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Theoretical Modeling of a Magnetic Loop Antenna for Ultra Wide Band Application

Moses Emetere
Physics Department, P.M.B. 1023, Covenant University, Ota, Nigeria
E-mail: emetere@yahoo.com

Abstract

The functionality of an improved magnetic loop antenna (MLA) is a prominent research which has span almost three decades. Its shape and size had metaphorsize from the usual analogue to a digital device-which is now used for experiments in space. In this paper, the application of MLA for ultra wide band (UWB) design was proposed. A new concept was introduced -angular displacement theory which was used to mitigate fading in multipath propagation.

Keyword: *magnetic loop antenna, functionality, ground plane, ultra wide band, radiation pattern*

1. INTRODUCTION

The typical magnetic loop antenna (MLA) is a high-Q tuned antenna with a very narrow pass band (as shown in Figure 1 below). It is made up of two loops of varying sizes i.e. a large loop and small loop, support structures of either unpainted wood, plastic or fiberglass, resonant circuit, transceiver. The large loop operates on a low frequency (i.e. 10-25KHz which makes it suitable as radiator) and the small loop on high frequency [1]. MLAs were not recon with due to: necessity to retune as the operator significantly changes frequency, malfunctioning when brought near metal, slight de-tuning of the antenna when brought close to any biological body.

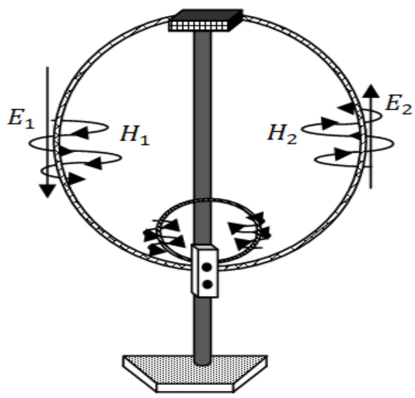

Figure 1. Typical Diagram of Magnetic Loop Antenna

Thereafter, several improvements have been made on the functionality of the MLAs. The useable frequency was improved upon from 20KHz to 55MHz by the introduction of an amplifier to separate the magnetic loops [2] and the introduction of an electrically small material to the near-field of the electrically small radiator [3, 4]. That type of MLA was referred to as the magnetic EZ antenna which has been proven to operate at 100MHz [5]. Recently, the MLA application can be found in plasma physics i.e. heating and ionization for processing plasmas [6, 7], laser-plasma interactions, plasma opening switches, and active experiments in space [8], excitation of large amplitude whistler modes in magnetized plasmas [9, 10]. Certainly there are

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more to its functionality than already known. In this paper, we propose a magnetic loop antenna (MLA) – suitable for mitigating fading in multipath propagation by applying the angular displacement theory on the slots of a ground plane.

2. Theoretical Background

The time- independent Schrödinger equation was modeled to open up the electron dynamics. The time- independent Schrödinger equation is given as:

$$i\hbar\frac{\partial}{\partial t}\psi - \frac{\hbar^2}{2m}\nabla\psi + V\psi = 0 \quad (1)$$

The langrangian density related to Equation (1) is given as:

$$\mathcal{L}_1 = \frac{1}{2}\left[\left|\frac{\partial\psi}{\partial t}\right|^2 - \frac{\hbar^2}{2m}|\nabla\psi|^2 - V|\psi|^2\right] \quad (2)$$

Applying the minimum coupling rule to describe the interaction of ψ with the electromagnetic field i.e.

$\frac{\partial}{\partial t} \longmapsto \frac{\partial}{\partial t} + ieV,$ $\nabla \longmapsto \nabla - ieA$ where $V = V(r,\theta) = V_o + E_o(\frac{a^2}{r} - r)$

Where V_o is a constant on the surface of the faraday loop of the MLA, E_o is the field, r is the radius of the circular loop.

Equation (2) transforms into:

$$\mathcal{L}_1 = \frac{1}{2}\left[\left|\frac{\partial\psi}{\partial t} + ie\psi\phi\right|^2 - \frac{\hbar^2}{2m}|\nabla\psi - ieA\psi|^2 - V|\psi|^2\right] \quad (3)$$

The circular conductor is accounted for where $r = x$.

$$\mathcal{L}_1 = \frac{1}{2}\left[\left|\frac{\partial\psi}{\partial t} + ie\psi V_o + iE_o e\psi\left(\frac{a^2}{x} - x\right)\cos\omega t\right|^2 - \frac{\hbar^2}{2m}|\nabla\psi - ieA\psi|^2 - V|\psi|^2\right] \quad (4)$$

Applying the solution of the standing wave $\psi(x,t) = e^{iS(x,t)}T(x,t)$ in Equation (4)
Where E, B : $\mathbb{R}^3 X\, \mathbb{R} \rightarrow \mathbb{R}$, the lagrangian density takes the form:

$$\mathcal{L}_1 = \frac{1}{2}\left\{E_{rt}^2 - |\mathrm{E_z}|^2 - \left[\frac{\hbar^2}{2m}|\mathrm{B_r} - eA|^2 + |B_z + V_o e|^2 - \left(\left|B_z - E_o e\left(\frac{a^2}{x} - x\right)\right|^2 - |B_z|\right) + \right.\right.$$
$$2EoVoe2Er2 \quad (5)$$

Considering the lagrangian density of the particle electromagnetic field E-H field of the circular monopole plasma antenna.

$$\mathcal{L}_o = \frac{1}{8\pi}(|E_1|^2 - |E_2|^2 - |H_1|^2 - |H_2|^2)$$

Where the values of electric and magnetic was adapted from Glenn [11] and restructured into the circular magnetic loop antenna [12].

$$E_1(a,z) = (\beta E_r(a,z)e_r + E_z(a,z)e_z)e^{-j\beta r}sin\theta \quad (6)$$

$$E_2(a,z) = (\beta E_r(a,z)e_{r1} + E_z(a,z)e_{z1})e^{-j\beta r}cos\theta \quad (7)$$

$$H_1(a,z) = (\beta B_r(a,z)f_r + B_z(a,z)f_z)e^{-j\beta r}sin\theta \quad (8)$$

$$H_2(a,z) = (\beta B_r(a,z)f_{r1} + B_z(a,z)f_{z1})e^{-j\beta r}cos\theta \quad (9)$$

Where $e_r = e_{r1} = \frac{\xi m}{4\pi r}$ and $e_z = e_{z1} = \frac{\xi mj}{4\pi z^2}$; $f_r = f_{r1} = \frac{\mu_o mj}{4\pi r^2}$ and $f_z = f_{z1} = \frac{\mu_o m}{4\pi z^3}$.

The boundary conditions for Equation (6) are:

$$\begin{cases} E_1(a,0) = E_\alpha(z) \\ E_1(\infty,z) = 0 \\ E_1(a,x) = E_\alpha(z).\alpha \\ E_1(a,\infty) = 0 \end{cases} \tag{10}$$

The boundary conditions for Equation (7) are:

$$\begin{cases} E_2(a,0) = E_\gamma(z) \\ E_2(\infty,z) = 0 \\ E_2(a,x) = E_\gamma(z).\gamma \\ E_2(a,\infty) = 0 \end{cases} \tag{11}$$

The boundary conditions for Equation (8) are:

$$\begin{cases} B_1(a,0) = B_\vartheta(z) \\ B_1(\infty,z) = 0 \\ B_1(a,x) = B_\vartheta(z).\vartheta \\ B_1(a,\infty) = 0 \end{cases} \tag{12}$$

The boundary conditions for Equation (9) are:

$$\begin{cases} B_2(a,0) = B_\sigma(z) \\ B_2(\infty,z) = 0 \\ B_2(a,x) = B_\sigma(z).\sigma \\ B_2(a,\infty) = 0 \end{cases} \tag{13}$$

Where α and γ are the attenuation factors of the electrical fields; σ and ϑ are the attenuation factors of the magnetic fields; $B_\vartheta(z)$ and $B_\sigma(z)$ are the magnetic fields at the boundary of the plasma antenna; $E_\gamma(z)$ and $E_\alpha(z)$ are the electric fields at the boundary of the plasma antenna; x is the length of plasma antenna; β is the frequency of excited power; j is the radio frequency current; r represents the radius or horizontal component of the antenna; z represents the vertical component of the antenna; m represents the quality of the electrons; $\boldsymbol{\xi}$ represents the electrical permeability; μ_o represents the magnetic permeability; e_r is the spin factor which determines the electron spin along the horizontal component of the plasma; e_z is the spin factor which determines the electron spin along the vertical component of the plasma; e_{r1} is the spin factor which determines the electron spin along the horizontal component within the electric field of the sheath; e_{z1} is the spin factor which determines the electron spin along the vertical component within the electric field of the sheath; f_r is the spin factor which determines the electron spin along the horizontal component within the magnetic field of the plasma antenna; f_{r1} is the spin factor which determines the electron spin along the horizontal component within the magnetic field of the sheath; f_z is the spin factor which determines the electron spin along the vertical component within the magnetic field of the plasma; f_{z1} is the spin factor which determines the electron spin along the vertical component within the magnetic field of the sheath.

Therefore the total action of lagrangian density is given by:

$$D = \iint \mathcal{L}_1 + \mathcal{L}_o \tag{14}$$

Then the Euler-Lagrange equation associated to the function $S = S(E_r, E_z, \mathrm{B_r}, B_z, r, \theta, z)$ gives rise to the following systems of equation:

$$E_{rt} + \left[\frac{\hbar^2}{2m}|\mathrm{B_r} - eA|^2 + |B_z + V_o e|^2 - \left(\left|B_z - E_o e\left(\frac{a^2}{r} - r\right)\right|^2 - |B_z|\right) + 2E_o V_o e^2 + \beta e_r\right] E_r = \beta E_r e_r e^{-j\beta r}(sin\theta + cos\theta) \tag{15}$$

$$\frac{\partial}{\partial t}\left[(B_z + V_o e){E_r}^2\right] - \frac{\partial}{\partial t}\left[\left(B_z + E_o e\left(\frac{a^2}{x} - x\right)\right){E_r}^2\right] - \frac{1}{2}\frac{\partial B_z}{\partial t} = 0 \quad (16)$$

$$\frac{\hbar^2}{2m}{E_r}^2\frac{\partial}{\partial t}(\mathrm{B_r} - eA) = \beta B_r f_r e^{-j\beta r}(sin\theta + cos\theta) \quad (17)$$

$$\frac{\partial}{\partial t}E_z = \frac{\partial}{\partial t}E_z e_z e^{-j\beta r}(sin\theta + cos\theta) \quad (18)$$

$$2\left|B_z - E_o e\left(\frac{a^2}{r} - r\right)\right| E_r E_o e\left(\frac{a^2}{r^2} - 1\right)$$
$$= \frac{j\beta}{8\pi}\left[\frac{E_r e_r}{r}(sin\theta + cos\theta) + \frac{2B_r f_r}{r}(sin\theta + cos\theta)\right]\beta e^{-j\beta r} \quad (19)$$

$$\frac{1}{8\pi}[\beta E_r(a,z)e_r + \beta B_r(a,z)f_r + E_z(a,z)e_z + B_z(a,z)f_z][cos\theta - sin\theta] = 0 \quad (20)$$

$$\frac{1}{8\pi}[-\frac{2}{z}e^{-j\beta r}sin\theta(B_z(a,z)f_z + E_z(a,z)e_z)$$
$$-\frac{2}{z}e^{-j\beta r}cos\theta(B_z(a,z)f_z + E_z(a,z)e_z)] = 0 \quad (21)$$

3. Experimental Arrangement

For the purpose of this study, we shall be concentrating on Equation (18) which expresses the functionality of the antenna. We propose an introduction of a varactor diode of capacitance range between 25 to 0.5pF to be installed at either the front open port or alongside the variable capacitor. The varactor is used to limit the absorption at the resonance by the help of a high series resistance. A series inductor (L) and protection resistor (R) of respective rating 1Ω and 5.5μH are expected to allow only direct current (dc) and truncate the alternative current flow. The type of coil used for this model is not specified largely due to constraints of access to materials and the flexibility to incorporate recent discoveries in material science, though; we acknowledge that coil material is the source of discrepancy between measured and simulated radiation patterns.

4. Results and Discussion

The radiational angular displacement theory is all about substituting the slots on the ground plane with the radiation angle which had been properly accounted for in section II. From Equation (18), slot with higher width is represented by the sine of the radiation angle; slot with lower width is represented by the cosine of the radiation angle. The sum of both cosine and sine of radiation angle represents the MLAs without slot. We simulated the relationship between the radiation angle and its effect on the functionality of the antenna as shown in Figure 2. Though the radiation patterns of the MLA with and without slots on the ground plane are very similar but the performance of the MLA differs at various conditions. First, the slot with higher width was more effective on the ground plane to minimize the ground plane effects on planar UWB magnetic loop antenna. The slot with lower width was less effective. This concept is in agreement with the experimental discoveries made in the past [13]. The new discovery is that the MLA is functionally active when a slot-less ground plane is angularly displaced. This idea was applied to slot of higher width (sin(x)-cos(x)) and the slot of lower width (cos(x)-sin(x)) as shown in Figure 3, It improved the functionality as the transmission increased considerably to the magnitude of the MLA without slot. Another discovery was the reversal of functionality betwwen slots of varying widths i.e. slot with lower width was more active than slot with higher width.

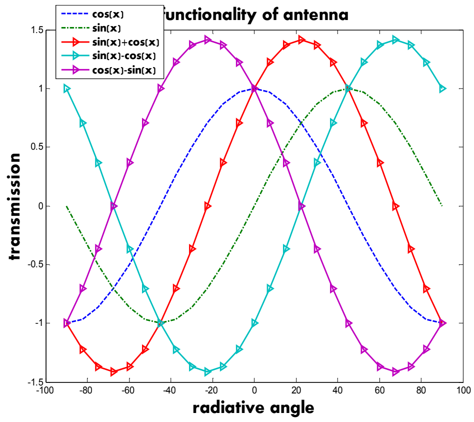

Figure 3. Verification of the Angular Displacement Theory on the Functionality of the MLA

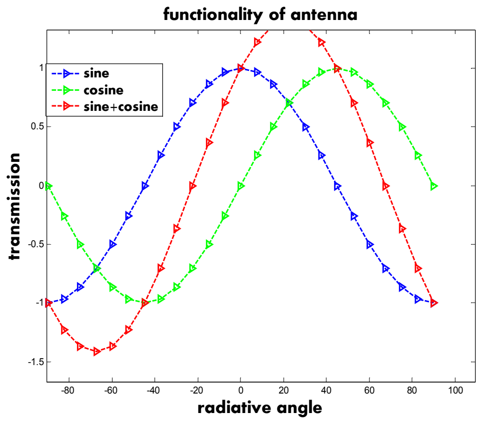

Figure 2. The Functionality of the MLA with or without Slot

The frequency variation of the MLA as shown in Figure 4, suggest that MLA can cover the entire ultra wide band (UWB) with a reflection coefficient of about -2dB. The integration of the varactor diode into the mechanism of the MLA enables the impedance matching which is dependent on the slot of antenna at lower frequencies. Again, the MLA with and without slot was tested, the reflection coefficient was better than -2dB over the entire UWB with significant difference between MLA with and without slot. In Figure 5, the MLA without slot – under the angular displacement theory was tested under different low frequencies i.e. 1.3MHz, 2MHz, 2.5MHz, 5MHz. The lower the frequency was confirmed to favor impedance matching.

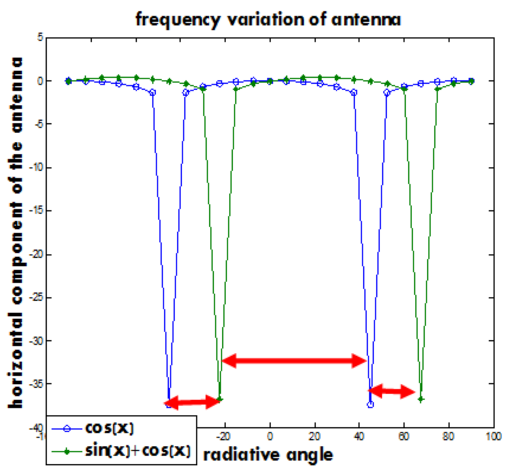

Figure 4. Frequency Testing of MLA with and without Slot

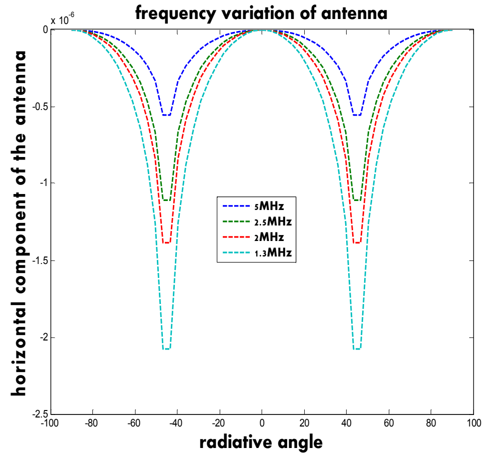

Figure 5. Frequency Tuning of MLA without Slot

5. Conclusion

The MLA has shown additional functionality i.e. UWB by incorporating a varactor diode to the front open port. The radiational angular displacement theory supports the MLA without slot. The MLA covers the entire ultra wide band (UWB) with a reflection coefficient of about -2dB. Therefore MLA can be of greater interest for commercial and military wireless technologies if improved-upon.

References

[1] Unknown, Amplifier for Small Magnetic and Electric Wideband Receiving Antennas Model AAA-1 Rev.1.1-1.9., www.active-antenna.eu. 2010.
[2] Unknown, Wideband Active Small Magnetic Loop Antenna. http://www.lz1aq.signacor.com/docs/wsml/widebandactive-sm-loop-antenna.htm
[3] P Guittienne, E Chevalier, C Hollenstein. Towards an optimal antenna for helicon waves excitation. *J. Appl. Phys.* 2005; 98: 083304.
[4] RL Stenzel, JM Urrutia, KD Strohmaier. Nonlinear electron magneto hydrodynamic physics. VII. Magnetic loop antenna in a field-free plasma. *Physics of Plasmas.* 2009; 16; 022103.
[5] Richard W Ziolkowski, Chia-Ching Lin, ean A Nielsen, Minas H Tanielian, Christopher L Holloway. Design and Experimental Verification of a 3D Magnetic EZ Antenna at 300 MHz. *IEEE Antennas and Wireless Propagation Letters*. 2009; 8: 989-993.
[6] KD Strohmaier, JM Urrutia, RL Stenzel. Nonlinear electron magnetohydrodynamics physics. III. *Electron energization Phys. Plasmas.* 2008; 15**:** 042309.
[7] JM Urrutia, RL Stenzel, KD Strohmaier. Nonlinear electron magnetohydrodynamics physics. IV. *Whistler instabilities Phys. Plasmas.* 2008; 15: 062109.
[8] JM Urrutia, RL Stenzel, KD Strohmaier. Nonlinear electron magnetohydrodynamics physics. I. Whistler spheromaks, mirrors, and field reversed configurations. *Phys. Plasmas*. 2008; 15: 042307.
[9] RW Ziolkowski, A Erentok. Metamaterial-based efficient electrically small antennas. *IEEE Trans. Antennas Propag.*, 2006; 54(7): 2113–2130,.
[10] A Erentok. RW Ziolkowski. An efficient metamaterial-inspired electrically-small antenna. *Microw. Opt. Tech. Lett.*, 2007; 49(6):1287–1290.
[11] Glenn SS. Radiation Efficiency of Electrically Small Multiturn Loop Antennas IEEE Trans Antennas Propagat. 1972; 20(5): 656-657.
[12] Junwei Lv, ZiliChen, Yingsong Li. *Journal of Electromagnetic Application and Analysis*. 2011; 3(8): 123-121.
[13] yang Lu, Yi Huang, Hassan Tariq, Ping Cao. Reducing ground-plane effects on UWB monopole antennas. *IEEE Antennas & Wireless Propagation Letters*. 2011; 10; 147-150.