

# **Numerical Analysis of Reactively Loaded and Actively Reconfigurable Plasma Monopole Antenna using 2-D FDTD Method**

*A Dissertation submitted in the partial fulfillment of requirement for the award of degree of*

## **MASTER OF ENGINEERING IN WIRELESS COMMUNICATION**

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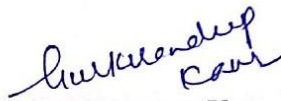
**JULY-2016**

## DECLARATION

I, **Gurkirandeep Kaur**, hereby declare that the work which is being presented in this dissertation entitled "Numerical Analysis of Reactively Loaded and Actively Reconfigurable Plasma Monopole Antenna using 2-D FDTD Method" is an authentic record of my own work carried out for the award of degree of Master of Engineering in Wireless Communication from Thapar University, Patiala, under the supervision of **Dr. Rana Pratap Yadav**, Assistant Professor, Electronics and Communication Engineering Department.


The matter presented in this dissertation has not been submitted in any other University/Institute for the award of any other degree.

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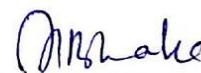
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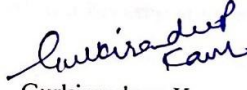
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## ABSTRACT

Now a day per person data requirements is looming large. One requires access the large amount of data in a very short period. Therefore development of efficient data network is always being topic of on-going research. Broadband refers to telecommunication system in which a wide band of frequencies is available to transmit information. Because a wide band of frequencies is available, information can be multiplexed and sent on many different frequencies or channels within the band concurrently, allowing more information to be transmitted in a given amount of time. Therefore antenna is plays important role in broadband network for transmission and reception of signals. All available antenna system for communication and data network is worked on limited frequency band. And it is unable to provide the requirement of bandwidth, therefore a development of wider bandwidth frequency antenna is inevitable.

Plasma Antenna offers a new solution to the requirement for wider frequency band, which replaces solid metal conductor element with plasma for guiding electromagnetic waves. Basically, plasma is pre-ionized gas contains equal nos. of positive and negative charge particles that's collective effect is neutral. Highly ionized plasma is essentially a good conductor, and therefore plasma filaments can serve as transmission line elements for guiding waves, or antenna surfaces for radiation. The plasma antenna has ability to transmit when the gas is electrified and became stealth when no excitation is provide to gas for further ionization. Therefore it can be “turned off” to make it electrically invisible for the purpose of reducing its scattering signature and eliminating its coupling and interference with other nearby antennas. This peculiar behavior provides numerous positive points to use plasma antenna as conducting elements in numbers of applications.

Simple plasma monopole antenna is numerically simulated and analysis of antenna properties using full wave computational technique i.e. finite difference time domain method (FDTD) in two dimensions with MATLAB software has been presented in detail. Here the far field analysis can be done by considering the magnitude of electric field lying on grids which is located at certain radius  $R$ . Radiation characteristic for the monopole has been studied for the variable antenna length and signal frequency which results significant change in radiation parameters like beam-width, radiation

intensity, directivity etc. and found as similar to that of metallic antenna. In advance, capacitive loaded plasma monopole antenna is numerically simulated using similar FDTD approach to investigate its radiation characteristics and perspective comparison is done with simulation results of simple plasma monopole. The loaded plasma monopole is defined as a plasma column incorporated with regular structural discontinuity where resultant effect of the discontinuity provides the capacitive loading on antenna element. The study found that the incorporated discontinuity enhances the effective length of antenna and also creates an array effects which improves the radiation parameters of antenna. Further, the same effect can also be achieved in an active manner where external DC magnetic field of certain magnitude has to be applied at specific section of plasma monopole. The study explores that it provides the similar results as obtained in capacitive loaded antenna and also gives an option to online control on radiation pattern which can be reconfigured as desired. To analyze the simulation outcomes in detail, a novel theoretical procedure has been developed. The developed theory found an agreement to the FDTD simulation outcomes.

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## **LIST OF ACRONYMS**

ABC	: Absorbing boundary condition
CEM	: Computational electromagnetics
EM	: Electromagnetic
ECM	: Electronic counter measure
FDTD	: Finite difference time domain
FEM	: Finite element method
FSS	: Frequency selective surfaces
GPR	: Ground penetrating radar system
MoM	: Method of Moment
PEC	: Perfect electric conductor
PMC	: Perfect magnetic conductor
PML	: Perfectly matched layer
PRLC	: Piecewise linear recursive convolution
RC	: Recursive convolution
RCS	: Radar cross section
SNR	: Signal to noise ratio
VSWRs	: Voltage standing wave ratio

### Brief overview of plasma antenna

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#### 1.1 Preamble

Since the discovery of radio frequency ("RF") signal, the process of transmitting and receiving signals become a necessary part for high speed communication in current civilization. Therefore, an antenna system plays important role for the purpose of transmission and reception of waves. Basically, it is an electrical conducting medium of specified height which emits EM wave produce by transmitter at one end and received wave at another end by receiving device. In general, an antenna can be emitted radiation at one or more selected frequencies in a communication system. The structure of metallic antenna is shown in Fig.1.1.

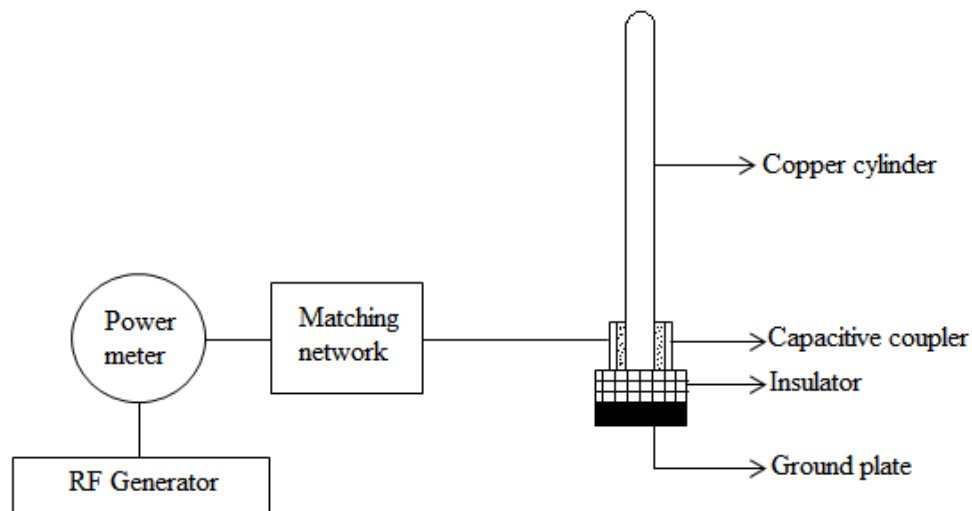


Fig. 1.1: Metal conducting antenna [15-16].

All available antenna system for communication and data network is worked on limited frequency band. It is unable to meet the demand of bandwidth of communication network system; therefore a development of wider bandwidth frequency antenna is inevitable. Here, Plasma Antenna offers a new solution to the requirement for wider frequency band in the era of defense, communication and

homeland security. It has peculiar properties that provide numerous advantages over conventional RF antennae.

## 1.2 Plasma antenna

A plasma antenna utilizes plasma as a guiding medium for electromagnetic waves which replaces a solid metal conductor that is widely used in the metallic antennae. The concept of plasma antenna is not new; a patent is dated back by J. Hettinger in 1919 [31-33]. The term plasma was first identified as “radiant matter” by Sir William Crookes an English Physicist in year 1879. Later, the “nature of the matter” is identified by Thomson in year 1897 and I. Langmuir in year 1928 was assigned a name as "plasma". The term plasma “fourth state of matter” separate from traditional form of matters like solid, liquid or gas and formation of plasma from changing state of matter is shown in Fig.1.2.

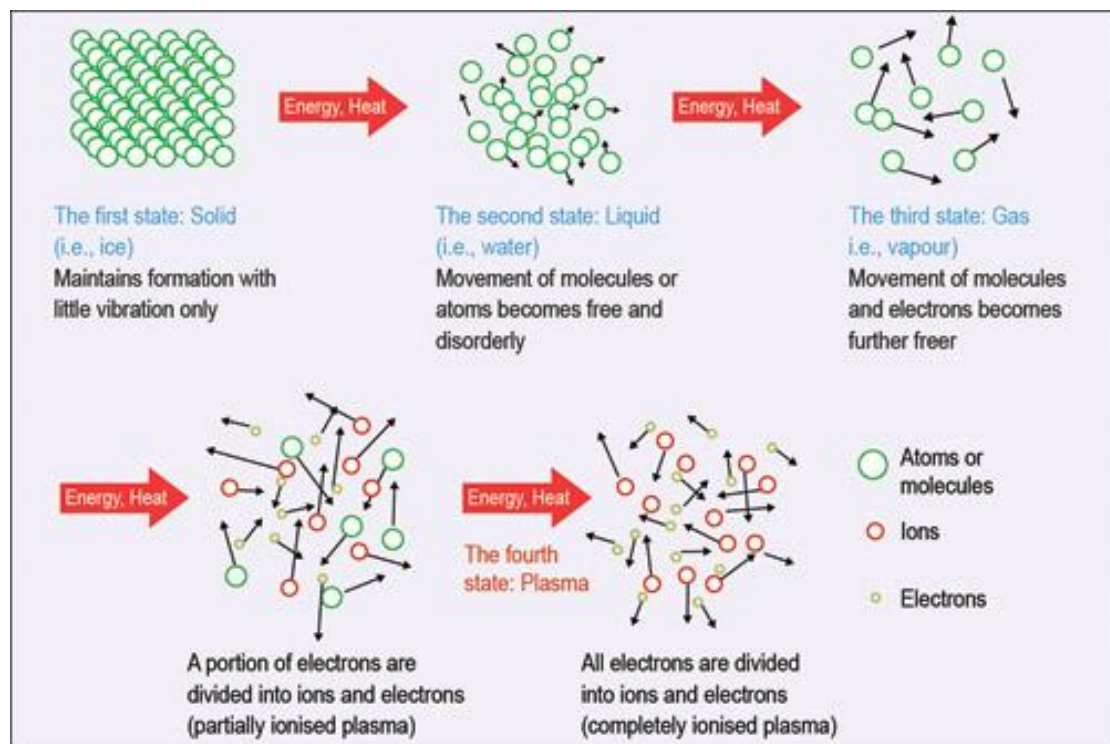


Fig. 1.2: change of states of matter [35].

Plasma is the conductive assemblies of charged and neutral particles and fields that exhibit collective effects. Basically, it is pre-ionized gas contains equal nos. of positive and negative charge particles that's collective effect is neutral. To form plasma, gas is needed to be ionized. Ionization process means heating gas by some

external sources till the molecules breakdown into charge particles to form positive ions and electrons. It is generate from a noble gas i.e. neon or argon enclosed in discharge tube that can accomplish with electrodes, RF heating, laser, fiber, microwaves signal, or electromagnetic couplers. A method that utilizes discharge tube to create plasma require minimum amount of energy to maintain the sustainability of plasma state, because the gas filled in tube is pure and prevents from dissipation of gas. A highly ionized plasma behaving as good electrical conducting medium and therefore plasma filaments can provide transmission elements for propagating EM waves or antenna surface for radiating signals. Therefore, plasma with distinct behavior is utilized as conducting element into antenna technology. The plasma antenna has ability to transmit when ionized while the gas is electrified and became stealth when no excitation is provide to gas for further ionization. Therefore it can be “turned off” to make antenna electrically invisible to reduce its scattering signature and eliminates its mutual interference and coupling with adjacent antennas [29, 19]. In recent, variety of plasma antenna like plasma loop, plasma column, reflector plasma antenna, parabolic plasma antenna, plasma array etc. is experimentally fabricated and utilizes in numerous field of communication system. Most commonly used antenna is plasma column or plasma monopole antenna and provides numerous advantages and peculiar properties over conventionally used metallic antenna.

### **1.3 Plasma column and its parameters**

A plasma column is constructed from insulating tubes encloses noble gas like argon, xenon, and neon where gas inside the column is ionized by applying bursts of rf power generated from high power voltage source. In Fig.1.3, the structure shows the generation of plasma column. To create and sustain plasma inside column two different signals are required i.e. the “excitation signal”, which is given to the tube to ionize the gas, and the “radiated signal” that contain information which is needed to be transmitted. When plasma is built, sheath is created inside plasma and electrode to maintain energy and charge particle balance. This creates a positive column which contains uniform plasma where the density and dimension of column are determined from the ion diffusion and generation mechanism.

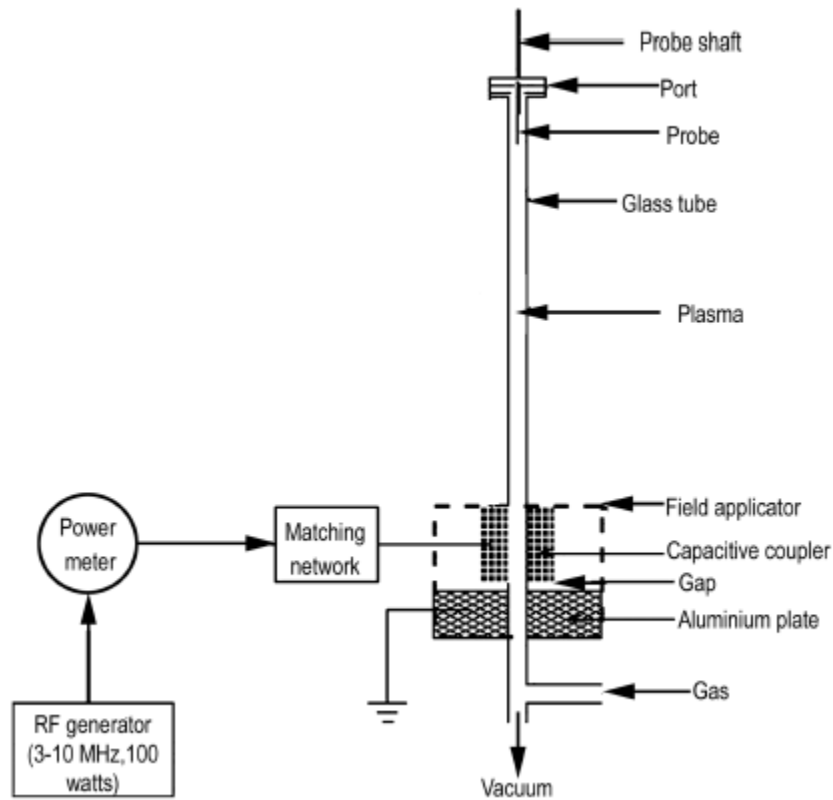


Fig. 1.3: Generation of plasma column by RF source [15-16].

The tubes are energized formed plasma that behaves as conducting elements which is used to send and receive rf signals. When gas is not electrified no plasma is created and column transformed into non-conducting components which become stealth. In general, for electrically on state, plasma act as conducting element and provide electrical path for guiding electromagnetic waves. Whereas in absence of plasma formation, electric conductivity does not exhibits and such device remains passive.

### 1.3.1 Plasma properties and parameters

Plasma in terms of electromagnetic properties is a non-homogeneous, non-linear and Debye dispersive material. Then, the relative permittivity and nonzero conductivity of plasma medium is given by [25],

$$\epsilon_r = 1 + \frac{\omega_p^2}{\omega(j\nu_c - \omega)}, \quad (1.1)$$

$$\sigma = \frac{e^2 n_e \nu_m}{m(\omega^2 + \nu_m^2)}, \quad (1.2)$$

where permittivity ( $\epsilon_0$ ), and conductivity ( $\sigma$ ) of plasma medium can be varied in terms angular plasma frequency  $\omega_p$ , wave frequency  $\omega$ , electron collision frequency  $\nu_c$  and electron density  $n_e$ . For simulation and analysis of antenna few parameters are necessarily i.e. plasma frequency, collision frequency and electron density.

### **Plasma frequency:**

Plasma frequency is defined as when electron are displaced from their uniform background; to restore the neutrality of plasma, fields is built up which pulls the electron back to their respective position where the electron will overshoot and oscillate around their respective equilibrium position with plasma frequency and it is denoted by  $\omega_p$ .

$$\omega_p = \sqrt{\frac{N_e e^2}{m \epsilon_0}}$$

The plasma frequency depends on other parameters listed as  $N_e$  is plasma density or electron density;  $e$  is a charge of electron and  $m$  represents mass of electron. To propagation of electromagnetic waves inside plasma there are three special cases of interest:

### **Collusion frequency:**

It is defined as the average rate at which particle of type one is collide with particle of another type. Two type of collusion can be defined: collusion between the charge particle and neutral particles and the collusion between the charge particles.it is denoted as  $\nu_c$ .

## **1.4 Unique characteristics of plasma antenna**

Plasma column antenna has properties that are distinct from metallic conductors. This different behavior of plasma antenna has important consequences in many applications. One of the major characteristic is the ionization process can give resistance whereas at deionization the gas has with infinite resistance. This property prevents from the interaction of waves with plasma and make unable to radiate signals. Therefore, this property makes antenna invisible and eliminating the effect of electronic warfare [4, 31-35].

Second key point is that, the antenna become deionized when it sends a wave that overcomes the ringing effect observed in metal antenna elements. The effect of associated noise and ringing of conventional antenna limits the abilities for high frequency transmissions. Because of this limitation, antennae are often accompanied by sophisticated computer signal processing systems for operated at high frequency. Where in case of plasma antenna technology, ringing and noise effects associated with antenna are reduces that limits the requirement of signal processing systems. These advantages enhance the accuracy and performance of antenna that are crucial in cutting edge applications in radar engineering and high-speed wireless communication networks. Based on the finding from experimental and theoretical aspects, plasma antenna technology has also additional features and attributes as follows,

- It has ability to focus a signal beam easily and communicate signals in very short duration which is extremely useful feature in the various field of communication networks like as digital system and radar applications.
- The antenna characteristics like frequency, beam-width, gain radiation intensity, and efficiency can be easily reconfigurable by altering the values of operating parameters such as signal frequency, electron density, conductivity, gas pressure, and column length etc.
- The electromagnetic waves can be transmitted and received with single antenna structure for widely separated frequencies range and make single column structure works as array antenna by dynamically changing the antenna's operating parameters without changed its physical configurations that is required in metallic antenna.
- Reduction in radar cross section (RCS) gives stealth behavior with the absence of metal conducting elements whereas it does not improving signal to noise ratio (SNR) and multipath signal distortion.
- For instantaneous variation in frequency bandwidth over wide dynamic ranges can be obtained while changing the values of plasma parameters as electron density and conductivity.
- A circular scan can be performed with electronically reconfigure the antennae dimensions at a very high speed instead of mechanically based antenna structures.

## 1.5 Comparison between Plasma Antenna and Conventional Antenna

The perspective comparison of plasma antenna with conventionally used metallic antenna is presented in Table 1.1. The plasma antenna has properties that differ from metal antenna which enhance the performance characteristics of antenna.

Table 1.1: Comparison between plasma antenna and conventional antenna

<b>PROPERTY</b>	<b>PLASMA ANTENNA</b>	<b>CONVENTIONAL ANTENNA</b>
<b>Operating frequency reconfigurability</b>	Easy and Electrically reconfigurable based on plasma parameters.	Low and reconfigure manually
<b>Radiation characteristics reconfigurability</b>	Highly reconfigurable electrically based on plasma parameters.	Low and reconfigure mechanically
<b>Bandwidth reconfiguration</b>	Dynamically reconfigure for Narrow, Multiband, Broadband	Narrow
<b>Thermal Noise</b>	Decreased by ~40 factor as metal antenna noise	Provide Less noise
<b>Radar cross section (RCS)</b>	Reduced or completely vanished	Provide High RCS
<b>Power Consumption</b>	Required high Rf power to generate the plasma discharge	Only for Ohmic losses
<b>Co-interference</b>	less sensitive to nearby antenna system	More

## 1.6 Advantages and disadvantages/limitation

This section describes the advantages and disadvantages of plasma antenna are shown in table 1.2.

Table 1.2: A list of important advantages and disadvantages along with their attributes

<b>PROPERTY</b>	<b>ADVANTAGES</b>	<b>DISADVANTAGES</b>
<b>Turn-On period/Turn-Off period</b>	Reduce RCS, ringing, and mutual interference	Decay times and ionization limit scanning
<b>Reconfigurable</b>	Dynamically reconfigure plasma parameters to control pattern and bandwidth	Plasma volumes must be stable and repeatable
<b>Plasma generator</b>	Provide good RF coupling for electrically small antenna elements and increases visibility by glow discharge	More power consumption and complex ionizer adds weight and volume.
<b>Confined Plasma</b>	Stable, efficient, and repeatable	Not durable or flexible
<b>Atmospheric path</b>	Flexibility in length and direction of path	Higher ionization energy than for a tube

## **1.7 Market applications of plasma antenna technology**

Plasma antennas offers distinct behavior in antenna technology and its advantages over conventionally used metallic components are most obvious suitable for stealth and electronic warfare which are primary concerns in military applications. Along with military benefits it can also be applicable in commercial applications [35].

### Potential military applications

Plasma antenna technology has military applications in

- Replacement of Stealth aircraft antenna
- EMI/ECI mitigation and ECM (electronic counter-measure) antennas
- Easily detection and tracking of ballistic missiles
- Phased array element replacements
- Shipboard / submarine antenna replacements

### Potential commercial applications

It also has commercial applications in

- Telemetry and wireless communication system
- Ground penetrating radar system (GPR)
- Navigation and weather radar
- Public security network
- Cellular radiation protection
- High-speed data (for e.g. Internet) communication spread spectrum communication

## **1.8 Organization of dissertation**

This dissertation consists of 8 chapters which are organized as below:

Chapter 1: Introduction, in this chapter brief overview of plasma monopole antenna has been introduced. This chapter also discusses the key features and their applications of plasma antenna compared with metallic antenna.

Chapter 2: Literature review, in this chapter study the work which has been done regarding for simulation design and analysis of plasma antenna experimentally or theoretically has been discussed in this chapter.

Chapter 3: Identified gaps and proposed methodology, this chapter discuss the gaps related to work find from survey along with objective and explaining method that how this work can be processed.

Chapter 4: Review of simulation technique, this chapter gives brief introduction about computational electromagnetic i.e. FDTD simulation technique used for analyzed plasma antenna characteristics.

Chapter 5: Analysis of simple plasma monopole antenna using 2-D FDTD method, this chapter describes the simulation and analysis of plasma monopole for evaluating radiation characteristics using FDTD formulation.

Chapter 6: Analysis of capacitive loaded plasma monopole antenna, in this chapter the numerical simulation of capacitive loaded plasma monopole using FDTD approach has been presented and theoretical procedure is developed to investigate its effects.

Chapter 7: Analysis of actively loaded plasma monopole antenna, the chapter describes the actively loaded plasma monopole using FDTD approach and radiation characteristics are investigated is also presented in chapter.

Chapter 8: Conclusion and future scope, in this chapter whole work has been concluded, on the basis of observations and also future scope has been discussed.

To start any research project, initially individual/researcher has to study and understand the research papers that are relevant to respective work. This approach gives detailed information about the latest research that has been done in chosen project and help to perform this project. This chapter gives overviews based on theoretical and experimental studies related to plasma antenna technology is presented in this concern.

**Borg *et al.* in 2000 [1]:** focused on plasma column driven by surface wave used as Radio frequency antenna which leads to better noise performance and low radar cross section to be useful for broadcast communications. Experimental setup is created to generate plasma column inside a tube of length 2430 mm and 38 mm diameter respectively which is driven at 30 MHz operating frequency. Analysis of antenna parameter can be done in terms of current distribution, efficiency and radiation pattern.

**Fan *et al.* in 2000 [2]:** represented two different method of FDTD algorithm which involves RC and PLRC methods used to simulate Electric and magnetic fields for general conductive, inhomogeneous, and dispersive media. Initially, FDTD algorithm is verified for two different medium like homogeneous and inhomogeneous with three different types of dispersive material i.e. Debye, Lorentz material and unmagnetized plasma. Further, simulated outcomes for both RC and PRLC techniques are compared to analytical solutions which show excellent agreement for all media. From simulation analysis reveals that RC approach has better accuracy and less complicated from another used PRLC method. By utilizing these techniques, author demonstrated several applications for ground-penetrating radar (GPR) to detecting of mine objects.

**Xiang-qin *et al.* in 2003 [3]:** focused on the numerical investigation of radiated pattern for monopole antenna coated with plasma by using shift operator technique in FDTD method. From the simulation results, states that the monopole antenna with plasma coating layer penetrate more electromagnetic wave and also retarded the

excitation source pulse which travels towards the antenna's direction. In addition, a shift in resonant frequency is observed whereas the field distribution of antenna is strongly influenced and may significantly vary the radiation pattern.

**Rayner et al. in 2004 [4]** : experimental design of plasma column antenna filled with argon gas driven by surface wave generated at 500 MHz and taking gas pressures in range of 0.03 mb - 0.5 mb. Result outcomes reveal that, the increase in antenna's length with increase of applied power whereas plasma density decreases linearly. In addition to this, noise obtained from plasma is found to be in range of 10 MHz - 250 MHz which is sufficiently low. Observations from radiation pattern shows linear changes in conductivity and resistance of the plasma which reduces the depth of nulls and consequently increases observed in beam-width of major lobe.

**Loui et al. in 2004 [5]**: demonstrates the propagation of E and H fields in one dimension used finite difference approximation method with MATLAB software. In this paper, author study the implementation of different absorbing boundary conditions (ABC) perfect magnetic conductor (PMC), perfect electric conductor, Mur and Scattered field /Total field boundaries and investigate its effects. In addition to this, dielectric slab is incorporated and calculate E and H field along with reflection coefficients measurements.

**Lee et al. in 2005 [6]**: presents the full wave electromagnetic analysis of simple plasma monopole antenna configurations by using 3-D FDTD algorithm to demonstrate some of their characteristics and evaluates the radiated power, antenna pattern, field distribution, antenna impedance and efficiency of the plasma column antenna using numerical approximation technique. Finding demonstrates that the plasma antenna is found to be efficient and have similar characteristics to conventionally used RF antennae. Furthermore, variation in plasma characteristics provides dynamic reconfiguration in the radiation pattern of antenna.

**Qian et al. in 2005 [7]**: in this, Frequency dependent FDTD method is used for analyzed return loss characteristics of rectangular whip antenna. Resonant frequency of plasma whip antenna is computed for different antenna's length found that frequency 5624 decrease from 1.3 to 1.1 6GHz at L=160mm and resonant frequency increases to 1.3GHz at L=134mm. Further study explores that the effective length and

operating frequency of whip antenna can be adjusted as per requirement by changing the plasma density.

**Anderson et al. in 2007 [8]:** describes four phase of plasma antenna work; in 1st phase the idea of coaxial plasma closing switch was used. In 2nd phase, plasma antenna was used to prevent the ringing effect on signal and the noise generated by plasma was very low. Further, 3rd phase presents parabolic reflector plasma antenna for stealth, reconfigurability, and protection from electronic warfare applications. In last phase, antenna installed in anechoic chamber and also designed metal antenna which is identical with plasma based antenna. A theoretical model developed for plasma frequency selective surfaces (FSS) and presented in detail. FSS is used for filtering EM waves. Genetic algorithm is implemented to determine the stacking for required filtering purposes. The mathematical model is developed for FSS using array of dipole elements on substrate.

**Cerri et al. in 2007 [9]:** experimentally design a self-consistent model of plasma column antenna fed by single electrode to evaluate its efficiency and conductivity in plasma. Basically, a new methodological approach is derived to characterize its physical behavior. In cylindrical antennas, plasma formation and its existence can be attained by excitation wave i.e. surface wave; where knowledge of the interaction between plasma and EM fields is the main point to characterize behavior of plasma. The plasma antenna's efficiency is found comparable and efficient as metallic antenna. Whereas results finding reveal that conductivity of plasma is dependent on different antenna properties that affect the antenna losses characteristics and is important key to establish effective length of plasma column. For conductivity measurements, the experimental model is set up where plasma column is covered with waveguide and changes the characteristics of dielectric; reflection coefficient is calculated which is dependent on the conductivity of inserted portion of tube in the waveguide. Analysis of S11 parameter gives behavior of reflection coefficient where the dielectric medium i.e. plasma behaves like a lossy metal and used as good conducting material for many antenna applications when  $\sigma$  observed to be greater than 100 S/m.

**Chao et al. in 2008 [10]:** describes the simulation and analyses a 0.4-m-long plasma column antenna by adopt cylindrical-coordinate FDTD algorithm. The radiation efficiency and input impedance of plasma based antenna are computed at frequency range 75MHz - 400MHz. Some specific characteristics of antenna are investigated where plasma antenna behave similar as of a metallic antenna. When the ratio of  $f/f_p$  is observed low then a resonant behavior is obtained in antenna impedance. Whereas, plasma parameters like plasma frequency ( $f_p$ ) and collision frequency ( $\nu_c$ ) is dynamically altered to obtained reconfigurable radiation pattern of antenna. Furthermore, with changes of collision frequency and ion density produce significant effects on the radiation efficiency of antenna.

**Qian et al. in 2008 [11]:** in this, propagation behavior of EM waves along a plasma column included uneven axial density distribution is studied. For this purpose, current distribution pattern is derived along with it radiation parameters of a unipolar plasma antenna are also calculated on the VHF band.

**Cerri et al. in 2008 [12]:** focused on the case study of two test benches for the characterization of electromagnetic wave interacting with plasma column that is utilized as conducting path. The major parameters like as efficiency, turn on time, and plasma conductivity of antenna are to be quantified. However, two main parameters have been investigated by measure radiated fields from the plasma antenna which compared to the results obtained from copper antenna.

**Zheng et al. in 2008 [13]:** experimentally design, developed and fabricated a fluorescent loop plasma antenna driven by 220 W A.C power source and RF source. For reference, metallic antenna also simulated. Analysis of radiated field, VSWRs and average gains of designed three plasma antennas has been evaluated and compare these results to metal conducting element that considered as reference antenna. Findings reveals that the obtained gains from these two designed plasma antennas are observed 6.0dB and 6.7dB decreased in case of antenna driven by AC and RF power source respectively instead of metal based antenna.

**Luo et al. in 2008 [14]:** presented FDTD simulation of simple cylinder plasma monopole antenna of dimension 300mm as length and 4mm as radius of antenna. For FDTD method, the near field far field transformation is used to compute radiated

electric and magnetic field of plasma monopole antenna in far field zone. Further, pattern is reconfiguring for the variable dielectric permittivity and sinusoidal signal frequency. From simulation results, observed that radiation intensity of antenna is function of permittivity of dielectric medium where the radiation intensity is increases as the value of dielectric permittivity increase and reaches to maximum value when permittivity is equal to 4.5. Afterwards the radiation intensity goes decreases as still value of permittivity rises. Whereas, at permittivity reaches to value equal to 7 the magnitude of ration intensity goes broaden. Later on, the radiation is investigated for variable operating frequency ranging from 50-500 MHz by taking other parameters constant throughout the analysis i.e. permittivity = 4.5, plasma frequency = 20GHz, collision frequency = 10GHz.

**Kumar et al. in 2010 [15]:** experiments are carried out for generation of plasma column that is excites with surface wave and analyzed their field properties i.e. Current distributions along the column, radiated field and power patterns, directivity and also antenna efficiency are investigated. Further, a copper antenna is designed as reference model where perspective comparison of simulated result with plasma antenna is presented. From experimental results, observed that the harmonics components in power content of plasma antenna shows prominent behavior as of reference antenna where only fundamental frequency components exist. However, a bi- spectral analysis is done to give clear understanding of non-linear interactions in power pattern. The study also explores that radiation pattern of both antenna found similar. In this, some specific characteristics of antenna are evaluated that enhances the performance level of antenna that can be useful in RF based applications.

**Kumar et al. in 2010 [16]:** investigated the antenna properties of different plasma column structure which can be created as reconfigurable antenna simply by altering the values of working parameters. Further, by inverting these parameters a single column can converted into many small elements called blobs or striations where experiments are carried out to study field distribution profile i.e. current profile, conductivity profile, potential profile, radiation power patterns. This study proven that entire antenna element can be transformed into phased array antenna by changing the antenna parameters that is more directive and provide narrow radiated pattern as of plasma column without any blobs.

**Ja'afar et al. in 2012 [17]:** design and development of plasma monopole antenna is done by taking antenna dimension given as  $L=150\text{mm}$ ,  $r=5.2\text{mm}$  length and radius of plasma column respectively at frequency range  $550\text{MHz}$  -  $600\text{MHz}$ . and taken aluminum ground plane of radius  $40\text{mm}$ . In this project, simulation of antenna is performed using computer simulation technology (CST) Microwave Studio. Based on this software simulation of antenna is done to evaluate its performance in terms of average gain, bandwidth, radiation pattern and return losses. Whereas from these observations study show that plasma antenna has similar characterization as of equivalent model of metal antenna.

**Halili et al. in 2012 [18]:** experimentally fabricated three types of plasma antenna that are containing three different noble gases listed as xenon, neon, and argon with 1 Torr gas pressure by using RF heating technique for ionizing the gas. Here, the performance of every plasma antenna has been calculated to investigate the antenna characteristics in term of return losses. From design measurements, findings indicates that, all noble gases yield return losses below  $-10\text{dB}$  in the frequency range  $3.5\text{GHz}$  -  $5.5\text{GHz}$  which is better than the antenna without formation of plasma in all cases and observed that improvement of 2 to 8 dB is obtained whereas neon gas yield a significant shift of  $200\text{MHz}$  in the optimum frequency from original value while measured with plasma state.

**Zali et al. in 2013 [19]:** proposed a monopole plasma antenna with parabolic reflector of cylindrical dimension located at back section of antenna to reflect the focused signal that is receives from transmitter and then sending back for improving directivity and gain of antenna. Plasma monopole antenna of configuration  $310\text{mm}$  antenna height and  $12\text{mm}$  of diameter respectively is placed at center location of parabolic reflector and studied the difference on antenna's average gain for both antennas and the performance is calculated terms involves return loss characteristics and radiated pattern throughout numerical simulations. From result, it observed that the applicability of reflector significantly increases the average gain ranging from  $2.54\text{dB}$ - $7.19\text{dB}$  and yield return losses below than  $-10\text{dB}$  at frequency  $4.0\text{GHz}$  -  $4.7\text{GHz}$ . This property makes antenna acceptable for indoor wireless transmission applications.

**Darvish et al. in 2013 [20]:** investigate a basic theory of the plasma material and then a design of a Plasma antenna at VHF band based on these theories is presented in detail. The plasma antenna simulation process can be done with help of computer aided software i.e. CST Microwave Studio Suite 2011. In order to validate the outcomes obtained from designed plasma antenna, an experimental fabrication is performed to develop proposed antenna model. Results outcomes from experimentally implemented antenna shows a good agreement with the simulation results which has been obtained based on proposed design of plasma antenna.

**Sadeghikia et al. in 2013 [21]:** broadband characteristics can be obtained by increasing the diameter of the plasma tube whereas depth of minor lobes can also be diminishing as diameter increase. Further study reveals that with decrease in collision frequency the gain and radar cross section of antenna can be increased. To wider the BW there is need to decrease the  $L/r$  ratio, where  $L$  is length of plasma antenna and  $r$  is radius of tube i.e. by increase the radius, BW will increase. Impedance variation becomes less sensitive as a function of frequency as  $L/r$  decreases. The plasma conductivity decreases and RCS also reduce with increase in collision frequency that affects all the characteristics of plasma antenna.

**Zhou et al. in 2014 [22]:** investigates the radiation characteristic of plasma antenna finite difference time domain technique under two dimensions. Using FDTD method, initially the propagation of electromagnetic waves in free space in stretched coordinates is studied and derived update equations from modified Maxwell equations. In advance, propagation of electromagnetic waves in plasma is also studied by using Boltzmann-Maxwell theory. The near field-far field (NF-FF) transformation is used to obtained radiation characteristics. Whereas results show the influence of electron density on radiation pattern that can changes significantly with the variation of degree of ionization.

**Ja'afar et al. in 2015 [23]:** numerically and experimentally simulate monopole antenna structure that consisting 12 adjacent fluorescent tubes which involves the combination of argon gas and mercury vapor. These tubes are further electrified and created plasma inside tubes which acts as radiating element. In this report, numerical simulation and experimental outcomes in terms of gain, radiation characteristics and

S- parameter. are investigated at operating frequency 4.9 GHz. Findings reveals that plasma monopole antenna pointed in different three beam shapes i.e.  $0^\circ$ ,  $90^\circ$ , and  $180^\circ$  where it can be electrically switchable and provides better gain as 6.691dB which is higher than metallic antenna i.e. is generally 2-3dB. The study explores good agreement in both simulated and experimental outcomes.

### Gaps analysis, objective and methodology

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#### 3.1 Gaps in study

At present, more attention is being given to plasma based antenna technology and the subject is still a part of active research at national/international level where experimental and theoretical analysis should be done to analyzing their respective parameters for contributing good results. Based on literature survey, study explore many of work is done on plasma antenna using numerical FDTD approach.

##### 3.1.1 Problem Encountered

- Plasma column antenna is simulated for various parametric analyses and a lot of positive features are obtained which make it distinct from metal antenna.
- From recent survey, here we find that numerical analysis of plasma column antenna with variation in spatial configuration using any simulation approach is not performed.
- Secondly, for more computational speed finite difference technique is used instead other simulation method which provides accurate and precise way for numerically simulate the interaction between plasma and radio waves travel through plasma column antenna.

#### 3.2 Objective

- In analysis, it is observed that for every change in design parameters of antenna leads to a distinct behavior in terms of radiation characteristics along with providing enhanced performance in comparison to the conventional design. That's why; plasma antenna is still a part of active research.
- This motivates to achieve a narrow beam pattern for wide frequency range by changing plasma parameters such as plasma density, conductivity, length, gas pressure, operating frequency, and input power using finite difference time domain analysis.

### 3.3 Methodology

The steps involved to numerically simulation plasma monopole antenna using 2-D FDTD method by passive and active approach and to characterize the output are as follows:

- i. Detailed study of plasma monopole antenna
- ii. Brief overview of MATLAB software.
- iii. Study and detailed understanding of numerical technique i.e. finite difference time domain method under two dimensions which is used to analyses antenna properties.
- iv. Initially analysis of simple plasma monopole with 2-D FDTD using MATLAB software is carried out. In next discontinuity is implemented in plasma column antenna configuration and compares the simulated results with simple antenna.
- v. Advance, plasma monopole is simulated by applying magnetic field which is completely active approach and analyzed its far field radiation parameters.

### Review of numerical simulation technique

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#### 4.1 Introduction

This chapter gives brief overview of numerical simulation technique that is used to analyze physical characteristics of plasma antenna experimentally or theoretically. The manual experiments show that the mold-ability of the structure is limited as it can be seen in the example, as a person wish to design plasma columns experimentally of different structure and dimensions, this should be first built manually beforehand. Computer design software ease the difficulties associated with numerical simulation and hence provide an effective tool to evaluate the capabilities of plasma having the mold-ability at a very low cost for different types of complex geometries.

#### 4.2 Computational electromagnetics (CEM) technique

For design and simulation of plasma antenna various types of software is available in market which can analyzed antenna's parameters such as current distribution, beam-width, radiation intensity, gain, directivity, return losses, impedance, conductivity distribution, field and power pattern, and efficiency etc. Apart from software, there is simulation techniques i.e. computational electromagnetic (CEM) technique is used to evaluate antenna radiated fields characteristics using coding language. The CEM are the techniques which are used to model the interaction of EM fields with object and the physical surrounding [28, 30]. This method realizes the space and time coordinates in terms of grids and solves Maxwell's curls equations for every point that lies on the grids. This technique can be classified as:

- Finite difference time domain method (FDTD)
- Method of Moment (MoM)
- Finite Element method (FEM)

#### 4.3 Key characteristics of the methods

Some of the key characteristics of full wave computational electromagnetic (CEM) technique i.e. MoM, FDTD, and FEM are listed in Table 4.1 and Table 4.2 that

illustrates a correlation of strength and weakness of CEM methods for both the radiating and scattering regions with respect to guided waves.

- Strengths and weaknesses of method for open region.
- Strengths and weaknesses of method for guided wave problem.

Table 4.1: Strength and Weakness of CEM method as widely implemented for open region

Method	Equation Type	Domain	Radiation Condition	PEC Only	Homogeneous Penetrable	Inhomogeneous Penetrable
MoM	Integral	Frequency	Yes	^	^	~
FEM	Differential	Frequency	No	~	^	^
FDTD	Differential	Time	No	~	^	^
<b>KEY: Good (^), Not-Optimal (~)</b>						

Table 4.2: Strength and Weakness of CEM method as widely implemented for guided wave problem.

Formulation	Equation Type	Domain	Wideband	PEC Only	Homogeneous Penetrable	Inhomogeneous Penetrable
MoM	Integral	Frequency	Yes	>	^	~
FEM	Differential	Frequency	No	>	^	^
FDTD	Differential	Time	No	^	^	^
<b>KEY: Good (^), Not-Optimal (~) , Satisfactory (&gt;)</b>						

#### 4.4 Finite difference time domain (FDTD) method

FDTD is a full wave CEM technique used to tackle the problem of electromagnetics. This method eliminates the usage of variable functional or weighted residuals which are used in other CEM methods. Perhaps it executes finite difference approach between the space and time derivatives for approximation [28, 30]. Its algorithm firstly proposed by Kane Yee in year 1966 which implements the second-order of central differences. The summary of FDTD YEE's algorithm is stated as:

- Firstly, replace the existing derivatives of Maxwell's law equations into finite differences approximation. Then, discretized them into grids; so the electromagnetic fields in equations can be staggered into both time and space.
- Secondly, solve derived equations obtained from difference approximation to form "update equations" which represents the unknown (future) value of fields in terms of known (past) value of fields.
- Evaluate the update equation of electric fields and magnetic fields at every grid over single time step.
- In last, the previous step is repeated again until the value of electric and magnetic fields are obtained for defined domain.

##### 4.4.1 Propagation of Electromagnetic waves in medium

In one dimension, time dependent Maxwell's Ampere's and Faraday's laws in free space are written as

$$\frac{\partial E}{\partial t} = \frac{1}{\epsilon} \nabla \times H \quad (4.1)$$

$$\frac{\partial H}{\partial t} = -\frac{1}{\mu} \nabla \times E \quad (4.2)$$

In 1-D space, the variations occur only in X-direction and the electric field has components in z direction. For this, Faraday's law can be given as

$$-\mu \frac{\partial H}{\partial t} = \nabla \times E = \begin{vmatrix} \hat{a}_x & \hat{a}_y & \hat{a}_z \\ \frac{\partial}{\partial x} & 0 & 0 \\ 0 & 0 & E_z \end{vmatrix} = -\hat{a}_y \frac{\partial E_z}{\partial x} \quad (4.3)$$

Thus for Ampere's law,  $H_y$  is only the non-zero term and also time varying component. Then, law equation can be formularized as

$$\varepsilon \frac{\partial E}{\partial t} = \nabla \times H = \begin{vmatrix} \hat{a}_x & \hat{a}_y & \hat{a}_z \\ \frac{\partial}{\partial x} & 0 & 0 \\ 0 & H_y & 0 \end{vmatrix} = \hat{a}_z \frac{\partial H_y}{\partial x} \quad (4.4)$$

Then both above scalar equations are written in terms of temporal and spatial derivative of electric and magnetic fields respectively.

$$\mu \frac{\partial H_y}{\partial t} = \frac{\partial E_z}{\partial x} \quad (4.5)$$

$$\varepsilon \frac{\partial E_z}{\partial t} = \frac{\partial H_y}{\partial x} \quad (4.6)$$

The next step is to replace the derivatives terms in both above Maxwell's equations with finite differences approximation. For this, discrete behavior between space and time is required.

$$E_z(x, t) = E_z(m\Delta_x, q\Delta_t) = E_z^q[m], \quad (4.7)$$

$$H_y(x, t) = H_y(m\Delta_x, q\Delta_t) = H_y^q[m], \quad (4.8)$$

where  $\Delta_t$  and  $\Delta_x$  is temporal offset and spatial offset respectively. The index  $m$  and  $q$  is spatial step and temporal step which presents the spatial and temporal location. The arrangement of EM field nodes for FDTD grids in space and time is shown in Fig.4.1.

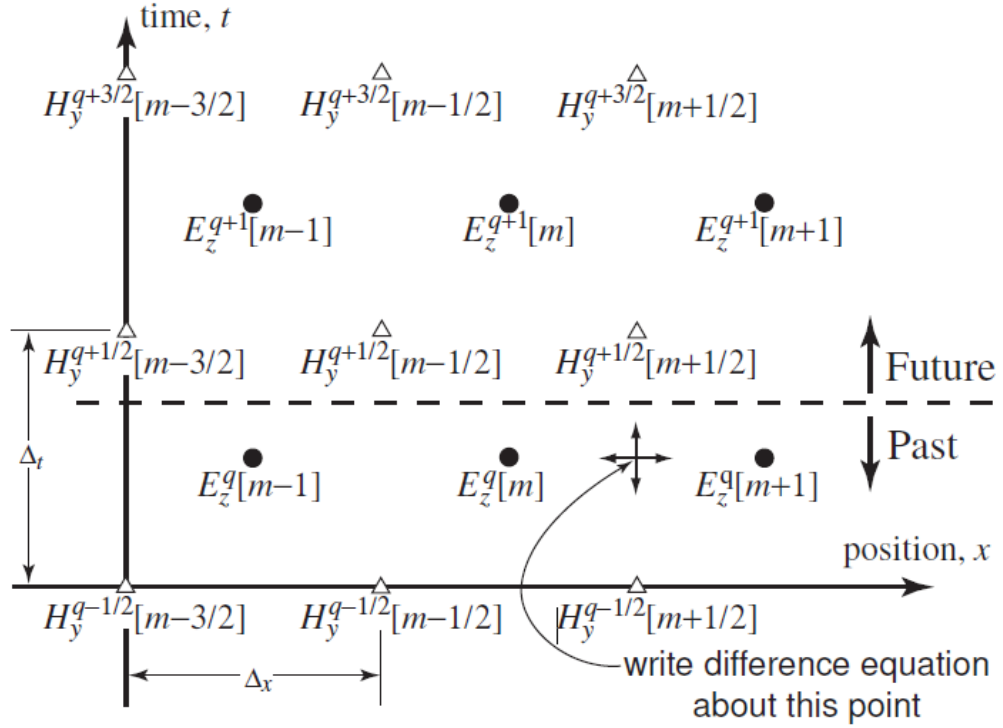


Fig. 4.1: Represents E and H field nodes in one dimension for space and time grids. The difference equation is written at marked point to get 1-D update equation for  $H_y$  [30].

According to indicated point in above mention fig. 4.1, write 1-D update equation for magnetic field. Further, the temporal and spatial derivatives are converted to a finite difference equation involves the future and past fields components. Solve these obtained finite equations to get 1-D update equation of magnetic and electric field.

$$H_y^{q+\frac{1}{2}}\left[m+\frac{1}{2}\right] = H_y^{q-\frac{1}{2}}\left[m+\frac{1}{2}\right] + \frac{\Delta t}{\mu\Delta x} (E_z^q[m+1] - E_z^q[m]) \quad (4.9)$$

This is known as an update equation in one dimension for magnetic field  $H_y$  component. The Fig.4.2 represent the updating values for electric field depending upon past of magnetic field.

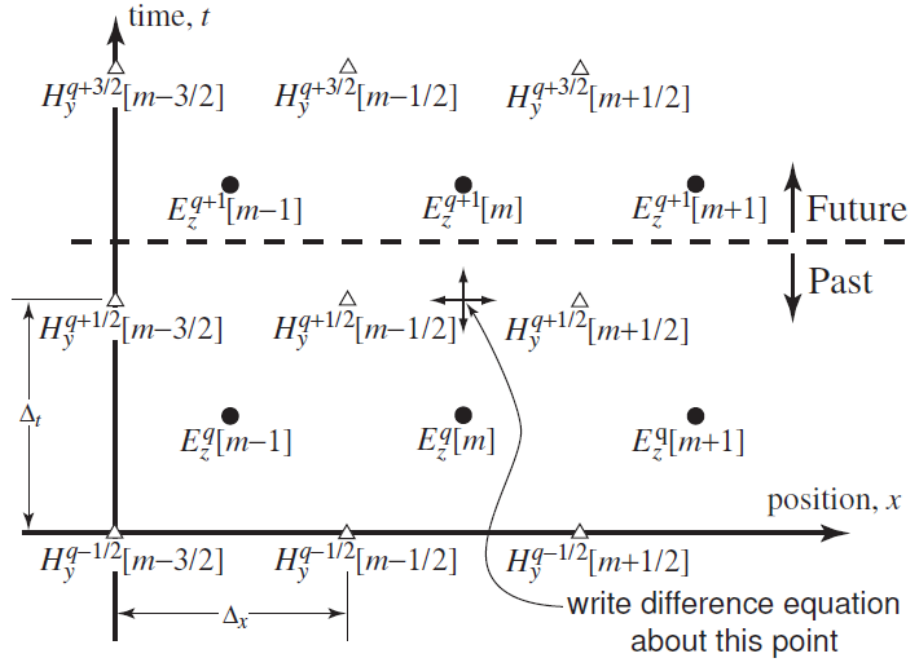


Fig. 4.2: Represents E and H field nodes in one dimension for space and time grids. The difference equation is written at marked point to get 1-D update equation for  $E_z$  [30].

Similarly, solve finite difference for  $E_z^q[m]$  to obtain 1-D update equation of electric field.

$$E_z^{q+1}[m] = E_z^q[m] + \frac{\Delta_t}{\epsilon \Delta_x} \left( H_y^{q+\frac{1}{2}} \left[ m + \frac{1}{2} \right] - H_y^{q+\frac{1}{2}} \left[ m - \frac{1}{2} \right] \right) \quad (4.10)$$

This is update equation for electric field in one dimension which depends upon past values of magnetic field. The update coefficients  $\frac{\Delta_t}{\epsilon \Delta_x}$  and  $\frac{\Delta_t}{\mu \Delta_x}$  is presented in the ratio i.e. how far the waves can travel in a single spatial step for one time step. The speed of EM waves which can propagate into medium is equivalent to the speed of light denoted as  $c = \sqrt{\frac{\epsilon_0}{\mu_0}}$ , where  $\epsilon_0$  and  $\mu_0$  is permittivity and permeability of free space respectively. The maximum distance that EM energy can propagate in a temporal step is  $c\Delta_t$ .

$$S_c = \frac{c\Delta_t}{\Delta_x} \quad (4.11)$$

The ratio of  $\frac{c\Delta_t}{\Delta_x}$  is called the Courant number which is labeled as  $S_c$ .

## 2-D Update equation

In two dimensions, here the fields are presumed to differ in both X and Y directions. The arrangement of EM field nodes under two dimension spaces for TM<sup>z</sup> mode is presented [30]. Thus, Faraday's law is modified for medium parameter can be written as

$$-\sigma_m H - \mu \frac{\partial H}{\partial t} = \nabla \times E = \begin{vmatrix} \hat{a}_x & \hat{a}_y & \hat{a}_z \\ \frac{\partial}{\partial x} & \frac{\partial}{\partial y} & 0 \\ 0 & 0 & E_z \end{vmatrix} = \hat{a}_x \frac{\partial E_z}{\partial y} - \hat{a}_y \frac{\partial E_z}{\partial x} \quad (4.12)$$

Therefore, Ampere's law becomes as

$$\sigma E + \varepsilon \frac{\partial E}{\partial t} = \nabla \times H = \begin{vmatrix} \hat{a}_x & \hat{a}_y & \hat{a}_z \\ \frac{\partial}{\partial x} & \frac{\partial}{\partial y} & 0 \\ H_x & H_y & 0 \end{vmatrix} = \hat{a}_z \frac{\partial H_y}{\partial y} - \hat{a}_z \frac{\partial H_x}{\partial x} \quad (4.13)$$

Then, the Maxwell's equation becomes

$$-\sigma_m H_x - \mu \frac{\partial H_x}{\partial t} = \frac{\partial E_z}{\partial y}, \quad (4.14)$$

$$\sigma_m H_y + \mu \frac{\partial H_y}{\partial t} = \frac{\partial E_z}{\partial x}, \quad (4.15)$$

$$\sigma E_z + \varepsilon \frac{\partial E_z}{\partial t} = \frac{\partial H_y}{\partial x} - \frac{\partial H_x}{\partial y}, \quad (4.16)$$

Space and time is now discretized to express fields in the terms of finite difference approximation. This resulting difference equations can be solved for future field value which depends on the past fields value. Here, the spatial arrangement of E and H field nodes for TM<sup>z</sup> mode is shown in Fig.4.3.

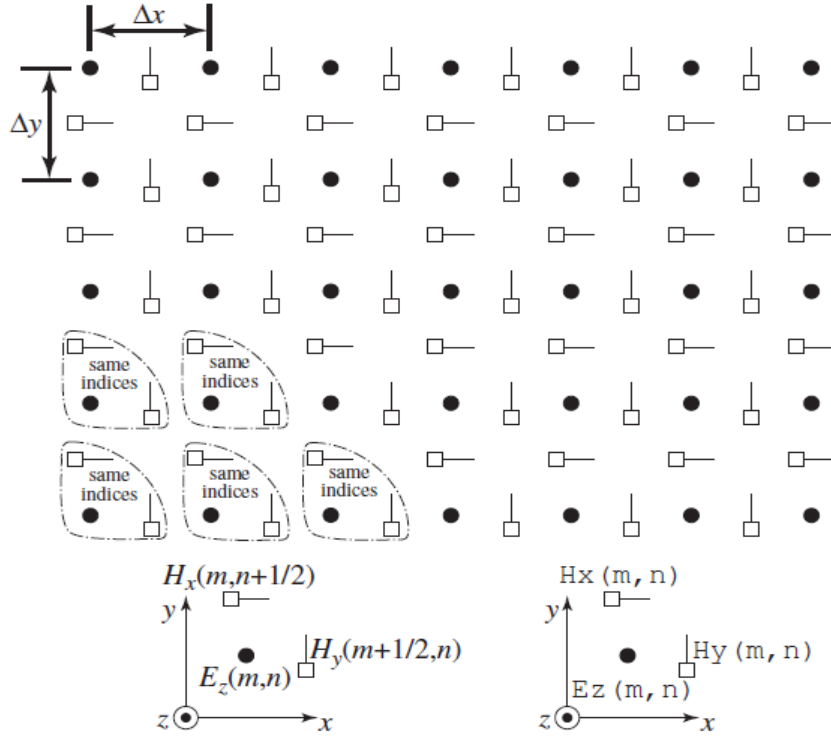


Fig. 4.3: Represents arrangement of electric and magnetic field nodes in two dimensional spaces for  $TM^z$  polarization [30]

Solve finite difference equation to obtain 2-D update equation for  $H_y\left(m, n + \frac{1}{2}\right)$

$$H_y^{q+\frac{1}{2}}\left[m + \frac{1}{2}, n\right] = \frac{1 - \frac{\sigma_m \Delta t}{2\mu}}{1 + \frac{\sigma_m \Delta t}{2\mu}} H_y^{q-\frac{1}{2}}\left[m + \frac{1}{2}, n\right] + \frac{1}{1 + \frac{\sigma_m \Delta t}{2\mu}} \frac{\Delta t}{\mu \Delta x} (E_z^q[m+1, n] - E_z^q[m, n]), \quad (4.17)$$

Then update equation for  $H_x\left(m + \frac{1}{2}, n\right)$  in two dimensions.

$$H_x^{q+\frac{1}{2}}\left[m, n + \frac{1}{2}\right] = \frac{1 - \frac{\sigma_m \Delta t}{2\mu}}{1 + \frac{\sigma_m \Delta t}{2\mu}} H_x^{q-\frac{1}{2}}\left[m, n - \frac{1}{2}\right] - \frac{1}{1 + \frac{\sigma_m \Delta t}{2\mu}} \frac{\Delta t}{\mu \Delta y} (E_z^q[m, n+1] - E_z^q[m, n]), \quad (4.18)$$

Update equation for electric field  $E_z(m, n)$  in two dimensions is

$$E_z^{q+1}[m, n] = \frac{1 - \frac{\sigma \Delta t}{2\epsilon}}{1 + \frac{\sigma \Delta t}{2\epsilon}} E_z^q[m, n] + \frac{1}{1 + \frac{\sigma \Delta t}{2\epsilon}} \left( \frac{\Delta t}{\epsilon \Delta x} \left\{ H_y^{q+\frac{1}{2}}\left[m + \frac{1}{2}, n\right] - H_y^{q+\frac{1}{2}}\left[m - \frac{1}{2}, n\right] \right\} - \frac{\Delta t}{\epsilon \Delta y} \left\{ H_x^{q+\frac{1}{2}}\left[m, n + \frac{1}{2}\right] - H_x^{q+\frac{1}{2}}\left[m, n - \frac{1}{2}\right] \right\} \right), \quad (4.19)$$

These are the update equations of electric and magnetic field for FDTD under two dimensions in  $TM^z$  mode.

#### **4.5 Absorbing boundary condition (ABC)**

The absorbing boundary conditions (ABC) are necessary to perfectly absorb outgoing electromagnetic waves or E and H fields from being prevented to reflect back into the problem space. There are many boundary conditions which are being used to eliminate the reflection of waves in problem space listed as

- Perfect electric condition (PEC)
- Perfect magnetic condition (PMC)
- Perfectly matched layer (PML)

The artificial boundary layer was originally proposed in 1994 by J.P. Berenger called Berenger split perfectly matched layer (PML) [5]. The PML layer behaves as a lossy layer and fulfills the purpose of absorbing of the EM fields which are moving towards the outer boundary of the computational grids. It is constructed in such a manner that it will not affect the EM waves which are tangential to the intersecting surfaces of PML and lossy region. For Berenger split PML, the field component comprises of two parts where the original one is the superimposition of two parts which provide an immunization from reflections at the interfacing junction by splitting the field with appropriate phase velocity and conductivity. Further, CPML is introduced by Chew and Weedon in 1994 and construct for an anisotropic and dispersive material. It eliminates the need of splitting the fields and hence can be efficiently used for implementation.

In this chapter, the numerical analysis of simple plasma monopole antenna by using full wave computational electromagnetics technique, finite difference time domain (FDTD) is presented. In simulation, far field radiation is analyzed by considering the electric field on grids located in certain radius lying in far field regions. Radiation characteristic for the simple plasma monopole has been studied for the variable length and plasma frequency which results significant change in radiation parameters such as beam-width, radiation intensity, directivity etc.

#### 5.1 FDTD Formulation of Electromagnetic Wave in medium

The propagation of electromagnetic wave in a medium follows the Maxwell equation which is basically depends on medium parameters. The general form of Maxwell equations are written as,

$$\nabla \times E = -\sigma_m H - \mu \frac{\partial H}{\partial t}, \quad (5.1)$$

$$\nabla \times H = \sigma E + \varepsilon \frac{\partial E}{\partial t}, \quad (5.2)$$

where  $E$  and  $H$  are the electric and magnetic fields of wave and  $\varepsilon$ ,  $\mu$ ,  $\sigma$  and  $\sigma_m$  are electric permittivity, permeability, electric conductivity and magnetic conductivity of the medium. In FDTD, Maxwell equations are written in a time and space coordinate which are given by [28].

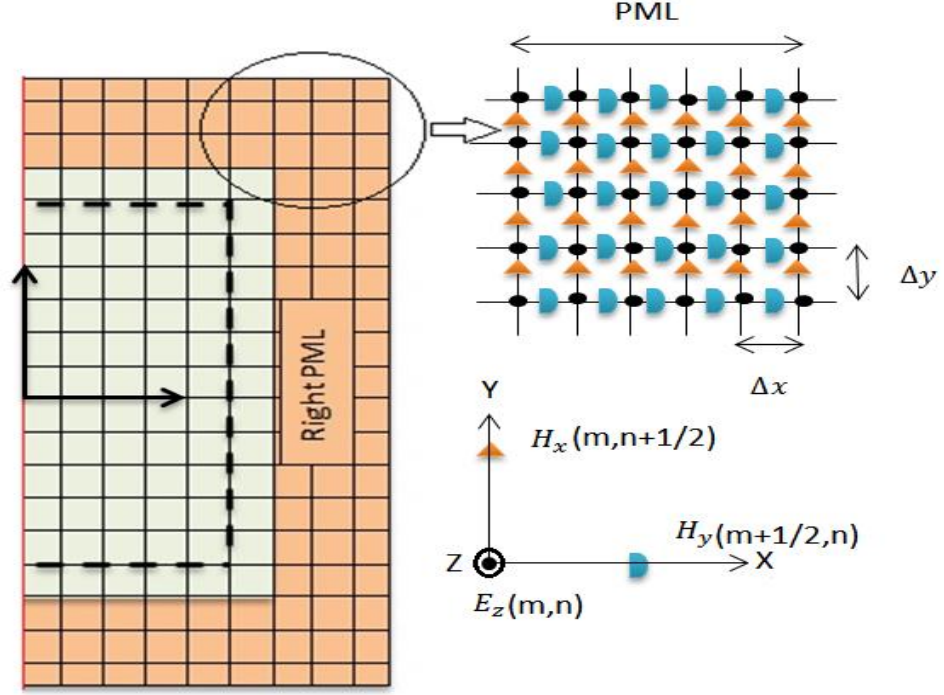


Fig. 5.1: Geometry of FDTD computational domain

$$E_z^{q+1}[m, n] = \frac{1 - \frac{\sigma \Delta t}{2\varepsilon}}{1 + \frac{\sigma \Delta t}{2\varepsilon}} E_z^q[m, n] + \frac{1}{1 + \frac{\sigma \Delta t}{2\varepsilon}} \left( \begin{aligned} & \frac{\Delta t}{\varepsilon \Delta x} \left\{ H_y^{q+\frac{1}{2}} \left[ m + \frac{1}{2}, n \right] - H_y^{q+\frac{1}{2}} \left[ m - \frac{1}{2}, n \right] \right\} \\ & - \frac{\Delta t}{\varepsilon \Delta y} \left\{ H_x^{q+\frac{1}{2}} \left[ m, n + \frac{1}{2} \right] - H_x^{q+\frac{1}{2}} \left[ m, n - \frac{1}{2} \right] \right\} \end{aligned} \right), \quad (5.3)$$

$$H_x^{q+\frac{1}{2}} \left[ m, n + \frac{1}{2} \right] = \frac{1 - \frac{\sigma_m \Delta t}{2\mu}}{1 + \frac{\sigma_m \Delta t}{2\mu}} H_x^{q-\frac{1}{2}} \left[ m, n - \frac{1}{2} \right] - \frac{1}{1 + \frac{\sigma_m \Delta t}{2\mu}} \frac{\Delta t}{\mu \Delta y} (E_z^q[m, n+1] - E_z^q[m, n]), \quad (5.4)$$

$$H_y^{q+\frac{1}{2}} \left[ m + \frac{1}{2}, n \right] = \frac{1 - \frac{\sigma_m \Delta t}{2\mu}}{1 + \frac{\sigma_m \Delta t}{2\mu}} H_y^{q-\frac{1}{2}} \left[ m + \frac{1}{2}, n \right] + \frac{1}{1 + \frac{\sigma_m \Delta t}{2\mu}} \frac{\Delta t}{\mu \Delta x} (E_z^q[m+1, n] - E_z^q[m, n]), \quad (5.5)$$

Where  $\Delta_x$ ,  $\Delta_y$  are spatial parameters of grid in x-y direction and  $\Delta_t$  is temporal step equivalent to time taken by the wave to travel the grid distance where indices [q] and [m, n] denotes the time and spatial steps, respectively as shown in Fig.5.1. The value of electric field and magnetic field at any grid location can be calculated by using above equations and its iteration provides the simulation of wave propagation in computational space.

In case of plasma medium relative permittivity and conductivity are the function of plasma parameters like angular plasma frequency  $\omega_p$ , wave frequency  $\omega$ , electron collision frequency  $\nu_c$  and electron density  $n_e$  which are written as, [14].

$$\epsilon_r = 1 + \frac{\omega_p^2}{\omega(j\nu_c - \omega)}, \quad (5.6)$$

$$\sigma = \frac{e^2 n_e \nu_c}{m(\omega^2 + \nu_c^2)}, \quad (5.7)$$

where  $\omega_p = \sqrt{n_e e^2 / m \epsilon_0}$ ,  $m$  and  $e$  are mass and charge of electrons and  $\epsilon_0$  is permittivity of free-space. The value of plasma permittivity and conductivity can be changed by changing the plasma parameters.

## 5.2 Simple plasma monopole antenna using FDTD simulation

A plasma monopole antenna is analyzed using numerical technique finite difference time domain (FDTD). Schematic of computational space used in FDTD simulation is shown in Fig.5.2, where total space,  $v$  is composed in  $200 \times 200$  grids i.e. divided by Plasma column, free space and PML boundary at each side of problem space and length of each are defined as  $L=80$  grids,  $PML = 40$  grids and rest is free space. A circle of certain radius  $R > 2L^2/\lambda$  has been marked to analyze far field radiation where  $\lambda$  is wavelength of wave frequency. The grids lies on circle are considered to calculate the electric field imping at grids positions at particular time step. To analyze the plasma column as monopole antenna PEC is implemented at below end and marked with black line.

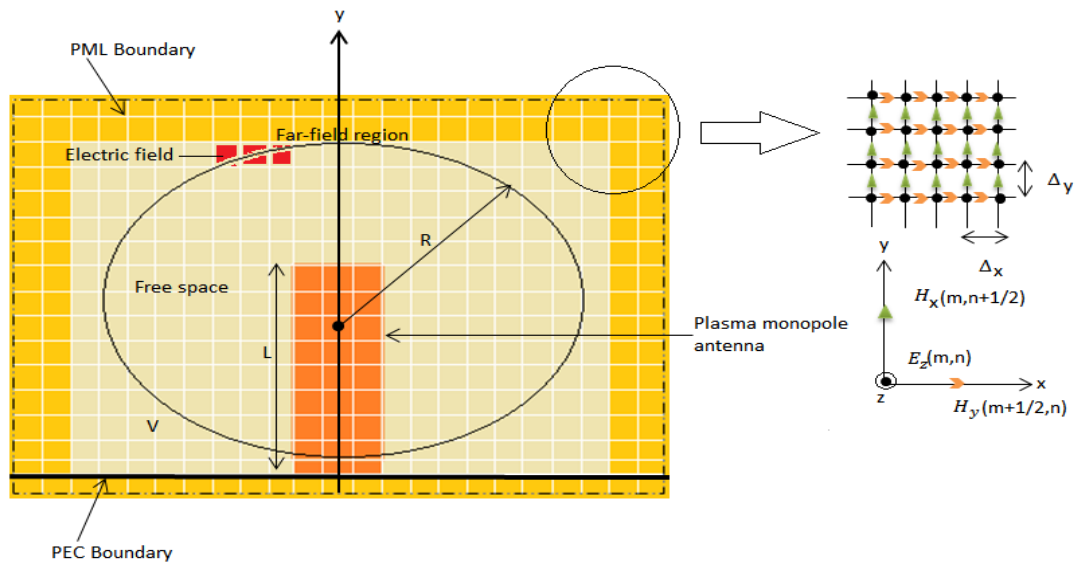
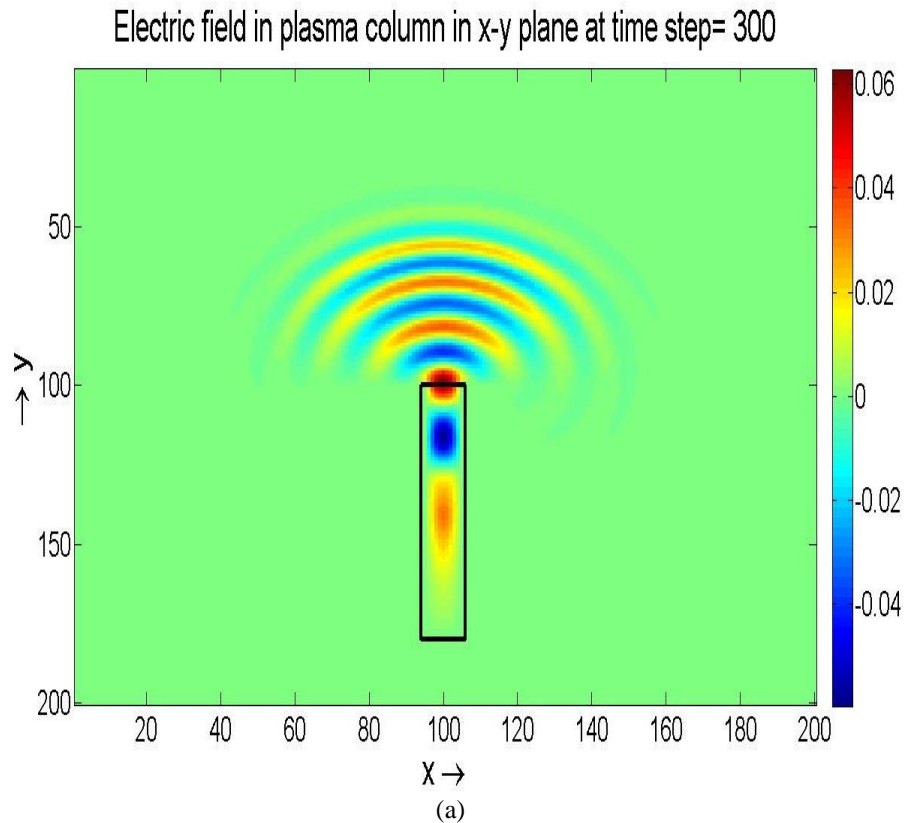


Fig. 5.2: Geometrical view of plasma monopole antenna using FDTD approach.

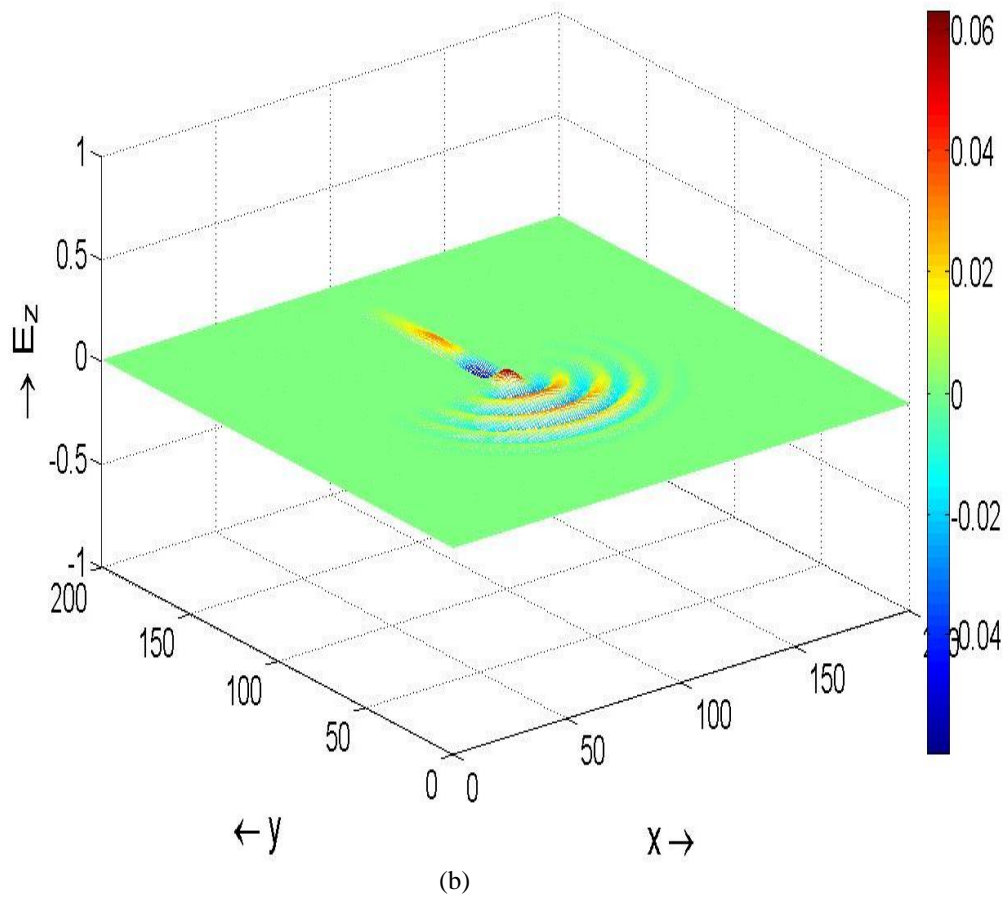
### 5.3. Numerical results

The results obtained from the FDTD simulation describes the electric field radiated from plasma monopole in X-Y plane. Here, computational space is composed in  $200 \times 200$  grids having spatial step  $\Delta x = \Delta y = 0.003$  m and temporal step is  $\Delta t = 6.9344 \times 10^{-12}$  s. A Gaussian pulse  $E(T) = 2 \left( \frac{T-t_c}{d} \right) e^{\left( \frac{-(T-t_c)}{d} \right)^2}$ , is used as excitation source at one end of plasma column where pulse parameters are taken as,  $t_c = 20$  and  $d = 10$  that travels along directions of plasma monopole and radiated over the free space in total time step of 300s. The number of PML grid is taken as 40. Plasma parameters are initialized from  $\epsilon_r = 1 + \frac{\omega_p^2}{\omega(j\nu_c - \omega)}$ , where  $\omega_p = 1.8 \times 10^{10}$  rad/sec,  $\omega = 3.1484 \times 10^{10}$  rad/sec and  $\nu_c = 1.5 \times 10^9$  GHz.

To plot the far field radiation pattern, magnitude of electric field is analyzed at grids which are lying on the circle of certain radius. In Fig.8, concerned circle is represented with dark line which passes through a set of grids lies on far field locations R. The electric fields magnitudes, on these set of grids are extracted and plotted for its polar location. The obtained results are shown in Fig.5.3 and Fig.5.4; whereas Fig.5.3, (a), (b), and (c) represent the radiated electric field in computational space for top view, side view and on grids of the marked circle respectively.



Electric field in plasma monopole antenna at time step = 300



Electric field lying on far field region at time step = 300

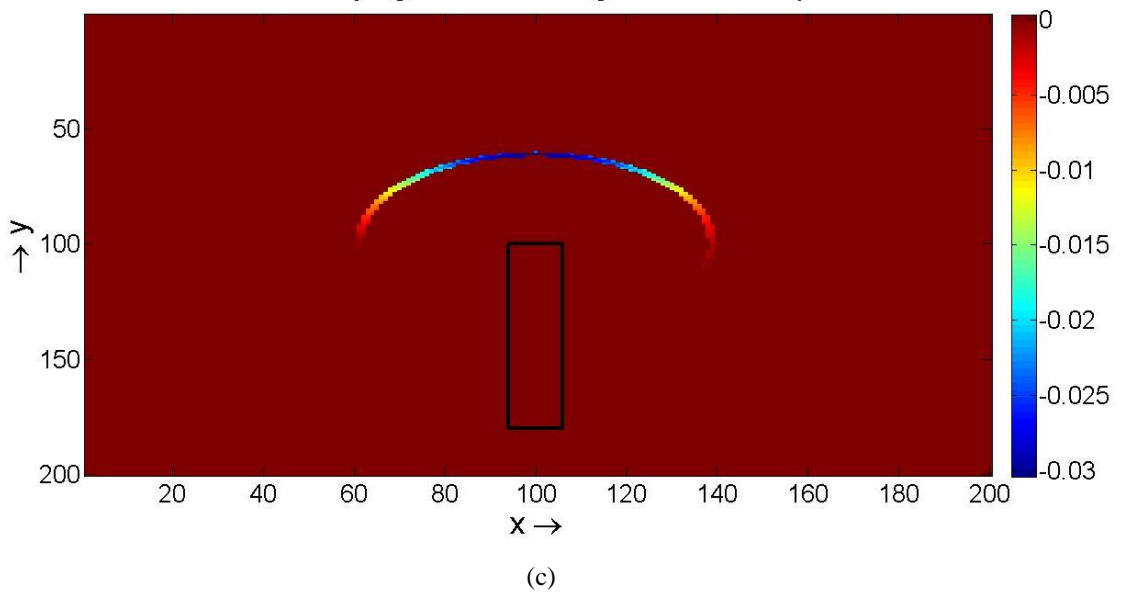


Fig. 5.3: Represents electric field in simple plasma monopole. a) Top view b) Side view c) Electric field on grids located in far field region.

Fig.5.4 (a) and 5.4 (b) show the polar plot of electric field for different antenna height i.e.  $L_1 = 0.3$  m,  $L_2 = 0.24$  m and  $L_3 = 0.36$  m and operating frequency  $f_1 = 5.5$ GHz,  $f_2 = 6.0$ GHz, and  $f_3 = 6.5$ GHz. In polar plot, it can be observed that beam-width of radiated electric field become narrow as length of dipole is increased and same can be observed in case of variable frequency. These observations are very obvious in metallic monopole antenna and plasma antenna is also found in same agreement.

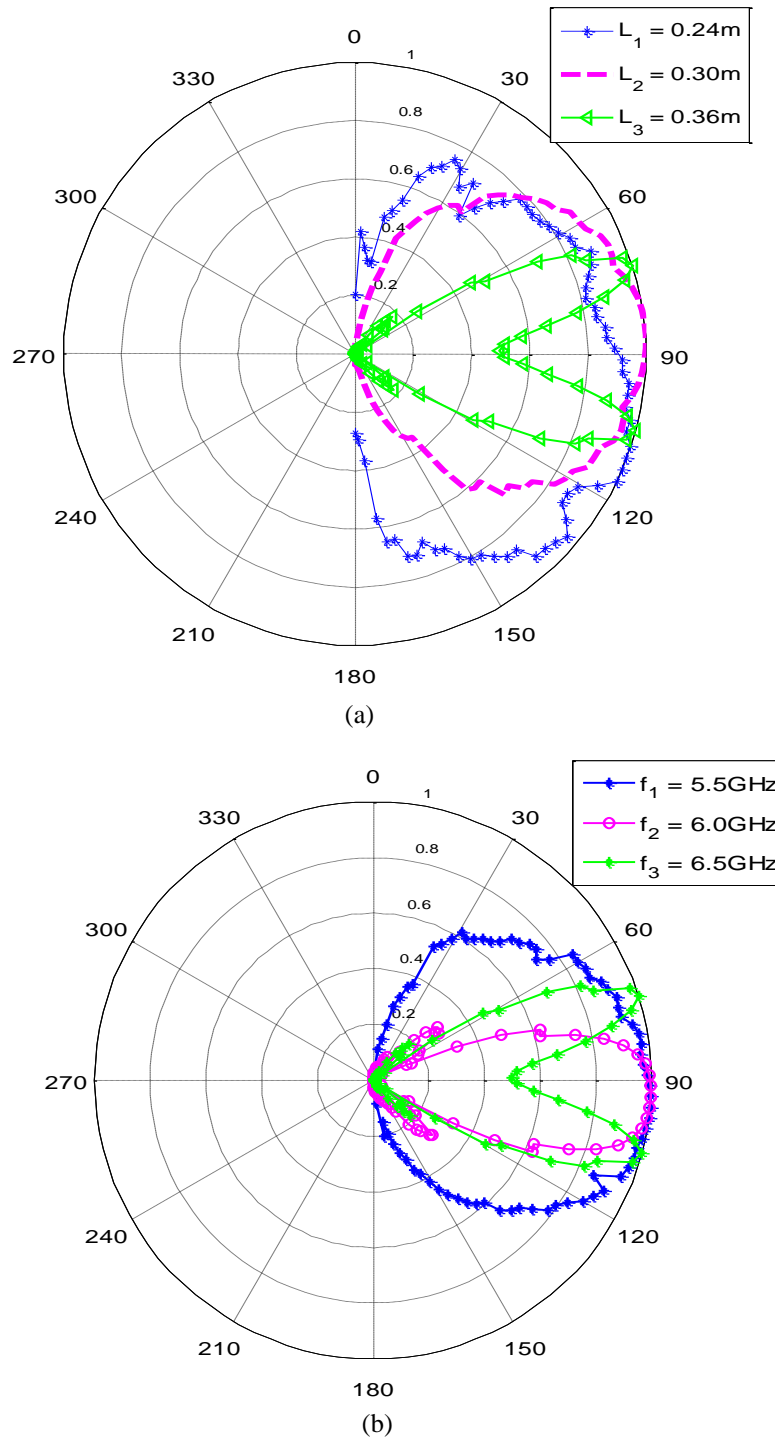


Fig. 5.4: Polar plot of radiated electric field from simple monopole for a) variable length b) variable frequency.

**Analysis of capacitive loaded plasma monopole antenna**

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In previous chapter 5, analysis of simple plasma monopole antenna is explained. The numerical analysis shows that the radiation of plasma column is found as efficient as metallic antenna. It provides an alternative method for achieving wider bandwidth in the era of communication because of its interesting behavior and also provides ability to change the radiation pattern without changing the antenna dimension. Here this chapter represents analysis and simulation of capacitive loaded plasma monopole antenna using FDTD technique has been presented. The loaded plasma monopole is defined as a plasma column incorporated with regular structural discontinuity where resultant effect of the discontinuity provides the capacitive loading on antenna element. This property can be very useful to design an antenna for desired radiation parameters. This method is completely passive where no active control is required. To analyze the simulation outcomes in detail, a novel theoretical procedure has been developed. The developed theory found an agreement to the FDTD simulation outcomes.

**6.1 FDTD simulation of capacitive loaded plasma monopole antenna**

In this section, a capacitive loaded plasma monopole antenna is analyzed using FDTD numerical technique explained in previous section 5.1. Here, Fig.6.1 represents the geometrical view of computational space used in FDTD simulation where total space is composed in  $200 \times 200$  grids. The plasma column of length  $L$  is positioned at center of X-side and aligned in Y-direction. The boundary at each side of problem space is assigned for perfectly matched layer (PML) and rest is free space. The dimensions of monopole and PML are taken as  $L=80 \times 12$  grids,  $PML = 40 \times 200$  grids in each side. To analyze the plasma column as monopole antenna perfect Electric conducting (PEC) boundary is implemented. The plasma column is excited with Gaussian pulse source at bottom end that travels along the direction of monopole and spread out from plasma column. A circle of certain radius  $R > 2L^2/\lambda$  has been marked to analyze far field radiation where  $\lambda$  is wavelength at wave frequency. Here

grids on marked circle are provides the values of radiated electric field at distance  $R$  which are used to plot the radiated field in polar coordinate. The capacitive loaded monopole has been simulated for the given parameters as taken for simple plasma monopole antenna explained in section 5.3. The electric field plot obtained from FDTD simulation is shown in Fig. 6.2 (a), (b) and (c) which represents the magnitude of radiated electric field in computational space for top view, side view and on grids of the marked circle respectively where magnitude of radiated field is to be extracted for polar locations.

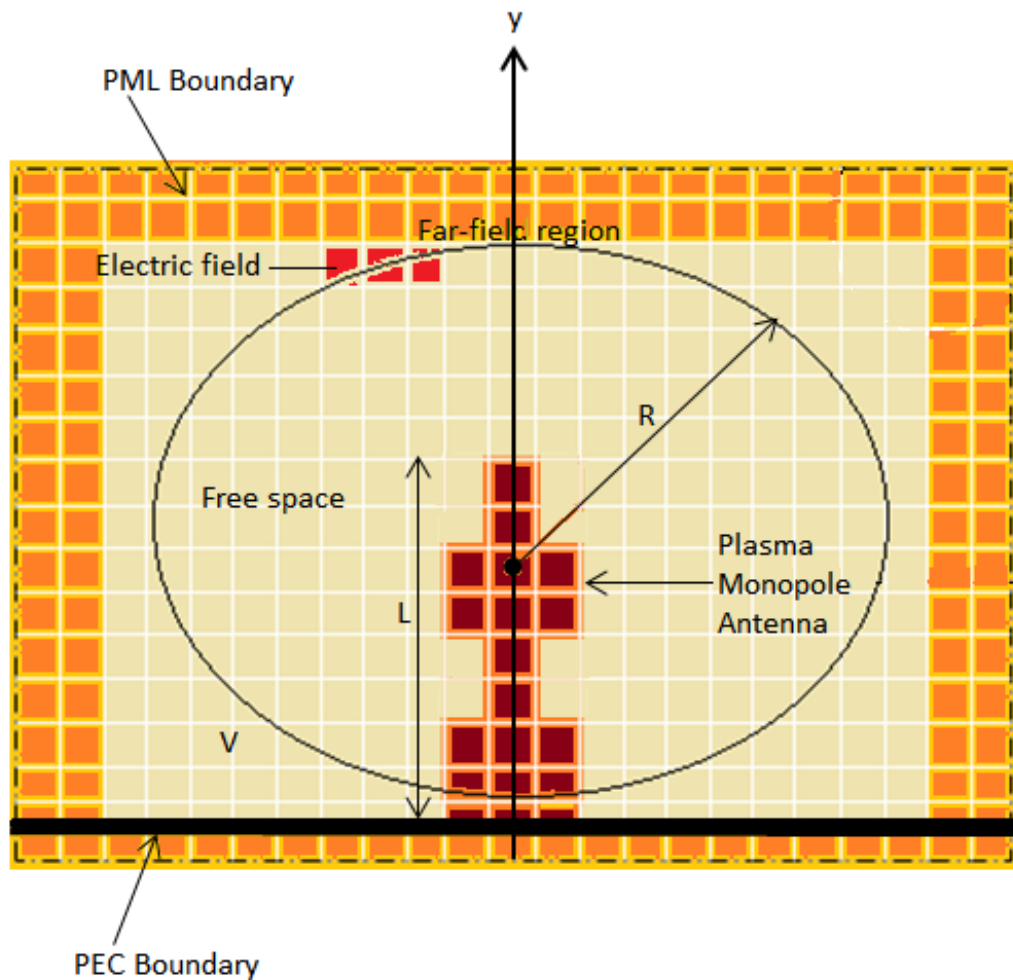
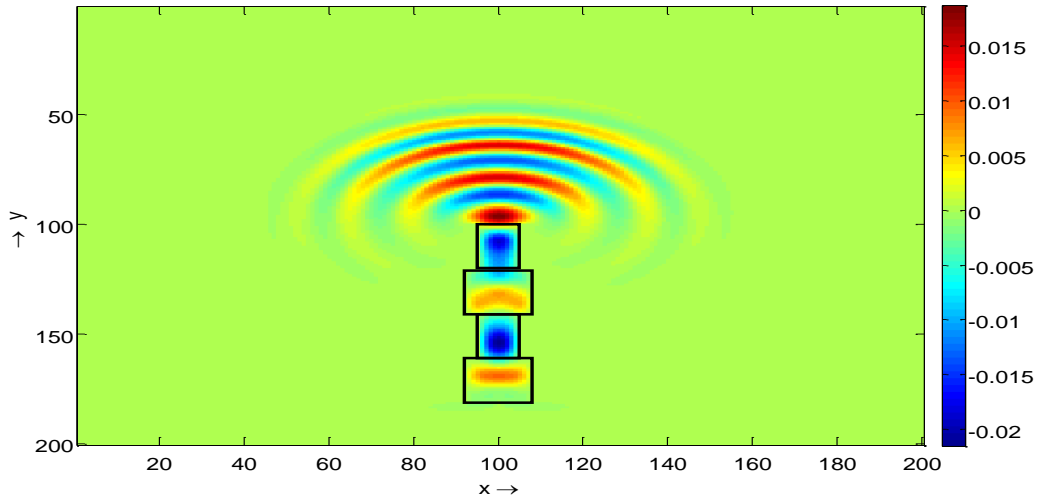


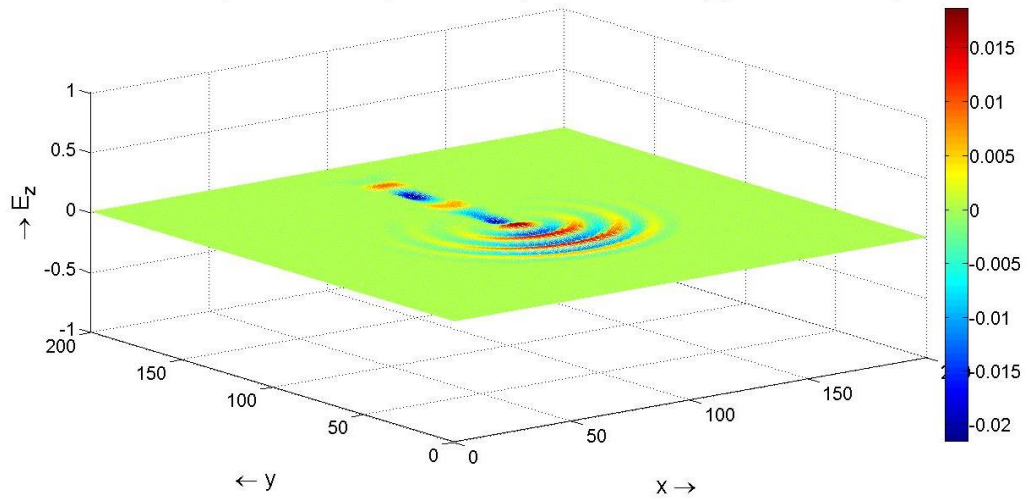
Fig. 6.1: Geometrical view of computational space for loaded antenna

Electric field in capacitive loaded plasma monopole antenna in x-y plane at time step = 300



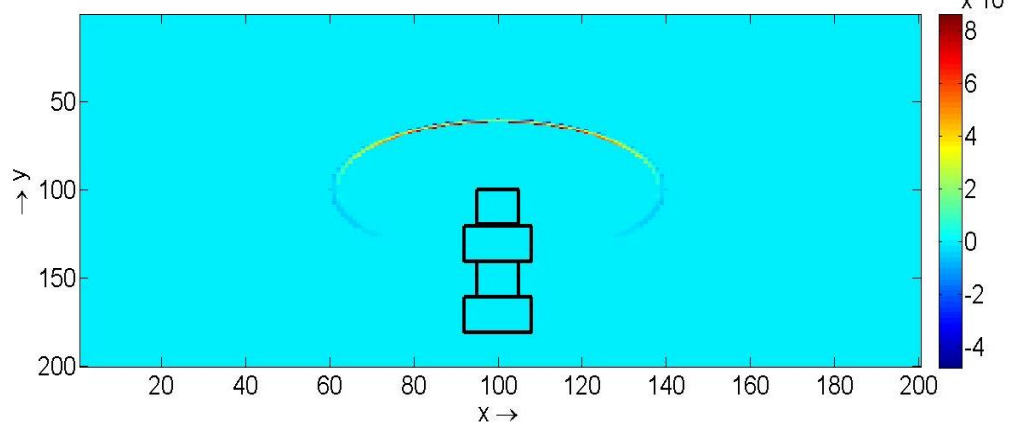
(a)

Electric field in capacitive loaded plasma monopole antenna in x-y plane at time step = 300



(b)

Electric field in capacitive loaded plasma monopole antenna in x-y plane at time step = 300

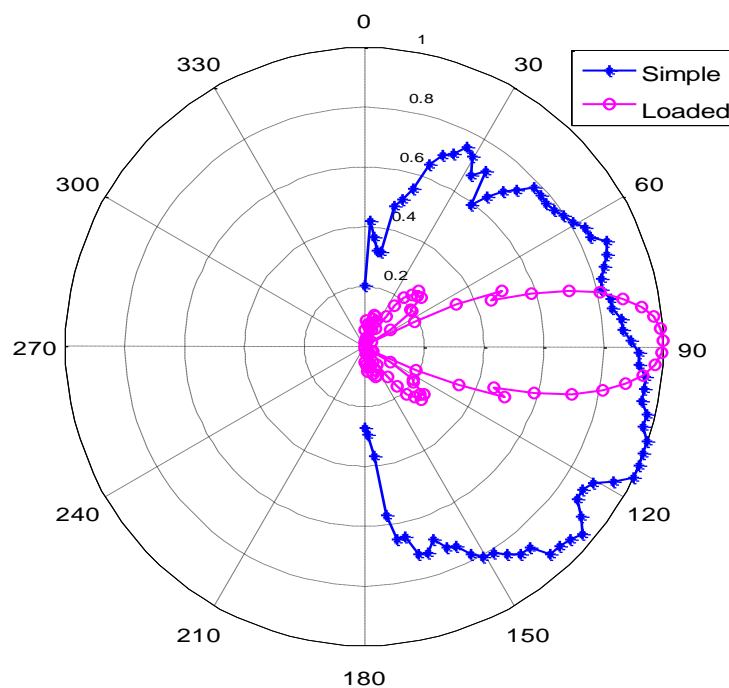


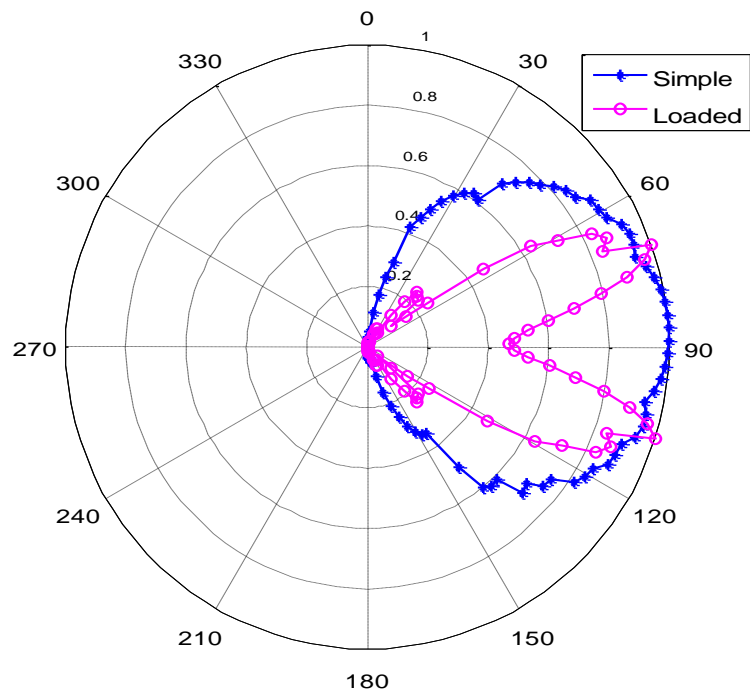
(c)

Fig. 6.2 : Represents electric field in capacitive loaded plasma column. a) Top view b) Side view c) Electric field on grids located in far field region.

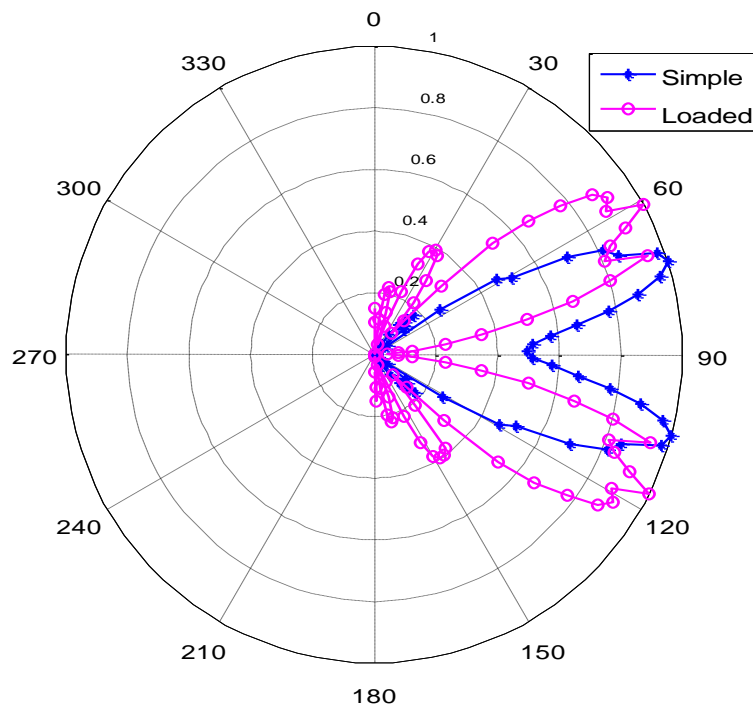
## 6.2 Numerical results

The results obtained from the simulation of loaded monopole are shown in Fig.6.3 in perspective comparison of simple monopole. Here, Fig.6.3, (a), (b) and (c) show the comparison of radiated electric field of simple and loaded monopoles at different lengths  $L_1 = 0.24\text{m}$ ,  $L_2 = 0.30\text{m}$  and  $L_3 = 0.36\text{m}$  whereas Fig.6.3, (d), (e) and (f) represent comparison of electric field at different frequencies  $f_1 = 5.5\text{GHz}$ ,  $f_2 = 6.0\text{GHz}$  and  $f_3 = 6.5\text{GHz}$ . It can be observed that the beam-width of loaded monopole is found narrow and more directional as compared to simple monopole in each and every case. The comparative differences in radiated electric field of these two antennae are found similar as it can be observed in comparison of any one kind of antenna at two different lengths or frequencies as shown in Fig.5.4. In each case, the loaded antenna provides radiation that seems to be radiated by simple monopole of greater height as compared to it. This means effective height of antenna is increased as discontinuity is incorporated. As the height of antenna increases, lobeing is observed first in loaded antenna and then after in simple monopole. For example, in case  $L_2 = 0.30\text{m}$  shown in Fig.6.3 (b) radiation pattern of loaded antenna provides the two lobes whereas simple one has only one lobe. The similar result can also be observed in case of radiation at different frequency.

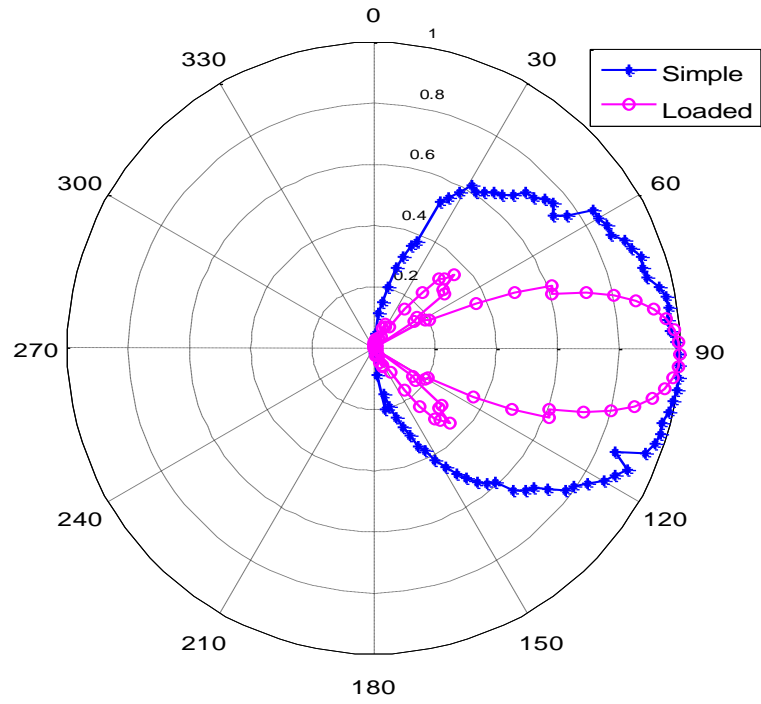




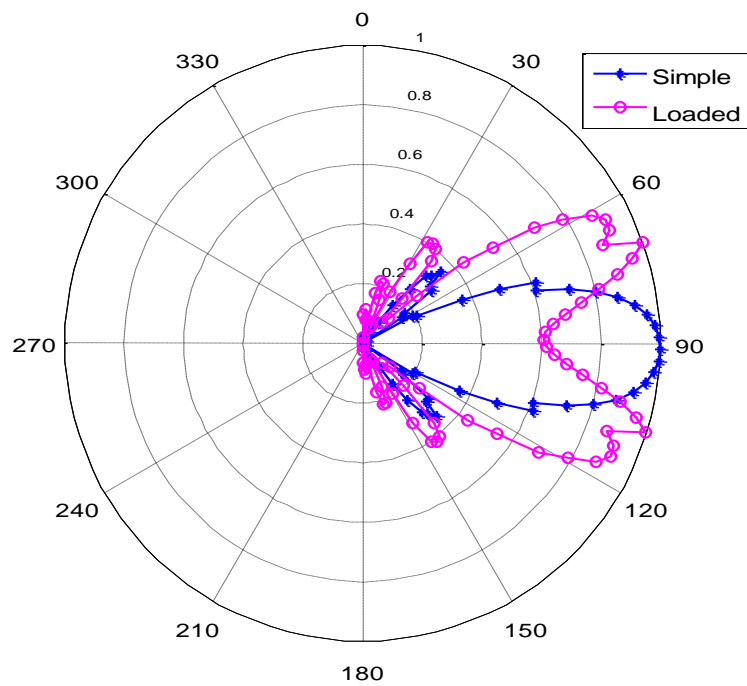
(b)



(c)



(d)



(e)

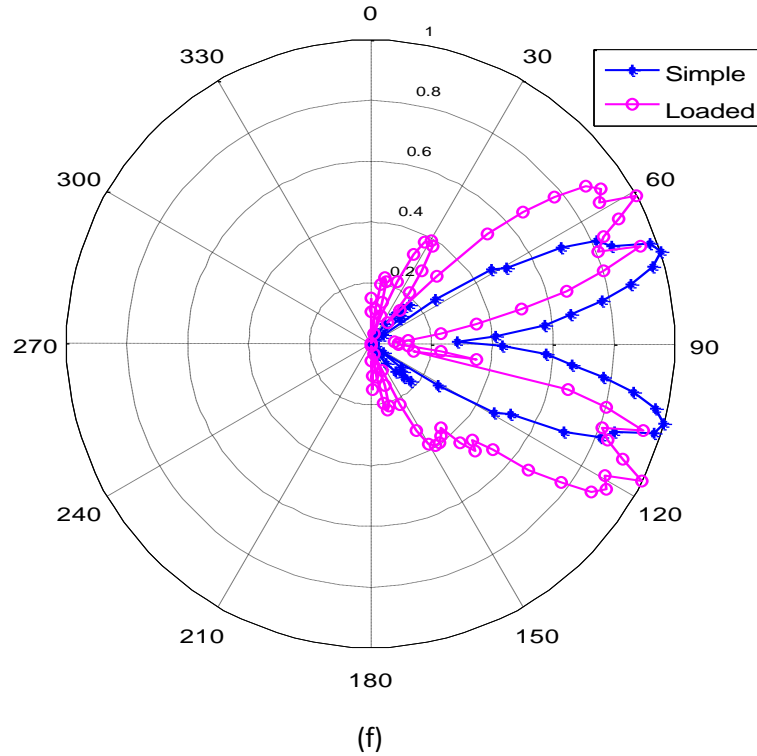


Fig 6.3: Perspective comparison of the radiated electric field from simple and loaded monopole antenna at lengths a)  $L_1 = 0.24\text{m}$  b)  $L_2 = 0.30\text{m}$  c)  $L_3 = 0.36\text{m}$  and frequencies d)  $f = 5.5\text{GHz}$  e)  $f = 6.0\text{GHz}$  f)  $f = 6.5\text{GHz}$ .

As per above observation it can be concludes that the effective height of antenna is increased as discontinuity is incorporated in antenna structure. To analyze the effect of discontinuity in detail, a mathematical analysis of loaded antenna structure is presented in next section.

### 6.3. Mathematical analysis of capacitive loaded plasma monopole

Schematic of loaded plasma monopole is shown in Fig.6.4 (a) that represent stepped and discontinuous cylindrical structure. This is obtained from cascading the two cylindrical structures of different diameters. Plasma is filled inside tube and provides conductive path for propagation of rf signals. The composite assembly behaves as monopole. The segment of bigger cross sections provides lower resistance for charge carriers as compared to narrow one. This could be analyzed by given eqn. (6.1),

$$R = \rho \frac{l}{A}, \quad (6.1)$$

Here  $R$  is resistance,  $\rho$  is specific resistance that depends on material properties,  $A$  is area of cross section and  $l$  is length of conductor.

As the area is a decreased resistance increase. Thus the rf signal experiences lower impedance in bigger section. By considering this analysis, the electrical equivalence of plasma monopole is shown in Fig.6.4 (b). The smaller X-section of  $Z_1$  impedance is attached with bigger sections of  $Z_2$  impedance where  $Z_2 \ll Z_1$ . The two identical unit of this equivalent can be cascaded to get the total of monopole. The analysis of the single unit is presented herewith.

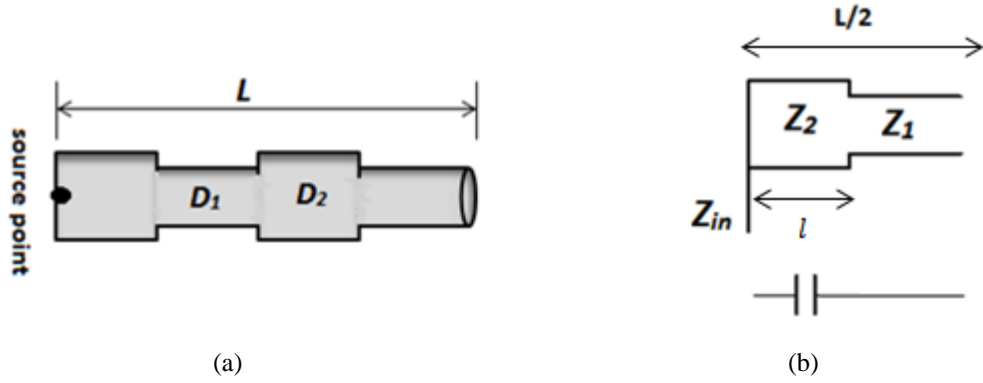


Fig 6.4: Plasma monopole a) schematic b) Electrical equivalent.

Transferred impedance  $Z_{in}$ , at either side of junction is given by,

$$Z_{in} = Z_2 \frac{Z_1 + jZ_2 \tan \beta l}{Z_2 + jZ_1 \tan \beta l} \quad (6.2)$$

Where  $l$  is length of bigger section and  $\beta$  is propagation constant. For  $Z_2 \ll Z_1$ , and  $l < \frac{\lambda}{4}$  above equation can be approximated as [17-18],

$$Z_{in} = \frac{Z_2}{j \tan \beta l} = \frac{1}{jX_c} \quad (6.3)$$

This means discontinuity in antenna structure introduces an equivalent reactive effect in monopole and provide capacitive loading on plasma antenna. This changes the current profile of plasma antenna. The radiated field from monopole antenna can be expressed as [27]

$$E_\theta \cong jn \frac{ke^{-jkr}}{4\pi r} \sin \theta \int_0^{L/2} I(z) e^{jkz \cos \theta} dz \quad (6.4)$$

where  $I(z)$  is current profile of the monopole having in  $z$  direction,  $r$  and  $\theta$  are the distance angle of far field location form antenna and  $k$  is propagation constant of the wave. Here  $I(z)$  is defined as

$$I(z) = \widehat{a}_z I_0 \sin \left( k \left( \frac{L}{2} - z \right) \right), \quad 0 < z < L/2 \quad (6.5)$$

Substituting the value of  $I(z)$  in eqn. (6.4)

$$E_{\theta} \cong jn \frac{kI_0 e^{-jkr}}{4\pi r} \sin\theta \left\{ \int_0^{L/2} \sin(k(L/2 - z)) e^{jkz \cos\theta} dz \right\} \quad (6.6)$$

The analysis shows that the incorporated discontinuity provide progressive phase shift in current profile. This is also be included eqn. (6.6) and the modified eqn. is written as,

$$E_{\theta} \cong jn \frac{kI_0 e^{-jkr}}{4\pi r} \sin\theta \left\{ \int_0^{L/2} \sin(k(L/2 - z + \phi)) e^{jkz \cos\theta} dz \right\} \quad (6.7)$$

Where  $\phi$  is taken as progressive phase shift introduced by discontinuity. It can be solved with the help of standard form of integral equation which is given as,

$$\int e^{\alpha z'} \sin(\beta z' - \gamma) dz' = - \left[ \frac{e^{\alpha z'}}{(\alpha^2 + \beta^2)} (\alpha \sin(\beta z' - \gamma) - \beta \cos(\beta z' - \gamma)) \right] \quad (6.8)$$

Comparison of eqn. (6.7) and (6.8) gives,

$$\begin{aligned} \alpha &= \pm jk \cos\theta \\ \beta &= \pm k \\ \gamma &= \frac{kl}{2} + \phi \end{aligned}$$

From eqn. (6.7) and (6.8), radiated electric field for the loaded unit is derived as,

$$E_{\theta(\text{loaded})} = jn \frac{I_0 e^{-jkr}}{2\pi r} \left[ \frac{\cos\left(\frac{kL}{2} \cos\theta\right) \cos\phi - \cos\left(\frac{kL}{2} + \phi\right)}{\sin\theta} \right] + jX \quad (6.9)$$

Where,  $X = \left\{ \sin\left(\frac{kl}{2} \cos\theta\right) - \cos\left(\frac{kl}{2} \cos\theta\right) \right\} \cos\theta \sin\phi - \cos\theta \sin\left(\frac{kl}{2} + \phi\right)$  is a reactive form.

By omitting the complex reactive term, the above equation can be rewritten as,

$$E_{\theta(\text{loaded})} = jn \frac{I_0 e^{-jkr}}{2\pi r} \left[ \frac{\cos\left(\frac{kL}{2} \cos\theta\right) \cos(\phi) - \cos\left(\frac{kL}{2} + \phi\right)}{\sin\theta} \right] \quad (6.10)$$

This is simplified as,

$$E_{\theta(\text{loaded})} = jn \frac{I_0 e^{-jkr}}{2\pi r} \left[ \frac{\cos\left(\frac{kL}{2} \cos\theta\right) \cos(\phi) - \cos\left(\frac{kL}{2}\right) \cos(\phi) + \sin\left(\frac{kL}{2}\right) \sin(\phi)}{\sin\theta} \right] \quad (6.11)$$

$$E_{\theta(\text{loaded})} = E_{\theta(\text{simple})} \cos\phi + jn \frac{I_0 e^{-jkr}}{2\pi r} \left[ \frac{\sin\left(\frac{kL}{2}\right) \sin(\phi)}{\sin\theta} \right] \quad (6.12)$$

Here electric field radiated from the loaded monopole,  $E_{\theta(\text{loaded})}$  is obtained from multiplying a factor  $\cos\phi$  in field radiated by metallic monopole in addition of  $jn \frac{I_0 e^{-jkr}}{2\pi r} \left[ \frac{\sin\left(\frac{kL}{2}\right) \sin(\phi)}{\sin\theta} \right]$ . The first term  $\cos\phi$  provides the array effect in monopole whereas second part is an equivalence of incremental length. The combine effect of these two is observed in FDTD simulation results.

The analysis explores that the radiation pattern of antenna can be changed by change of  $\cos \theta$  and  $\sin \theta$  and it can be reconfigured for variable  $\theta$  which depends on the magnitude of capacitive loading. The loading in plasma antenna depends on the discontinuity in plasma structure. Plasma is an assembly of charge particle which can be confined by applying the DC magnetic field. Applications of magnetic fields on simple monopole at alternative segment of the length of plasma column will create an equivalent of discontinuity which forms the structure of loaded antenna. The variable of external magnetic field provides the reconfigurable radiation pattern that can be altered in very fast manner. This property of antenna is very useful for many applications like defense, communication utilities where online control on radiation pattern is required. This method is completely active. This mathematical elevation may be proven for very useful outcomes. It has been verified in next section using FDTD simulation.

### Analysis of actively reconfigurable plasma monopole antenna

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This chapter describes actively loaded plasma monopole antenna using similar finite difference approach presented in chapter 5. Here the plasma monopole is actively controlled by applying external magnetic field of certain magnitude at specific location which provides the same effect that can be achieved in previous simulated capacitive loaded plasma monopole. This property provides similar results as found in capacitive loaded antenna and also gives an option to online control on radiation characteristics where it can be reconfigured as desired.

#### **7.1 FDTD simulation of actively loaded plasma monopole**

To verify the theoretical outcomes i.e. explained in previous section-6.3, actively loaded plasma monopole has been simulated using FDTD method. Geometry shown in Fig.7.1 represents the computational space for simulation of the actively loaded plasma monopole. To form an equivalent structure like loaded antenna, external magnetic field is applied at alternative segment of the plasma column. The grids where magnetic field applied are marked with blue color. All other parameters except magnetic field are taken same as in simple plasma monopole. The actively loaded plasma monopole has been simulated for the different length and frequency and simulation result is shown in Fig.7.2 and Fig.7.3.

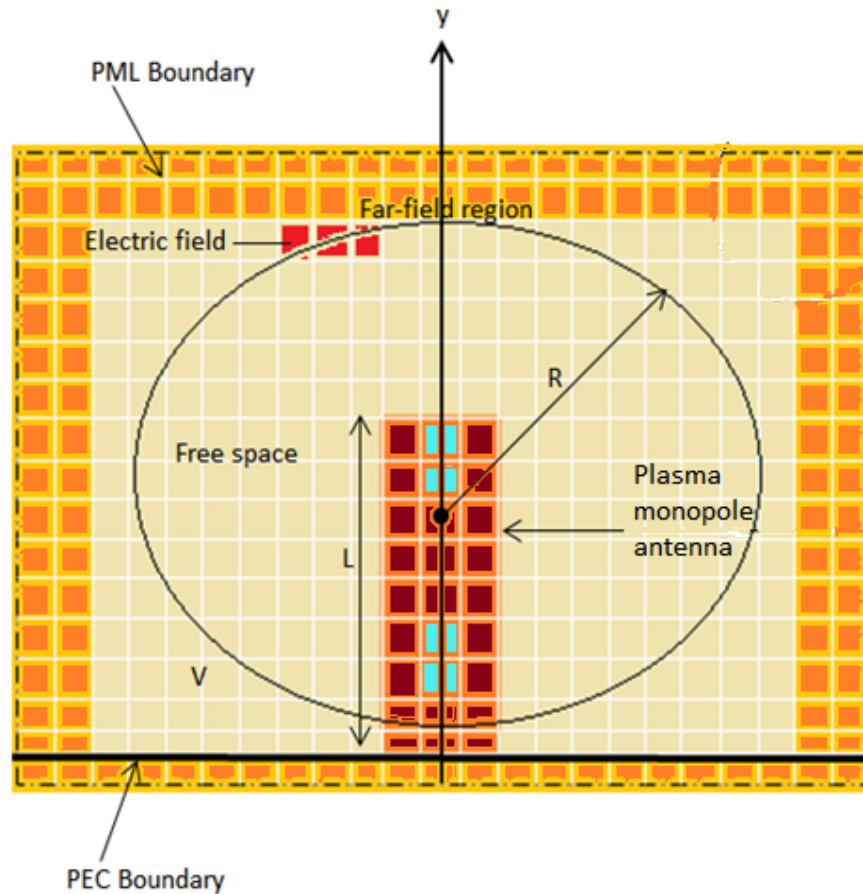
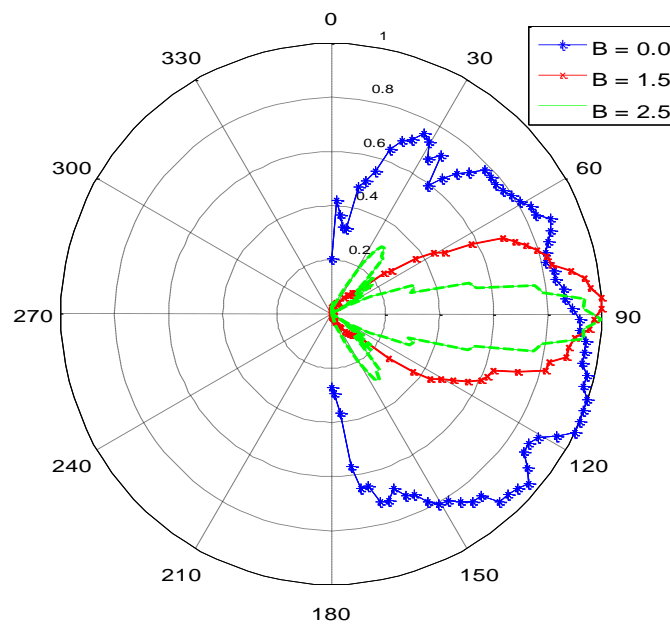


Fig. 7.1: Geometrical view of FDTD computational space of actively loaded plasma antenna.

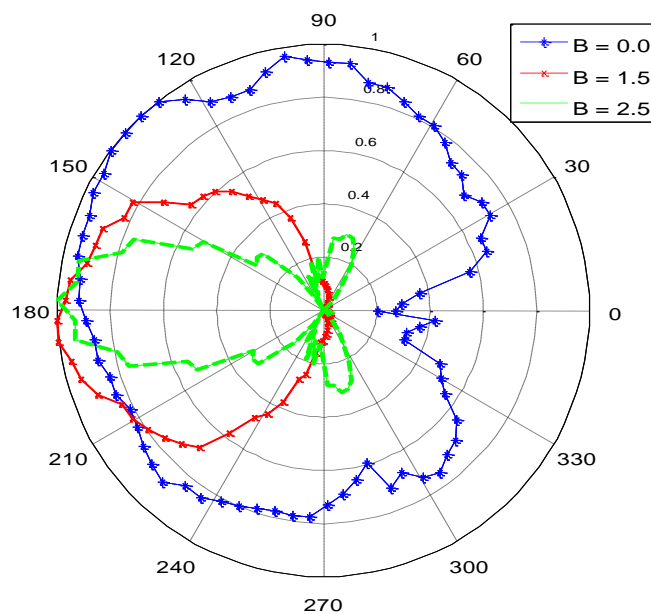
## 7.2 Simulation results

Fig.7.2, (a), (b) and (c) shows the radiated electric field and magnetic field of actively loaded antenna at different lengths  $L_1 = 0.24\text{m}$ ,  $L_2 = 0.30\text{m}$  and  $L_3 = 0.36\text{m}$  respectively. In each of the cases magnetic field is varied from 0 to 2.5 Tesla and results are presented in comparative manner. It can be observed that the beam-width of radiated fields become narrow and more directional when magnetic field is applied. The property is found as similar to the discontinuity in loaded antenna and it becomes more prominent as magnitude of the applied magnetic field is increases. For Example, in case  $L_3 = 0.36\text{m}$ , as shown in Fig.7.2 (c); at  $B = 0$ , two lobes are present in polar plot. As magnetic field applied more lobes are appeared; at  $B = 1.5$  Tesla, polar plot of electric field forms four lobes that looks in very initial shape. As the magnetic field increases by  $B = 2.5\text{Tesla}$ , side lobes become more prominent and beam width become narrow. In Fig.7.3, polar plots of the radiated electric fields of the actively loaded at  $B = 1.5$  and simple monopole at  $B= 0$  are presented. In prospective

comparison of these results, the radiation of actively loaded antenna observes more directional and side lobes are also found more prominent in it. The applied magnetic field creates the similar conductive assembly as found in passively loaded monopole. The simulation results demonstrate that the radiation of plasma monopole can be improved by incorporating the discontinuity in plasma column which can be incorporated by active or passive method. These methods provide an additional degree of freedom to control the radiation parameters. The idea is useful to develop a plasma monopole for reconfigurable pattern.

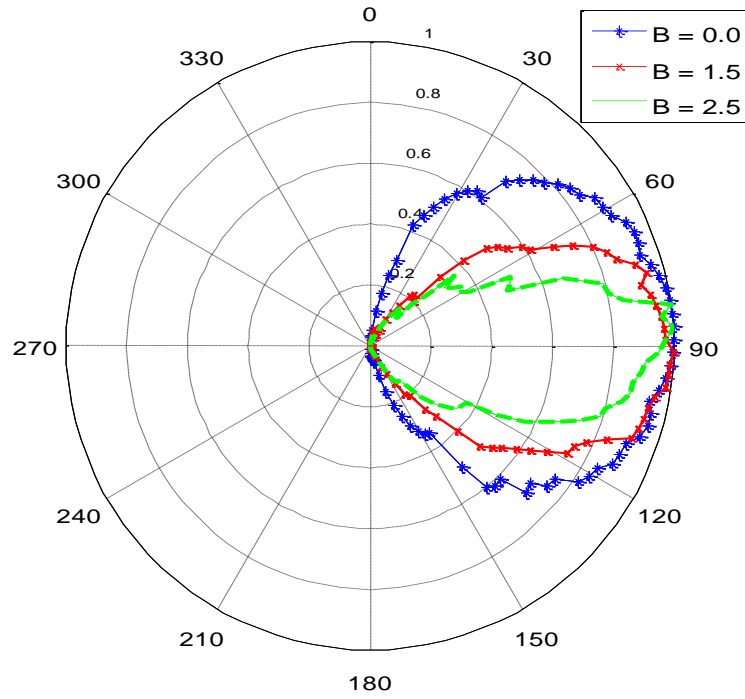


Electric field

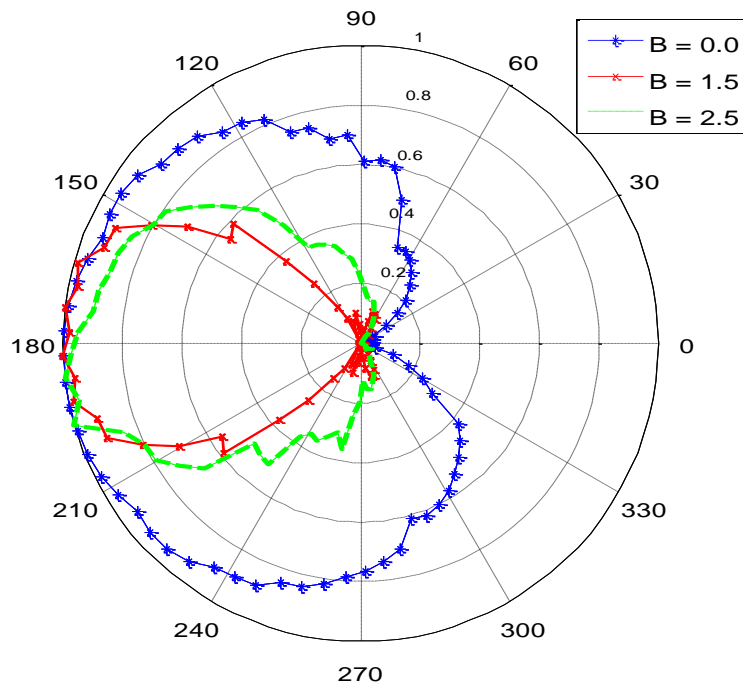


Magnetic field

(a)

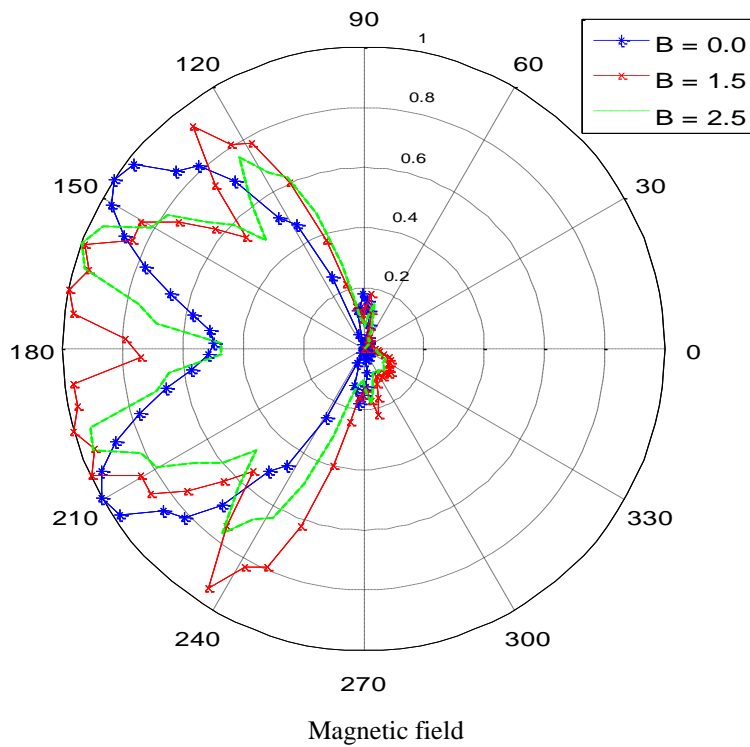
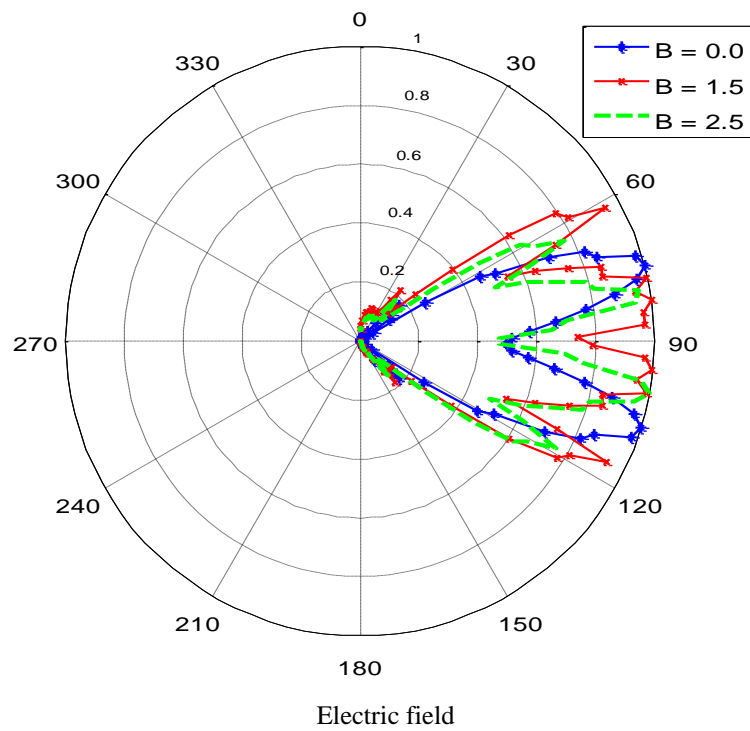


Electric field



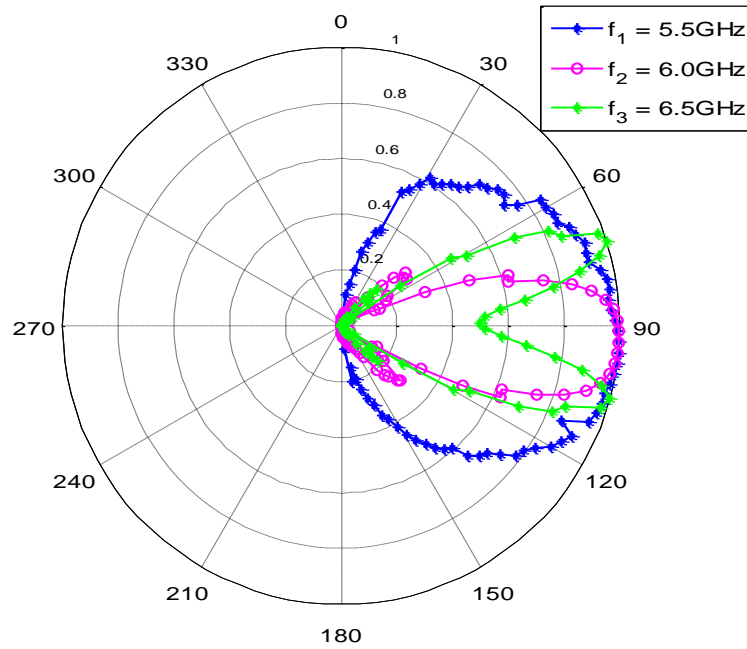
Magnetic field

(b)

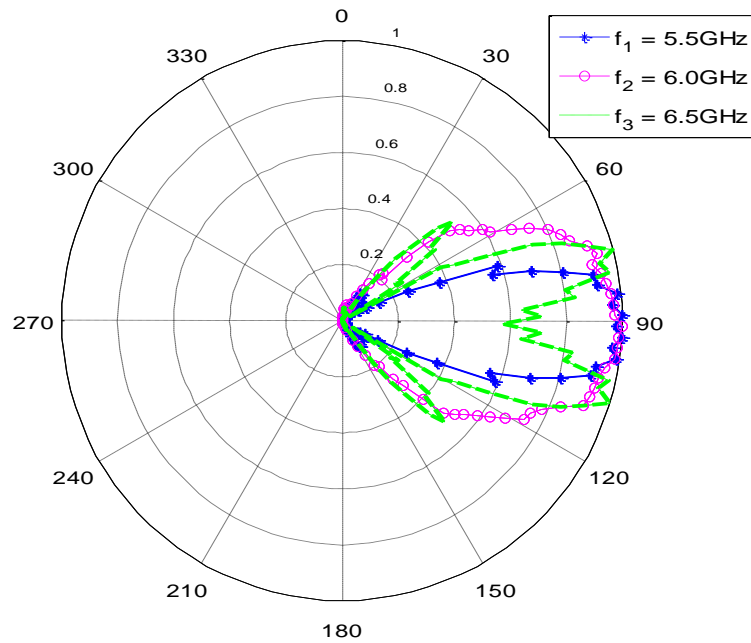


(c)

Fig 7.2: Polar plot of radiated fields of actively loaded monopole antenna of variable length and magnetic field a) E and H field plots at  $L_1 = 0.24m$  b) E and H field plots at  $L_2 = 0.30m$  c) E and H field plots at  $L_3 = 0.36m$ .



(a)



(b)

Fig. 7.3: Polar plot of radiated field from simple monopole and actively loaded monopole antenna for variable signal frequency a) simple monopole at  $B = 0.0$  b) actively loaded monopole at  $B = 1.5$ .

**8.1 Conclusion**

The numerical simulation and analysis of plasma monopole antenna to reconfigure its radiation characteristics by using passive and active approach is presented in this report. Here, the analysis of simple plasma monopole antenna using FDTD technique in two dimensional X-Y plane is discussed where electric field radiation from plasma monopole is analyzed in polar coordinate and found similar as metallic antenna. Study also reveals that radiation pattern is significantly affected by change of operating frequency and offers a new solution to the requirement for wider beam-width in field of high speed digital communication systems.

Further, a loaded plasma monopole including discontinuity in plasma column is studied. Presence of the discontinuity in plasma monopole provides the capacitive loading on radiating elements which enhance the effective height of antenna and also added an array effect in its radiation pattern. This provides an additional degree of freedom in selection of designing parameters which is generally be found while designing of antenna array. Study explores that antenna radiation parameters like directivity, gain, power density; radiation intensity etc. is improved for capacitive loaded monopole. In order to this a theoretical procedure has been developed where expression for radiated electric is derived and found in agreement to the FDTD simulation out comes. This theory is very useful for designing of discontinuity in antenna structure and provides novel techniques which can be utilized to get desired radiation pattern by having the passive approach.

In further analysis derived expression, explores that the capacitive loading in plasma monopole can also be made in active manner by applying the variable magnetic field which can also be utilize to get a reconfigurable radiation pattern. At low frequency antenna length is very high and this could provide certain limitation in its use. This study provides an alternative approach to increase the effective length of antenna without increasing its physical length.

## 8.2 Future scope

In this study, plasma monopole antenna is simulated with incorporated discontinuity utilizing 2-D FDTD method and far field analysis is done to compute its radiation pattern where the similar effect is achieved by actively implemented external magnetic field of certain magnitude on simple plasma monopole. Here, the simulation results are investigated for variable length and frequency for both passively and actively loaded plasma monopole. In future to optimize its performance in terms of directivity, beam-width, and radiation intensity of antenna; radiation pattern of antenna will be evaluated for various plasma parameters like electron density, different gases, plasma confinement, conductivity, collision frequency and antenna configurations and will also simulate plasma monopole antenna by using 3-D FDTD method.

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## List of Publications

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1. Gurkirandeep Kaur, Rana Pratap Yadav, “Study of the radiation characteristics of plasma antenna using 2-D FDTD method,” accepted in *Progress in Electromagnetics Research Symposium (PIERS)*, shanghai, China.
2. Gurkirandeep Kaur, Rana Pratap Yadav, Dhiraj Bora, “Analysis of capacitive loaded and actively reconfigurable plasma monopole antenna using FDTD method,” communicated to *IEEE Transactions on Antennas & Propagation*.

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