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RADIATION PATTERN ANALYSIS OF SMALL CIRCULAR LOOP ANTENNA

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Abstract
Small loops are often represented as Magnetic radiators, reasonably efficient and necessarily narrow band antennas. So, retuning of antenna is required for small changes in frequency. Loops are derived from linear antennas but loops have significant inductive reactance whereas liner antennas have capacitive reactance. These antennas are named as small based on their size (0.12λ perimeter). This paper gives the fundamental knowledge of implementation, operation and characteristics of small circular loop antenna. The simulation results are explained accordingly.

Keywords:
Small loop, Radiation pattern, Radiation resistance, directivity, intensity, Power density.

I. Introduction

Basically, loop antenna is a radiating coil with its ends connected to a balanced transmission line or also to a Balan [1]. The coil may be of one turn or more with different shapes like square, circle, rectangular, triangular and rhombic etc., [2] used for particular application. In general loop antennas are used to categorize based on the size as electrically small and large loops, the former is used at low frequencies for receiving radio signals and confined in almost all the AM broadcast receivers, the latter is used at VHF and UHF where the characteristics of the loop are relatively similar to that of folded dipoles. As the frequency of operation and size increases, the radiation efficiency of the loop is also high and similar to that of a dipole [1].

The radiation resistance of electrically small loop is low but its reactance is high which leads to mismatch in the impedance and they are seldom used for transmission. It is mostly used for low frequencies applications such as radios and pagers. The radiation pattern of electrically small loop and Hertzian dipole is almost similar. The pattern of the loop can be changed to maximum from the plane of the loop to the axis of the loop by increasing its length, most probably when its circumference is comparable with free space wavelength [3].

When compare with dipole antenna, loop antenna has more advantages particularly its ease of design. Vertical loops with a small size can be used for direction finding of an un known transmitter led to implement them in applications such as navigating ships and aeroplanes. Crossed loop or Bellini Tosi direction finder is one of the practical applications which uses radio gonio-meter (an instrument measures the angle) that combines the output voltages of the antennas [2]. Also, vertical loops are more useful in mobile communication applications. Electronically shielded loop antennas are used to improve directional characteristics. Reception of bi-directional signals can be achieved by a vertical loop antenna [4]. Shape does not influence the directional patterns.

The small loop antenna can be demonstrated to have two lowest modes corresponds to magnetic dipole (zero-order mode) and folded dipole (first-order mode). The radiated field produced by loop mode is 11 dB more than the radiated field produced by folded-mode for the frequency at which loop circumference is one eighth wavelength [5]. However, the folded mode becomes relatively more significant at the rate of 6 dB per octave for the specified frequency range.

A precision VLF antenna coil can be used to operate from 1 KHz to 60 KHz. By the addition of an external capacitor of 0.1 μF, the coil can tune 13 KHz and for the capacitor of 0.3 μF, tuning capacity

turns to 8 KHz. The operating frequency range can be increased for tuning from 100 KHz to 1710 KHz with AM/LW loop-stick antenna consisting of two different coils, one is the smaller coil used to couple an outdoor long wire antenna and another larger coil used for tuning. These coils are wound and centered on a ferrite rod. Air variable capacitor of range from 15 pF to 384 pF offer sharp, narrow-band tuning which allows the antenna for tuning in the long wave, AM, and shortwave bands ranges from 50 KHz to 10 MHz [6].
A compact and tunable slot loop antenna (slow wave loop) is capable of operating in the frequency range between 2.34 GHz and 4 GHz with the measured input reflection coefficient better than – 7.5 dB on periodically loading the slot line with varactor diodes [7].

II.Theoretical Explanation of Loop Antenna and its Characteristics

II, I Geometry of small circular loop:

The small circular loop (also small magnetic loop) is used to specify with small dimensions such as its radius (a) is comparatively very small with wavelength (λ). The fields produced by this antenna can be analyzed by placing the antenna symmetrically on the x-y plane at z = 0 as shown in the figure 1. Assume the conducting coil (by which antenna is made) is very thin and small circumference and thus the current flowing through it is also assumed to be constant. The spatial current distribution is given by $I_{\phi} = I_0$ --------- (1)

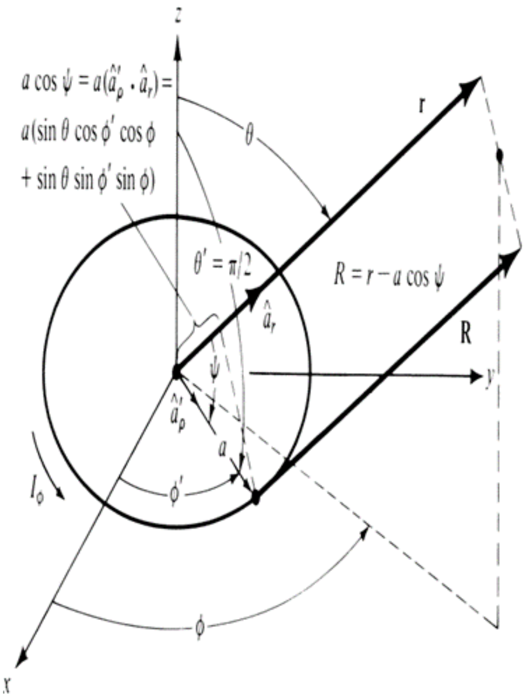

Figure: 1. *Geometrical analysis for loop antenna*

According to the procedure used to fine the radiated fields produced by the small loop, firstly the magnetic vector potential **A** is to be evaluated and is given by

$$\mathbf{A}(x,y,z) = \frac{\mu}{4\pi}\oint \boldsymbol{I}(x',y',z')\frac{e^{-jkR}}{\boldsymbol{R}}dl \qquad (2)$$

Where R is the distance from any point on the loop to the observation point and dl' is differential element length of the loop referring to the figure 1(a). For the convenience the spatial current distribution can be written in terms of rectangular coordinates. As the current flow is along the circular path, for analysis, it is more convenient to write the current components in terms of cylindrical components (ρ, ϕ, z) using the transformation [1]. Then the current components in the expanded form can be written as

$I_x = I_\rho \; cos\phi' - I_\phi \; sin\phi', \; I_y = I_\rho \; sin\phi' + I_\phi \; cos\phi'$ and $I_z = I_z$ (3)

Usually, the radiated fields are determined in spherical coordinates (r, θ, ϕ), the rectangular unit vectors are transformed to spherical unit vectors using the transformation matrix. Note that source coordinates are designated as primed (ρ', ϕ', z') and the space coordinates at a point far away from the antenna are designated as unprimed

I = $\bar{\boldsymbol{a}}_r$ [$I_\rho \; sin\,\theta \cos(\phi - \phi') + I_\phi \; sin\,\theta \sin(\phi - \phi') + I_z \; cos\,\theta$]

+ $\bar{\boldsymbol{a}}_\theta$ [$I_\rho \; cos\,\theta \cos(\phi - \phi') + I_\phi \; cos\,\theta \sin(\phi - \phi')$ - $I_z \; sin\,\theta$]

+ $\bar{\boldsymbol{a}}_\phi$ [- $I_\rho \; \sin(\phi - \phi') + I_\phi \; \cos(\phi - \phi')$] (4)

The current flow of the circular loop is azimuthally means in ϕ- direction. Hence equation (4) reduces to

I = $\bar{\boldsymbol{a}}_r \; I_\phi \; sin\,\theta \sin(\phi - \phi') + \bar{\boldsymbol{a}}_\theta \; I_\phi \; cos\,\theta \sin(\phi - \phi') + \bar{\boldsymbol{a}}_\phi \; I_\phi \; \cos(\phi - \phi')$] -(5)

The distance R, from any point on the loop to the observation point, can be written as

R = $\sqrt{(x - x')^2 + (y - y')^2 + (z - z')^2}$ (6)

Since x = r $in\,\theta \; cos\,\phi$, y = r $sin\,\theta \; sin\,\phi$ and z = r $cos\,\theta$

$x^2 + y^2 + z^2 = r^2$ (7)

$x' = a \; cos\,\phi'$, $y' = a \; sin\,\phi'$ and $z' = 0$. Also $x'^2 + y'^2 + z'^2 = a^2$. Equation (6) reduces to

R = $\sqrt{r^2 + a^2 - 2arsin\theta \; cos\,(\phi - \phi')}$ (8)

From the fig.1, the length of the differential element of the loop can be written as
$dl' = a \; d\phi'$ (9)
As the current is constant from equation (1), the radiated field by the loop will not be the functions of ϕ that means any observation angle can be choose. For simplicity, assume ϕ = 0, the ϕ-component of equation (2) can be written as

$$A_\phi = \frac{a\mu}{4\pi} \int_0^{2\pi} I_0 \; cos(\phi') \frac{e^{-jk\sqrt{r^2 + a^2 - 2ar\,sin\theta\,cos\,(\phi\prime)}}}{\sqrt{r^2 + a^2 - 2ar\,sin\theta\,cos\,(\phi\prime)}} \, d\phi' \quad (10)$$

Let f = $\frac{e^{-jk\sqrt{r^2 + a^2 - 2ar\,sin\theta\,cos\,(\phi\prime)}}}{\sqrt{r^2 + a^2 - 2ar\,sin\theta\,cos\,(\phi\prime)}}$ (11)

Equation (11) is a part of the integrand of (10) valued for small loops which can be expanded in a Maclaurin series. Consider only two terms, then equation (10) can be reducing to

$$A_\phi \cong \frac{a\mu \, I_0}{4\pi} \int_0^{2\pi} cos\phi' \; \left[\frac{1}{r} + a\left(\frac{jk}{r} + \frac{1}{r^2}\right) sin\,\theta \; \cos\phi'\right] e^{-jkr} \; d\phi'$$

Industrial Engineering Journal
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Volume : 53, Issue 3, No. 1, March : 2024

$$A_\phi \;\cong\; \frac{a^2\ \mu\, I_0}{4} e^{-jkr} \left(\frac{jk}{r} + \frac{1}{r^2}\right) sin\ \theta \qquad (12)$$

Similarly, the remaining two components of equation (2) in the directions r and θ, can be written as

$$A_r \;\cong\; \frac{a\mu\, I_0}{4\pi} sin\ \theta \int_0^{2\pi} sin\phi' \;\left[\frac{1}{r} + a\left(\frac{jk}{r} + \frac{1}{r^2}\right) sin\ \theta\ \cos\phi'\right] e^{-jkr} \quad d\phi' \text{ --(12a)}$$

$$A_\theta \;\cong - \frac{a\ \mu\, I_0}{4\pi} cos\ \theta \int_0^{2\pi} sin\phi' \;\left[\frac{1}{r} + a\left(\frac{jk}{r} + \frac{1}{r^2}\right) sin\ \theta\ \cos\phi'\right] e^{-jkr}\, d\phi' \text{ -- (12b)}$$

After integration is applied, it reduces to zero. Thus

$$\boldsymbol{A} \;\cong\; \bar{\boldsymbol{a}}_\phi\, A_\phi = \bar{\boldsymbol{a}}_\phi \frac{a^2\ \mu\, I_0}{4} e^{-jkr} \left(\frac{jk}{r} + \frac{1}{r^2}\right) sin\ \theta$$

$$= \bar{\boldsymbol{a}}_\phi\ j\ \frac{k\, a^2\ \mu\, I_0\ sin\ \theta}{4r} e^{-jkr} \left(\frac{1}{jkr} + 1\right) \qquad (13)$$

Substitute equation (13) in the following expression which represents the relation between magnetic field (H_A) and vector potential (**A**)

$$H_A = \frac{1}{\mu} (\nabla\ X\ \mathbf{A})$$

Now the magnetic field components reduce to

$$H_r = j\ \frac{k\, a^2\ \ I_0\ cos\ \theta}{2r^2} e^{-jkr} \left(\frac{1}{jkr} + 1\right) \text{ -- (14a)}$$

$$H_\theta = -\ \frac{(k\, a)^2\ \ I_0\ sin\ \theta}{4r} e^{-jkr} \left(1 + \frac{1}{jkr} - \frac{1}{(k\ r)^2}\right) \qquad (14b)$$

$$H_\phi = 0 \qquad (14\ c)$$

The electric field components can also be obtained using the relation below

$$E_A = -j\omega\mathbf{A} - j\frac{1}{\omega\mu\epsilon} \nabla(\nabla.\mathbf{A}) \qquad (15)$$

Thus, the corresponding electric field components for free space (**J** =0) can be written as

$$E_r \;=\; E_\theta = 0 \qquad (16a)$$

$$E_\phi = 30\ \pi \frac{(k\, a)^2\ \ I_0\ sin\theta}{r} e^{-jkr} \left(\frac{1}{jkr} + 1\right) \qquad (16b)$$

The above field expressions radiated by a small loop are almost equivalent to the fields produced by an infinitesimal magnetic dipole of length l and constant magnetic spatial current I_m .this can be achieved based on duality property. Thus a magnetic dipole of magnetic moment $I_m l$ is equivalent to a small electric loop of radius 'a' and constant electric current I_0 provided that

$$I_m l \;=\; js\omega\mu\, I_0 \qquad (17)$$

Where s = πa^2 (area of the loop). Thus for analysis purposes, the small electric loop can be replaced by a small linear magnetic dipole of constant current.

II.II Power Density and Radiation Resistance:

As for the case of infinitesimal dipole, the power in the near field region (very close to the antenna, $kr \ll 1$) is predominantly reactive and in the far field region (far away from the antenna,$kr \gg 1$) is predominantly real. To illustrate this for the loop, the complex power density can be formed as

$$\mathbf{W} = \frac{1}{2}(\mathbf{E}\times \mathbf{H}^{*}) = \frac{1}{2}\left[\left(-\,\bar{\boldsymbol{a}}_r\ E_\phi\ \ H_\theta^{*}\right) + \left(\ \bar{\boldsymbol{a}}_\theta E_\phi\ \ H_r^{*}\right)\right] \qquad (18)$$

When equation (18) is integrated over a sphere, only its radial power component is given by

$$W_r\ = \eta\frac{(ka)^4}{32}|I_0|^2\frac{\sin^2\theta}{r^2}\left[1 + j\ \frac{1}{kr^3}\right] \qquad (18a)$$

Contributes to the complex power P_r and can be evaluated by

$$P_r\ = \oiint \mathbf{W}.\,d\boldsymbol{S}$$

Therefore

$$P_r\ = \eta(\pi)\frac{(ka)^4}{12}|I_0|^2\left[1 + j\ \frac{1}{kr^3}\right] \qquad (19a)$$

The real part is,

$$P_{rad}\ = \eta(\pi)\frac{(ka)^4}{12}|I_0|^2 \qquad (19b)$$

The above indicates that the power density in the near field of a small loop is inductive where as in case of small dipole it is capacitive.

Now the radiation resistance can written as,

$$R_{rad}\ = \eta(\pi)\frac{(ka)^4}{6} = \eta\,\frac{\pi}{6}\frac{\left(k^2a^2\right)^2}{1} = \eta\,\frac{2\pi}{3}\left(\frac{ks}{\lambda}\right)^2 = 20\,\pi^2\ \left(\frac{c}{\lambda}\right)^4 \cong\ 31.171\left(\frac{s^2}{\lambda^4}\right) \qquad (20)$$

Where s = πa^2 , area of the loop and c = $2\pi a$, circumference of the loop.

The above equation is used to calculate the radiation resistance of single turn loop. It can be extended to loop of N turns given as

$$R_{rad}\ = \ \eta\,\frac{2\pi}{3}\left(\frac{ks}{\lambda}\right)^2 N^2 = 20\,\pi^2\ \left(\frac{c}{\lambda}\right)^4 N^2\ \cong\ 31.171\left(\frac{s^2}{\lambda^4}\right)N^2 \qquad (20a)$$

The radiation efficiency (dimensionless quantity) can be obtained from the radiation resistance (Rrad) and loss resistance (RL) and is given by

$$e_{cd} = \left[\frac{R_{rad}}{R_{rad}+R_L}\right] \qquad (21)$$

in general, as the value of R_L is more the value of ecd for a single turn is very low. To increase the value of ecd multiturn loops are employed. Wheeler and Q methods are used to measure the ecd. The loss resistance of a single turn small loop can be assumed to be the same with loss resistance of a straight wire of length equivalent to the circumference of the loop, and is determined based on uniform current distribution as given below, $R_{hf} = \frac{l}{p} R_s = \frac{l}{p}\sqrt{\frac{\omega\mu_0}{2\sigma}}$

Industrial Engineering Journal
ISSN: 0970-2555
Volume : 53, Issue 3, No. 1, March : 2024

Where Rhf is the high frequency resistance, p is the perimeter of the wire, Rs = conductor surface resistance , ω is the angular frequency, μ_0 is the permeability of free space, and σ is conductivity. But, the current flowing through the multi turn loop is not uniform and depends on the skin and proximity effects. The contribution of the proximity effect to the loss resistance is more for close spacing between turns. For an N-turn circular loop antenna with loop radius a, wire radius b and the loop seperation2c as shown in fig. 2 and is given by

$$R_{ohmic} = \frac{Na}{b} R_s \left(\frac{R_p}{R_0} + 1\right) \quad (22)$$

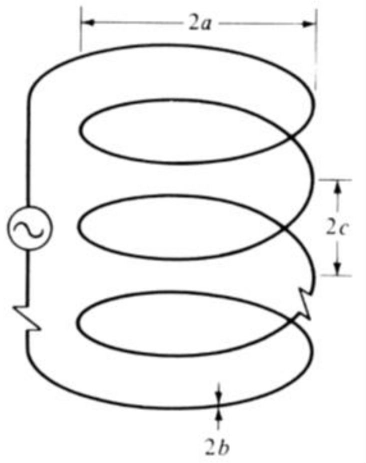

Figure: 2 *N- Turn circular loop*

Where

$R_s = \sqrt{\frac{\omega\mu_0}{2\sigma}}$ is the surface impedance of conductor

R_p is the ohmic resistance per unit length due to proximity effect

$R_0 = \frac{N R_s}{2\pi b}$, is ohmic resistance per length due to skin effect

The ratio, $\frac{R_p}{R_0}$ can be computed as a function of the spacing $\frac{c}{b}$ for small loops with $2 \le N \le 8$, which results that for close spacing the ohmic resistance is twice as large as that in the absence of proximity effect($\frac{R_p}{R_0}$ = 0).

Near field ($kr \ll 1$) region:
The radiated field expressions (18a and 19b) can be simplified if the observations are made in the near field. Thus

$$H_r = \frac{a^2 I_0}{2r^3} e^{-jkr} \cos\theta \quad (23a)$$

$$H_\theta = \frac{a^2 I_0}{4r^3} e^{-jkr} \sin\theta \quad (23b)$$

$$H_\phi = E_r = E_\theta = 0 \quad (23c)$$

$$E_\phi = -j \frac{a^2\ k\, I_0}{4r^2} e^{-jkr}\ \sin\theta \qquad (23d)$$

The above expressions are referred as quasy-stationary fields. The two H-field components are in time phase also in time quadrature with those of E-fields which indicates that the average power (real power) is zero. The condition ($kr \ll 1$) can be satisfied for moderate distances away from the antenna at low frequencies.

Far field ($kr \gg 1$) region: the fields in this region are given by

$$H_\theta = -\frac{k^2\ a^2\ I_0}{4r} e^{-jkr}\ \sin\theta = -\frac{\pi\, s\, I_0}{\lambda^2\ r} e^{-jkr}\ \sin\theta \qquad (24a)$$

$$E_\phi = -\eta\ \frac{k^2\ a^2\ I_0}{4r} e^{-jkr}\ \sin\theta = -\ \eta \frac{\pi\, s\, I_0}{\lambda^2\ r} e^{-jkr}\ \sin\theta \qquad (24b)$$

$$H_r = H_\phi = E_r = E_\theta = 0 \qquad (24c)$$

Wave impedance (Z_w) can be written as

$$Z_w = -\frac{E_\phi}{H_\theta} \cong \eta \qquad (25)$$

Where η is the intrinsic impedance ($120\ \pi$) for free space.

Thus the E- and H- field components of the loop in the field region are perpendicular to each other and transverse to the direction of propagation and forms Transverse Electro Magnetic (TEM) field which is the same as for the infinitesimal dipole.

II. III Radiation Intensity and Directivity:

$$U = r^2\, W_r = \frac{\eta}{2} \frac{(k^2 a^2)^2}{4^2} |I_0|^2 sin^2\theta = \frac{r^2}{2\eta} \left| E_\phi\ (r, \theta, \phi) \right|^2 \qquad (26)$$

The maximum value occurs at $\theta = \frac{\pi}{2} \rightarrow U_{max} = \frac{\eta}{2} \frac{(k^2 a^2)^2}{4^2} |I_0|^2$ (27)

The directivity of the loop is, $D_0 = 4\pi \frac{U_{max}}{P_{rad}} = 3/2 = 1.5$ (28)

The maximum affective area of the loop is, $A_{em} = \frac{\lambda^2}{4\pi}\ D_0 = \frac{3\lambda^2}{8\pi}$ (29)

Radiated fields of a circular loop of any radius with constant current:

Although the current is uniformly distributed along the perimeter of the loop, the circumference must be less than about 0.1 λ (radious less than about 0.016 λ) provided constant current.

Industrial Engineering Journal
ISSN: 0970-2555
Volume : 53, Issue 3, No. 1, March : 2024

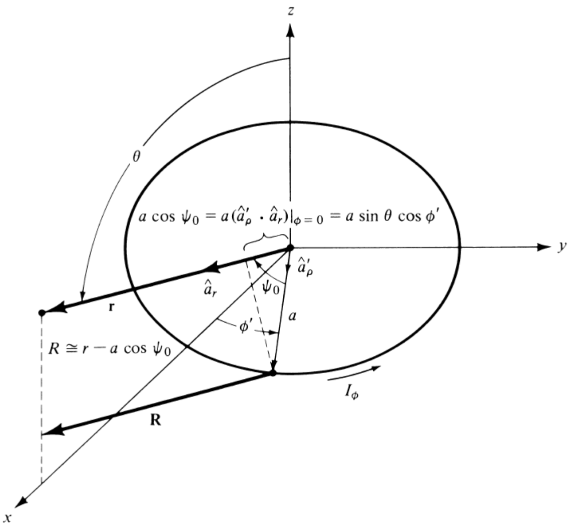

Figure: 3**.** Geometry for far-field analysis of circular loop of any radius with constant current

$E_r = E_\theta = 0,$

$$E_\phi = \eta \frac{ak\, I_0}{2r} e^{-jkr}\ J_1\ (k\ a\ sin\ \theta), \tag{30a}$$

$H_r = H_\phi = 0$, and $H_\theta = -E_\phi\ /\ \eta$

$$= -\frac{ak\, I_0}{2r} e^{-jkr}\ J_1\ (k\ a\ sin\ \theta) \tag{30b}$$

Power Density, Radiation Intensity, Radiation Resistance and Directivity:
The time- average power density can be formed to find these parameters

$$\boldsymbol{W}_{avg} = \overline{\boldsymbol{a}}_r\ W_r = \overline{\boldsymbol{a}}_r \frac{(a\omega\mu)^2}{8\eta r^2} |I_0|^2 . J_1{}^2 (k\ a\ sin\ \theta) \tag{31}$$

And the radiation intensity is given by,

$$U = r^2\ W_r = \frac{(a\omega\mu)^2}{8\eta} |I_0|^2 . J_1{}^2 (k\ a\ sin\ \theta) \tag{32}$$

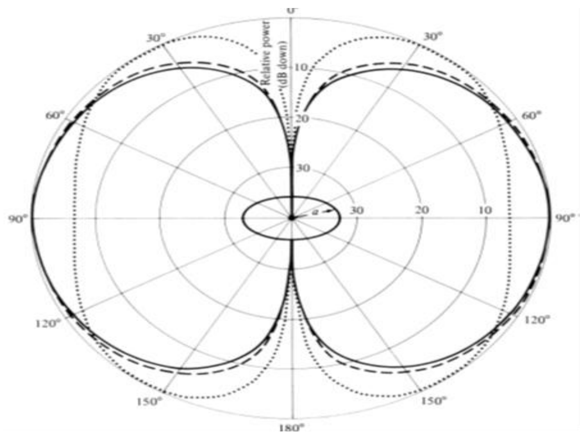

Figure.4**.** *elevation plane amplitude for a circular loop of constant current (a = $\lambda/10$, $\lambda/5$, and $\lambda/2$)*

Industrial Engineering Journal
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Volume : 53, Issue 3, No. 1, March : 2024

Fig.4 shows the two dimentional radiation pattern radiated by loop and can be observed that the pattern along the axis of the loop is zero ($\theta = 0$) and the shape of pattern is just like dumbel or igure of eight similar to radiation pattern of infinitesimal dipole. The field intensity along the plane of the loop diminishes and forms a null when radious of the loop increases (a$\cong 0.61\lambda$).
Beyond this radious (a$> 0.61\lambda$), the radiation along the plane of the loop begins to intensify and the pattern attains a multilobe form which is shown in the Fig 5.

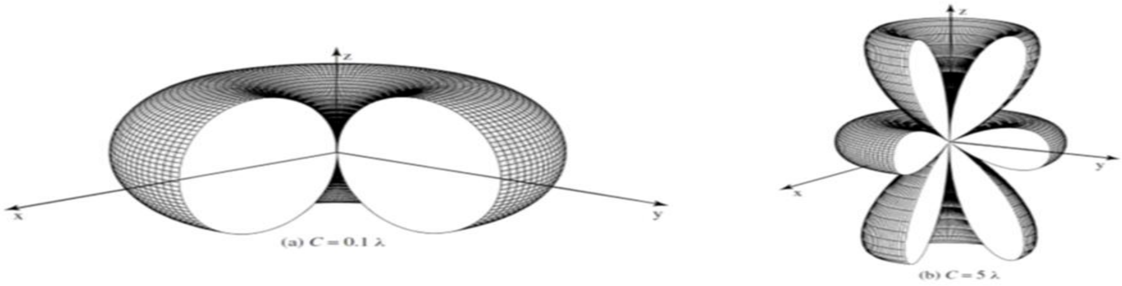


Figure:5**.** three dimensional amplitude pattern of a circular loop with constant current distribution, (a) a$\cong 0.0159\lambda$ and (b) a$\cong 0.796\lambda$

III.Simulation and Results

The parametrs that are taken for the simulation are :

- Geometry
  - (0.1,0,0) starting point
  - (0.1,0,0) Ending point
  - Length of loop -1.97m
  - Wavelenght-3.29m
- Attributes
  - Circular crosssection
  - One voltage source(1V)
  - Radius of wire 5mm
- Materials
  - Resistivity-0(Ω/m)
  - Relativity Permittivity-1
  - Relative Permeability- 1

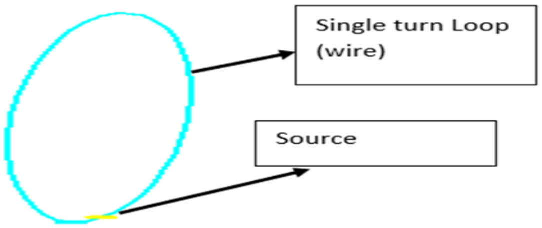


Figure 6(a) Simulated loop with source

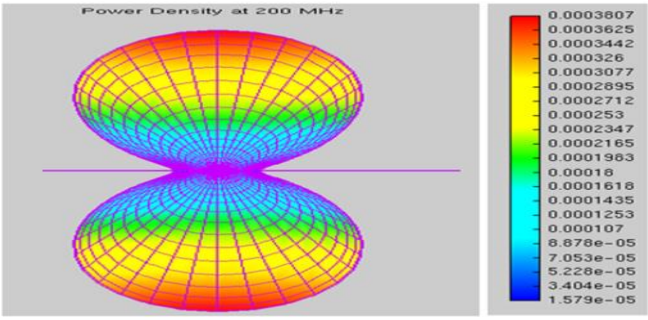


Figure :6(b) *3D Power Density pattern*

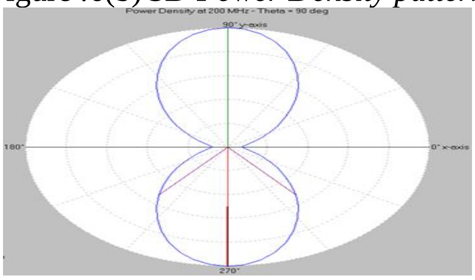
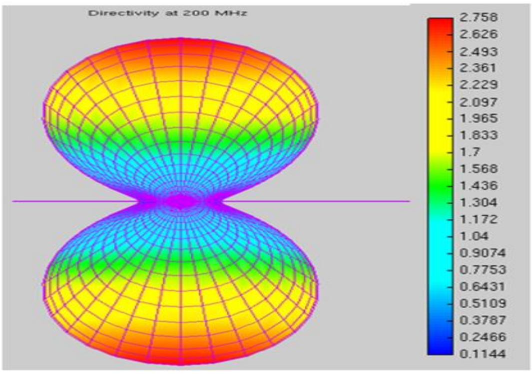


Figure**:** 6(c) 2D Power Density Pattern



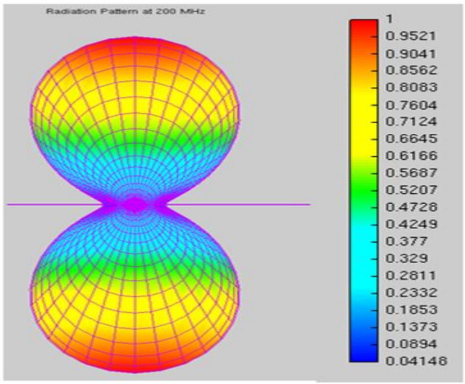


Figure 6(d) Directivity pattern

Figure **:**6(e) Radiation pattern

IV. CONCLUSION

This paper has provided the fundamental knowledge of implementation, operation and characteristics of small circular loop antenna. The simulation results are shown in figure 6 which are satisfactory. The directivity, power density and Radiation pattern have been observed in both two and three dimensional for the operating frequency 200 MHz.

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