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بِسْمِ اللَّهِ الرَّحْمَنِ الرَّحِيمِ

The image features a central piece of blue calligraphic text in a highly stylized, cursive script. The text is arranged in a roughly horizontal line, starting with a large, ornate initial letter 'B' (Bismillah). The script is dense and intricate, with many overlapping strokes and sharp angles. Below the main text, there are several decorative elements: two small blue squares on the left side, one on the right side, and a long, sweeping blue flourish that extends from the bottom of the text towards the left. The entire composition is set against a plain, light-colored background.

## **On the Experimental Antenna Measurements: Study and Investigations**

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**Abstract:** This study focuses on the experimental measurement and analysis of antenna characteristics, aiming to provide a deeper understanding of antenna performance in real-world conditions. The investigation involves systematic assessment of key parameters such as radiation patterns, gain, impedance, and bandwidth. Using a variety of measurement techniques and equipment, including network analyzers, signal generators, and anechoic chambers, the study evaluates different types of antennas under various test scenarios. The experimental results are compared with theoretical predictions to identify discrepancies and refine antenna design methodologies. The findings of this study offer valuable insights into the practical performance of antennas, highlighting the importance of precise measurements in the design and optimization of antenna systems for communication and radar applications. The results also underscore the necessity of accounting for environmental and operational factors in antenna performance assessments.

## I. Theory

### Improving the Open Waveguide

If a transmission line propagating energy is left open at one end there will be radiation from this end [1]. The open waveguide acts as an antenna. In the case of a rectangular waveguide, this "antenna" presents a mismatch of about 2:1 (i.e., the  $SWR = 2$ ) and it radiates in many directions as shown in Figure 1.a. The match will be improved if the open waveguide is given a "horn" shape [2]. This will also result in a more concentrated radiation, because of the larger radiating area of aperture as shown in Figure 1.b.

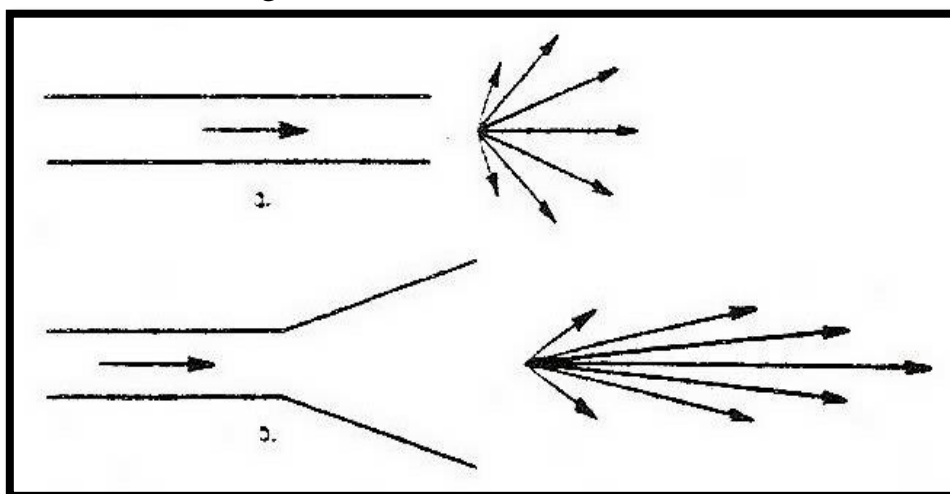


Figure 1. Radiation from a) an open waveguide b) a waveguide horn.

### The Antenna Radiation Pattern

The radiation pattern of an antenna is a diagram of the field strength, or more often the power intensity as a function of the aspect angle at a constant distance from the radiating antenna. If the antenna is a receiving antenna, the diagram will be the same but show the receiving sensitivity in various directions [3]. An antenna pattern is three dimensional but for practical reasons it is normally presented as a two-dimensional pattern in one or several planes [4]. These planes are for a rectangular horn antenna: the E-plane and the H-plane as illustrated in Figure 2.

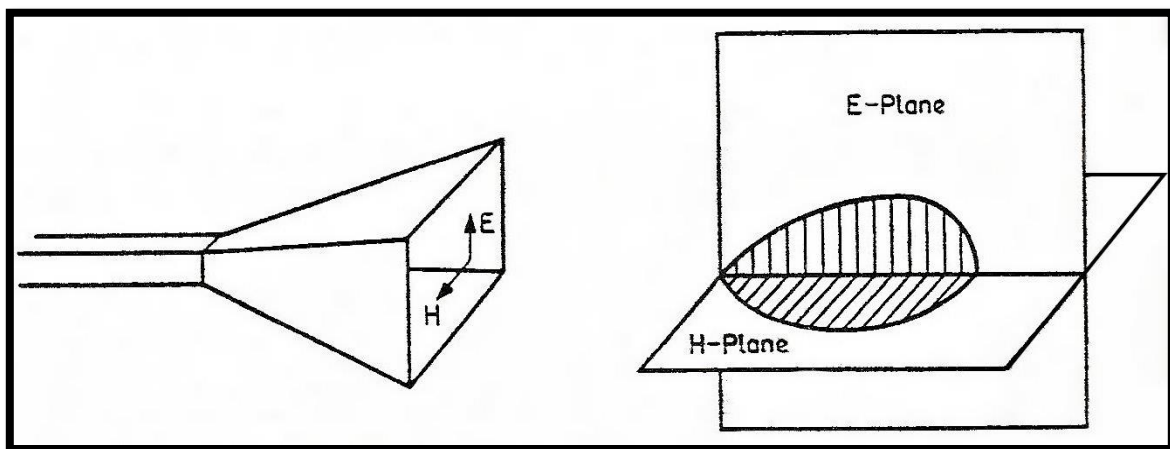


Figure 2. Definition of E-plane and H-plane.

An antenna pattern consists of several *lobes*: the main (or major) lobe, the side lobes, and the back lobe. The major power is concentrated in the main lobe and it is normally desirable to keep the power in the side lobes and the back lobe as low as possible.

### The Antenna Gain

The antenna gain ( $G$ ) is the power intensity at the maximum of the main lobe compared to the power intensity achieved from an imaginary isotropic antenna (i.e., radiating equally in all directions) [4], with the same power fed to the antennas as demonstrated in Figure 3.

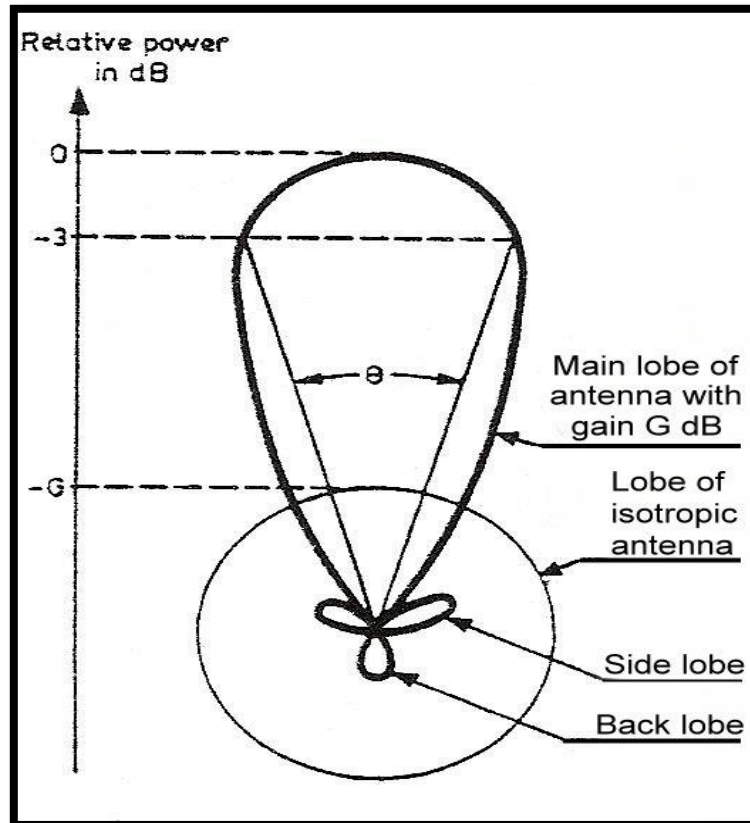


Figure 3. Typical directional antenna radiation pattern and an isotropic pattern.

### The Half-Power Beam Width

The Half-Power Beam Width (HPBW) is the angle between the two points on a main lobe where the power intensity is half the maximum power intensity [5]. Therefore, it is also called the 3dB-beamwidth.

### The Antenna Far Field

When measuring an antenna pattern, it is normally most interesting to plot the pattern far from the antenna. The pattern close to the antenna looks different [6]. A far-field pattern is achieved at a minimum distance of  $R_{min} = 2D^2/\lambda_o$  for a rectangular horn antenna, where  $D$  is the size of the broad wall of the horn antenna, and  $\lambda_o$  is the free space wavelength.

### Parabolic Antenna

A parabolic antenna consists of a parabolic dish and feed. The illumination of the dish by the feed can be direct or indirect [7]. In the indirect type, a sub-reflector is needed. The basic property of a perfect paraboloid is that it converts a spherical wave from a point source at the focus into a plane wave in the aperture. Conversely, all energy received from a distant source is reflected to a single point at the focus. This means that the waves from different "rays" are in phase at the aperture plane. A portion of the wave from the feed will be spread outside the

dish. This effect is called spill-over. Antennas based on parabolic reflectors are the most important type for microwave bands. Theoretically, they can operate at any frequency and in principle, they can be made to have as large a gain as is required. Recalling the relationship between the gain and the effective area

$$G = \frac{4\pi A_e}{\lambda^2} \quad (1)$$

It is seen that an increased gain is achieved by an increased aperture area; each time the paraboloid diameter is doubled, the gain is increased by 4 times or 6dB. Increasing the diameter will also decrease the beam width. If the diameter of the feed is small (not more than 0.3 of the paraboloid diameter) the loss in gain due to this obscuring feed is less than 1 dB.

### Slot Antenna

Slot antennas are very useful for fast-moving vehicular applications, where in order to reduce air resistance it is often important that the antenna does not protrude from the surface [8]. Babinet's principle shows that the electric field (magnetic current) distribution in the slot is identical with the electric current distribution on a thin-sheet wire [9]. There are several possibilities to cut a slot in a waveguide, however, only those slots which cut the "current lines" effectively will radiate. The slots are usually cavity backed to enclose the field and to restrict radiation to one side of the metal plane [10]. To achieve a narrower beam-shape, several slots are cut in the waveguide. The slots are cut  $\lambda_g/2$  apart and on opposite sides of the symmetrical axis to achieve phase coherence. Notice that  $\lambda_g$  is the waveguide wavelength.

## II. Antenna Gain Measurements

It is also very important to avoid disturbing reflections. Antenna measurements are normally made at outdoor ranges or in so called anechoic chambers made of absorbing material. Antenna measurements are mostly made with the unknown antenna as receiver. There are several methods to measure the gain of an antenna, two of them will be stated here. A third method is to compare the unknown antenna with a *standard gain* antenna with well-known gain.

### 1) The Two Identical Antennas Method

This method uses two identical antennas, one as transmitter and the other as receiver. The following formula can be proved, where its symbols are demonstrated in Figure 4.

$$P_r = \frac{P_t G^2 \lambda_o^2}{(4\pi R)^2}$$

where  $\lambda_o$  is the free space wavelength.

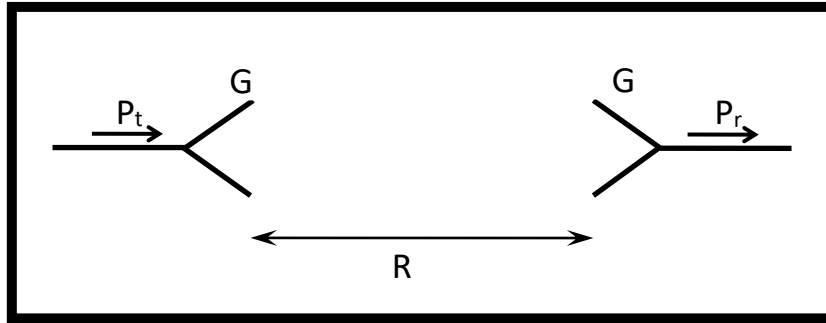


Figure 4. Definition of the symbols that are used in the gain formula.

Thus, from the above formula, one can find the antenna gain ( $G$ ) as

$$G = \frac{4\pi R}{\lambda_o} \sqrt{\frac{P_r}{P_t}} \quad (2)$$

So, by measuring  $P_t$ ,  $P_r$ , and  $R$ , one can calculate  $G$ . As can be seen from the formula, it is not necessary to know the absolute values of  $P_t$  and  $P_r$ , only the ratio of them is required. This ratio can be measured with a square-law detector (matched).

## 2) The Three-Antenna Method

If two identical antennas are not available, gain can be determined with three different antennas. The test configuration commences with antennas A and B, exchanging antenna B with antenna C and finally, exchanging antenna A with antenna B gives three equations

$$G_A G_B = \left( \frac{4\pi R}{\lambda_o} \right)^2 \cdot \frac{P_R}{P_T} \Big|_1 \quad (3)$$

$$G_A G_C = \left( \frac{4\pi R}{\lambda_o} \right)^2 \cdot \frac{P_R}{P_T} \Big|_2 \quad (4)$$

$$G_B G_C = \left( \frac{4\pi R}{\lambda_o} \right)^2 \cdot \frac{P_R}{P_T} \Big|_3 \quad (5)$$



where the distance  $R$  and the wavelength  $\lambda_o$  should be held constant in the three measurements.

Thus, we have three equations with three unknowns. Now, let

$$K = \left( \frac{4\pi R}{\lambda_o} \right)^2 \quad (6)$$

From equation (5),

$$G_B = \frac{K}{G_C} \frac{P_R}{P_T} \Big|_3 \quad (7)$$

From equation (4),

$$G_C = \frac{K}{G_A} \frac{P_R}{P_T} \Big|_2 \quad (8)$$

Substituting equations (7) and (8) into equation (3) and rearranging yields

$$G_A = \sqrt{\frac{K \cdot \frac{P_R}{P_T} \Big|_1 \cdot \frac{P_R}{P_T} \Big|_2}{\frac{P_R}{P_T} \Big|_3}} \quad (9)$$

Or in dB

$$G_A|_{dB} = \frac{1}{2} \left[ K + \frac{P_R}{P_T} \Big|_1 + \frac{P_R}{P_T} \Big|_2 - \frac{P_R}{P_T} \Big|_3 \right] \quad (10)$$

Knowing  $G_A$  we easily get  $G_B$  and  $G_C$ . Thus the gain of the three antennas is obtained without any extra information.

### III. Procedure

#### 1. Initial settings

1.1 Set up the equipment as shown in Figure 5. The scale on the goniometer should indicate  $0^\circ$  when the two antennas are *in line*. To avoid disturbing reflections, make sure no objects are close to the propagation path.

1.2 On the klystron power supply, check that the high-tension button "HT" is out (i.e., off). Switch on the "Power" button. Only 6.3 volt (heater voltage) is now supplied to the klystron. To get a uniform electronic emission from the Klystron heater (filament), it is necessary to wait for at least 30 seconds before applying the high tension by switching on the "HT" button.

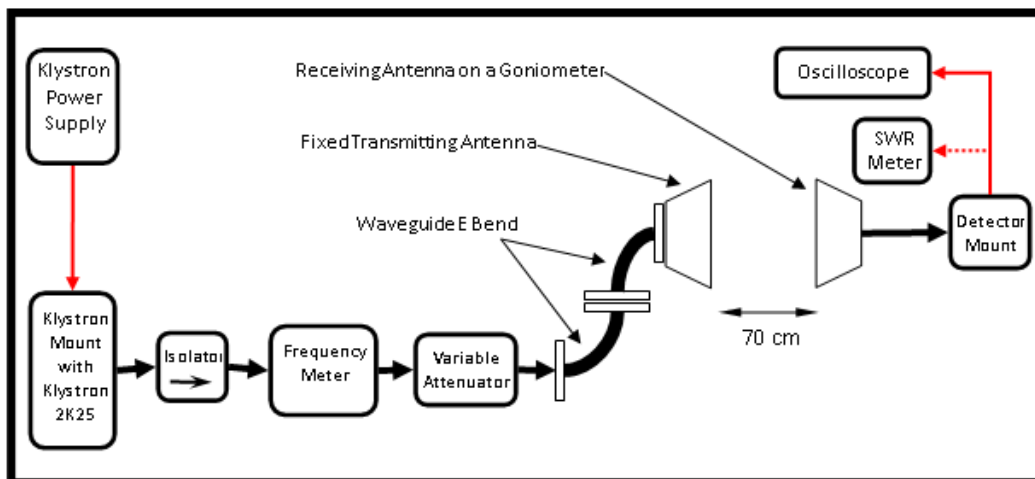


Figure 5. Set up for measuring the radiation pattern and gain of an antenna.

1.3 Set the attenuator to apply no attenuation by adjusting its plunger depth to more than " $b$ " dimension of the waveguide, where  $b = 10.16$  mm.

1.4 Connect the output of the detector to channel 2 of the oscilloscope with the following settings: Trigger mode: Auto; Trigger source: CH2; Vertical amplifier mode: CH2; and DC-couple channel 2. Always make sure that the zero-axis trace is set to the middle horizontal line (zero-volt position) specially when changing the oscilloscope vertical amplifier setting in volt/division.

1.5 Having more than 30 seconds since applying the 6.3-volt power, we can now switch on the "HT" button.

1.6 Set the beam voltage to 300 volt and the reflector (repeller) voltage to -238 volt. Set the modulator to CW to apply continuous wave. Note and record the exact beam voltage, reflector voltage and the resonator current from the Klystron power supply digital read-out in Table 1.

## 2. Measuring the frequency

To get stable operation, it is advisable to let the klystron warm up 10 minutes before performing this step.

2.1 Adjust the detector mount plunger to maximize the output voltage.

2.2 Fine-tune both of the reflector voltage and the klystron mount plunger for further maximizing the output voltage. Note and record the output voltage in Table 1.

Table 1. The basic settings of the reflex klystron oscillator.

Step	Quantity	Measured value	Units
1.6	Beam voltage (by the klystron power supply)	3.3	V
1.6	Reflector voltage (by the klystron power supply)	3.8	V
1.6	Resonator current (by the klystron power supply)	205	mA
2.2	Maximum output voltage (by the oscilloscope)	23	mV
2.4	Frequency (by the frequency meter)	8.9	GHz

2.3 Tune the frequency meter until a "dip" is observed in the oscilloscope. Keep tuning the frequency meter to obtain minimum output voltage in the oscilloscope.

2.4 Note the frequency meter setting and record it in Table 1.

2.5 Detune the frequency meter by at least 50 MHz to return back the power that has been coupled inside the cylindrical cavity of the frequency meter.

### 3. Radiation pattern measurements

Do not stand too close to the set up. Try to move slowly near the propagation path and you will see a change in the output voltage in the oscilloscope.

3.1 Make sure the setup is still adjusted for maximum output voltage.

3.2 Using the goniometer platform, turn the receiving horn antenna in  $10^\circ$  steps and note the oscilloscope reading. Keep on out to  $360^\circ$  from initial position. Record in Table 2.

3.3 Use the obtained values in Table 2 to draw a polar antenna radiation pattern.

**Table 2. The radiation pattern measures of the horn antenna.**

Azimuth angle (degree)	Output voltage (mV)	Azimuth angle (degree)	Output voltage (mV)
0°	122	190°	125
5°	112	200°	117
10°	120	210°	137
20°	109	220°	150
30°	149	230°	140
40°	108	240°	131
50°	145	250°	111
60°	145	260°	131
70°	133	270°	117
80°	110	280°	102
90°	103	290°	108
100°	131	300°	123
110°	121	310°	120
120°	122	320°	118
130°	116	330°	122
140°	144	340°	127
150°	142	350°	144
160°	133	355°	139
170°	119	360°	118
180°	147		

#### 4. Antenna pattern angles

4.1 Measure the output voltage from the oscilloscope (at full alignment of the two antennas) as  $V_{max}$ . Note and record in Table 3.

4.2 Rotate the receiving antenna using the goniometer till you read  $0.707V_{max}$  in the oscilloscope. Record the angle on the goniometer as  $\phi_{h1}$  then rotate the antenna in the other direction till you read  $0.707V_{max}$  in the oscilloscope. Record the goniometer angle as  $\phi_{h2}$ .

4.3 Calculate the half-power beam width (HPBW) as the difference between the two angles. Record in Table3.

4.4 Repeat step 4.1 and record  $V_{max}$  in Table 3. Ideally, you should have the same measurement that you got in step 4.1; however, you may not get the same result, why?

**Table 3. The radiation pattern angles measurements of the horn antenna.**

Step	Quantity	Measured value	Units
4.1	Maximum received voltage ( $V_{max}$ ) (by the oscilloscope)	5.5	V
4.2	First half-power angle ( $\phi_{h1}$ ) (by the goniometer)	90	°
4.2	Second half-power angle ( $\phi_{h2}$ ) (by the goniometer)	89	°
4.3	Half-Power Beam Width (by calculating the difference of $\phi_{h1}$ and $\phi_{h2}$ )	91	°
4.4	Maximum received voltage ( $V_{max}$ ) (by the oscilloscope)	6.5	V
4.5	First null angle ( $\phi_{n1}$ ) (by the goniometer)	34	°
4.5	Second null angle ( $\phi_{n2}$ ) (by the goniometer)	56	°
4.6	Beam Width between First Nulls (by calculating the difference of $\phi_{n1}$ and $\phi_{n2}$ )	23	°

4.5 Rotate the receiving antenna from the two sides of  $V_{max}$  as you did in step 4.2 but this time stop when you read the first minimum in the oscilloscope. Note them as  $\phi_{n1}$  and  $\phi_{n2}$  in Table 3.

4.6 Calculate the beam width between first nulls (BWFN) as the difference between the two angles. Record it in Table 3.

### 5. Gain measurement: The two identical antennas method

Here, we will measure the gain of the pyramidal horn antenna using two identical horn antennas.

5.1 Make sure the transmitting and receiving horn antennas are exactly the same (i.e., identical).

5.2 While the "HT" switch is off, switch on the "power" switch of the klystron power supply.

5.3 Adjust the two horn antennas to maintain 70-cm distance between them. Also, make sure that the two antennas are in line.

5.4 Set the attenuator plunger depth to zero mm.

5.5 After at least 30 seconds of switching on the "power" switch, switch on the "HT" switch. Adjust the klystron reflector voltage, the klystron mount plunger, and the detector mount plunger to obtain a maximum received voltage on the oscilloscope.

5.6 Note and record the output voltage as the received voltage ( $V_r$ ) in Table 4.

5.7 Switch off the "HT" button then switch off the "Power" button of the klystron power supply.

**Table 4. The gain measurements of the horn antenna.**

Step	Quantity	Measured value	Units
5.6	Received voltage ( $V_r$ ) (by the oscilloscope)	4.3	V
5.10	Transmitted voltage ( $V_t$ ) (by the oscilloscope)	4.5	V
5.11	Distance: Tx to Rx antennas (R) (by a measuring tape)	120	cm
5.11	Free space wavelength ( $\lambda_o$ ) (by calculation from the frequency)	133	cm
5.11	Gain (by calculation: using eqn. 2)	23	---
5.12	Gain (by calculation: using eqn. 11)	15.8	dB

5.8 Remove the detector from the receiving antenna and let it replace the transmitting antenna as illustrated in Figure 6. Keep everything else untouched.

5.9 Switch on the "Power" button of the klystron power supply then after about 30 seconds switch on the "HT" button.

5.10 Note and record the output voltage as the transmitted voltage ( $V_t$ ) in Table 4.

5.11 Assuming that the detector is matched, antenna gain can be estimated using equation (2) as follows

$$G \cong \frac{4\pi R}{\lambda_o} \sqrt{\frac{(V_r)^2}{(V_t)^2}} = \frac{4\pi R}{\lambda_o} \frac{V_r}{V_t}$$

where R is the distance between the transmitting antenna and the receiving antenna and  $\lambda_o$  is the free space wavelength, which can be found from the measured frequency in step 2.4. Record them in Table 4.

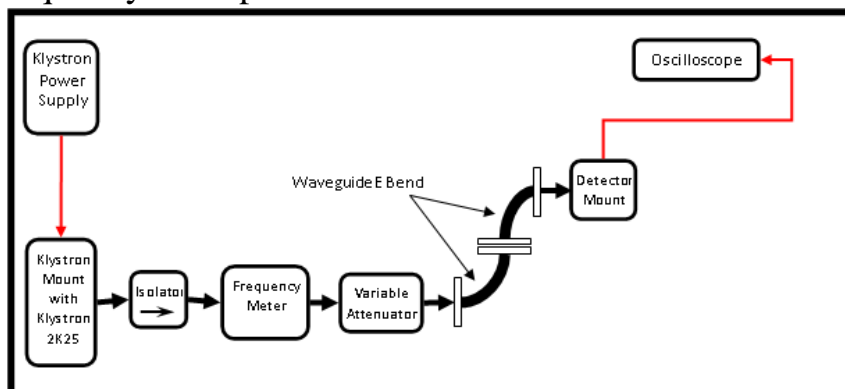


Figure 6. Replacing the transmitting horn antenna by the detector to measure the transmitted power.

5.12 Enter the value of gain in dB into Table 4 by using the equation

$$G_{dB} = 10 \log_{10}(G) \quad (11)$$

5.13 Switch off the "HT" button then switch off the "power" button.

6. Gain measurement: The three-antenna method

**Stage 1: Slot the antenna to dielectric antenna:**

6.1 Set up the equipment as shown in Figure 7 such that the transmitting antenna is the broad-wall slot antenna connected to a variable short; and the receiving antenna is the dielectric antenna connected to the twist waveguide section to adjust the vertical polarization of the slot antenna.

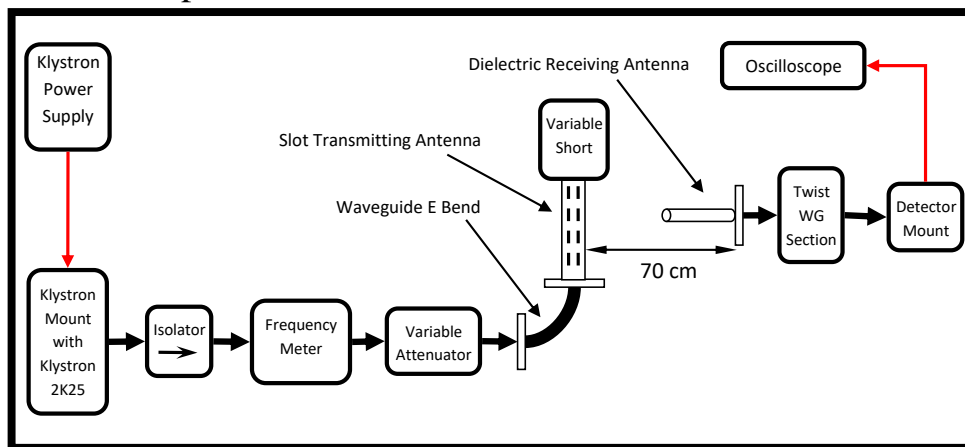


Figure 7. Set up for measuring the antenna gain using the three-antenna method. First stage is slotting antenna to dielectric antenna.

6.2 Make sure the "HT" switch is off then switch on the "power" switch of the klystron power supply.

6.3 Adjust the two antennas to maintain 70-cm distance between the transmitting slot antenna and the base of the receiving dielectric antenna. Also, make sure that the two antennas are in line.

6.4 Set the attenuator plunger depth to apply no attenuation, like you did in step 1.3.

6.5 After at least 30 seconds of switching on the "power" switch, you can switch on the "HT" switch. Adjust the Klystron reflector voltage, the klystron mount

plunger, and the detector mount plunger to obtain a maximum received voltage on the oscilloscope.

6.6 Note and record the output voltage as the received voltage ( $V_r$ ) in Table 5.

6.7 Switch off the "HT" button then switch off the "Power" button of the klystron power supply.

6.8 Remove the detector and the twist waveguide section from the receiving dielectric antenna and let it replace the transmitting slot antenna as shown in Figure 8. Keep everything else untouched.

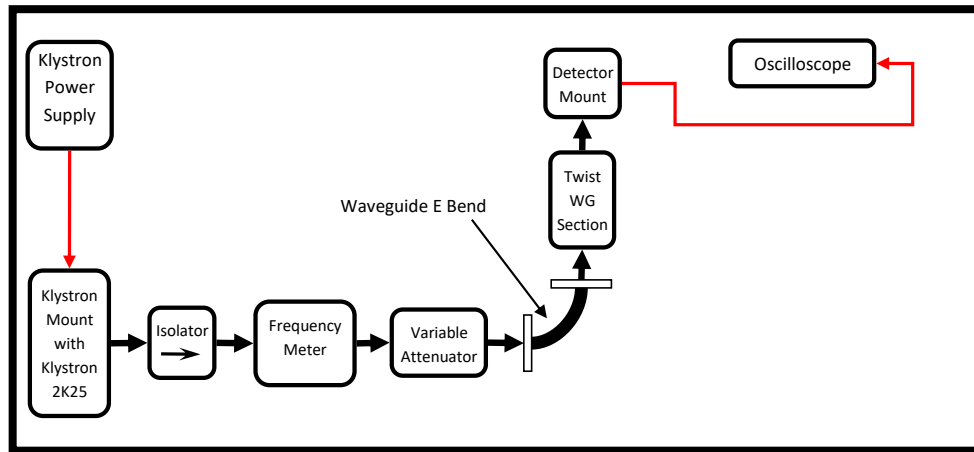


Figure 8. Replacing the transmitting slot antenna by the detector to measure the transmitted power. Notice that the twist waveguide section is used to consider its loss of insertion.

6.9 Switch on the "Power" button of the klystron power supply then after about 30 seconds switch on the "HT" button.

6.10 Note and record the output voltage as the transmitted voltage ( $V_t$ ) in Table 5.

6.11 Assuming that the detector is matched, calculate the power ratio in dB from equation (12) and record it in Table 5.

$$\left. \frac{P_R}{P_T} \right|_{dB} = 20 \log_{10} \left( \frac{V_r}{V_t} \right) \quad (12)$$

6.12 Switch off the "HT" button then switch off the "power" button.

### Stage 2: Slot the antenna to parabolic reflector antenna:

6.13 Set up the equipment as shown in Figure 9 such that the transmitting antenna is the broad-wall slot antenna connected to a variable short; and the receiving antenna is the parabolic reflector antenna connected to the twist waveguide section to adjust the vertical polarization of the slot antenna.



6.14 Make sure the "HT" switch is off then switch on the "power" switch of the klystron power supply.

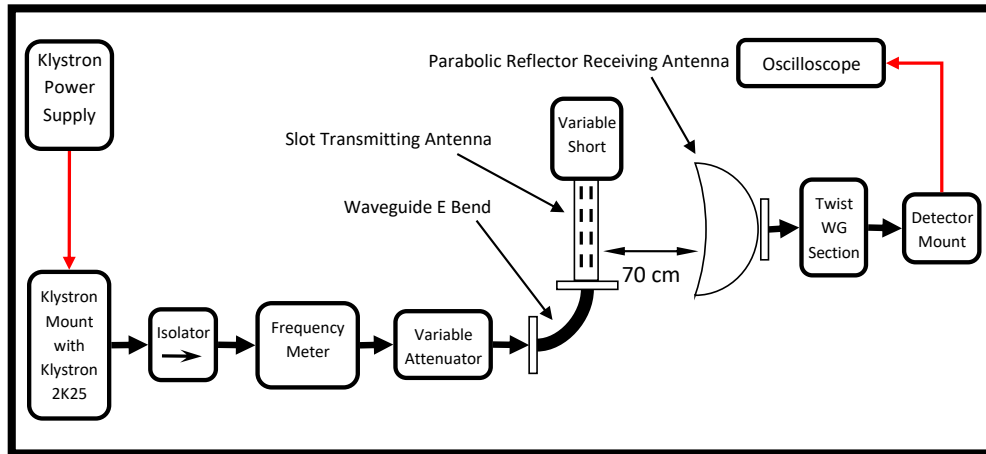


Figure 9. Set up for measuring the antenna gain using the three-antenna method. Second stage is slot antenna to parabolic reflector antenna.

6.15 Adjust the two antennas to maintain 70-cm distance between the transmitting slot antenna and the aperture of the receiving parabolic reflector antenna. Also, make sure that the two antennas are in line.

6.16 Make sure the attenuator does not apply attenuation.

6.17 After at least 30 seconds of switching on the "power" switch, you can switch on the "HT" switch. Adjust the Klystron reflector voltage, the klystron mount plunger, and the detector mount plunger to obtain a maximum received voltage on the oscilloscope.

6.18 Note and record the output voltage as the received voltage ( $V_r$ ) in Table 5.

6.19 Switch off the "HT" button then switch off the "Power" button of the klystron power supply.

6.20 Remove the detector and the twist waveguide section from the receiving parabolic reflector antenna and let it replace the transmitting slot antenna as shown in Figure 8. Keep everything else untouched.

6.21 Switch on the "Power" button of the klystron power supply then after about 30 seconds switch on the "HT" button.

6.22 Note and record the output voltage as the transmitted voltage ( $V_t$ ) in Table 5.

6.23 Assuming that the detector is matched, calculate the power ratio in dB from equation (12) and record it in Table 5.

6.24 Switch off the "HT" button then switch off the "power" button.

**Stage 3: Dielectric antenna to parabolic reflector antenna:**

6.25 Set up the equipment as shown in Figure 10 such that the transmitting antenna is the dielectric antenna, and the receiving antenna is the parabolic reflector antenna.

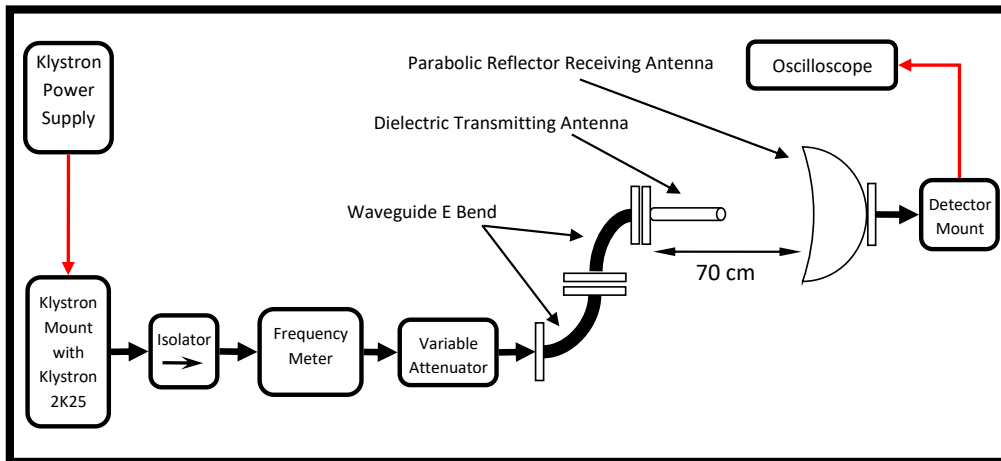


Figure 10. Set up for measuring the antenna gain using the three-antenna method. Third stage is dielectric antenna to parabolic reflector antenna.

6.26 Make sure the "HT" switch is off then switch on the "power" switch of the klystron power supply.

6.27 Adjust the two antennas to maintain 70-cm distance between the base of the transmitting dielectric antenna and the aperture of the receiving parabolic reflector antenna. Also, make sure that the two antennas are in line.

6.28 Keep the attenuator setting to apply zero dB attenuation.

6.29 After at least 30 seconds of switching on the "power" switch, you can switch on the "HT" switch. Adjust the klystron reflector voltage, the klystron mount plunger, and the detector mount plunger to obtain a maximum received voltage on the oscilloscope.

6.30 Note and record the output voltage as the received voltage ( $V_r$ ) in Table 5.

6.31 Switch off the "HT" button then switch off the "Power" button of the klystron power supply.

6.32 Remove the detector and the twist waveguide section from the receiving parabolic reflector antenna and let it replace the transmitting slot antenna as shown in Figure 11. Keep everything else untouched.

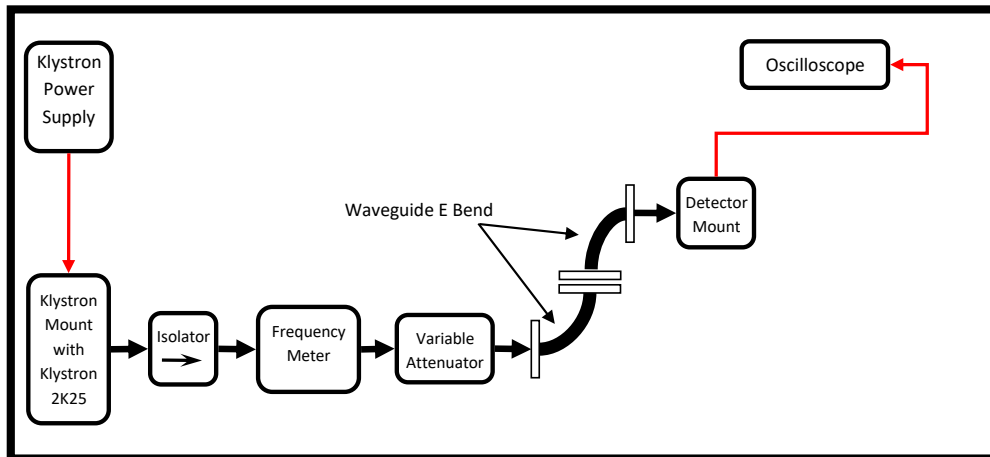


Figure 11. Set up for measuring the antenna gain using the three-antenna method. Third stage is a dielectric antenna to parabolic reflector antenna.

6.33 Switch on the "Power" button of the klystron power supply then after about 30 seconds switch on the "HT" button.

6.34 Note and record the output voltage as the transmitted voltage ( $V_t$ ) in Table 5.

6.35 Assuming that the detector is matched, calculate the power ratio in dB from equation (12) and record it in Table 5.

6.36 Switch off the "HT" button then switch off the "power" button.

### Preparing and solving the three gain equations simultaneously

6.37 Calculate the constant K as given in equation (6). Find its value in dB. Record its value in Table 5.

6.38 Solve the three gain equations in dB and find the gain values of the three antennas using the equations (3) to (10). Record them in Table 5. From equations (3) to (10), the following solution can be found.

**Table 5. The three-antenna method gain measurements.**

		Received voltage ( $V_r$ ) (by the oscilloscope)		Transmitted voltage ( $V_t$ ) (by the oscilloscope)		Power ratio ( $P_R/P_T$ ) (by calculation using eqn. 12)	
1.	Step:	6.6		6.10		6.11	
	S→D Value:	5	V	7.5	V	6.3	dB
2.	Step:	6.18		6.22		6.23	
	S→P Value:	6.6	V	7.5	V	7.2	dB
3.	Step:	6.30		6.34		6.35	
	D→P Value:	6.3	V	8.4	V	5.6	dB
Step 6.37		K (by calculation using eqn. 6)				3.4	---
Step 6.37		$K_{dB}$ (by calculation using $10\log_{10}K$ )				4.5	dB
Step 6.38		$G_S$ (by calculation using eqn. 13)				7.4	dB
Step 6.38		$G_D$ (by calculation using eqn. 14)				5.1	dB
Step 6.38		$G_P$ (by calculation using eqn. 15)				4.2	dB

$$G_S|_{dB} = \frac{1}{2} \left[ K_{dB} + \frac{P_R}{P_T} \Big|_{S \rightarrow D} + \frac{P_R}{P_T} \Big|_{S \rightarrow P} - \frac{P_R}{P_T} \Big|_{D \rightarrow P} \right] \quad (13)$$

$$G_D|_{dB} = K_{dB} + \frac{P_R}{P_T} \Big|_{S \rightarrow D} - G_S|_{dB} \quad (14)$$

$$G_P|_{dB} = K_{dB} + \frac{P_R}{P_T} \Big|_{S \rightarrow P} - G_S|_{dB} \quad (15)$$

#### IV. Conclusion

The experimental investigation into antenna measurements has provided significant insights into the practical performance of various antenna designs. By systematically measuring key parameters such as radiation patterns, gain, impedance, and bandwidth, the study has demonstrated the critical role that precise experimental techniques play in validating and optimizing antenna performance. The comparison between experimental results and theoretical predictions revealed areas of alignment as well as discrepancies, highlighting the complexities involved in antenna design. These findings emphasize the importance of considering environmental and operational factors when evaluating antenna performance, as real-world conditions can significantly impact the expected outcomes. Overall, the study reinforces the value of experimental measurements in the development and refinement of antenna systems, ensuring their reliability and effectiveness in communication, radar, and other applications. Future work may focus on refining measurement techniques and exploring advanced antenna designs to further enhance performance.

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