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Electromagnetic Wave Propagation and Radiation Through Plasma Domain

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Abstract

This study investigated the propagation and radiation of electromagnetic waves through a plasma environment. The key objectives were to simulate the behavior of plane electromagnetic waves in a lossy medium, analyze the corresponding electric and magnetic field intensities, examine the attenuation characteristics of millimeter waves in plasma, evaluate the reflection properties of transverse magnetic (TM)-polarized waves, and compare the attenuation trends of transverse electric (TE) and TM-polarized waves. A quantitative, simulation-based research approach was adopted, with MATLAB serving as the primary modeling tool due to its strong numerical and analytical capabilities. The study was grounded in Maxwell's equations and fundamental wave theory, which were used to develop mathematical models for simulating wave interactions in both lossy and plasma media across a spatial range of 0 to 50 meters. Critical physical parameters such as electron density, plasma frequency, collision frequency, electrical conductivity, and permittivity were factored into the simulations. The results indicate that electromagnetic wave behavior in plasma is strongly influenced by these parameters. Attenuation was found to be more pronounced in lossy media than in plasma, and TM-polarized waves demonstrated higher reflection intensity compared to TE-polarized waves. The study concludes that a deep understanding of the interaction between wave properties and plasma parameters is vital for accurately predicting wave behavior in ionized environments. It is recommended that future studies incorporate experimental validation and expand the analysis to include a wider range of environmental conditions—such as varying frequencies and dynamic plasma states—to improve the reliability and practical relevance of simulation models for applications in telecommunications, radar systems, and space communication technologies.

Keywords: Electromagnetic Wave Propagation, Plasma Medium, Attenuation, Transverse Polarization (TE/TM), MATLAB Simulation, Maxwell's Equations

INTRODUCTION

Electromagnetic wave propagation is a core principle in physics and engineering that described how energy is transmitted through space via oscillating electric and magnetic fields. This phenomenon encompasses a

broad spectrum of wave including radio, microwave, infrared, visible light, ultraviolet, X-rays, and gamma ray which interact differently with materials based on their electrical and magnetic properties (Jackson, 2021).

While propagation through vacuum and conventional dielectric materials is well understood, wave behavior in complex environments such as plasmas introduces significant challenges. Plasmas, composed of freely moving ions and electrons, exhibit non-linear and dispersive characteristics that greatly influence wave dynamics. These properties are especially important in advanced applications such as space exploration, nuclear fusion, and next-generation communication systems (Chen, 2022).

The growing focus on controlled fusion experiments and space-based technologies has intensified interest in how electromagnetic waves interact with plasma environments. Unlike traditional media, plasmas can alter wave characteristics through phenomena like Landau damping, cyclotron resonance, and wave-particle interactions, all of which complicate classical wave theory (Kumar & Shukla, 2023; Liu et al., 2023). Moreover, factors such as plasma density gradients, magnetic field orientation, and wave frequency critically determine whether waves are transmitted, absorbed, or reflected. These complexities are central to optimizing communication in space missions and maintaining plasma stability in fusion reactors like those at the International Thermonuclear Experimental Reactor (ITER).

As a result, accurate simulation and analysis of electromagnetic wave propagation in plasma are essential for both theoretical advancement and engineering applications. Computational tools such as finite-difference time-domain (FDTD), particle-in-cell (PIC) methods, and MATLAB-based models have become indispensable for exploring wave behavior under diverse physical conditions. Recent research has employed these techniques to study wave interaction in non-uniform plasmas, evaluate signal attenuation, and refine antenna designs for plasma-rich environments (Ahmed et al., 2023; Zhao & Dong, 2024). These approaches help translate theoretical concepts into practical solutions across aerospace, defense, and energy sectors.

Given the increasing relevance of plasmas in emerging technologies, from re-entry communication blackouts and plasma-based antennas to controlled nuclear fusion, the need for a comprehensive understanding of electromagnetic wave propagation in such media is more critical than ever. Despite the availability of theoretical models, practical and numerical investigations particularly involving different polarizations and wave types remain underexplored.

This study seeks to bridge that gap by using MATLAB simulations to investigate the propagation and radiation of electromagnetic waves, focusing specifically on transverse electric (TE) and transverse magnetic ™ modes in both lossy and plasma environments.

MATERIALS AND METHODS

Effective Dielectric Constant of Plasma

The effective dielectric constant of plasma, denoted as ϵ_{eff}, is a crucial parameter in analyzing how electromagnetic (EM) waves interact with ionized media. It is typically described using a complex permittivity model, which includes both the real and imaginary components to capture the material's response and energy loss mechanisms.

This parameter depends on factors such as electron density, frequency of the incident EM wave, and collision frequency. In the case of cold plasma, where thermal motion of electrons is negligible, simplified expressions from plasma physics are used to approximate the dielectric behavior. One such approximation is given by:

$$\epsilon_{eff} = 1 - \frac{\omega_p^2}{\omega^2} \quad 1$$

Where ω_p is the plasma frequency given by

$$\omega_p = \sqrt{\frac{n_e e^2}{\epsilon_0 m_e}} \quad 2$$

Here, n_e is the electronic density, e is the electron charge, ϵ_0 is the permittivity of free space, and m_e is the electron mass. For high-frequency scenarios where collisional effects are non-negligible, the effective permittivity becomes complex:

$$\epsilon_{eff} = \epsilon' - j\epsilon'' \quad 3$$

Where ϵ' is the real part, and ϵ'' denotes the imaginary part which accounts for energy loss due to collisions.

Refractive Index of Plasma

The refractive index of plasma n_p is another fundamental property that governs wave propagation through ionized media. It is also frequency-dependent and is given by:

$$n_p = \sqrt{1 - \frac{{f_p}^2}{f^2}} \quad 4$$

Where n_p is the refractive index of plasma, f_p is plasma frequency and f is the propagation frequency.

METHODS

Vertical and Horizontal Polarization

In electromagnetic (EM) wave propagation, it is often necessary to direct wave transmission along a specific path. For a plane wave incident at an oblique angle θ_i with respect to the normal, and propagating along the +z axis, the plane of incidence is defined as the plane formed by the incident wave vector and the boundary's normal.

When the electric field (E) lies within the plane of incidence, the wave is said to be transverse magnetic (TM) polarized. Conversely, when the electric field is perpendicular to the plane of incidence, the wave exhibits transverse electric (TE) polarization.

TM polarization is also referred to as parallel, vertical, or P-polarization, while TE polarization is alternatively called perpendicular, horizontal, or S-polarization.

Considering an incident wave vector k_i lying in the plane of incidence, its orientation in spherical coordinates is characterized by the zenith angle (θ_i) and the azimuth angle (φ_i). The incident wave vectors denoted $\hat{k}_i$, $\hat{v}_i$, and $\hat{h}_i$ can be mathematically expressed as follows:

$$\hat{k}i = \sin\theta i \cos\varphi i\hat{x} + \sin\theta i \sin\varphi i\,\hat{y} + \cos\theta i\hat{z} \quad 5$$

$$\hat{v}i = \cos\theta i \cos\varphi i\hat{x} + \cos\theta i \sin\varphi i\hat{y} - \sin\theta i\hat{z} \quad 6$$

$$\widehat{h}i = -\sin\varphi i\hat{x} + \cos\varphi i\hat{y} \quad 7$$

Likewise, the wave vectors $\hat{k}$s, $\hat{v}$s and $\hat{h}$s in the scattering plane associated with angles θs and φs are:

$$\hat{k}s = \sin\theta s \cos\varphi s\,\hat{x} + \sin\theta s \sin\varphi s\,\hat{y} + \cos\theta s\,\hat{z} \quad 8$$

$$\widehat{v}s = \cos\theta s \cos\varphi s\,\hat{x} + \cos\theta s \sin\varphi s\,\hat{y} - \sin\theta\,\theta s\,\hat{z} \quad 9$$

$$\hat{h}s = -\sin\varphi s\hat{x} + \cos\varphi s\hat{y} \quad 10$$

Boundary Conditions by Fresnel's Equations

When a plane electromagnetic wave strikes the interface between the sea foam bottom layer (denoted as the nth layer) and seawater (medium 2) at an incident angle θ_n, the boundary conditions are governed by Fresnel's equations. The reflection coefficients, also known as Fresnel factors, are determined for both vertical and horizontal polarizations based on the dielectric constants ε_n (for the foam layer) and εsw (for seawater).

$$\Gamma\perp = \frac{cos\theta_n - \sqrt{\frac{\varepsilon_{sw}}{\varepsilon_{sn}} - sin^2\theta_n}}{cos\theta_n + \sqrt{\frac{\varepsilon_{sw}}{\varepsilon_{sn}} - sin^2\theta_n}}$$

Where Γ⊥ denotes Fresnel's reflection coefficient for T E polarization and Γ‖ is the TM Fresnel's reflection

$$\Gamma\perp = \frac{\frac{\varepsilon_{sw}}{\varepsilon_n}cos\theta_n - \sqrt{\frac{\varepsilon_n}{\varepsilon_{sw}} - sin^2\theta_n}}{\frac{\varepsilon_{sw}}{\varepsilon_n}cos\theta_n + \sqrt{\frac{\varepsilon_{sw}}{\varepsilon_n} - sin^2\theta_n}} \quad 11$$

Given the field intensity incident angle θ_n= 300 and the azimuth angle of the sea foam bottom layer $\emptyset_n$= 300 onto the interface, we obtained the reflected angle using Snell's law.

$$\theta_n = \theta_{sw} \quad 12$$

The transmitted angle is obtained from Snell's law

$$ref_n sin\theta_n = ref_{sw}\theta_{sw} \quad 13$$

Single and Multiple Scattering

Single scattering refers to the phenomenon where an incident electromagnetic field interacts with a single, localized scattering center. However, in most practical scenarios, scattering centers are clustered or

distributed, leading to multiple scattering. The key distinction between the two lies in their treatment: single scattering is typically modeled as a random event, while multiple scattering is viewed as a stochastic process due to the cumulative effect of numerous scattering events.

In single scattering, the precise location of the scattering center relative to the incident radiation path is often unknown, causing the scattering outcome to appear random. A classic example is an electron deflected by an atomic nucleus. In contrast, multiple scattering results in a more deterministic intensity distribution because the randomness of individual events is statistically averaged out—similar to how a beam of light behaves when passing through dense fog. In many contexts, the terms "multiple scattering" and "diffusion" can be used interchangeably. A notable phenomenon in this regime is coherent backscattering, where constructive interference from multiply scattered coherent waves leads to enhanced backscatter—commonly associated with weak localization.

Fluctuating Fields

In random scattering problems, due to the irregular distribution of inhomogeneities, both the electromagnetic fields and the resulting intensity fluctuate. When scatterers are discrete and randomly arranged—differing in position, shape, size, and orientation—the scattered fields become inherently random. This underpins the concept of random fields, which is fundamental in modeling scattering from random media and rough surfaces. Unlike deterministic systems, which yield a single unique solution, problems involving random media only offer unique outcomes per realization.

Changes in realization, such as the movement of the media or the motion of transmitters and receivers, alter the spatial configuration and observed fields, leading to variability in measurements.

Elastic and Inelastic Scattering

In elastic scattering, the scattered radiation retains the same frequency (or wavelength) as the incident wave. Classic examples include Rayleigh and Mie scattering. By contrast, inelastic scattering involves a shift in frequency between the incident and scattered waves, as seen in Raman and Compton scattering processes.

In elastic scattering, the incident energy's momentum has little to no influence on the particle's scattering behavior. Instead, the orientation and distribution of dipole moments within the material are primary determinants. This mechanism is somewhat analogous to the Doppler effect observed in radar systems.

Propagation Media Characteristics

Electromagnetic (EM) waves travel with minimal loss through free space or air but experience increased attenuation in materials like plasma, especially as frequency rises. These propagation characteristics are defined by the medium’s electromagnetic constitutive parameters: conductivity, permittivity (dielectric constant), and permeability.

Conductivity

Conductivity (σ) is a key material property that influences wave attenuation. A homogeneous medium has spatially uniform constitutive parameters, while an isotropic medium has direction-independent properties. An ideal conductor has infinite conductivity ($\sigma = \infty$) and zero electric field ($E = 0$), whereas an ideal dielectric

has zero conductivity (σ = 0) and no conduction current (J = 0). In the context of plane wave propagation, the interplay between conductivity and permittivity determines whether a medium behaves as lossless or lossy.

Dielectric Constant and Refractive Index

Understanding the dielectric properties of hydrometeors is crucial for evaluating their scattering behavior. In a linear, isotropic, and homogeneous medium, the complex permittivity is defined as $\epsilon_c = \epsilon - \frac{\sigma}{\omega}$, where $\epsilon_c = \epsilon^I - \epsilon^{II} =$, with ϵ^I as the real component and ϵ^{II} the imaginary component.

An applied electric field $\vec{E}$ exposed to a dielectric material causes the polarization of the atoms or molecules of the material to create dipole moments that augment the total displacement flux $\vec{D}$. The appended polarization vector is called the electric polarization $\vec{P}_e$, where

$$\vec{D} = \epsilon_o \vec{E} + \vec{P}_e \qquad 14$$

In a linear medium, the relationship between $\vec{P}_e$ and $\vec{E}$is given by

$$\vec{D} = \epsilon_o \vec{E} + \vec{P}_e = \epsilon_o \vec{E} + \chi_e \epsilon_o \vec{E} \qquad 15$$

where $\epsilon_c \cong \epsilon^I - \epsilon^{II} = \epsilon(1 + \chi_e)$,

is the complex permittivity of the medium. For a lossless medium with σ = 0, $\epsilon^{II} = 0$, and $\epsilon_c = \epsilon^I = \epsilon$. The higher the dielectric constant the more scattering we expect from a particle after collision.

Higher dielectric constants typically indicate stronger scattering. In materials with complex permittivity (e.g., ocean foam, snow, rain, aerosols), the imaginary part captures energy losses. These dielectric properties can alternatively be described using the complex refractive index $\epsilon_c \cong \epsilon^I - \epsilon^{II}$or complex refractive index $n = n^I - n^{II}$ with the two quantities related by $= \sqrt{\epsilon}$.

Lossless and Lossy Media

A lossless medium has zero conductivity (σ = 0) and an attenuation constant (α = 0), implying no energy absorption due to conductive losses. Here, the real part of the dielectric constant dominates. Conversely, in lossy media, the finite conductivity contributes to energy absorption and attenuation. The imaginary component of the complex permittivity quantifies these losses.

Considering wave propagation in a conducting medium with propagation constant

$$\gamma^2 = -\omega^2 \mu \epsilon_c \qquad 16$$

$$\gamma^2 = -\omega^2 \mu \epsilon_{c,} \gamma^2 = -\omega^2 \mu (\epsilon^I - \epsilon^{II}) \qquad 17$$

Where

$$\epsilon^I = \Re\epsilon, \epsilon^{II} = \Im\epsilon = \frac{\sigma}{\omega\epsilon}$$

The wave propagation in such media is characterized by the propagation constant γ.

Scattering Parameters

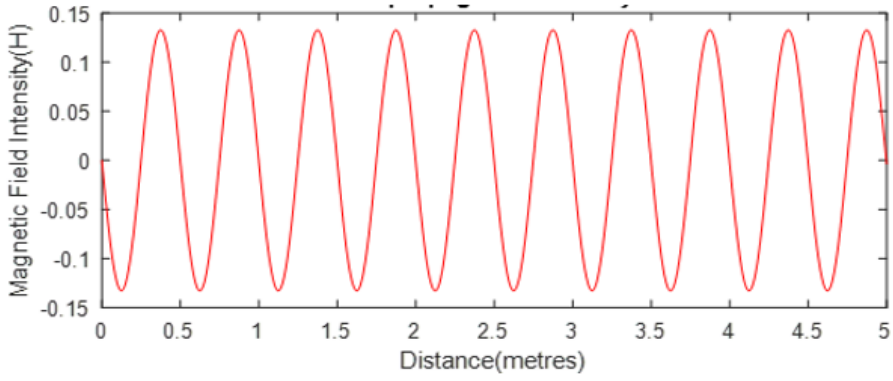
The scattering plane is defined as the plane containing the incident wave vector and the observation direction or the vector from the scatterer to the observer.

The extinction cross-section accounts for total energy loss (scattering + absorption) and is influenced by the scatterer's complex refractive index or dielectric constant. In media like sea foam (a composite of air and water), both scattering and absorption contribute significantly to extinction.

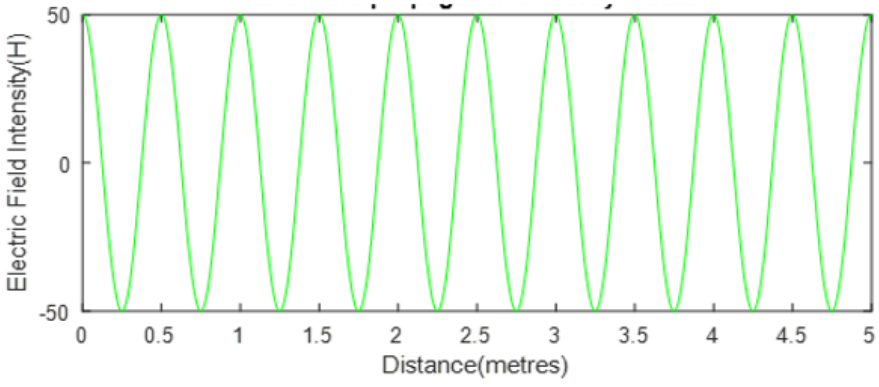
DATA ANALYSIS AND DISCUSSIONS

Simulation of EM Wave Propagation in Lossy Media

Figure 4.1 illustrates the simulation results of electromagnetic (EM) wave propagation through a lossy medium, demonstrating the impact of material losses on wave amplitude, phase, and attenuation. The simulation emphasizes how energy is dissipated as EM waves interact with both conductive and dielectric materials, providing valuable insight into wave behavior in such environments.



(a)



(b)

Figure 1: Plane wave propagation in a lossy medium (a) TM and (b) TE polarized Field.

This graph clearly demonstrates how a plane electromagnetic wave behaves as it propagates through a lossy medium. Due to energy dissipation within the medium, both the electric and magnetic field intensities gradually diminish with distance, resulting in attenuation. The simulation results reveal that both the magnetic and electric fields display sinusoidal patterns, which are typical of electromagnetic wave propagation.

Attenuation of Millimeter Waves in Plasma

Figure 2.2 illustrates the simulated attenuation of millimeter waves as they travel through a plasma medium, emphasizing how factors such as plasma density, collision frequency, and wave frequency influence signal degradation.

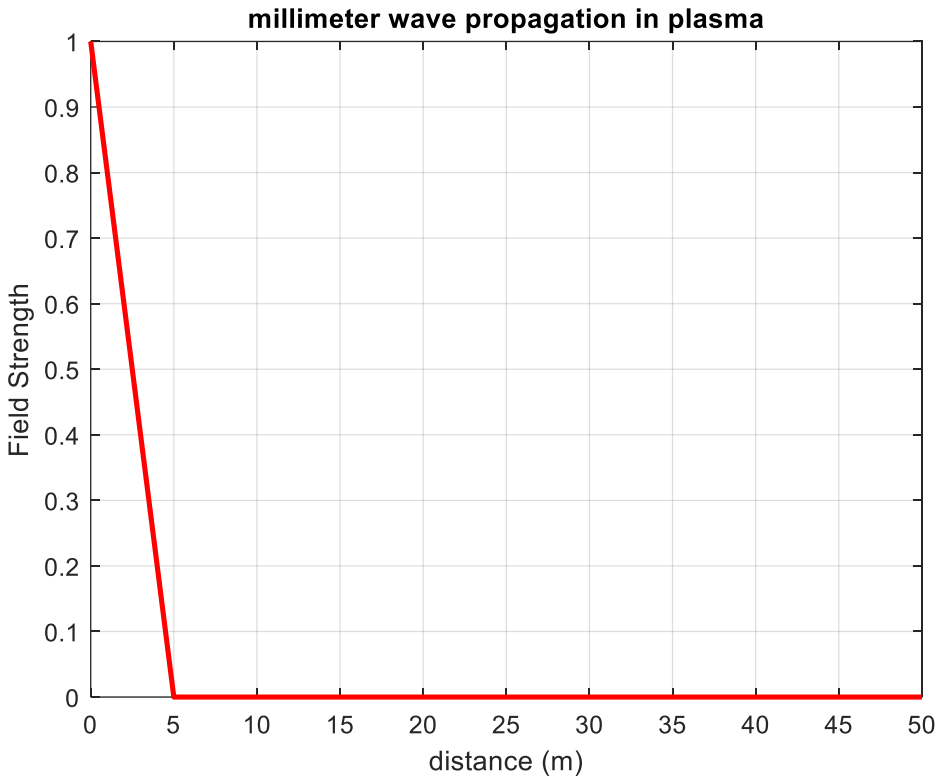


Figure 2: Plane wave propagation in Plasma Domain

As shown in Figure 2, the simulation results demonstrate a rapid attenuation of the electromagnetic field. The field strength begins at its peak value of 1 at 0 meters and declines sharply to near zero within the first 5 meters, after which significant propagation is no longer observed.

This steep reduction indicates that the plasma medium strongly absorbs millimeter-wave energy—an effect attributed to its high electrical conductivity and pronounced interaction with electromagnetic waves at specific frequencies. The graph also points to the presence of a plasma cutoff phenomenon, wherein waves below the plasma frequency are either absorbed or reflected. In this scenario, the high plasma density likely contributes to the rapid energy dissipation, effectively halting further wave propagation.

Reflection Behavior of TM-Polarized Waves in Plasma

The graph in Figure 4.3 below, illustrates that the reflected TM-polarized wave in plasma experiences rapid attenuation within the first 5 meters, after which it becomes negligible.

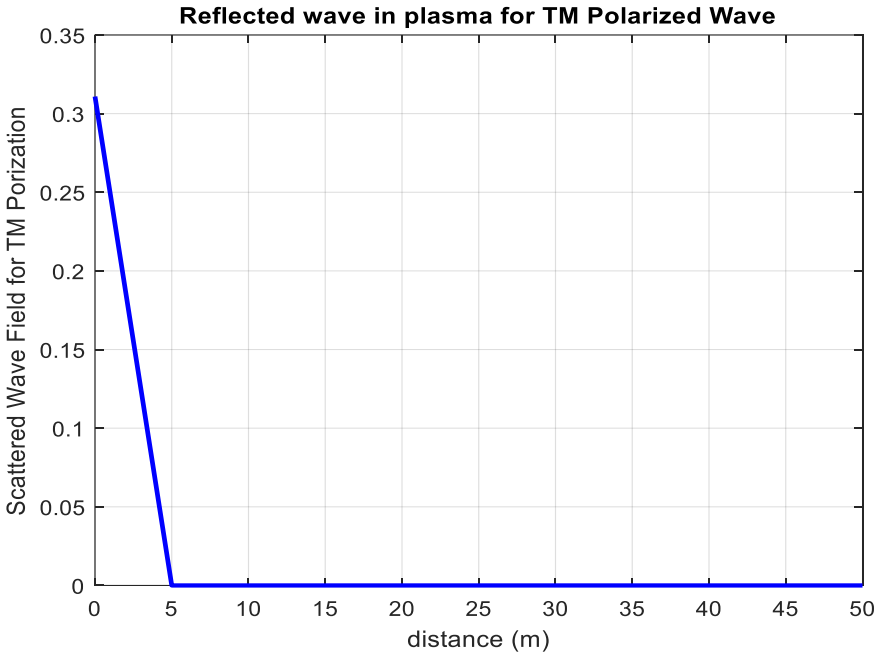


Figure 3 Reflected wave in plasma for TM polarised wave

Comparative Behavior of TE and TM Modes

Figure 4.4 shows the reflection characteristics of TE polarized wave in a plasma medium.

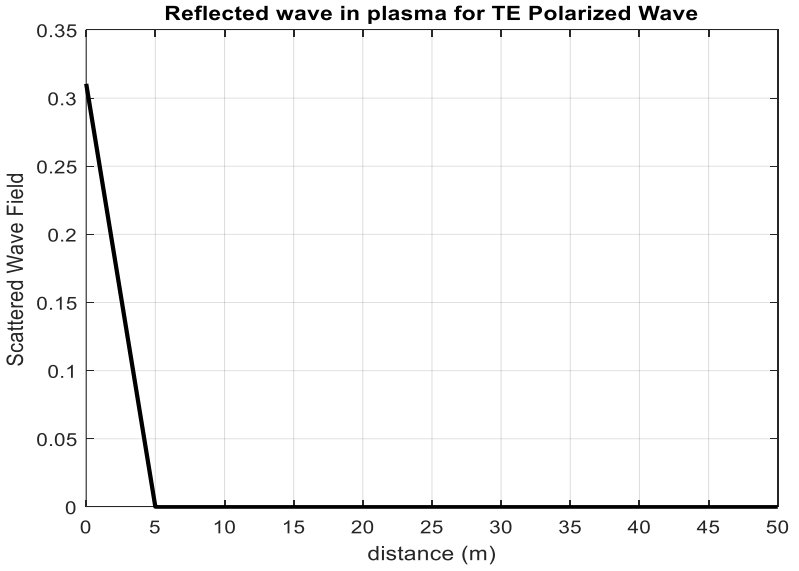


Figure 4: Reflected wave in plasma for TE polarised wave

The graph shows a rapid decay of the scattered wave field, starting at approximately 0.3 at the origin and

dropping sharply to near zero within 5 meters, remaining negligible beyond that.

3D Field Simulation in Plasma Domain

Time-Step Visualization of Propagation

The graph shows the electric field (in V/m) at time step 900 across a simulation grid (cell indices 100–700). A sharp change near index 400 indicates a material transition, with electric field values ranging between 1.4 and 1.5 V/m across the regions.

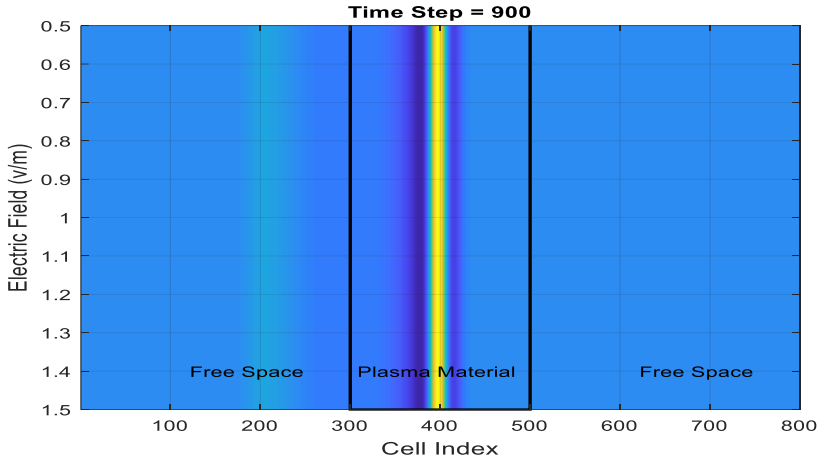


Figure 5: Electric field at a given time step

Spatial Propagation of Electric Field in Plasma

The graph displays two 2D plots showing the spatial distributions of the electric field and magnetic field over a region from -1 m to +1 m along both x and y axes. The left plot shows , while the right plot shows.

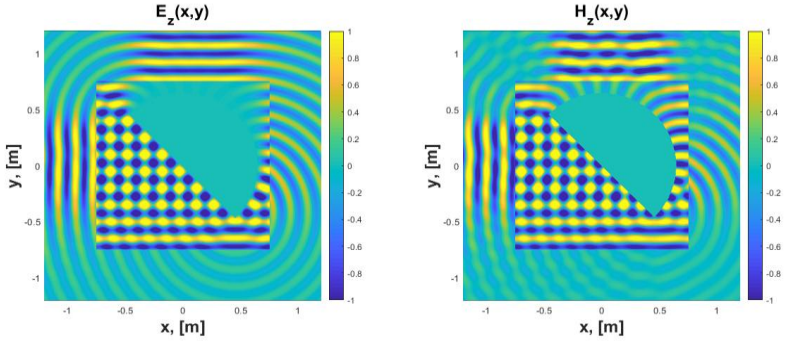


Figure 6 Spatial distributions of electric and magnetic field

Electric Field Across a Region in XY-Plane

Figure 7 displays a three-dimensional plot of the electric field (in V/m) distributed over the XY-plane, with both axes indicating spatial positions in meters.

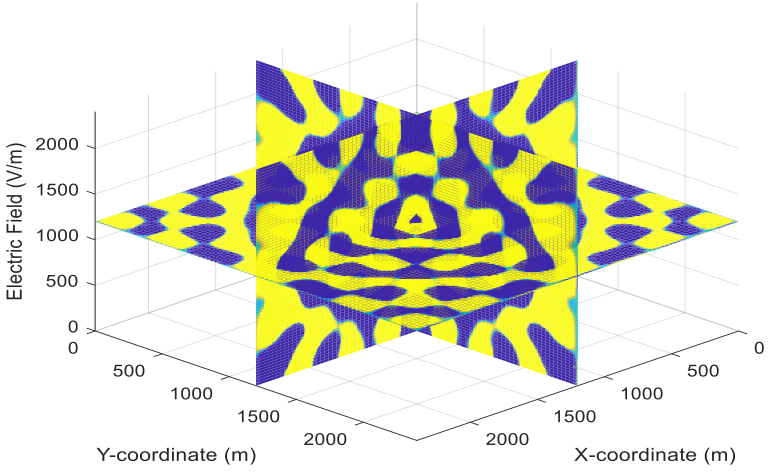


Figure 7: Electric field across a region in XY-plane

The 3D surface plot illustrates the spatial distribution of the electric field, with a color map showing field intensity yellow indicating high values and blue indicating low values.

Propagation of EM Wave in Plasma Domain

The propagation of an electromagnetic (EM) wave through a plasma domain is shown in Figure 8 above, where the electric field intensity is measured at various points along the distance.

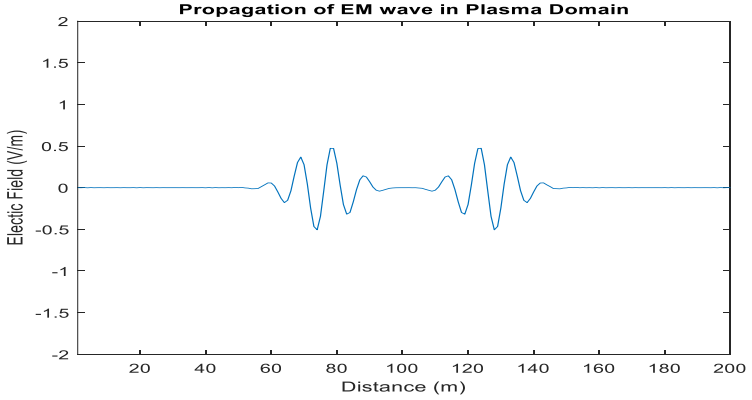


Figure 8: Propagation of EM wave in plasma domain

DISCUSSION

This study provides an in-depth interpretation of electromagnetic (EM) wave behavior in both lossy and plasma media through simulation results, connecting the findings with established theories and previous empirical studies. Key insights highlight how electromagnetic waves attenuate more rapidly in lossy media due to higher conductivity, while plasma allows for extended propagation due to its frequency-dependent permittivity and lower energy dissipation.

A comparative analysis of Transverse Electric (TE) and Transverse Magnetic (TM) wave polarizations showed that TM waves exhibit stronger reflections and higher field retention at plasma boundaries, especially in high-density plasma regions. This is attributed to their stronger interaction with dielectric variations, making them more suitable for reflective applications in plasma environments.

The study also emphasizes the influence of plasma parameters such as collision frequency, plasma density, and relative permittivity. Variations in these parameters significantly affect wave attenuation and propagation characteristics. Notably, higher collision frequency increases energy loss, while changes in plasma density affect the cutoff and reflection conditions for wave transmission. These observations are consistent with theoretical models like the Appleton–Hartree relation and underscore the necessity of incorporating plasma's nonlinear, frequency-dependent properties in wave propagation modeling.

CONCLUSION

This study investigated the propagation and radiation of electromagnetic waves through plasma environments, employing MATLAB-based simulations to analyze the behavior of electric and magnetic fields under both TE and TM polarizations in lossy and plasma media. Results showed that wave attenuation in plasma is significantly lower than in conventional lossy materials, supporting theoretical predictions regarding plasma's reactive and frequency-dependent characteristics. TM-polarized waves exhibited stronger reflection and better energy retention than TE waves, particularly at plasma boundaries, highlighting their potential for high-precision plasma-based applications. The research also emphasized the crucial influence of key plasma parameters—such as electron density and collision frequency—on wave dynamics, affecting attenuation, propagation range, and reflection.

These findings enhance our understanding of wave-plasma interactions and provide practical insights for optimizing signal performance in aerospace systems, radar technology, and plasma antennas. Overall, the study reinforces the value of dynamic simulation in accurately predicting wave behavior within ionized media.

Declaration of Conflicting Interests

The authors declare no potential conflicts of interest with respect to the research, authorship and publication of this article.

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