International Journal of Applied Engineering Research ISSN 0973-4562 Volume 14, Number 7 (2019) pp. 1499-1504

A Study of the Radiation Characteristics of a Circular Loop Antenna Using Genetic Algorithm Technique

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Abstract

This paper presents a study on the radiation characteristics of a small loop antenna**.** Loop antenna, although structurally simple is a special type of wire antenna with the shape of a circle, square or rectangle. It can be small or large and its design challenging. Different studies have been made on small loop antennas. Here, the radiation characteristic is studied by carrying out a simple loop antenna design using the physical dimensions of both the wire conductor and antenna loop. The dimensions of the antenna were determined using Genetic algorithm (GA) technique which presented various options of choice. Radiation efficiency for each option was computed and results presented. Antenna parameters were also computed and presented. The radiation pattern obtained was based on the antenna conductor that yielded the highest computed radiation efficiency. This showed that small loop antenna produces high radiation efficiency if the conductor and loop dimensions are properly chosen.

Keywords: Genetic algorithm, circular loop antenna**,** radiation pattern, ohmic resistance

I. INTRODUCTION

Loop antenna is a special type of wire antenna that have the shape of a circle, square, or rectangle. It is simple to construct, low cost and versatile in applications. They are classified as electrically small or large antennas. Electrically small antennas have their overall length smaller than about one-tenth of a wavelength while electrically large loops have overall length or circumference equivalent to one wavelength of the operating frequency.

Genetic Algorithm (GA) is a branch of artificial intelligence (AI) used to solve human problems. It utilizes the concept of chromosomes, alleles, genes, mutation and mating. GA, by combination of these concepts, helps to obtain the optimum or best possible solution to antenna problems some of which are discussed in [1]. GA is a veritable tool that can be used to find optimal results where traditional techniques fail. This is the reason for the adoption of this technique.

Working on electrically small loop antennas are challenging with many design concepts to consider [2]. Antenna size, design time, limited bandwidth, radiation efficiency, portability and the interaction of the antenna with other supporting components are some of the challenges. Of interest here is the antenna radiation characteristics which is the main focus of this paper. The study includes determination of the design parameters of the circular loop antenna, formulation of the mathematical model and simulation to obtain the radiation pattern.

GA technique is a well known approach used in the study of antennas. A simple genetic algorithm to study antenna characteristics was used in [3]. Their objective was to demonstrate that pattern synthesis could be successfully applied to such nonlinear arrays thus paving the way for lower cost array systems. Elsewhere in [4] the design of a novel printed antenna configured with circular loop geometry of approximately one wavelength perimeter for operation at 5.8 GHz with near omni-directional radiation pattern was discussed. Their result showed that the printed loop antenna has the potential to be used as a low power transceiver for both WLAN (wireless local area network) and RFID (radio frequency identification) applications.

The work in [5], investigated how circular loop antenna and human tissue interact at 434MHz. The study was based on the analysis of the antenna radiation efficiency which was found to be least when placed parallel to the body indicative of maximum interaction between the loop and the tissue. A study on circular loop in the Tetra Hz (THz) and optical region was discussed in [6]. The results presented an exact function for the input impedance at all frequencies,

Another work documented in [7] was on rectangular loop antenna in a broadband, hexa-band and dual polarized for mobile communications. A compact dual-polarized loop antenna was proposed. With the advantages of compact size, broad bandwidth, high isolation, stable gains, and excellent diversity performance, they believed that their proposed dual-polarized loop antenna is suitable for mobile communication systems. This study is also on loop antenna as those described above however it concentrates on investigating the effect of conductor and antenna loop dimensions on the antenna's radiation pattern and its suitability for mobile communication. Therefore the 935-955MHz frequency band for mobile communication was applied as against the frequency bands discussed elsewhere in the literature.

The paper is arranged as follows, section I is the introduction which also include a brief review of related works, section II is the method used for the study, the result is discussed in section III and conclusion is the last section.

II. METHODOLOGY

A. Design considerations

The study was carried out by first determining the loop antenna diameter. This was done by obtaining the radius a using GA. The diameter ($2a$) was used for the loop formation. The loop was formed by bending the copper wire with radius

b into the shape of a circle and allowing a small gap as the feed point. This is illustrated in Fig 1.

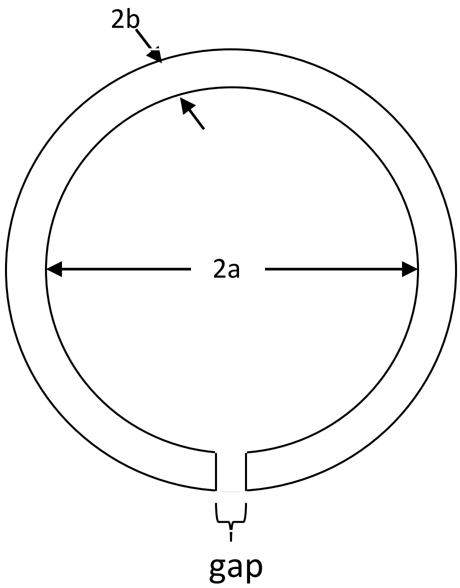

Fig 1. Structure of Wire Loop

B. Design model

For uniform current distribution in the loop, [8]

$\boldsymbol{a} < 0.016\boldsymbol{\lambda}$ 2.1

Where a and λ are the loop radius and wavelength respectively. The frequency band chosen is 935-955MHz. The center frequency f_c is obtained from

$f_c = \frac{955-935}{2}(MHz) = 945MHz$ 2.2

The wavelength $\boldsymbol{\lambda}$ is given as

$\boldsymbol{\lambda} = \frac{velocity\ of\ free\ space}{frequency} = \frac{3x10^8}{945x10^6} = 0.3175m$ 2.3

From 2.1, the radius of the loop must be less than 5.08mm. Therefore the design model was obtained using the following guidelines

Objective Function: Max (radiation resistance) and Min (ohmic resistance)

Subject to

$1mm \le a \le 5mm$ 2.4

$0.5mm \le b \le 3mm$ 2.5

$b - a \le -1mm$ 2.6

The radiation resistance R_r for n turns of wire is given by [8]

$R_r = \frac{20\pi^2 C^4}{\lambda^4}$ 2.7

For $C = 2\pi a$ and $n = 1$,

$R_r = \frac{320(3.141592654)^6 a^4}{0.3175^4} = 30274312.95a^4$ 2.8

The ohmic resistance $\boldsymbol{R_l}$ for a single turn is given by

$R_l = \frac{a}{b}\sqrt{\frac{\omega\mu_0}{2\sigma}}$ 2.9

Here ω is the radial frequency, σ is the conductivity of copper with ($5 * 10^7 S$) and μ_0 the permeability of free space($4\pi * 10^{-7} H/m$).

Using $\omega = 2\pi f$ in 2.9, the ohmic resistance is obtained as

$R_l = \frac{a}{b}\sqrt{\frac{5937610115*4\pi*10^{-7}}{2*5.7*10^7}} = \frac{a}{b}\sqrt{\frac{7461.420927}{114*10^6}} = \frac{a}{b} * 8.09 * 10^{-3}$ 2.10

The objective function to be minimized by the GA is formulated using the two independent variables a and b involving the parameters of radiation and ohmic resistances. The radiation and ohmic resistances are minimized subject to the constraints of 2.4, 2.5, and 2.6. Using 2.8 for the first objective function yields

$y_1 = -(30274312.95 * a^4)$ 2.11

The negative sign is to ensure that the solver maximizes the function instead of minimizing it.

Similarly, 2.10 for the second objective function gives

$y_2 = 8.09 * 10^{-3} * \frac{a}{b}$ 2.12

Converting to millimeter ($1m = 10^3 mm$), 2.11 gives

$y_1 = -(30274312.95 * 10^3 * a^4)$mm 2.13

C. Genetic algorithm

An initial population of individuals corresponding to the variables X_1 and X_2 were randomly generated by GA. The population size of twenty was evaluated using the fitness test (the constraints and objective function) and the best ones selected became parents. The parents were chosen to be the next generation of individuals and then subjected through the fitness test again to generate new parents that will become the next generation. The following options were set for the GA to improve the algorithm for better results

- The population size was set to 50 to increase the range of values to be evaluated at any given iteration.
- The initial range was set to [1:2] to give a good diversity of the population.
- Crossover function was set to Heuristic with a ratio of 1:2. It created children that are randomly closer to the parents with better fitness value than the parent with the worst fitness value.
- The level of display in 'display to command' window set to iterative in order to display output information of the algorithm in the command window.

The values obtained for a and b using GA solver are tabulated in Table 1 and were used in calculating the corresponding antenna efficiency, e_r. Also tabulated are the computed e_r.

International Journal of Applied Engineering Research ISSN 0973-4562 Volume 14, Number 7 (2019) pp. 1499-1504

Table 1. Results from GA Solver($b = 1.25mm$)

S/N	Radius of the loop (a) (mm)	Radius of the conductor (b) (mm)	Efficiency (e_r) (%)
1	5.07	1.2509765625000002	37.89194
2	1.2480468749999991	1.2490234374999993	0.900452
3	3.77658959884517	1.2504551609479064	20.13123
4	2.8261439790598857	1.2498091237791167	9.549155
5	2.176853507661907	1.2494969157777807	4.601406
6	4.420994945173345	1.2507725558509437	28.79772
7	4.7037981241570845	1.2506880159084846	32.75516
8	4.243672351427978	1.2509589549781026	26.3494
9	4.565457448004878	1.2505500040701547	30.81154
10	4.466337568769228	1.2506630675245907	29.42764
11	3.377403537329342	1.25007889455558	15.2703
12	4.913325420666342	1.250767426414151	35.6985
13	3.6930229581413196	1.2502360318114036	19.07081
14	3.285526944284433	1.250033932759503	14.22981
15	2.6191964681789814	1.250313939415577	7.755167
16	3.9067533876046228	1.250359635064293	21.81409
17	4.954709643970057	1.2505972170010702	36.27502
18	3.8507166494122207	1.2504581844177527	21.08521
19	2.9881927316657304	1.249634881221954	11.09349
20	3.618402427336065	1.2501875008472392	18.14294
21	3.5591043404238007	1.2502570482350064	17.41914
22	1.6474596823083862	1.2492167766927682	2.047498
23	5.020868152770967	1.2507821132835837	37.20326
24	4.420994945173345	1.2507725558509437	28.79772
25	4.313824904693354	1.2508629474267827	27.31347
26	3.9494994734972835	1.2503843557148708	22.37636
27	4.593373066123254	1.250875657374131	31.20835
28	4.688031491307221	1.2508454092101553	32.53645
29	4.995718380130198	1.2509466179813404	36.85505
30	2.4881927316657304	1.249634881221954	6.719715
31	4.660779646406112	1.2506567237778985	32.15043
32	4.6011381075222815	1.2497935877532003	31.29863
33	3.1073557241830914	1.2499355171244362	12.30698
34	4.379748609882785	1.2499115185452518	28.21063
35	4.356205381085499	1.25086814764953	27.89969
36	4.135793743610866	1.250094511752991	24.86496
37	4.000794776568476	1.2504140204955643	23.05638
38	4.872282421111936	1.250241976780048	35.11337
39	4.842448494763568	1.2506737601337479	34.70253
40	4.7245889621973465	1.250830832552177	33.04977
41	4.044540971341303	1.2504191418958124	23.64031
42	4.53505060432557	1.250835430137582	30.39065
43	4.274667722554007	1.250553001370091	26.7689

S/N	Radius of the loop (a) (mm)	Radius of the conductor (b) (mm)	Efficiency (e_r) (%)
44	4.185489277762283	1.250650438145747	25.54887
45	1.2480468749999991	1.2490234374999993	0.900452
46	5.041869449398568	1.2503370901155182	37.48794
47	3.1769246749884674	1.249842402841844	13.04114
48	5.07	1.2509765625000002	37.89194
49	2.1474596823083862	1.2492167766927682	4.424705
50	4.495718380130198	1.2509466179813404	29.84254

From Table 1, using 2.8 with known a and b the radiation resistance was computed as

$R_r = 30274312.95 * a^4$, thus

$$R_r = 30274312.95 * (2.701197201544 * 10^{-3})^4 = 1.611757 m\Omega \quad 2.14$$

The ohmic resistance using 3.11 is

$$R_l = 8.09 * 10^{-3} * \frac{a}{b}$$

$$= 8.09 * 10^{-3} * \frac{2.701197201544*10^{-3}}{0.50097263225*10^{-3}} = 0.043621\Omega \quad 2.15$$

The corresponding radiation efficiency e_r for each loop antenna with radius a was calculated as

$$e_r = \frac{R_r}{R_r + R_l} \quad 2.16$$

$$e_r = \frac{0.001611757}{0.043621} = 0.03563289 \quad 2.17$$

Examining Table 1 it observed is that the highest radiation efficiency is obtained when the loop and conductor radii (a and b) are 5.07mm and 1.251mm respectively. These dimensions were considered for the antenna structure. A copper wire of $2a$ (10mm) and $2b$ (2.5mm) was therefore chosen for the construction of the loop antenna as shown in Fig 2

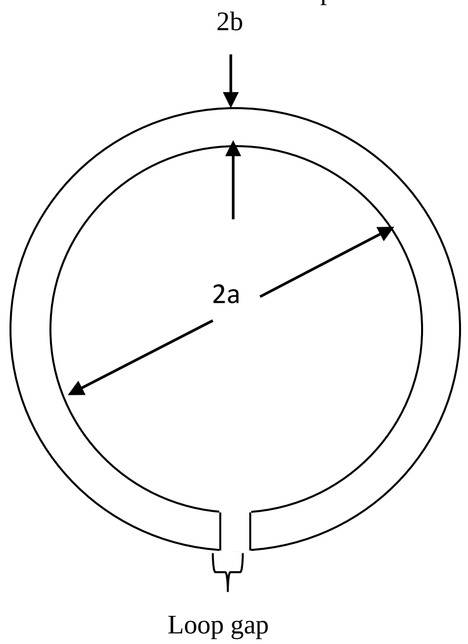

Fig 2. Circular loop antenna

D. Antenna parameters

With known values of a and b the following antenna parameters were also determine: maximum effective aperture, resonance capacitance, resonance input impedance and inductance. These parameters effectively describe the characteristics of the loop antenna.

The maximum effective area is given as

$$A_{em} = \frac{3\lambda^2}{8\pi} = \frac{3*0.3175^2}{8\pi} = 0.012m^2. \quad 2.18$$

Physical area of the loop is

$$S = \pi r^2 \quad 2.19$$

For $r = a + 2b$, the physical area is obtained as

$$S = \pi(7.5 * 10^{-3})^2 = 1.7672 * 10^{-4} m^2 \quad 2.20$$

The resonance capacitance is given as

$$C_r = \frac{1}{2\pi f}\frac{X_{in}}{{R_{in}}^2 + {X_{in}}^2} \quad 2.21$$

$X_{in} = 2\pi f(L_A + L_i)$, where L_A and L_i are the external and internal inductances of the loop respectively, and are given by

$$L_A = \mu_0 a\left[\ln\left(\frac{8a}{b}\right) - 2\right] \text{ and } L_i = \frac{a}{\omega b}\sqrt{\frac{\omega\mu_0}{2\sigma}} \quad 2.22$$

Therefore,

$$L_A = 4\pi * 10^{-7} * 10 * 10^{-3}\left[\ln\left(\frac{8*5*10^{-3}}{1.25*10^{-3}}\right) - 2\right] = 9.2095 * 10^{-9} H \quad 2.23$$

And

$$L_i = \frac{5*10^{-3}}{2\pi*945*10^6*1.25*10^{-3}} * \sqrt{\frac{2\pi*945*10^6*4\pi*10^{-7}}{2*5.7*10^7}} = 5.45 * 10^{-12} H \quad 2.24$$

Therefore,

$$X_{in} = 2\pi * 945 * 10^6(9.2095 * 10^{-9} + 5.45 * 10^{-12}) = 54.7148\Omega \quad 2.25$$

$$R_{in} = R_r + R_l = 0.0189 + 0.0324 = 0.0513\Omega \quad 2.26$$

The input impedance is given by

$$Z_{in} = R_{in} + jX_{in} = 0.0513 + j54.7148\Omega \quad 2.27$$

The resonance capacitance C_r is computed as

$$C_r = \frac{1}{2\pi * 945 * 10^6} \frac{54.7148}{0.0513^2 + 54.7148^2} = 3.0783 * 10^{-12} F \qquad 2.28$$

And the input resonance impedance Z'_{in} is obtained using 2.25 and 2.26. That is

$$Z'_{in} = R_{in} + \frac{X_{in}^2}{R_{in}} = 58.357\Omega \qquad 2.29$$

Table 2 summarizes the computed parameters

Table 2 Antenna Designed Parameters

Parameter	Value
Radius of the conductor (mm)	1.25
Radius of the loop (mm)	5
Radiation resistance (mΩ)	18.9215
Ohmic resistance (mΩ)	32.3600
Maximum effective area (m^2)	0.0120
Physical area (m^2)	0.0002
Efficiency (%)	37.89194
Resonance frequency (MHz)	945
External inductance of loop (nH)	9.2095
Internal inductance of conductor (pH)	5.4500
Input resistance (mΩ)	51.2815
Input reactance (Ω)	54.7148
Input impedance (Ω)	58.3570
Resonance input impedance (kΩ)	58.3780

III. RESULTS

A. *Fields of the antenna*

The antenna parameters were used to develop appropriate Matlab codes for the simulation. In Fig 3, the far-field radiation pattern is illustrated. The pattern is basically the shape of figure 8 with no side lobes when looked at from the plane of the antenna and provides a null at the center where no fields exist. This is an important characteristic of electrically small loop.

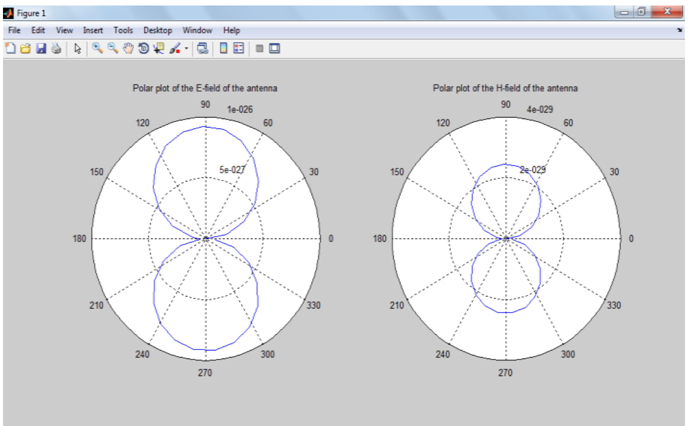

Fig 3. Figure-8 far-field radiation pattern

The radiation patterns in 3D are shown in Figs 4 and 5. The shapes represent an Omni-directional doughnut figure when observed from the azimuth and radiates equally at all elevation angles.

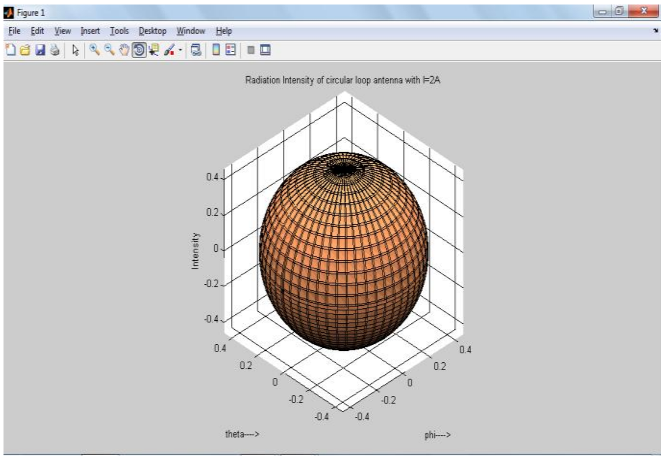

Fig 4. 3-D Radiation Pattern of Circular Loop Antenna**.**

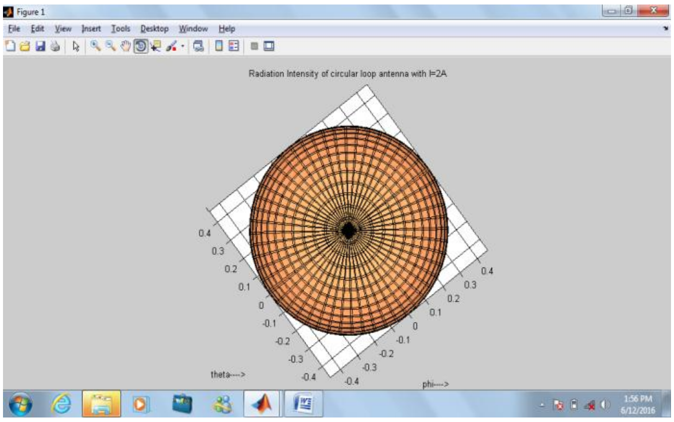

Fig 5. 3-D Radiation Pattern of Circular Loop showing the null

The two figures are the same but Fig 4 is Fig 5 rotated to show the unique property of small loop antennas known as null (the point within the antenna where there is no effect of field strength). This work has been able to show that small loop antenna with conductor and loop radii properly chosen will theoretically radiate electromagnetic waves efficiently without side lobes. Hence efficiency is high since power loss is very minimal as a result of the absence of side and back lobes.

IV. CONCLUSION

The method of Genetic Algorithm (GA) was used to obtain the best solution for radius of the loop and wire which satisfies the design aims and constraints. The parameters used to describe the performance of the antenna were easily computed knowing the two radii. The designed antenna was simulated for efficiency using the computed parameters. The result was obtained in terms of efficiency versus loop radius. It was observed that efficiency increases with loop size. The radiation pattern is omnidirectional with no back and side lobes. This study has shown that for maximum radiation efficiency of a small loop antenna it is appropriate to carefully select the conductor and antenna loop diameters.

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