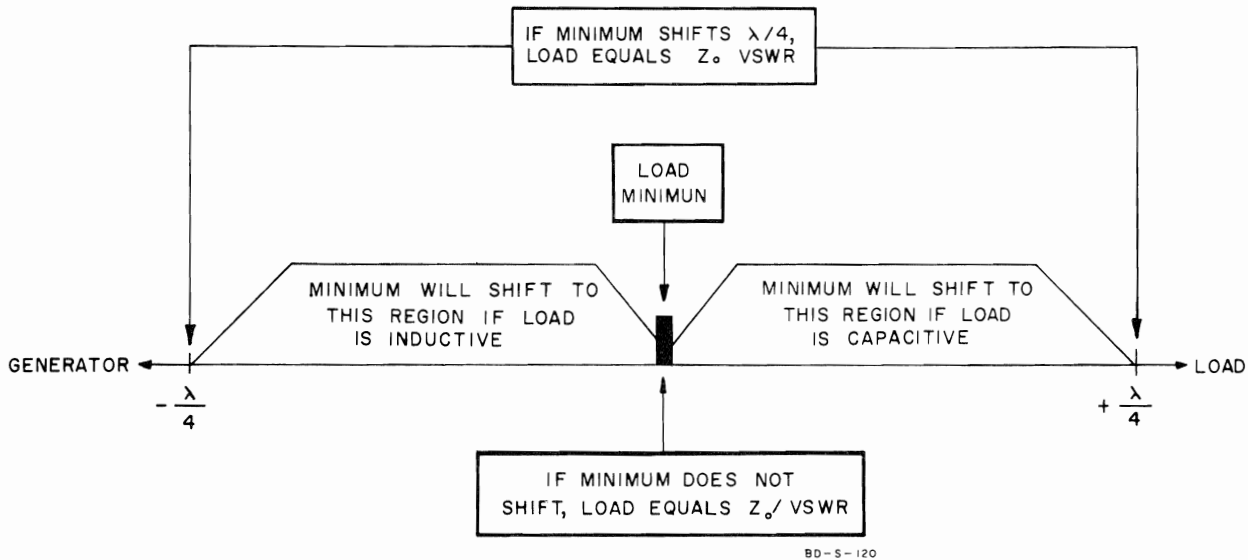
Figure 4-5. Summary of Rules for Impedance Measurement
(Experiment 5)
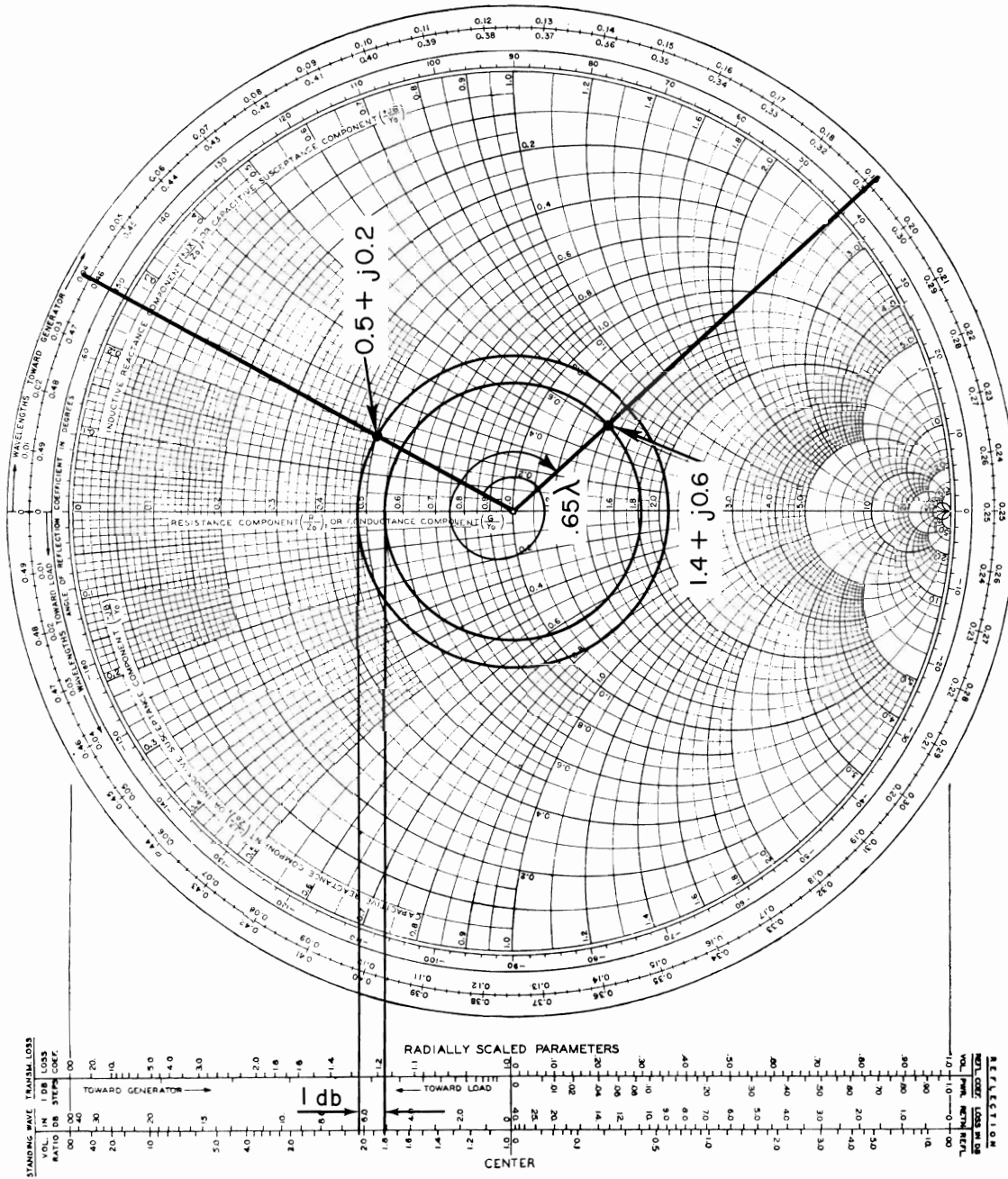
Figure 4-6. Question 2
(Experiment 5)

RADIALLY SCALED PARAMETERS

RADIALLY SCALED PARAMETERS

CENTER
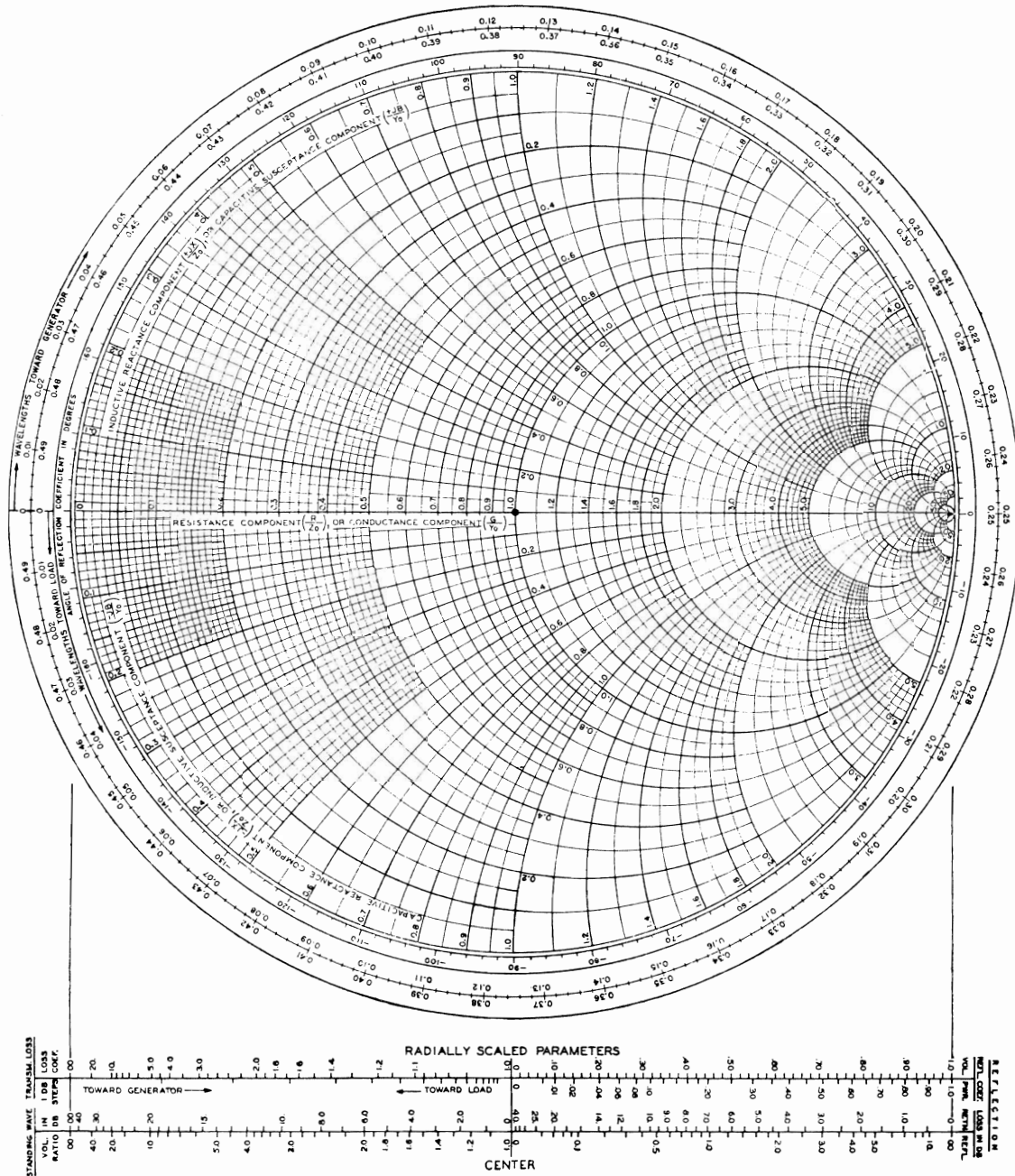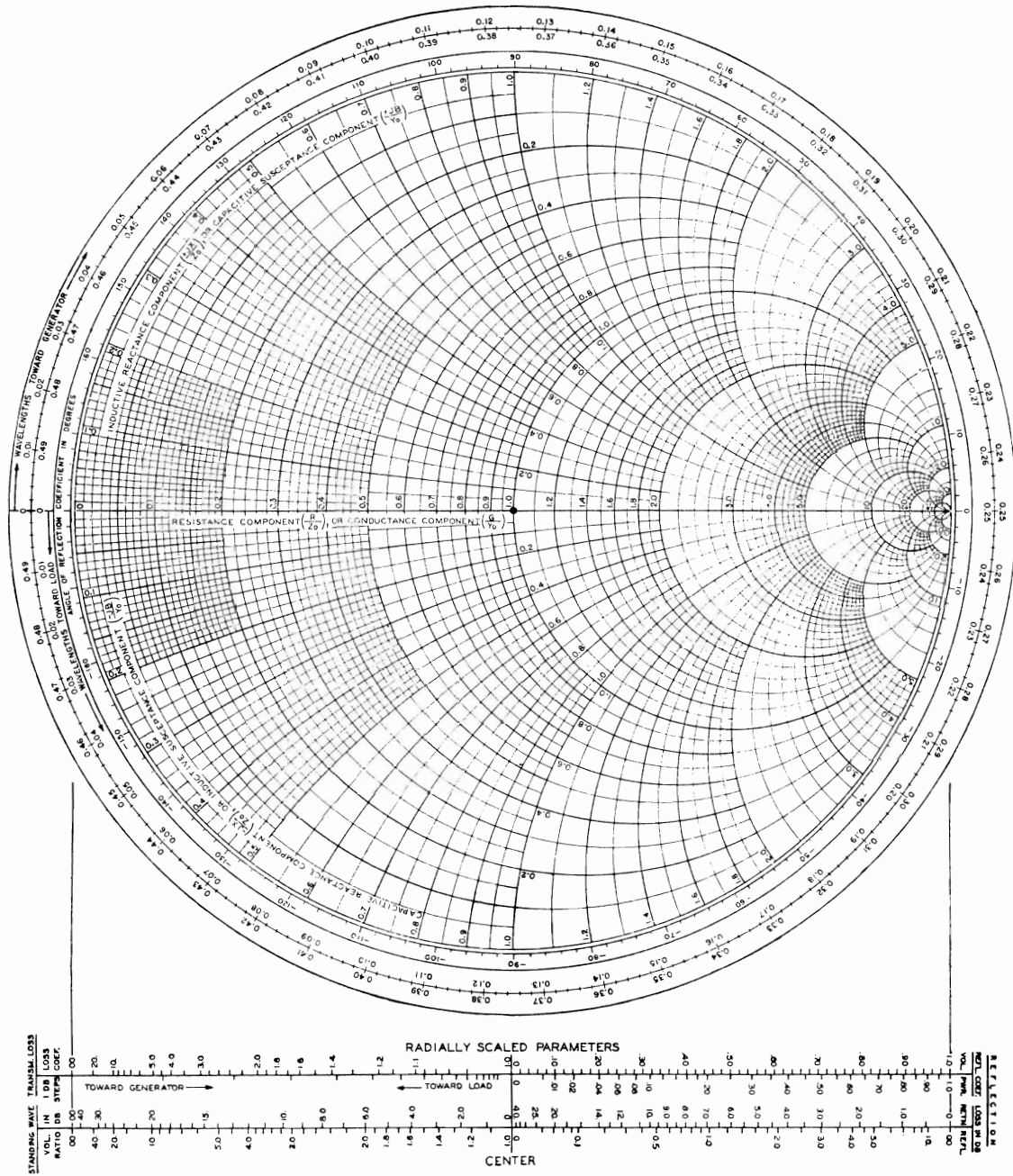
Experiment 6
Impedance Measurement,
Application of the Smith Chart

OBJECT

To gain additional experience in using the Smith Chart and in determining impedance through measurements of Standing Wave Ratio.

INTRODUCTION

An important characteristic of any microwave apparatus is the manner in which impedance varies with frequency. Since many transmission systems must carry a broad band of frequencies, variation of impedance with frequency could cause undesirable reflections and fluctuations in transmitted power.

In this experiment the basic method of swr measurement introduced in experiment 2 is used to provide information from which the impedance over a broad frequency band can be plotted on a Smith Chart.

A tunable signal generator such as the ⓗⓟ Model 620 is the most convenient means of providing source frequencies where variation of impedance or other parameters as a function of frequency is being studied. However, the necessary frequencies can be obtained from a bench klystron and wavemeter in the same manner as was done in experiment 1.

PROCEDURE

1) Set up the equipment as shown.

2) For each source frequency, record the data in - cated in the table below.

F_0	Short Circuit* Data		Load Data		ΔL	$\Delta L / \lambda$
	L_s	λ	L_t	SWR		
8.5 kmc	___	___	___	___	___	___
9.0 kmc	___	___	___	___	___	___
9.5 kmc	___	___	___	___	___	___
10.0 kmc	___	___	___	___	___	___
10.5 kmc	___	___	___	___	___	___
11.0 kmc	___	___	___	___	___	___
11.5 kmc	___	___	___	___	___	___
12.0 kmc	___	___	___	___	___	___

---

* Short circuits may be obtained by using a brass plate to short the end of the guide. Open circuits, while reflecting some power, are not as reliable or repeatable because of fringing fields and should not be used.
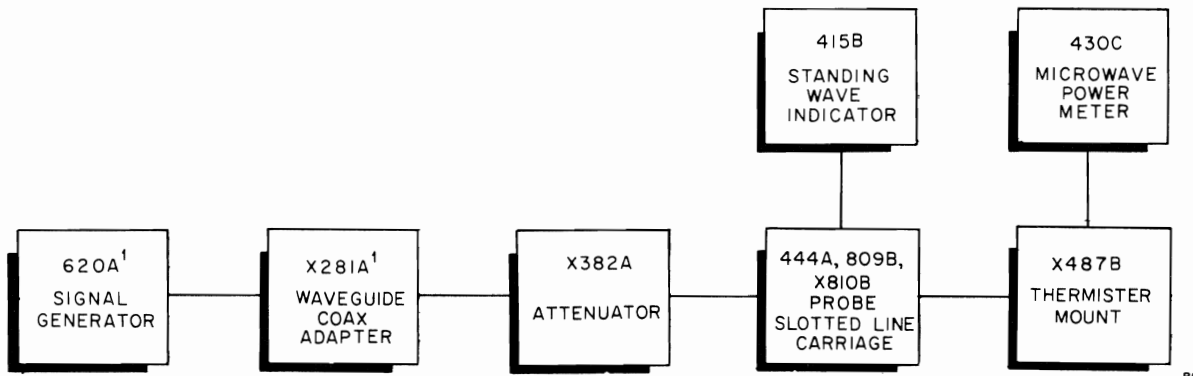
[1] Klystron/wavemeter arrangement as used in Experiment 1 can be substituted for the signal generator to provide a microwave source.

Where F_o = Oscillator Frequency

L_s = Position in cm indicated on the slotted section for the shorted condition voltage minimum

λ = Twice the length in centimeters between adjacent voltage minima for the shorted condition. This is the guide wavelength.

L_t = Position in cm indicated on the slotted section for the loaded condition voltage minimum (for convenience, the probe should be moved towards the generator from the L_s position)

SWR = Standing Wave Ratio for the loaded condition as read directly with the 415B Standing Wave Indicator

ΔL = $L_s - L_t$, the shift in cm in the voltage minimum between the loaded and shorted conditions

$\Delta L/\lambda$ = Fractional guide wavelengths voltage minimum shifts when the load is replaced by a short

3) Locate the complex impedance point on the Smith Chart for each frequency. (Refer to experiment 5 for detailed procedure.) See if the X487B meets its swr specification of 1.5:1 from 8.2 - 12.4 kmc. (Hint: Draw 1.5:1 swr circle)

4) Repeat measurements at all frequencies with no bias current in X487B to see how badly the mount is mismatched when the thermistor element is not biased to 100 ohms.

RADIALLY SCALED PARAMETERS

CENTER

RADIALLY SCALED PARAMETERS
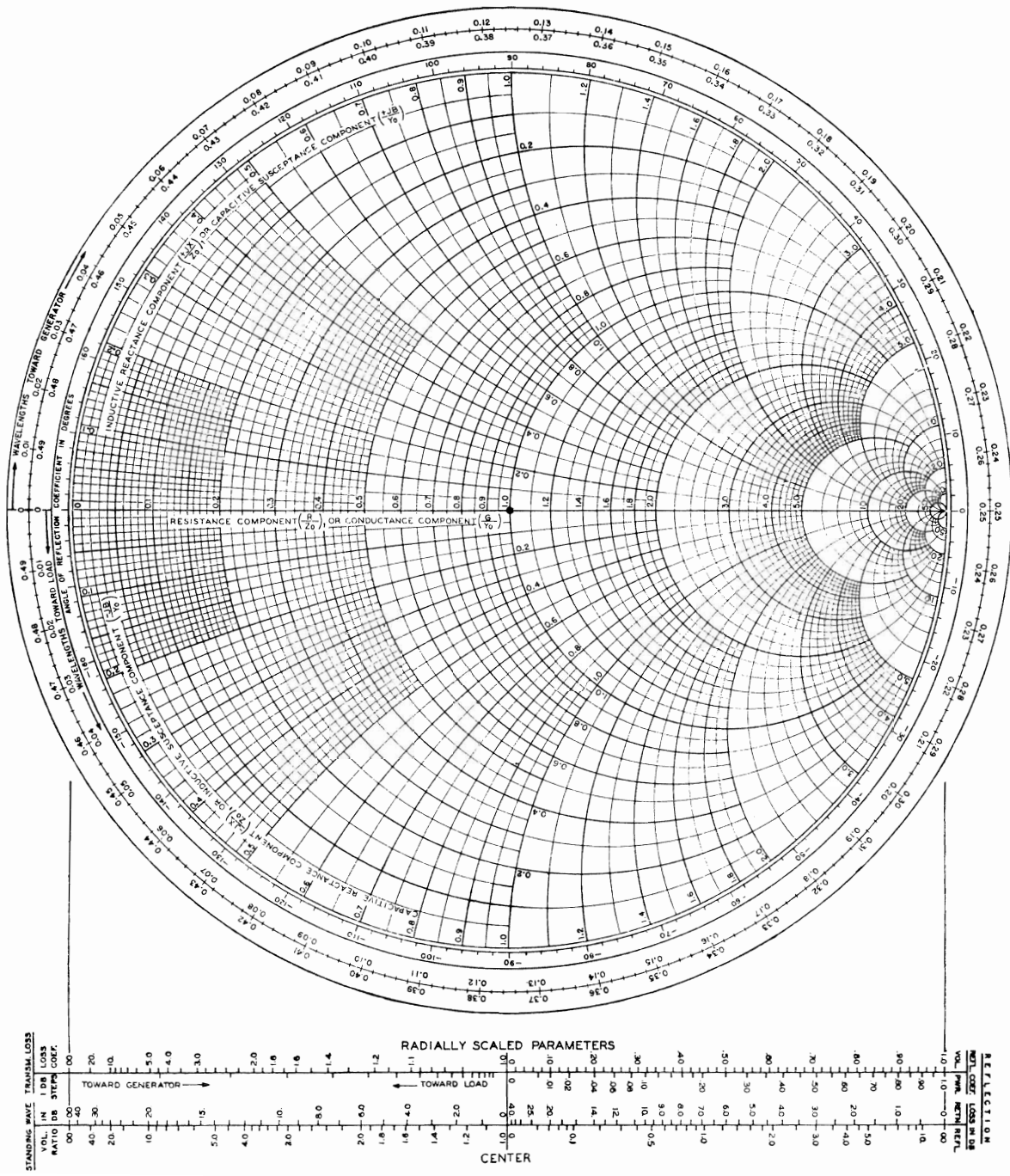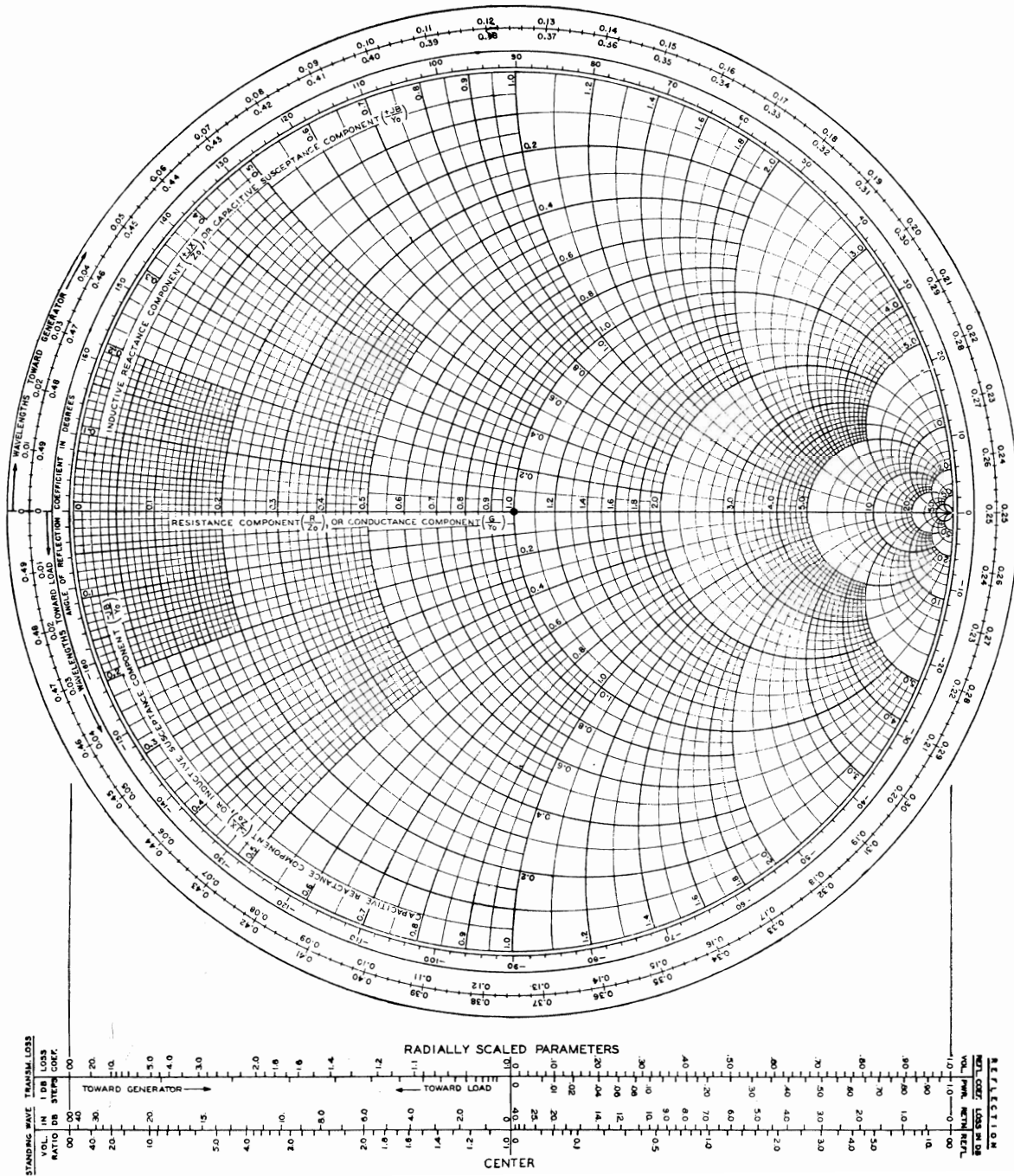
Experiment 7
Bolometer Mounts for
Microwave Power Measurements

OBJECT

To compare two basic types of bolometer mounts and their applications in the detection and measurement of microwave power.

INTRODUCTION

Power measurements are usually considered more basic than voltage or current measurements at microwave frequencies because power does not vary with the position of measurement along a distributed type transmission line as voltage and current do. By power measurement we mean the determination of the absolute power in the system. This type of measurement should be differentiated from the detection of microwave power where the relative power is of interest or where the characteristics of the modulation envelope are desired.

The measurement of rf power at high frequencies is accomplished by means of a device called a bolometer. "Bolometer" is a very general term that is applied to several different devices whose resistance changes with application of power (temperature). The bolometer is mounted in a suitable holder so that the bolometer and mount are well matched to the rf system. The rf energy that is applied to the bolometer causes it to heat and in turn the heat causes the dc resistance of the bolometer to change.

BOLOMETER TYPES

The two general classifications of bolometers are:

1) Conductors -
   (Positive Temperature Coefficient)

Conductors are exemplified by the barretter which consists of a very fine platinum wire mounted in a holder so that resistance changes can be readily measured. The most common type of barretter is constructed of Wollaston wire which consists of a platinum core plated with silver and soldered in place. The silver is then etched away, leaving the platinum core of about 50×10^{-6} inches in diameter.

Fuses, of the type used to protect sensitive meters, are also useful as positive temperature coefficient bolometers and feature lower replacement cost.

2) Semiconductors -
   (Negative Temperature Coefficient)

The most popular semiconductor type bolometer is the thermistor. The thermistor is constructed in the form of a small bead of semiconducting material suspended between two fine lead-in wires. The tiny bead, about .04 cm in diameter, is composed of a mixture of oxides of manganese, cobalt, nickel and copper. The bead is coated with a film of glass to prevent oxidation and improve stability. It may be mounted directly in waveguide or encapsuled to provide physical protection.

COMPARISON OF BOLOMETERS

1) CW Power Measurement

While thermistors and barretters can be made to operate over the same range of power, they both have certain specific attributes which make them more useful in some applications. Both of them can be made in very small sizes and can be easily mounted in waveguide transmission systems. The thermistor is basically more sensitive than the barretter, making it more desirable in some low power applications. Simultaneously, however, it is much more sensitive to changes in ambient temperature than the barretter and requires very special mount design to achieve its maximum sensitivity.

Thermistors are less delicate than barretters and may be mounted directly in waveguide. They also have the protective property of changing their resistance with power. Thus, high rf powers drastically lower the resistance and thus reflect much of the power back down the line. Barretters, on the other hand, are operated near their maximum dissipation point and are very susceptible to burnout. Barretters can be made with remarkable uniformity with regard to their rf and dc characteristics. A defective unit can be replaced by a new one without readjusting any of the rf matching sections.

2) Modulated Power Measurements

Pulsed power as well as cw power can be measured with bolometers. Since bolometers have time constants in the order of 100 μsec or longer, the measurement of the usual pulse train provides an automatic averaging process. The measurement of pulsed power by means of bolometers also introduces some special considerations which can lead to considerable error. These errors can arise because the bolometer resistance during the measurement is not constant. The evaluation of these errors can become quite complicated and are most serious with barretters which have a relatively short time constant. Since thermistors have longer time constants than barretters, they are more suitable for application in pulse measurements.

POWER DETECTION

The most common detector in use is the silicon or germanium crystal although some bolometers can be used. It should be noted here that the output of the crystal will be current whereas the bolometer output will be a resistance change.

The crystal acts as a current generator with a certain dynamic impedance. When the rf signal is applied to the crystal (a non-linear device), the rectified current is proportional to the square of the applied voltage. Because of this, these low level detectors are often called square-law detectors. (Current out proportional to power in.) This detection law exists for input powers less than 1/10 mw. The barretter can also be used as a detector or demodulator. The barretter is supplied with dc bias power and mounted in a suitable holder so that a good match is presented to the rf system. The rf signal will cause the resistance of the barretter to change in accordance with the modulation envelope. Since the current remains constant, output voltage changes occur across the barretter. The signal is then amplified by a sensitive audio amplifier. When used in this manner, the barretter exhibits square-law response provided rf power is sufficiently small compared to dc bias power. The time constant of the barretter must be small compared with the period of the modulation envelope. The sensitivity of the barretter amplifier combination is appreciably lower than the crystal rectifier (about twenty times less sensitive than the crystal). The barretter, however, has the important advantages of stability, precisely known response law, relative ruggedness compared to some crystals, comparable dynamic range and superior stability.

In this experiment power is measured with two types of ⓗ Waveguide Bolometer Mounts. The Model X485B is a tunable barretter mount which can also accommodate a 1N21 crystal. Maximum swr is 1.25 in the usable band. Characteristics of the X485B are compared with those of the Model X487B broadband, fixed tuned thermistor mount which has a maximum swr of 1.5:1.

PROCEDURE

1) Set up the instruments as shown.

2) With the X485B in position operate the source at 10 kmc. Tune the X485B for maximum output. Adjust the attenuator to provide an output power of 1 mw. Record the swr.

Caution: Be sure X382A has at least 20 db set in to start to assure that rf power in the X485B always stays below 10 mw. Burnout rating on Sperry 821 Barretter is about 20 mw rf.

3) Replace the X485B with the X487B and repeat step 2.

4) Insert the X870A before the 487B and tune it for maximum power. Record swr and Power Output.

Mount	SWR	Power Output
X485B		
X487B		
X487B and X870A		

5) Note the change in power output from step 3 to step 4. Explain.

6) By measuring swr of the X487B at three different power levels 10 mw, 1 mw and 0.1 mw, assure yourself that the 430C power bridge maintains the thermistor element at 100 ohms regardless of the rf power input.

7) Adjust power into thermistor mount (X487B) for 10 mw. Cut out an additional 6 db attenuation in the X382A to provide 40 mw into the thermistor mount. Now measure swr of X487B to see that power is being reflected back down the line and protecting the thermistor. From swr, calculate what percentage power is being reflected.

QUESTIONS

1) Where does additional power of step 4 come from?

2) Could additional power be read on the X485B if the X870A were used to provide another degree of tuning freedom?
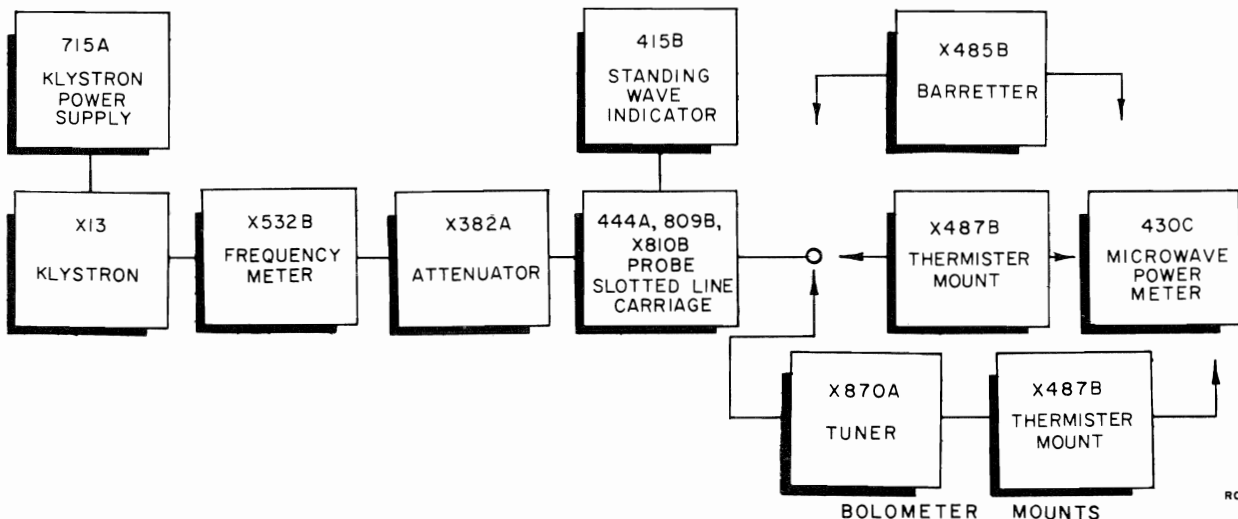
BOLOMETER   MOUNTS

Experiment 8
Power Bridges for Microwave
Power Measurements

OBJECT

To study the operation, use, accuracy and limitations of the ⏦ 430C Microwave Power Meter.

INTRODUCTION

RF power is ordinarily measured by means of a bolometer mounted in a suitable holder. The rf power causes the dc resistance of the bolometer to change and the input rf power can be determined from this change.

In the simplest case, a circuit to translate microwave power to a meter reading can look like this:
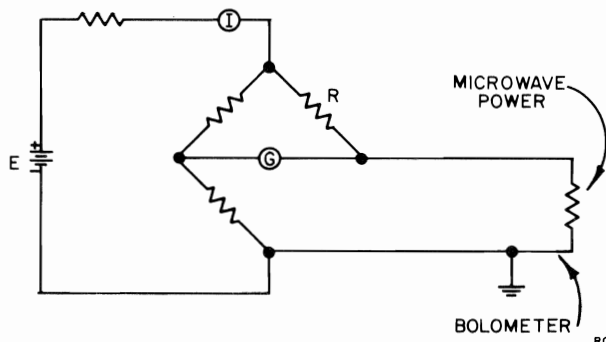
With this simple Wheatstone bridge, sufficient power is supplied by the battery so that the resistance of the bolometer is made equal to its normal operating resistance. The remaining bridge resistors are chosen so that the bridge balances in this condition. When microwave power is supplied to the bridge, the bolometer heats, its resistance changes and the bridge becomes unbalanced. The balance is restored by decreasing the battery power and this decrease is taken as a measure of the rf power.

To eliminate the somewhat tedious adjustments and measurements needed to determine the rf power with a simple bridge circuit, specially designed bridges such as the ⏦ Model 430C are used.

In the 430C, the bolometer element is brought to its predetermined operating resistance (100 or 200 ohms) in the absence of rf power by the application of both dc and audio frequency power. The circuit is so arranged that audio power is automatically removed as
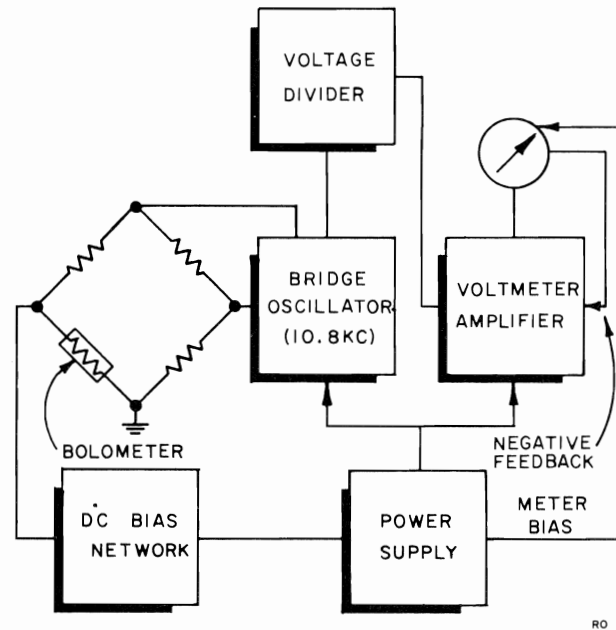
430C Block Diagram

rf power is applied. The amount of power removed is displayed as a meter reading, calibrated to show a decrease in audio power as an increase in rf power. The bolometer bridge is brought to balance with no rf power applied to the bolometer by supplying both dc bias power and af power (at approximately 10.8 kc) from an rc oscillator. Assume 16 mw are needed to bring a bolometer to its operating resistance. If 10 mw were supplied by the dc bias, 6 mw would be automatically supplied by the af source. There are many combinations of dc and af that might be used but certain requirements are imposed since the af power is monitored by built-in VTVM circuits. The VTVM (which incorporates a substantial amount of negative feedback to minimize the effect of non-linear crystal resistance in the meter circuit) is arranged to zero on a specific level of audio power.

For example, on the 10 mw range, the meter zeros on 12 mw of audio power. For a 16 mw bolometer this means that 4 mw of dc power must come from the bias supply. For this range (10 mw), the meter reads full scale (+10 mw rf) with 2 mw of audio power. Remember, when rf power is applied, the bridge automatically subtracts af power. On the

lower power ranges the amount of audio power required to cover the range (zero to full scale) decreases so that the dc requirements increase. For example, on the most sensitive .1 mw range, .12 mw audio and 15.88 mw dc are required for the 16 mw bolometer.

The everyday use of the 430C is rather straightforward. Set zero, apply power, read. Some of the error-producing effects of modulated power are explained in this experiment.

PROCEDURE

1) Set up the instruments as shown.

2) Set the 620A to 10 kmc, pulse modulated, maximum width, 1000 cps repetition rate. With the X485B in place, set the power output to approximately .8 mw.

3) Reduce the pulse rate slowly and watch the 430C reading for a beat note. Also observe the 430C oscillator voltage on the scope, if one is used.

Record several beat frequencies _____

Record deviation in % of full scale _____

Repeat the same procedure for the thermistor mount, X487B. Any difference? Why?

When measuring pulse modulated power, avoid repetition rates which are sub-multiples of the bridge oscillator, 10.8 kc. This effect is especially noticeable on the low ranges when using a barretter since the barretter will respond quickly to the modulation envelope.

4) Square wave modulate the 620A at a 1000 cps rate. Set a maximum power level on the 430C and slowly reduce the rate. Record the frequency where the reading increases.

(X485B)_____cps   (X487B)_____cps

At low modulation frequencies, the bolometer attempts to follow the modulation envelope. The modulation frequency becomes impressed upon the oscillator frequency and the average responding meter will indicate the average of the troughs and peaks of the modulation envelope. The fast response of the barretter makes it quite susceptible to this effect.

The maximum error occurs when a barretter is used on the 10 mw range of the instrument at repetition frequencies below 200 to 300 cps. On other ranges or when using a thermistor, the critical frequency is below 100 cps.

Above these critical frequencies the readings are accurate for either sine wave pulse or square wave operation. Remember: be especially careful when using barretters for modulated power measurements.
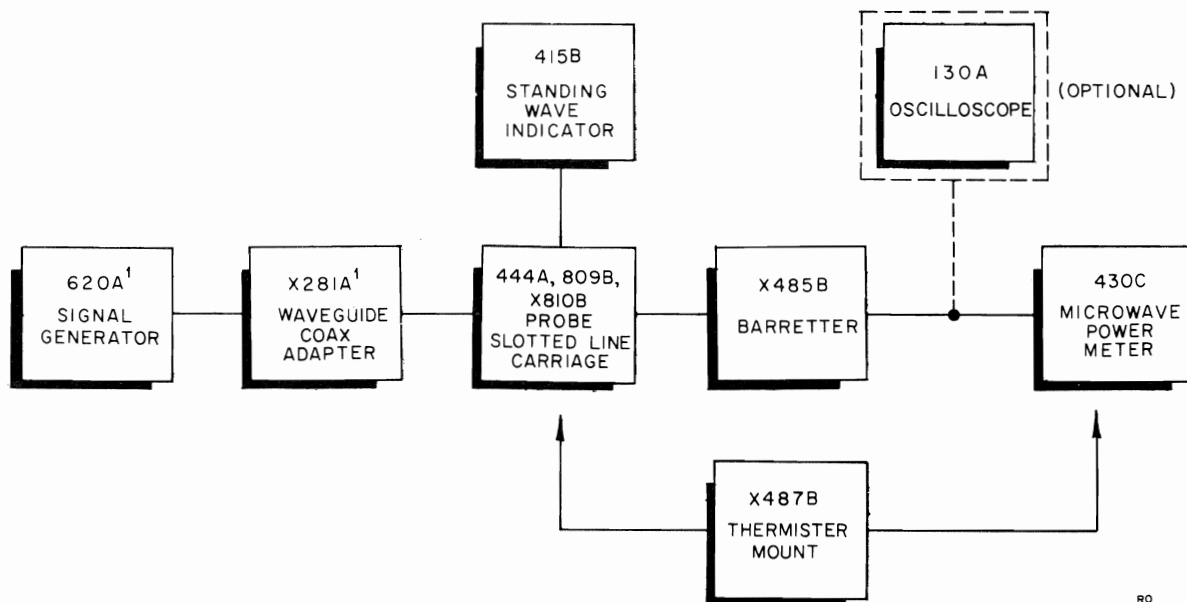
APPENDIX I
GLOSSARY OF MICROWAVE TERMS

Attenuation:
Decrease in magnitude of current, voltage or power of a signal in transmission between points.

Attenuation Constant:
For a traveling plane wave of a given frequency, the rate of exponential decrease of the amplitude of a field component (or of the voltage or current) in the direction of propagation. Expressed in Nepers or decibels per unit length.

Attenuator, Flap:
A device designed to introduce attenuation into a waveguide circuit by means of a resistive material moved into the guide.

Attenuator, Rotary Vane:
A device designed to introduce attenuation into a waveguide circuit by means of varying the angular position of a resistive material in the guide.

Barretter:
A metallic resistor with a positive temperature co-efficient of resistivity used for detection and level measurements.

Bend, E Plane:
A bend in a waveguide in the plane of the electronic field.

Bend, H Plane:
A bend in a waveguide in the plane of the magnetic field.

Bolometer:
A barretter, thermistor or any other device utilizing the temperature coefficient of resistivity of some resistance element.

Choke Joint:
A type of joint for connecting two sections of wave-guide. It is so arranged that there is efficient ener-gy transfer without the necessity of an electrical contact at the insides of the guide.

Coaxial Line:
A transmission line in which one conductor com-pletely surrounds the other, the two being coaxial and separated by a continuous solid dielectric or dielectric spacers. Such a line is characterized by no external field and by having no susceptibility to external fields from other sources.

Coupler, forward:
A directional coupler used to sample incident power.

Coupler, reverse:
A directional coupler used to sample reflected power.

Coupling Coefficient:
A ratio between power entering the main arm of a directional coupler in one direction to the power coupled into the auxiliary arm in the same direction.

Cutoff Frequency:
The lowest frequency at which lossless waveguide will propagate energy in some particular mode without at-tenuation.

Cutoff Wavelength:
The ratio of the velocity of electromagnetic waves in free space to the cutoff frequency.

Demodulator, Square Law:
A device whose output voltage is proportional to the square of its input voltage.

Directional Coupler:
A device consisting of two transmission lines coupled together in such a way that a wave traveling in one line in one direction excites a wave in the other guide, ideally, in one direction only.

Directivity:
The ratio of the power flowing in the forward direction in the auxiliary arm of a directional coupler, to the power flowing in the reverse direction when power is flowing only in the forward direction in the main arm.

Directivity Signal:
A spurious signal present in the output of a coupler because the directivity of the coupler is not infinite.

Efficiency, Bolometer Mount:
The percentage of net applied power that is absorbed by the rf termination.

E-H Tee:
A junction composed of a combination of E and H plane tee junctions having a common point of inter-section with the main guide.

E-H Tuner:
An E-H tee used for impedance transformation, having two arms terminated in adjustable plungers.

Impedance, Characteristic
  (of a rectangular waveguide):
For the dominant TE_{10} mode of a lossless rectangular waveguide at a frequency above the cut-off frequency, the ratio of the square of the rms voltage between midpoints of the two conductor faces normal to the electric vector, and the total power flowing when the guide is match terminated.

Impedance, Characteristic
  (of a two-conductor transmission line):
For a traveling, transverse electromagnetic wave, the ratio of the complex voltage between the conductors to the complex current on the conductors.

Impedance, Normalized:
Any impedance of a system divided by the characteristic impedance of that system.

Incident Power or Signal:
Power flowing from the generator to the load.

Iris:
In a waveguide, a conducting plate or plates, of thickness small compared to a wavelength, occupying a part of the cross section of the waveguide. When only a single mode can be supported, an iris acts substantially as a shunt admittance.

Isolator Ferrite:
A microwave device which allows rf energy to pass through in one direction with very little loss while rf power in the reverse direction is abosrbed.

Junction, Hybrid:
A waveguide arrangement with four branches which, when branches are properly terminated, has the property that energy can be transferred from any one branch into only two of the remaining three. In common usage this energy is equally divided between the two branches.

MASER (Microwave Amplification by Stimulated
  Emission of Radiation):
A low noise, microwave amplifier utilizing a change in energy level of a material to obtain signal amplification. Common materials are gases (ammonia) and crystals (ruby).

Loss Return:
The ratio, expressed in db, between the power incident upon a discontinuity and the power reflected from the discontinuity. (The number of db reflected power is down from incident power.)

Loss, Mismatch (reflection loss):
The ratio, expressed in db, of the incident power to the difference between the incident power and the reflected power. A measure of the loss caused by reflection.

Matched Termination (Waveguide):
A termination producing no reflected wave at any transverse section of the waveguide.

Microstrip:
A microwave transmission component utilizing a single conductor supported above a ground plane.

Microwave Region:
That portion of the electromagnetic spectrum lying between the far infra-red and conventional radio frequency portion. Commonly regarded as extending from 1000 megacycles (30 cm) to 300,000 megacycles (1mm).

Mode (of transmission propagation):
A form of propagation of guided waves that is characterized by a particular field pattern in a plane transverse to the direction of propagation. The field pattern is independent of the position along the axis of the waveguide and for uniconductor waveguide, independent of frequency.

Parametric Amplifier (MAVAR - Mixer Amplification by Variable Reactance):
A microwave amplifier utilizing the non-linearity of a reactance element to obtain amplification.

Propagation Constant:
A transmission characteristic of a line which indicates the effect of the line on the wave being transmitted along the line. It is complex quantity having a real term, the attenuation constant and an imaginary term, the phase constant.

Rat Race (Hybrid Ring):
A hybrid junction which consists of a re-entrant line (waveguide) of proper electrical length to sustain standing waves, to which four side arms are connected. Commonly used as an equal power divider.

Reflected Power or Signal:
Power flowing from the load back to the generator.

Reflection Coefficient (ρ):
A numerical ratio between the reflected voltage and the incident voltage.

Reflectometer:
A microwave system so arranged to measure the incidental and reflected voltages and indicate their ratio.

Resonator Cavity:
A closed section of coaxial line or waveguide, completely enclosed by conducting walls.

Reike Diagram:
A polar-coordinate load diagram for microwave oscillators, particularly klystrons and magnetrons.

Rotator:
In waveguides, a means of rotating the plane of polarization. Done simply in rectangular waveguide by twisting the guide itself.

Slotted Section:
A length of waveguide in the wall of which is cut a non-radiating slot used for standing wave measurements.

Smith Diagram:
A diagram with polar co-ordinates, developed to aid in the solution of transmission line and waveguide problems.

Thermistor:
A resistance element made of a semiconducting material which exhibits a high negative temperature coefficient of resistivity.

Tube, Backward Wave:
A traveling wave tube in which the electrons travel in a direction opposite to that in which the wave is propagated. A microwave oscillator.

Tube, Traveling Wave:
A broadband, microwave tube which depends for its characteristics upon the interaction between the field of a wave propagated along a waveguide and beam of electrons traveling with the wave.

Tuning Screw (slide screw tuner):
A screw or probe inserted into the top or bottom of a waveguide (parallel to the E field) to develop susceptance, the magnitude and sign of which is controlled by the depth of penetration of the screw.

UHF:
Ultra-high frequency, the band of frequencies between 300 and 3000 mc.

VHF:
Very high frequency, the band of frequencies between 30 and 300 mc.

Voltage Standing Wave Ratio (SWR):
The measured ratio of the field strength at a voltage minimum to that at an adjacent maximum.

Wave Circuits, Slow:
A microwave circuit designed to have a phase velocity considerably below the speed of light. The general application for such waves is in traveling wave tubes.

Wave, Dominant:
The guided wave having the lowest cutoff frequency. It is the only wave which will carry energy when the exitation is between the lowest cutoff frequency and the next higher frequency of a waveguide.

Waveguide Phase Shifter:
A device for adjusting the phase of a particular field component at the output of the device relative to the phase of that field component at the input.

Waveguide Tee:
A junction used for the purpose of connecting a branch section of waveguide in series or parallel with the main transmission line.

Waveguide Tuner:
An adjustable device added to a waveguide for the purpose of an impedance transformation.

Waveguide Wavelength:
For a traveling plane wave at a given frequency, the distance along the waveguide between points at which a field component (or the voltage or current) differs in phase by 2π radians.

Wave, Phase Velocity:
The velocity with which a point of constant phase is propagated in a progressive sinusoidal wave.

Wave, Group Velocity:
The velocity with which the envelope of a group of waves of neighboring frequencies travels in a medium; usually identified with the velocity of energy propagation.

Wave, Transverse Electric (TE Wave):
In a homogeneous isotropic medium, an electromagnetic wave in which the electric field vectors are everywhere perpendicular to the direction of propagation.

Wave, Transverse Electromagnetic (TEM Wave):
In a homogeneous isotropic medium, an electromagnetic wave in which both the electric and magnetic field vectors are everywhere perpendicular to the direction of propagation.

Wave, Transverse Magnetic (TM Wave):
In a homogeneous isotropic medium, an electromagnetic wave in which the magnetic field vector is everywhere perpendicular to the direction of propagation.

Wave, TE_{mn} (In Rectangular Waveguide):
In a hollow, rectangular metal cylinder, the transverse electric wave for which m is the number of half-period variations of the electric field along the longer transverse dimension, and n is the number of half-period variations of the electric field along the shorter transverse dimensions.

Wave, TM_{mn} (In Rectangular Waveguide):
In a hollow rectangular metal cylinder, the transverse magnetic wave for which m is the number of half-period variations of the magnetic field along the longer transverse dimension, and n is the number of half-period variations of the magnetic field along the shorter transverse dimensions.

Wavemeter, Absorption:
A device which utilizes the characteristics of a resonator which causes it to absorb maximum energy at its resonant frequency when loosely coupled to a source.

APPENDIX II
MICROWAVE EQUIPMENT DATA SHEETS

ⓗ Model Number	Equipment
281A	Waveguide to Coaxial Adapters
375A	Variable Flap Attenuators
382A	Broadband Precision Waveguide Attenuators
415B	Standing Wave Indicator
421A, 485D	Waveguide Reflectometer Detector Mounts
430C	Microwave Power Meter
434A	Calorimetric Power Meter
440A, 442B, 444A	Detector Mount and Probes
485A/B	Detector Mount
487B	Broad Band Waveguide Thermistor Mount
532	Direct Reading Frequency Meter
620A	Signal Generator
715A	Klystron Power Supply
809B, 810, 806B	Slotted Sections and Universal Probe Carriage
870A	Slide Screw Tuners

TECHNICAL DATA

HEWLETT-PACKARD COMPANY · 1501 PAGE MILL ROAD · PALO ALTO, CALIFORNIA, U.S.A.
CABLE "HEWPACK"   TELEPHONE DAVENPORT 6-7000

(hp) MODEL 281A

WAVEGUIDE TO COAXIAL ADAPTERS
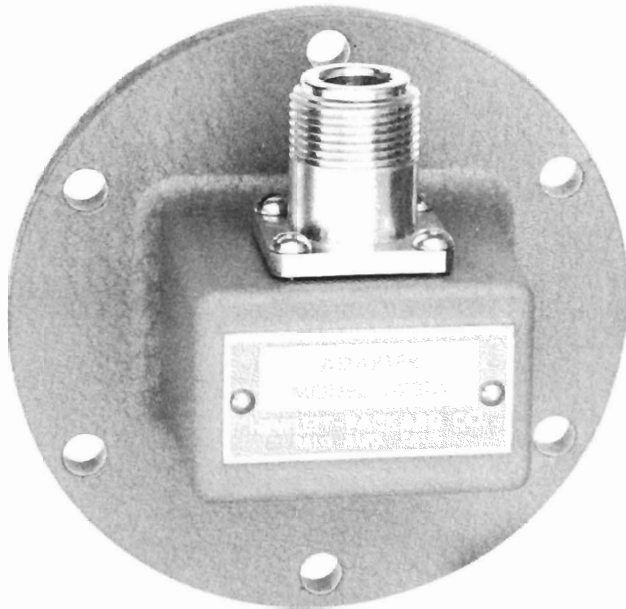
These adapters provide a convenient coupling between waveguide and coaxial systems. Power may be transmitted in either direction, and each adapter covers the full frequency range of its waveguide size with SWR of less than 1.25:1. These instruments use a probe with a low-loss dielectric sheath to transform waveguide impedance into coaxial cable impedance. They are fitted with a standard Type N female connector to a coaxial cable and a plain AN flange for connection to waveguide.
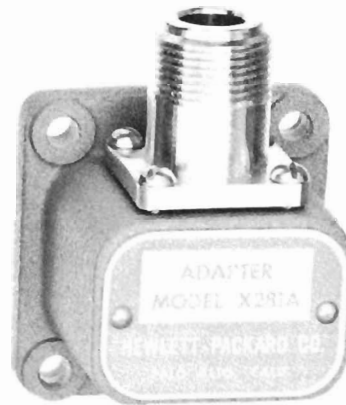
SPECIFICATIONS, (hp) 281A Adapters

Model	Length (In.)	Cover Flange	Frequency Range KMC	► Fits Waveguide Size (in.)	Shipping Weight (lbs.)	Price
S281A	2-1/2	UG-53/U	2.60 - 3.95	3 x 1-1/2	4	$50.00
G281A	2-1/8	UG-149A/U	3.95 - 5.85	2 x 1	4	$40.00
J281A	2	UG-344/U	5.30 - 8.20	1-1/2 x 3/4	3	$35.00
H281A	1-5/8	UG-51/U	7.05 - 10.00	1-1/4 x 5/8	2	$30.00
X281A	1-3/8	UG-39/U	8.20 - 12.40	1 x 1/2	1	$25.00

Maximum SWR: 1.25:1 over entire frequency range, except J281A which has maximum SWR 1.30 from 5.30 to 5.85 KMC.

(hp) 281A   EEM 2100

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Complete Coverage in Electronic Measuring Instruments

TECHNICAL DATA

hp

HEWLETT-PACKARD COMPANY · 1501 PAGE MILL ROAD · PALO ALTO, CALIFORNIA, U.S.A.

CABLE "HEWPACK"   TELEPHONE DAVENPORT 6-7000

hp MODEL 375A

VARIABLE FLAP ATTENUATORS

DESCRIPTION

Variable flap attenuators provide a simple convenient means of adjusting waveguide power level, or isolating source and load. They consist of a single slotted section in which a matched resistive strip is inserted a variable amount. The degree of strip penetration determines attenuation. A dial shows average reading over the frequency band, and a dust cover with shielded braid reduces external radiation and eliminates hand capacity effects.

Model 375 Attenuators have a maximum swr of less than 1.15 over the guide frequency range. Attenuation is variable 0 to 20 db; the equipment dissipates average power of 1 watt (except small waveguides where maximum dissipation is 0.5 watts). Dial calibration is accurate within ±1 db from 0 to 10 db, ±2 db from 10 to 20 db. K and R band models are available having either precision cover flanges or circular flanges; all other bands have precision
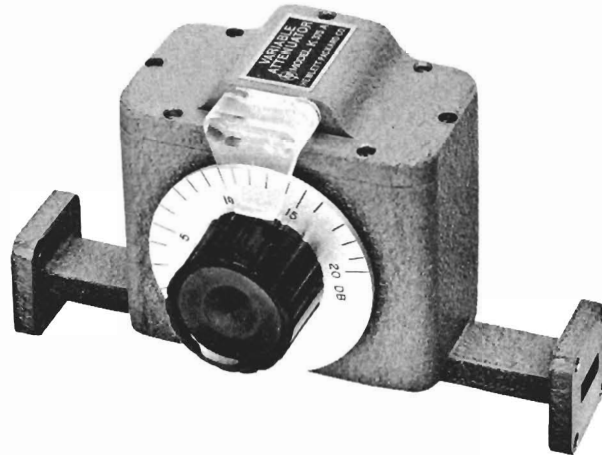
cover flanges. Models with circular flanges are designated by following the standard model number with a "C".

SPECIFICATIONS

Model	Freq. Range kmc	Fits Waveguide Size (Inches)	Flange Type	Power Dissi- pation	Price
S 375A	2.60 - 3.95	3 x 1-1/2	UG-53/U	1 watt	$120.00
G375A	3.95 - 5.85	2 x 1	UG-149A/U	1 watt	110.00
J 375A	5.20 - 8.20	1-1/2 x 3/4	UG-344/U	1 watt	100.00
H375A	7.05 -10.0	1-1/4 x 5/8	UG-51/U	1 watt	90.00
X375A	8.20 -12.4	1 x 1/2	UG-39/U	0.5 watt	90.00
P375A	12.4 -18.0	.702 x .391	UG-419/U	0.5 watt	100.00
K375A	18.0 -26.5	.500 x .250	UG-595/U	0.5 watt	140.00
► K375AC	18.0 -26.5	.500 x .250	UG-425/U	0.5 watt	180.00
R375A	26.5 -40.0	.360 x .220	UG-599/U	0.5 watt	180.00
► R375AC	26.5 -40.0	.360 x .220	UG-381/U	0.5 watt	180.00

All Prices f.o.b. Palo Alto, California

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# ℎ𝑝 TECHNICAL DATA

HEWLETT-PACKARD COMPANY · 1501 PAGE MILL ROAD · PALO ALTO, CALIFORNIA, U.S.A.
CABLE "HEWPACK"   TELEPHONE DAVENPORT 6-7000

ℎ𝑝 MODEL 382A BROADBAND PRECISION WAVEGUIDE ATTENUATORS
3.95 kmc to 40.0 kmc
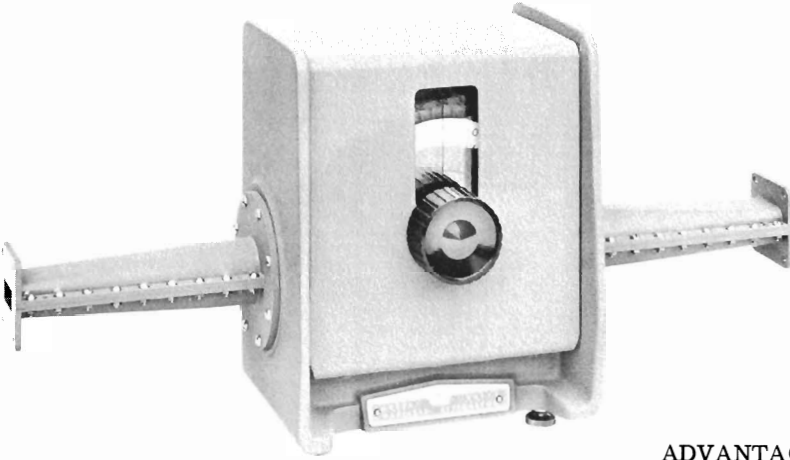
G, J, H, X, and P382A

OPERATION

The operation of these precision attenuators depends on a mathematical law rather than the resistivity of an attenuating material. They provide a thoroughly reliable, true standard of attenuation for use as precision calibrators in your laboratory, or for direct comparison measurements. Since attenuation is almost completely independent of film resistivity characteristics, no frequency correction is required. The law of attenuation is readily predictable so that production techniques can be applied to their manufacture, making prices reasonable.

DESCRIPTION

The attenuators consist of three sections of round waveguide with a resistive film stretched across the diameter of each. The films at each end are in line with each other and fixed at right angles to the E-field of an incoming wave. The center section is free to rotate axially. When all three films are in line, there is no current flow in the films and no attenuation. When the center section is rotated with respect to the plane of the other two films, attenuation increases according to a cosine-squared law. The attenuation does not depend on the specific resistance of the films, but is dependent on the orientation of the central film. Hence the attenuation is independent of frequency, and variations due to temperature and humidity are minimized. Rectangular to circular transitions are provided so that the attenuators operate in standard rectangular waveguide systems. K and R band models are available having either precision cover flanges or circular flanges; all other bands have precision cover flanges. Models with circular flanges are designated by a "C" following the standard model number.

ADVANTAGES

- Accurate attenuation over full guide frequency range.

- Stable under varying temperature and humidity conditions.

- Direct-reading - no charts or interpolation required.

- High power-handling capacity.

- Large, easily read dial provides fast accurate setting.

ℎ𝑝 382 EEM 3400

K and R382A

SPECIFICATIONS

Model:	G382A	C382A	J382A	H382A	X382A	P382A	K382A[1]	R382A[2]
Frequency Range, KMC:	3.95 - 5.85	4.7 - 7.05	5.3 - 8.2	7.0 - 10.0	8.2 - 12.4	12.4 - 18.0	18.0 - 26.5	26.5 - 40.0
Waveguide Size (in):	2 x 1	1.718 x .923	1-1/2 x 3/4	1-1/4 x 5/8	1 x 1/2	.702 x .391	1/2 x 1/4	.360 x .220
Flange UG- :	149/U		344/U	51/U	39/U	419/U	595/U	599/U
Power handling capacity, watts, average continuous duty:	15	10	10	10	10	5	2	1
► Size Length: (in)	31-5/8	23-1/8	25	19-15/16	15-5/8	12-1/2	7-5/8	7-1/2
Height:	9-3/4	9-11/16	8	7-15/16	7-1/4	7-3/4	5-1/2	6
Depth:	7-3/16	7-11/16	6-1/2	6-15/16	4-3/8	4-3/4	3-5/8	3-5/8
Weight (lbs) Net:	25	18	12	10	5	5	4	4
Shipping:	75	28	32	30	16	16	6	6
Price:	$500.00	$500.00	$350.00	$350.00	$275.00	$275.00	$425.00	$450.00

1. Available at the same price with UG-425/U flange, specify K382AC (length = 8-1/2 inch).
2. Available at the same price with UG-381/U flange, specify R382AC (length = 8-1/4 inch).

For All Models

Calibrated Range:	0 - 50 db
Phase Shift:	Less than 3° variation from 0 to 50 db
Attenuation at Zero Setting:	Less than 1 db
SWR:	Less than 1.15 entire range of attenuation and frequency.
Accuracy:	±2% of the reading in db, or 0.1 db, whichever is the greater. Includes calibration error plus frequency error.

6/30/59
5/30/60

Prices f.o.b. Palo Alto, California

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hp TECHNICAL DATA

HEWLETT-PACKARD COMPANY · 1501 PAGE MILL ROAD · PALO ALTO, CALIFORNIA, U.S.A.
CABLE "HEWPACK"   TELEPHONE DAVENPORT 6-7000

hp MODEL 415B
STANDING WAVE INDICATOR

USE IT FOR

- SWR measurement in conjunction with slotted lines.

- Determining reflection coefficient in db in conjunction with reflectometer.

- Sensitive modulated RF detector for crystals or barretters.

- Audio-frequency null indicator.

ADVANTAGES

- Expanded scale for full scale indication of 1.3:1.

- Makes all measurements in accurate, upper portion of indicating meter scale.

- 70 db calibrated range.

- Operates with crystals and high or low current bolometers.

- Optional high impedance input for null detection.

- Direct reading – eliminates tedious computations.

- Output provided to drive recorder.

The hp 415B[1] is a sensitive tuned voltmeter designed to make SWR measurements with the hp slotted lines and detector mounts. It may also be used as a null indicator, for bridge measurements, and has a 200,000 ohm input circuit for this application. Outstanding features of the 415B include an expanded SWR scale, a meter shift attenuator for increased reading accuracy, recorder output and a vernier gain control.

The hp 415B consists of a high gain amplifier with very low noise level, operating at a fixed audio frequency. Amplifier output is measured with a square-law calibrated vacuum tube voltmeter. This meter reads direct in SWR, and in db. A gain control adjusts the instrument to a convenient level.

Three scales of SWR – 1 to 4, 3 to 10, and an expanded scale of 1 to 1.3 – provide exceptional readability for all types of SWR measurements. A 60 db attenuator adjustable in 10 db range steps provides a calibrated range of 70 db. The unit is therefore ideally suited for measuring both high and low SWR's with exceptional accuracy.

The recorder output is designed for a recording milliammeter having a 1 ma full scale deflection and an internal resistance of approximately 1500 ohms.

A logarithmic meter scale, such as the db scale of the 415B, is more accurately read on the upper half than on the lower half of the scale (see Fig. 1). In order to make all readings occur on the upper half of the scale, a minus 5 db attenuator has been incorporated in the 415B. If an indication appears on the lower half scale merely dropping one range step and switching in the 5 db attenuator will bring the meter indicator within the upper half of the scale.

1 Don Carmean, "A New Standing Wave Indicator with an Expanded VSWR Scale," Hewlett-Packard Journal Vol. 6 No. 7.
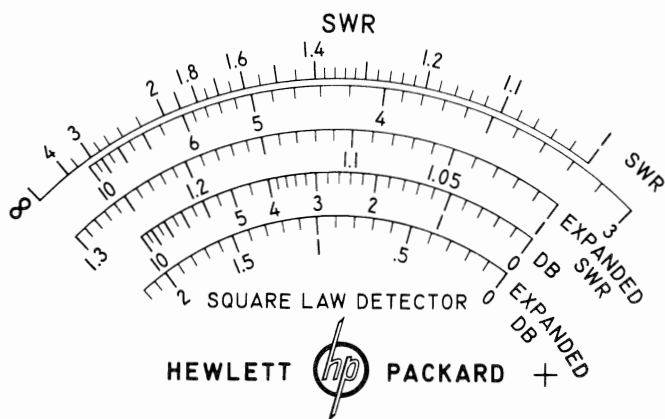
Figure 1.   Detail of Meter Face

Three input arrangements are provided. A switch selects a 200 ohm termination, with bias of 4.3 or 8.4 ma, or unbiased for crystals; or a 200,000 ohm load for null measurements. A jack and monitor cable are provided for connecting an external milliameter to measure bolometer current.

The instrument is normally arranged for operation at a filter frequency of 1000 cps and a power line frequency of 60 cps. On special order Model 415B is available equipped for operation at any filter frequency from 315 to 2020 cps. However, the filter frequency should not be harmonically related to the power line frequency. The frequency determining network is a plug-in unit. Units for converting the 415B to operate at frequencies in the above range can be obtained at nominal charge and installed in the field.

APPLICATION

The ⓗⓟ Model 415B Standing Wave Indicator has been specifically designed for use with the ⓗⓟ series of Slotted Lines and Detector Mounts. A complete series of Slotted Line equipment for impedance and SWR measurements in coaxial and waveguide transmission systems is available to cover the entire frequency range from 500 mc to 40 kmc. Also available is a convenient line of waveguide and coaxial detector mounts for the range from 10 mc to 40 kmc.

SPECIFICATIONS

► FREQUENCY:	1000 cps ±2%. Other frequencies 315 to 2020 cps available on special order. Should not be harmonically related to power line frequency.
SENSITIVITY:	0.1 μvolt at a 200 ohm level for full scale deflection.
NOISE LEVEL:	Less than 0.03 μvolt ref. to input operated from a 200 ohm resistor at room temperature.
AMPLIFIER Q:	25 ±5.
CALIBRATION:	Square law. Meter reads SWR, DB.
RANGE:	70 db. Input attenuator provides 60 db in 10 db steps. Accuracy ±0.1 db per 10 db step. Maximum cumulative error ±0.2 db.
SCALE SELECTOR:	"Normal", "Expand", and "-5 db".
METER SCALES:	SWR 1-4, SWR 3-10, Expanded SWR 1-1.3, DB 0-10, Expanded DB 0-2.
GAIN CONTROL:	Adjusts to convenient reference level. Range at least 10 db.
INPUT:	"Bolo" (200 ohms). Bias provided for 8.4 ma bolometer or 1/100 amp fuse; or 4.3 ma low current bolometer.
	"Crystal" 200 ohms for crystal rectifier.
	"200,000 ohms". High impedance for crystal rectifier as null detector.
RECORDER OUTPUT:	Jack provided for recording milliammeter having 1 ma full scale deflection, internal resistance of 1500 ohms or less.
INPUT CONNECTOR:	BNC.

SPECIFICATIONS (CONT'D.)

POWER: 115/230 volts ±10%, 60 cps, 55 watts. Other frequencies on special order.

► DIMENSIONS: Cabinet Mount: 7-3/8" wide, 11-3/4" high, 12-1/2" deep.
                          Rack Mount: 19" wide, 7" high, 11" deep behind panel.

► WEIGHT: Cabinet Mount: Net 13 lbs., shipping 19 lbs.
                          Rack Mount: Net 17 lbs., shipping 29 lbs.

ACCESSORIES FURNISHED: 41A-16E Cable Assembly.

ACCESSORIES AVAILABLE: 415B-42B Plug-In Filter 315-700 cps, $45.00
                                             700-2020 cps, $32.00

AC-16D Cable Assembly, 44 inches of RG-58/U 50 ohm coaxial cable terminated at one end only with a UG-88/U Type BNC male connector. $2.65.

AC-16K Video Cable Assembly, 4 feet of RG-58/U 50 ohm coaxial cable terminated at each end with UG-88/U Type BNC male connectors. $5.00.

PRICE: ⓗⓟ Model 415B Standing Wave Indicator, Cabinet Mount $200.00
                        ⓗⓟ Model 415BR Standing Wave Indicator, Rack Mount $205.00

All prices f.o.b. Palo Alto, California

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   3/1/59

TECHNICAL DATA

HEWLETT-PACKARD COMPANY · 1501 PAGE MILL ROAD · PALO ALTO, CALIFORNIA, U.S.A.
CABLE "HEWPACK"   TELEPHONE DAVENPORT 6-7000

WAVEGUIDE REFLECTOMETER DETECTOR MOUNTS
(hp) MODEL S485D, G485D, AND J485D BARRETTER MOUNT
(hp) MODEL H421A, X421A, AND P421A CRYSTAL DETECTOR MOUNT

ACCURATE, SQUARE-LAW DETECTORS FOR DETERMINING SYSTEM FLATNESS

Reflectometer Detector Mounts are available for the six most commonly used waveguide sizes. They are supplied as barretter mounts for the three lower frequency ranges and as silicon diode mounts for the higher frequency ranges. All the mounts are characterized by a low SWR, a flat frequency response, a true square-law characteristic and a high sensitivity to provide maximum accuracy in a reflectometer installation.

All other elements required for a waveguide reflectometer setup in any of the six frequency ranges are avaliable from Hewlett-Packard Co. For details and application information, see Hunton, J. K., and Pappas, N. L., the (hp) Microwave Reflectometers, Hewlett-Packard Journal, Volume 6, No. 1-2, September - October, 1954.
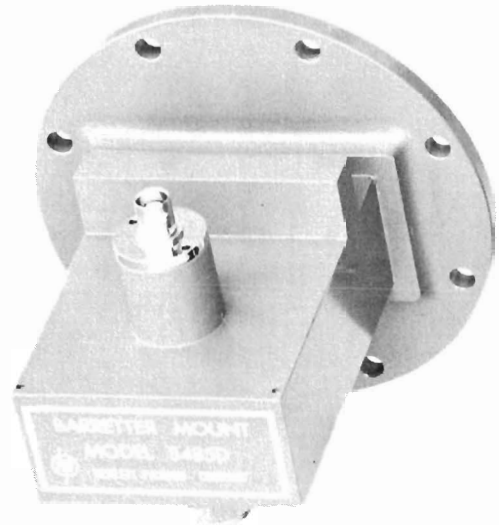
485D WAVEGUIDE BARRETTER MOUNTS

These instruments are available with barretters installed and tested for SWR, frequency response, and square-law characteristics. They are supplied complete with factory selected barretters to insure maximum accuracy. The (hp) AC-60K Barretter Matching Transformer is required to interconnect the 485D Detector Mounts and the (hp) 416A Ratio Meter.
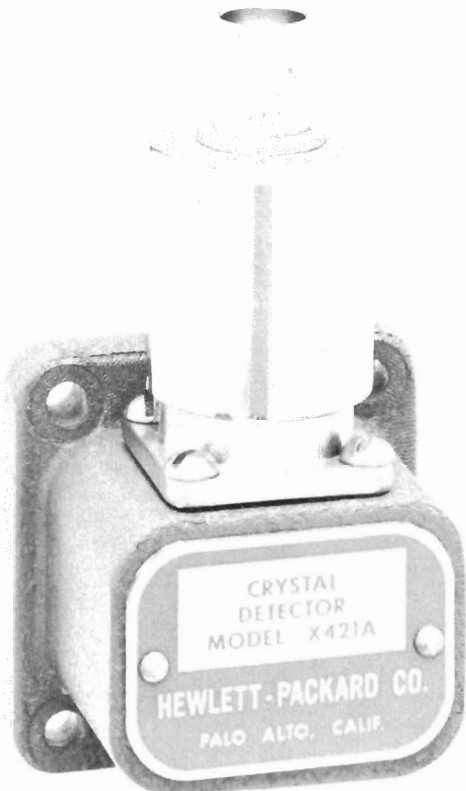
421A WAVEGUIDE CRYSTAL DETECTOR MOUNTS

At higher waveguide frequencies, better standing wave characteristics can be obtained with crystals than with barretters. Instruments for the "H", "X", and "P" bands therefore use 1N26 silicon diodes, which are furnished installed in the mounts. These crystals exhibit an accurate square law characteristic over a 40 db range when operated into a selected value video load resistor. Such a resistor is factory selected and included in each mount. It is possible to select pairs of 421A Crystal Detector Mounts which exhibit similar frequency response and square-law characteristics for reflectometer applications. The units are available as "matched pairs" for a small additional charge.

Waveguide Reflectometer Detector Mounts

SPECIFICATIONS

	S485D	G485D	J485D	H421A	X421A	P421A
Frequency Range, KMC:	2.6 - 3.95	3.95 - 5.85	5.2 - 8.2	7.05 - 10	8.2 - 12.4	12.4 - 18.0
Sensitivity (Average Value):	0.02v/0.1mw	0.02v/0.1mw	0.02v/0.1mw	0.01v/0.1mw	0.01v/0.1mw	0.01v/0.1mw
SWR (maximum):	1.5	1.5	1.5*	1.5	1.5	1.5
Frequency Response. Maximum variation over full range, less than:	±1 db	±1 db	±1 db	±2 db ✝	±2 db ✝	±2 db ✝
Square-Law Characteristic (maximum variation over 40 db range, maximum input power less than 1 mw:	±0.5 db	±0.5 db	±0.5 db	±1 db ✝	±1 db ✝	±1 db ✝
Detector Element:	Barretter	Barretter	Barretter	Crystal	Crystal	Crystal
Video Load:	Not required	Not required	Not required	Selected & Installed	Selected & Installed	Selected & Installed
Waveguide Size:	3" x 1-1/2"	2" x 1"	1-1/2" x 3/4"	1-1/4" x 5/8"	1" x 1/2"	.702" x .391"
▲ Replacement Unit:				ⓗ H421A-95C#, $55.00, ⓗ H421A-95D#, $130.00**	ⓗ X421A-95C#, $45.00, ⓗ X421A-95D#, $110.00**	Factory installed assembly.
Shipping Weight, approx.:	7 lbs.	5 lbs.	4 lbs.	2 lbs.	1 lb.	1 lb.
Accessories Available:	ⓗ AC-60K Barretter Matching Transformer for interconnection with ⓗ 416A Ratio Meter $45.00.			Matching Transformer not Required.		
▲ Price. f.o.b. Palo Alto, Calif.	$170.00	$170.00	$170.00	$ 95.00 / $105.00**	$ 75.00 / $105.00**	$105.00 / $115.00**

*Over frequency range 5.2 to 7.5 kmc. Increases to approximately 2.0 at 8.2 kmc.   **Unit price for detectors of a matched pair.

✝When ordered as "matched pairs", tolerance on frequency response and square-law characteristics combined, but excluding basic crystal sensitivity, is held to within ±2 db for the pair.

#Supplied with matched video-load resistors.

DATA SUBJECT TO CHANGE WITHOUT NOTICE

hp

TECHNICAL DATA

HEWLETT-PACKARD COMPANY · 1501 PAGE MILL ROAD · PALO ALTO, CALIFORNIA, U.S.A.
CABLE "HEWPACK"   TELEPHONE DAVENPORT 6-7000

hp MODEL 430C
MICROWAVE POWER METER

ADVANTAGES

- Fast readings

- Read power directly in mw and dbm

- Use 100 or 200 ohm, positive or negative temperature coefficient bolometers

- Read cw and modulated power from 10 w to 10mw

- Extend range with attenuators, directional couplers

- Bolometer mounts available from 10 mc to 40 kmc

- Simple operation

DIRECT, AUTOMATIC READINGS OF PULSED OR CW POWER

This *hp* Microwave Power Meter gives instantaneous rf power readings in dbm or mw - and completely eliminates tedious computation and troublesome adjustments during operation. The instrument may be used at any frequency for which there are bolometer mounts - and measurements are entirely automatic.

In measuring cw power, *hp* 430C can use an instrument fuse, barretter, or thermistor as the bolometer element. Pulsed or cw power may be measured using either a negative or positive temperature coefficient element at 100 - or 200-ohms. Power is read directly in milliwatts, from 0.01 to 10 mw, or in dbm from -20 to +10 dbm. Higher powers may be measured by inserting attenuators or by using directional couplers to sample energy.

When used in an appropriate bolometer mount, instrument fuses are generally satisfactory for measuring cw, and modulated power at frequencies up to 4 kmc. Barretters and thermistors can be used for these measurements at much higher frequencies, up to 12.4 kmc for barretters (in *hp* mounts) and up to 40.0 kmc for certain thermistors.

hp waveguide bolometer mounts are available covering frequencies from 2.6 kmc to 40 kmc. Each waveguide bolometer mount covers a complete waveguide band. In addition, coaxial bolometer mounts cover the frequency spectrum from 10 mc to 10 kmc. Model 430C Microwave Power Meter furnishes dc bias current for bolometer mounts which require up to 16-ma bias current. Fine as well as coarse control of the bias current permits exact balancing of the bolometer element in the bridge over wide-range ambient temperature variations.

CIRCUIT DESCRIPTION

ⓗ Model 430C consists of an audio bridge, one arm of which is a power-sensitive element. Initially, the bridge is balanced with no rf power in the element. When rf power is applied, an equivalent audio power is automatically removed, so the bridge remains balanced. The change in audio power level is indicated directly on a vacuum tube voltmeter which is calibrated to show rf power.*

*See "Power Measurements from 10 to 12,400 Megacycles" and "More Conveniences in the Microwave Power Meter", Hewlett-Packard Journal V2 #7-8 and V6 #7.

SPECIFICATIONS

POWER RANGE:
5 ranges. Full scale readings of 0.1, 0.3, 1, 3, and 10 milliwatts. Also calibrated in dbm from -20 dbm to +10 dbm (0 dbm =1 mw).

EXTERNAL BOLOMETER:
Frequency range depends on bolometer mount. Bolometers operate at resistances of 100 or 200 ohms and can have positive or negative temperature coefficients. Any dc bias current up to 16 ma is available for biasing positive or negative temperature coefficient bolometers. DC bias current is continuously adjustable and is independent of bolometer resistance and power level range.

ACCURACY:
Within 5% of full scale value.

POWER SUPPLY:
115/230 volts ±10%, 50-1000 cycles, approximately 90 watts.

SIZE:
Cabinet Mount: 7-3/8 in. wide, 11-1/2 in. high, 14-1/4 in deep.
Rack Mount: 19 in. wide, 7 in. high, 13 in. deep behind panel.

WEIGHT:
Cabinet Mount: Net 14 lbs., Shipping 19 lbs.
Rack Mount: Net 18 lbs., Shipping 30 lbs.

ACCESSORIES
AVAILABLE:
AC-16D   Cable Assembly, consisting of 44 in. RG-58/U cable terminated on one end with a UG-88/U BNC connector. $2.65.

COAXIAL BOLOMETER
MOUNTS:
ⓗ Model 475B 1 to 4 kmc, $225.00.
ⓗ Model 476A, 10 to 1000 mc $85.00.
ⓗ Model 477B, 10 mc to 10 kmc, $75.00.

WAVEGUIDE BOLOMETER
MOUNTS:
ⓗ Model 485A (less detector), S band, $140.00.
ⓗ Model 487B, G through R band, $75.00 to $225.00 each.
ⓗ Model 485B (less detector), G through X band, $75.00 to $95.00.

PRICE:
ⓗ Model 430C Microwave Power Meter, cabinet mount, $250.00.
ⓗ Model 430CR Microwave Power Meter, rack mount, $255.00.

All Prices f.o.b. Palo Alto, California

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8/30/59

TECHNICAL DATA

HEWLETT-PACKARD COMPANY · 1501 PAGE MILL ROAD · PALO ALTO, CALIFORNIA, U.S.A.
CABLE "HEWPACK"   TELEPHONE DAVENPORT 6-7000

ⓗ MODEL 434A   CALORIMETRIC POWER METER

ADVANTAGES

- 10 milliwatts to 10 watts basic range

- DC to 12,400 megacycles

- Fast reading

- Extremely simple to use

- Completely self-contained

- Direct reading in watts and DBW

MEASURE POWER FROM 10 MILLIWATTS TO 10 WATTS, FULLSCALE, FROM DC TO 12,400 MEGACYCLES WITH NO EXTERNAL BOLOMETER MOUNTS, DIRECTIONAL COUPLERS, OR PLUMBING.

The Hewlett-Packard 434A Calorimetric Power Meter offers a new standard of operating simplicity and convenience for power meters. Power measurements with the 434A can be quickly and confidently made by non-technical personnel. It is completely self-contained; requires no barretter, thermistor, external power termination, directional couplers or external plumbing. The 434A has only two operating controls, the meter range switch and a zero set. No other adjustments are necessary to make a power measurement at any frequency from dc to 12,400 megacycles. Simply connect the power to be measured to the 50-ohm, type N coaxial connector on the panel and read the power from the meter directly in watts and in DBW.

The power range of the 434A - 10 milliwatts fullscale to 10 watts fullscale - fills the gap between bolometer type microwave power meters whose upper limit is 10 to 100 milliwatts, and conventional calorimeters, whose lower limit is in the neighborhood of 10 watts. In addition, the 10-watt upper limit of the 434A can be conveniently extended to many times this value by the use of calibrated attenuators or directional couplers.

The 434A offers a new high in stability and response time. The use of a self-balancing bridge as shown in Figure 1, and a highly efficient heat transfer to and from the oil stream results in a response time of 5 seconds or less, a fraction of the time required by conventional calorimeters. This quick response permits power measurements while tuning circuits,

where the power meter must follow the effects of small adjustments. The use of twin power-sensitive elements immersed in a single oil stream makes the
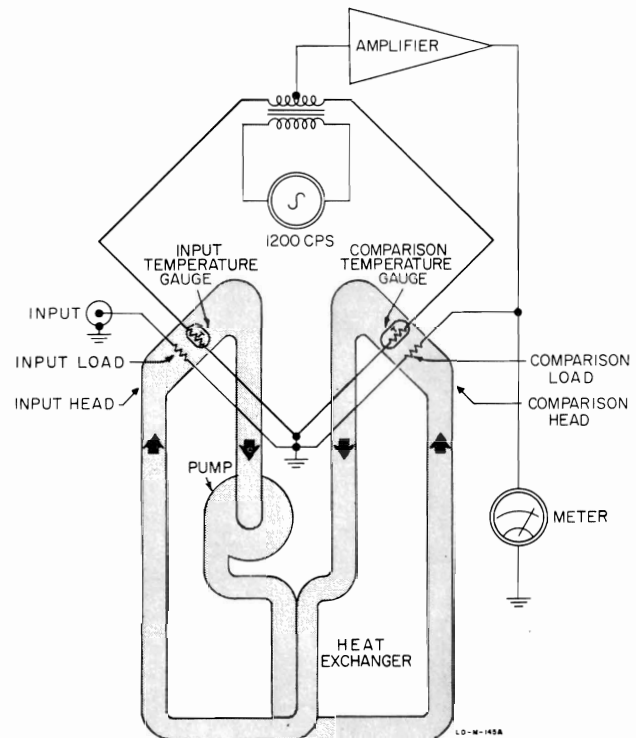
Figure 1.   Simplified Diagram of the ⓗ 434A

434A   EEM2900

434A independent of variations in oil flow rate and temperature. The circuits are conservatively designed and constructed to give troublefree operation and simplified service.

DESCRIPTION

The Model 434A, shown simplified in Figure 1, consists of a self-balancing bridge which has identical temperature-sensitive resistors (gauges) in two legs, an indicating meter and two load resistors, one for the unknown input power and one for the comparison power. The input load resistor and one gauge are in close thermal proximity so that heat generated in the input load resistor heats the gauge and unbalances the bridge. The unbalance signal is amplified and applied to the comparison load resistor which is in close thermal proximity to the other gauge so that the heat generated in the comparison load resistor is transfered to its gauge and nearly rebalances the bridge.

The meter measures the power supplied to the comparison load to rebalance the bridge. The characteristics of the gauges are the same and the heat transfer characteristics from each load are the same, so the power dissipated in each load is the same, and the meter may be calibrated directly in input power.

An efficient heat transfer from the loads to the temperature gauges is accomplished by immersing the components in an oil stream.

The power measurement is accurate, because the flow rates through the two heads are the same and the oil enters the heads at nearly the same temperature. To insure constant temperature and to bring the streams to nearly the same temperature, they are passed through a parallel-flow heat exchanger just prior to entering the heads. Identical flow rates are obtained by placing all elements of the oil system in series as shown in the figure.

SPECIFICATIONS

INPUT POWER RANGE:	Seven meter ranges. Full-scale readings of .01, .03, .1, .3, 1.0, 3.0 and 10 watts. Meter scale also calibrated from -10 to 0 DBW, providing continuous readings from -30 to +10 DBW. Power range can be extended upward with attenuators or directional couplers.
PEAK INPUT POWER:	1 kilowatt, maximum
FREQUENCY RANGE:	DC to 12.4 kmc
DC INPUT IMPEDANCE:	50 ohms ± 5 ohms at type N input jack
INPUT VSWR:	DC to 5 kmc: less than 1.3
	5 to 10 kmc: less than 1.5
	10 to 12.4 kmc: less than 1.7
METER RESPONSE TIME:	Less than 5 seconds for full scale deflection
INTERNAL CALIBRATOR:	100 mw dc ± 1% into 45 to 55 ohms
►ACCURACY:	Within ± 5% of full scale. Includes dc calibration and rf termination efficiency but not mismatch loss. Greater accuracy can be achieved through appropriate techniques.

ESTIMATED ATTAINABLE ACCURACY:		UPPER RANGES 1/2%			TWO LOWEST RANGES 2%		
DC		"	"		"	"	"
0 to 1 kmc		"	"	1%	"	"	" 3%
1 to 4 kmc		"	"	2%	"	"	" 4%
4 to 10 kmc		"	"	3%	"	"	" 5%
10 to 12.4 kmc		"	"	4%	"	"	" 5%

POWER SUPPLY:	115/230 volts ± 10%, 50/60 cycles, approximately 155 watts with no input, 175 watts with 10 watts input.
DIMENSIONS:	Cabinet Mount: 20-3/4 in. wide, 12-3/4 in. high, 14 in. deep
	Rack Mount: 19 in. wide, 10-1/2 in. high, 13 in. deep behind panel.
WEIGHT:	Cabinet Mount: Net 49 lbs. shipping 71 lbs.
	Rack Mount: Net 44 lbs. shipping 66 lbs.
PRICE:	ⓗⓟ Model 434A Calorimetric Power Meter, Cabinet Mount $1,400.00
	ⓗⓟ Model 434AR Calorimetric Power Meter, Rack Mount $1,385.00.

Prices f.o.b. Palo Alto California

ⓗⓟ 434A EEM 2900

hp TECHNICAL DATA

HEWLETT-PACKARD COMPANY · 1501 PAGE MILL ROAD · PALO ALTO, CALIFORNIA, U.S.A.
CABLE "HEWPACK"   TELEPHONE DAVENPORT 6-7000

hp MODELS 440A, 442B, and 444A

MODEL 440A DETECTOR MOUNT - Simplifies Detection of RF Energy in Coaxial or Waveguide Systems.

Model 440A is a simple, easy-to-use instrument for detecting rf energy in either coaxial or slotted waveguide systems.

In coaxial use, the equipment operates at any frequency from 2.4 to 12.4 kmc. Just one adjustment is required for tuning. Silicon crystals or bolometers may be used interchangeably in the same holder. A built in rf bypass is provided. The coaxial connector is equivalent to a UG21B/U Type N plug. Detector output appears at a BNC jack.

In conjunction with *hp* 442B Broadband Probe, *hp* 440A becomes a sensitive and easy-to-tune detector for use with slotted waveguide sections. The *hp* 809B carriage is designed to accept this combination.

SPECIFICATIONS -
Frequency Range: 2.4 to 12.4 kmc.
Detector (not supplied): 1N21 or 1N23 silicon crystals or Sperry 821 barretter.
Tuning: Single stub.
Connectors: UG21B/U (rf input); BNC jack (Detector output).
Price: $85.00 f.o.b. Palo Alto, California.

MODEL 442B BROADBAND PROBE -

Model 442B is a probe whose depth of penetration into a waveguide section is variable. It is held in position by friction, and may be fixed in place by a locking ring. Sampled rf appears at a Type N jack, permitting direct connection to a receiver, spectrum analyzer or other instrument.

This broadband Probe may be connected to a Model 440A Detector Mount to form a sensitive and convenient rf detector for slotted waveguide sections.

The probe is shielded and polyiron inserts are provided to prevent spurious resonances. Model 442B fits *hp* 809B Universal Probe Carriage or other carriages with a 3/4" diameter mounting hole.

► Price: $40.00 f.o.b. Palo Alto, California.
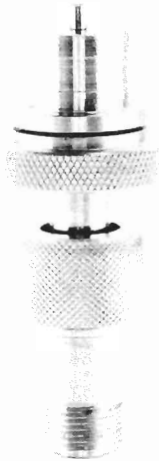
MODEL 444A UNTUNED PROBE -

This probe consists of a crystal plus a small antenna in a convenient housing that permits probe penetration to be varied quickly and easily. The probe is held in position by friction, or may be fixed in place by a locking ring. No tuning is required, and sensitivity is equivalent to or excels many elaborate single-and double-tuned probes, particularly over the 8.0 to 18.0 kmc range. Polyiron inserts damp out spurious resonances.

Model 444A fits *hp* 809B Universal Probe Carriage or other carriages with a 3/4" mounting hole.

SPECIFICATIONS -
Frequency Range: 3.0 to 18.0 kmc.
Output Connector: BNC
Detector: Supplied
Replacement Crystal: *hp* Stock Number 444A-25E, $15.00
► Price: $40.00 f.o.b. Palo Alto, California.

hp 440 EEM 3400

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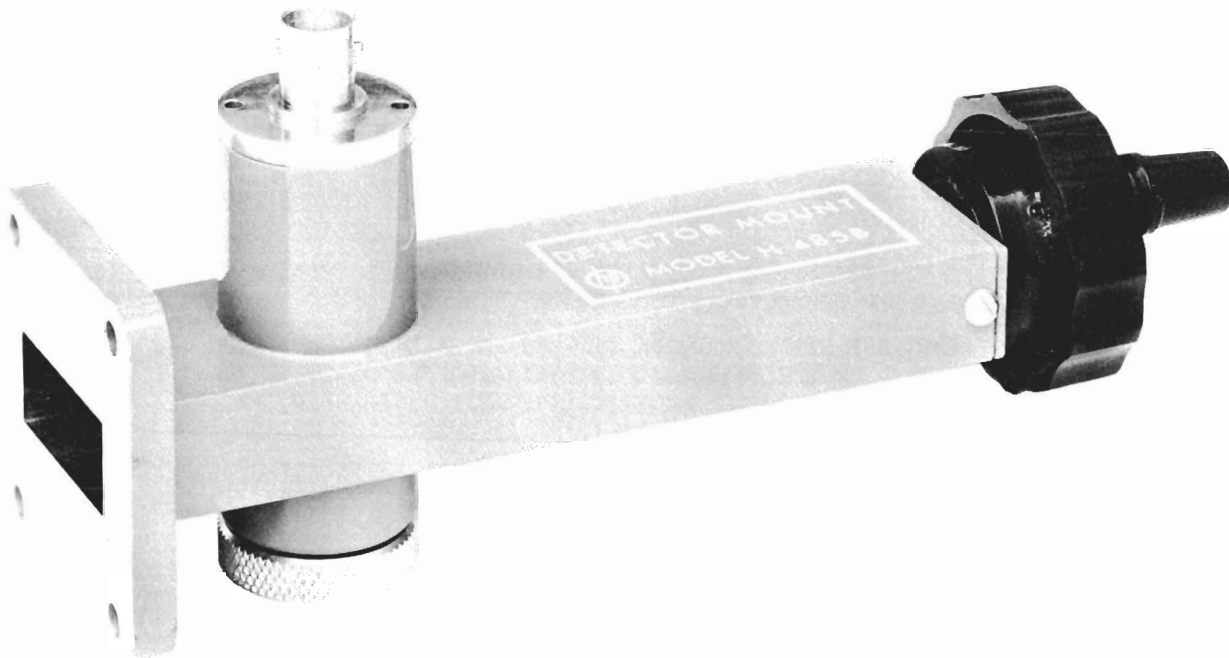   1/1/59

ⓗ TECHNICAL DATA

HEWLETT-PACKARD COMPANY · 1501 PAGE MILL ROAD · PALO ALTO, CALIFORNIA, U.S.A.
CABLE "HEWPACK"   TELEPHONE DAVENPORT 6-7000

ⓗ MODEL 485A/B DETECTOR MOUNT

USES - Measure Microwave Power Sensitive RF Detector

SIMPLE DEVICE FOR MEASURING OR DETECTING RF POWER -

Offered in two basic models, these detector mounts are designed so that a single tuning control is sufficient to match accurately waveguide sections to a bolometer element for measuring power. For maximum sensitivity in the detection of rf energy where swr is not critical the bolometer element of the 485B series can be replaced by a crystal.

Model S485A (2.6 to 3.95 kmc) uses a Sperry 821 Barretter or a Narda N821 and requires no tuning. It has swr of less than 1.35 over entire waveguide band.

The 485B series, for G, J, H, and X bands (3.95 to 12.4 kmc) is tuned by a variable short. When a Sperry 821 or a Narda N821 barretter is used, these

mounts can be adjusted to a swr of less than 1.25 over the respective waveguide bands. For power measurements this results in a reflection loss of less than 0.1 db. For maximum sensitivity in the detection of rf energy in applications where the swr is not critical, the barretter element can be replaced with a 1N21 or a 1N23 silicon crystal. If a low swr is desired, precede the 485B with an appropriate slide screw tuner such as an ⓗ 870A.

In all models detected output appears at a BNC jack mating with a UG88/U plug. Detector elements can be quickly interchanged. For measuring maximum power from a mismatched source, these detectors may be preceded by a slide screw tuner such as ⓗ 870A. The detectors are ideal for use with ⓗ 430B Microwave Power Meters, or ⓗ 415A or 415B Standing Wave Indicator.

ⓗ 485A/B EEM 3400

SPECIFICATIONS

Model	Maximum swr[1]	Frequency Range (kmc)	► Fits Waveguide Size (in)	► Length (in.)	Shipping Weight	Price
S485A[2]	1.35	2.60 - 3.95	3 x 1.5	4-11/16	7 lbs	$140.00
G485B[3]	1.25	3.95 - 5.85	2 x 1	9-5/16	5 lbs	95.00
J485B[3]	1.25 1.35 1.50	5.85 - 8.20 5.50 - 5.85 5.20 - 5.50	1.5 x 0.75	7-3/8	4 lbs	90.00
H485B[3]	1.25	7.05 - 10.00	1.25 x 0.625	6-3/8	3 lbs	85.00
X485B[3]	1.25	8.20 - 12.40	1 x 0.5	6	3 lbs	75.00

Detectors not supplied.

Accessories Available: ⓗ AC-16D Cable Assembly, 44 inches of RG-58/U 50 ohm coaxial cable terminated at one end only with a UG-88/U Type BNC male connector. $2.65.

ⓗ AC-16K Cable Assembly, 4 feet of RG-58/U 50 ohm coaxial cable terminated at each end with UG-88/U Type BNC male connectors. $5.00.

[1] With Sperry 821 or Narda N821 barretter
[2] Sperry 821 or Narda N821 only
[3] May use 1N21 or 1N23 for maximum detection sensitivity where swr is not critical.

Prices f.o.b. Palo Alto, California

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hp TECHNICAL DATA

HEWLETT-PACKARD COMPANY · 1501 PAGE MILL ROAD · PALO ALTO, CALIFORNIA, U.S.A.
CABLE "HEWPACK"   TELEPHONE DAVENPORT 6-7000

hp MODEL 487   BROAD BAND WAVEGUIDE THERMISTOR MOUNTS

NEW WAVEGUIDE THERMISTOR MOUNTS PROVIDE SWIFT WAVEGUIDE POWER MEASUREMENTS, 4 KMC to 40.0 KMC -

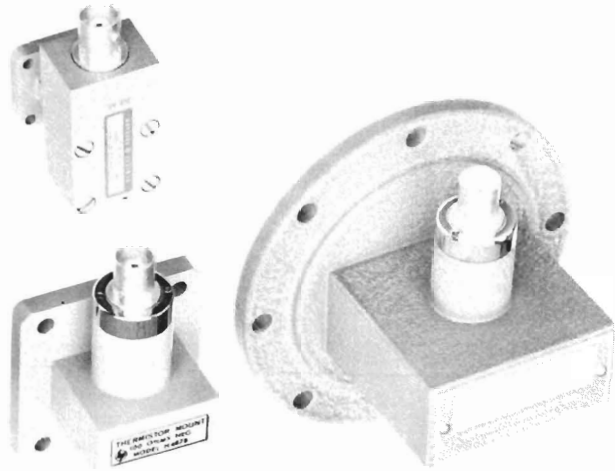These thermistor mounts each cover full frequency range of the waveguide size. They have a low swr at all frequencies and require no tuning. Their use simplifies setups, saves operator time and provides maximum accuracy in measurement of microwave power. They employ permanently installed thermistors; thus are ideal for measuring average power of low duty cycle pulses. The units are rugged, and because the thermistors have high temperature coefficients and large overload factors, time consuming replacement operations due to detector element burnout are virtually eliminated.

Thermistor replacement, if necessary, can be accomplished in the field by skilled personnel. If desired, the Thermistor Mounts can be returned to the factory for thermistor renewal and certification at a nominal charge.

The thermistor mounts are designed for use with a microwave power meter such as the hp Model 430C, which is responsive to negative temperature coefficient bolometers which operate at a 100 or 200 ohm level. They have BNC-type connectors for output connection to the microwave power meter. K and R band models are available having either precision cover flanges or circular flanges; all other bands have precision cover flanges. Models with circular flanges are designated by a "C" following the standard model number.

ADVANTAGES -

- Cover full waveguide frequency range
- No tuning required
- Low swr
- Not susceptible to burn-out
- Long time-constant for accurate modulated power measurements

SPECIFICATIONS

Model	Frequency (kmc)	Maximum swr	Detector (VECO)	Oper. Resis.	Fits Waveguide Size (OD-in.)	Equiv. ► Flange	Approx. Length	Ship. Wt. (lb.)	Price
G487B	3.95 - 5.85	1.5	32A5	100	2 x 1	UG-149A/U	2-1/8"	4	$95.00
J487B	5.3 - 8.2	1.5	32A5	100	1-1/2 x 3/4	UG-344/U	1-3/4"	3	$90.00
H487B	7.05 - 10.0	1.5	32A5	100	1-1/4 x 5/8	UG-51/U	1-5/16"	2	$80.00
X487B	8.2 - 12.4	1.5	32A5	100	1 x 1/2	UG-39/U	1-3/16"	1	$75.00
P487B	12.4 - 18.0	1.5	33A9	100	0.702 x 0.391	UG-419/U	13/16"	3/4	$110.00
►K487C	18.0 - 26.5	2	33A9	200	1/2 x 1/4	UG-595/U	1-5/8"	1/2	$150.00
K487BC	18.0 - 26.5	2	33A9	200	1/2 x 1/4	UG-425/U	1-5/8"	1/2	$150.00
R487B	26.5 - 40.0	2	33A9	200	0.360 x 0.220	UG-599/U	1-3/8"	1/2	$225.00
R487BC	26.5 - 40.0	2	33A9	200	0.360 x 0.220	UG-381/U	1-3/8"	1/2	$225.00

hp 487 EEM 2100

Complete Coverage in Electronic Measuring Instruments

ALL MODELS

Maximum Power Level: 10 mw when used with an (hp) Model 430B or 430C Microwave Power Meter.

Thermistor Time Constant: Approximately one second when cooling on an open circuit.

Accessories Available: (hp) AC-16D Cable Assembly, 44 inches of RG-58/U 50 ohm coaxial cable terminated at one end with a UG-88/U Type BNC male connector, $2.65.

                           (hp) AC-16K Cable Assembly, 4 feet of RG-58/U 50 ohm coaxial cable terminated at each end with UG-88/U Type BNC male connectors, $5.00.

Prices f.o.b. Palo Alto, California

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ⓗ TECHNICAL DATA

HEWLETT-PACKARD COMPANY · 1501 PAGE MILL ROAD · PALO ALTO, CALIFORNIA, U.S.A.
CABLE "HEWPACK"   TELEPHONE DAVENPORT 6-7000

ⓗ MODEL 532

DIRECT READING FREQUENCY METER

7.0 kmc to 40.0 kmc

DESCRIPTION

The ⓗ Model 532 direct reading frequency meters are inexpensive general purpose test instruments each offering good accuracy over an entire waveguide band. Each consists of a high Q TE_{111} mode resonant cavity which is tuned by a choke plunger. There are no sliding contacts. The cavity is mounted on a special waveguide section so designed that a small amount of power is reflected at resonance, while the major portion is transmitted. Resonance in the meter is indicated by a dip of approximately 1.5 db in output. The reaction at resonance is approximately constant over the entire waveguide range, and there are no spurious modes or resonances.

Scale divisions are well separated giving a high order of resolution to the ⓗ 532. It is tuned with a precision lead screw which is spring-loaded to prevent backlash. Resetability is .01% (1 mc at 10 kmc).
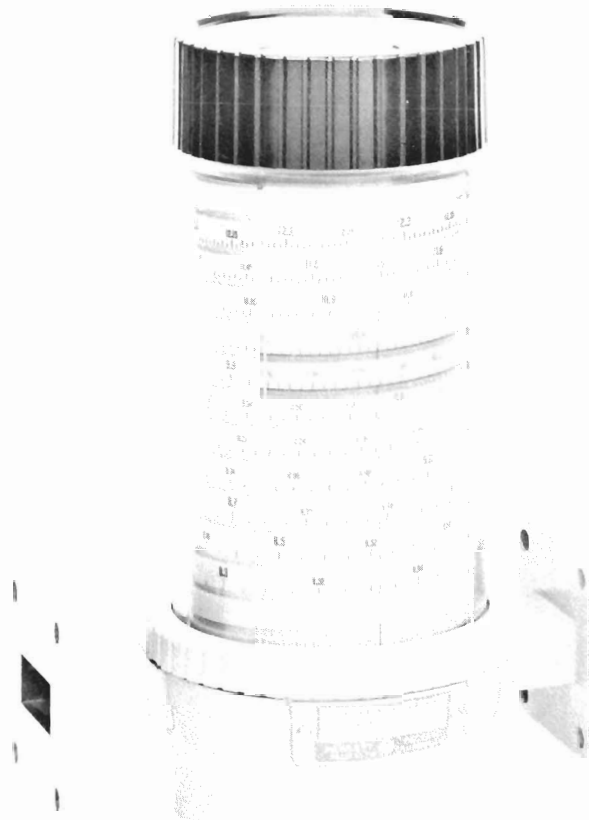
SPECIFICATIONS

For all Models

Dip at resonance: 1 db or more

Model	H532A	X532B	P532A	K532A	K532AC	R532A	R532AC
Accuracy:	0.08%	0.08%	0.1%	0.1%	0.1%	0.2%	0.2%
Frequency Range (kmc):	7.0-10	8.2-12.4	12.4-18.0	18.0 26.5	18.0-26.5	26.5-40.0	26.5-40
Calib. Increments (mc):	2.0	5.0	5.0	10.0	10.0	10.0	10.0
Fits Waveguide Size, (in):	1.250 x 0.625	1 x 1/2	0.702 x 0.391	1/2 x 1/4	1/2 x 1/4	0.360 x 0.220	0.360 x 0.220
Equivalent Flange:	UG51/U	UG39/U	UG419/U	UG595/U	UG425/U	UG599/U	UG381/U
► Dimensions (in): Length:	6-1/4	4-1/2	4-1/2	4-1/2	5-5/16	4-1/2	5-5/16
Height:	8	6-1/4	6-1/4	5-1/2	5-1/2	5-1/2	5-1/2
Depth:	4-3/8	2-3/4	2-3/4	2-3/4	2-3/4	2-3/4	2-3/4
Weight (lbs) Net:	3-1/2	3-1/2	3	1-1/2	1-1/2	1-1/2	1-1/2
Shipping:	5-1/2	5-1/2	5	4	4	4	4
Price:	$195.00	$150.00	$210.00	$230.00	$230.00	$250.00	$250.00

All Prices f. o. b. Palo Alto, California

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Complete Coverage in Electronic Measuring Instruments

hp TECHNICAL DATA

HEWLETT-PACKARD COMPANY · 1501 PAGE MILL ROAD · PALO ALTO, CALIFORNIA, U.S.A.
CABLE "HEWPACK"   TELEPHONE DAVENPORT 6-7000

-hp- MODEL 620A
SHF SIGNAL GENERATOR
7,000 - 11,000 mc

ADVANTAGES

- Direct reading frequency control

- Direct output level control

- CW, FM or pulsed output

- Internal square wave modulation

- Broad pulsing capabilities

- Wide frequency range

- High stability, accuracy

- Sturdy, compact, precision-built

VARIED PULSING CAPABILITIES

New Model 620A Signal Generators bring the simple yet versatile operation and the varied pulsing capabilities of -hp- 616A, 614A and 618B Signal Generators into the frequency range 7,000 - 11,000 mc. This new generator offers internal or external pulse modulation, internal square wave modulation and frequency modulation. The repetition rate is continuously variable from 40 to 4,000 pps, and pulse width is variable from 1/2 to 10 microseconds. Sync-out signals are simultaneous with the rf pulse, or in advance of the rf pulse by any time span from 3 to 300 microseconds. The instrument may be synchronized with an external sine wave or with positive or negative pulse signals.

USE TO MEASURE

- Receiver sensitivity

- Selectivity or rejection

- Signal-to-noise ratio

- Conversion gain, VSWR

- Antenna gain

- Transmission line characteristics

SAW-TOOTH SWEEP

For internal frequency modulation, Model 620A also offers a saw-tooth sweep rate variable between 40 to 4,000 cps. Frequency deviation is variable up to ±3 mc. For external frequency modulation the instrument provides capacitive coupling to the repeller of the klystron oscillator. Maximum deviation is approximately ±5 mc.

Complete Coverage in Electronic Measuring Instruments

Model 620A maintains the same standards of accuracy and stability found in -hp- 614A, 616A and 618B Signal Generators. And, it features the same simplicity of operation. Carrier frequency is set and read directly on one central tuning dial. No voltage adjustments are necessary during operation. (This is because the exclusive -hp- developed coupling device causes oscillator repeller voltage to track frequency changes automatically.) RF output is also set and read directly. No calibration charts are needed either for voltage or frequency control or their determination.

REFLEX KLYSTRON OSCILLATOR

Like Model 618B, the new 620A features an oscillator of the reflex klystron type, with an external resonant cavity. Oscillator frequency is determined by a movable plunger which varies the length of the cavity. Oscillator output is monitored by a temperature-compensated thermistor bridge circuit. This circuit operates virtually unaffected by ambient temperature conditions. Voltage beyond the monitored output level is passed through a piston attenuator. This attenuator is designed to provide attenuation that is linear over a range of 120 db or more.

Model 620A is perhaps the most useful and accurate commercial generator now offered in its frequency range. Because of its wide range, great stability, extreme accuracy and varied pulsing capabilities, it is ideal for almost any SHF application requiring a precision instrument. Like other -hp- instruments, it is sturdily built of finest components. Circuitry is clean and easily accessible. Design and assembly is such as to provide years of reliable service with little or no attention to the instrument.

SPECIFICATIONS

Frequency Range:	7000 to 11,000 mc covered in a single band. Repeller voltage automatically tracked and proper mode automatically selected.
Calibration:	Direct reading. Frequency calibration accuracy better than 1%.
Output Range:	1 milliwatt or 0.223 volts to 0.1 microvolt (0 dbm to -127 dbm) into 50 ohms. Directly calibrated in microvolts and db (coaxial Type N connector). Uncalibrated output at least 2 milliwatts.
Output Accuracy:	Within ±2 db from -7 dbm to -127 dbm; within ±3 db from 0 dbm to -7 dbm, at panel connector, terminated in 50-ohm load.
Internal Impedance:	50 ohms nominal. (VSWR less than 2).
Modulation:	Internal or external pulse and f-m; internal square wave.
Internal Pulse Modulation:	Repetition rate variable from 40 to 4000 pps, pulse width variable 1/2 to 10 microseconds.

SPECIFICATIONS (Cont'd)

Sync Out Signals:	1. Simultaneous with r-f pulse - positive.
	2. In advance of r-f pulse - positive, variable 3 to 300 microseconds. (Better than 1 microseconds rise time and 25 to 100 volts amplitude into 1000 ohm load.)
External Synchronization:	1. Sine wave: 40 to 4000 cps, amplitude 5 to 50 volts rms.
	2. Pulse signals: Zero to 4000 pps and 5 to 50 volts amplitude, both positive and negative, pulse width 0.5 to 5 microseconds, rise time 0.1 to 1 microseconds.
Internal Square Wave Modulation:	Variable 40 to 4000 cps, controlled by "pulse rate" control.
Internal Frequency Modulation:	Saw-tooth sweep rate adjustable between 40 to 4000 cps. Frequency deviation up to ±3 mc.
External Pulse Modulation:	Pulse requirements: amplitude from 15 to 70 volts positive or negative, width 0.5 to 2500 microseconds.
External Frequency Modulation:	Provides capacitive coupling to repeller of klystron. Maximum deviation approximately ±5 mc.
Power Source:	115/230 volts $\pm10\%$, 50/60 cps, 250 watts.
Size:	17-1/8" wide, 13-7/8" high, 17-5/8" deep. Weight: 94 pounds. Shipping weight: 170 pounds.
Accessories Supplied:	(hp)AC-16Q Cable Assembly, 6 feet of specially treated RG-9A/U 50 ohm coaxial cable terminated at each end with UG-21B/U Type N male connectors. Each cable is tested and selected for minimum SWR at frequencies above 4,000 MC.
Accessories Available:	(hp)AC-16K Cable Assembly, 4 feet of RG-58/U 50 ohm coaxial cable terminated at each end with UG-88/U Type BNC male connector, $5.00 f.o.b. Palo Alto, California.
Price:	(hp) Model 620A SHF Signal Generator, 7,000-11,000 mc, $2,250.00 f.o.b. Palo Alto, Calif.

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ⓗⓟ TECHNICAL DATA

HEWLETT-PACKARD COMPANY · 1501 PAGE MILL ROAD · PALO ALTO, CALIFORNIA, U.S.A.
CABLE "HEWPACK"   TELEPHONE DAVENPORT 6-7000

ⓗⓟ MODEL 715A

KLYSTRON POWER SUPPLY

be square-wave modulated internally at the nominal frequency of 1000 cps or sinewave modulated at the power line frequency.

To minimize the chance of damage to a klystron, the instrument's reflector supply is arranged with a protective circuit preventing the reflector from becoming appreciably more positive than the resonator.

This supply is suitable for use with such klystrons as:

RETMA Type Tubes		
		726C
2K22	5976	6063
2K25/723B	2K29	QK202
2K26	726A	6BM6
2K28/707B	726B	6BL6

Varian Tubes		
	V-53	V-157
X-12	V-54	V-260
X-13	V-55	V-261
X-26B	V-58	V-262
X-26D	V-151	V-270
X-26E	V-153	V-280
X-26F	V-154	V-290

DESCRIPTION

The beam current is obtained from a conventional regulator circuit providing approximately 1% regulation under various combinations of load and line voltage. The reflector voltage is obtained from a regulated rf supply that provides high dc voltages. This circuit provides extreme economy of weight and size.

The reflector 1000 cps square-wave modulation is adjustable in frequency ± 100 cps and in amplitude 0 to 120 volts peak-to-peak. To keep incidental fm of klystrons low, the time of rise and fall is less than 10 microseconds.

The unit is provided with a plug-in output cable that is shielded to minimize hum pick-up. Direct reading controls set the regulated voltages and a meter monitors the beam current.

VERSATILE POWER SOURCE FOR LOW-POWER KLYSTRONS -

The ⓗⓟ Model 715A Power Supply was designed to meet the need for a compact, portable bench supply capable of operating many different types of low-power klystrons.

The supply offers a regulated -250 to -400 volt beam voltage (continuously variable), a 0 to -900 volt regulated and continuously variable reflector supply, and a 6.3 volt ac filament supply. The reflector supply, which is stacked on the beam voltage, can

SPECIFICATIONS

►SUPPLY NO. 1 (Beam Supply):   Voltage range -250 to -400 volts; maximum current, 30 ma at 250 volts, 50 ma at 400 volts; regulation, less than 1% change from no load to full load or for line voltage variations of 115 volts ±10%; ripple, less than 7 mv; calibrated voltage controls provided.

►SUPPLY NO. 2 (Reflector Supply):   Voltage range 0 to -900 volts with respect to supply No. 1; maximum current, 10 μa; regulation, within 1% for line voltages of 115 volts ±10% for fixed currents; ripple, less than 10 mv; calibrated voltage controls provided.

FILAMENT SUPPLY: Provides 1.5 amperes maximum at 6.3 volts ac.

MODULATION: Square-wave modulation provided on supply No. 2; amplitude adjustable from 0 to 120 volts peak-to-peak. Square-wave rise and decay times less than 10 microseconds each; square-wave frequency adjustable over ±100 cycle range from nominal 1000 cps center frequency. Sinusoidal modulation on supply No. 2 at the power line frequency; adjustable 0 to 350 volts peak-to-peak.

EXTERNAL MODULATION: Terminals and circuit provided for modulation from external source. Input impedance at external modulation terminals is approximately 100,000 ohms.

►POWER SOURCE: 115/230 volts ±10%, 50/60 cps, 200 watts.

►DIMENSIONS: 7-3/8" wide, 11-1/2" high, 13-3/4" deep.

►WEIGHT: 19 pounds. Shipping weight, 24 pounds.

ACCESSORIES FURNISHED: 715A-16C Shielded Output Cable (for connection to klystron).

PRICE: ⓗⓟ Model 715A Klystron Power Supply $300.00 f.o.b. Palo Alto, Calif.
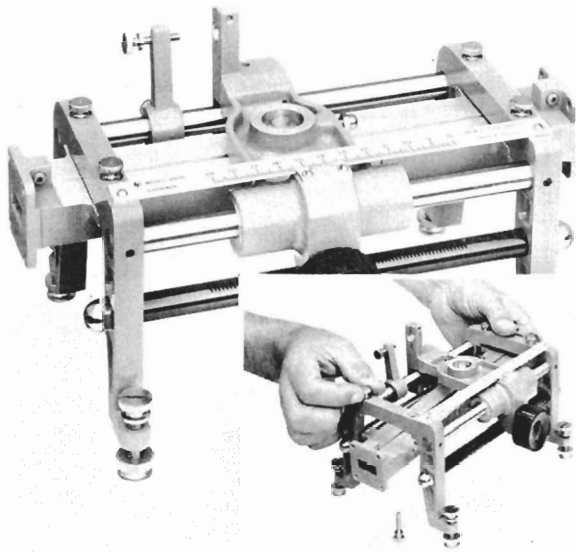

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9/30/58

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CABLE "HEWPACK"   TELEPHONE DAVENPORT 6-7000

-hp- MODEL 809B
UNIVERSAL PROBE CARRIAGE

-hp- MODEL 810
WAVEGUIDE SLOTTED SECTION

-hp- MODEL 806B
COAXIAL SLOTTED SECTION

ADVANTAGES

- Universal Carriage mounts 6 different slotted sections

- Broad Usefulness, 3,000 to 18,000 mc

- Carriage operates with -hp- waveguide or coaxial slotted sections

- Precision accuracy, high stability

- Sections interchange in 30 seconds

- Mounts dial gauge for high accuracy

- Simple operation, compact, low cost

USE IT TO MEASURE

LOW-COST, PRECISION TOOLS FOR MICROWAVE READINGS

- Characteristics of rf waveguide systems or coaxial transmission lines

Model 809B Universal Probe Carriage is a precision-built mechanical assembly designed to operate with five -hp- 810B Waveguide Slotted Sections covering frequency ranges from 3.95 kmc to 18.0 kmc and with -hp- 806B Coaxial Slotted Section, 3.0 to 12.0 kmc.

- Standing wave magnitude and phase

- Impedance

- System flatness, connector reflection

- Degree of antenna-match

- Percent of transmitted or reflected power

Model 809B provides, in one compact instrument, equipment that greatly simplifies waveguide measurements over a number of frequency bands and eliminates the cost of a probe carriage for each waveguide band. It saves appreciably on engineering time since waveguide sections can be interchanged in 30 seconds or less. It is lightweight and easily portable and is designed for use with either -hp- 444A Untuned Probe or -hp- 440A Detector and -hp- 442B Broadband Probe in combination. The unit has a centimeter scale with a vernier reading to 0.1 mm. Provision is also made for mounting a dial gauge where more accurate readings are required.

ⓗ 806B EEM 3400

-hp- Model 809B Universal Probe Carriage
-hp- Model 810   Waveguide Slotted Section
-hp- Model 806B Coaxial Slotted Section

Page 2 of 4

The instrument is simple in mechanical design and is carefully manufactured to assure trouble-free operation. The probe carriage moves on ground stainless steel rods, and its 3-point suspension system includes two linear-motion ball bearings with dust seals and permanent lubrication. A conventional ball bearing forms the third point of suspension. Accuracy is superior or equal to the most expensive custom-made slotted lines.

-hp- 810B WAVEGUIDE SLOTTED SECTIONS

Waveguide slotted sections are fundamental tools for the measurement of magnitude and phase of standing waves in a waveguide system. Such data may be transformed readily into impedance of terminal load of the system or components. Slotted sections may also be used to measure reflection, percent of transmitted power, degree of antenna match and other waveguide characteristics.
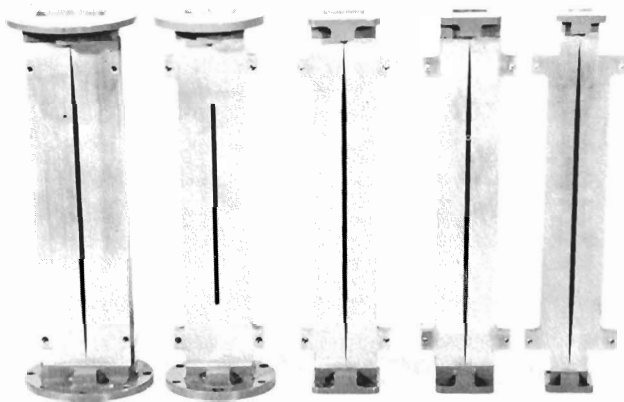
-hp- 810B Waveguide Slotted Sections comprise an accurately-machined section of waveguide in which a small longitudinal slot is cut. They are designed and finished to fit -hp- 809B Carriage in a precisely indexed position. A traveling probe mounted on the 809B Carriage samples the waveguide's electric fields along the slot and permits precise plotting of variations along the entire length of probe travel. The slotted sections are carefully machined from normalized aluminum castings to insure a uniform cross-section.

Ends of the slots are tapered to reduce slot reflection to less than 1.01 SWR. A high order of accuracy and stability is maintained. -hp- 810B sections are available for seven common waveguide frequency-sizes.

-hp- 806B COAXIAL SLOTTED SECTION

This instrument provides continuous coverage from 3.0 to 12.0 kmc and is designed for use with -hp- 809B Universal Probe Carriage. Impedance is 50 ohms to match flexible coaxial cables. This broadband coaxial slotted section has special fittings mating with Type N connectors to assure a minimum SWR.

-hp- Model 809B   Universal Probe Carriage
-hp- Model 810   Waveguide Slotted Section
-hp- Model 806B   Coaxial Slotted Section

Page 3 of 4

-hp- S810A WAVEGUIDE SLOTTED SECTION
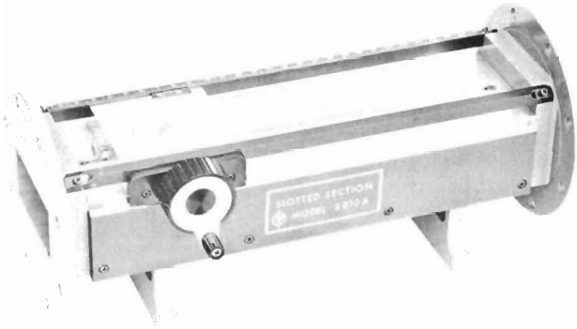
This instrument is a conventional type of slotted waveguide complete with probe carriage mounted directly on the section. Model S810A is available in the 3" x 1-1/2" (2.6 to 3.95 kmc) frequency only. The carriage accepts ⓗⓟ Model 442B Broadband Probe for sampling rf or Model 444A Untuned Probe which supplies a detected output.

SPECIFICATIONS

-hp- 809B UNIVERSAL PROBE CARRIAGE

Carriage:	Mounts all -hp- 810B Waveguide Slotted Sections and -hp- 806B Coaxial Slotted Section.
Probe Required:	-hp- 442B Broadband Probe in combination with -hp- 440A Detector or -hp- 444A Untuned Probe.
Probe Travel:	10 Centimeters.
Calibration:	Metric. Vernier permits readings to 0.1 mm. Provision for dial gauge installation.
Leveling Screws:	Knurled thumb screws provided on all 4 carriage legs.
Accuracy:	When used with waveguide sections, SWR's to 1.02 can be easily read. Slope error of slotted sections may be eliminated by adjustment.
Size:	8" long, 6-1/4" wide; height 5".
Price:	$160.00 f.o.b. Palo Alto, California.

-hp- S810A WAVEGUIDE SLOTTED SECTION

Conventional waveguide slotted section with probe carriage mounted directly on waveguide. Will accept -hp- 442B or 444A Probes.

Frequency Range:	2.6 to 3.95 kmc.
Slope:	Less than 0.05 db.

-hp- Model 809B Universal Probe Carriage
-hp- Model 810 Waveguide Slotted Section
-hp- Model 806B Coaxial Slotted Section

Page 4 of 4

SPECIFICATIONS (Continued)

-hp- S810A WAVEGUIDE SLOTTED SECTION

Residual SWR:	Less than 1.01.
Waveguide Size:	3" x 1-1/2".
Length:	12-3/4".
Price:	$450.00 f.o.b. Palo Alto, California.

-hp- 806B COAXIAL SLOTTED SECTION

Carriage:	Fits -hp- 809B Universal Probe Carriage.
Frequency Range:	3.0 to 12.0 kmc.
Connections:	Type N, one male, one female. Special fittings provide minimum SWR. Either end may be connected to load. Includes shorting connectors, male and female, for phase measurements.
Residual SWR:	Less than 1.04, 3.0 to 8.0 kmc. Approx. 1.06, 8.0 to 10.0 kmc. Approx. 1.1, 10.0 to 12.0 kmc.
► Pick-up Error:	Probe pick-up variation along line is less than 0.1 db except at extreme ends where it is less than 0.4 db.
Length:	10".
Price:	$200.00 f.o.b. Palo Alto, California.

-hp- 810B WAVEGUIDE SLOTTED SECTIONS

Model	Frequency Range kmc	Fits Waveguide Size (Inches)	Equiv. Flange	Length (Inches)	Price
G810B	3.95 - 5.85	2 x 1	UG-149A/U	10-1/4	$110.00
C810B	4.9 - 7.05	1.718 x .923	------	10-1/4	110.00
J810B	5.20 - 8.20	1-1/2 x 3/4	UG-344/U	10-1/4	110.00
H810B	7.05 - 10.00	1-1/4 x 5/8	UG-51/U	10-1/4	110.00
M810B	10.0 - 15.0	.850 x .475	------	10-1/4	110.00
X810B	8.20 - 12.40	1 x 1/2	UG-39/U	10-1/4	90.00
P810B	12.40 - 18.00	.702 x .391	UG-419/U	10-1/4	110.00

Discontinuity due to slot results in SWR of less than 1.01.

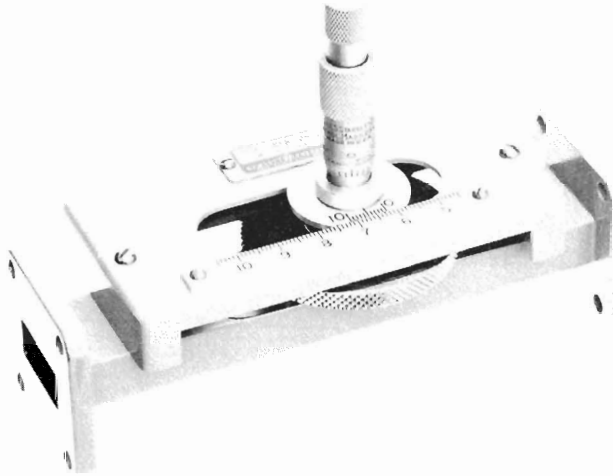Prices f.o.b. Palo Alto, California

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ⓗⓟ TECHNICAL DATA

HEWLETT-PACKARD COMPANY · 1501 PAGE MILL ROAD · PALO ALTO, CALIFORNIA, U.S.A.
CABLE "HEWPACK"   TELEPHONE DAVENPORT 6-7000

ⓗⓟ MODEL 870A
SLIDE SCREW TUNERS

Model X870A

Probe penetration into the guide is varied with a threaded adjustment on the S, K and R band units and by a micrometer drive on the others. Position of the probe along the guide of the G, J, H, X and P band units is adjusted by a thumb-operated wheel and position is read to 0.1 mm on a vernier scale. K and R band instruments have a micrometer drive to move the probe along the guide and its graduations can be to 0.01 mm. The maximum swr values (see specifications) can be corrected with an accuracy of 1.02, and small swr's may be exactly corrected. K and R band models are available having either precision cover flanges or circular flanges; all other bands have precision cover flanges. Models with circular flanges are designated by a "C" following the standard model number.
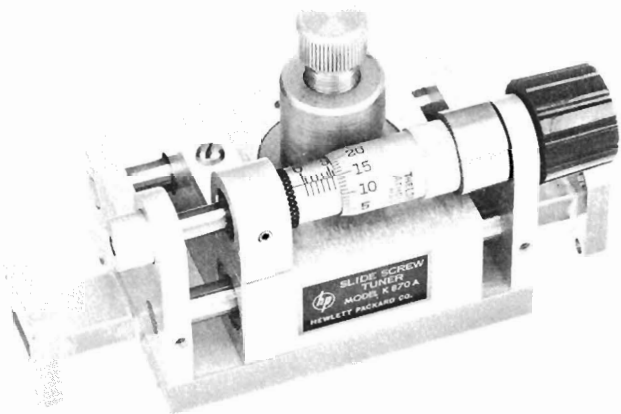
USES

Waveguide slide-screw tuners are used primarily for correcting discontinuities or "flattening" Waveguide systems. They are also used to match loads, terminations, bolometer mounts or antennas to the characteristic admittance of the waveguide. They are particularly valuable in determining experimentally the position and magnitude of matching structures required in waveguide systems.

DESCRIPTION

The tuners consist of a waveguide slotted section with a precision-built carriage on which is mounted an adjustable probe. The position and penetration of the probe is adjusted to set up a reflection which is used to cancel out an existing reflection in a system.

Model K870A

SPECIFICATIONS

Model	Freq. Range kmc	Fits Waveguide Size (in.)	Equivalent Flange Type	Correct-able swr	Insertion Loss (db) at corrected swr of 20	Length (in.)	Ship. Wt. (lbs.)	Price
S870A	2.6 - 3.95	3 x 1-1/2	UG-53/U	20	2	11	15	$225.00
G870A	3.95 - 5.85	2 x 1	UG-149A/U	20	2	8-1/4	7	185.00
► C870A	4.9 - 7.05	1.718 x .923	------	20	2	9-1/4	7	170.00
J870A	5.3 - 8.20	1-1/2 x 3/4	UG-344/U	20	2	7-5/8	7	150.00
H870A	7.05 - 10.00	1-1/4 x 5/8	UG-51/U	20	2	6	4	130.00
► M870A	10.0 - 15.0	0.850 x 0.475	------	20	2	5-7/8	3	130.00
X870A	8.20 - 12.40	1 x 1/2	UG-39/U	20	2	5-1/2	3	125.00
P870A	12.40 - 18.00	0.702 x 0.391	UG-419/U	20	2	5	3	130.00
► K870A	18.00 - 26.50	1/2 x 1/4	UG-595/U	20	3	4-1/4	3	250.00
► K870AC	18.00 - 26.50	1/2 x 1/4	UG-425/U	20	3	4-5/16	3	250.00
► R870A	26.50 - 40.00	0.360 x 0.220	UG-599/U	20	3	4-3/8	3	300.00
► R870AC	26.50 - 40.00	0.360 x 0.220	UG-381/U	20	3	4-7/16	3	300.00

Prices f.o.b. Palo Alto, California   4/30/59
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