MICROWAVE MEASUREMENTS MANUAL

Including illustrations and experiments

at X BAND using the

NARDA MODEL 117

Laboratory Training Kit

THE NARDA MICROWAVE CORPORATION
Revised May 16, 1963

FIGURE 1: NARDA MODEL 117 LABORATORY TRAINING SET

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THEORY AND APPLICATION

A. INTRODUCTION

The term "microwaves" is a name given a region of radio frequencies beyond the more commonly known short waves. Microwaves simply means extremely short waves. For example, international short wave broadcasts operate in the 50 to 10 meter region, while microwaves are considered to be the region from about 1/3 meter and less. A simple tabulation will help visualize this comparison. The numerical data is approximate, but nevertheless illustrative.

BAND	FREQUENCY RANGE	WAVELENGTH RANGE
Broadcast	550KC - 1600KC	500 - 200 meters
Short Waves	1.6MC - 30MC	200 - 10 meters
TV Channels 2 - 13	54MC - 216MC (VHF)	6 - 1 1/2 meters
TV Channels 14 - 83	470MC - 890MC (UHF)	2/3 - 1/3 meters
Radar	1000MC and up	30 centimeters (12 inches) and less

Some very interesting characteristics are apparent from the above table. First the wavelengths and frequencies move in directly opposite extremes. As the wavelength increases, the frequency correspondingly decreases. Thus, a 500KC wave is 600 meters (almost 2,000 feet) long, while a 1,000MC wave (2,000 times shorter) is but 1 foot long. Second, and this is also apparent from the numerical example just cited, one increases just as many times as the other decreases. Third, and this stems from the other two, there seems to be (and actually is) a definite relationship between the two. This relationship can best be stated in a generally true axiom that the product of wavelength and the corresponding frequency is a constant. Numerically this is expressed in the familiar formula,

$$\lambda = \frac{c}{f} = \frac{3 \times 10^8}{f} = \frac{300,000,000}{f}$$

where λ is in meters
f is cycles per second
c is the velocity of light (a constant)
In this case in meters per second.

From this tabulation it is also plain that a 1000MC radar wave is about 1000 times shorter than a broadcast band radio wave.

B. MICROWAVES VS CONVENTIONAL CIRCUITS

Just as in the case of wavelength and frequency, so also in the case of circuit components and measurements, the microwave system is but an extension of the lower frequency structures and techniques with the appropriate modifications. These modifications may be briefly outlined as follows:

1. Tuned Circuits

In the lower frequency regions, tuned circuits consist of "lumped constants", namely inductance and capacitance, with some unavoidable incidental resistance. Theoretically, the same structure would apply to microwaves if the components could successfully be scaled down both electrically and physically as is required with the increase in frequency (decrease in wavelength). Unfortunately, this is not feasible, except to a limited degree, and then only in the lowest frequency region of the microwave spectrum (around 1000MC). In practical cases, the tuned circuit for the microwave region becomes a resonant cavity. It is actually a metallic container or cavity, whose physical dimensions have a direct relation to the operating frequency. As a logical consequence, tuning involves a physical change in the cavity dimensions, such as moving a plunger in or out, thereby changing the length of the cavity.

2. Energy Transmission

At the lower frequencies, energy may be coupled from an r-f oscillator, by using conventional conductors, such as parallel or concentric (coaxial) transmission lines. In microwaves, the corresponding transmission medium is the waveguide, although coaxial lines are used to a certain extent, particularly at the lower microwave frequencies. The waveguide is essentially a single conductor, in the form of a hollow rectangular tube, whose cross-sectional dimensions are directly related to the frequency or range of frequencies over which the waveguide is to operate. This analogy also applies to antennas, where the usual dipoles are often replaced by waveguide horns and similar structures.

3. Measurements

The customary low frequency measurements of voltage, current and resistance or impedance do not readily lend themselves to direct application to microwave circuits. However, equally important and just as useful information may be obtained through measurements of the electric field within a waveguide, as well as the wavelength, phase and power output. The voltmeter, ammeter and similar instruments are replaced here by the tunable probe, crystal detector, standing wave amplifier and the ordinary centimeter (or inch) scale mounted on a slotted section of transmission line.

C. CHARACTERISTICS OF MICROWAVES

While the microwave spectrum is in many ways "peculiar", presenting problems that do not exist at lower frequencies, there are inherent in some of these peculiarities advantages not found elsewhere. A few of these advantages are listed and described here.

1. Radar

One of the greatest advantages of the peculiar characteristics of microwaves is their similarity in behavior to light waves. Like light, microwaves can be focused, aimed at and reflected from many objects. This property is the basis for an unlimited list of applications, the greatest and best known of which is radar. In simplest terms, radar is a means of accurately locating many types of objects, determining the distance and direction of such objects from the radar transmitter-receiver, through the reflection of microwave energy.

2. Wavelength Measurements

Another very useful characteristic of microwaves is the fact that the physical dimensions of the components (cavity, waveguide, etc.) are large relative to the wavelength. Thus, at 3,000 megacycles, the wavelength is only about 4 inches. This produces some very novel and useful phenomena in comparison to the lower frequencies.

For instance, in most microwave applications, it is actually possible to directly measure the wavelength of the energy along a section of waveguide. At lower frequencies such as 30 megacycles, for instance, the length of one wave is 10 meters, or roughly 33 feet! Not only is this length cumbersome beyond convenient measurement, but, what is more important, the electric field variations are extremely difficult to follow or compare from point to point along the wave. From a practical viewpoint, direct measurement is virtually impossible.

3. Standing Waves

The measurement of microwave lengths just mentioned is intimately related to another phenomenon peculiarly, although not exclusively, characteristic of microwaves. This phenomenon is the standing wave. Briefly, the standing wave is a distribution of energy along a transmission path, such as a waveguide, having wave-like crests and troughs. For example, when a microwave generator (a signal source, such as a klystron oscillator) is connected to a load, through a length of waveguide, energy flows from the generator to the load, much like current flowing along conductors from a source to a load in low frequency circuits. Under ideal ("matched") conditions, the energy level along the waveguide is substantially uniform from the generator to the load. More often, however, not all of the energy is absorbed by the load, but is "reflected" back in the direction of the generator. This simultaneous wave motion in both directions gives rise to a periodic energy distribution in the waveguide. It is called a "standing wave" because the energy no longer resembles wave motion along the guide, but would appear, if visible, as a stationary wave, with the peaks and valleys always in the same position. Figure 2 illustrates this condition. The standing wave has two major characteristics of interest to us. First the physical distance between a maximum and its adjacent minimum is 1/4 guide wavelength. Second, the degree of mismatch is indicated by the height or depth of the wave from crest to trough. From the guide wavelength, the frequency of operation can be calculated, as will be described later.

4. Signal Sources

At microwave frequencies the familiar CW oscillator

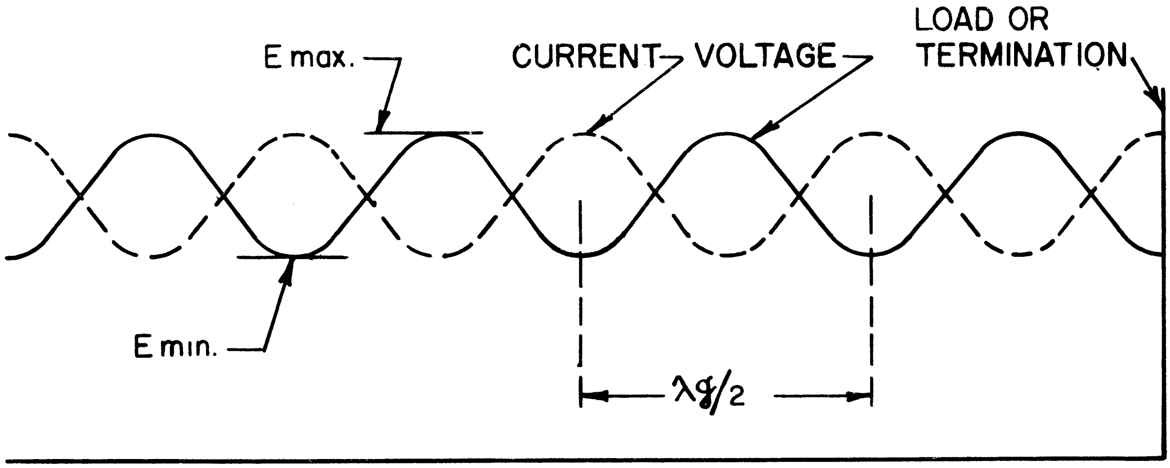


FIGURE 2: EXAMPLE OF A STANDING WAVE, VOLTAGE OR CURRENT

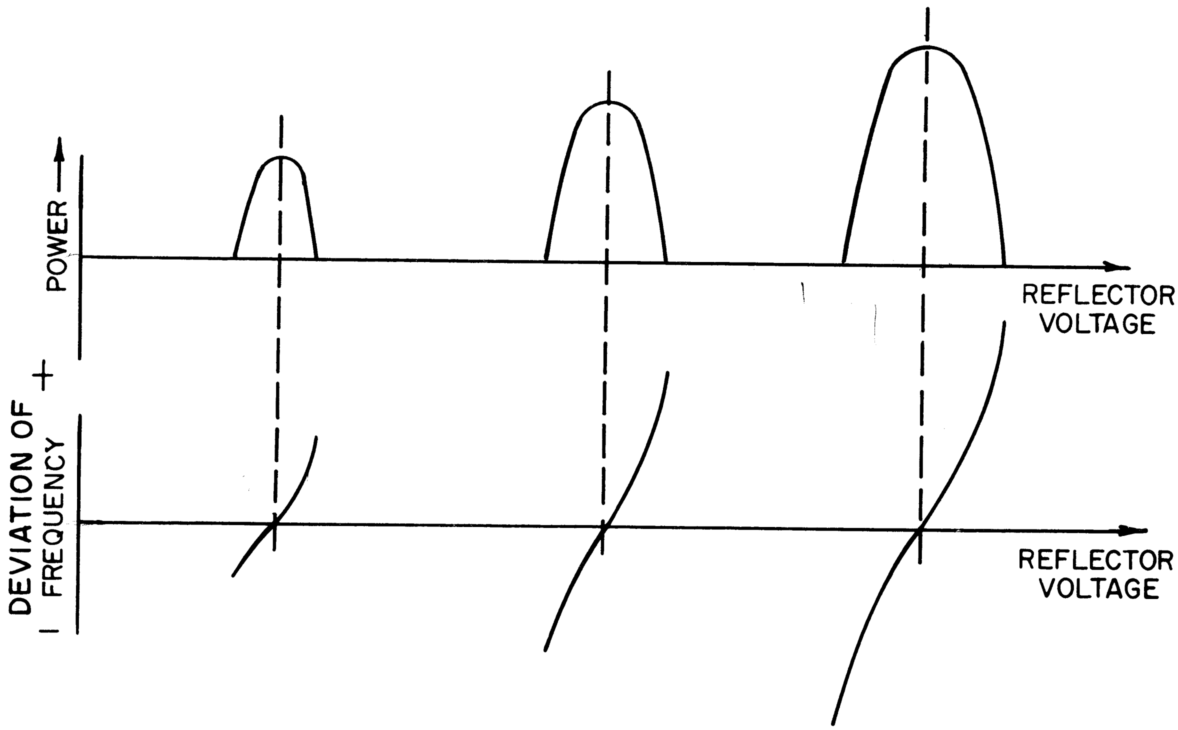


FIGURE 3: TYPICAL KLYSTRON OUTPUT, SHOWING "MODES"

becomes impractical, except in some very rare cases, due to the extreme smallness of the required components. Instead, a special version of the vacuum tube oscillator called the klystron is generally used. Both the manner of generating the energy as well as the nature of the generated RF differ materially and radically from the low frequency vacuum tube oscillator case. In the klystron, the electron beam is focused, "bunched", accelerated, then reflected back in a manner to produce a net energy output. This will be further described later. Unlike the output of the conventional CW oscillator, the output energy of the klystron, as a function of the frequency appears in "spurts" or "modes". Figure 3 illustrates this mode output of a klystron. While this behavior is not necessarily an advantage, it is nevertheless very characteristic of many microwaves sources.

D. MEASUREMENT DEVICES AT MICROWAVE FREQUENCIES

The most common microwave measuring "tools" are the slotted section, the probe, the detector and the standing wave amplifier. There are many other devices in use in microwave work. The four mentioned here, however, are basic, indispensible working tools. Their detailed descriptions follow.

1. The Slotted Section

The slotted line is essentially a section of waveguide with dimensions to suit the particular frequency range in use. The longitudinal slot in the waveguide (see Figure 4) serves to make the slotted section a valuable test device. Specifically, the slot allows an exploring probe to be moved along the interior of the waveguide for sampling the electric field energy being transmitted and reflected. Impedance, standing wave ratio, wavelength, frequency and other related information can be obtained from this.

2. The Probe

This instrument is just what its name implies - a probe for exploring the energy of the electric field within a suitably constructed section of waveguide. It might be considered as a pickup device, sampling the energy under examination and applying it to other devices for measurement and observation. These devices are, in sequence, the crystal detector, the

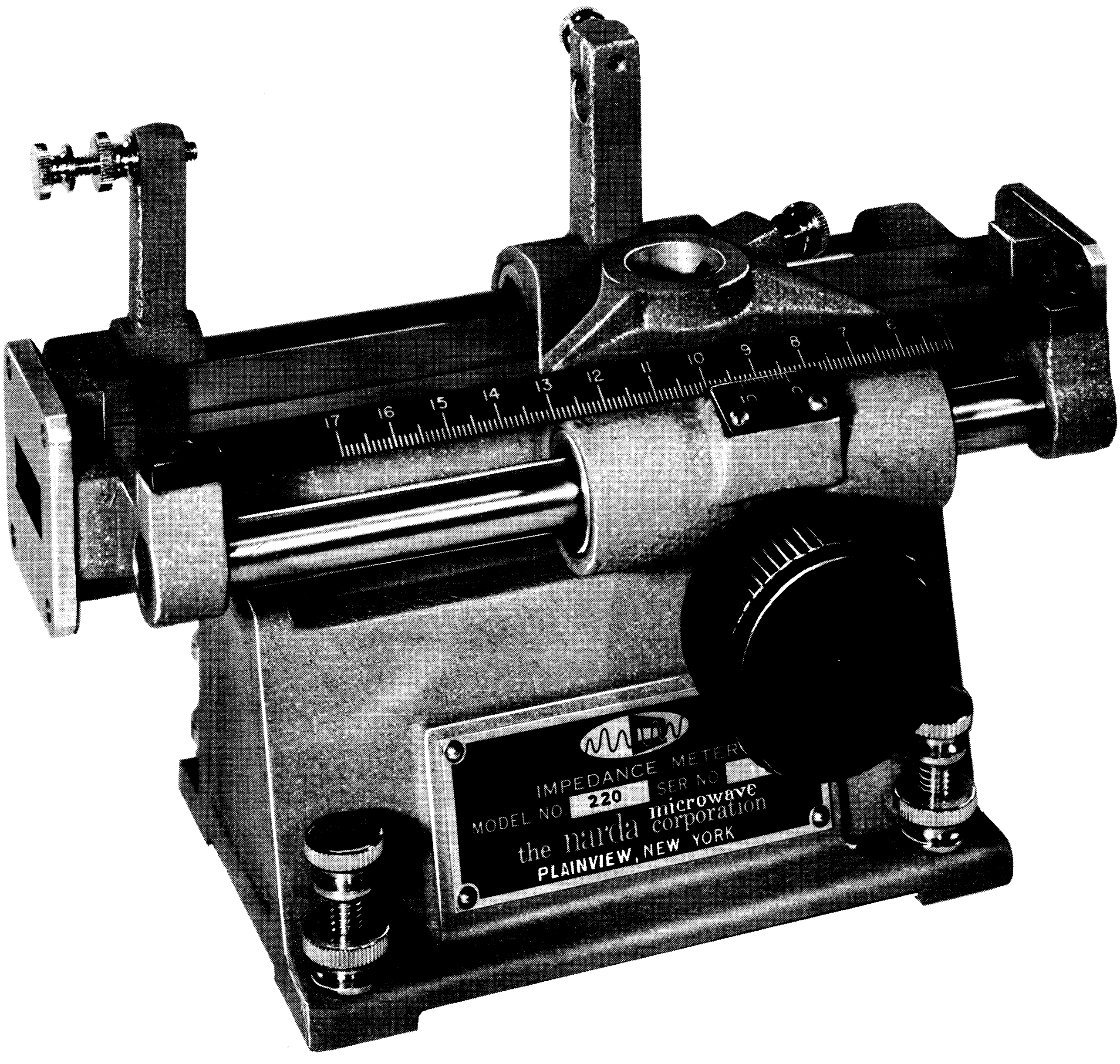


FIGURE 4: X-BAND SLOTTED SECTION - NARDA MODEL 220

standing wave amplifier and the indicator. These will be described in detail later.

Figure 5 shows one type of probe capable of being mounted atop a section of slotted waveguide, as in figure 10, and capable of being moved along this waveguide. The probe housing mounts a crystal detector, which is connected to the input of a standing wave amplifier. The center wire-like projection of the probe - the tip, extends into the waveguide through the slot cut along the long dimension of the guide. Because the probe tip moves in an energy field, a current flows in the probe. When the energy level in the waveguide is constant, the probe current, too, is constant. If, as is usually the case, a standing wave exists in the guide, the current in the probe varies in a manner duplicating the field variations in the waveguide. It may therefore be said that the probe reproduces the standing wave in the guide, and passes it on to the detector and amplifier for examination and visual display.

3. The Crystal Detector

The crystal detector is one of a family of so-called unidirectional conductors - energy readily flows in them in one direction, but very slightly, if at all, in the other direction. This makes them ideally suited as rectifiers of AC. The most popular materials used for crystals are germanium and silicon. The 1N23 crystal used in the experiments to follow is of the silicon type, and is particularly suitable for use at microwave frequencies. Like most devices of this type, the crystal is a low voltage device - it can easily be damaged through the application of an excessive voltage. Another characteristic of crystals is the relation of the crystal output current (or voltage) to input voltage. They are not directly proportional; i.e., the current does not double when the voltage doubles, etc. Instead the crystals are said to follow essentially a "square law" within a certain limited range of applied input power - that is, the output current is proportional to the square of the input voltage, which is another way of saying the output voltage is directly proportional to the input power. This characteristic is of importance in calibrating meters, etc.

4. The Bolometer

Another important device in microwave power measurements is the bolometer. The usefulness of this device lies in the fact that its resistance varies directly with the power applied to it,

FIGURE 5: TUNABLE R-F PROBE - NARDA MODEL 229B

i.e. the bolometer resistance increases, within limits, as the power applied to it increases. Unlike the crystal the bolometer can be operated "square law" over a larger range of input power. There is a large variety of bolometers for use in the microwave spectrum. The most common are the Wollaston Wire types (such as the NARDA N610B series) and the deposited metal film types. In use the bolometers are operated with a fixed dc bias current such that the element has a nominal resistance, usually 200 ohms. When r-f power is applied to the element, the element resistance increases. This change in resistance can be used for the measurement of either relative or absolute power levels. The usual nominal operating range of bolometers is from 0.01 to 1.0 milliwatts, but power levels of almost any magnitude may be measured, through the use of suitable attenuators.

Bolometer elements may be housed in either coaxial or waveguide mounts. In operation, the mounted bolometer is physically inserted in the path of the energy it is to measure. In absolute power measurements the element forms one arm of a bridge. This bridge is normally balanced when the bolometer element has a resistance of 200 ohms, through adjustment of the bias. When power is next applied to the bridge, the resultant unbalance produces a net output voltage. Balance is then reestablished manually or automatically. The energy required to do this can be applied to a calibrated amplifier-output meter system, which reads the power level of the energy being measured.

Relative power levels are indicated when a bolometer is biased by a constant current dc source and when a modulated r-f (usually square wave) is applied. The magnitude of the alternating voltage developed across the bolometer is related directly to the applied r-f power level.

5. The Standing Wave Amplifier

The standing wave amplifier is essentially a high gain precision audio amplifier. It is designed to operate from such input sources as the crystal or bolometer just described, as well as other similar low level input devices. It also has an accurately calibrated gain or amplification, which may be readily changed by any amount within the range built into the amplifier. In addition, the amplifier almost always has a calibrated meter in its output circuit, so that extremely accurate measurements of the input energy ratio may be made. This meter is calibrated to read voltage standing wave ratio (VSWR) either as a number, or as a relative level, in decibels (DB). The scale calibration assumes that the detector (bolometer or crystal) is a "square law" detector.

E. COMPONENT DESCRIPTION

1. The Klystron

The reflex klystron or the velocity modulated klystron, is a vacuum tube radically different in structure and in operation from the conventional vacuum tube oscillator. As shown in Figure 6, the tube consists of two main portions - the beam forming assembly, including heater, cathode and focusing electrode, and the oscillatory group, containing the resonant cavity, the resonating grids and the reflector or repeller. In operation, the focused electron beam is accelerated by the anode, but due to their high velocity, the electrons actually pass through the anode grid structure toward the negative reflector. Here they are repelled, and forced to turn about and travel toward the grids. Now they meet a new stream of electrons traveling forward toward the reflector. The cavity, in the manner of a resonant L-C circuit, effects an alternating speeding up and slowing down of the electron stream. "Bunching" of electrons now takes place at regular intervals in the cavity - oscillation thus results. A pickup loop couples the energy out of the cavity into the waveguide.

Tuning of the cavity is accomplished by a tuning "strut", which reacts against a flexible diaphragm. This results in a change in cavity dimensions, hence a change in frequency. The tuning range of most klystrons is rather limited in comparison to lumped L-C circuits. A minor contributory effect on the klystron frequency is due to changes in operating potentials. Thus, a change in reflector voltage may shift the klystron into a different "mode" of oscillation.

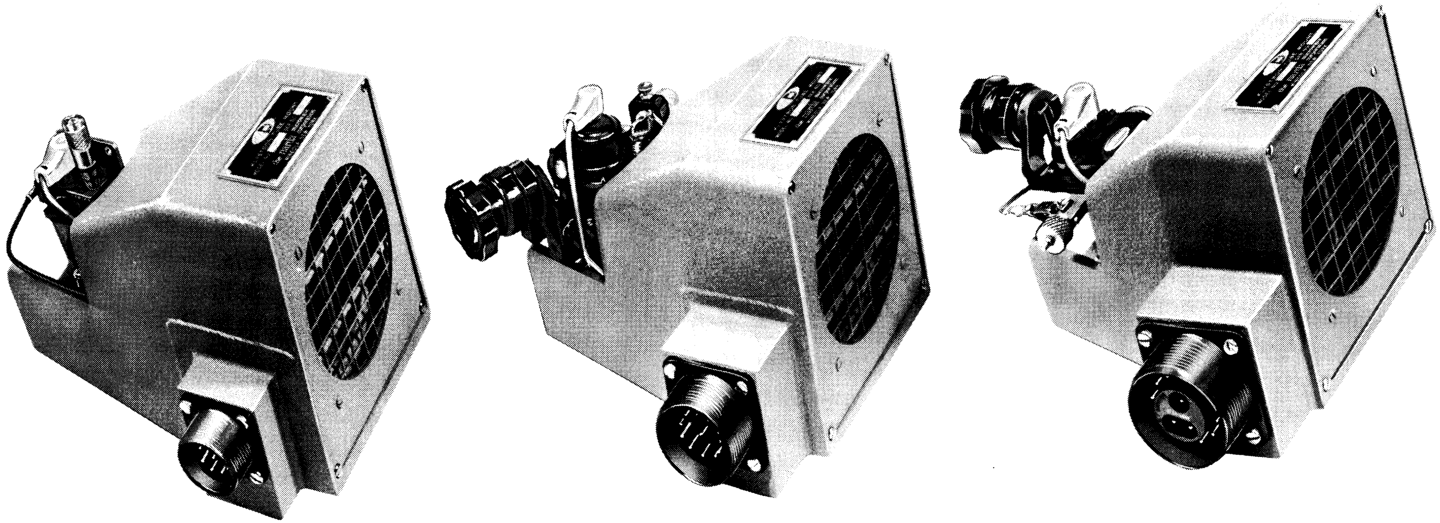


FIGURE 6A: KLYSTRON TUBE MOUNT - NARDA MODEL 990

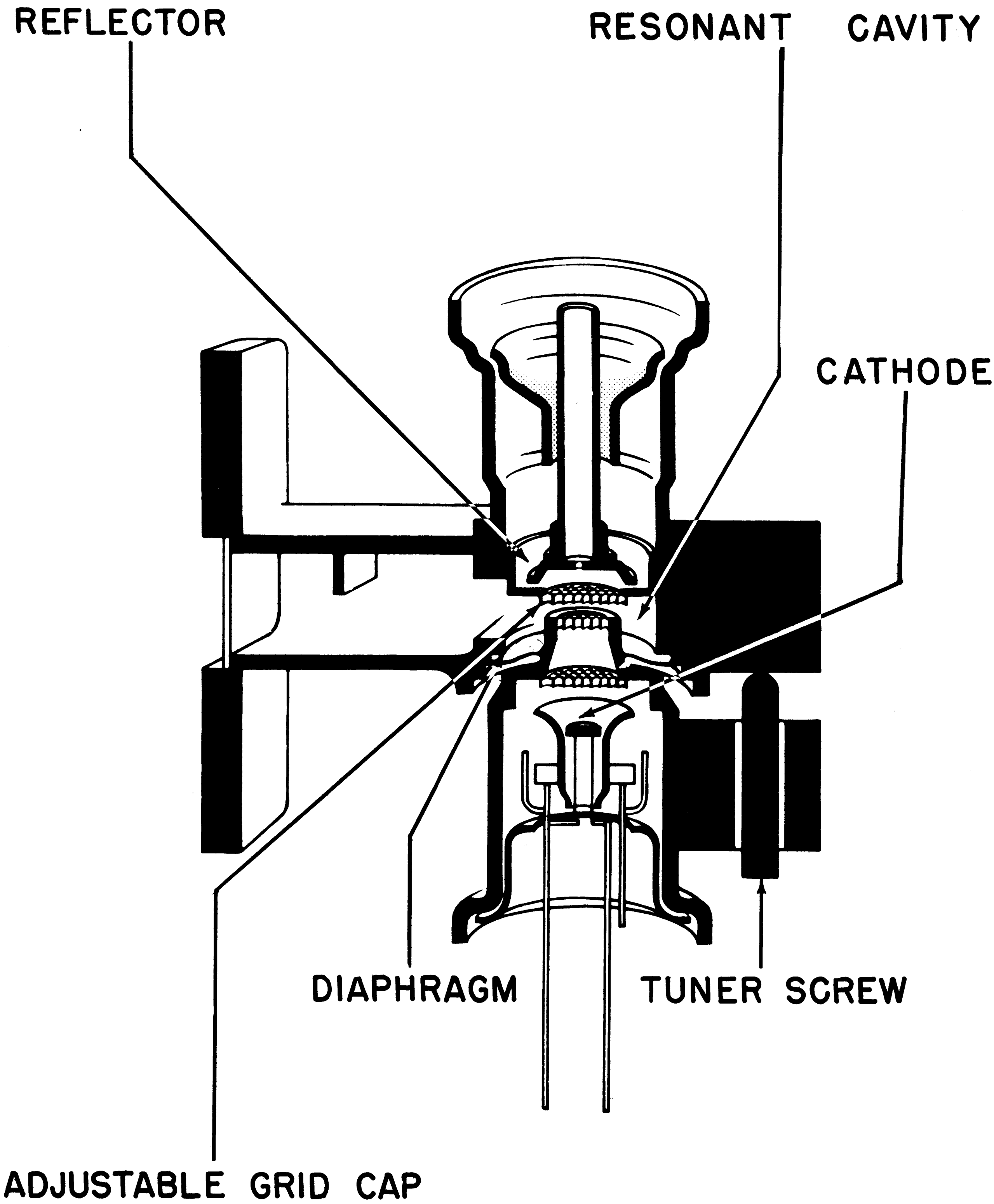


FIGURE 6B: SCHEMATIC REPRESENTATION OF KLYSTRON

The concept of modes is illustrated in Figure 3. As the reflector voltage is changed, the rate of bunching of the electrons also changes, but not in continuous fashion. Instead, there appear areas or lobes of oscillations, which are called modes. In effect, when a sufficient change in reflector voltage is produced, the oscillations cease, only to begin at a different frequency and amplitude, resulting in the pattern shown. Thus, to a limited degree, a klystron is voltage tunable.

2. The Attenuator

In microwave terminology, an attenuator is any dissipative element inserted in the energy field. A typical variable attenuator or "pad", as it is often called is illustrated in Figure 7. Essentially it consists of a resistive or "lossy" surface, sometimes referred to as a "card", placed in a section of waveguide, and adjustable to any position between two narrow walls. When the card moves towards the center (or plane of maximum energy) of the waveguide, the card absorbs more energy and the attenuation therefore increases. As the card is moved toward either of the end walls, where the field is weakest, the attenuation decreases toward a minimum. The adjustment knob or screw often carries a dial or scale, related to the attenuation. The whole assembly is then called a calibrated variable attenuator. Depending upon the size of the card, a variety of attenuation ranges is obtained, usually ranging from 0-6 DB to as high as 0 - 60 DB. The term "pad" stems from the fact that such an attenuator placed between a signal source such as a klystron oscillator, and a load which might be an antenna, for example, produces isolation between the two (this might be thought of as "padding" or "cushioning" the shock or effect of one on the other), and thereby prevents or minimizes interaction between them. Without such isolation, the effect of a load on the signal source might be to produce frequency changes, power changes, reflections and other undesirable effects; even damage to the oscillator tube.

In addition to the type just described, there are other types of attenuators, both variable and fixed. The fixed type appears just like any other attenuator, minus

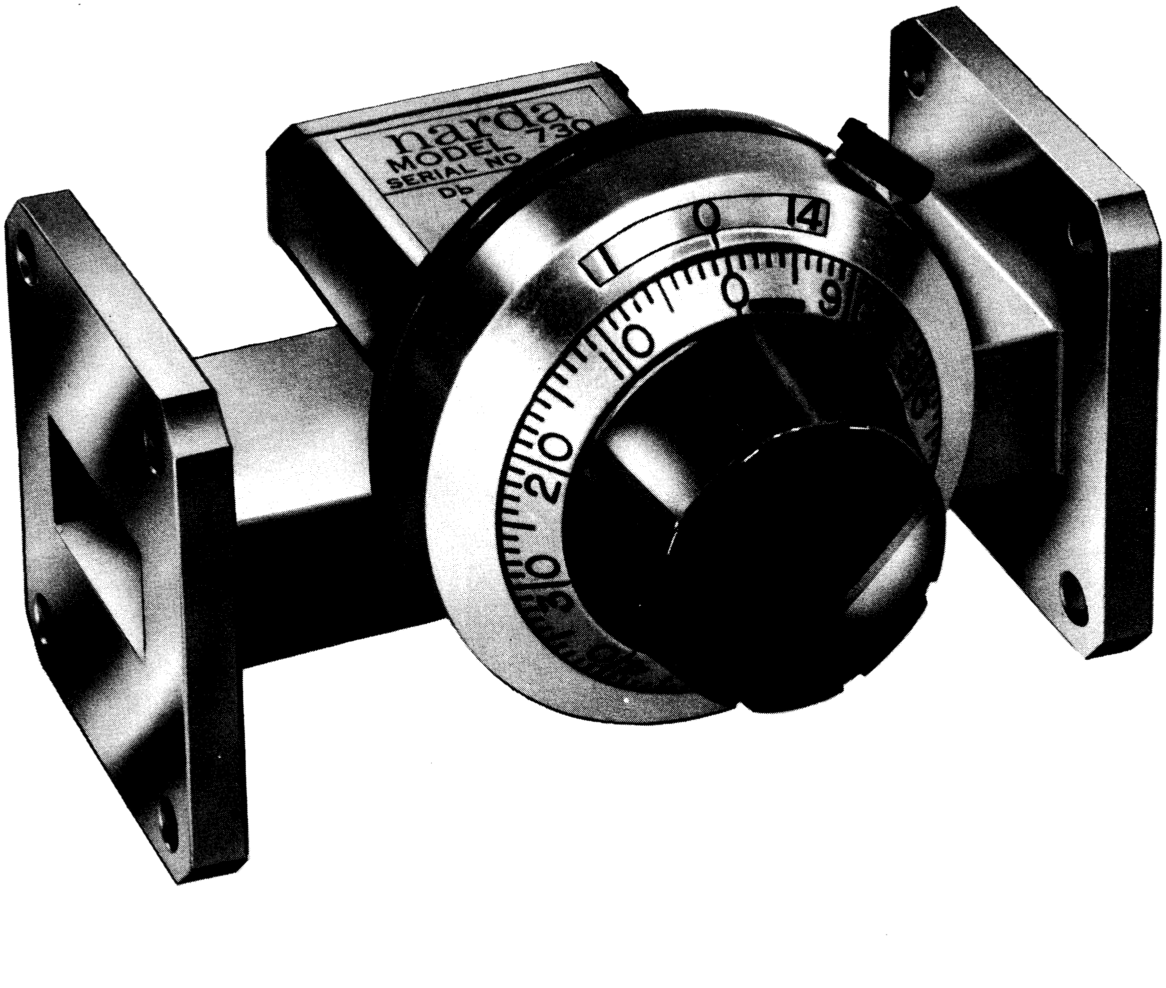


FIGURE 7: VARIABLE WAVEGUIDE ATTENUATOR - NARDA MODEL 730

the knob or dial. The resistive card or element is permanently fixed within the guide. Depending upon the type of element and its size fixed attenuators may have almost any value of insertion loss* between 3 and 60 DB. A third type is the so-called "flap" attenuator. This is similar in function to the attenuator first described. Here the variation in attenuation is obtained through insertion of more or less of the resistive "flap" into the waveguide through the slot. This type of attenuator is usually uncalibrated, or just roughly calibrated. Where a variable attenuator is required, and extreme accuracy is not important, the flap attenuator is often used. Other, more sophisticated attenuator designs have also been produced in recent years.

4. The Frequency Meter

In the Introduction it was stated that wavelength could be measured along the standing wave pattern of the waveguide slotted section, and further, that frequency could be calculated from this measurement. While this is true, it is nevertheless very desirable to be able to quickly and easily measure

* Insertion loss is a term very common in microwave terminology. It applies to attenuators, waveguides, frequency meters and many other microwave circuit components. It simply means the energy loss (usually in decibels) resulting from "insertion" or connection of the component into the circuit resulting from the resistive losses as well as reflections. This is due to the fact that a 100% lossless component is virtually impossible to construct. Thus, even when a high grade calibrated attenuator is inserted in a circuit and the dial adjusted to the minimum or "zero" position, there still remains the insertion loss of the component. In a good quality component, this loss may be as low as 0.5 DB or less, but it is still an unavoidable minimum. This holds true, as mentioned above, even in cases of components which are not intended to have any loss, such as frequency meters, adapters, etc.

frequency without resorting to the slotted line. The microwave frequency meter is the standard instrument used for this purpose. As in the case of the klystron oscillator, the heart of the frequency meter is the resonant cavity. For any particular cavity size, a single frequency will be "supported". If the cavity size can be varied, resonance at a whole range of frequencies may be obtained. Figure 8 illustrates a typical tunable instrument of this type. The adjustable plunger, movable through a calibrated dial-knob assembly, decreases the cavity size as the plunger is moved inward, thus increasing the resonant frequency. The cavity is connected to the source of energy whose frequency is to be measured through a section of waveguide. A "port" or "window" allows some energy to enter the cavity, or, as is often said to be absorbed by the cavity, (hence, the often used name "absorption frequency meter"). The maximum absorption takes place when the cavity is tuned exactly to the frequency of the energy being measured. For greatest accuracy, the "Q" of the cavity is made very high, often as high as 20,000. This means that the tuned circuit is extremely sharp, absorbing a maximum of energy at the exact frequency but much less at slightly different frequencies. Thus, if one observes at which exact frequency dial setting the maximum or peak absorption takes place, he will obtain an accurate frequency measurement. An indicating meter placed in the circuit so as to indicate the energy level of the source would show a sudden drop in such level the moment energy is absorbed by the frequency meter cavity. A frequency measurement would therefore consist of tuning the cavity of the frequency meter until a maximum "dip" occurs on the indicating meter and then reading the calibrated frequency dial.

Accuracies of 0.1% or better are not unusual in this type of instrument. The tuning range, too, can be quite extensive. A typical X-Band frequency meter such as illustrated here has a tuning range from 8.2 to 12.4 kilomegacycles.

The Narda Digital Direct Reading Meter Model 840, supplied with this kit, is the only microwave frequency meter indicating frequency on a digital counter. Digital readout permits rapid frequency measurements without ambiguity or interpolation of a dial. It is accurate to within .08 percent.

FIGURE 8: WAVEGUIDE FREQUENCY METER

4. The Slotted Section

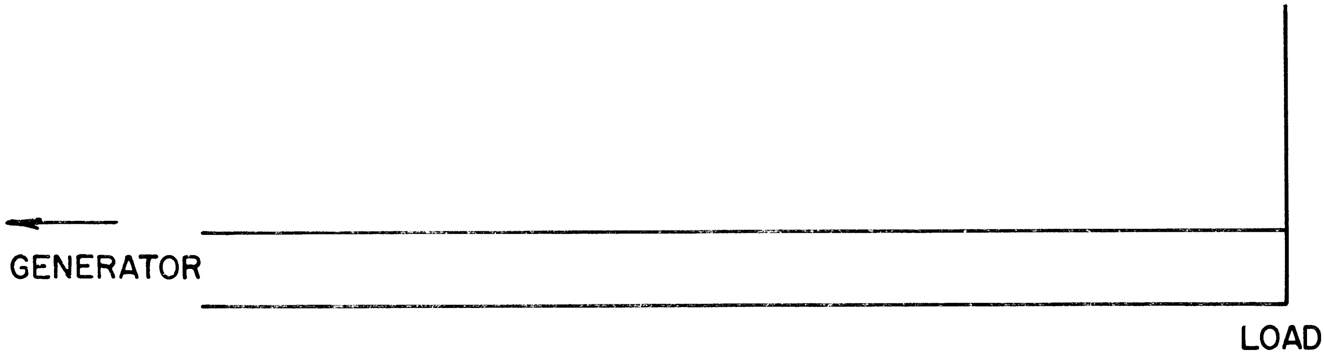
A brief description of this component was given in Paragraph D-1. To fully understand the use of the slotted line, the illustrations of Figure 9 will be helpful. In Paragraph C-3, the basic characteristics of the standing wave were briefly explained. Here we shall add a few details in the interest of clarity. In Figure 9A, the load at the end of the waveguide is a resistance of the correct (matched) value. The corresponding graph of the energy along the line, as might be obtained by sliding the probe along the line and measuring and plotting the energy picked up, is virtually a straight line.

Considering now Figure 9B, we have the opposite extreme. Here the end of the waveguide is terminated by a non-dissipative metallic short. As a result practically all of the energy is reflected, producing (as explained earlier) a standing wave of extreme shape, with the minimum points reaching zero. This condition, too, is rather unusual, although not impossible. It should be pointed out here, that a mismatch of this type is very undesirable for operation, since practically no energy is absorbed by a load of that type.

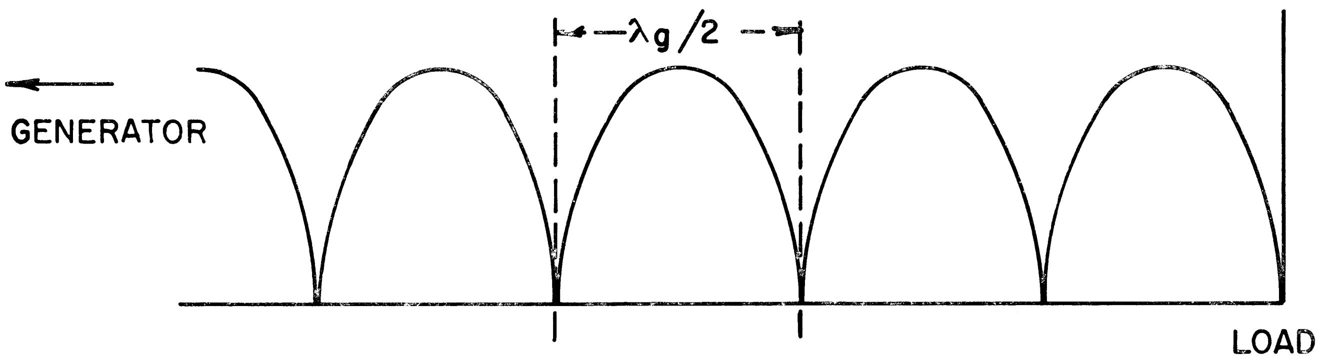
A practical example, representative of the more usual cases of microwave transmission, is shown in Figure 9C. Most of the energy goes into the load, where it belongs. However, because of imperfections in the system, some reflection takes place, and a standing wave results. Note that the minima are not too deep, indicating a rather mild standing wave, compared to that shown in Figure 9B.

Standing Wave Ratio

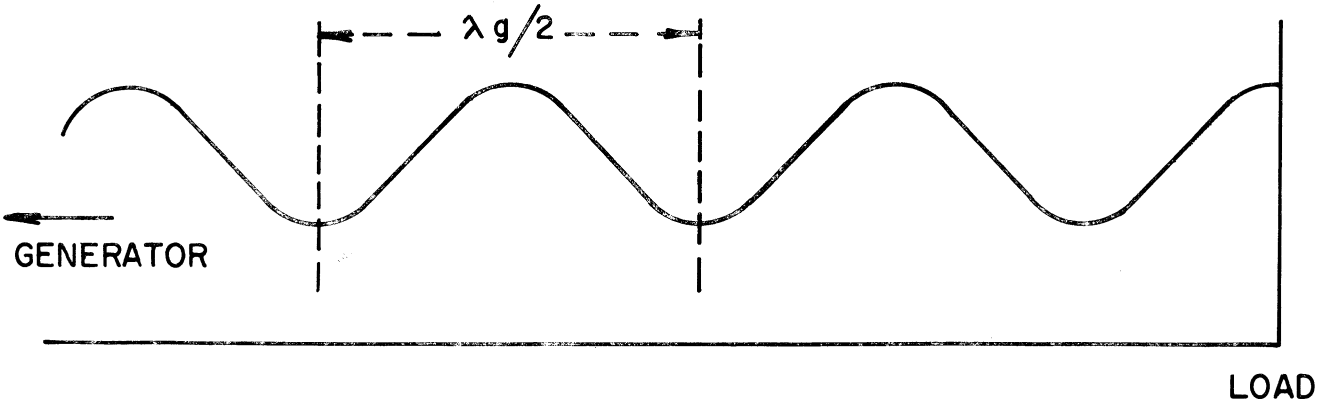
In the above examples of energy transmission the height of the wave was not emphasized. This is because the maximum of the wave may or may not be indicative of the level of the transmitted energy. What is important is the depth of the minimum, or the relative value of this minimum to the maximum. This relative value, regardless of the height of the wave, is called the standing wave ratio. When the measurement is made in terms of voltage, we call this the



a. VOLTAGE STANDING WAVE, MATCHED LOAD.



b. VOLTAGE STANDING WAVE, SHORT CIRCUIT AT LOAD END.



c. VOLTAGE STANDING WAVE, LOAD IMPEDANCE TOO HIGH.

FIG. 9 THE EFFECT OF VARIOUS TERMINATIONS ON STANDING WAVE voltage standing wave ratio, abbreviated VSWR. Power ratios are also frequently used and are so identified to avoid confusion. Numerically, the voltage standing wave ratio is the ratio of the highest to the lowest point in the wave. Thus,

$$VSWR = \frac{E_{max}}{E_{min}}$$

Applying this standard to the three examples given above, we have the following: In the case of the "matched" circuit, the maximum and the minimum are of the same value (there is no minimum), and the ratio is 1:1, or just plain 1.0. It may therefore be said that under ideal conditions the VSWR of a circuit is 1.0. The extreme mismatch condition has zero for its minimum (Figure 9B); the ratio 1/M as M approaches zero is infinity. Finally, in the most common cases, as exemplified by Figure 9C, the ratio is some number greater than 1.0. For example, if the minimum value is 40% of the maximum, the VSWR is 1/.4 or 2.5. In a well designed circuit using matched components, a VSWR of as low as 1.02 is not rare.

The wavelength (and indirectly frequency) measuring facility of the slotted section is based on the fact that on a standing wave pattern the successive peaks (as well as troughs) are spaced exactly 1/2 guide wavelength apart. From a maximum to a minimum, or vice versa, the distance is 1/4 guide wavelength. In connection with this fact it must be added that the physical length along the waveguide is somewhat longer than the exact length of the wave. It becomes necessary, therefore, to make appropriate corrections when it is desired to know the exact length. Specifically the guide wavelength λ_g is longer than the wavelength in the air, λ_0. Their relation is expressed as

$$\lambda_g = \frac{\lambda_0}{\sqrt{1 - \frac{(\lambda_0)^2}{(2a)^2}}}$$

where a = inside wide dimension of the waveguide

From this one can solve for λ_0 and thus find frequency from

$$f = \frac{3 \times 10^{10}}{\lambda_0 \text{ (cm)}}$$

(for example see solution page 46)

5. The Probe

Both the probe and the detector were mentioned in the introductory discussion. At this time it is desirable to examine the probe-and-detector assembly as a unit, since they are invariably used that way, and since neither one without the other can accomplish the function of coupling the energy from the waveguide to the amplifier and indicator. A combination waveguide probe-detector is shown in Figure 10. Since the prime function of the instrument is to absorb a sample of the energy without otherwise disturbing the circuit, the waveguide section must in every way meet the requirements for the particular frequency of operation. A tuning adjustment is used so that the probe assembly, including the crystal mount, is matched to the system and produces a maximum output from a minimum pickup from the waveguide and the transmission system as a whole. The crystal is essentially a diode rectifier, and is chosen for the most suitable characteristics for the frequency band in which it is to operate. The output is the modulated envelope of the klystron output, and not microwave RF. Actually, there is a filter in the output circuit of the crystal mount (usually it is part of the physical structure) to bypass or filter out the high frequency variations. Because of the nature of the output, waveguide is no longer needed; a simple coaxial (BNC) connector is most commonly used for coupling the crystal output to the input of the standing wave amplifier. For accurate measurements over a larger input power range, a bolometer should be substituted for the crystal.

6. Tunable Waveguide Detector

One of the most important needs for microwave circuits is the detection of the power level of the transmitted energy. As mentioned in the introductory discussion, the conventional voltage-current power measurement techniques used at lower frequencies are completely unsuitable here. As a matter of interest, the heating effect method of power detection in the microwave spectrum is no less fundamental than the voltage-current measurements at lower frequencies. Figure 11 illustrates the waveguide type power detecting assembly. The essential element of this power detecting technique is a heat-sensing element, of

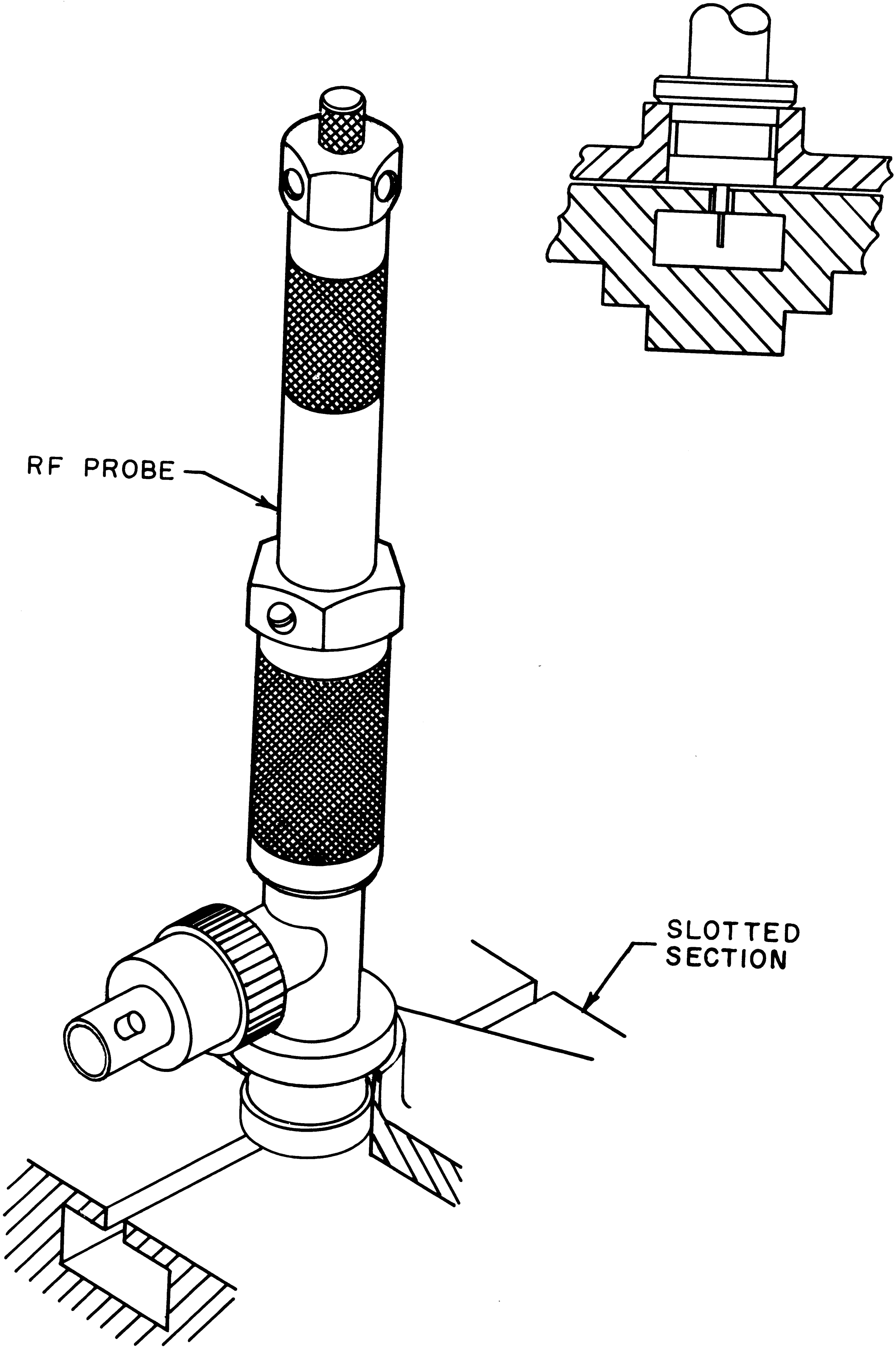


FIGURE 10: SLOTTED LINE PROBE ASSEMBLY

which there is quite a variety. The most widely used are the bolometer and the thermistor. These devices are accurate indicators of power levels dependent upon the manner in which they are used. The bolometer can be used in conjunction with a d-c bias source and an a-c amplifier and voltmeter to detect relative power levels. A crystal can be used in place of the bolometer to indicate the relative power levels. Its limitation to small ranges of power must be realized to obtain any accuracy. In many cases the mount can be used just to monitor power. The tunable short is always adjusted for either the best match or maximum output. For absolute power measurements the thermistor and bolometer can be used in conjunction with a manual or self-balancing bridge network which employs the power substitution.

In a resistance bridge method of power measurement, the bolometer or thermistor is used as one arm of the bridge. By feeding a current to the bolometer, its resistance can be adjusted until the bridge just balances. This is the "zero" reading. When r-f power is applied to the element, its resistance further changes, unbalancing the bridge. This is now brought back into balance by appropriately changing another arm of the bridge, the latter being an accurately calibrated resistance. The dial operating this resistance can be calibrated directly in units of power (milliwatts or watts), so that power measurements are made and read directly on this dial.

The Power Substitution Method

As mentioned earlier, the basis for power measurement in microwave circuits is the fact that within certain limits the heating effect of DC, low frequency AC and microwave power is the same. This principle is also utilized in the automatic power substitution type of power meters. The operation is briefly as follows: The bolometer or other sensing element is connected in a balanced circuit, such balance being obtained by feeding a certain amount of low frequency power (audio, for example) to the element to bring its resistance to the value required for balance. When the r-f power is applied to the element, its resistance further changes, causing unbalance. By means of feedback some of the originally applied power is removed. The amount removed

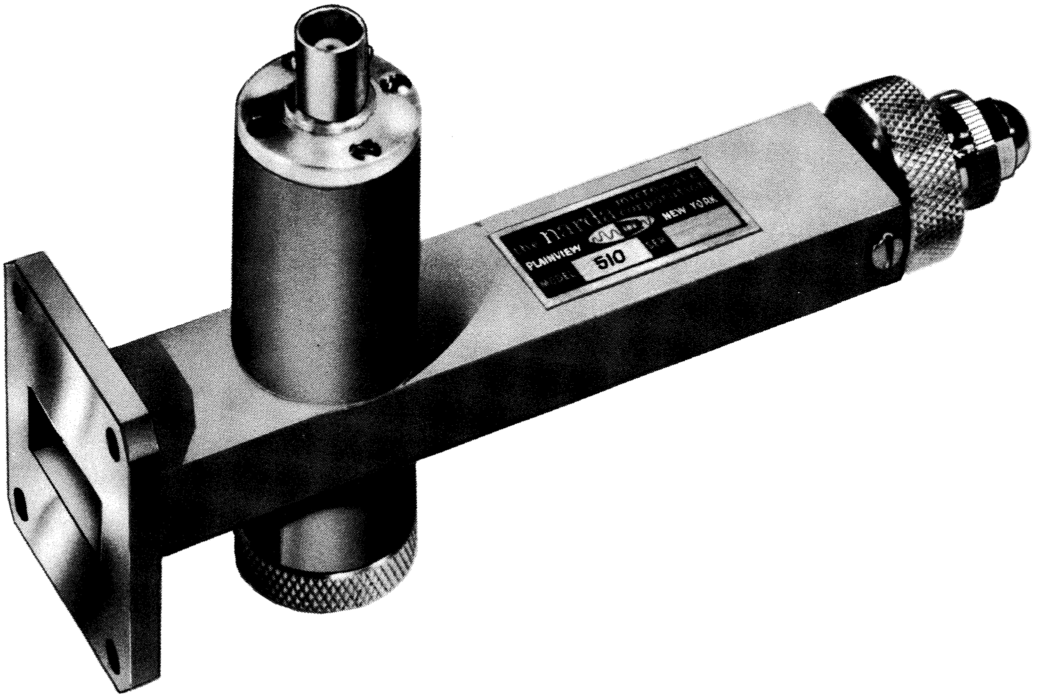


FIGURE 11: TYPICAL TUNABLE WAVEGUIDE DETECTOR - NARDA MODEL 510

is just equal to the microwave power added, when balance is obtained. The meter actually reads the power thus removed, but is calibrated for r-f power applied, for direct reading.

7. Sliding Termination

As the name suggests, this is a termination or a load for a microwave power setup. As was discussed earlier, standing waves occur whenever a load does not completely absorb the power reaching it. In microwave measurements, whether for power or component characteristics (VSWR of a slotted section, etc.), it is usually necessary to have the setup properly terminated for minimum reflection. The sliding termination serves this purpose. Figure 12 shows this device. The closed end houses a resistive element of suitable electrical and mechanical characteristics for providing a near-perfect load. The sliding feature allows for the small reflection of the termination to be taken into account. The VSWR obtained with this device is actually far better than is required for any use except for laboratory measurements and calibration of other components. VSWR's as low as 1.005 are not unusual in well designed sliding terminations.

8. The E-H Tuner

The E-H tuner is essentially a mismatch correcting device. Before describing it however, some explanation of the energy field within a waveguide is in order. In all of the discussions so far, reference was made to the "energy field". This terminology, although correct, was extremely brief and oversimplified. In a somewhat more fundamental manner, the description is as follows:

The energy generated by a system such as described here is a wave motion of electromagnetic energy. This clearly implies that both electric and magnetic fields are involved. Briefly, the electric field is most commonly represented by the field between capacitor plates to which a voltage has been applied. The magnetic field is that surrounding an inductance when a current is flowing through it. The energy in the waveguide - electromagnetic energy - is a combination of the two in a specific and definite manner.

FIGURE 12: WAVEGUIDE SLIDING TERMINATION

The relation between these fields and the resultant wave motion may be understood from this simple example. If a rectangular piece of cardboard were held so that it would stand on the table the edge standing on the table would represent the magnetic field, the adjoining edge pointing upward would represent the electric field, while the direction of propagation (wave motion) would be indicated by moving the cardboard, in its upright position, along the table in a direction perpendicular to its face. In the waveguide the electric field is top to bottom between the narrow walls, the magnetic field perpendicular to it, is horizontally across between the wide walls, while the direction of propagation is along the waveguide length. A useful analogy is that these fields correspond to, or have, low frequency equivalent circuit concepts. Thus the H-field (magnetic) could be represented in equivalent form as a series resonant, low impedance circuit, while the E-field (electric) would correspond to the high impedance parallel resonant circuit. The practical utility of the E-H tuner lies in the use of these combined series-parallel resonance characteristics.

Figure 13 shows an X-Band E-H tuner. It consists of a section of waveguide with flanges at both ends for connection into a microwave system. At the center of this section are two waveguide arms, at right angles to each other. These arms are each terminated in a movable short, with a tuning adjustment for accurate setting. The section extending from the wide wall of the main waveguide is called the E-plane arm and is equivalent to series tuning element. The arm extending from the narrow side of the main waveguide is the H-plane arm and is essentially a shunt tuning element.

This availability of ranges of series and shunt reactances in the form of tuned circuits makes the E-H tuner valuable as a matching device. When inserted in a microwave circuit having a high standing wave ratio - an admittedly undesirable characteristic - it is possible to reduce this high VSWR to an acceptably low value. Thus a microwave circuit with a VSWR of 15:1 to 20:1 could be matched to 1.05:1. The tunable feature of the device makes it adaptable to a range of frequencies, in addition to the ability of accurate tuning at any point.

9. <u>Standard Gain Horns</u>

The waveguide horn illustrated in Figure 14 is essentially

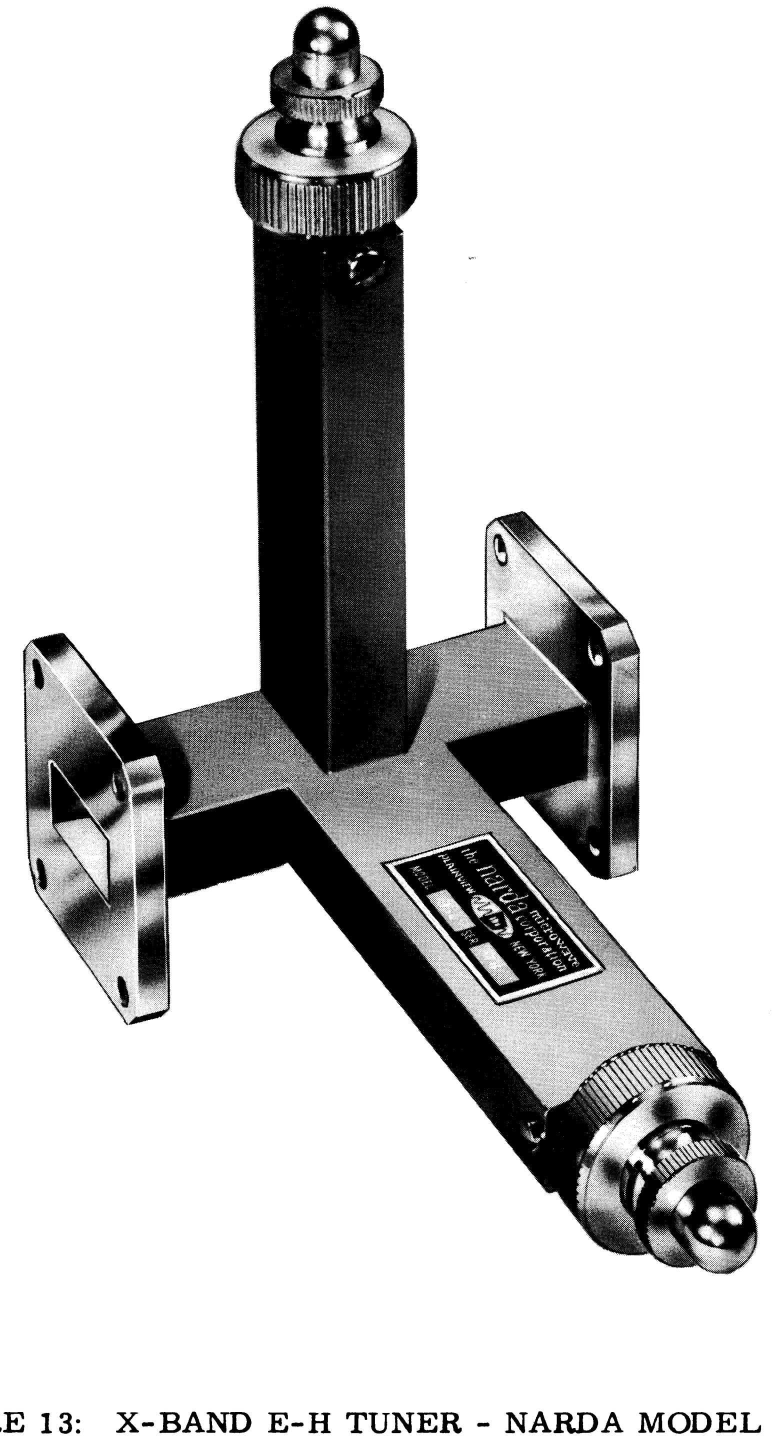


FIGURE 13: X-BAND E-H TUNER - NARDA MODEL 960

a modification of a section of waveguide. Because of its shape, the horn has some very directional characteristics. It concentrates the energy emitted from the flared end in a specified beam and effectively increases the power output, in comparison with an unconcentrated beam. The waveguide horn may be used as an actual antenna, as a standard of comparison or as a pickup device for measuring received energy from a source. A most common application of the waveguide horn is the calibration of gain of experimental and other antennas of unknown characteristics. The standard gain horn is rated in DB of gain, meaning how many times more effective it is than a basic (isotropic) antenna that radiates equally well in all directions.

Standard gain horns characteristics are described by their beam width in degrees, and their power gain in decibels. Both of these characteristics vary with frequency, with the gain usually increasing with frequency. The specified gain is usually at some nominal frequency, or at the mid-frequency of the operating range.

10. Standing Wave Amplifier

The standing wave amplifier is basically a high gain, low noise audio amplifier, as already stated previously. However, it has a number of specific qualifications that make it particularly suitable for VSWR measurements, relative power level indications and similar specialized functions. For instance, the input circuit is designed to bias a bolometer to the proper initial resistance value. When used with a bolometer the standing wave amplifier is accurately calibrated for measurements of relative power, in db (see paragraph D4), as well as for VSWR measurements. Another input position is designed to work from a crystal detector such as is commonly used in microwave work (see paragraph D3). Still another specialized feature of this amplifier is the calibrated gain variation - the gain may be changed in fixed steps, to a high order of accuracy. The very high overall gain

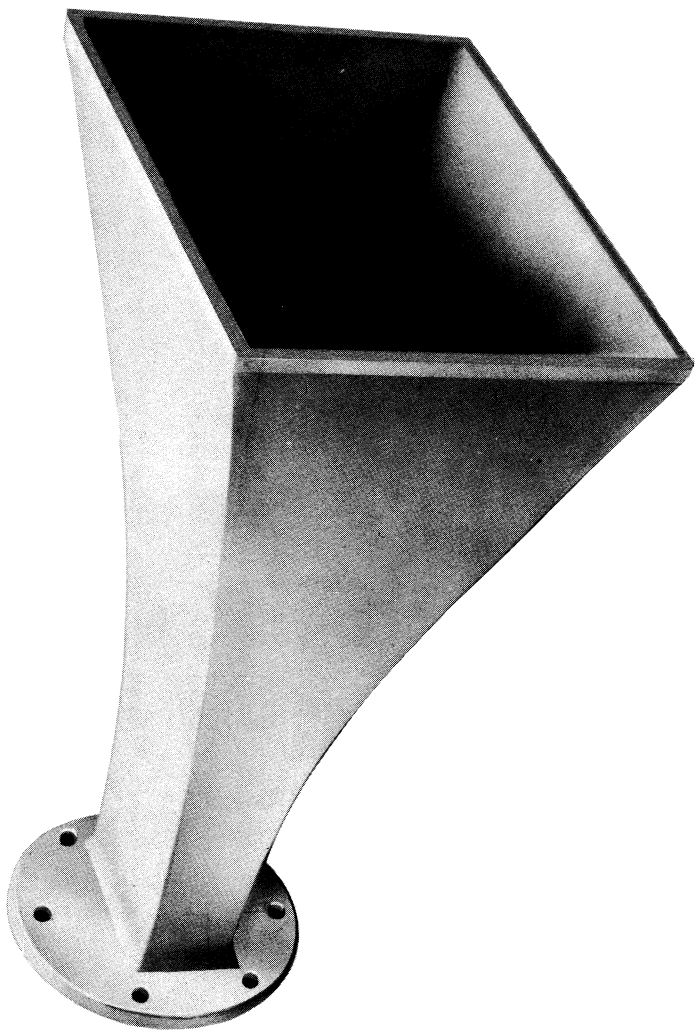


FIGURE 14: EXAMPLES OF STANDARD GAIN HORNS

coupled with extremely low noise figure makes this amplifier suitable for use with extremely low level input signals.

The VSWR amplifier shown in Figure 15 is a good example of the above. In addition, it has some other desirable constructional features. These include a self-contained power supply. An optional rechargeable battery can be supplied, making the instrument independent of power line supply and power line fluctuations; a protective circuit to insure against damage to, or burnout of, the very delicate bolometer element; transistorized amplifier circuitry which avoids filament heating problems, with resultant instability, warmup requirements, etc. The manual supplied with the unit for this kit has additional pertinent information.

11. Klystron Power Supply

Earlier in this manual, the klystron tube was described as a main source of r-f energy in the microwave spectrum. While the polarities of the various elements were indicated at that time, it is necessary to specify the power supply requirements of the klystron tube more definitely at this time, in order to understand the rather complex nature of the klystron power supply.

The cathode, grid and focusing elements (grids) of many klystrons have approximately the same power supply requirements as a medium power receiving tube. Because of the nature of the klystron and the purpose and use to which it is put, this supply has to be much more stable and regulated than the usual amplifier or oscillator power supply at low frequencies. Similarly the hum content (ripple voltage) for the klystron "gun" must be much lower than for ordinary vacuum tube applications. The second power supply requirement for the klystron is the negative reflector supply. Here

FIGURE 15: NARDA MODEL 441C TRANSISTORIZED VSWR AMPLIFIER, SHOWING OPERATING CONTROLS

the voltage is much higher perhaps as high as 750 volts, but the current requirements are comparatively low, being in the order of a few microamperes. Since, as explained earlier, the reflector voltage has a direct bearing on the klystron frequency, it is essential that this voltage be well regulated, and free from ripple.

The third requirement of the klystron power supply, that of supplying the modulation for the klystron, stems from the nature of a microwave transmission system. This is essentially a pulsed RF system. The klystron at the transmission end of the system, is usually square-wave modulated by a series of extremely steep rectangular ("square") waves called pulses. At the receiving end, this pulsed RF is demodulated, very much in the manner of low frequency demodulation, and the average pulse envelope is considered as the output. The klystron power supply usually provides this modulation source. Figure 16 shows the NARDA type 438 power supply. The characteristics of the self-contained square wave modulation source of this supply are as follows:

Frequency Range	300 to 3000 pulses per second (this is sometimes called the pulse repetition frequency, or PRF).
Pulse Amplitude	0 to 150 volts peak to peak
Pulse Rise Time	10 microseconds maximum
Pulse Decay Time	10 microseconds maximum

In addition to square wave modulation, this unit also supplies saw tooth and sine wave modulation when required. As with the standing wave amplifier the manual supplied with this unit contains much additional information.

FIGURE 16: A TYPICAL KLYSTRON POWER SUPPLY - NARDA MODEL 438

SECTION II

LABORATORY EXPERIMENTS

A. SUGGESTIONS TO INSTRUCTOR

1. General

The purpose of these experiments is to demonstrate some basic principles as well as methods which are unique and peculiar to microwaves. These principles and methods obviously apply to the microwave spectrum in general. The choice of X-Band components was dictated by convenience of physical size as well as by the predominant importance of this band.

The numerical results and their accuracies (or relative inaccuracies) are important only insofar as they demonstrate the principles and mechanics involved. Obviously, these calculations are not intended to serve as designs for actual construction. It is for these reasons that it is important to study and understand the introductory discussions preceeding the experiments.

2. Specific Instructions

In the experiments to follow, it is essential that the student is adequately prepared for each experiment, if he is to get the maximum benefit. The preparation should include study of the introductory material at the beginning of the experiment, preparation of a table of data for the experiment, and a careful listing of the operating characteristics such as voltages, currents, polarities, etc., of the klystron tube as well as the thorough familiarization with the operation of the auxiliary instruments. This includes the VSWR amplifier and the klystron power supply. All the above should be done under the instructor's guidance prior to the actual conduction of the experiment.

3. Reports

The instructor should advise the student in advance that the experiment is intended to supply the data for answering the questions at the end of the experiment as well as to enable carrying out any other assignments called for. Since the intent of these questions is to elicit logical, well thought out answers, it follows that simple "yes" and "no" answers are worthless. For the same reason, answers must be properly justified on the basis of experiment.

4. Techniques

Every effort should be made by the instructor to have the student "carry on" with a minimum of help. These experiments have been written with this purpose in mind. However, the newcomer to microwave techniques cannot be expected to be self-sufficient; the example set by the instructor as well as his assistance in the finer points of the experimental techniques can be of invaluable aid to the student. Furthermore, due to the nature of some of the equipment (klystron, bolometer, crystal, etc.,), it is imperative that the student is not put in a position of having to guess. A few specific instances where the instructor's assistance is required are given below. Many others will suggest themselves in individual cases.

a. Basic Setup

This includes the application of proper potentials in correct sequence to the klystron, tuning to the right mode and frequency, adjusting the termination, provision for warmup and stabilization, and otherwise optimizing the setup for maximum power output. For the first time at least, the student shall be a careful observer, and the instructor shall be the performer.

b. Discussion

As a follow-up to the student's preparation, the instructor shall briefly give his version of the introductory material, call attention to the highlights of the experiment and point out any "do's" and "dont's" wherever they apply. Subjects which may be new to the student require, of course, more extensive effort by the instructor.

The list of topics which may require such additional effort are:

1. <u>Concept of "Field"</u>

The explanation of the E and H components and field propagation, already explained under Paragraph E-8 of Section I (E-H Tuner) may be enhanced by further discussion with some blackboard illustrations.

2. <u>Standing Wave</u>

This idea should be elaborated upon, perhaps as a follow-up to the explanation of the "field". Since practically all measurements in these experiments as well as in general microwave work are intimately associated with the standing wave pattern, a good understanding of this phenomenon is essential.

3. <u>Complex Notation</u>

This includes a number of important ideas. It is sufficiently extensive to justify a considerable effort. It is suggested that the instructor extend this discussion, based on the needs of the particular group, over a number of sessions, with perhaps a fifteen minute discussion each session. The topics should include the "j" operator, the meaning of the absolute value, phase, vector algebra, and the manipulation of the infinity symbol ∞ in fractional notation. The idea of limits (..."as something approaches zero or infinity...") may also be introduced here, at the discretion of the instructor.

4. <u>Smith Chart</u>

This important topic can most usefully be introduced and taught as the last part of the work on complex notation. It might perhaps be prefaced by the introduction of rectangular coordinates plotting, then by the presentation of the curvilinear coordinate system. The advantages of curvilinear coordinates, including the concept of a "continuous plot" should also be pointed out here. A few actual examples, followed by simple "problems" to be worked out by the student, should make this task both interesting to the student and productive of results.

5. Discontinuity

The instructor can perform a double service to the student when demonstrating the effect of a slight cocking of a pair of mating flanges for the purpose of producing a discontinuity and consequently a standing wave pattern. While a standing wave pattern is deliberately obtained here for the purpose of the experiment, the student is also made aware of the importance of carefully connecting and mating waveguide components in normal operation in order to obtain as perfect a match and as low a VSWR as possible. Other examples of producing discontinuities may be demonstrated, such as partial obstruction, an iris etc. The analogy to poorly connected components in conventional wire circuits may be put to good use by the instructor.

6. Power, DB, DBM

Both the concept of absolute power levels and the significance of relative power levels should be explored fully by the instructor. He should aim to make the student as adept as possible in the use of the decibel scale for expressing power levels. Such an apparently great step as the doubling of a power output might be put in its proper perspective when it is pointed out that as far as results are concerned, the increase is but 3 DB ! In addition, the popular power level base and the associated DBM scale should be fully developed by the instructor. Finally, the relation between average and peak power levels, as expressed by the term "duty cycle", should be elaborated upon from the viewpoint of practical radar applications.

7. Microwave Behavior

The instructor should make use of the opportunity offered by the experiment on the standard gain horns to demonstrate the great similarity in behavior between microwaves and light. The directional characteristics of X-Band energy, for example, lend themselves readily to this purpose. It is further advisable that the student be given a careful demonstration of reflection, direction and other radiation pattern phenomena, as far as the circumstances permit. It is quite probable that the student may not appreciate at first the effects of small changes in horn positions on the direction and magnitude of the resultant beam.

B. EXPERIMENTS

EXPERIMENT 1: WAVELENGTH, FREQUENCY, GUIDE WAVELENGTH

Object

1. To learn the procedure for wavelength measurement using the slotted line.

2. To learn the difference between free space wavelength and guide wavelength.

3. To learn to appreciate the capabilities of microwave components for basic measurements.

Discussion

Electromagnetic waves have three basic related characteristics namely: wavelength, frequency and velocity of propagation. The product of the wavelength and the frequency give the velocity of the energy. In low frequency circuits this relation is commonly expressed as

$$\lambda \times f = v$$

where λ is in meters, f is in cycles per second and v is in meters per second. The symbol c (indicating a constant) is often used instead of v, since in free space the velocity of propagation equals the velocity of light, namely 300,000,000 meters per second. While this general relationship holds true at microwaves as well, there are some differences that require mention. First is the fact that for any specific wave, the frequency is constant, while the velocity of propagation and wavelength vary to a degree with the medium in which the the wave is propagated. Since waveguides are common media of propagation of microwave energy, this variation in velocity and wavelength is important. A second difference, although not basic, is nevertheless very useful and therefore worthy of notice. This is the fact that the length of the transmission medium (such as a waveguide) is relatively large compared to the wavelength of the energy. This, of course, enables measurement of one or more wavelengths along a small enough section of waveguide, (a slotted line, for instance).

When making wavelength measurements using a slotted line setup such as is shown in this experiment, it is important to take cognizance of the difference in the length of the wave in free space and that in the waveguide. This difference is dependent upon the physical dimensions of the guide, which is specifically related to the lowest frequency wave that will be propagated by the guide, commonly called the "cutoff wavelength". Dimensionally, this corresponds to twice the large inside dimension of the rectangular waveguide. Thus the formula for the guide wavelength is

$$\lambda_g = \frac{\lambda_o}{\sqrt{1 - \left(\frac{\lambda_o}{2a}\right)^2}}$$

where a is the large dimension of the inside of the guide.

Observe that the denominator cannot ever be greater than 1, hence the guide wavelength λ_g is never shorter than the free space wavelength λ_o, but almost always longer. In making measurements for the determination of an unknown wavelength, the correction indicated by the above formula must therefore be made.

In the experiment to follow there is also included a precision frequency meter. It has a dual function. First, it enables setting the klystron oscillator to the desired frequency. Second, it is an indirect method of wavelength measurement through the relation between λ_g, v and f. It also serves as a check on the experimental data and the resultant calculation, as well as a calculation of the velocity of propagation on the basis of guide wavelength and frequency. Two other seeming "peculiarities" need be explained before proceeding with the experiment. First is the placement of an attenuator on either side of the frequency meter. Second is the deliberate misalignment or "cocking" of the flanges joining the slotted section and the sliding termination. The attenuators flanking the frequency meter are not placed there merely for the purpose of reducing the energy level. Their purpose is more exactly termed as that of isolation, i.e., separation of the frequency meter, whose main and perhaps only value is accuracy, from the loading effects of adjacent components, including the klystron, which can tend to "pulling". In other words, the padding attenuators on either side of the frequency meter insure greater freedom from frequency inaccuracy due to the mutual effects of adjacent components upon the klystron and the frequency meter. The misalignment of the termination is done for the following purpose: The measurement of wavelength along the slotted section obviously depends on the existence of maxima and minima, or a standing wave, along the line Since a standing wave exists only under conditions of mismatch, the normal connection of a matched termination, such as the NARDA Model 380, would preclude the existence of a standing wave. One of the simplest ways of producing a reflection and hence a standing wave pattern is to produce a mismatch or discontinuity. Such a discontinuity results from imperfect mating of waveguide flanges, misalignment of components, etc. Since it is desired to obtain the highest possible accuracy in our wavelength measurement, the standing wave ratio should be fairly high, because this kind of a pattern gives the sharpest minimum and maximum points. The directions given below are intended to give such a pattern.

Figure 17 shows in block form the test setup for wavelength-frequency measurements. The various precautions and procedures for obtaining best results are given in the individual steps of the procedure.

Procedure

1. Set up the components as shown in Figure 17. Align all waveguide flanges carefully and tighten securely.

2. Switch on the filament switch on the model 438 power supply and allow a 5 minute warmup period. Also switch on the model 441C Standing Wave Amplifier.

3. Set up the controls on the klystron power supply in strict agreement with the instructions in the 438 Instruction Manual and the recommended operating potentials for the type X-13 klystron.

3(a). X-13 DATA

Frequency Range	8.2 to 12.4 gc
Beam Voltage	500 V
Beam Current	30 ma min. - 55 ma max.
Output Power	100 mw min.
Heater Voltage	6.3 V at .44 amps
Reflection	-300 to -350V

Pin Connection

1. Heater
2. Cathode
3. Heater

Pins 1 and 2 are internally connected.

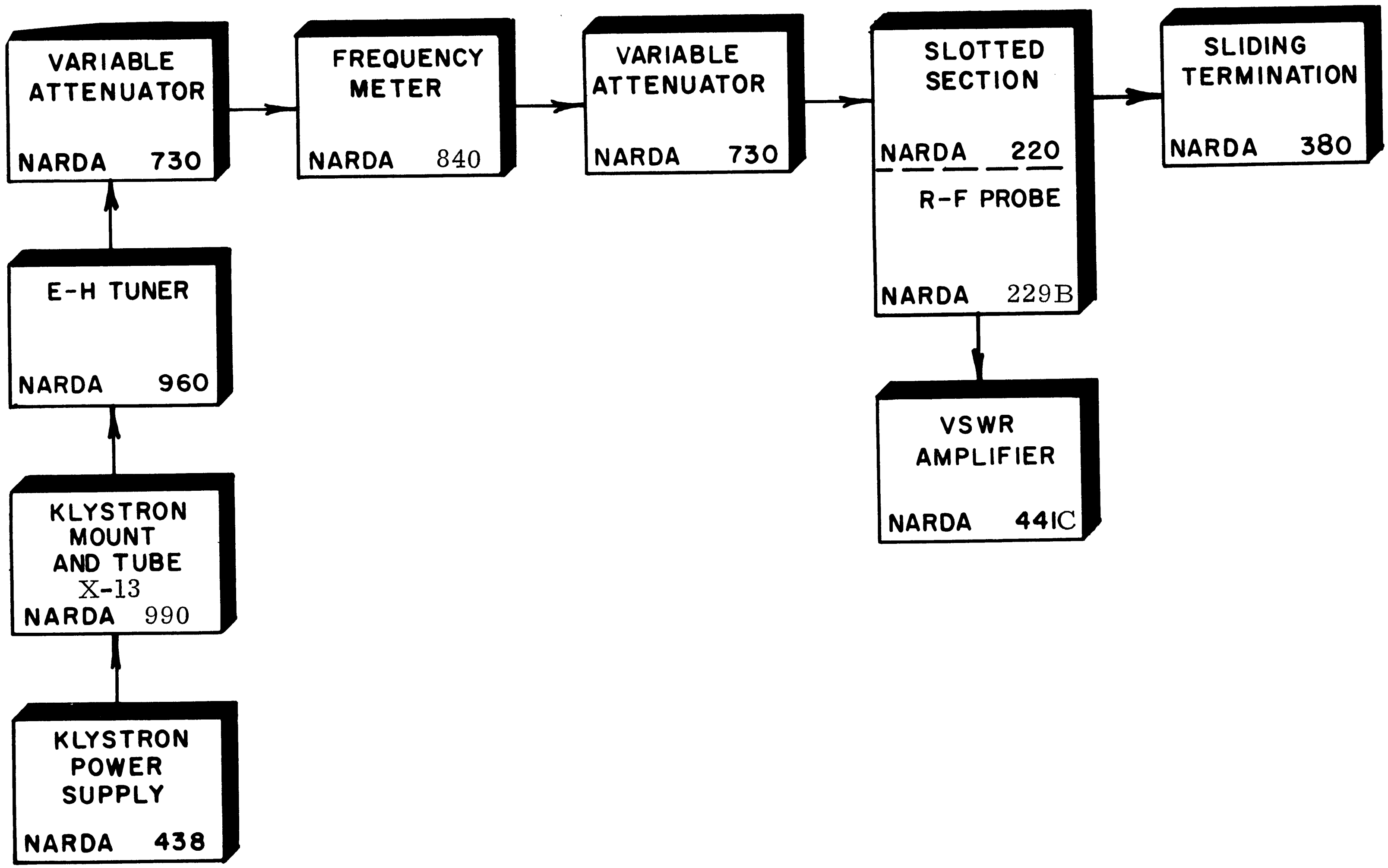


FIGURE 17: WAVELENGTH-FREQUENCY MEASUREMENTS EXPERIMENT SET-UP

4. In an effort to get initial output on the meter of the SWR amplifier, it may be necessary to advance the GAIN control on the amplifier to maximum, set the RANGE switch to 50 and adjust the probe tip insertion depth beyond the desirable normal operating position.

5. Adjust the REFLECTOR control, in the immediate vicinity of the recommended operating voltage, until a maximum output is obtained, resetting the controls previously set to maximum (in step 4 above) for an "on-scale" reading. It is particularly important to decrease the probe tip insertion to a minimum, (approximately 1/32") to avoid contributory inaccuracy to the measurements being made.

6. Slowly tune the type 840 frequency meter while watching the meter for a sudden drop in reading, or "dip". Repeat this procedure, turning the drive handle back and forth about the minimum point until the most accurate setting possible is obtained. Read and record the frequency setting. Change the frequency setting sufficiently to completely "lose" the dip, indicating that the frequency meter is detuned from the signal frequency.

7. Move the probe along the slotted section. There should be very little variation on the SWR amplifier meter, since the setup is still well matched.

8. Loosen the screws between the slotted section and the sliding termination and cock the flanges with respect to each other, leaving a gap of about 1/4 inch at the corner. The whole setup should now be carefully checked for stability. Any relative movement between components may affect accuracy.

9. Carefully move the probe over the whole length of the slotted section and read and record the positions of the minimum readings on the centimeter scale. A minimum point on the 441C VSWR amplifier appears as the downscale reading.

10. Switch off the power supply and the VSWR amplifier.

11. Using the formula $\lambda_g = \dfrac{\lambda_o}{\sqrt{1 - \left(\dfrac{\lambda_o}{2a}\right)^2}}$ solve for the

value of λ_o, bearing in mind the fact that the distance between minima on the slotted line corresponds to $\lambda_g/2$. It is therefore necessary to multiply the lengths obtained in step 9 by 2 to obtain the guide wavelength. Since more than one value of $\lambda_g/2$ was obtained (two values would result from the measurement of three minima in sequence), it is necessary for the sake of accuracy, to first average these values, then to multiply the average by 2 before substituting in the formula.

[For convenience $\lambda_o = \dfrac{\lambda_g}{\sqrt{1 + \left(\dfrac{\lambda_g}{2a}\right)^2}}$]

12. From the value of λ_g obtained in step 12, and the value of f obtained in step 6, calculate the velocity of propagation, v, of the energy in the waveguide, using the formula $v_g = \lambda_g \times f$.

13. Using the calculated value of λ_o and the frequency obtained from the frequency meter, calculate the velocity v, as being $v = \lambda_o \times f$. Compare the two values obtained.

14. Using the value $v = 3 \times 10^{10}$ CM (300,000 kilometers), calculate the guide wavelength λ_g of the following three different frequencies in the X-Band microwave region: 8,700 megacycles, 9,100 MC and 9,600 MC. Express the answers in centimeters.

Questions

1. Tabulate the operating potentials of the X-13 klystron as used in this experiment. What modulation was used on the signal?

2. Was the energy along the slotted section, as examined in step 7, absolutely constant? If not, what does this indicate?

3. Could wavelength measurements have been made in step 7 without resorting to the procedure outlined in step 8? If so, why was this not done?

4. Draw two examples of standing wave patterns, one having a VSWR of roughly 1.05 and the other corresponding to a VSWR of about 3.0. Arrange the two patterns one below the other on the paper, so that their minima and maxima are exactly under each other (on the same vertical line). With a pencil, mark all the minima and maxima on each wave. What can you say about the accuracy of your locating the points in question?

5. In the light of the exercise just performed in question 4, what can you say about the purpose of cocking the sliding termination in step 8 of the above experiment?

6. How does the measured value of guide wavelength and the calculated value of λ_o compare with each other.

7. Using the value of $v = 3 \times 10^{10}$ and the frequency obtained in step 6 of the experiment, calculate the wavelength λ_o. Compare with the value obtained in step 11. How do you account for any difference in the two?

8. In the above experiment, the probe passed through periodic maxima, located 1/4 wave away from the minima, and spaced from each other by 1/2 waves. Why are not maximum points used for wavelength measurements? Could they be used?

EXPERIMENT 2: POWER AND POWER MEASUREMENTS

Object

1. To learn the practical differences between low frequency and microwave power.

2. To study the types of power measurements most useful in microwaves.

3. To study the various devices used in microwave power measurements.

Discussion

While the basic concept of power is the same for microwaves as for low frequencies, the practical aspects of the two are quite different. For instance, in most circuits up to about 300 megacycles, power can be specified and measured in terms of voltage across the circuit and the current flowing through the circuit as a result of such voltage. In the microwave region, such voltage and current can neither be simply specified, nor can it ordinarily be measured. A second, although less significant difference is in the levels of power being measured. In microwaves, power measurements are often made in the milliwatt region, (although average powers of many killowatts are not uncommon). The higher powers are measured by indirect techniques using directional couplers, attenuators, etc. Thirdly, the concept of relative power measurements and levels is much more widespread than in the lower frequency regions. This concept finds wide application in measurements of coupling, attenuation, transmission losses and many other related subjects. Finally, and as a result of the above, the methods and devices used for microwave power measurements are distinct and completely different from the equipment and practices common at lower frequencies. To understand these differences, a brief explanation of the most important ones will be given here.

Average and Peak Power

In most microwave systems, the r-f power consists of a CW signal which is modulated by square waves or pulses.

Often the pulse width is relatively narrow in relation to the interval between pulses. For example, the output of an X-Band klystron may be modulated by a pulse having a repetition frequency (equivalent to frequency in low frequency systems) of 2,000 pulses per second, and a pulse width of 4 microseconds. Since the total number of pulses per second is 2,000, it follows that there is an interval of 500 microseconds from one pulse to the next one. But if the pulse width or duration is only 4 microseconds, it follows that the "dead" space, or "off" time between pulses is 496 microseconds, during which time there is zero power output. This immediately suggests that care must be taken in measuring or specifying the power output of such a system. In connection with the figures given above, the term duty cycle (a very useful and common term in microwaves) is of great significance. Duty cycle is a number which indicates the fraction of the total time that the specified power output of the system is available. In the above example, we have, in every second, 2,000 pulses of 4 microseconds duration each, for a total of 8,000 microseconds out of 1,000,000, or 8 parts per 1,000. The duty cycle is therefore said to be .008. The average power therefore, is the energy during the 8,000 microseconds of pulse duration "spread out" over the total second. The peak power, however, is independent of the pulse duration, and is simply the maximum pulse power amplitude. Most microwave power measurements are average power levels. Should it be desired to know the peak pulse power, it can be obtained from the value of the average power and the duty cycle. Thus $P_{av} = P_{pk}$ x Rep. Rate x Pulse Width $= P_{pk}$ x Duty Cycle.

Relative Power Levels, DB, +DBM, -DBM

As important as absolute power values are, the use of relative power levels is nevertheless extremely significant in microwaves. Even at low frequencies it is quite meaningful. The significance of relative power measurements stems from the fact that these measurements are usually more indicative of circuit performance than absolute levels. This applies equally as well to high frequency antennas, circuit selectivity and even to the very low frequency audio loudness. Simply stated, the decibel (written DB) is a ratio of two voltage levels or power levels expressed in logarithmic form. Numerically this is written as follows:

$$DB = 10 \log \frac{P_1}{P_2}$$ or, (since power is proportional to

the square of the voltage) $$DB = 20 \log \frac{E_1}{E_2}$$

It is informative to cite one or two examples to see the significance of the logarithmic factor instead of the usual aritmetical ratio. Let us assume two power levels, 10 watts and 1,000 watts. Their arithmetical ratio is obviously 1,000/10 or 100:1. However the decibel ratio is 10 x log 100 = 10 x 2 = 20. We therefore say that 1,000 watts is 20 DB above 10 watts. If this were a power amplifier with an input of 10 watts and an output of 1,000 watts, we would say, on the basis of the above that the amplifier had a power gain of 20 DB. The concept of +DBM and -DBM is very similar, except that it refers to a standard base. Specifically, the level of any signal described in DBM is referred to a 1 milliwatt base. Thus +DBM means a level of some number of decibels above a milliwatt, and conversely, -DBM refers to decibels below a milliwatt. Using the figures of the example above, the 10 watt level (10,000 milliwatts) corresponds to +40 DBM while the 1,000 watt level is equivalent to + 60 DBM. The difference between them, hence their relative level, is still 20 DB. For an example of - DBM consider a power level of 1 microwatt (1/1,000,000 watt) The ratio is of course 1:1,000, and in logarithmic form this equals 10 x (-3) = -30 DBM. Small as this level may seem, it is nevertheless a very common and substantial level in receiver antenna circuits, in some signal generator output levels and many other applications where high sensitivity circuits are involved.

Absolute and Relative Power Measurements

In consonance with the above explanation of absolute and relative power specifications, the measurement of power also may be either on an absolute numerical basis, or as an increase or decrease of the power level between two points in a transmission system. In the absolute measurement system, the actual power in a system is measured in milliwatts or watts, as the case may require. In the relative measurement system, either of the two levels in question may be taken as a base, or "zero" level. The second level is then measured in terms of a number of decibels above or below the reference level just established. This relative method is closely allied with the measurement of attenuation, which is discussed in detail in Experiment 3. The same concept of attenuation is also involved in the absolute power measurement techniques used in connection with high power level measurements. This will be further outlined in this experiment.

The experiment below is intended for relative power measurements. While it may seem less definite than absolute measurements, it involves a greater amount of judgement by the user, in addition to being by far the more common application in microwave work. At the end of this experiment, the power bridge method of absolute power measurement is also outlined for the information and convenience of the user of such a bridge.

Procedure

1. Set up the equipment as shown in Figure 18, Block Diagram.

2. Switch on the klystron power supply and allow it to warm up.

3. Follow instructions for applying the operating potentials to the X-13 tube as given in 3(a) of Experiment 1 and as outlined in the Instruction Manual for the Narda Model 438 klystron power supply.

4. Set the controls on the Model 441C amplifier to BOLOMETER HIGH, the range-DB switch to about 40 or 50, the Gain control near maximum and the scale selector to Normal.

5. Set the Model 730 attenuators to about midway between maximum and minimum.

6. Adjust the reflector voltage, the VSWR amplifier gain and the attenuator setting until an output is shown on the meter. Continue to adjust for the maximum klystron output, readjusting the attenuator settings, as required. Tune the detector for maximum output or minimum VSWR. With the klystron output at a maximum, adjust the GAIN setting on the VSWR amplifier until the meter reads some convenient value on the DB scale, preferably near the middle of the scale. Record this meter

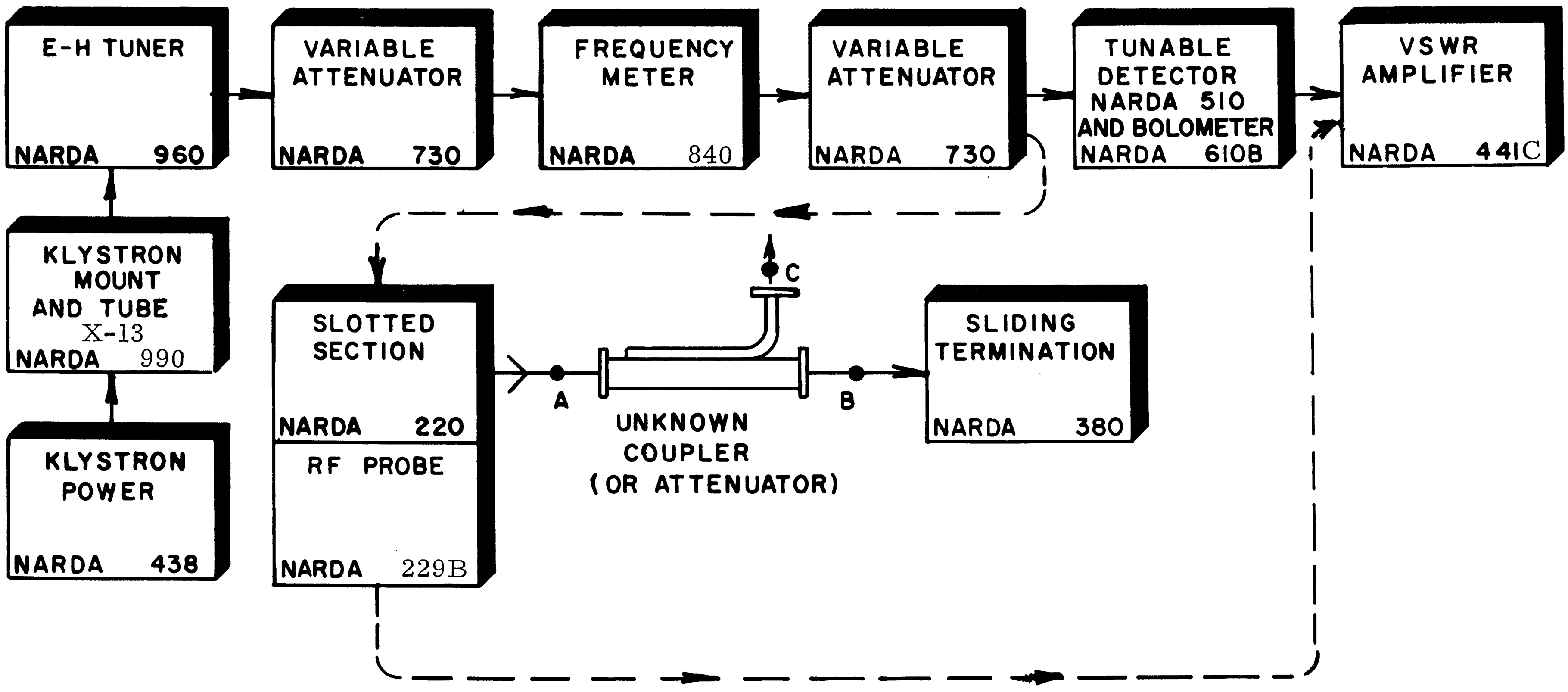


FIGURE 18: RELATIVE POWER MEASUREMENT EXPERIMENT SET-UP

reading, and the RANGE-DB control position.

7. Reset the RANGE-DB knob on the amplifier to the 0 position (extreme clockwise). Observe the dial reading on one of the Model 730 Attenuators, then rotate this dial to its zero position, corresponding to approximately zero attenuation.

8. Gradually advance the RANGE-DB knob from the 0 position counter-clockwise until the meter reads on scale. The GAIN control setting shall not be changed during this procedure. Read and record the Range knob setting and the meter reading on the DB scale.

9. Calculate the relative power level of the two different attenuator settings as follows: Assuming that the original RANGE setting in step 6 was 50 DB and the meter reading was 4 DB, while the second set of readings taken in step 8 was 40 DB for the RANGE switch and 6 DB on the meter, the relative power is -2 DB on the meter (since meter is calibrated downscale) and +10 DB on the RANGE scale, for a total of 8 DB. When referring to the final level setting, this would be called +8 DB while the original measurement would, by comparison, be called -8DB.

Questions

1. In the above measurement, could the power level be expressed in milliwatts or in watts? Explain your answer.

2. What would be the difference in the relative levels in the type of measurement just concluded between a power source having an output of 10 watts and a klystron source with an output of 10 milliwatts. How would this affect the conduction of the experiment?

3. Why was it specified in step 8 that the GAIN control setting not be changed?

4. How could the above experiment be used to calibrate an attenuator such as the Model 730?

5. Had a calibrated attenuator been used in the above experiment what would account for discrepancies if any, between calculated DB levels and those indicated on the attenuator dial?

6. What is the relation, if any, between the DB rating of an attenuator

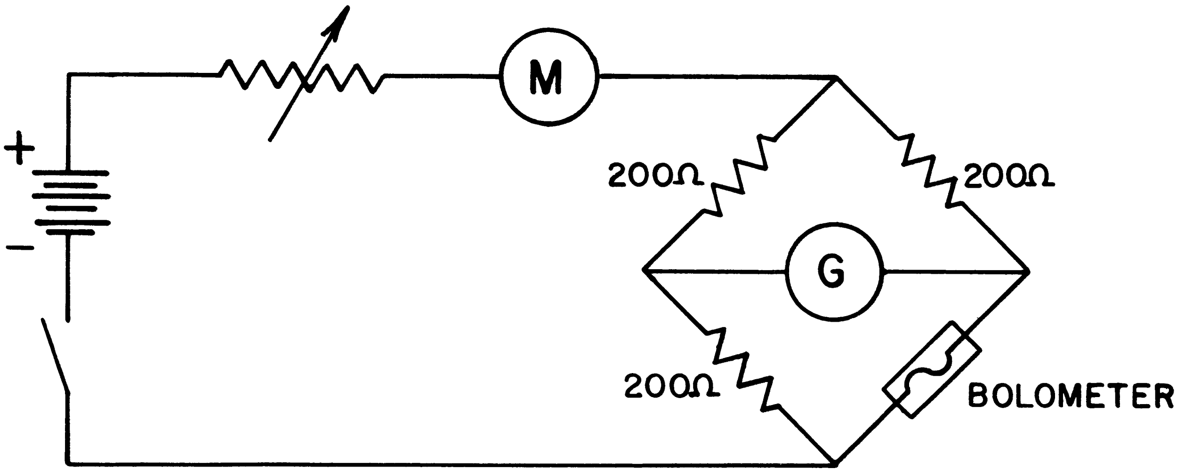
and its dissipation rating in watts? Explain your answer in the light of the above experiment.

7. Could a load or termination be considered as an attenuator? What is the essential difference between the two?

ABSOLUTE MEASUREMENTS WITH THE POWER BRIDGE

In addition to the relative power measurements discussed and illustrated above, there is often a need for absolute power level measurements, such as in transmitter output calibration and similar applications. For these uses the power bridge is most suitable.

Figure 19 shows a simplified diagram of one type of power bridge. The power sensitive element (bolometer, for instance) is made one arm of a modified Wheatstone Bridge. In the initial (zero input) state, the bridge is balanced by adjustment of the resistance of the bolometer element through the value of DC flowing in it. When the bolometer is next placed in the path of the r-f power it is to measure (see setup block diagram, Figure 20), the additional power in the element changes its resistance, thus unbalancing the bridge. A removal of DC in the amount of the RF just introduced into the bolometer would restore the bolometer to its original resistance and therefore bring the bridge back to balanced condition. The RF power in the bridge can either be simply calculated (as shown below) or may actually be calibrated on the dial of the current control. A simple example of calculating the RF power is shown here. Referring to Figure 19 and starting with the balanced condition it is assumed on the basis of bolometer specifications, that the bolometer resistance is 200 ohms. If the milliammeter reads 17.5 MA, the current in the bolometer is 8.75 MA and the power in the bolometer is $200 \times (8.75 \times 10^{-3})^2$, or I^2R. This amounts to 15.3 milliwatts. Next the r-f power is applied to the bolometer, causing the bridge to unbalance. A readjustment of the d-c bias control will bring the bridge back to the balance condition, indicating that the bolometer resistance is back to the original value of 200 ohms, hence the power in the element is the same as before, or 15.3 milliwatts. However, the d-c has been reduced from the original 17.5 MA to (for example) 16 MA, making the d-c in the bolometer = 8 MA. Calculating, as before, we obtain the d-c power in the element to be 12.8 milliwatts.



(M) MILLIAMMETER BOLOMETER BIAS INDICATOR.

(G) GALVANOMETER, BRIDGE BALANCE INDICATOR.

NOTE:
METER TO READ TWICE THE SPECIFIED BOLOMETER BIAS (17.5 MA TO BIAS BOLOMETER TO 200Ω OR 8.75 MA)

FIGURE 19: SIMPLIFIED DIAGRAM OF POWER BRIDGE

The added r-f power must therefore be 15.3-12.8 or 2.5 milliwatts.

Another type of r-f power bridge is the automatic, or self-balancing type. Its operation still depends on the temperature - resistance characteristics of the bolometer, which is brought to its nominal (usually 200 ohms) resistance when the bridge is initially adjusted to "zero". However, this initial condition is produced by a combination of DC plus AC, the latter usually being an audio frequency voltage. When RF is additionally applied to the bolometer, an automatic feedback circuit restores the bridge to balance by reducing the amount of the audio AC. This latter amount, which is equivalent to the r-f power just added, is measured on a vacuum tube voltmeter integral with the bridge, and indicated on a meter, which is calibrated in milliwatts.

Figure 20 shows a typical setup for power measurements using a manual or a self-balancing bridge. If the experiment is conducted for study purposes, the accuracy of the absolute power measurement is obviously not too important. In such a case, the Model 730 uncalibrated variable attenuators may be used.

For measurements using a manual bridge, with both attenuators at their maximum attenuation settings, the setup is first adjusted for maximum output. The r-f power source is then switched off, the bridge balanced with the d-c bias adjustment, and the bias current recorded. Next the r-f power is switched on again, and the attenuators adjusted if necessary, for some convenient on-scale reading on the meter. This setting will be considered the "unknown" power to be measured. The DC is now readjusted until the bridge is again balanced, and the meter reading recorded. The calculations for the value of the unknown power are made as illustrated above. For an actual measurement of the original maximum unknown power level, uncalibrated attenuators cannot be used. Instead, a calibrated variable attenuator and/or a fixed attenuator of known value must be used. The procedure is still as just outlined, except that the final value for power measured must take into account the added attenuation. (The uncalibrated attenuator can be approximately calibrated by using the 441C SWR amplifier) For example, if a total of 6 DB of attenuation was used and the calculated power was 3 milliwatts, the original power level is therefore 6DB higher or 12 milliwatts. This value is arrived at by considering the power calculated as P_2, the actual power as P_1 , and using the formula

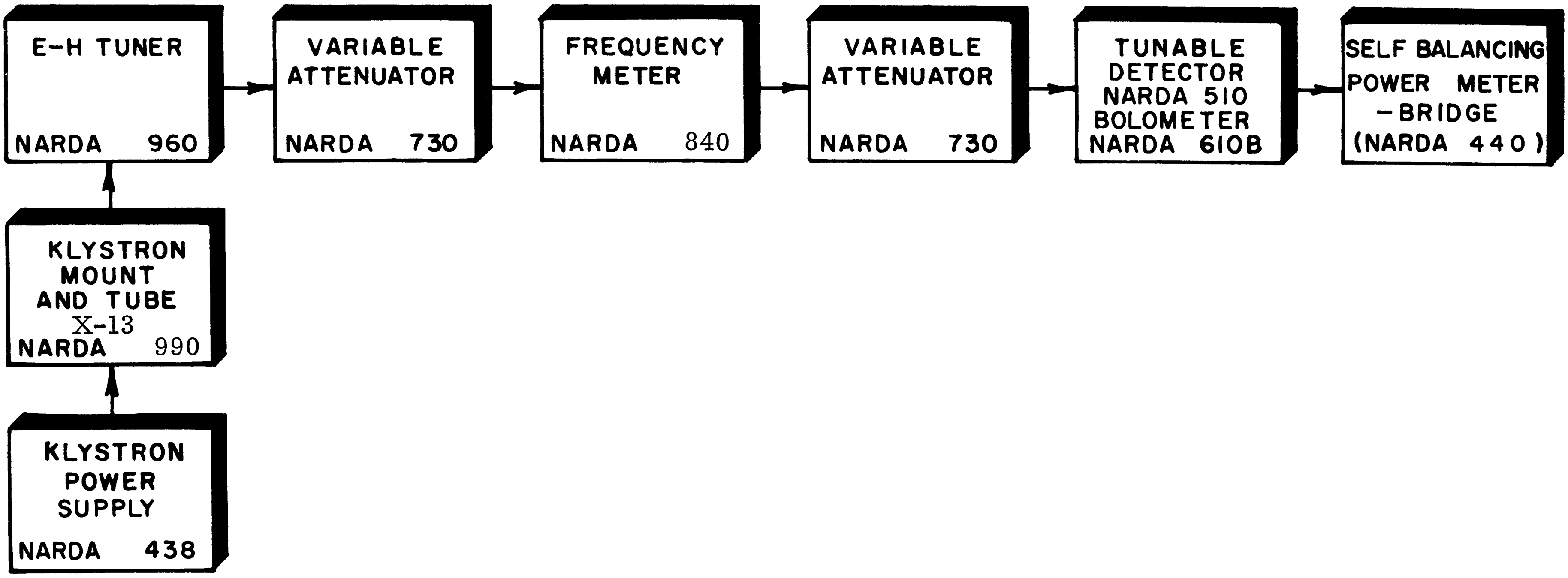


FIGURE 20: ABSOLUTE POWER MEASUREMENT EXPERIMENT SET-UP

previously given, DB = 10 log P_1/P_2.

In the case of the self-balancing bridge, the setup is still the same, and the comments just made about requiring known values of attenuation, if any are used, still apply. As previously, the bridge is first balanced with zero r-f power input. The RF is then applied and the meter reading noted. This reading is directly in milliwatts (or some other unit of power), except for some correction that may be required if attenuators are used. In all of the above cases, the user must first ascertain the approximate order of power level that is intended to measure. The meter may be set to the highest scale, but in no case may the power input exceed the rated bolometer or thermistor power handling capacity.

EXPERIMENT 3: ATTENUATION AND ITS MEASUREMENTS

Object

1. To learn and understand the theoretical and practical significance of attenuation.

2. To learn the functions and application of attenuators in microwave circuits.

Discussion

Technically, the term attenuation means reduction or decrease. While the same general meaning applies here, the term has come to signify some specific relations in electrical terminology in general and in microwave circuits in particular. Specifically, attenuation describes the effect of a dissipative component (or a slightly imperfect non-dissipative component, such as any high grade component which is nevertheless not 100% ideal or perfect) on the system power level in which it is inserted. Numerically, attenuation is the ratio of the power level at the input to the component to the power level at the output of the same component. The value of attenuation is most often expressed in decibels. A simple example of attenuation is shown in Figure 18. The attenuator might be a component such as the NARDA Model 730, set to a definite position with the adjusting dial. For example, going from the source in the direction of the load, suppose the power at the input to the attenuator, P_1, is given as 20 milliwatts. At the other end of the same attenuator, the output power, P_2, is given as 5 milliwatts. To obtain the value of attenuation from P_1 to P_2 in decibels, we use the now familiar formula, $DB = 10 \log P_1/P_2$.

Substituting, $DB = 10 \log 20/5 = 10 \log 4 = 10 \times .6021 = 6.02$ DB. The Model 730 at the particular setting therefore has an attenuation of just slightly over 6 DB.

Insertion Loss

This is a term numerically identical with attenuation as described above. However, it has a slightly different connotation. Attenuation, as used in the above description, refers most of the time to a component which was designed to be an attenuator; it is not intended as a description of an undesirable characteristic of a component. By contrast, the term insertion loss usually refers to the imperfection of an otherwise desirable component, which was not intended to have any attenuation. For example, the waveguide slotted section is one of a long list of microwave components whose function is to transmit energy without any loss or attenuation. The slight loss usually associated with these components is due to the difference between the perfect theoretical component and the near-perfect practical physical part. This slight difference between the ideal and the practical, as regards attenuation, is called insertion loss. In the great majority of high grade microwave components this loss is a small fraction of a DB, and practically negligible. It must be taken into account, however, in precision measurements.

Coupling and Directivity

Both of these terms are forms of attenuation characteristics and their measurements are similarly related. Since they apply particularly to a component known as the directional coupler, a brief description of this item will be given here.

Figure 21 illustrates a typical directional coupler, such as might be used in an X-Band setup. The device has the general appearance of a section of waveguide with the addition of a second parallel section of guide with one end terminated. These two sections are known as the main and auxiliary lines, respectively. The two lines are internally separated from each other except for the coupling mechanism, which can consist of one or more holes, of suitable sizes and locations, through which energy may be coupled from the main line to the auxiliary line. In operation assume that energy is fed into end A of the main line (Figure 18). Most of this energy will appear at the output end B of the same line. A fraction of this energy, however, (such fraction depending on the nature of the coupling mechanism), will also appear at the output C of the secondary or auxiliary line. Perhaps the most important characteristic of the directional coupler, and one from which its name stems, is its directivity. In other words, energy entering end B of the main line will appear at end A, but practically none of the energy will appear at the auxiliary output C. This characteristic has wide application in the measurement of reflections and other microwave characteristics in waveguide setups. The coupling of a directional coupler is therefore the ratio of the power fed to end A of the main line to the power appearing at the auxiliary line output C. It is usually specified in decibels, and is calculated as any other form of attenuation. The directivity, on the other hand, is a measure of isolation obtainable with power in the main line being fed in the opposite direction. It is calculated in the same manner as previously outlined, except that the values of P_1 and P_2

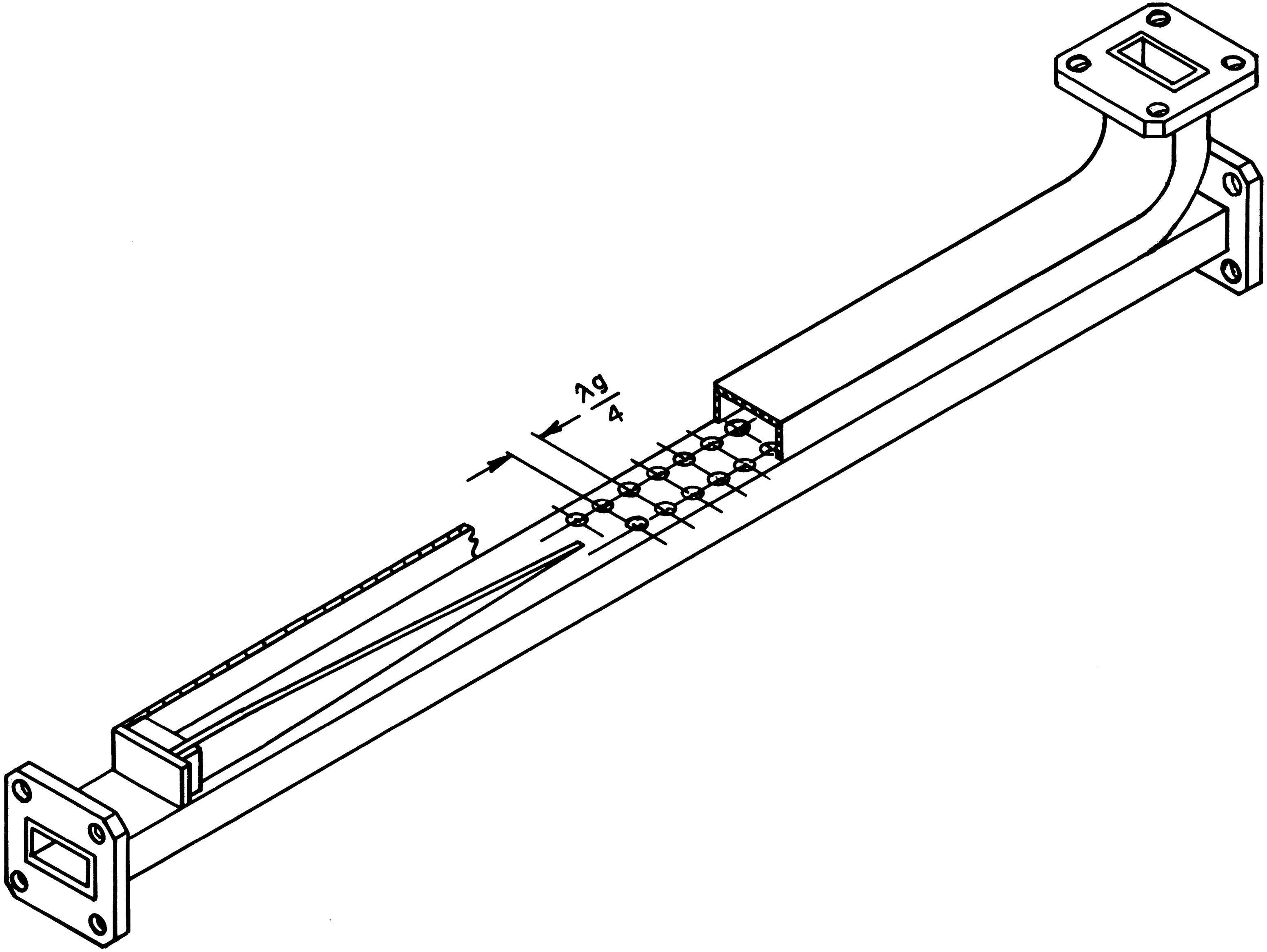


FIGURE 21: TYPICAL DIRECTIONAL COUPLER

refer, respectively, to the power at C with power input at A and the power at C with the power input at B. Since the intention is to have as little as possible energy couple out of end C, the values of the directivity are usually very high (40 DB, for instance), while the values of coupling may range from as low as 1 or 2 DB on up to beyond 70 DB.

From the above it is evident that a directional coupler is a very useful device for insuring that an absolute minimum of energy in the reverse direction (such as reflected energy due to a mismatch) reaches the load or other device at end C of the secondary arm.

In the experiment to follow, the basic principle, i.e., the measurement of attenuation will be demonstrated. The actual testing of a directional coupler will be briefly outlined, should it be found feasible to conduct such testing of an available coupler.

Procedure

1. Set up the experiment as shown in the block diagram, Figure 18. Make sure the detector is tuned for maximum output (or minimum VSWR).

2. With both attenuators at or near their maximum attenuation setting, and with the VSWR amplifier set for one of the middle ranges of the RANGE-DB scale, gradually adjust the klystron source for maximum power output. Reset the RANGE switch, if necessary, to obtain a good on-scale indication on the meter of the VSWR amplifier.

3. Measure, as follows, the attenuation of one of the model 730 units at three different settings of the duo-dial (i.e., attenuation at output of unit when going from zero setting to a particular setting). Incidentally, this amounts to calibration of the attenuator over the limited range. In making the attenuation measurements of three different settings of the model 730, use is made of the fact that the DB scales on the meter in conjunction with the 10-DB step of the RANGE switch allow readings over a sufficiently wide range of power levels.

4. With the RANGE switch set to 30 or 40, and one of the model 730 attenuators set at some convenient position, the signal source is adjusted to give a good upscale deflection. The attenuator just mentioned may have to be readjusted for this purpose, and possibly, the RANGE switch may have to be changed one step in either direction. The second model 730 should be at its zero attenuation position. Record the meter reading and the RANGE switch position in DB.

5. Set the second attenuator at about its 1/4 or 1/3 position from minimum.

6. If the meter reading is on scale, read the meter in DB. Should the meter be off scale on the low side, change the RANGE switch position one step, until the meter reads on scale. Record the RANGE-DB and meter readings in decibels.

7. Repeat the procedure of steps 5 and 6 for two additional settings of the second attenuator. In each case, record the dial reading on the attenuator as well as the "before" and "after" readings of the meter in DB and the settings of the RANGE-DB switch.

8. Calculate the values of attenuation in each of the three cases as if they were separate and distinct attenuators. If the RANGE switch did not have to be changed during measurements, the value of attenuation in that case is simply the difference between the first and second meter readings. If the RANGE switch was changed, the value of attenuation must be increased by 10 DB for each step of the switch. Since the maximum attenuation of the model 730 is approximately 20 DB, there should be no need to shift the RANGE switch more than one or two steps during a measurement.

9. From the data obtained, plot a curve of dial reading vs attenuation in DB for the particular attenuator tested. This is a rather limited calibration curve, because of the few points actually measured and the non-linearity of the attenuation characteristic.

10. At the discretion of the lab instructor, proceed to make one or two attenuation measurements in the following variation of the above procedure:

    a. Set both attenuators to approximately their mid positions and adjust the setup for maximum deflection on the meter. The RANGE switch should be either in the 50 or the 40 position. Record the meter reading in DB, the RANGE switch position and the dial reading on one of the attenuators. This will be the unknown attenuator.

    b. Carefully remove the unknown attenuator from the setup. Reassemble the equipment, and switch the RANGE-DB control two steps in a clockwise direction.

    c. Observe the meter. If it does not read on scale, change the RANGE-DB switch one step at a time in the counter-clockwise direction until the meter reads up-scale. Record the meter reading in DB. The attenuation of the "unknown" equals the difference in meter reading plus the change in the RANGE position. Thus, if the meter read 6 DB with the RANGE switch at 40, while the "after" readings were 4 and 30, respectively the attenuation of the unknown is -6 +4 -10, or -12 DB. Had the original meter reading been 2, with the other readings remaining the same, the value of attenuation would have been -2 +4 -10, or -8 DB.

Coupling and Directivity Tests with a Directional Coupler

Figure 18 shows the setup for measuring the coupling of a typical directional coupler. The procedure is as follows:

1. Connect the equipment as shown and allow the usual time for warmup.

2. With the RANGE switch in one of the middle (30 or 40) range positions, tune the klystron for maximum output. Record the meter and the RANGE settings.

3. Insert the directional coupler in the line, according to Figure 18. The main line output of the coupler is now terminated, (end B) while the detector and indicator are connected to the auxiliary line output (end C).

4. If the meter reads on scale, read and record the meter reading in DB. If the meter does not read up-scale, change the RANGE switch one step at a time in the counter-clockwise direction and read the meter.

5. Calculate the coupling of the directional coupler in the same manner as outlined in Step 10C above.

To measure directivity, the procedure is generally the same as the one just outlined, except for the following differences requiring some added precautions. Since, as outlined in the introduction to this experiment a maximum attenuation is desirable at end C when the power is fed in the main line in the reverse direction (end B) the reading may be very low. It is therefore desirable to adjust the klystron output for maximum with the RANGE switch of the VSWR amplifier set to as low a numerical position as possible. The meter DB scale and the RANGE switch position are then read and recorded, as usual, but now with power in at A and detector at C. Keeping detector at C, reverse coupler so that power enters at B. The meter is almost certain to remain off scale on the low end until the RANGE switch is advanced, probably a few steps, counter-clockwise. As good precautionary practice, the switch should be advanced one step at a time and the meter reading observed. When an on-scale reading is finally obtained, the calculation of directivity in DB is made as outlined previously.

Questions

1. In measuring the attenuation of the Model 730 at different settings, was the insertion loss of the device included?

2. If a curve of attenuation vs dial setting for the Model 730 is made, what is the effect of the insertion loss on the curve? Is the accuracy affected? Is the scale reading affected? In which way?

3. If the power level at ends A and B of a directional coupler were measured, what would be the usual result (i.e., how much would these levels differ) ? What is the difference in levels, if any, due to?

4. What is the relation, if any, between coupling and attenuation in a particular directional coupler.

5. If it were desired to use a single antenna for both a transmitter and a receiver (receiver and transmitter need not function simultaneously) how could a directional coupler be used to prevent the transmitter output from "hitting" the receiver? Sketch the connections.

6. To what use or uses could a directional coupler be put in making transmitter characteristics measurements during transmitter operation?

EXPERIMENT 4: IMPEDANCE (including VSWR, Reflection Coefficient, Phase)

One of the most important measurements at microwave frequencies is that of impedance. In low frequency circuits, the term impedance may be simply expressed as the ratio of terminal voltage to circuit current. Since there are no exactly corresponding concepts of voltage and current at microwave frequencies, the value of impedance cannot be measured in this simple manner.

A common example of the significance of impedance is in the transmission of power from a source, such as a klystron oscillator, to a load, by means of a transmission medium, such as a section of waveguide. Both the ideal condition, in which all of the energy is absorbed by the load, as well as the opposite extreme, in which no absorption takes place, are not the most common cases. Most practical cases fall between these two conditions. Only in the ideal case is there no reflection from the load end back toward the generator, hence no standing waves. In all practical cases, where the load impedance differs even slightly from the source or transmission line impedance, some energy is reflected back and a standing wave pattern appears. Since the load impedance, the reflected wave and the standing wave pattern are all interrelated, it is possible to determine the load impedance by measurements of the other characteristics, namely the standing wave ratio and the reflection coefficient. It is the purpose of this experiment to measure the impedance of an "unknown" load by just such means.

Concept of Complex Impedance - Review

In d-c circuits, impedance and resistance are identical, consisting solely of dissipative ohmic resistance. In most a-c circuits, however, there usually are the additional non-dissipative, or reactive components due to inductance (X_L) and capacitance (X_c). These two are measured in ohms, but they are not subject to arithmetical addition with resistance. Instead, they are added vectorially. A simple example of vector addition would be the right triangle, in which the diagonal may be considered as the vector sum of the other two sides. Numerically, the diagonal is the square root of the sum of the squares of the other two sides. Applying this process of addition to the concept of adding resistance and reactance to produce impedance, we consider one side of the triangle to represent R, the other side representing X and the diagonal being Z. Numerically,

$$Z^2 = R^2 + X^2 \quad \text{and} \quad Z = \sqrt{R^2 + X^2}$$

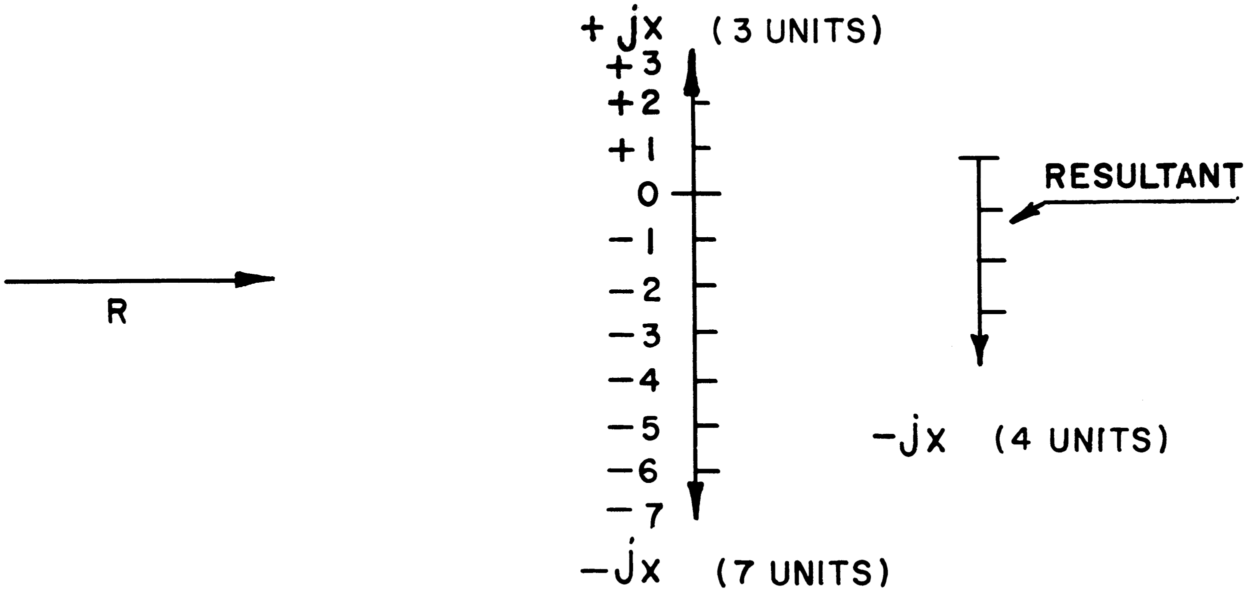
This is illustrated graphically in Figure 22B. One other concept remains to be reviewed to make the analogy completely clear. Both inductive and capacitive reactances are usually involved in the term X. However, since the two have opposite effects in the circuit, they are considered to be of opposite polarity and are directly subtractive. Thus,

$$X = X_L - X_c$$

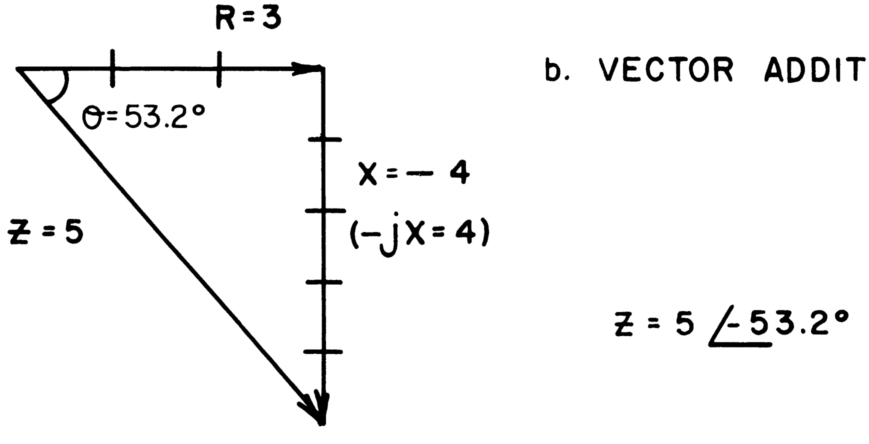
The popular terminology for these two takes this into account. For X_c we usually write -jX, and for X_L we write +jX or just plain jX. The significance of the j in both cases is to indicate that these are reactive components, or at right angles to R in graphic representation. Figure 22A illustrates the relative positions of the two. Another common notation is that of writing the impedance in separate terms of resistance and reactance. Thus, for example, R = 3 ohms, X_L = 20 ohms and X_c = 16 ohms. X is therefore 4 ohms ($X = X_L - X_c$) and $Z = \sqrt{3^2 + 4^2} = \sqrt{9 + 16}$ or Z = 5 ohms. This is more significantly written as Z = R + jX or Z = 3 + j4. Had X_c been numerically larger than X_L, the net value of X would have been negative and the impedance would then have been written as Z = R - jX.

Another notation for complex impedance is that represented by the vector magnitude and phase, and written as $Z = |Z| \angle \theta$. This is related by the vector triangle in construction, since the phase angle is the angle that the resultant vector, or the diagonal makes with the reference or the R component. Using the numerical values as above, R = 3, X = 4 and $|Z|$ = 5 (the bars indicating that this is the "absolute" or numerical value of Z, regardless of phase), θ is the angle Z makes with the reference vector, and depends on the relative magnitudes of R and X. Specifically, θ is the angle whose cosine is the fraction R/Z. Again using the sample numbers, Cos θ = 3/5, = 0.6, and θ = 53.2 degrees. This then is the phase angle of Z in the above notation, which may be written as $Z = 5 \angle 53.2^\circ$.

Figure 23 shows in block form a setup for measurement of impedance through the measurements of VSWR and phase. The resultant wave pattern will depend on the nature of the terminating element or load. Should this load be a short circuit, the standing wave patterns would be as in Figure 24A. Here the voltage is zero at the load and a maximum at a position 1/4 wave back. Furthermore, the minimum voltage points would repeat every 1/2 wavelength back along the slotted section. Similarly, the maxima repeat themselves at 1/2 wave intervals, occuring at 1/4, 3/4, 5/4 waves along the line, starting from the



a. RELATION BETWEEN +jX AND -jX. R IS SHOWN FOR REFERENCE.



b. VECTOR ADDITION

FIGURE 22: VECTOR REPRESENTATION OF R, JX, AND Z

load. From the above it also follows that the voltage and impedance minima as well as their maxima are coincidental.

The standing wave pattern of Figure 24B corresponds to an open circuit at the load end. This is an exact opposite condition from the short circuit case of Figure 24A. It should be apparent from these two examples that placing different load impedances at the end of the transmission line would produce different standing wave patterns, with the voltage at the load varying anywhere between zero and maximum. The dashed lines $Z_1 - Z_1$, $Z_2 - Z_2$ and $Z_3 - Z_3$ in Figure 24C represent three different conditions of load impedance and the corresponding voltage values at the load. It is not necessary (nor desirable), however, to measure these terminal voltages. Knowing the wavelength of the energy involved, it is quite easy to determine the position of any of these lines in terms of wavelength by measuring the distance from the load to the nearest minimum on the standing wave pattern.

It but remains to define a few terms in popular use in these measurements before proceeding with the experiment. These terms are defined and explained, as follows:

Normalized Impedance

The normalized impedance is the relative numerical expression of the value of the unknown impedance in terms of the known (generator and / or line), regardless of the actual absolute value in ohms. For example, the microwave components used in this series are of 400 ohms (approximately) nominal impedance. The normalized value of this impedance, as far as calculations or measurements are concerned is 400/400, or 1. On this basis, an unknown impedance which calculates to be $1.3Z_o$, would have an absolute value of 1.3 x 400 or 520 ohms. Similarly, $Z' = 0.8$ would correspond to a value of 0.8 times nominal value, or 320 ohms. In the use of the Smith Chart (Figure 25) in this experiment normalized values are used throughout. As can be seen on that chart, normalized values are also used for admittance (Y, the numerical inverse of impedance, written as $Y = 1/Z$). What has been said about waveguide components with regard to normalized values applies equally to coaxial components, where the common 50-ohm impedance would be considered unity in normalized form. All other values would be related to this value, so that a 70-ohm component would have a value of 1.4 in normalized terminology, while a 45-ohm impedance would be written as 0.9 in normalized form.

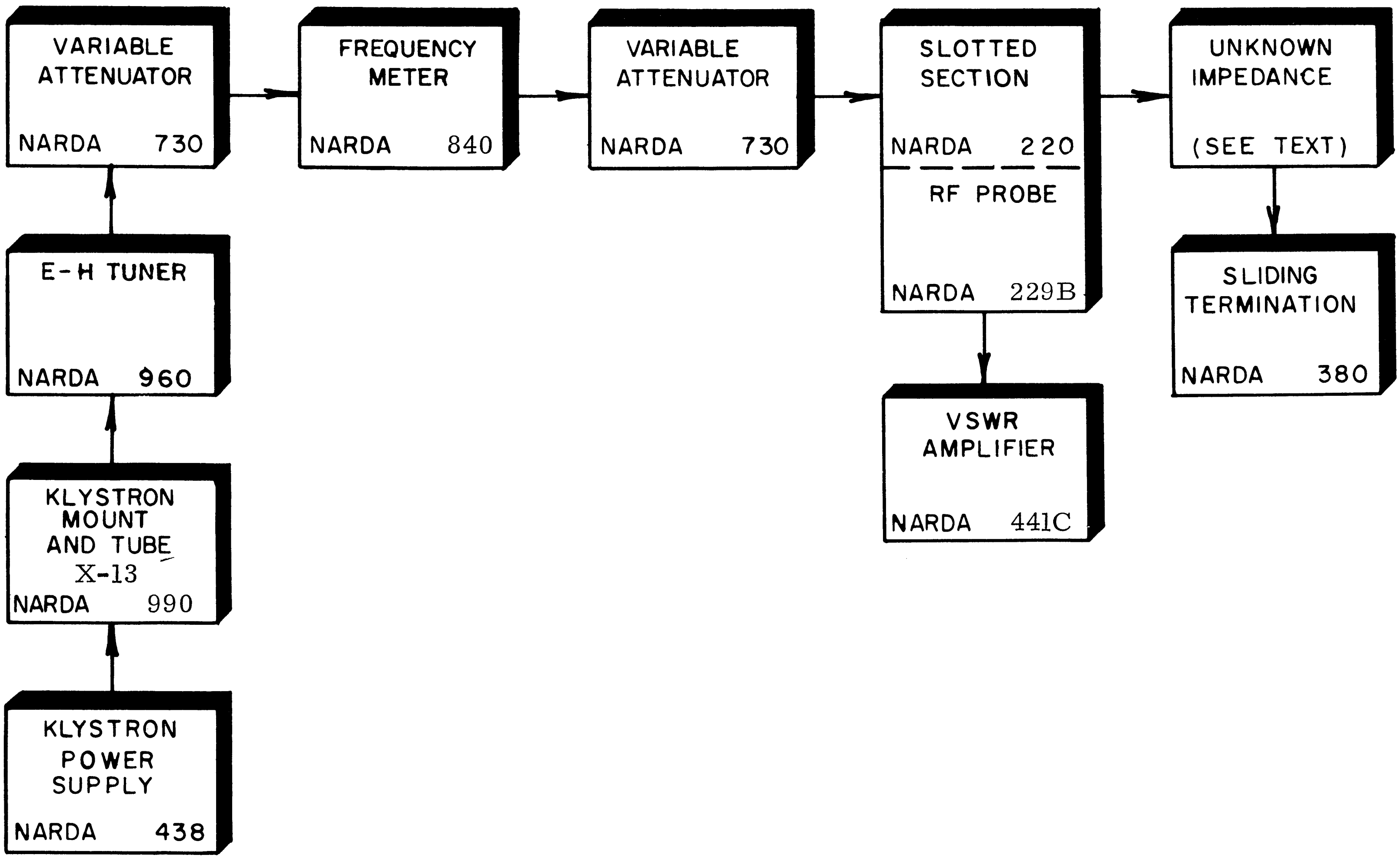


FIGURE 23: IMPEDANCE MEASUREMENT SET-UP

Reflection Coefficient

This is a complex number (written Γ and pronounced Gamma) which indicates the degree of reflection of the energy due to a mismatch. Numerically, it is the ratio of the voltage value of the reflected wave to the voltage value of the incident wave at the same point. Thus, if V_1 is the voltage on the incident wave, and V_2 is the corresponding voltage on the reflected wave, the reflection coefficient Γ is the ratio of the two, or V_2 / V_1. The magnitude of this coefficient is always less than unity, since the reflected wave cannot exceed the incident wave (in case of 100% reflection the value would be unity). The voltage standing wave ratio is obviously related to this coefficient, and can therefore be expressed in terms of gamma, thusly:

$r = \frac{1 + |\Gamma|}{1 - |\Gamma|}$ and conversely $|\Gamma| = \frac{r-1}{r+1}$ where $|\Gamma|$ = amplitude of Γ.

Again observe that in practical conditions, the VSWR must be greater than unity, although it may approach 1 under the best matched conditions.

Phase

As stated above, the reflection coefficient is a complex quantity, having both a numerical value (magnitude) and an angular value or phase angle. Graphically, the phase angle is the angular difference (" or the phase ") between the incident and the reflected wave at the reference plane. Since this phase can readily be expressed in terms of a fraction of the guide wavelength, the phase of the reflection coefficient can be determined by measurement of the distance, in terms of guide wavelength, from the plane of the load back to the nearest minimum. It remains to be added that the reflection coefficient vector makes two complete turns in the complex plane for a one wavelength displacement along the guide.

The Smith Chart

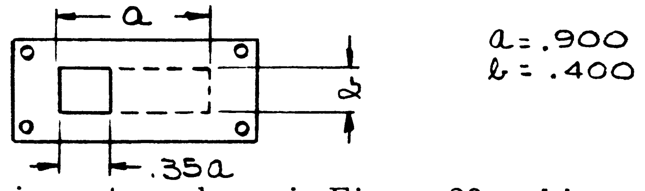
This is essentially a graph (Figure 25) which enables rapid solution of problems in impedance, VSWR, reflection coefficient, etc. It differs from the usual graph paper charts in that the orthogonal coordinates are in curvilinear form, and, what corresponds to the usual "zero" point is located in the center of the chart. The Smith Chart is to impedance calculations what the slide rule is to the more general engineering calculations. The use of this chart can best be explained by actual examples. This will be done at the end of the experiment.

Impedance and Admittance (Review)

As in the case of simple resistive circuits, calculations can often be simplified by considering conductivity instead of resistivity. A brief review of the pertinent terms concerning admittance are given here. The inverse of resistance alone (1/R) is conductance (G). The inverse of impedance (1/Z) is admittance (Y) and the inverse of reactance alone (1/jX) is susceptance (-jB). In solving a problem or making a calculation, it is but one step to convert from one form to the other if desired. On the Smith Chart it is but necessary to read the diametrically opposite ($\lambda/4$ away) values on the chart to obtain the conversion.

Procedure

1. Prepare an "unknown" reactive obstacle (iris) by cutting out a thin (approximately 1/32 inch or less) copper or brass rectangle to fit between the slotted line and the sliding termination. Make the holes slightly oversize. Cut off one side along the narrow dimension, so that when the shim is assembled, there will be an opening from the slotted line to the termination approximately .35 of the inside guide width.



2. Connect the equipment as shown in Figure 23 making sure that all flanges are carefully aligned and fastened together.

3. Carefully read the instructions for operating the klystron power supply and the standing wave amplifier. Failure to do so may permanently damage the klystron.

4. Switch on the Filament on the power supply. Allow the equipment to warm up for at least 5 minutes.

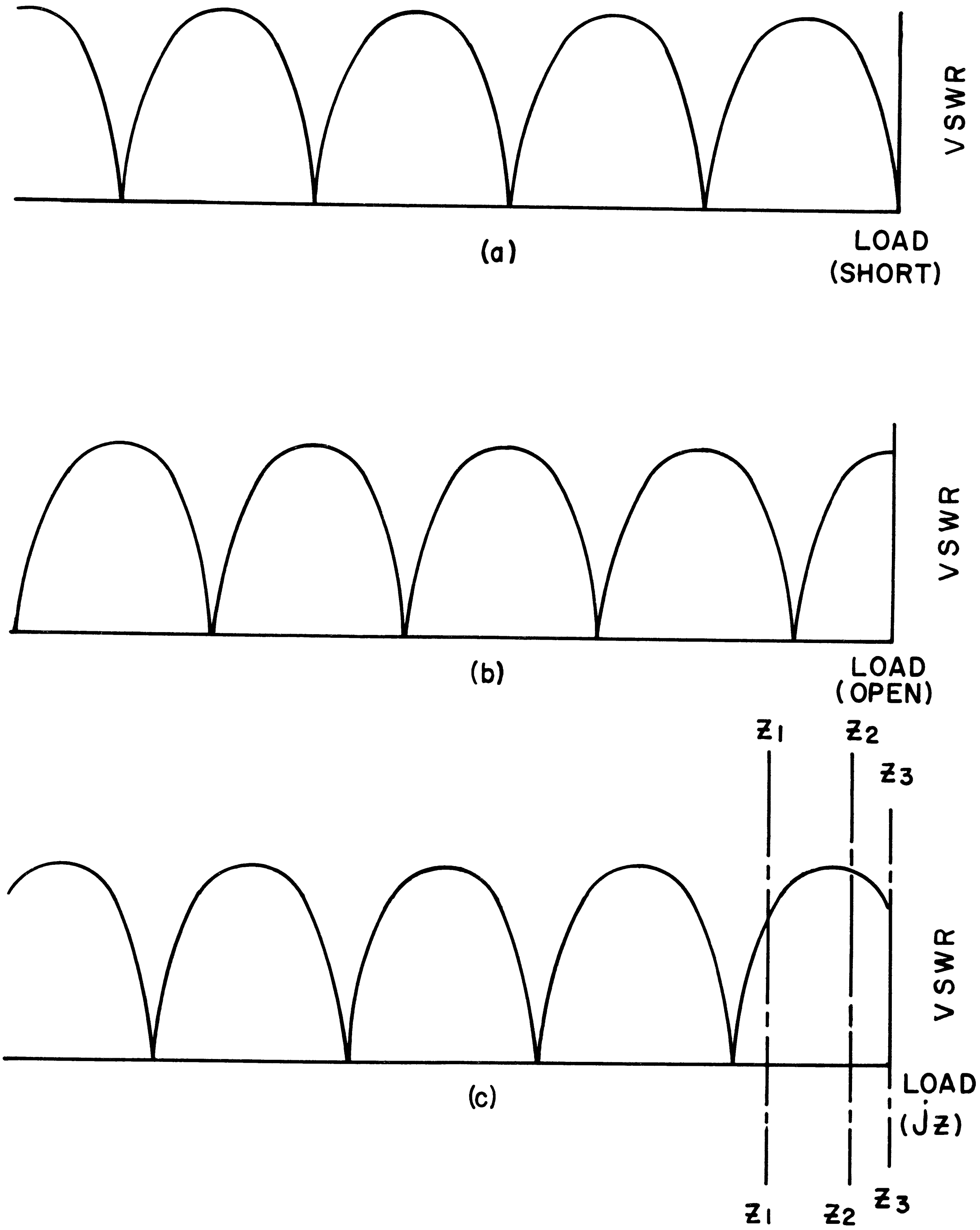


FIGURE 24: EXAMPLES OF STANDING WAVE PATTERN

5. Set the VSWR amplifier controls to CRYSTAL (if crystal is used in probe), GAIN control to extreme clockwise position and the RANGE-DB knob to 60.

6. Switch on the power supply voltages, following the instructions in the power supply manual. Adjust the REFLECTOR CONTROL for a maximum indication on the VSWR amplifier meter.

NOTE: As a preliminary aid in obtaining a reading, it may be necessary to keep the amplifier gain near maximum. In addition, the probe tip insertion may also have to be deep. As soon as an output is obtained, the probe insertion should be reduced to a minimum (approximately 1/32") and the probe should be fully tuned. If necessary the RANGE-DB switch may then be changed from 50 to 40. It is advisable for the beginner to avoid the 60 DB scale so as to avoid noise output due to the extremely large gain.

7. Slowly move the probe along the slotted line until a maximum reading is obtained on the meter. Readjust the GAIN control until the meter reads full scale, or "1".

NOTE: If the difference between the maximum and minimum readings are too small, switch the VSWR amplifier to EXPANDED and readjust for full scale at maximum.

Move the probe carefully along the full length of the slotted section. Observe and record all minimum readings on the VSWR meter as well as the probe position for those indicated on the scale of the slotted section. For all these readings have the sliding termination adjusted so that VSWR taken are maximum values.

$$(VSWR)_{actual} = \frac{(VSWR)_{max.}}{(VSWR)_{sliding\ term.}}$$

8. From the data obtained in step 7, calculate the guide wavelength λ_g, as being $2(d_2 - d_1) = 2(d_3 - d_2)$, etc., the values of d being the readings of the minimum points. The final value of λ_g should be the average of the values calculated.

9. Compute the distance of the "unknown" from the nearest minimum in terms of wavelength, as follows: For example,

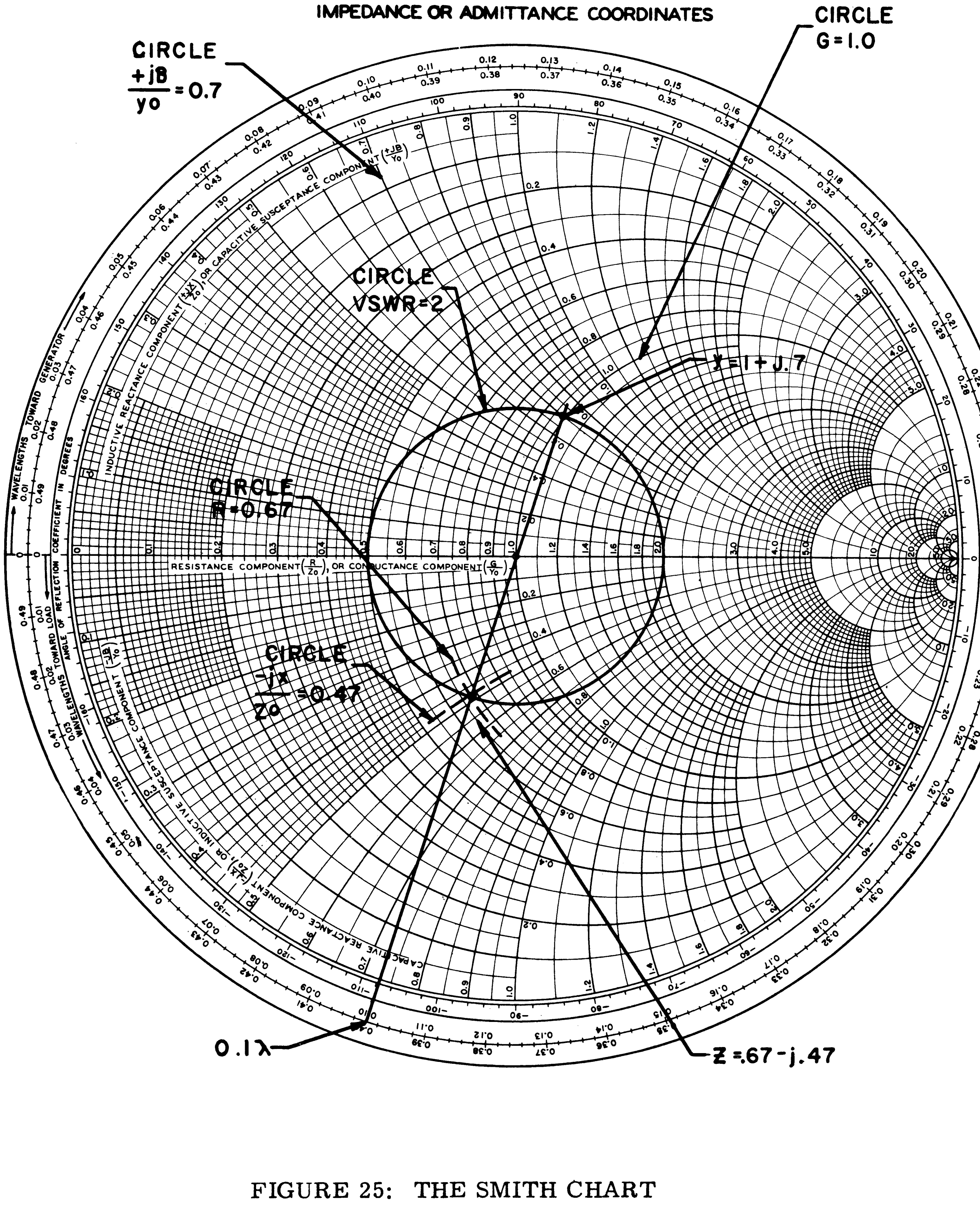


FIGURE 25: THE SMITH CHART

assuming that λ_g was found to be 30 mm and the distance from the minimum was 18 mm, this indicates that there was another minimum 1/2 wavelength (or 15 mm) closer, or 3 mm from the load. This corresponds to 1/10 wavelength.

10. Plot the data obtained, on the Smith Chart, as follows: Observe the horizontal line on the Smith Chart. It is marked "RESISTIVE COMPONENT" and is graduated from 1 to zero starting from the center and decreasing toward the left, and going from one to infinity from the center toward the right. Using the point "1" on this line (center of chart) as a center, draw a circle corresponding to the VSWR obtained in the experiment. For example, assuming the VSWR to be 2, the circle will intersect the vertical line at 0.5 above the center and at 2.0 below the center. The numbers from 1 to ∞ can always be used as an indication of VSWR. Next locate the point 0.10 on the next-to-outermost scale on the periphery of this chart. This scale is marked "WAVELENGTHS TOWARD LOAD" and increases in a counter-clockwise direction starting from the left side of the chart. Draw a straight line from this point, through the center of the chart, continuing the line clear across the chart. This line will intersect the circle just drawn at two points, one on each side of the center of the chart. The lower point falls on the $R/Z_o = 0.67$ circle and on the $jX/Z_o = 0.47$ circle or $Z = 0.67 - j0.47$. To convert these into the equivalent admittance form, it is only necessary to go to the diametrically opposite point on the chart (this is the other point intersected on the VSWR = 2 circle) to get $Y = 1.0 + j0.7$. It should be remembered that these numbers are in normalized form, or in fractions of the characteristic impedance, Z_o or admittance Y_o. If Z_o is 400 ohms, the impedance expression above would therefore have to be multiplied by 400 to obtain the results in ohms.

Questions

1. In step 7 what was the effect, if any, of adjusting the sliding termination?

2. What was the effect of inserting the partially open shim? What is the admittance of this iris?

3. Does this partial obstruction absorb or dissipate any incident energy?

4. In computing the distance from the minimum in terms of wave-

length the measured wavelength λ_g instead of λ_o was used. Does this affect the accuracy in any way? Explain why or why not.

5. What is the value of an unknown impedance (or admittance) if the measured VSWR is 1.6 and the distance from the minimum is 0.069? VSWR = 2.8, distance = 0.090?, VSWR = 1.8, distance = 0.40?

6. In the above experiment, the value of VSWR was obtained by adjusting the amplifier for a full scale deflection on the maximum probe position and then reading the minimum value. How could the VSWR be obtained without this "automatic meter" calibration?

EXPERIMENT 5 : MICROWAVE TRANSMISSION, RADIATION PATTERNS, ANTENNA GAIN

Object

1. To learn the characteristic behavior of radiated microwave energy.

2. To observe the directional effects of radiated beams.

3. To learn the significance of antenna gain.

Discussion

In the first section of this manual, it was pointed out that the most obvious difference between microwaves and the much longer, low frequency waves was the fact that the electrical components (such as slotted sections, antennas, etc.) at microwaves become extremely large in comparison to a wavelength. By contrast, at low frequencies the components are very small in comparison to a wavelength. At microwave frequencies, dimensions are so many thousands of times smaller than, for instance, broadcast frequency dimensions, that microwaves are beginning (relatively speaking) to approach the dimensions of visible light wavelengths. Actually they exhibit many characteristics of this form of energy. Specifically, microwaves may be focused, directed, reflected and in other ways treated like "invisible light". It is the purpose of this experiment to discuss and illustrate some of the more outstanding characteristics of this behavior, namely, attenuation in space, reflection and direction, as well as magnification through direction and beam forming.

Attenuation

As in low frequency communication, the greatest loss in transmission at microwave frequencies is due to what is called "free space attenuation". It depends on a number of factors including the mission medium, and varies in a direct manner with frequency. For any particular frequency, the greatest factor in this attenuation is the distance between the signal source and the receiver. When the distance is extremely short, as when a lab setup such as this is employed, a measurement of attenuation may be more conveniently made.

Reflection

This characteristic of microwaves, as stated previously, is fairly similar to the behavior of light waves. Energy may be "bounced off" a suitable surface and directed toward a receiver located in a path other than the direct path from the signal source.

Focusing and Magnification

This is a characteristic of practically all microwave antennas. Regardless of the particular shape an antenna may have, its electrical structure is such as to direct the output of the transmitter in a particular limited sector of space, varying in dimensions with the particular requirement of the nature of the transmission. For instance a general purpose radar transmitter, usually called a "search radar" would usually have a fairly wide area of coverage (actually it is a volume of coverage). By contrast, gunfire radar sets have extremely narrow beams and angles of coverage, and are often referred to as "pencil beams", since these are intended to distinguish between fairly small objects close to each other.

The magnification, or "gain" of an antenna is very analogous to the intensification of a light beam by directing or focusing, instead of allowing it to scatter. In antenna terminology, gain is a relative indication, and is based on the comparative intensification of magnification of the particular antenna in question over a basic antenna. Thus, if a transmitter output is measured at the receiving end, using such a basic antenna, and, if a second measurement is made with some other non-standard antenna, the increase in DB at the receiver with the second antenna is due to the gain of the latter. This applies equally to receiving and transmitting antennas. In microwave measurements, the gains of unknown antennas may be measured on scaled down models, for convenience. The standard of comparison for such an antenna measurement is the standard gain horn.

Standard Gain Horn

Figure 14 shows the NARDA Model 640 Standard Gain Horn. Since this experiment is conducted at X-Band frequencies, the horn dimensions are correspondingly chosen. The waveguide flange of the horn mates with other X-band components in this setup. As can be seen, the overall appearance of the horn resembles that of a megaphone. Thus, instead of the energy emerging from the flange end of a piece of waveguide and dispersing, it is directed by the flared shape of the horn along a particular angle in both the vertical and horizontal directions. The configuration of the horn flare is designed to provide the required angles (both vertical and horizontal) as well as the gain of the device.

The most important characteristics that have to be specified for a horn are gain and beam width. The gain refers to the increase in the level of output energy in decibels of the horn over a basic radiator, which is non-directional (isotropic). Since the horn is usually designed to operate over a range of frequencies, and since the gain is not constant but varies approximately inversely with the square of the wavelength, it is necessary to specify gain at a particular frequency (usually the mid-frequency of the operating range), from which the gains at other points in the band may easily be calculated. For instance, if the gain of a horn is given as 16 DB at 8 kilomegacycles, the gain at 10 KMC can be calculated (approximately) by using the fact that the wavelength and the frequency are inversely proportional to each other. The wavelength at 10 KMC is therefore 0.8 of the wavelength at 8 KMC, and the gain is therefore $1/0.8^2$ times the original gain, or about 1.55 times greater (or 10 log 1.55 in DB). The beam width of a horn refers to the vertical and horizontal angles subtended by the solid angle of the radiated beam. This is usually referred to as the width in degrees in the E and H planes. These letters, respectively, refer to the electric field in the vertical direction and the magnetic field in the horizontal plane.

Among the salient features of a horn are included its gain variation over the frequency band and the accuracy of such gain specification.

In the calibration of the gain of an unknown antenna, it is desired to know the gain of the unknown in comparison to the simplest type of radiator (isotropic radiator). By comparison with an antenna of known gain, such as the standard gain horn, the unknown antenna gain can then be obtained in absolute terms.

Procedure

A.

1. Set up the equipment as shown in Figure 26. Set the Model 730 attenuators for approximately half of the maximum attenuation. Set the RANGE control on the VSWR amplifier to one of the low scales (approximately 50).

2. Tune up the klystron for maximum output on the meter. If no output is obtained, readjust the two attenuators as well as the GAIN control on the amplifier until an output is obtained. Tune for maximum klystron output and record RANGE and meter readings in DB.

3. Remove both horns from the setup and connect the system together again (frequency meter to right hand attenuator in Figure 26). Readjust the tuneable detector and again note the reading on the meter and the RANGE-DB switch.

NOTE: The switch may have to be set to one of the highest ranges (perhaps the 30 range), since the power level will be considerably higher.

4. Calculate the relative power reading P_t / P_r from steps 2 and 3 in the same manner as outlined in the earlier experiments on power and attenuation. Call the power obtained in step 2 the received power, P_r and the power of step 3 the transmitted power, P_t. The relative level can be given either as a ratio or left in DB.

5. Replace both horns in the setup, but in interchanged positions, and repeat the measurements of steps 2 and 3. This is primarily done as an experimental verification that the results are identical.

B.

6. Uncouple both horns from the setup, and fasten the two Model 730 attenuators together at their flanges. Set the RANGE switch to its lowest position (0 DB). If the meter reads off scale on the high end, increase the attenuation settings of the Model 730 attenuators until the meter reading is on scale, preferably near the maximum of the scale. Record the meter reading and the RANGE-DB switch setting.

7. Uncouple the two attenuators and space their flanges 1 inch. Read meter. If necessary, change RANGE-DB switch setting until a reading is obtained.

8. Continue to increase the spacing between the Model 730 flanges in measured amounts and obtain and record the reading in DB each time until the RANGE-DB switch is set to the 50 position.

9. Calculate the attenuation in the air for each position checked. Then express the attenuation in DB per inch.

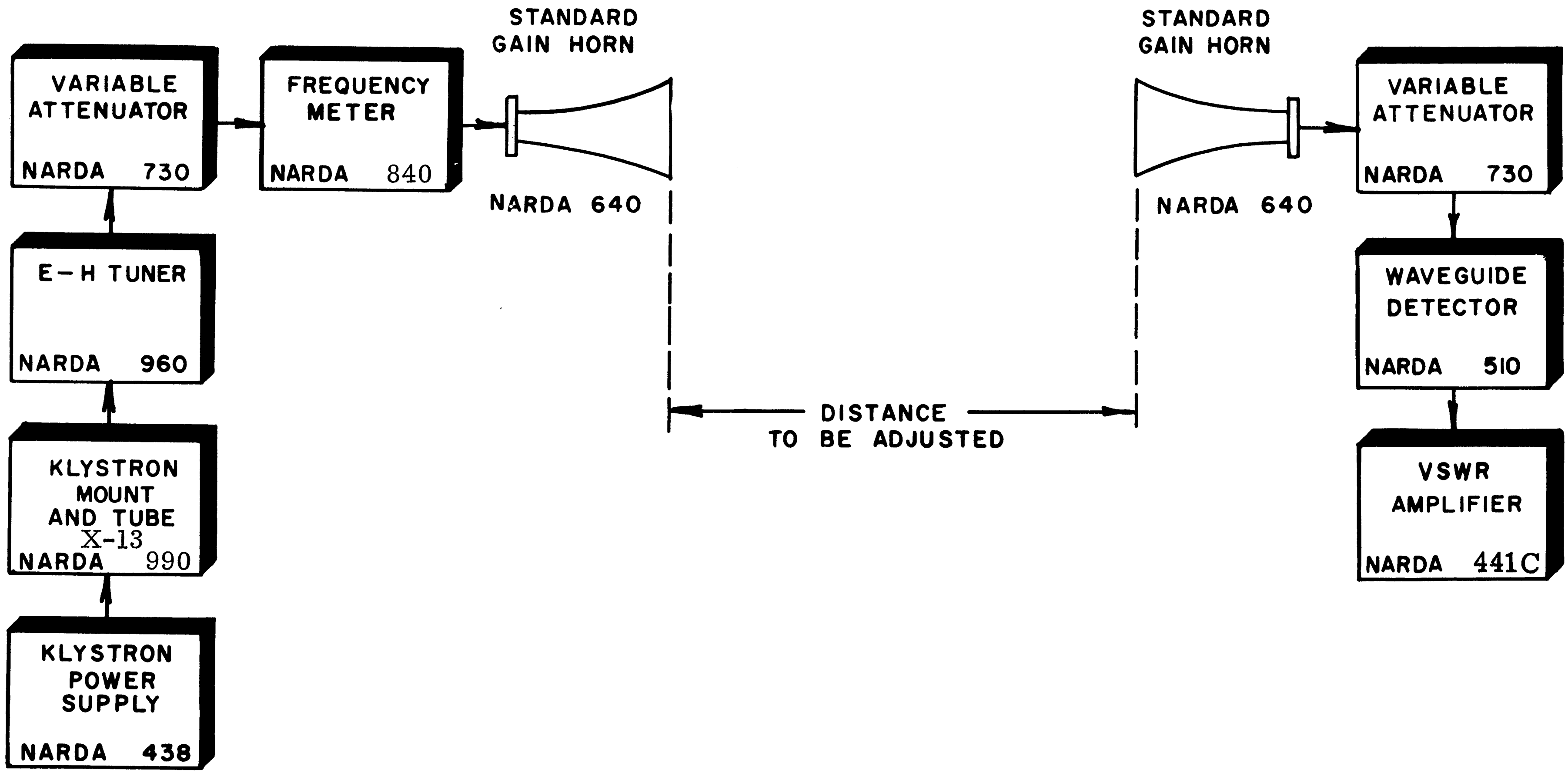


FIGURE 26: BLOCK DIAGRAM OF SETUP FOR GAIN MEASUREMENTS

C. 10. Replace the two horns in the setup as in steps 1 through 5. With the RANGE-DB switch on one of the middle positions (30 or 40), adjust the spacing of the horns for a near-maximum reading on the meter.

11. Rotate the receiver (right hand) end of the setup so that the horns are no longer in line, but at a small angle (about 15 degrees to each other. Record the meter reading. Reset the RANGE switch , if necessary.

12. Repeat step 11 with the receiver horn at about 45 degrees offset. Repeat with about 90 degree offset, adjusting the amplifier as required to obtain a reading. Record all data.

13. Repeat steps 10 through 12 with the horn rotated in the opposite direction, but with the angles approximately the same as in the first case.

D. 14. With the horns still at about 90 degrees to each other, slowly and carefully introduce a metallic reflector (such as a rectangular sheet of aluminum or cardboard covered with aluminum on one side) somewhat as shown in Figure 27. Vary the angle of the reflector and observe the change in the meter reading. Reset the RANGE-DB switch as required to keep the meter reading on scale. Record the approximate reflector positions and the corresponding meter readings in DB.

15. Substitute a piece of cardboard for the aluminum or metallic sheet. Observe the result.

16. Switch off the power supply and dismantle the setup.

Questions

1. Calculate the gain of the horns in the following manner which assumes the gain of each to be identical:

$$G = \frac{4\pi R}{\lambda} \frac{P_r}{P_t} \quad \text{or in DB, Gain} = 10 \log \frac{4\pi R}{\lambda} - \frac{K}{2}$$

where G is the receiving antenna gain, and R is the spacing

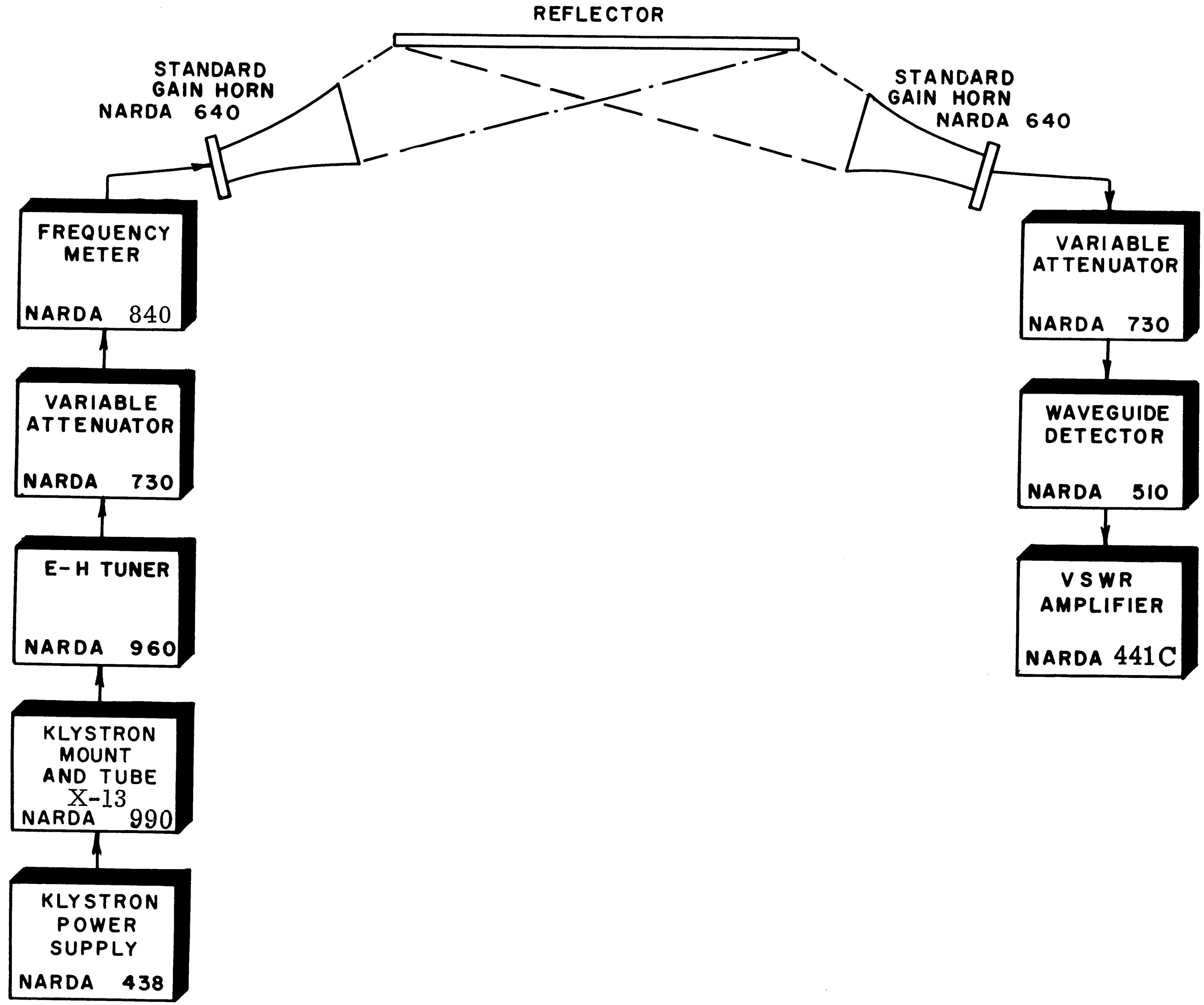


FIGURE 27: BLOCK DIAGRAM OF SETUP FOR REFLECTION MEASUREMENTS

between horn mouths in centimeters. (The value of λ in centimeters can be calculated from the measured frequency). $K = 10 \log P_t/P_r$, which is the DB value found from step 4.

2. On the basis of the definition of "gain" for horns, are the results obtained from steps 4 or 5 true gains? Explain your answer.

3. On the basis of the results in steps 6 through 9, how does the attenuation of the signal vary with the length of the path in air? What factors, if any, may have affected the accuracy of your answer (can this method of signal coupling be considered as true transmission through space?)

4. Assuming the setting in step 10 of this experiment corresponds to a maximum coupling between horns (corresponding to best focusing in optical systems), and based on the readings obtained with the horns at various angles to each other, what would be the shape of the plane area "covered" by signal under such maximum coupling? Draw such an area, indicating the strength of the signal in DB by the length of a line from the source of the signal, for angles of 15, 30, 45 and 60 degrees on either side of center.

5. What was the effect of the metallic obstruction in step 14? How did the plain cardboard "obstruction" behave? What can you say about the relative characteristics of metallic or conducting surfaces and non-conductors, such as paper?

6. Would the non-conducting "reflector" behave as in step 14 regardless of the level of power involved?