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Modeling and Simulation of Electromagnetic Fields on Biological Cells Using the Transverse Wave Approach

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Abstract

— This paper investigates the electromagnetic (EM) interactions between biological cells and nanosecond Pulse Electric Fields (nsPEF), using the Transverse Wave Approach (TWA) and microstrip line technology for simulations. TWA allows for efficient modeling of complex EM wave behaviors in heterogeneous environments like biological tissues. The study explores both medical and industrial applications of nsPEF, focusing on cancer treatment, such as melanoma destruction, and food decontamination. Simulations of EM wave propagation through biological cells reveal key insights into how electromagnetic fields behave at varying distances between the microstrip line and the biological cell. The results demonstrate that strong coupling at shorter distances enhances the effectiveness of cancer treatments, while weaker coupling at longer distances provides a safe and efficient approach for industrial applications such as bacteria elimination. These findings emphasize the importance of optimizing distance and field intensity for specific applications and lay the groundwork for future developments in EM-based treatments and technologies.

Keywords: Electromagnetic fields, Transverse Wave Approach (TWA), Biological cell modeling, Nanosecond Pulse Electric Fields (nsPEF), Electromagnetic simulation.

1. Introduction

Electromagnetic (EM) fields have become increasingly prevalent in modern society due to the widespread adoption of new technologies, ranging from wireless communication systems to medical devices. As the exposure to these fields rises, it becomes essential to study and understand their interactions with biological tissues, particularly at the cellular level. The effects of EM fields on biological systems are of paramount importance, not only in terms of potential health risks but also for their practical applications in fields such as medicine, telecommunications, and food safety.

In recent years, the focus has shifted towards more sophisticated methods of EM modeling to capture the complex interactions between electromagnetic fields and biological tissues. Traditional modeling approaches, while useful, often struggle with the highly heterogeneous and complex nature of biological tissues. This complexity is evident in the varying electromagnetic properties of different tissues, which can range from highly conductive (e.g., blood) to weakly conductive (e.g., fat), each with distinct permittivity and permeability values [1]. These properties further change with frequency, as Aram et al. and Gabriel et al. demonstrated in their seminal work on the electromagnetic properties of over 45 tissue types [2][18-19]. Such variation necessitates more advanced simulation techniques, like the Transverse Wave Approach (TWA) [3-5] and its extended version, TWA+[6,7].

TWA was first introduced to model EM wave behavior in complex environments, where analytical solutions are either non-existent or too difficult to compute. The method operates iteratively, coupling incident and reflected waves, and has proven particularly useful for scenarios involving complex boundary conditions, such as those found in biological tissues [8]. The extended version, TWA+, incorporates Non Uniform Fast Fourier Transform (NUFFT) as well as Anisotropic Mesh Technique (AMT) to further improve computational efficiency and accuracy. These transformations allow for faster simulation of EM waves in heterogeneous environments, which is critical for both medical and industrial applications [9, 10].

In the medical field, electromagnetic fields have been used extensively for both diagnostic and therapeutic purposes. Techniques such as Magnetic Resonance Imaging (MRI) rely on the precise interaction of EM fields with biological tissues to generate images of the body's interior [11]. Additionally, emerging therapies, such as electrochemotherapy, use EM fields to enhance the delivery of chemotherapeutic drugs to cancer cells, offering a promising non-invasive treatment option for tumors such as melanomas [12]. The role of EM fields in inhibiting tumor growth and improving the efficacy of cancer treatments is an area of active research [13-14].

On the industrial side, EM fields have proven useful in applications such as food decontamination. The ability to eliminate harmful bacteria using short, high-amplitude EM pulses has made processes like nanosecond Pulse Electric Fields (nsPEF) an efficient method for ensuring food safety without compromising quality [15]. These processes rely heavily on the accurate modeling of EM field interactions with bacterial cells, where small-scale electromagnetic phenomena must be captured to optimize the sterilization process [16]. Understanding how EM fields interact with biological cells, both in the medical and industrial contexts, is crucial for advancing these technologies.

The present work builds on these developments by exploring the Transverse Wave Approach (TWA) and its application in modeling biological cells under electromagnetic exposure. The aim is to provide a comprehensive analysis of how TWA and TWA+ can be employed to simulate the behavior of biological cells when subjected to EM fields. We will focus on two main applications: medical (specifically, cancer treatment) and industrial (food decontamination). Additionally, we will provide a detailed analysis of the coupling between microstrip lines and biological cells, offering insight into the implications of these interactions in practical scenarios.

Through the modeling of a biological cell, treated as an electrically heterogeneous material, and its interaction with electromagnetic fields, this study demonstrates the versatility of the TWA method. The cytoplasm and membrane of the cell exhibit distinct electromagnetic properties, leading to complex interactions that require advanced simulation techniques [17]. The iterative process of the TWA method allows for accurate reflection and diffraction modeling, which is crucial for predicting how EM fields behave in heterogeneous environments.

The remainder of this paper is organized as follows: In Section 2, we describe the theoretical foundations of the Transverse Wave Approach and its mathematical formulations. Section 3 presents the modeling process of biological cells under electromagnetic exposure. Section 4 focuses on the simulation results, particularly the coupling of microstrip lines with biological cells. Finally, we conclude by discussing the broader implications of these results for both medical and industrial applications.

2. Theoretical Foundations of the Transverse Wave Approach (TWA)

The Transverse Wave Approach (TWA) provides an efficient method for modeling electromagnetic (EM) wave interactions in complex environments. Initially developed to simulate the behavior of EM waves in non-homogeneous media, TWA employs an iterative process that captures the mutual coupling between incident and reflected waves. This iterative method bridges spatial and modal domains, ensuring that boundary conditions are met accurately while minimizing computational costs.

2.1. Basic Formulation of TWA

The Transverse Wave Approach (TWA) is a numerical method designed to model electromagnetic wave interactions by iteratively coupling incident (A) and reflected (B) waves. The method operates using reflection (Γ) and diffraction (S) operators, expressed mathematically as:

$$A = \Gamma B \quad \text{and} \quad B = SA + B_{(0)} \quad (1)$$

Where:

- Γ: Reflection operator, connecting incident and reflected waves in the modal domain.
- S: Diffraction operator, linking the incident and reflected waves in the spatial domain.
- B(0): The global excitation wave from the source.

This fundamental approach includes the use of Fast Fourier Transform (FFT) and Fourier Modal Transform (FMT), ensuring efficient transitions between spatial and spectral domains.

2.2. Extensions in TWA+: Incorporating NUFFT and AMT

TWA+ extends the basic TWA formulation by incorporating two key advancements that enhance its performance in handling complex, heterogeneous environments:

a. **Non-Uniform Fast Fourier Transform (NUFFT):** Unlike traditional FFT, which operates on uniform grids, NUFFT allows for efficient transformations on non-uniform grids. This is particularly useful when dealing with biological tissues or other environments where the spatial distribution of electromagnetic properties is irregular.
b. **Anisotropic Mesh Technique (AMT):** AMT optimizes mesh resolution based on the anisotropy of the material being modeled. This technique improves accuracy by refining the mesh in areas with significant electromagnetic variations, such as the thin membrane of biological cells, while coarsening it in regions with less variation. This leads to enhanced computational efficiency without sacrificing precision.

By incorporating NUFFT and AMT, TWA+ achieves more accurate modeling of electromagnetic interactions in complex biological environments, building on the foundation of FFT and FMT already established in the TWA framework. These extensions are critical for applications involving non-homogeneous media, such as biological cells, where uniform grids and standard techniques may not provide the desired level of detail and accuracy.

2.3. Iterative Process of TWA

TWA works by iterating the interaction of incident and reflected waves until the system reaches convergence, meaning the wave behavior stabilizes. The iterative process helps to resolve complex boundary conditions in biological tissues.

- **First Iteration**: Generates initial incident waves {$A_1^{(1)}$ and $A_2^{(1)}$} and corresponding reflected waves {$B_1^{(1)}$ and $B_2^{(1)}$}.
- **Subsequent Iterations**: Incident waves create new reflected waves, driving the system towards convergence.
- **Convergence**: The system stabilizes when subsequent iterations produce minimal differences in incident and reflected waves.

This iterative approach allows TWA to handle complex boundary conditions effectively, making it ideal for modeling electromagnetic wave behavior in biological tissues, which often exhibit varying electromagnetic properties.

3. Modeling Electromagnetic Interactions with Biological Tissues

The rapid expansion of modern technologies has resulted in a substantial rise in electromagnetic (EM) sources, significantly increasing human exposure to EM fields. This has led to a surge in studies examining the interaction of these fields with biological tissues, given their critical importance in both medical and industrial contexts.

In medical applications, EM fields are pivotal, from diagnostic imaging tools like Magnetic Resonance Imaging (MRI) to emerging therapeutic techniques such as electrochemotherapy, which harnesses EM fields to enhance cancer treatment. Additionally, the industrial application of EM fields, such as in food decontamination through nanosecond Pulse Electric Fields (nsPEF), has also gained traction. However, while the benefits of EM fields are clear, there remain concerns about their biological impact, necessitating rigorous modeling of their interaction with human tissues.

Modeling electromagnetic interactions in biological tissues is challenging due to several factors. First, biological tissues exhibit distinct electromagnetic properties compared to traditional materials used in electromagnetism. Second, EM fields induce thermal effects, which alter tissue fluid dynamics, creating a complex interplay between heat and electromagnetic fields that must be accounted for in simulations. Third, the complex geometry and heterogeneous nature of biological tissues further complicate both mathematical modeling and numerical simulations.

When the human body interacts with the near field of an antenna, it acts as a lossy dielectric material, meaning that energy is dissipated as heat. This interaction affects the performance of the antenna in three significant ways:

- **Radiation pattern distortion**: The body alters the distribution of the electromagnetic field emitted by the antenna.
- **Efficiency reduction**: Biological tissue absorbs part of the energy, leading to heating and a decrease in the overall efficiency of the antenna.
- **Impedance variation**: The interaction changes the impedance of the antenna, affecting its ability to transmit and receive signals.

To quantify these effects, simulations using the High-Frequency Structure Simulator (HFSS) have been conducted on planar inverted-F antennas (IIFA). These simulations highlight the impact of electromagnetic fields on biological tissues.

3.1. Electromagnetic Field Interaction with Biological Tissues

Understanding how electromagnetic fields interact with biological tissues is essential for developing effective medical technologies. Biological tissues exhibit unique electromagnetic properties that differ significantly from traditional materials. EM fields, particularly in the radiofrequency (RF) range (30 KHz to 300 GHz), induce electric and magnetic fields that generate currents within tissues. The strength and distribution of these fields depend on several factors, including:

- The distance between the EM source and the body.
- The intensity of the EM emission.
- The frequency, polarization, and incidence angle of the wave.
- Anatomical characteristics such as tissue composition, height, and body mass index.

The induced fields within the body are not uniform. Localized regions often exhibit higher sensitivity, creating complex patterns of electromagnetic activity that vary greatly across different tissues. Unlike conventional materials, the human body is highly heterogeneous, consisting of tissues with vastly different electromagnetic properties.

Over the past five decades, the work of Gabriel et al. has been particularly influential in defining the electromagnetic properties of over 45 different human tissues, ranging from highly conductive tissues like blood to more resistive tissues like fat [18]. This research demonstrates that biological tissues behave as lossy dielectric materials due to their high-water content, causing them to absorb EM energy and convert it into heat.

Figure 1 illustrates the electromagnetic properties—permittivity and conductivity—of three types of tissues (blood, muscle, and fat) as a function of frequency. As shown, the permittivity of muscle tissue is exceptionally high, exceeding 30,000 at 1 kHz. Conductivity, on the other hand, varies more subtly but still plays a significant role in how tissues interact with EM fields.

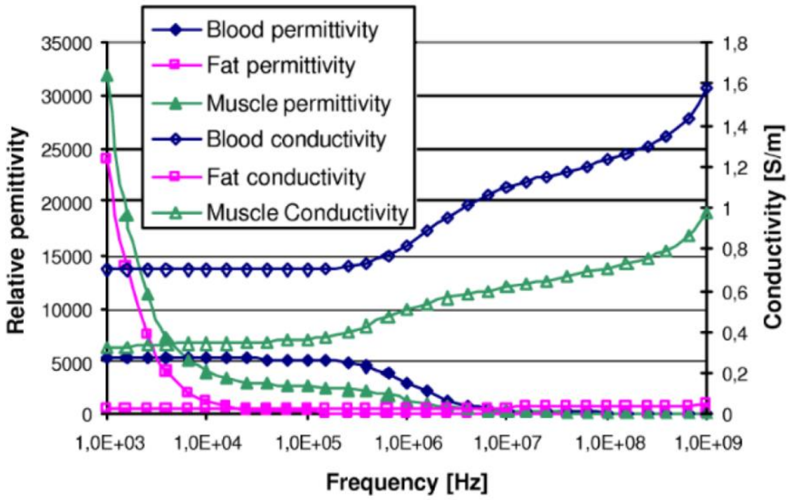

Figure 1. Electromagnetic properties of blood, fat, and muscle in function of frequency [20]

The behavior of biological tissues as dielectric materials requires special consideration when applying electromagnetic field equations. Standard electromagnetic field models, such as Ampere's law, are not always sufficient. The ratio $\omega\times\epsilon/\sigma$, which compares conduction currents to displacement currents, shows that in tissues like blood, muscle, and fat, displacement currents are more dominant than conduction currents, as demonstrated in Figure 2.

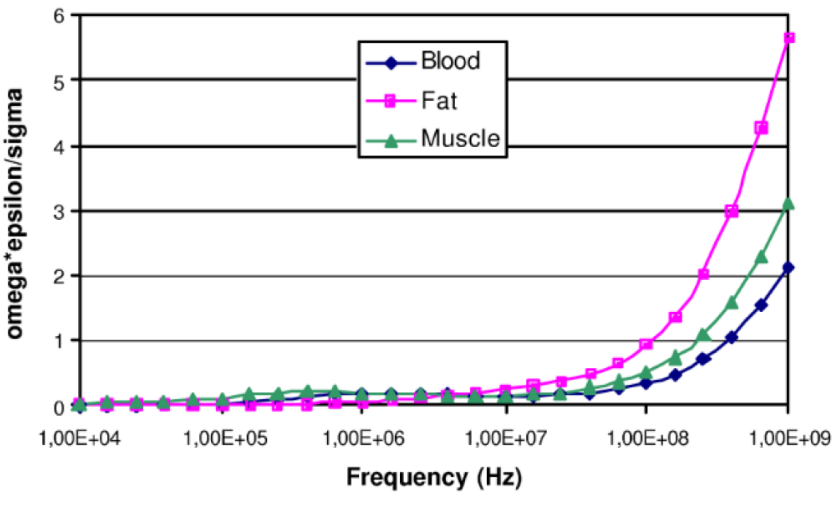

Figure 2. Evolution of the $\omega\times\epsilon/\sigma$ ratio in function of frequency [20]

This displacement dominance means that biological tissues interact with EM fields differently from non-biological materials, highlighting the need for precise modeling of these interactions.

3.2. Challenges in Modeling Electromagnetic Field Interactions

Despite significant advancements, accurately modeling the behavior of EM fields in biological tissues presents several challenges. The macroscopic electromagnetic properties of tissues, while informative, do not account for microscopic phenomena. For example, while Gabriel's data offer comprehensive insights, they cannot predict how EM fields interact with small-scale structures, such as tumors. Moreover, discrepancies between different studies highlight the complexity of obtaining consistent experimental results due to challenges in measuring live tissue.

Biological tissues are typically measured post-mortem, which introduces variables such as tissue preparation, the elapsed time since tissue death, and metabolic changes that can alter their electromagnetic properties. Additionally, the inherent variability in human tissue properties between individuals makes it nearly impossible to generate universally applicable data.

3.3. Multiscale Modeling of Electromagnetic Fields in Biological Tissues

One of the most effective approaches for accurately modeling EM fields in biological tissues is to begin at the microscopic level and then use homogenization techniques to create a macroscopic model. This approach allows researchers to bridge the gap between cellular-level interactions and organ-wide electromagnetic behavior. The process involves combining detailed electrical models of biological cells with an understanding of how EM fields propagate through tissues.

Biological cells, which are the fundamental units of life, typically range from 1 to 10 micrometers in size. These cells, whether prokaryotic or eukaryotic, share a basic structure: a plasma membrane composed of a lipid bilayer surrounds the cytoplasm, which houses vital organelles like the nucleus, mitochondria, Golgi apparatus, and endoplasmic reticulum. This complex structure must be carefully modeled to accurately simulate how electromagnetic fields interact with the cell.

Figure 3 and Figure 4 depict the general structure of eukaryotic and prokaryotic cells, respectively. These illustrations highlight the universal organization of living cells, which must be accounted for in EM field simulations. The plasma membrane, often a thin insulating layer, plays a crucial role in EM interactions, especially when considering its impact on intracellular electromagnetic field distribution.

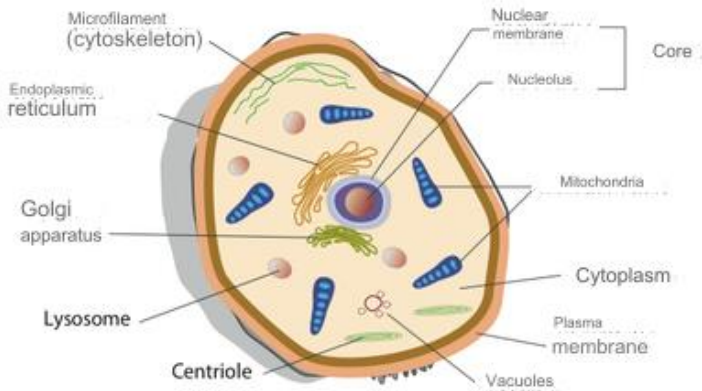

Figure 3. Eukaryotic cell [21]

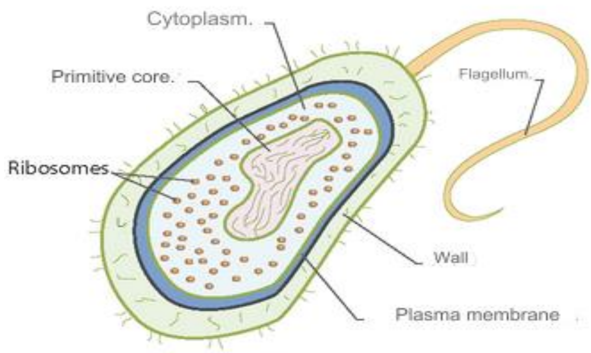

Figure 4. Prokaryotic cell [21]

Researchers like Fear and Stuchly, as well as Foster and Schwan, have extensively studied how electric fields interact with biological cells. Most models treat the cytoplasm as a homogeneous material, but the plasma membrane requires a more detailed examination due to its unique electromagnetic properties. As cells respond to EM fields, the complex geometry and compartmentalized structure of the cytoplasm and membrane influence the electromagnetic wave propagation.

Given the sensitivity of biological systems to EM fields, precision in modeling these interactions is essential for both medical applications—such as targeted cancer therapies—and industrial processes, including food sterilization. The modeling techniques developed for these applications must not only be accurate but also adaptable to the inherent variability in biological tissues.

4. Modeling of the biological cell

4.1. Biological Cell as an Electromagnetic Material

Biological cells, when interacting with electromagnetic (EM) waves, are modeled as electrically heterogeneous materials due to the distinct electromagnetic properties of their components. The cell consists of two primary elements: the cytoplasm and the plasma membrane.

- **Cytoplasm**: This behaves as a conductive medium, with a typical conductivity of approximately 1 Siemens per meter (S/m).
- **Plasma Membrane**: The membrane acts as an insulating layer, with conductivity ranging between $10^{-7} S/m$ and $10^{-5} S/m$, depending on the specific type of cell.

The significant difference in the relative permittivity between the cytoplasm and the membrane adds to the complexity of the cell's electromagnetic properties. The relative permittivity of the cytoplasm is approximately 80, whereas the membrane has a much lower permittivity, around 11.3. This contrast creates unique electromagnetic interactions, particularly when the cell is exposed to external EM fields. Furthermore, the physical scale of the cell introduces additional challenges—biological cells are on the micrometer scale, with their membranes typically only a few nanometers thick.

Figure 5 summarizes these critical electromagnetic parameters, which serve as the foundation for modeling the complex behavior of biological cells under EM field exposure.

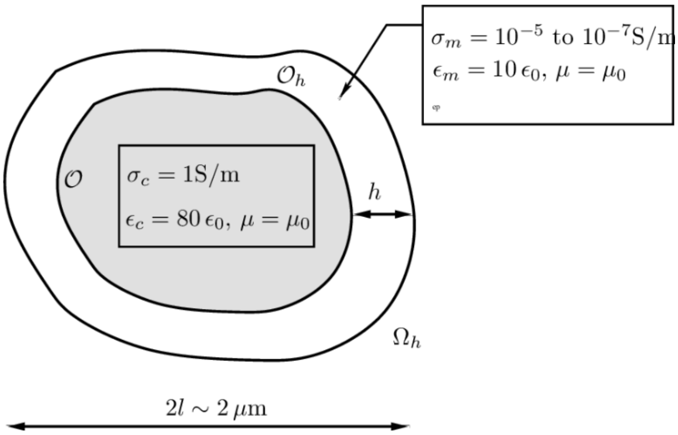

Figure 5. Parameters of the biological cell

The properties outlined in Figure 5 reveal that the plasma membrane, despite its small thickness, plays a significant role in controlling the cell's interaction with electromagnetic fields. These factors must be considered when developing accurate models for simulating the interaction between biological cells and EM fields.

4.2. Surface Impedance Model

Surface impedance is a key factor in modeling the interaction between EM fields and biological cells. Surface impedance Z_s relates the electric and magnetic fields at the boundary between the cell and the surrounding medium.

Surface impedance (Z_s) plays a crucial role in characterizing the interaction between electromagnetic fields and biological cells. It relates the electric field (***E***) and magnetic field (***H***) at the boundary between the cell and the surrounding medium. Surface impedance is particularly useful in modeling the thin insulating layer of the plasma membrane and its effect on the overall EM behavior of the cell.

The surface impedance is given by the following equation:

$$Z_s = (1 + i)(\frac{\mu_0 \omega}{2\sigma})^{\frac{1}{2}} \qquad (2)$$

Where:

- μ_0: Permeability of free space.
- ω: Angular frequency.
- σ: Conductivity of the biological material.

This equation captures the complex behavior of electromagnetic waves as they interact with the thin membrane of the cell. The term $(1 + i)$ accounts for the phase shift and amplitude changes caused by the wave's passage through different media, while the square root term reflects the frequency-dependent nature of the impedance.

The surface impedance model is critical in considering the dual behavior of the cell, acting both as a conductive and dielectric material depending on the frequency of the incident electromagnetic field.

4.3. Dual Electromagnetic Behavior

Biological cells exhibit different electromagnetic behaviors depending on the frequency of the external EM field:

- **Below 10^7 Hz:** At lower frequencies, the cell behaves as a heterogeneous material, with the cytoplasm acting as a conductive medium and the plasma membrane functioning as an insulator. In this regime, the electric fields primarily affect the cytoplasm, while the membrane serves as a boundary, reflecting and diffracting incident waves.
- **Above 10^8 Hz:** At higher frequencies, the behavior of the cell shifts to that of a slightly heterogeneous dielectric material. The thinness of the plasma membrane, combined with the large difference in permittivity between the cytoplasm and the membrane, becomes the dominant factor in determining the cell's interaction with EM fields. The membrane's insulating properties attenuate the fields, while the cytoplasm exhibits dielectric characteristics, resulting in different field propagation patterns inside the cell.

This dual-frequency-dependent behavior is critical for precise electromagnetic field modeling in biological applications. For instance, nanosecond Pulse Electric Fields (nsPEF) used in cancer treatment rely on high-frequency fields to penetrate the plasma membrane and disrupt the cellular structure, making accurate modeling essential for predicting treatment outcomes.

5. Simulation Results and Analysis

5.1. Usefulness of the Microstrip Line in This Context

Nanosecond Pulse Electric Fields (nsPEF) have demonstrated significant potential in both medical and industrial applications. In the medical field, nsPEF is increasingly used for the destruction of cancerous cells, such as melanomas, as well as for inhibiting tumor growth. The industrial applications are equally promising, particularly in the field of food decontamination, where nsPEF has proven effective in eliminating harmful bacteria. The success of nsPEF depends on a variety of factors, including pulse duration, amplitude, shape, and the number of pulses. Hence, it is critical to develop generators that can produce highly customizable pulse shapes and durations, generating an impulse field of very short duration and high amplitude to optimize treatment and industrial processes.

One of the most effective methods for generating such fields involves the use of transmission lines. Technologies such as microstrip lines, coaxial lines, and coplanar lines can store energy and control pulse shaping. This section focuses on the coupling between a microstrip line and a biological cell, examining how this interaction evolves based on the distance between the cell and the microstrip line.

5.2. Geometric and Modeling Constraints for Electromagnetic Analysis

The interaction between a microstrip line and a biological cell is modeled in a periodic network, as shown in Figure 6, where the coupling behavior between the cell and the electromagnetic field generated by the microstrip line is studied.

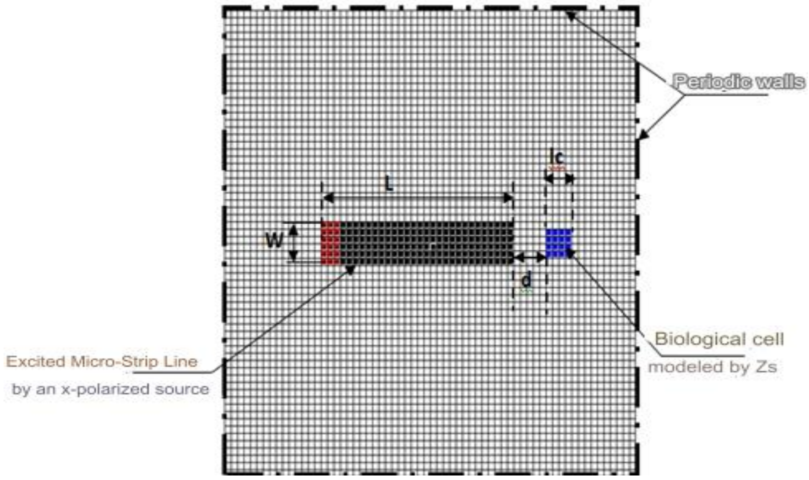

Figure 6. Microstrip line interacting with a biological cell in a periodic network

The geometric characteristics and modeling constraints used for the electromagnetic analysis are provided in Table 1. These parameters ensure accurate simulation results, taking into account the spatial and spectral requirements of the study.

Table 1: Geometric and modeling constraints of the biological cell interacting with the microstrip line.

Parameter	**Value**
Case dimension	$a = b = 0.1\ mm$
Mesh resolution	64×64
Line length	$L = 30\ /\ 64\ pixels$
Line width	$W = 6\ /\ 64\ pixels$
Biological Cell Dimensions	$Length = Width = 4\ /\ 64\ pixels = \ 6.25\mu m$
Substrate height	$H = 1\ mm$
Frequency range	$0.1\ GHz \leq F \leq 3GHz$
Frequency step	$0.1\ GHz$
Surface Impedance	$Z_s = (1 + i)(\frac{\mu_0 \omega}{2\sigma})^{\frac{1}{2}}$

The modeling considers different physical properties of the biological cell, such as its conductivity and permittivity. For instance, at a frequency of 1 GHz, the surface impedance is given as$Z_S = 20\pi(1 + i)\Omega$, assuming a conductivity σ=1 S/m. The two environments studied have permittivities ϵ_{r1}=1and ϵ_{r2}=2.2.

5.3. Electromagnetic Behavior in Different Subdomains

The electromagnetic behavior within the biological cell is further understood through the intrinsic functions associated with the different subdomains in the structure. These subdomains include:

- Dielectric (Hi),
- Metal (Hm),

- Source (Hs),
- Surface Impedance (H_{ISurf}).

The detailed representation of these subdomains is shown in Figure 7.

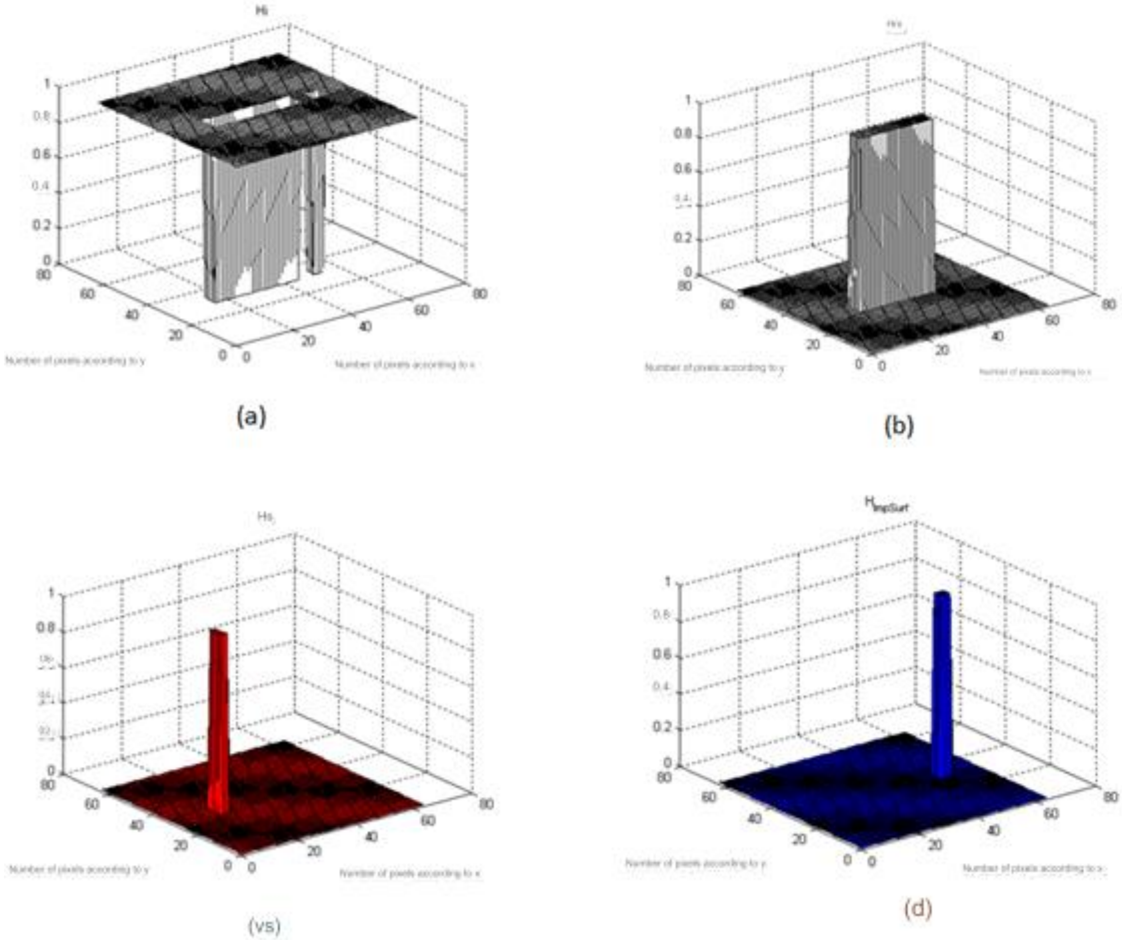

Figure 7. The intrinsic functions associated with the different subdomains ((a) Dielectric 'H_i', (b) Metal 'H_m', (c) Source 'H_s', (d) Surface Impedance 'H_{ISurf}')

5.4. Analysis of Results for Different Distances

The coupling effect between the microstrip line and the biological cell is analyzed at different distances from the source. In this study, the frequency is set at 1 GHz, and the behavior of the electromagnetic field is examined for two distinct distances: D1=2pixels and D2=28pixels. The following figures provide insights into the system's behavior, focusing on the evolution of the input admittance (Yin), electric field distribution, and current density.

Figure 8 shows the evolution of the input admittance (Yin) over several iterations. The admittance converges after a sufficient number of iterations, indicating the system's stabilization.

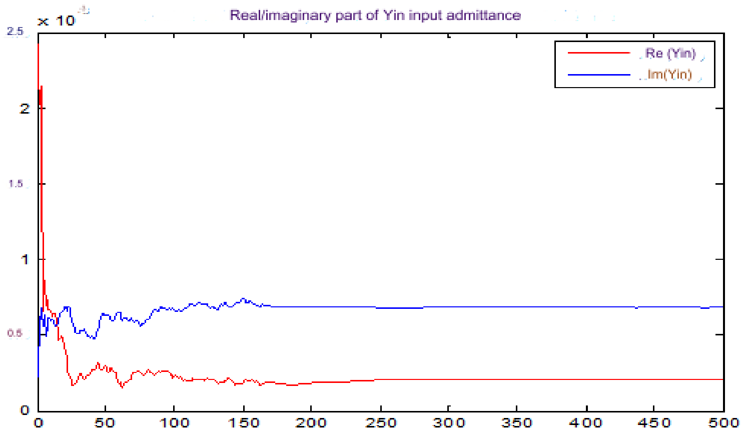

Figure 8. Evolution of Yin depending on the number of iterations

Figure 9 illustrates the electric field distribution (|Ex|) and current density (|Jx||) at a distance of 2 pixels. This figure reveals a strong interaction between the microstrip line and the biological cell, with high electric field intensity near the cell.

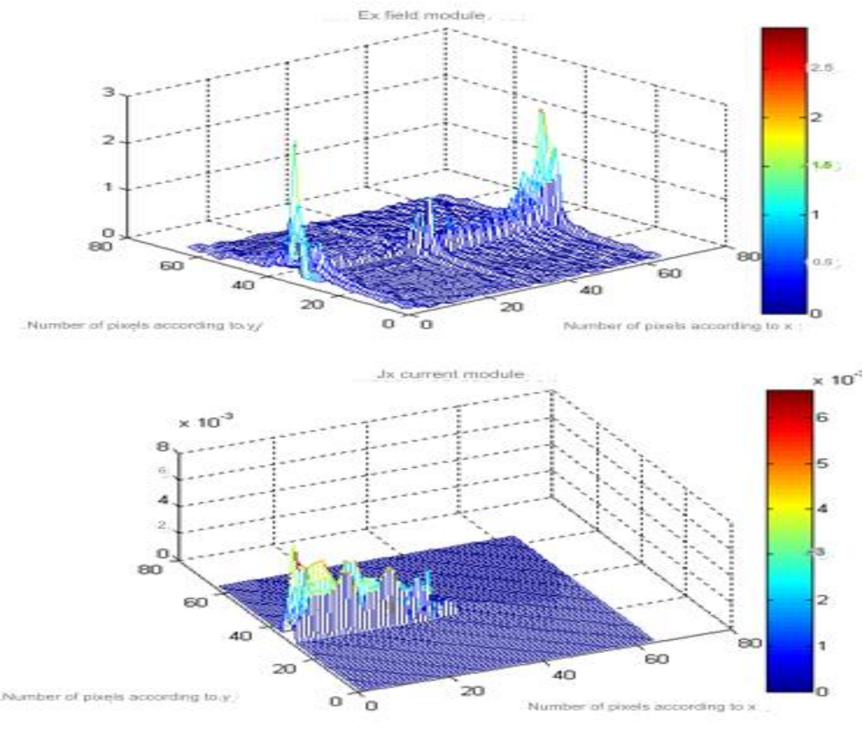

Figure 9. Electric field distribution |Ex| and the current density |Jx| at 1GHz for D=2pixels

Figure 10 provides a detailed view of the electromagnetic behavior of the biological cell when exposed to the microstrip line at a distance of 2 pixels. The fields are concentrated near the cell, creating strong coupling effects.

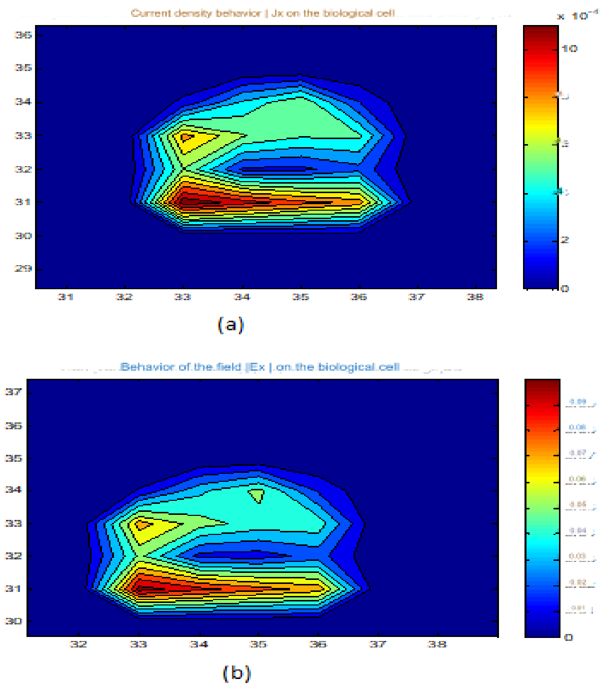

Figure 10. EM behavior of the biological cell by coupling effect with the micro-strip line for F=1GHz and D=2pixels (a) Field |Ex| and (b) Density |Jx|

Figure 11 shows the electric field distribution and current density at a distance of 28 pixels. In this case, the coupling is significantly weaker, as the field intensity decreases with increased distance from the source.

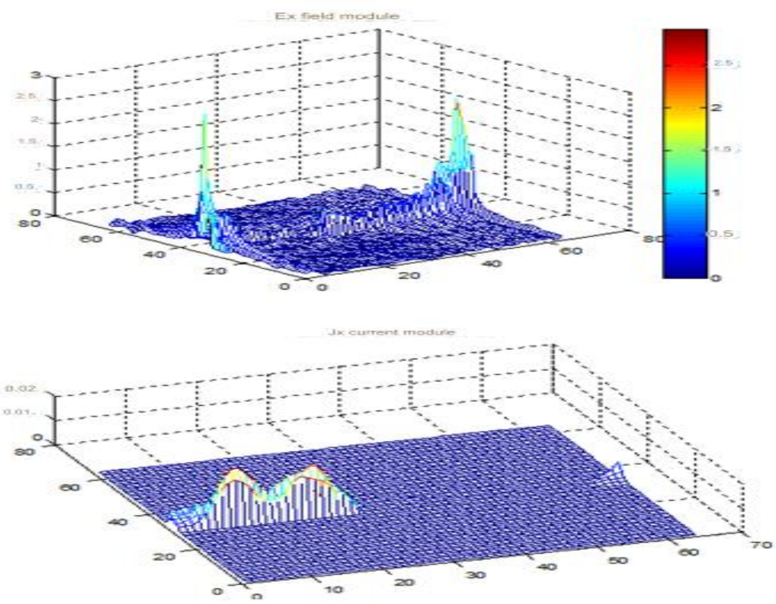

Figure 11. Electric field distribution |Ex| and the current density |Jx| at 1GHz for D=28pixels

5.5. Interpretation and Implications

The simulation results provide critical insights into the interaction between the electromagnetic field generated by a microstrip line and a biological cell. The analysis, conducted at two distinct distances (2 pixels and 28 pixels) and at a frequency of 1 GHz, highlights the significant differences in electromagnetic coupling and its practical implications for both medical and industrial applications.

Short-Distance Interaction (2 Pixels)

At a distance of 2 pixels, the electromagnetic interaction between the microstrip line and the biological cell is particularly strong. As demonstrated in Figures 9 and 10, the electric field distribution and current density are highly concentrated around the biological cell. This strong coupling is especially important in medical applications, such as cancer treatment using nanosecond Pulse Electric Fields (nsPEF).

In these treatments, the highly localized electromagnetic fields generated at close distances are critical for targeting and disrupting cancer cells. The intense fields can penetrate the plasma membrane and impact intracellular components, leading to the destruction of cancerous cells. This targeted approach allows for the precise application of nsPEF to malignant tissues while minimizing damage to surrounding healthy cells. The strong coupling effect observed at short distances also suggests the possibility of optimizing pulse duration, amplitude, and frequency to maximize therapeutic efficiency, making this method highly effective for conditions like melanoma or other tumor types.

Additionally, the ability to generate high electric field intensities at close proximity allows for the application of lower overall energy levels, which reduces potential side effects such as tissue heating or unwanted thermal damage. This is critical in ensuring that the treatment remains minimally invasive while still effective in disrupting cellular activity within tumors.

Long-Distance Interaction (28 Pixels)

At a distance of 28 pixels, as shown in Figure 11, the intensity of the electric field and current density decreases significantly. This weaker electromagnetic interaction is more suited to industrial applications, where the goal is often not to penetrate deep into biological structures but to achieve surface-level effects.

One of the primary industrial applications of nsPEF is food decontamination, where electromagnetic fields are used to eliminate bacteria and other microorganisms on the surface of food products. In this context, the reduced electromagnetic field intensity at greater distances is beneficial. A controlled, weaker field is sufficient to disrupt bacterial cells without damaging the food's texture or quality. Furthermore, the simulation results suggest that the field distribution at longer distances could be tailored to cover larger surface areas efficiently, making the process scalable for industrial use.

Another industrial implication of this research involves materials sterilization, where high-power fields at short distances might be overkill. The ability to adjust the field intensity by altering the distance between the source and the target enables precise control over the sterilization process. This flexibility is crucial when dealing with sensitive materials, where excessive field strength could cause unwanted damage.

Optimization of Distance and Frequency in Applications

The results demonstrate that the electromagnetic behavior of the system is highly dependent on the distance between the microstrip line and the biological cell, as well as the frequency of the EM field. Shorter distances result in stronger coupling and higher field intensities, which are ideal for medical treatments that require precise, high-impact electromagnetic exposure. Conversely, longer distances produce weaker interactions, which are better suited to industrial applications that do not require deep penetration of electromagnetic fields.

This frequency-dependent and distance-sensitive behavior has broad implications for both fields:

- **In medical applications**, optimizing the distance between the treatment device and the target tissue can lead to improved outcomes by delivering more focused energy to cancer cells, thereby enhancing therapeutic effects while reducing side effects.
- **In industrial applications**, adjusting the distance and intensity allows for more controlled processing environments, ensuring that food products or other materials are decontaminated without compromising quality.

The findings from this research underline the versatility of using microstrip lines in conjunction with nsPEF for both medical and industrial purposes. By demonstrating the importance of precise distance control, the study opens avenues for the development of more advanced systems that incorporate distance modulation and real-time feedback mechanisms. Such systems could dynamically adjust the distance and intensity of electromagnetic fields based on the target's response, further optimizing the application for each specific use case.

Moreover, the simulations suggest that advanced techniques, such as adaptive mesh refinement (AMR) or non-uniform fast Fourier transform (NUFFT), could be integrated into future models to achieve even higher levels of accuracy in the simulation of complex electromagnetic interactions. This would allow for the fine-tuning of pulse parameters, such as duration, amplitude, and shape, making nsPEF a more adaptable tool across different fields.

The versatility and adaptability of electromagnetic modeling, particularly when applied to microstrip line coupling with biological cells, offer promising potential across various industries. The strong interaction at close distances highlights the potential for cancer treatments that are both effective and minimally invasive, while the weaker interaction at larger distances supports the efficient and safe decontamination of food products and materials. As this field of research progresses, the continued refinement of these models will play a crucial role in enhancing both therapeutic and industrial applications, leading to the development of more sophisticated and versatile electromagnetic systems.

6. Conclusion

This research demonstrates the versatility and potential of electromagnetic field modeling, specifically through the Transverse Wave Approach (TWA) and microstrip line coupling with biological cells. The simulation results provide a comprehensive understanding of how distance and frequency affect the interaction between EM fields and biological materials, offering valuable insights for both medical and industrial applications.

In medical contexts, strong electromagnetic coupling at short distances has significant implications for cancer treatments. The use of nanosecond Pulse Electric Fields (nsPEF) enables precise targeting of cancer cells, minimizing damage to surrounding healthy tissues. The ability to optimize field intensity and duration for maximum therapeutic effect is crucial for the advancement of non-invasive cancer therapies, particularly in the destruction of melanomas and the inhibition of tumor growth.

In industrial applications, the results demonstrate the effectiveness of weaker electromagnetic fields at longer distances, which are sufficient for surface-level processes such as food decontamination and materials sterilization. This controlled interaction allows for safe and efficient sterilization without compromising the quality of the materials being processed.

Overall, this research highlights the importance of optimizing distance, frequency, and field intensity to maximize the effectiveness of electromagnetic treatments. The insights gained from these simulations provide a strong foundation for future advancements in both medical therapies and industrial processing technologies, paving the way for more precise and adaptive EM-based systems.

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