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LOADED WIRE ANTENNA AS EMI SENSOR

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Abstract—This paper describes the performance of different loaded wire antennas (e.g., inverted L, T, I and C-shaped antennas) as electromagnetic interference (EMI) sensors. Loaded wire antennas in transmitting mode are widely used for low frequency communication. However, while using these antennas as EMI sensors, the extra loading is likely to introduce the reception of cross-polarized component of incident electric field and investigation on this has not yet been performed. This paper highlights the results of the initial investigation on the performance of these loaded antennas as EMI sensors in terms of the Antenna Factor for the desired and cross-polarized component of incident electric field. The Method of Moments with Pulse basis function and Point-matching technique has been used to evaluate the current distribution on the antenna surface and hence the Antenna Factor.

1. INTRODUCTION

Wire antennas are widely used as transmitting antenna and as sensor for electromagnetic interference (EMI) measurements. The term "wire" refers to metallic, highly conducting wire or wire-like structures. At low frequencies, the electrical length of the antenna to achieve self-resonance becomes very large. For this case, proper loading of the antenna is employed to reduce the resonant length of the antenna. Other researchers had already reported their studies on the loaded antennas (e.g., inverted L, T, I and C-shaped antennas) in transmitting mode [1]. Also, the broadband performance of a dipole loaded with circular disc had been studied as EMI sensor [2]. However, the extra loading is likely to introduce the reception of cross-polarized component of incident electric field that may degrade the performance of the sensor. Hence, while using these loaded systems as sensors, the cross-polarization characteristics must be known. The author has not noticed any appreciable work on this area and concentrated on the characterization of the loaded antennas as EMI sensors in terms of the Antenna Factor for the desired and cross-polarized incident electric field.

For EMI measurement it is required to determine the field strength at the point of measurement using a sensor. To use the sensor for this purpose, calibration data is required relating the electric field at the aperture of the receiving antenna to the voltage at the 50 ohms matched detector. The most common performance descriptor of EMI sensors is the Antenna Factor. The ratio of the incident electric field on the surface of the sensor to the received voltage at the antenna terminal when terminated with a 50 ohm load is known as the Antenna Factor [3]. Here, the Method of Moments with Pulse basis function and Point-matching has been used to evaluate the current distribution on the antenna surface and subsequently calculate the quantities of interest i.e. Antenna Factor in receiving mode [4]. For the validation of the theory, the results for input impedance of an inverted L-shaped antenna were compared with the results available using commercial software like IE3D, a Method of Moment-based electromagnetic simulation and optimization package by Zeland Software, Inc. The theoretical Antenna Factor of a broadband dipole (i.e., dipole top and bottom-loaded with circular disc) was compared with the experimental values available in literature [2].

2. THEORETICAL ANALYSIS

This paper presents the theoretical analysis of loaded wire antennas as EMI sensors. To solve antenna problems, it is a common practice to consider that the antenna and its load in the receiving mode parallels that for the transmitting mode. However, a closer look to the problem will reveal that this is not true and the transmitting and receiving impedance properties are not reciprocal. A transmitting antenna produces a continuous spectrum of plane waves whereas the receiving antenna, which is being analyzed here, is illuminated by a single plane wave coming from a particular direction i.e. an impulsive spectrum and not a continuous spectrum of incoming plane wave.

2.1. Boundary Condition

A wire antenna is considered to be placed in free space along the z-axis of the Cartesian (x, y, z) coordinate system. The inclined arm is considered to be making an angle θ_1 with the axis of the antenna element (Figure 1). To simplify the problem we first consider the inclined arm to be placed in the y-z plane with $x = 0$. We consider an incident electric field of 1 volt/meter impinging on the surface of a perfectly conducting wire. The assumptions made for the analysis are given below:

- The wire is perfectly conducting. For wires of good conducting material the assumption of a surface current is approximately true and leads to no complications. The infinite conductivity causes the total tangential electric field to vanish on the surface of the wire.
- The wire radius is taken to be much less than the wavelength so it can be assumed that only z-directed currents are present.

In general, the incident unit plane wave at the scatterer is expressed as follows

$$E^i = u_1 e^{-jk_t \cdot r_n} \tag{1}$$

For the simplification of the problem, the incident wave is considered to be propagating along the negative y-axis with z-directed electric field. This incident field induces linear current densities on the surface of the wires which reradiate and produce the scattered electric field, E^S. It should be noted that a general method has been used here. In no way it is limited to an incoming incident wave having the electric field in the z-direction. An incident incoming wave with arbitrarily directed electric field can be split up into corresponding x, y, and z components and the boundary condition of $E^{total}_{tan} = 0$ is applied over the conducting wire.

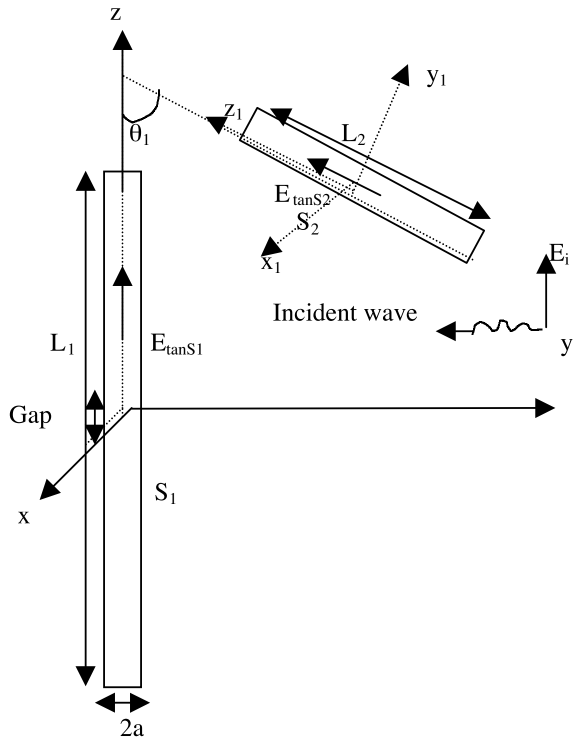

Figure 1. Plane wave incidence on wire antenna with parasitic element.

The surface of the antenna is defined as S_1 and that of the other element is defined as S_2. The total electric field contains the components of incident electric field E^i and scattered electric field E^s. The total tangential fields on S_1 and S_2 are written as follows

$$E_{tan_{S_1}} = E^i_{S_1} + E^S tan_{S_1,S_1} + E^S tan_{S_1,S_2} = 0 \quad (2a)$$

$$E_{tan_{S_2}} = E^i_{S_2} + E^S tan_{S_2,S_1} + E^S tan_{S_2,S_2} = 0 \quad (2b)$$

The terms of equation (2a) and (2b) are defined as below

$E_{tan_{S_1}}$, $E_{tan_{S_2}}$ — Total tangential electric field on S_1 and S_2 respectively.

$E^i_{S_1}$, $E^i_{S_1}$ — Incident electric field on S_1 and S_2respectively.

$E^S_{tan_{S_1,S_1}}$, $E^S_{tan_{S_1,S_2}}$ — Tangential component of scattered electric field on S_1 due to current distribution on S_1 and S_2 respectively.

$E^S_{tan_{S_2,S_1}}$, $E^S_{tan_{S_2,S_2}}$ — Tangential component of scattered electric field on S_2 due to source on S_1 and S_2 respectively.

The basic equations of magnetic and electric field used for the evaluation of the scattered electric field components on the surface of the wires are written as follows

$$\vec{H} = \frac{1}{\mu}\vec{\nabla} \times \vec{A} \tag{3}$$

$$\vec{E} = \frac{1}{j\omega\varepsilon}\vec{\nabla} \times \vec{H} \tag{4}$$

Here A is the magnetic vector potential which is expressed in terms of the current density induced on the surface of the wire

$$A = \frac{\mu}{4\pi}\int\int J\frac{e^{-jkR}}{R}ds' \tag{5}$$

For thin wire, the current is considered to be flowing only in the direction of the wire axes. Using equation (3)–(4), the field components (considering the axial current only) are evaluated as follows

$$\left.\begin{aligned} H_x &= \frac{1}{\mu}\frac{\partial A_z}{\partial y} \\ H_y &= -\frac{1}{\mu}\frac{\partial A_z}{\partial x} \\ H_z &= 0 \end{aligned}\right\} \tag{6}$$

$$\left.\begin{aligned} E_x &= \frac{1}{j\omega\varepsilon}\frac{\partial H_y}{\partial z} \\ E_y &= \frac{1}{j\omega\varepsilon}\frac{\partial H_x}{\partial z} \\ E_z &= \frac{1}{j\omega\varepsilon}\left(\frac{\partial H_y}{\partial x} - \frac{\partial H_x}{\partial y}\right) \end{aligned}\right\} \tag{7}$$

Equation (7) shows that for a z-directed current, the scattered electric field has non-zero x, y and z-components.

To evaluate the scattered electric field due to the parasitic element, it is convenient to define a new rectangular coordinate system (x_1, y_1, z_1) with its origin at the origin of the element and its z-axis parallel to the axis of that element (Figure 1).

Applying the boundary condition on the wire elements, the z-directed electric field components for equation (2a) are written as follows

$$\begin{aligned} E^i_{S_1} &= E^i_z \\ E^S_{tan_{S_1,S_1}} &= E^S_{z_{S_1,S_1}} \\ E^S_{tan_{S_1,S_2}} &= E^S_{z_{1_{S_1,S_2}}} cos\theta_1 + E^S_{y_{1_{S_1,S_2}}} sin\theta_1 \end{aligned} \tag{8}$$

The field components are defined as follows

$E^S_{z_{S_1,S_1}}$, $E^S_{z_{S_1,S_2}}$ — z-component of scattered electric field on S_1 due to current distribution on S_1 and S_2 resepctively.

$E^S_{y_{1_{S_1,S_2}}}$ — y-component of scattered electric field on S_1 due to current distribution on S_2.

θ_1 is the angle of inclination of the parasitic element with the axis of the main arm.

For equation (2b) the field components are written as follows

$$\left.\begin{aligned} E^i_{S_2} &= E^i_z cos\theta_1 \\ E_{tan_{S_2,S_1}} &= E^S_{z_{S_2,S_1}} cos\theta_1 - E^S y_{S_2,S_1} sin\theta_1 \\ E_{tan_{S_2,S_2}} &= E^S_{z_{1_{S_2,S_2}}} \end{aligned}\right\} \tag{9}$$

Here

$E^S_{z_{S_2,S_1}}$, $E^S_{z_{1_{S_2,S_2}}}$ — z-component of scattered electric field on S_2 due to current distribution on S_1 and S_2 resepctively.

$E^S_{y_{S_2,S_1}}$ — y-component of scattered electric field on S_2 due to current distribution on S_1.

The same technique can be extended for different loaded antennas with the parasitic element/elements in electrical contact to the main arm (e.g., inverted L, T, I, C antennas, broadband dipole i.e., a dipole loaded with circular disc) (Figure 2). Each circular disc of the broadband dipole is replaced by a large number of wires placed in the x-y plane and perpendicular to z-axis. In order to enforce the boundary condition on the surface of each element, the expressions for the tangential component of the electric field on each element have been evaluated in terms of the corresponding x, y, z components of scattered and incident electric field.

For a wire structure with interconnected wires, the continuity equations are to be satisfied at element interconnections [5]. For two

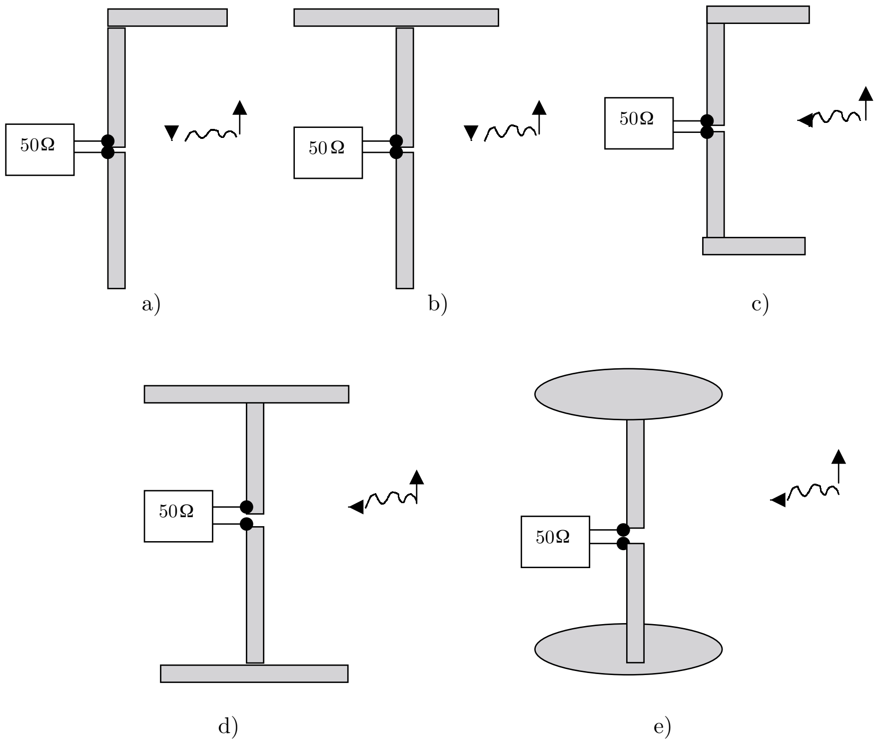

Figure 2. a) Inverted-L shaped sensor. b) T-shaped sensor. c) C-shaped sensor. d) I-shaped sensor. e) Broadband dipole.

wires connected with their second ends, the continuity equation for the interconnecting node is written in the form

$$I^{(1)}(s = L) + I^{(2)}(s = L) = 0 \tag{10}$$

where $I^{(1)}(s)$ and $I^{(2)}(s)$ are the total currents along the first and second wire, respectively.

The expressions for the scattered electric field are available in the literature [6] and hence are not repeated here. Putting the simplified expression for the scattered electric field, equation (2a)–(2b) has been transformed to an integral equation involving the unknowns used to describe the current distribution on the surface of the wire and the known incident electric field on the other side of the equation.

2.2. Matrix Solution

Here the Method of Moments with Pulse expansion function and Point-matching technique has been used [7]. The loaded antenna is considered to be divided into N number of segments each with constant current density. For a loaded antenna with J number of junctions each connecting M wire ends, the number of unknowns is reduced by $J*(M-1)$. Enforcement of the boundary condition leads to $(N-J*(m-1))$ number of equations are achieved with $(N-J*(m-1))$ number of unknowns. This is transformed to matrix equation by applying the point matching technique as follows

$$\left[V^i\right] = \left[Z\right]\left[I\right] \tag{11}$$

Here $[Z]$ matrix is a square matrix of dimension $[N-J*(m-1)] \times [N-J*(m-1)]$ and depend on the geometry of the problem and $[V^i]$ is the voltage excitation matrix of dimension $[N-J*(m-1)]$. From equation (11) the current matrix is solved as follows

$$\left[I\right] = \left[Z\right]^{-1}\left[V^i\right] \tag{12}$$

The current distribution on the surface of the wires are solved by approximating the integrals as the sum of integrals over N small segments (Figure 3) where the main arm is divided into N_1 subsections and the load arm into N_2 subsections.

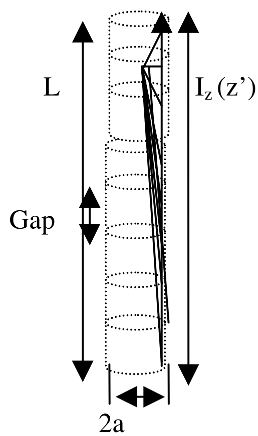

Figure 3. Dipole segmentation and its equivalent current.

The voltage matrix depends on the known incident field arising from either a source located on the wire (transmitting case) or from a source located at a large distance (receiving case).

2.3. Input Impedance

Once the current distribution is found, the input impedance is determined by the ratio of the input voltage to current i.e.

$$Z_{in} = \frac{V_{in}}{I_{in}} \tag{13}$$

2.4. Antenna Factor

The ratio of the incident electric field on the surface of the sensor to the received voltage at the antenna terminal when terminated by 50 ohms load is known as Antenna Factor.

$$Antenna\ Factor = \frac{Incident\ electric\ field\ (E_i)}{Received\ voltage\ (V)} \tag{14}$$

The Thevenin's equivalent circuit diagram of an EMI sensor is shown in Figure 4. The receiving antenna is replaced by an equivalent open circuit voltage at the two terminals of the antenna and its impedance. Generally the receiver (e.g., spectrum analyzer) impedance is considered as 50 ohm. The open circuit voltage V_{oc} at the gap of the antenna is related to the incident electric field on the antenna surface. The incident electric field E^i over each point on the wire antenna is uniform, whereas the impressed currents so produced on the wire is non-uniform. So to make an average, a crude approximation is made by introducing the effective length of the antenna, which when multiplied by the feeder current I_{sc}, equals to the integration of the impressed current over the length of the wire. Accordingly, the effective length is written as follows

$$l_{effective} = \frac{\int_{-1/2}^{1/2} I.dl}{I_{sc}} \tag{15}$$

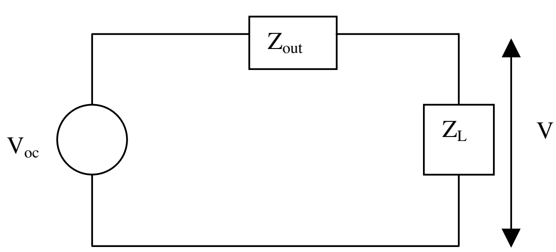

Figure 4. Equivalent circuit diagram of a sensor.

The open circuit voltage V_{oc} at the end terminals is written as follows

$$V_{oc} = \vec{E}_i . \vec{l}_{effective} \tag{16}$$

The integral in equation (15) is approximated by the summation over N subsections

$$l_{effective} = \frac{\sum_{n=1}^{N} I_n . \Delta_n}{I_{sc}} \tag{17}$$

The output impedance of the antenna is written as follows

$$Z_{out} = \frac{V_{oc}}{I_{sc}} \tag{18}$$

From the equivalent circuit diagram the voltage to the receiver is achieved as follows

$$V = \frac{Z_L}{Z_L + Z_{out}} V_{oc} \tag{19}$$

Generally Z_L i.e. impedance of the detector (e.g. spectrum analyzer) is considered as 50 ohms. To avoid the inaccuracy due to the approximations made in the evaluation of the open-circuited voltage in terms of the effective length of the antenna, the concept of the concentrated load is used later. In this method the load connected with the antenna is considered to be concentrated within the gap of the sensor. Hence, equation (11) is modified as follows

$$\left[V^i\right] = \left[Z'\right]\left[I\right] \tag{20}$$

with $[Z'] = [Z] + [Z_C]$ where $[Z_C]$ is a diagonal matrix with only one non-zero diagonal element. Solving equation (20) following the same method, will give the current through the load, which when multiplied by the load will directly give the output voltage.

2.5. Cross Polarization Effect

Due to the presence of the top and bottom loading, loaded sensors (Figure 2a–2d) are likely to suffer from cross polarization pick-up. Hence while dealing with loaded antennas, the cross polarization characteristics of the antennas should be known. Here these studies have been performed in terms of the Antenna Factor of these antennas for the desired and cross-polarized electric field (Figure 5a–5b).

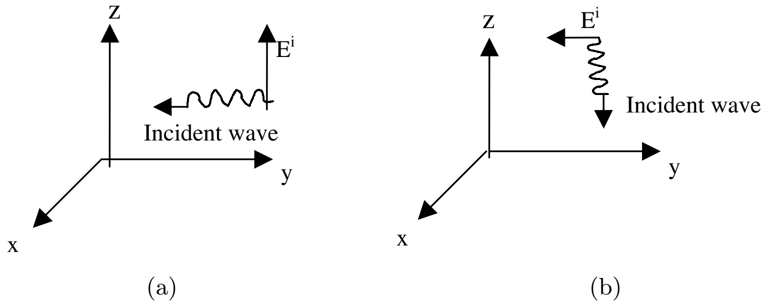

Figure 5. a) Desired polarization of incident field. b) Cross polarization of incident field.

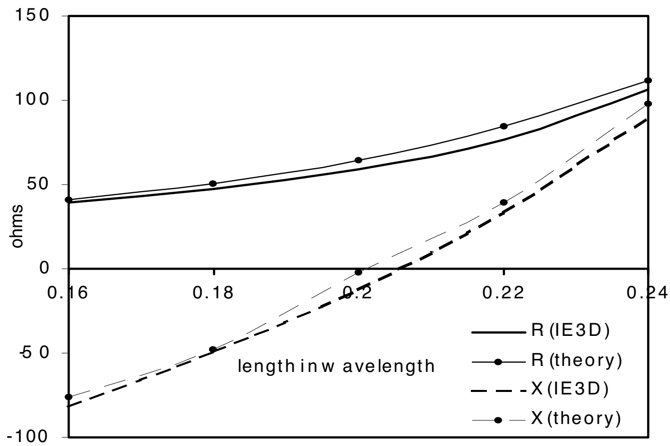

Figure 6. Input impedance vs. length of load arm to achieve resonance of inverted L-shaped antenna with main arm length=0.3λ; radius=0.004λ.

3. RESULTS

The results are achieved as the output of software written in FORTRAN 77 and run on a Pentium 350 MHz processor based personal computer running the LINUX operating system.

For the validation of the theory, the input impedance values of an inverted L antenna with main arm length = 0.3λ and radius=0.004λ has been compared with the simulated results a commercial Electromagnetic Simulator IE3D by Zeland Software, Inc. (Figure 6).

Investigations have been extended to obtain the load arm lengths for various main arm lengths to obtain the resonant effect and corresponding resonance resistance of inverted L, T, I and C-antenna (Figure 7a–7b). The results are achieved as the output of huge computation time and efforts. These data for the main arm length and the corresponding load arm length to achieve resonance in the transmitting mode have been used to study the Antenna Factor of these antennas in receiving mode. The Antenna Factors of different loaded sensors for the desired and also for the cross-polarized incident electric field is shown in Figure 8–11. The height reduction for different loaded antennas with the associated Antenna Factor and cross polarization isolation are presented in Table 1. The theory has been verified with the experimental results (Figure 12) for the broadband dipole available in literature [2]. The dimensions of different parts of the antenna are given below:

- Length of the central part of broadband dipole antenna=0.54 m;
- Radius of the central part of the dipole=2.244 cm;
- Radius of the capacitive hats=8.9 cm;
- Number of wires used to represent each circular disc=12.

4. DISCUSSIONS

In this paper, extensive analysis has been performed on different loaded wire antennas in receiving mode as EMI sensors. Though the theory applied is the extension of the classical theory, a genuine effort has been made to make a case study of different loaded configuration to get lower value of Antenna Factor in a frequency band and sometimes at the cost of cross-polarization effect.

The very good matching in the theoretical data of the input impedance for an inverted L antenna to that achieved using the commercial software IE3D (Figure 6) proves the validation of the theory. Also the correctness of the theory for the loaded sensor has been proved from the good match of the theoretical results to available experimental data (Figure 12).

Studies show that the Antenna Factor for the desired polarization for all these reduced height sensors did not show significant change from the corresponding Antenna Factor of unloaded dipole of resonant length (which is usually higher in length than the loaded length). The advantage has been achieved in terms of the reduction of main arm. From the study of the cross polarization pick up and cross polarization isolation the following points are noticed:

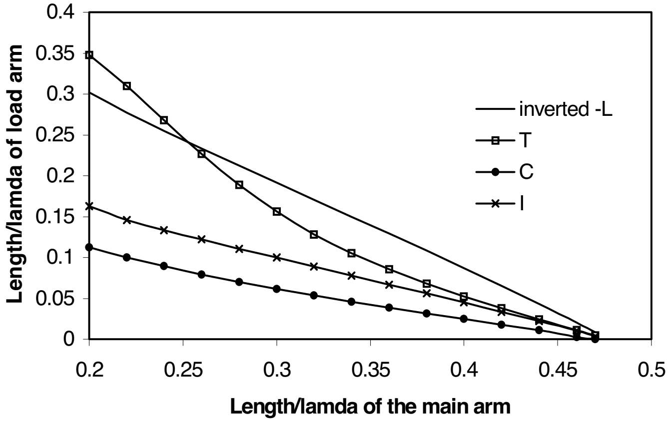

Figure 7a. Length in wavelengths of the load arm versus corresponding length of the main arm of loaded antennas.

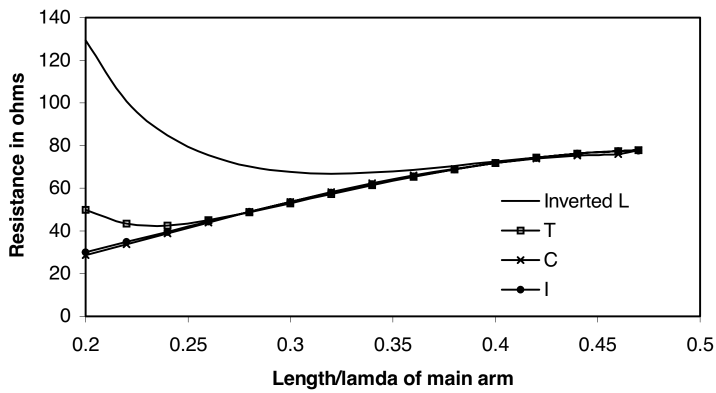

Figure 7b. Resonance resistance in ohms versus corresponding length of the main arm of loaded antennas.

The plot of Antenna Factor of the inverted L-shaped antenna (Figure 8) shows a cross polarization isolation of better than $0.8\,\mathrm{dBm}^{-1}$.

The cross polarization isolation for T-shaped antenna (Figure 9) is found as better than $73.4\,\mathrm{dBm}^{-1}$.

The plot of Antenna Factor vs. wavelength in Figure 10 shows that the isolation for I-shaped antenna is better than $21.3\,\mathrm{dBm}^{-1}$.

The cross polarization isolation for C-shaped antenna (Figure 11)

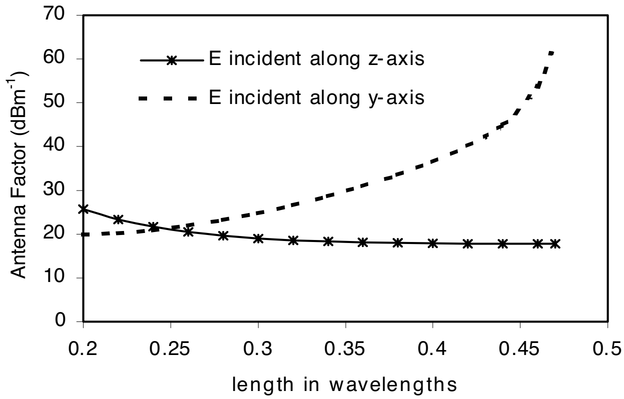

Figure 8. Antenna factor vs. resonant length of inverted L-shaped antenna.

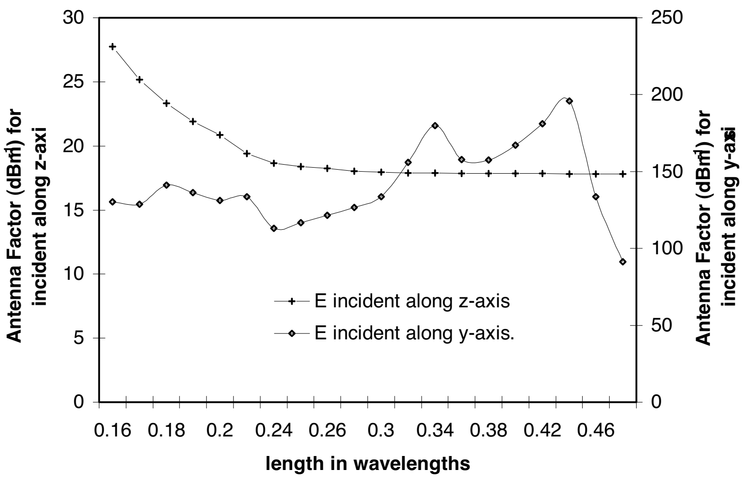

Figure 9. Antenna factor (dBm^{-1}) vs. length in wavelengths of T-shaped antenna.

is found as better than $0.22\,dBm^{-1}$.

For a good receiver the cross polarization pick up of the antenna is expected to be minimum. Hence the greater the value of cross polarization isolation, the better is the performance of the antenna as sensor. From the study of different loaded antennas it is seen that the cross polarization isolation of a T-shaped antenna is maximum i.e., the T-shaped resonant antenna is found as a better receiver/sensor

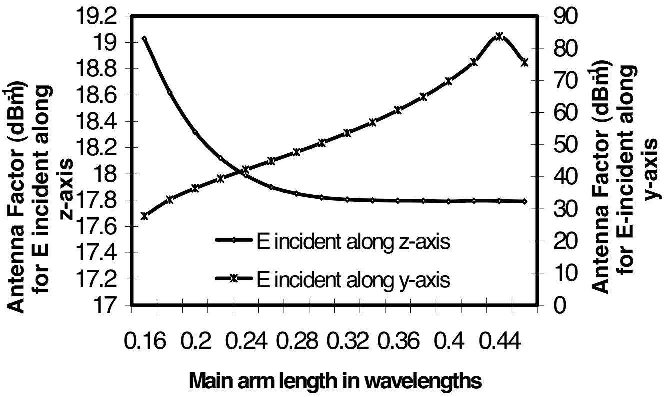

Figure 10. Antenna factor (dBm^{-1}) vs. length in wavelengths of I-shaped antenna.

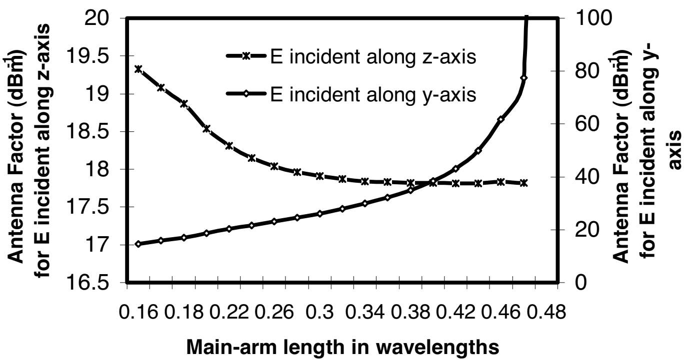

Figure 11. Antenna factor (dBm^{-1}) vs. length in wavelengths of C-shaped antenna.

compared to the inverted L, I and C-antennas/sensors.

Table 1 shows that for the minimum main-arm length (0.16λ), the Antenna Factor of the I-shaped antenna is the lowest ($19.03\,\text{dBm}^{-1}$) whereas, the cross-polarization isolation is maximum ($102.68\,\text{dBm}^{-1}$) for T-shaped antenna. Hence in terms of the Antenna Factor the I-shaped antenna behaves as a better sensor and in terms of the cross polarization isolation, the T-shaped antenna is considered as a better sensor compared to the other loaded structures. However, as the best compromise the T-shaped antenna may be considered as an optimum choice because of its low Antenna Factor and high cross-polarization isolation.

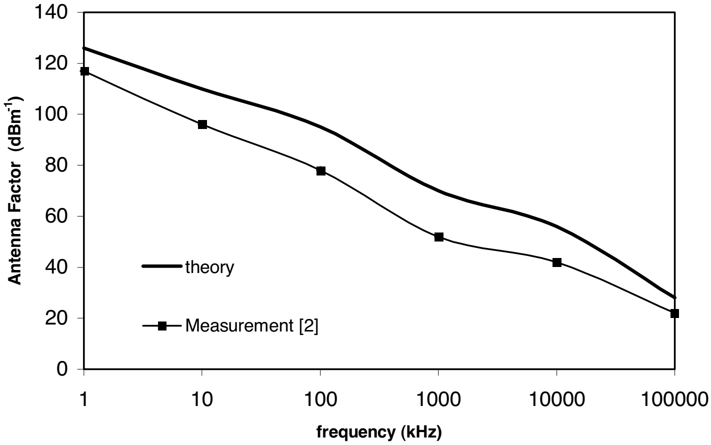

Figure 12. Antenna Factor vs. frequency plot of a broadband dipole.

Table 1. Comparison of the main-arm length, Antenna Factor and cross-polarization isolation of different loaded structures.

Main-arm length in wavelengths *	Antenna Factor (dBm^{-1})				Cross polarization isolation ($dB\,m^{-1}$)			
	Inverted L	T	I	C	Inverted L	T	I	C
0.16		27.73	19.03	19.33		102.68	8.77	- 4.78 **
0.2	25.68	20.85	18.32	18.54	- 5.72 **	110.29	18.08	0.22
0.24	21.69	18.63	17.99	18.15	- 0.8 **	94.51	24.23	3.51
0.28	19.65	18.04	17.85	17.96	3.57	108.53	29.83	6.58
0.32	18.6	17.89	17.81	17.87	7.99	138.15	35.83	9.99
0.36	18.11	17.86	17.79	17.83	12.81	139.98	42.88	14.36
0.4	17.9	17.84	17.79	17.82	18.61	149.46	52.0	20.64
0.44	17.83	17.83	17.79	17.81	27.05	178.06	65.90	32.03
0.46	17.82	17.82	17.79	17.83	35.85	115.91	57.84	43.97
0.47	17.82	17.82		17.82	46.13	73.39		59.55
0.4776 ***	17.78 ***				400 ***			

* In each case the load arm length has been calculated for resonance in transmitting mode using Figure 7a – 7b.

** The negative value of cross-polarization isolation denotes that the Antenna Factor for the desired polarization is greater than that for the cross-polarized electric field.

*** Dipole antenna without any loading.

5. CONCLUSION

It can be concluded from this work that the height of the sensors can be appreciably reduced by the introduction of the load arms without making any major compromise in the performance in terms of cross polarization isolation. However, it has been already noticed from the work published earlier [4] that the radiation impedance of transmitting antenna and output impedance of receiving antenna are different. This is because the two cases are not reciprocal. To apply the reciprocity in receiving case, it will be required to illuminate the antenna by a continuous spectrum of plane waves coming from various directions with spectral pattern resembling that of the radiation pattern. This requires to start with the study of a receiving antenna being illuminated by a number of plane waves from various directions. Further investigation will be based on this aspect leading to the verification of the reciprocity theorem.

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