DEVELOPMENT OF A LOG-PERIODIC DIPOLE ANTENNA SYSTEM

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Abstract

A 14-element log-periodic dipole antenna for VHF, UHF and SHF bands has been designed, constructed and characterized at a frequency band (300-5467)MHz. The experimentally measured values agree with the computed values with a standard deviation of 2.6. A gain of 20.33 ± 0.69 dB was achieved at a signal-to-noise ratio of 104.77 ± 1.04dB. The efficiency at frequencies above 500MHz is 97% and drops to 65% at frequencies below 200MHz.

***Keywords:** Dipole antenna, radio communication and space loss*

Introduction

An antenna is a device designed in shape and size to radiate and intercept electromagnetic (e.m) power efficiently. It is utilized in radio communication systems. Radio receivers working under poor antenna system struggle to pull as much signal as possible, leading to noise interference. Poorly designed antenna systems increase the effect of external interference and electrical radiation which may result in blot pictures on TV screens.

An antenna system performs in the free space medium and operates as a Transmit/Receive system. The transmitting antenna (Tx) couples e.m signals in to space either by means of transmission line or wave guide and the receiving antenna (Rx) intercepts the e.m signal and couple it to the receiver system. The signal power is radiated with in a substantial angular region of space. However, only a small fraction is intercepted by the Rx. The loss is algebraic and decreases as the inverse square of the distance between Tx and Rx (Balanis, 1982).

Space loss is evidently less than the transmission loss and for mobile and satellite communication systems, including space probes, the need for antennas are very essential. The radio signals of interest occupy a band of frequencies at VHF, UHF, and SHF band (300-5467) MHz and are propagated with the aid of antenna systems as space waves.

This paper highlights the design, construction and characterization of a 14- element log-periodic dipole antenna with a significant improvement on the bandwidth of operation. It operates at VHF, UHF, and SHF band. The relative performance of the characteristic values with the measured values will be presented in detail.

Radiation of E.M Waves

The knowledge of the scalar and vector potentials provides the determination of $\vec{H}$ and $\vec{E}$ fields intensities of the radiated e.m waves for an electric dipole. The scalar potential is given by (Balanis, 1982 and Kraus, 1988) as:

$$V(r,t)=\frac{I_oL\cos\theta\, e^{j\omega\left[t-\frac{r}{c}\right]}}{4\pi\varepsilon_o c}\left(\frac{1}{r}+\frac{c}{j\omega}\frac{1}{r^3}\right) \quad (\lambda >> L) \qquad (1)$$

Thus the potential propagates a wave with a phase

$$\omega\left[t-\frac{r}{c}\right]$$

The vector potential at the field point (r, t) is given by (Kraus, 1988) as:

$$A(r,t)=\frac{\mu_o L I_o e^{j\omega\left[t-\frac{r}{c}\right]}}{4\pi\ r} \qquad (2)$$

For a dipole antenna of length L carrying a current of amplitude I_o with angular frequency ω the instantaneous current, I is given as

$$I = I_o e^{j\omega\left[t-\frac{r}{c}\right]}$$

If the dipole moment is me = $I\pi L^2$ (Balanis, 1982); then

$$A(r,t)=\frac{\mu_o m_o\theta}{4\pi\lambda r}\,\frac{(\lambda+j)}{r}\sin\theta\, e^{j\omega\left[t-r/c\right]} \qquad (3)$$

Which depends, on r and only. Since $\vec{E}=-\partial\vec{A}/\partial t$

and assuming r>>L, then

$$E_{rad}=\frac{z_o m_o}{4\pi\, r\lambda^2}\sin\theta\, e^{j\omega\left[t-r/c\right]} \qquad (4)$$

The H field intensity $H(r,t)=\frac{1}{\mu_o}(\vec{\nabla}\times\vec{A})$

Hence,

$$H_{rad}=\frac{m_o}{4\pi\, r\lambda^2}\sin\theta\, e^{j\omega\left[t-r/c\right]} \qquad (5)$$

These E_{rad} and H_{rad} propagate through the free space with characteristic impedance $z_o=\sqrt{\frac{\mu_o}{E_o}}$ $= 377\,\Omega$(Tyona,2003).

The average poynting vector is given by

$\vec{S}_{av}=\frac{1}{2}\mathrm{Re}(\vec{E}\times\vec{H})$. It follows that for a dipole antenna, the total power, P radiated is

$$P=\iint S_r\,ds=\frac{1}{2}\sqrt{\frac{\mu}{E}\int_0^{2\pi}\int_0^{\pi}/H/^2\, r^2\sin\theta\, d\theta\, d\phi} \qquad (6)$$

Where $|H_\phi|=\frac{\omega I_o L\sin\theta}{4\pi cr}$ Hence the total radiated power is

$$P=\sqrt{\frac{\mu}{\varepsilon}}\,\frac{\beta^2 I_o^2 L^2}{12\pi} \qquad (7)$$

Where the radiation resistance of the dipole antenna is $R_{rad}=790L_\lambda^{\,2}\Omega$

The electric and magnetic fields intensities radiated by the dipole antenna into the space are useful in computing the transmitted power.

Characteristics of the Dipole Antenna

Radiation Resistance: In Tx, maximum conversion of radio frequency current to e.m energy is one of the desired characteristics. The radiation resistance of an antenna determines the efficiency of the conversion. For a dipole antenna, with a length L_λ, the radiation resistance, R_{rad} is given as:

$$R_{rad}=790L_\lambda^{\,2}\Omega$$

For a dipole antenna of n number of diploes,

$$R_{rad}=31200\left(\frac{nA}{\lambda^2}\right)^2 \qquad (8)$$

where A is the cross-sectional area of the dipole.

Radiation pattern: This is the spatial distribution of the radiated power as a function of direction (Balanis, 1982). It is determined by the field strength measurement taken in different directions at constant radial distance about the antenna, the plot of these variations gives the field pattern depending on the current distribution and beam width.

Directivity: This is a desired characteristic exhibited by all practical antennas. At points where the intensity is zero (null points) energy is redistributed to the preferred directions of radiation of the antenna. In Tx, it allows most of the transmitted power to be sent in the wanted direction and very little in the undesired directions (Tyona.2003). For an isotropic radiator, the field strength $\vec{E}=\sqrt{30\frac{P}{r}}\,Vm^{-1}$ giving a directivity of D=4P/Ω;where Ω is the solid angle and P is the radiated power.

Gain: The gain of a Tx and Rx is expressed as a power ratio (Akande and Alade 1999).

$$\mathrm{Gain}=\frac{P_{max}}{P_\theta}=\frac{\text{power density in the direction of maximum radiation}}{\text{power density of anisotropic radiator of the same power}}$$

$$\Rightarrow \mathrm{Gain}=\frac{4\pi A_e}{\lambda^2}$$

where A_e is the effective area of the antenna and $A_e = W_R/P^1$; W_R is the power available at the terminal of the antenna and P^1 is the power per unit area in the incident wave.

Input impedance Z_{in}: This is the impedance present at the terminal of the antenna.

Radiation efficiency K: The radiation efficiency of a dipole antenna is given by

$$K=\frac{R_{rad}}{R_L+R_{rad}}\times 100\% \qquad (9)$$

where R_{rad} is the radiation resistance at the terminal and R_L is the equivalent loss resistance at the terminals.

Effective height of antenna (h) is the ratio of the induced open circuit voltage V_{oc} to the incident field, E; ie

$$h_e = V_{oc}/E \qquad (10)$$

Practically, this is the height at which the electric field strength is not at zero level.

Design and Construction

A great number of antennas which are of practical and commercial importance for reception and transmission operate at a fixed frequency band due to the limitation on beam width imposed by the aperture size. The array antennas however, allow for more control on this problem by using a number of individual antenna elements grouped together to form a sample aperture (Smith, 1988). The phased array antenna has a tremendous advantage of adjusting their radiation beam electronically without any physically moving parts. A typical example is the Log-periodic antenna. Log-periodic dipole antennas have moderately high directive properties (Gain, Directivity and Radiation pattern). It is an out door antenna with a wide frequency band of operation. Typical designs of the log-periodic dipole array are suitable for apex half anglesand geometric ratio (design ratio). Figure1 illustrates the structure of the log-periodic dipole antenna.

The design of this antenna is less complex, inexpensive and meets the following objectives:

iit maximizes antenna gain and detects signals in the VHF, UHF, and SHF bands in a frequency range (300-5467) MHz with low noise and signal losses.

ii. it attempts a simultaneous control of both the signal intensity and signal flux density for use in telecommunication and radio astronomy.

Design and Construction Specifications (Tyona, 2003)

The design of the log-periodic antenna primarily depends on:

Geometrical ratio $\tau = 0.80$ (chosen)

Apex half angle $\propto = 25^0$ (chosen)

Spacing factor or relative spacing constant ó = 0.11; and a frequency range of (300-5467) MHz.

Aluminum tubing of diameter 1.3cm was selected for the elements. The choice of this conductor depends on:

I. Thermal and electrical properties of the material,
Ii. Skin depth
Iii. Resistance to atmospheric chemical attack and
iv. Radiation resistance.

Design Analysis (Tyona, 2003).

Figure 1 describes the basic geometry of the log-periodic dipole antenna (LPDA). Each element is shorter than the element to its left by a factor ô which is constant between each element and its adjacent neighbour.

The lengths of the longest and shortest elements (l_{max} and l_{min}) are given by

$$l_{max} = l_1 = 492/f_1;\ f_1 = 300\text{MHz} \qquad (11)$$

$$l_1 = 50.00\text{cm}.$$

$$l_{min} = 492/f_2;\ f_2 = 5467\text{MHz} \qquad (12)$$

$$l_{min} = 2.74\text{cm}$$

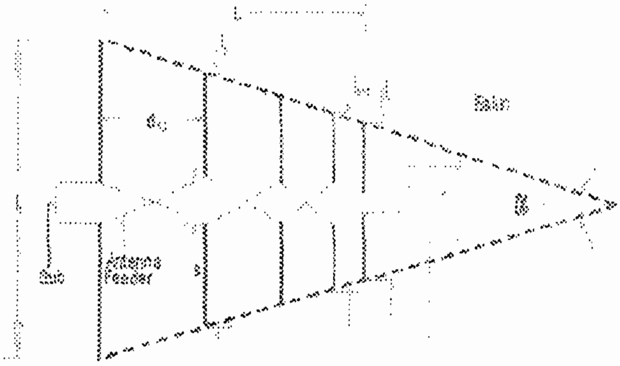

Fig. 1: Log periodic dipole antenna

The spacing between elements d, as in Figure 1, $d_{1,2}$ (ie the distance between the left most element and its nearest neighbour) is given by

$$d_{1,2} = \tfrac{1}{2}(l_1 - l_2)\cot\alpha \qquad (13)$$

But $l_2 = l_1\tau = 4.00$cm.

$$\Rightarrow \quad d_{1,2} = 10.72\text{cm}.$$

The band width of the active region B_{ar}, is given by

$$B_{ar} = 1.1 + 7.7\,(1-\tau)^2 \cot\propto \qquad (14)$$

$\Rightarrow$ $B_{ar} = 1.76$ Mhz.

In practice, a slightly larger band width (B_s) is usually designed than that which is required (B). The two band widths are related by (Balanis, 1982)

B_s = B B_{ar} = B[1.1+7.7 (1- τ)^2 cot ∝] ; B = 18.2MHz (15)

$\Rightarrow B_s = 32.0$ MHz.

The total length of the structure (antenna) L, from the longest (l_{ax}) to the shortest (l_{in}) element is given by

$$L = \frac{\lambda_{max}}{4}\left(1 - \frac{1}{B_s}\right)\cot\alpha \qquad (16)$$

where $\lambda_{max} = 2\, l_{max} = 100.00$cm.

$\Rightarrow$ L = 52.00cm

From the geometry of the system, the number of elements N, is given by

$$N = 1 + \frac{\ln(B_s)}{\ln(1/\tau)} \qquad (17)$$

$\Rightarrow$ N = 14 elements.

Thus the various lengths and spacing of the 14 elements throughout the whole length of the structure are shown in tables 1and 2.

The average characteristic impedance of the elements Z_a is given by

$$Z_a = 120\left[\ln\left(\frac{l_n}{d_n}\right) - 2.25\right] \qquad (18)$$

where l_n/d_n is the length to diameter ratio of the nth element of the array.

Using l_{mx}=50.00cm and d_{max}=1030cm,

$\Rightarrow Z_a = 168\Omega$.

The relative mean spacing, ó^1 is given by

$$\sigma^1 = \frac{\sigma}{\sqrt{\tau}} \qquad (19)$$

$\sigma^1 = 0.12$

The characteristic impedance of the transmission line that feeds the elements, Z_b which in our case also acts as the boom of the antenna is given by (Curtis and Straus, 2002)

$$Z_b = \frac{Z_i^2}{8\sigma^1 Z_a} + Z_i\sqrt{\left[\left(\frac{Z_i}{8\sigma^1 Z_a}\right)^2 + 1\right]} \qquad (20)$$

where Z_i is the impedance of the antenna as seen from its input terminals. Z_i = 50 Ω(for coax line).

$Z_b = 64\,\Omega = Z_o$.

An impedance ratio of about 3 is required for a good matching of the antenna to the transmission line; this is met by the design.

Table 1: Length of elements

Element	Formula	Length (cm)
l_1	(14996.16/300) cm	50.00
l_2	l_1 τ	40.00
l_3	l_2 τ	32.00
l_4	l_3 τ	26.00
l_5	l_4 τ	20.50
l_6	l_5 τ	16.40
l_7	l_6 τ	13.10
l_8	l_7 τ	10.50
l_9	l_8 τ	8.40
l_{10}	l_9 τ	6.70
l_{11}	l_{10} τ	5.40
l_{12}	l_{11} τ	4.30
l_{13}	l_{12} τ	3.40
l_{14}	l_{13} τ	2.70

ii. The field strength at the site of receiving antenna is given by (Kraus, 1988; Balanis, 1982)

$\vec{E} = \sqrt{30\frac{p}{r}}$ Vm^{-1}; r is selected to be

within 20km, hop distance and P = 20kW (NTA, Jos, Tx power). Computed E = 5.477Vm^{-1} but measured E = 5.623Vm^{-1}.

ii. The radiation resistance R_r = 31200(nA/ë^2)^2. Calculated value R_r = 47.51 Ω.

- The loss resistance

ohms; where ó = 3.6x 10^7 Ω^{-1}m^{-1},

μ_o =4π x 10^{-7} Hm^{-1}. It follows that R_L= 1.56 Ω

- The radiation efficiency of the dipole antenna, K is

$$K = \frac{R_r}{R_L + R_r} \times 100 \quad \% = 96.82\%$$

Iiii. The input (terminal) impedance at resonance is given by $Z_{in} = R_L + R_r = 49.07\ \Omega$.

- The Q-factor, $Q = \frac{2\pi fL}{Z_{in}}$

$L = 6.16\times10^{-6}$H; $Q = 552$.

- The half power band width in Hz, $(f_{HPBW}) = f/Q$ = 1.27Mhz

The directivity, D of the 14-element log-periodic dipole antenna is 21dB.

Iv. The gain, G = KD = 20.33dB.

V. The effective area,

Table 2: Elements'spacing, d (Tyona, 2003)

Elements	Formula (cm)	Distance (cm)
$d_{1,2}$	$0.5(l_1 - l_2)\cot\alpha$	10.72
$d_{2,3}$	$d_{1,2}\tau$	8.60
$d_{3,4}$	$d_{2,3}\tau$	6.90
$d_{4,5}$	$d_{3,4}\tau$	5.50
$d_{5,6}$	$d_{4,5}\tau$	4.40
$d_{6,7}$	$d_{5,6}\tau$	3.50
$d_{7,8}$	$d_{6,7}\tau$	2.80
$d_{8,9}$	$d_{7,8}\tau$	2.30
$d_{9,10}$	$d_{8,9}\tau$	1.80
$d_{10,11}$	$d_{9,10}\tau$	1.40
$d_{11,12}$	$d_{10,11}\tau$	1.14
$d_{12,13}$	$d_{11,12}\tau$	0.90
$d_{13,14}$	$d_{12,13}\tau$	0.70

Computations (Tyona, 2003)

If the Tx antenna has a gain of 30dB then, the effective area of the Tx is 31.85m^2.

The signal-to-noise ratio, $(S/N_s) = P_r/N_s$; where P_r is the received power and

$N_s = kT_s f_{HPBW}$. Where k = Botzmann's constant, T_s = Sky background temperature = 10^{10}K. Then, N_s = 1.75×10^{-7}W.

Thus, S/N_s = 104.77dB.

$$4\pi\ 10^{7} K \frac{R_r}{R_L R_r} 100$$

$$Q\ \frac{2\pi fL}{Z_{in}}$$

The skin depth, ä is given by (Keith and Garry, 1981) as:

$$\delta = \sqrt{\frac{1}{f\pi\mu_o\Omega}}$$

$= 3.17\times10^{-6}$m

Construction

The materials used in the construction include: Aluminum tubing (1.30cm in diameter) as elements, a rectangular bar of aluminum of cross-sectional area $2.16\times10^{-4}\text{m}^2$ is the antenna boom; plastic tubing of diameter 1.35cm is used to insulate the antenna elements from the boom and also to serve as carriers to the elements. The feed line is a twin pair cable and the elements are fed through a criss cross connection method as in Figure1 and the elements lengths and spacing followed Table 1 and 2.

Mode of operation

The log-periodic antenna designed in this paper will operate efficiently in the VHF, UHF, and SHF bands. By means of the mechanical criss cross connection method, figure1, a phase shift of 180^0 is provided between elements to produce a phase progression so that energy is beamed end-fire in the direction of the shortest element. The best sets of active elements for this feed arrangement are those that are near resonance.

For the practical broad band antenna, the structure is truncated at both ends to limit the frequency of operation to a given band width. The cut off frequencies of the structure are determined by the electrical length of the longest and the shortest elements. The active region moves across the dipole array and is usually near the elements whose lengths are nearly or slightly smaller than ë /2. The role of the active elements (radiation or reception) is passed from the longer to the shorter elements as the frequency increases.

Measurements

The measurement partially employs the compact measurement system. The receiver is tuned to the lower end of the desired broadcast band. The receiver is then tuned to the frequency of a broadcast station to obtain a stronger signal. The automatic directive properties of the antenna nulls out any interfering station.

The parameters, Z_{in}, R_i, R_r, K, E were measured for frequency range (200-800)MHz.

The experimental set up was made up of an RF generator, a field strength meter, an A.C bridge, an ohmmeter and an oscilloscope. A feed line connects the antenna and the A.C Bridge whose value is monitored on the meter.

To measure the voltage standing wave ratio (VSWR), the feed line from the antenna was connected through a T-splitter from the field meter and the generator.

Results and Discussion

Measured and computed values of input impedance(Z_{in}), radiation resistance (R_r), loss resistance(R_L), and radiation efficiency (K) of the log-periodic antenna for the frequency range of (200-800)MHz are presented in Table 3, while measured values of the antenna field strength are shown in Table 4.

Table 3: Measured and computed parameter values of the log-periodic antenna (Z_{in}, R_r, R_L, and K)

F(MHz)	λ (m)	Z_{in} (Ω) measured	Z_{in} (Ω) computed	R_r (Ω) measured	R_r (Ω) computed	R_L (Ω) measured	R_L (Ω) computed	K (%) measured	K (%) Computed
200	1.50	1.620	0.318	0.225	0.318	0.1190	0.0112	65.40	99.62
250	1.20	8.730	3.278	0.592	0.776	0.2200	0.0036	73.00	99.79
300	1.00	33.850	26.611	2.950	1.609	0.3820	0.0019	88.54	99.88
350	0.86	75.400	61.944	4.000	2.942	0.4200	0.0022	90.50	99.92
400	0.75	196.270	159.089	9.340	5.086	0.4900	0.0025	95.00	99.95
450	0.67	462.500	371.989	12.340	7.086	0.5600	0.0028	95.72	99.96
500	0.60	487.450	410.421	15.360	12.418	0.6600	0.0031	96.43	99.97
550	0.55	512.620	488.590	25.000	17.587	0.7300	0.0034	97.16	99.98
600	0.50	530.730	510.254	32.150	25.750	0.8000	0.0037	97.47	99.99
650	0.46	552.336	523.943	48.000	35.943	0.9100	0.0040	98.14	99.99
700	0.43	587.820	550.077	69.230	47.473	1.0950	0.0044	98.40	99.99
750	0.40	630.130	592.878	92.310	62.365	1.3300	0.0047	98.60	99.99
800	0.38	670.250	615.18	120.085	77.181	1.5200	0.0050	98.75	99.99

Table 4: Measured field strength of the log-periodic antenna

F(MHz)	200	250	300	350	400	450	500	550	600	650	700	750	800
E(dB)	10.00	-5.00	+1.00	+6.00	+12.00	+16.00	+21.00	+26.00	+30.00	+34.00	+37.00	+38.00	+39.00

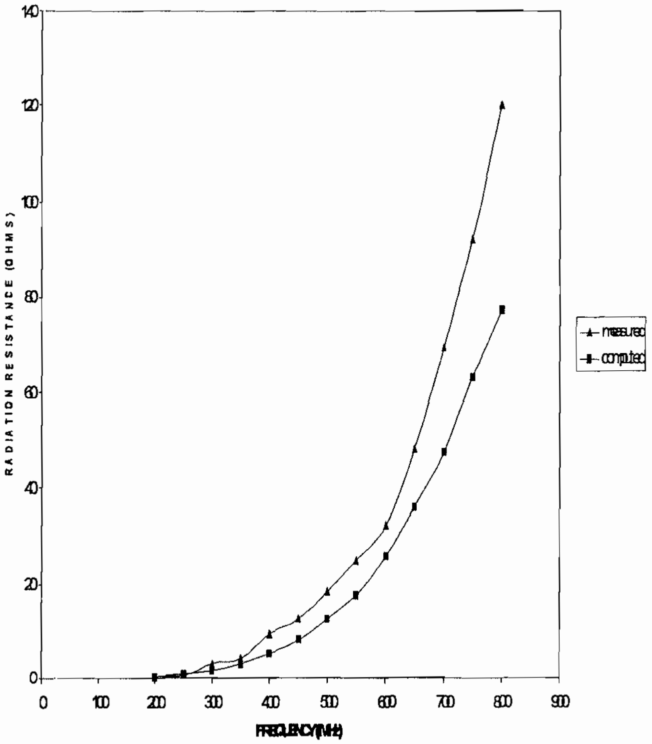

Fig. 2: Variation of radiation resistance with frequency

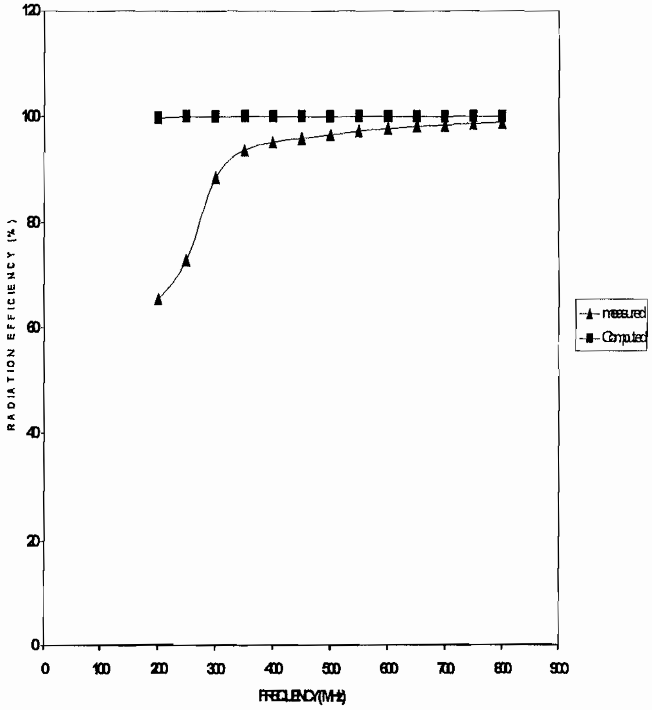

Fig. 3: Variation of K with frequency

Figure 2, shows the variation of R_r with frequency for measured and computed values. Figure 3, presents the variation of K with frequency for measured and computed values, while figure 4, shows the variation of K with R_r as measured and figure 5, shows the variation of K with R_r as computed. The variation of E with frequency is shown in figure 6.

In Figure 2, for both cases, it is observed that, the radiation resistance of the antenna is a function of frequency, increasing as frequency increases. However, for the practical antenna, R_r only approximates the predictions which is compatible with real situations (33.43± 0.70) ohms.

Generally, the measured and computed values of R_r are low for the antenna which implies that the antenna in both transmit and receive modes will incur very low signal losses.

From Figure 3, it is observed that K is directly proportional to frequency, f which implies that at higher frequencies, the radiation properties of the antenna are more developed. From the above results, at 600MHz, more than 97% of the input signal is radiated or captured, whereas at 200 MHz, only 65% of the signal is utilized. However, at the middle region of the UHF and obviously the lower SHF, the variation is less severe.

As observed from Table 3, the practical and the theoretical results for this antenna are compatible within a standard deviation of 2.6.

From Figure 6 and Table 4, E varies in direct proportion with f at the upper VHF and lower UHF but, variation becomes much slower at higher UHF. Thus at higher frequencies (ie up to lower SHF~5GHz), the antenna radiation properties becomes critical such that E is independent of frequency, but depends only on the distance between the transmit and receive antenna.

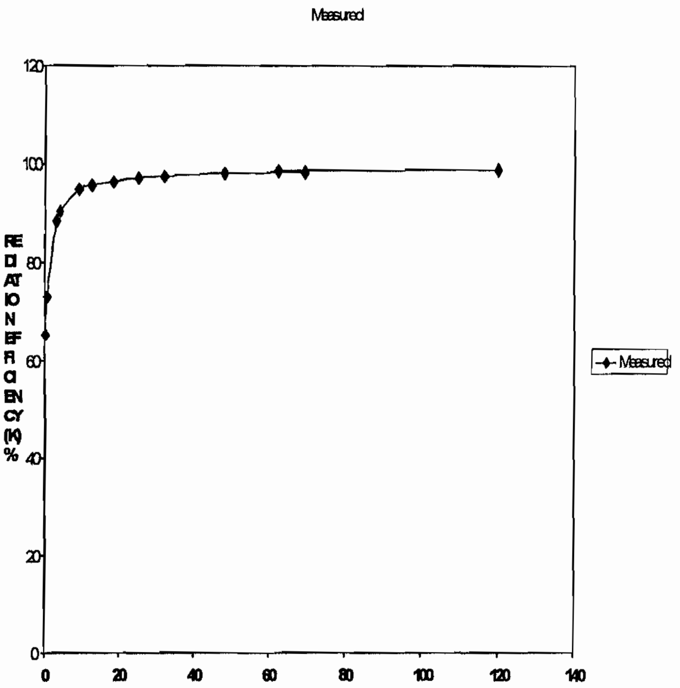

Fig. 4: Variation of K with R_r

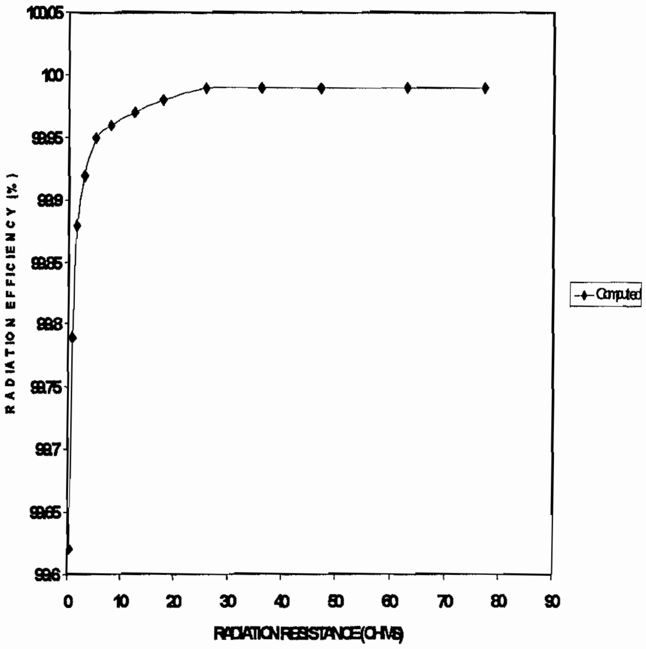

Fig. 5: Variation of Radiation Efficiency (K) with Radiation Resistance (R_r)

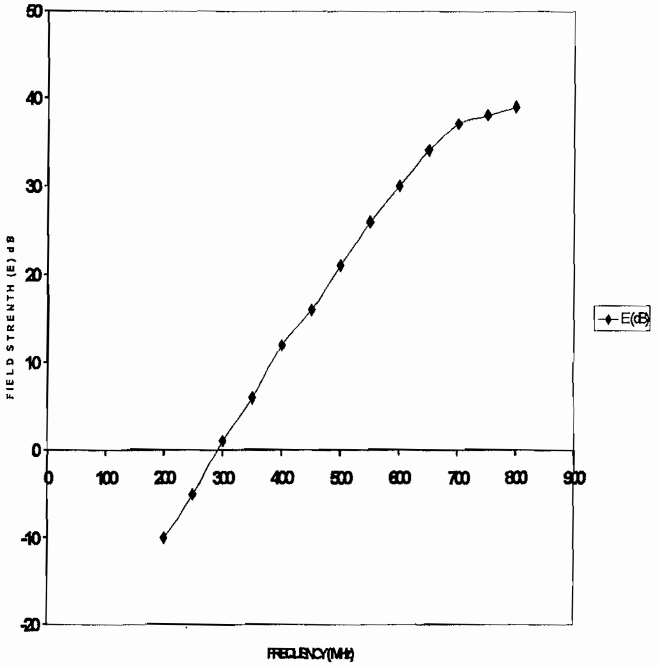

Fig. 6: Variation of Electric Field Strength (E) with Frequency

Conclusion

A log-periodic dipole antenna with fourteen elements was developed. It has a band-width improvement over the existing versions, with a frequency range of operation from (300-5467) MHz.

The antenna parameters, Z_i, R_r, R_L, K and E were measured and computed at those frequencies. The two sets of results (measured and computed) were compatible within a standard deviation of 2.6. The antenna has a gain of 20.33dB at a S/N of 104.77dB and can detect and monitor signals effectively from desired broadcast stations. The antenna is very useful for TV reception and FM broadcast including traffic control, mobile telephone communication and navigation aids. It is also useful in coast guard, military communication and radar systems.

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