Investigations of the Sheath Effect on the Resultant Magnetic Field of a Cylindrical Monopole Plasma Antenna

Moses E. EMETERE

Department of Physics, Covenant University Canaan Land, P. M. B 1023, Ota, Nigeria

Abstract The functionality of the plasma antenna has been narrowed to types and brand names only. The physics of its operation has been neglected and has stagnated technological innovations. The magnetic field in the sheath and plasma were investigated. Notable specifications were worked out in the proposed improved cylindrical monopole plasma antenna. The occurrence of femto spin demagnetization was discovered between the duration of switch on and switch off of the antenna. This phenomenon seems transient because magnetization is highest at the switch on/off point.

Keywords: cylindrical monopole plasma antenna, magnetic field, size, Schrödinger, spin

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(Some figures may appear in colour only in the online journal)

1 Introduction

Communication technology, which is now seen as the steering wheel of the recent economy drive, has occasionally been faced with challenges that have made companies keep circulating the same technology in various brand names or devices. For example, the metamorphosis of the loop antenna and the plasma antenna still involves the same technology but in different brand names. The first type of plasma antenna was the ionized gas plasma antenna. Currently, the silicon plasma antenna is in development to support other advanced communication devices, e.g. Wi-Gig-the planned enhancement of Wi-Fi. The loop antennas, on the other hand, have challenges, e.g. poor efficiency and are mainly used as transmitting and receiving antennas at low frequencies. Different types of loop antennas emerged [1,2]. Its greatest success was recorded in solving two out of the fundamental three challenges i.e. small size (in terms of wavelength), efficiency and broadband. This problem was theoretically solved by Uno & Emetere [3] where the basic principles of the loop antenna (i.e. its ability to respond to the magnetic component of an electromagnetic wave and transmit a large magnetic component in the extreme near field) were utilized by generating a Schrödinger equation, which was solved using the Euler-Lagrangian. Parameters in the form of three basic options (mentioned earlier) were tested via simulations, and the results showed a better technology towards solving communicational challenges. Later in the same year, Lv et al. [4] applied the Maxwell-Boltzmann equations to work out a new technology for the cylindrical monopole antenna using the surface wave excitation in a three dimensional structure. Actually, by then, the plasma antenna was not a new concept but not very efficient [4−6]. Although the transmitting loop antenna and the monopole plasma antenna are good for radio frequency (RF) communication applications, the plasma antenna is preferred to the loop antenna because of its good radiation capability [6], reduced thermal noise at higher frequencies and wide application in electronics. The beautiful work of Lv et al. [4] had its shortcoming, i.e. the electrostatic field distribution in the plasma and the effect of the sheath layer inside the antenna were not taken into consideration. The analysis of the effect of the sheath layer on the magnetic field inside the antenna is the objective of this paper. Specifications were suggested for the proposed-improved cylindrical monopole plasma antenna. First, the artificial dielectric effect was used to investigate the wave solution of the sheath [7]. Later, the TOPICA code was introduced by Lancelotti et al. [8] to calculate sheath parameters like the sheath width and the sheath boundary conditions. Crombe et al., [9] introduced the magnetized dielectric model which made use of the COMSOL multi-physics codes. Physics principles were applied to consolidate the proposed model, which was expected to improve the wide application of the monopole plasma antenna in military operations, civil security surveillance, mining work and coordination of activities in construction sites etc.

2 Theoretical background

To solve the shortcoming acknowledged in Lv et al. [4], the fundamental principles of electromagnetic waves were duly acknowledged, i.e. electromagnetic waves carry energy as they propagate through space and the energy can be transferred to objects placed in their path [10,11]. The electric and magnetic field dynamics are analyzed in Fig. 1(a). The plasma is generated by the ionization of electrons by heating the gas (see the glow in the tube in Fig. 1(b)). Once the plasma is formed, a sheath is formed between the electrode and the plasma to maintain the energy and particle balance [12]. Theoretically, the sheath layer decouples the antenna from its plasma and causes power losses in the sheath [9]. The sheath layer inside the antenna was assumed to reverse the electromagnetic signals, as shown in Fig. 1(a). Therefore, the preliminary effect on the electric and magnetic field component of the sheath can be resolved vectorially, as shown in Fig. 1(a). In resolving the electrostatic field, its distribution in the plasma and the effect of the sheath layer inside the antenna were taken into consideration. The time-independent Schrödinger equation was modeled to study the electron dynamics. The time-independent Schrödinger equation is given as

$$\mathrm{i}\hbar\frac{\partial}{\partial t}\psi - \frac{\hbar^2}{2m}\nabla\psi + V\psi = 0. \tag{1}$$

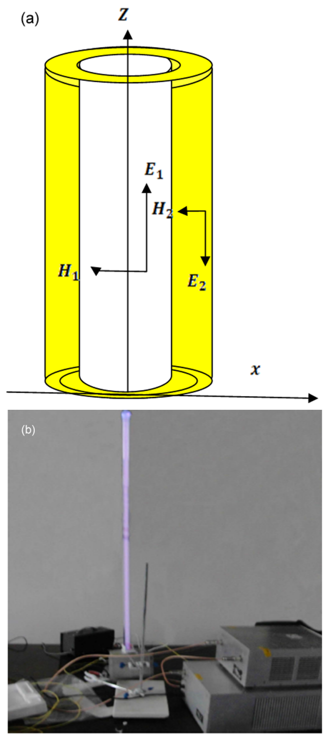

Fig.1 (a) Field analysis in the cylindrical monopole plasma antenna, (b) Cylindrical monopole plasma antenna

The Lagrangian density related to Eq. (1) is given as

$$L_1 = \frac{1}{2}\Big[\left|\frac{\partial\psi}{\partial t}\right|^2 - \frac{\hbar^2}{2m}\left|\nabla\psi\right|^2 - V\left|\psi\right|^2\Big]. \tag{2}$$

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

$$\frac{\partial}{\partial t} \to \frac{\partial}{\partial t} + \mathrm{i}eV, \nabla \to \nabla - \mathrm{i}eA,$$

where $V = V(r,\theta) = V_0 + E_0(\frac{a^2}{r} - r)$, V_0 is a constant on the surface of the conducting cylinder, E_0 is the field and r is the radius of the cylinder.

Eq. (2) transforms into

$$L_1 = \frac{1}{2}\Big[\left|\frac{\partial\psi}{\partial t} + \mathrm{i}e\psi\phi\right|^2 - \frac{\hbar^2}{2m}\left|\nabla\psi - \mathrm{i}eA\psi\right|^2 - V\left|\psi\right|^2\Big]. \tag{3}$$

The cylindrical conductor is accounted for where $r = x$

$$L_1 = \frac{1}{2}\Big[\left|\frac{\partial\psi}{\partial t} + \mathrm{i}e\psi V_0 + \mathrm{i}E_0 e\psi(\frac{a^2}{x} - x)\cos\omega t\right|^2 - \frac{\hbar^2}{2m}\left|\nabla\psi - \mathrm{i}eA\psi\right|^2 - V\left|\psi\right|^2\Big]. \tag{4}$$

Applying the solution of the standing wave $\psi(x,t) = \mathrm{e}^{iS(x,t)}T(x,t)$ in Eq. (4), where E, B: $R^3XR \to R$, the Lagrangian density takes the form of

$$L_1 = \frac{1}{2}\Big\{E_{rt}^2 - | E_z |^2 - \Big[\frac{\hbar^2}{2m} | B_r - eA |^2 + | B_z + V_0 e |^2 - (| B_z - E_0 e(\frac{a^2}{x} - x) |^2 - | B_z |) + 2E_0 V_0 e^2\Big] E_r^2\Big\}. \tag{5}$$

We considered the Lagrangian density of the particle electromagnetic E-H field of the circular monopole plasma antenna as

$$L_0 = \frac{1}{8\pi}(| E_1 |^2 - | E_2 |^2 - | H_1 |^2 - | H_2 |^2), \tag{6}$$

where the electric and magnetic values were adapted from Glenn [13] and restructured into the circular monopole plasma antenna [14]

$$E_1(a,z) = (\beta E_r(a,z)e_r + E_z(a,z)e_z)e^{-j\beta r}\sin\theta, \tag{7}$$

$$E_2(a,z) = (\beta E_r(a,z)e_{r1} + E_z(a,z)e_{z1})e^{-j\beta r}\cos\theta, \tag{8}$$

$$H_1(a,z) = (\beta B_r(a,z)f_r + B_z(a,z)f_z)e^{-j\beta r}\sin\theta, \tag{9}$$

$$H_2(a,z) = (\beta B_r(a,z)f_{r1} + B_z(a,z)f_{z1})e^{-j\beta r}\cos\theta, \tag{10}$$

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 Eq. (7) are

$$\begin{cases} E_1(a,0) = E_\alpha(z) \\ E_1(\infty,z) = 0 \\ E_1(a,\chi) = E_\alpha(z)\cdot\alpha \\ E_1(a,\infty) = 0 \end{cases}. \tag{11}$$

The boundary conditions for Eq. (8) are

$$\begin{cases} E_2(a,0) = E_\gamma(z) \\ E_2(\infty, z) = 0 \\ E_2(a,\chi) = E_\gamma(z)\cdot\gamma \\ E_2(a,\infty) = 0 \end{cases}. \tag{12}$$

The boundary conditions for Eq. (9) are

$$\begin{cases} B_1(a,0) = B_\vartheta(z) \\ B_1(\infty, z) = 0 \\ B_1(a,\chi) = B_\vartheta(z)\cdot\vartheta \\ B_1(a,\infty) = 0 \end{cases}. \tag{13}$$

The boundary conditions for Eq. (10) are

$$\begin{cases} B_2(a,0) = B_\sigma(z) \\ B_2(\infty, z) = 0 \\ B_2(a,\chi) = B_\sigma(z)\cdot\sigma \\ B_2(a,\infty) = 0 \end{cases}, \tag{14}$$

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; χ is the length of plasma antenna; β is the frequency of excited power; j is the radio frequency current; γ represents the radius or horizontal component of the antenna; z represents the vertical component of the antenna; m represents the magnitude of the electrons; ξ 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; and 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

$$D = \int\int L_1 + L_0. \tag{15}$$

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

$$E_{rt} + \big[\frac{\hbar^2}{2m} \mid B_r - eA \mid^2 + \mid B_z + V_0 e \mid^2$$

$$-\big(\mid B_z - E_0 e(\frac{a^2}{r} - r) \mid^2 - \mid B_z \mid \big) + 2E_0 V_0 e^2 + \beta e_r\big] E_r$$

$$= \beta E_r e_r e^{-j\beta r}(\sin\theta + \cos\theta), \tag{16}$$

$$\frac{\partial}{\partial t}\big[(B_z + V_0 e)E_r^2\big] - \frac{\partial}{\partial t}\big[(B_z + E_0 e(\frac{a^2}{x} - x))E_r^2\big] - \frac{1}{2}\frac{\partial B_z}{\partial t} = 0, \tag{17}$$

$$\frac{\hbar^2}{2m}E_r^2\frac{\partial}{\partial t}(B_r - eA) = \beta B_r f_r e^{-j\beta r}(\sin\theta + \cos\theta), \tag{18}$$

$$\frac{\partial}{\partial t}E_z = \frac{\partial}{\partial t}E_z e_z e^{j\beta r}(\sin\theta + \cos\theta), \tag{19}$$

$$2 \mid B_z - E_0 e(\frac{a^2}{r} - r) \mid E_r E_0 e(\frac{a^2}{r^2} - 1)$$

$$= \frac{j\beta}{8\pi}\big[\frac{E_r e_r}{r}(\sin\theta + \cos\theta) + (\frac{2B_r f_r}{r}(\sin\theta + \cos\theta)\big]\beta e^{-j\beta r}, \tag{20}$$

$$\frac{1}{8\pi}\big[\beta E_r(a,z)e_r + \beta B_r(a,z)f_r + E_z(a,z)e_z$$

$$+B_z(a,z)f_z][\cos\theta - \sin\theta\big] = 0, \tag{21}$$

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

$$-\frac{2}{z}e^{-j\beta r}\cos\theta\big(B_z(a,z)f_z + E_z(a,z)e_z\big)\big] = 0. \tag{22}$$

3 Methodology

A virtual laboratory made up of the MATLAB environment was adopted to test run the technological interpretation of Eq. (16) on a theoretical cylindrical monopole plasma antenna. First, some analytical approximations were employed to avoid cumbersome analysis of results. The solution of the standing waves in the cylindrical monopole plasma antenna is of the form

$$E_r = E_\alpha(z)\cdot\alpha, B_r = B_\vartheta(z)\cdot\vartheta = \beta r,$$

$$a = 1, \phi = \phi(r,\theta), \beta \in R,$$

In this paper, Eq. (16) is considered because of the objective of the paper, as stated in the introductory part. The terminologies from Eq. (16) are the potential energy possessed by the electrons, the horizontal surface magnetic field of the plasma, the magnetic field potential within the cylindrical monopole plasma antenna, the spin properties generated within the plasma antenna and the reflectivity factor, which enables the transmission and reception of the signal of a plasma antenna [17]. The terminologies are analyzed in a simulating format to interpret its characteristics.

4 Results and discussion

Fig. 1 confirmed that the cylindrical monopole plasma antenna (like the loop antennas) possess the ability to respond to the magnetic component of an electromagnetic wave and transmit a large magnetic component in the extremely near field. The magnetic field interactions between the plasma and the sheath were investigated in Fig. 2. The resultant magnetic field was higher than the magnetic fields in the sheath and the plasma. The magnetic field in the sheath is higher than that in the plasma at a lower angular shift. This may have its effect on the general functionality of the plasma antenna. Therefore, to improve the functionality of the plasma antenna, the vector redirection of the magnetic field of the sheath becomes paramount. Also, the functionality could be increased by arranging the plasma system (through a process called nesting) so that the angular shift of the sheath is high enough to produce a lower effect on the resultant magnetic fields. The ratio of the surface conductivity to the attenuation was calculated as $\frac{V_0}{\sigma} \approx -80$. This idea forms the basis for further analysis. Both magnetic fields (in the sheath and plasma) attained their maximum at $\theta = 45°$ within the nest. These results are validated by their conformity with experimental results [15].

The effect of the attenuation factor on improving the functionality of the antenna was investigated graphically, as shown in Fig. 3. The lower attenuation factor favored the improved functionality of the plasma antenna. This idea supports the fundamental concept of antennas and is validated experimentally, as shown in Fig. 3(b). Several power sources, i.e. 120 V AC/4.5 V DC source, 240 V AC/9.0 V DC source and 240 V AC/12.0 V DC source, were theoretically used to test the functionality of the plasma antenna, as shown in Fig. 4. An increased power source supported the proposed-improved functionality. Although a 240 V AC/9 V power source is preferred practically, the 240 V AC/12.0 V DC source would support the nesting of high and low frequency plasma antenna so that the high angular shift of the sheath would be maintained in the operational duration. The size of the antenna was seen to support the assumed power source. This idea is experimentally validated in Fig. 4 [18].

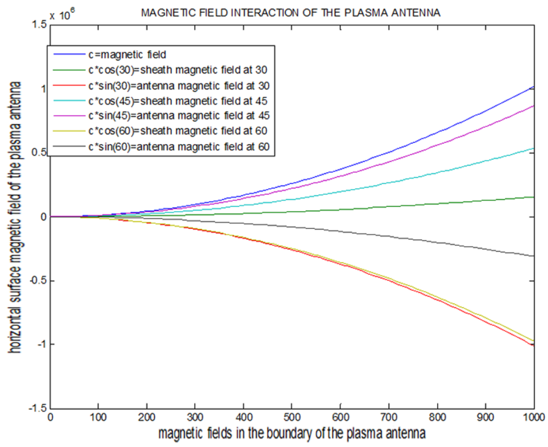

Fig.2 Magnetic fields of plasma and sheath under various angular shift

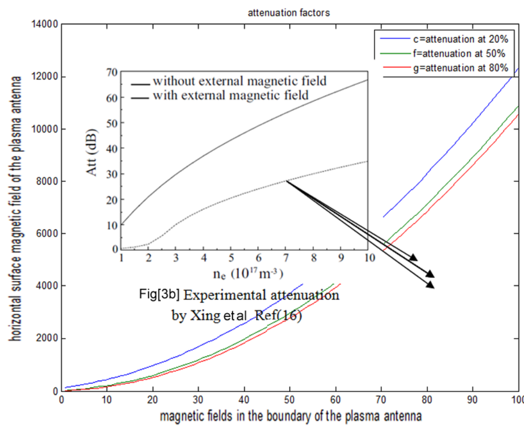

Fig.3 Effects of attenuation factor on surface magnetization of sheath

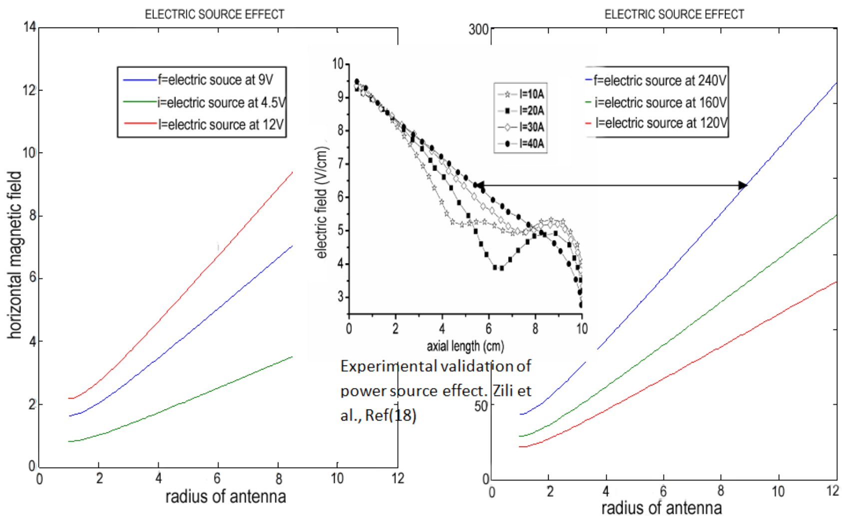

Fig.4 Power source effect on the functionality of the plasma antenna

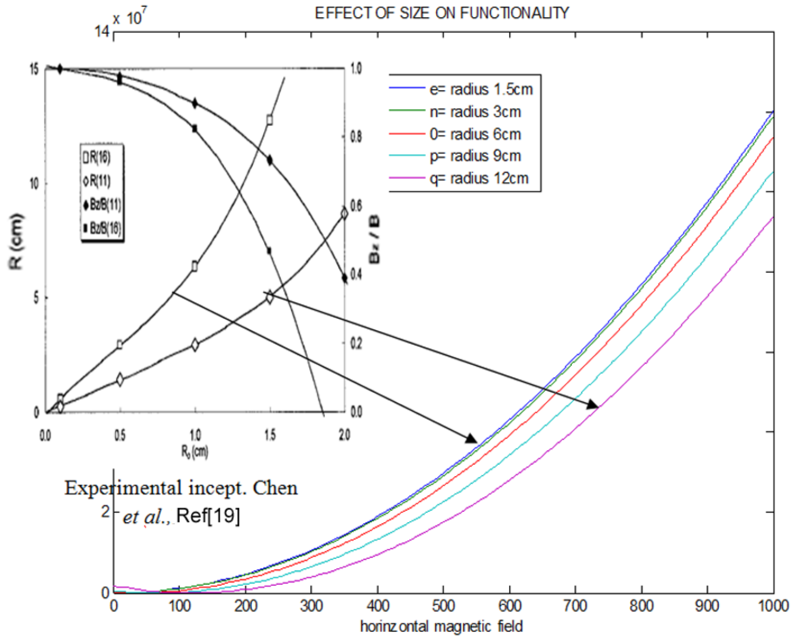

Fig.5 Effect of size of the plasma antenna on its functionality

The effect of the size on the plasma and sheath was investigated in Fig. 5. The lower radius of the cylindrical monopole plasma antenna supported the proposed improved plasma antenna. The size of the monopole cylindrical reduces the effects of the sheath on the general performance of the plasma antenna. This assertion may be inaccurate because it also supports the magnetic component of the sheath, as shown in Fig. 5. The spin properties were investigated to strengthen the accuracy of the results. To do this, we assumed an electric permeability and radio frequency current of the antenna to be equal to one. This idea was proposed to investigate near-ground state spin behavior.

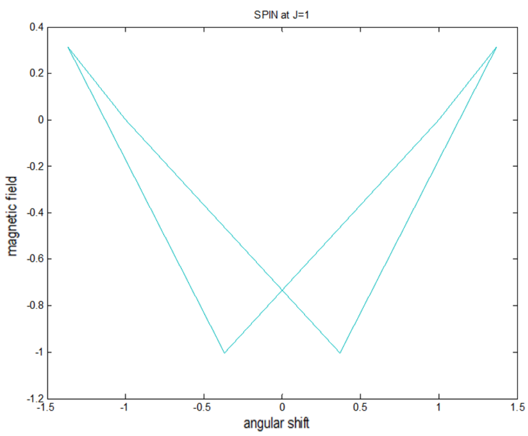

Fig.6 Spin state at near-ground level

The spin system under a very low magnetic field component of the sheath and angular shift (as shown in Fig. 6) revealed a fluctuating behavior which supported the femto spin demagnetization [15] on the sheath. We propose that this occurrence is responsible for the power loss. Therefore, the dynamics of femto spin demagnetization in the plasma antenna depends on the ionized gas within the tube. Also from the graph (Fig. 6), the femto spin demagnetization seems transient because at the point of switching on and off of the plasma antenna, the magnetic field components of the sheath are at maximum.

5 Conclusion

The theoretical prediction of the construction of an efficient cylindrical monopole plasma antenna was successful. The power source supported the 240 V AC/12 V DC source. At this rating, the production of the sheath is controlled with respect to the size of the antenna, attenuation factor and angular shift during nesting at high and low frequencies. The ratio of the surface conductivity to the attenuation was calculated as $\frac{V_0}{\sigma} \approx -80$ when both magnetic fields (of the sheath and plasma) were maximum at $\theta = 45°$. The femto spin demagnetization was seen to occur when the plasma antenna was in operation. This was reported to be the major source of power loss. At the point of switching on/off, the magnetic component is at its maximum.

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E-mail address of Moses E. EMETERE:
moses.emetere@covenantuniversity.edu.ng