Design and Development of a 2.4 GHz Slot Antenna

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ABSTRACT

The slot antenna was designed from the intuition of Babinet's principle, that a horizontal electric dipole in free space is the dual of a vertical slot and will have the same radiation pattern as the slot of the same dimension. With the use of a MathCAD program to calculate the number of slots with proper dimension and location, it was designed to radiate at an operating frequency of 2.4GHz with a wavelength of 0.125m. Longitudinal slot with proper spacing were cut into a galvanized conducting sheet fed with a probe and connected to the signal generator. The radiation pattern and other Antenna parameters were analyzed in the study which shows good agreement with real life simulation with half-wave dipoles arrayed horizontally in the z direction and fed through a transmission line with a characteristic impedance of 75 ohms at the center, with a signal of 2.4 GHz from the signal generator. With a monopole antenna serving as a receiver from a reasonable distance, the spectrum analyzer showed a good result. The electric field was measured from the spectrum analyzer at a far field region and it was analyzed.

(Keywords: slot antenna, MathCAD, antenna parameters, electric field, radiation pattern)

INTRODUCTION

An antenna can be described simply as a metallic device, for radiating or receiving radio waves. It can also be described as a structure between free-space and a guiding device. There are great varieties of antennas used in communications system. However, communication by electrical means began with the introduction of telegraphy in 1844, followed by telephony in 1878 [1]. In these systems, electrical signals are sent over two-wire transmission lines that connect the sender and recipient. During the same period that these systems were being developed, the theoretical foundation for electromagnetic radiation was being laid by Maxwell and others. Later, the transmission of voice, data, and video by means of electromagnetic radiation came into existence.

Antennas are a fundamental component of modern communications systems. By definition, an antenna acts as a transducer between a guided wave in a transmission line and an electromagnetic wave in free space. Antennas demonstrate a property known as reciprocity, which is an antenna will maintain the same characteristics if it is transmitting or receiving.

When a signal is fed into an antenna, the antenna will emit radiation distributed in space a certain way. A graphical representation of the relative distributed of the radiated power in space is called a radiation pattern. The radiation pattern of the antenna is of principle concern when engineering a communications system. Assume that a signal needs to be sent from an antenna that serves as a transmitter to another antenna that serves as a receiver [2]. This would require a radiation pattern with the majority of its radiated power focused into the receiver. If the antenna is not engineered to do so, contact cannot be established between the signal source and its target.

There are many different ways to manipulate a radiation pattern to meet the demands of a specific task. These concepts are the principle focus in this work. Since the exact form of a particular antenna is influenced by many requirements, among the more important requirements are the operating frequency, its range and the type of display required which in turn depends on the destination of the intelligence received. Some antennas are mere modifications while others are completely innovative.

There are different types of antennas ranging from sizes, shapes, etc., to operate at certain operating frequencies. Examples are wire antennas, aperture antennas, microstrip antennas, array antennas, reflectors antennas, lens antennas and so on. This leads us to the major concern of this project the Slot antenna which belongs to the aperture antenna family.

The source is called the "Far-Field". In the far-field, E, H, and power density are related by the equations: $E = H \times 377$ and $P_d = E \times H$. combining these two equations together we get:

$$P_d = H^2 \times 377 \quad \textbf{(1)}$$

and

$$P_d = E^2 \times 377 \quad \textbf{(2)}$$

Where P_d = the power density in watts per square meter (one W/m^2 is equal to 0.1 mW/cm^2).

H^2 = the square of the value of the magnetic field in amperes squared per meter squared,

E^2 = the square of the value of the electric field in volts squared per meter squared.

The above equations show that in the far-field, all that is really needed to measure is the E field, actually E^2. From this measurement, the power density and value of the H field can be calculated.

DESIGN OF SLOT ANTENNA

The distinctive shape of the slot antenna at an operational frequency of 2.4 GHz is shown in Figure 1.

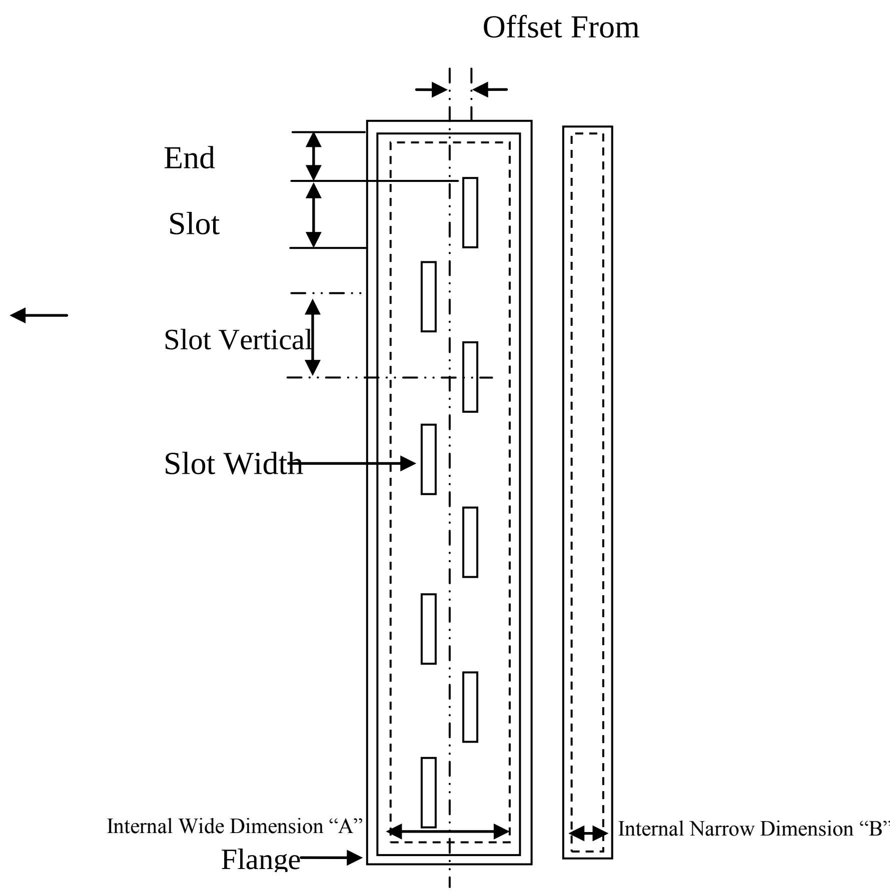


Figure 1: Slot Antenna.

Slots and Dipoles

As we have learnt that a thin slot in an infinite ground plane is the complement to a dipole in free space, and it shows that the slot will have the same radiation pattern as a dipole with the same dimensions as the slots.

To have a better understanding about Slot Antennas, Babinet's principle from optics was introduced (put into antenna by H. G. Booker in 1946). This principle relates the radiated fields and impedance of the slot antenna to that of the field of its compliment, the half-wave dipole antenna. The dual of a slot antenna would be if the conductive material and air were interchanged- that is, the slot from a metal sheet if imagined become a metal slab in space. An example of dual antennas is shown below:

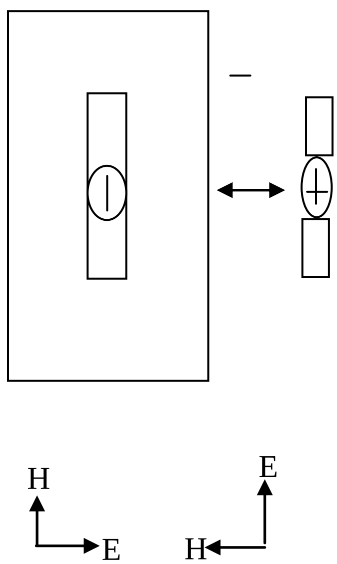


Figure 2: Babinet's Principle.

The slot is a magnetic dipole rather than an electric dipole. As a result, the polarization is rotated 90^0, so that radiation from a vertical slot is polarized horizontally. If a voltage source is applied across the short end of the slot, then an electromagnetic field will be generated within the slot and currents that travel within its perimeter, both contributed to the radiation. The dual antenna is similar to a dipole antenna. The voltage source is applied at the center of the dipole, so that the voltage source is rotated.

Babinet's principle relates these two antennas. The first result states that the impedance of the slot (Z_S) is related to the impedance of its dual antenna (Z_c) by the relation:

$$Z_s Z_c = \frac{\eta^2}{4} \qquad \textbf{(3)}$$

In the above, η is the intrinsic impedance of free space. The second major result of Babinet's/Booker's principle is that the fields of the dual antenna are almost the slot antenna (the field's components are interchanged, and called "duals"). That is, the fields of the slot antenna (given with a subscript S) are related to the fields of its compliment (given with a subscript D).

The radiation characteristics of wire antennas can be determined once the current distribution on the wire is known. For many configurations, however, the current distribution is not known exactly and only physical intuition or experimental measurements can provide a reasonable approximation to it.

Propagation Parameters of Slot Antenna

This work would have not been made possible without a proper and appropriate technical design. In this section we shall be considering the design technique of an antenna, the characterizations and the choice of the materials used.

The first step in this design is to select a section of waveguide which covers the desired frequency. As such for this project, a WR 340 was selected. The waveguide must match the dimension otherwise; there will be losses and inacceptable SWR if the waveguide is operated below its cutoff frequency.

These parameters that are relevant for the construction of the slot antenna are as calculated as follows:

Free Space Wavelength: At an Operating frequency of 2.4 GHz:

$$\lambda_0 = \frac{2\pi}{k} = \frac{c}{\frac{w}{2\pi}} = \frac{c}{f}$$

where λ_0 is the free space wavelength

C is the Speed of light: 3×10^8

And f is the frequency: 2.4×10^9

$$\lambda = \frac{c}{f} = \frac{3 \times 10^8}{2.4 \times 10^9} = 0.125 \text{ (m)} \qquad (4)$$

It should be noted that one (1) lambda of the operating frequency is 12.5cm as shown in Figure 3.

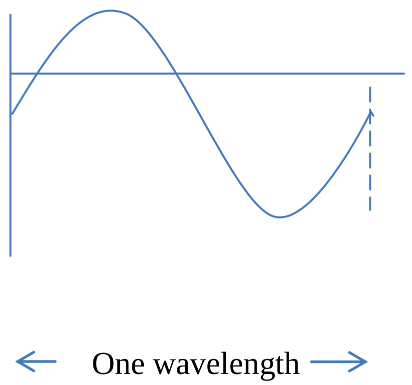


Figure 3: Display of a Single Wavelength.

Arrays of Slots

Specific radiation pattern requirements usually cannot be achieved by single antenna elements, because single elements usually have relatively wide radiation patterns and low values of directivity. To design antennas with very large directivities, it is usually necessary to increase the electrical size of the antenna. This can be accomplished by enlarging the electrical dimensions of the chosen single element. However, mechanical problems are usually associated with very large elements.

An alternative way to achieve large directivities, without increasing the size of the individual elements, is to use multiple single elements to form an array. An array is a sampled version of a very large single element. In an array, the mechanical problems of large single elements are traded for the electrical problems associated with the feed networks of arrays. It is possible to calculate the radiation pattern for an array of dipoles as well as a single dipole.

The usual technique will be to multiply the dipole pattern by the pattern of an array of ideal radiators. An array of slots may be configured to shape the radiation pattern as desired. Two-dimensional arrays of slots may be used to form a beam antenna, but there are easier ways to fabricate a beam antenna, so we will first concentrate on omni-directional antennas, with a linear array of slots.

The vertical collinear array, consisting of several vertical dipoles connected end-to-end, is a popular VHF omni-directional antenna with vertical polarization. A vertical dipole has an omni-directional pattern in the horizontal plane, or azimuth, and adding additional dipoles concentrates the beam into a flatter vertical dipoles passing through the hole; adding more collinear dipoles squishes the donut flat, like a pancake with a hole. The obtained cross-sectional dimensions were entered into the MathCAD program at an operating frequency of 2.4 GHz with desired no. of slots per face and the following result was generated as shown below.

The energy can be propagated in a number of different types of waves. In this case, a waveguide device was designed for transmission of a single wave type (most often the dominant wave or that having the lowest cutoff frequency).

Table 1: Dimensions as generated by the MathCAD File.

Dimensions	'A' Dim	'B' Dim	Offset From Centre	Slot Length	Slot Vertical Centre to Centre Spacing	Slot Width	Head Space	Guide Wavelength	Free Space wavelength	Waveguide Cutoff Wavelength
Inches	3.4	1.7	0.35	2.46	3.57	0.36	3.56	7.13	4.92	6.80
cm	8.64	4.32	0.889	6.2484	9.0678	0.9144	9.0424	18.1102	12.4968	17.272
mm	86.4	43.18	8.85	62.50	90.57	9.06	90.424	181.13	125.00	172.72

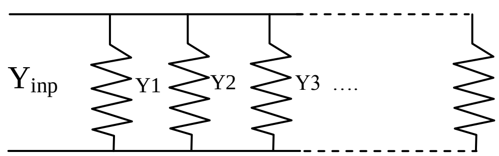
Slots Per/Face = 8

Wave Guide Cutoff frequency (MHz) = 1,736.92

Waveguide Slot Array Design

A sketch of a waveguide slot antenna with the pertinent dimensions is shown in Figure 4. The first design consideration is that the slots be resonant so that they provide a resistive load to the (waveguide) transmission line.

Normally, it is desirable for an omni-directional antenna to radiate in a horizontal (azimuth) plane. This is achieved by feeding all the slots in phase. The radiation pattern may be tilted upward or downward (visualize a shallow cone) by changing the phasing of the slots, if desired.



$Y_{input} = Y1 + Y2 + Y3 + \ldots + Yn$

Figure 4: Admittances of Slots.

Characterizations

The guide wavelength λ_g:

The slots are fed in phase by spacing their centers at electrical half-wavelength intervals along the waveguide. The electrical wavelength in waveguide is longer than in free space, so we must calculate the guide wavelength:

$$\lambda_g = \frac{2\pi}{\beta} = \frac{1}{\sqrt{\left(\frac{1}{\lambda_o}\right) - \left(\frac{1}{\lambda_c}\right)}} = \frac{\lambda_o}{\left(1 - \frac{\lambda_c^2}{4a^2}\right)^{1/2}} \quad \textbf{(5)}$$

λ_g is the guide wavelength
λ_c is the cutoff wavelength
where λ_0 is the free space wavelength
where β is the propagation constant.
and ("a") is the wide dimension (0.0864 m = 8.64 cm)

$$= \frac{0.125}{\left(1 - \frac{0.125^2}{4(0.0864)^2}\right)^{1/2}}$$

= 0.1811 m

In air, the guide wavelength λ_g is equal to the free-space wavelength λ_g.

The Cutoff Wavelength:

$$\lambda_c = \frac{2\sqrt{\mu\varepsilon}}{\sqrt{\left(\frac{m^2}{a^2}\right) + \left(\frac{n^2}{b^2}\right)}} \quad \textbf{(6)}$$

Where λ_c, the cutoff wavelength, equals 2 times the wide dimension of the waveguide.

Most frequently, the operation is limited to the TE_{10} or dominant wave in the waveguide. For simplified case, the important formulas are reduced to:

$$\lambda_c = 2a\sqrt{\mu\varepsilon} \quad \textbf{(7)}$$

= 2 (8.64)

= 17.27 cm

Waveguide Cutoff Frequency f_c:

Where a is the wide dimension, b is the narrow dimension, ε is the dielectric constant and μ is the permeability of the dielectric in the waveguide. Since propagation takes place only when the propagation constant is imaginary, the cutoff frequency for the rectangular waveguide is

$$f_c = \frac{c}{2\sqrt{\mu\varepsilon}}\sqrt{\left(\frac{m}{a}\right)^2 + \left(\frac{n}{b}\right)^2} \quad \textbf{(8)}$$

Where c is the velocity of light = 3×10^8 m\s
M is an integer and it takes a value of 1
While a is the largest dimension, 8.64 cm

Therefore:

$$f_c = \frac{c}{2\sqrt{\mu\varepsilon}}\sqrt{\left(\frac{m}{a}\right)^2 + \left(\frac{n}{b}\right)^2}$$

$$f_c = \frac{c}{2\sqrt{\mu\varepsilon}}\sqrt{\left(\frac{1}{8.64}\right)^2 + \left(\frac{0}{b}\right)^2}$$

$$f_c = \frac{c}{2a}$$

$$f_c = \frac{c}{17.27}$$

f_c = 17369212.5436

f_c = 1736.92 MHz

If the spacing is wrong, or if the frequency is changed significantly so the spacing is no longer $\lambda_g/2$, then the slots will not be fed in phase. A half-wavelength of transmission line has the useful property of repeating impedance: the input and output impedance is the same. As a result, the impedances, or admittances, of all the slots appear in parallel.

Each parallel resistor represents one slot, so there must be N resistances in parallel. Assuming that we are successful in making the slots resonant and spacing them exactly $\lambda_g/2$, then the admittance Y is purely resistive and the calculation is extremely simple: adding N identical admittances together, where N is the number of slots. So that the slot admittance should add up to 1.0; thus, each should have an admittance of 1/N.

Spacing the slots at $\lambda_g/2$ intervals in the waveguide is an electrical spacing of 180^0 – each slot is exactly out of phase with its neighbors, so their radiation will cancel each other. However, slots on opposite sides of the centerline of the guide will be out of phase (180^0), so we can alternate the slot displacement around the centerline and have a total phase difference of 360^0 between slots, putting them back in phase.

Design of Behavioral Parameters of Slot Antenna

The characteristics of the designed slot antenna of figure 4.1(λ) can be calculated as follows:

Slot Impedance in Waveguide:

Recall, $Z_s Z_c = \frac{\eta^2}{4}$

Using Babinet's principle, the impedance can be easily found:

$$Z_s = \frac{\eta^2}{4} \times Z_c = = \frac{(120\pi)^2}{4(73 + j42.5)} = \frac{142159.1616}{292+}\Omega \quad \textbf{(9)}$$

The longitudinal slots cut into the wall of a waveguide interrupt the transverse current flowing in the wall, forcing the current to travel around the slot, which induces an electric field in the slots. The position of the slots in the waveguide determines the current flow. Thus, the positions determine the impedance presented to the transmission line and the amount of energy coupled to the slot and radiated from the slot.

The current in the walls of the guide must be proportional to the difference in electric field between any two points. Therefore, a slot in the exact center of the broad wall of the waveguide will not radiate at all, since the electric field is symmetrical around the center of the guide and thus is identical at both edges of the slot. As the slot is positioned away from the centerline, the difference in field intensity between the edges of the slot is larger, so that more current is interrupted and more energy is coupled to the slot, increasing radiated power.

As we approach the sides of the waveguide, the field is very small, since the sidewalls are short circuits for the electric field. The induced current must also be small; longitudinal slots far from the center or in the sidewall will not radiate significantly. From the point of view of the waveguide, the slot is a shunt impedance across the transmission line, or an equivalent admittance loading the transmission line (admittance is the reciprocal of impedance). Slots further from the centerline of the guide present a larger admittance (lower impedance) to the transmission line. When the admittance of the slot (or combined admittance of all the slots) equals the admittance of the guide, then we have a matched transmission line, or low VSWR.

GAIN of the Antenna: A simple way to estimate the gain of a slot antenna is to remember that it is an array of dipoles. Each time we double the number of dipoles; we double the gain, or add 3 dB. The approximate gain formula is Gain = 10 log (N) dB, for N total slots. Since it is really the vertical aperture of the slots rather than just the number of slots that determine the gain and vertical beam-width, then:

$$\text{Gain} = 10\log\left(\frac{N \times slotspacing}{\lambda}\right)\text{dB} \quad \textbf{(10)}$$

$$= 10 \log \frac{16 \times 9.07}{12.5} \text{ dB}$$

$$= 10 \log 11.6096 \text{ dB}$$

$$= 10.65 \text{ dB}$$

Half Power Beam-width:

Beamwidth=$50.7\times\left(\frac{\lambda}{\frac{N}{2}\times slotspacing}\right)$ degrees **(11)**

$= 50.7 \times \frac{12.5}{8\times 9.07}\ degrees$

= 50.7 × 0.1723 degrees

= 8.7^0

Where N is the total no. of slots and slot-spacing is half the guide wavelength.

Directivity of an Omni-Directional Antenna:

$D_0 = -172.4+191\sqrt{0.818+\frac{1}{HPBW}(degrees)}$ **(12)**

$D_0 = -172.4 + 191\sqrt{0.818 + 1/8.7}$

$D_0 = -172.4 + 191\sqrt{0.818} + 0.1149$

$D_0 = -172.4 + 191\sqrt{0.9329}$

$D_0 = -172.4 + 191 \times 0.9658$

$D_0 = -172.4 + 184.5$

$D_0 = 12.1$

For this formula, the radiation intensity is expressed as:

$U = Sin^n \Theta$

Since the half power beam-width is 8.7^0, the angle at which the half power point occur is $\Theta = 4.35^0$

Design of Coaxial Monopole Antenna

The monopole antenna (i.e. coaxial electric field probe) was designed with the following parameters.

Length of a Monopole Antenna: Length of the monopole antenna is calculated using the equation below:

$L_{monopole} = \frac{\lambda}{4}$ **(13)**

Since the monopole antenna is designed to operate at a frequency f = 2400MHz and wavelength is calculated to be:

$\lambda_0 = \frac{c}{f} = \frac{3\times 10^8}{2.4\times 10^9} = 0.125$ (m)

$L_{monopole} = \frac{\lambda}{4} = \frac{0.125\,(m)}{4} = 0.03125$(m)

$L_{monopole} = 3.125$ cm

Impedance: The impedance Z of a $\frac{\lambda}{4}$ monopole antenna is given as 36.5Ω

Bandwidth: The bandwidth of a monopole antenna is given as f ± 10%, i.e.,

Bandwidth = f – 0.1f ≤f≤f + 0.1f **(14)**

The lower frequency band is given as:

f -0.1f = 2400MHz – (0.1 ×2400MHz)
= 2160MHz **(15)**

And the upper frequency band is given as:

f+0.1f = 2400MHz + (0.1 ×2400MHz) = 2640MHz **(16)**

Gain and Directivity: Gain G of a $\frac{\lambda}{4}$monopole antenna is given as 3.09dB. if there is no power loss, Gain G and directivity D_0. But if there is power loss G >D_0.

Polarization and Axial Ratio: Monopole antenna has an axial ratio of zero and is horizontally polarized.

CONSTRUCTION OF THE SLOT ANTENNA

Slot antennas can be built from surplus waveguide sections, which will give an omni-directional pattern and horizontal polarization. This project offers a computer aided method to calculate the proper dimensions for the slots and their locations. Because the antenna is of a one-piece construction, it is rugged and can be built without much resource, requiring only access to a reasonably precise drill press, milling machine, or a hand tool if left with the option.

The galvanized sheet was cut to dimension obtained for internal wide and narrow dimension of the waveguide (8.64cm) and (4.32cm) respectively. The first design consideration is that the slots be resonant so that they provide a resistive load to the (waveguide) transmission line. Normally, it is desirable for an omni-directional antenna to radiate in a horizontal (azimuth) plane.

This is achieved by feeding all slots in phase. The slots are fed in phase by spacing their centers at electrical half-wavelength intervals along the waveguide. The electrical wavelength in waveguide is longer than in free space, giving the guide wavelength as 18.1102cm. The slots spacing are at half the guide wavelength ($\lambda_g/2$) which is 9.0678 cm. The slots have identical length and spacing along the waveguide. Note how the slot position alternates about the centerline of the guide.

The far wall of the waveguide has an identical slot pattern, so that you can see through the slots. If the pattern on the far wall were reversed, the two sides would have opposite phasing and the resultant radiation pattern would have a null on each side. One of the walls is given an extension (flange), so that the antenna could be opened and inspected and when closed be tightened and fastened with the bolts and nuts.

Construction of a Monopole Antenna

A monopole antenna was constructed using a 75Ω coaxial cable with an insulator and a BNC connector. The outermost insulator and the outer conductor (aluminum conductor) of the coaxial cable were peeled off and the inner or core conductor (copper conductor) and the dielectric were retained**.** The combination of the inner core and the dielectric were inserted into a suitable BNC end holder. At one end, the inner conductor of the coaxial cable was allowed to extend out so as to pick up electric field illuminated from the source, which is the slot antenna. With no loop structure to carry current, the probe reject magnetic field. At the other end, the combination of the copper pipe and the inner conductor were terminated with a BNC. A multimeter was then used to verify the continuity of this monopole antenna.

Construction of Electric Field Probe

The electric field probes design and construction is described as thus: The 75-ohms impedance coaxial cable was used to fabricate this probe of half wave-length where a portion of the shield was peeled with the insulation. The center conductor was left to protrude and a copper wire was added to it. Then, with about 1cm of the cable from the end of the added copper wire, is a termination. This is inserted into the feed point of the designed antenna through the F connector that was already attached to the antenna.

MEASUREMENTS

Measurements were carried out at the documentation room of the Nigerian telecommunication (NITEL) Laboratory at Marina, Lagos, Nigeria. Electric fields were measured at various distances from the slot antenna, fed by -5dBm power at 2.4GHz RF from RF signal generator. The test antenna was illuminated with a plane wave. This was possible by using a source antenna with no radiation pattern and characteristics, in such a way that the fields incident upon the test antenna are approximately planar.

- A source antenna and transmitter – The slot antenna is used to illuminate the test antenna.

- A receiver system – This determines how much power is received by the monopole antenna.

A positioning system would have been used to rotate the monopole antenna relative to the slot antenna, to measure the radiation pattern as a function of angle but it was done by hand with the use of a compass.

Measurements for Different Planes

Measurements were obtained with the aid of Agilent E4407B, 9 KHz – 26.5 GHz ESA-E Series Spectrum Analyzer. The spectrum analyzer was placed in a suitable position and a constructed monopole antenna was connected to the analyzer.

The analyzer was connected to AC power supply through a BC 2650 AC adapter and it was powered. With the spectrum analyzer ON, the following setting were effected on the analyzer before the marker indicating the Analyzer level before subtracting the Noise level to get the actual signal level converted to dBµV.

Centre Frequency = 2.4 GHz

Vertical Scale = 10dB/division

Peak reference level = -10dbm

Noise level = 69.5dBm @ no signal

Resolution Bandwidth = 3MHz

Video Bandwidth = 3MHz

Sweep Time = 4ms (401pts)

Input Attenuation = 0dB

The H Plane (Azimuth)

For this plane, the monopole antenna faces the source of illumination that is the slot antenna. In this case, the received power comes from direction $(\Theta,\phi) = (0^0, 0^0)$.

RESULTS, ANALYSIS AND DISCUSSION

The experiments were performed in different categories and the corresponding results were recorded accordingly.

Results of Measurements at a Distance to the Antenna

As usual, let the direction the monopole antenna is towards the y-axis. The slot antenna illuminates the monopole antenna from +y-direction and the corresponding results were recorded.

The measurements are taken with maximum voltages (in dBµV) were converted to equivalent electric fields (in dBµV) given by:

$$E\ (dB\mu V/m) = V_{SA}\ (dB\mu V) + AF + K + 51.5 \quad \textbf{(16)}$$

Since monopole antenna length is just about 3.125cm, cable loss K is assumed to be negligible (i.e., K ≈ 0) therefore, electric field value becomes:

$$E\ (dB\mu V/m) = V_{SA}\ (dB\mu V) + AF + 51.5 \quad \textbf{(17)}$$

Antenna Factor AF can be calculated by using the equation shown below:

$$AF = 20\log f - G\ (dB) - 29.8dB \quad \textbf{(18)}$$

Where f = frequency in MHz and
G (dB) = gain of the antenna in dB

Since gain of the monopole antenna is 3.09dB and the frequency is 2400MHz, equation then becomes:

$$AF = 20\log(2400MHz) - 3.09dB - 29.8dB = dB \quad \textbf{(19)}$$

By substitution of Equation (18) into Equation (16), the result in Equation (19) below is derived:

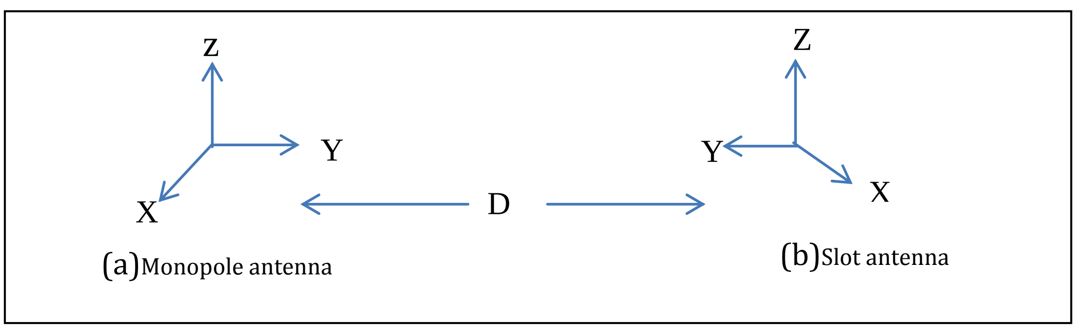


Figure 5: Antenna Locations. (a) Monopole Antenna at a Distance from the Slot Antenna. (b) Slot Antenna at a Distance towards the y-axis of the Monopole Antenna.

$E\ (dB\mu V/m) = V_{SA}\ (dB\mu V) + 34.7 + 51.5$ **(20)**

Therefore:

$E\ (dB\mu V/m) = V_{SA}\ (dB\mu V) + 86.2$ **(21)**

Electric fields (in dBµV/m) were also converted to their equivalent electric field (in V/m) by using the equations below:

$E\ (dB\mu V/m) = 20\log_{10} E$ **(22)**

$E\ (\mu V/m) = 10^{(E(dB\mu V/m)/20)}$ **(23)**

$E\ (V/m) = 10^{(E(dB\mu V/m)/20)} \times 10^{-6}$ **(24)**

Equation (21) and (24) above were used to convert the voltage levels (in dBµV/m) to corresponding electric field (in dBµV/m and V/m). The result of maximum voltages measured (in dBµV/m) and the corresponding maximum electric field (both in dBµV/m and V/m) are shown in tables below for Horizontal and Elevation Planes.

Results of Measurements at Various Distances to the Antenna.

The maximum power in dBm was measured when the signal generator (with transmitted output power of -5dBm at 2.4GHz) was connected directly to the spectrum analyzer. The spectrum analyzer reading was found to be -7.6 dBm. Since the noise level was -69.5 dB then, the actual signal level is given as:

Actual Signal Level =
(-7.6dBm) – (-69.5dBm) = (-7.6 + 107) – (-69.5 +107) **(25)**

= 99.4 – 37.5

= 61.9dBµV

For normalized pattern in dB:

Actual Signal Level = (-7.6dBm) – (-69.5dBm)

$= 61.9dBm\ 61.9 - 10\log 10^{-3} = 31.9dB$ **(26)**

Electric field (in dBµV/m) and Electric field(in V/m) are calculated using Equation (21) and (24), respectively.

$E(dB\mu V/m) = V_{SA}\ (dB\mu V) + 86.2$
$E(dB\mu V/m) = 61.9(dB\mu V) + 86.2$ **(27)**

E(dBµV/m) = `148.1 dBµV/m **(28)**

And
$E(V/m) = 10^{(E(dB\mu V/m)/20)} \times 10^{-6}$
$E(V/m) = 10^{((148.1/20)/20)} \times 10^{-6}$ **(29)**

E(V/m) = 25.4 V/m **(30)**

For Azimuth Plane

Actual Signal Level (in dBµV) and the Corresponding Electric Field (both in dBµV/m and V/m) measured at various distances away from the Slot Antenna. For this plane, where $\Theta^0 = 0$ and $\phi = 0 - 180^{0.}$

Table 2: Maximum Signal Level (in dBµV) and the Corresponding Electric Field(both in dBµV/m and V/m) measured at 50 cm away from the Slot Antenna for HORIZONTAL PLANE.

Theta 0	Phi ϕ	Signal Level Of Analyzer		Noise Level		Actual Signal Level	E field (dBµV/m)	E field (V/m)
		power (dBm)	voltage (dBµV)	power (dBm)	voltage (dBµV)	voltage (dBµV)		
0	180	-70.6	36.4	-69.5	37.5	-1.1	85.1	0.02
0	165	-68.0	39.0	-69.5	37.5	1.5	87.7	0.02
0	150	-65.4	41.6	-69.5	37.5	4.1	90.3	0.03
0	135	-60.1	46.9	-69.5	37.5	9.4	95.6	0.06
0	120	-58.2	48.8	-69.5	37.5	11.3	97.5	0.07
0	105	-57.8	49.2	-69.5	37.5	11.7	97.9	0.08
0	90	-56.3	50.7	-69.5	37.5	13.2	99.4	0.09
0	75	-58.2	48.8	-69.5	37.5	11.3	97.5	0.07
0	60	-60.6	46.4	-69.5	37.5	8.9	95.1	0.06
0	45	-61.5	45.5	-69.5	37.5	8.0	94.2	0.05
0	30	-66.7	40.3	-69.5	37.5	2.8	89.0	0.03
0	15	-69.2	37.8	-69.5	37.5	0.3	86.5	0.02
0	0	-69.8	37.2	-69.5	37.5	-0.3	85.9	0.02

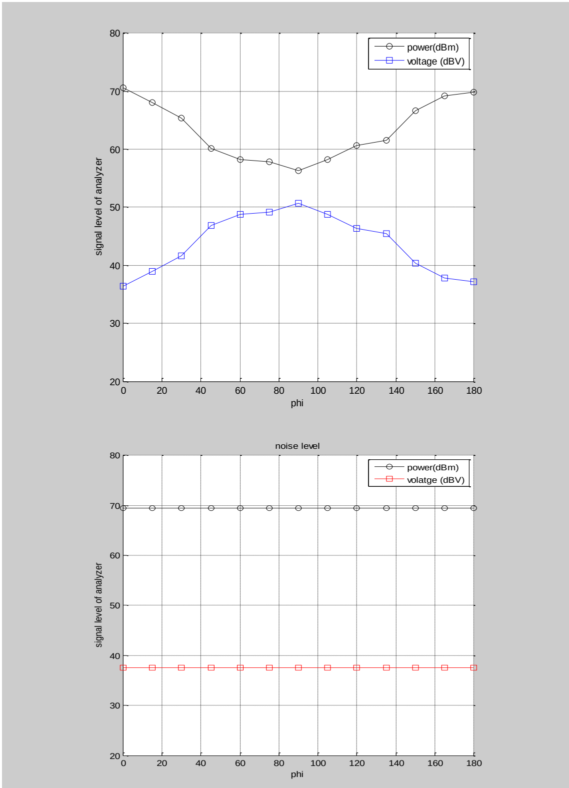


Figure 6: Signal Levels of the Analyzer.

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