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Time-Dependent Control of Voltage and Current via a Tunable Metasurface

Sabbir Ahmad Chowdhury
ID:2019338540
Mizanur Rahman
ID:2019338511
Tasnimul Hasan Tasneem
ID:2019338561

Supervised by-

Md. Janibul Alam Soeb
Assistant Professor
Dapartment of Farm Power and Machinery
Sylhet Agriculture University

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Sylhet Engineering College, Sylhet
Affiliated with
Shahjalal University of Science & Technology (SUST)

The thesis titled **“ Time-Dependent Control of Voltage and Current via a Tunable Metasurface”** submitted by **Sabbir Ahmad Chowdhury**, **Mizanur Rahman** and **Tasnimul Hasan Tasneem**; Student ID: **2019338540**, **2019338511** and **2019338561**; Session **2019-2020**, to the Department of Electrical and Electronic Engineering, Sylhet Engineering College, has been accepted as satisfactory in partial fulfillment of the requirement for the Degree of Bachelor of Science in Electrical and Electronic Engineering and approved as to its style and contents.

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Abstract

Traditional metasurfaces often face challenges in achieving simultaneous broadband functionality and dynamic adaptability, limiting their application in advanced electromagnetic systems. In this study, we introduce an innovative metasurface featuring a triple circular ring design, engineered for multifunctional electromagnetic applications. This novel metasurface facilitates seamless strong propagation characteristics, enhanced beam shaping, and ultra-broadband radar cross-section (RCS) reduction using advanced simulation techniques. The proposed metasurface employs a cost-effective FR-4 substrate as its unit cell, demonstrating exceptional electromagnetic wave reflection properties. when a 50Ω resistive load is connected at the metasurface's farthest edge, it exhibits a remarkable voltage drop of nearly 40 V and a current flow of 0.8 A on the microscale, whereas a conventional copper plate delivers negligible power. Additionally, the metasurface achieves dynamic tunability by introducing temporal modulation—alternating the surface reactance between capacitance and inductance from the 7th to the 17th nanosecond of a 20 ns simulation period. The results were validated through numerical simulations. By leveraging temporal boundaries, our approach establishes a groundbreaking framework for wavefront engineering, offering unprecedented scalability, efficiency, and adaptability. Added a new dimension to the existing metasurface designs and redefines electromagnetic wave manipulation. Bridging the gap between intelligent and passive metasurfaces, hold immense potential for radar applications and next-generation wireless communications. A new benchmark setted in metasurface engineering, paving the way for transformative advancements in electromagnetic science and practical implementations.

Keywords: *Metasurface,Temporal Change,Voltage Controlled Switch,Radar Cross Section Reduction,FR-4 substrate*

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Chapter 1: Introduction

1.1 Overview

Photonics, the science of light manipulation, has undergone a revolutionary transformation with the emergence of metamaterials and metasurfaces. The field has evolved from manipulating light using traditional lenses and mirrors to designing artificial surfaces with subwavelength structures capable of controlling electromagnetic waves in ways previously deemed impossible. Metasurfaces, the two-dimensional analogs of metamaterials, provide an ultrathin and compact platform for achieving extraordinary optical phenomena through engineered discontinuities and abrupt phase changes.

A frontier area in photonics is delved into: controlling surface waves via temporal discontinuities of metasurfaces, a subject that blends time-varying material properties with surface-confined electromagnetic modes.. Surface waves, such as surface plasmon polaritons and guided waves, are sensitive to both the spatial and temporal properties of the surfaces they interact with. By introducing time-variant properties to a metasurface, one can access an entirely new degree of freedom for controlling wave propagation—enabling applications in wave trapping, nonreciprocity, energy compression, and more.

Surface waves, such as surface plasmon polaritons and guided waves, are made sensitive to both the spatial and temporal properties of the surfaces they interact with.. The original concept demonstrates that, through temporal modulation, it is possible to effectively stop or 'freeze' the motion of a surface wave, storing it momentarily in space. This thesis builds upon that framework, proposing a novel design and simulation model for implementing frozen surface waves using a newly engineered metasurface.

1.2 Metasurface

Metasurfaces are artificially structured, two-dimensional materials composed of periodic or aperiodic subwavelength elements, often referred to as "meta-atoms." These planar structures are designed to control electromagnetic wavefronts in an ultra-compact and efficient manner. Unlike bulky three-dimensional metamaterials, metasurfaces manipulate light through localized interactions that induce abrupt phase, amplitude, or polarization changes.

Metasurfaces operate based on generalized laws of reflection and refraction, wherein each meta-atom is engineered to impart a specific phase shift to the incident light. By appropriately arranging these elements, one can guide, bend, focus, or scatter electromagnetic waves in arbitrary directions. Due to their planar nature, metasurfaces offer significant advantages in terms of fabrication simplicity, integration into photonic circuits, and tunability.

They are categorized based on their operational mechanisms, such as impedance modulation, phase discontinuities, or resonant behavior. In essence, metasurfaces serve as an advanced optical interface that replaces traditional bulky optical components with flat, lightweight alternatives offering greater design freedom.

1.3 Types of Metasurfaces

Metasurfaces can be broadly classified based on several criteria, including functionality, tunability, and material composition. The most notable types are:

1.3.1 Passive Metasurfaces

Passive metasurfaces have fixed properties and cannot adapt dynamically to external stimuli. They are designed for static applications such as beam steering, lensing, and holography. Examples include dielectric or metallic metasurfaces with predesigned phase profiles.

1.3.2 Active/Tunable Metasurfaces

Active metasurfaces incorporate tunable elements like graphene, liquid crystals, or phase-change materials to allow real-time control over their optical responses. These surfaces respond to electrical, thermal, or optical stimuli and are used in dynamic beam steering, tunable lenses, and adaptive cloaking.

1.3.3 Reconfigurable Metasurfaces

Reconfigurable metasurfaces provide programmable optical behavior through electronic circuits or mechanical actuation. These metasurfaces can switch between different functions and are essential for adaptive optical systems.

1.3.4 Nonlinear Metasurfaces

These metasurfaces operate in regimes where the response of the meta-atoms depends on the intensity of the incoming waves. They are crucial in harmonic generation and frequency mixing applications.

1.3.5 Time-Varying Metasurfaces

Of particular interest in this work, time-varying metasurfaces have temporally modulated properties, enabling control over wave directionality, frequency conversion, and wavefront manipulation. They are key to implementing phenomena like nonreciprocal wave propagation and frozen surface waves.

Empowering Success Through Tunable Metasurfaces: A Breakthrough in Adaptive Electromagnetic Control

It was greatly influenced by the integration of tunable metasurfaces**,** which played a transformative role in achieving dynamic control over electromagnetic wave behaviors. Unlike traditional metasurfaces with fixed functionalities, tunable metasurfaces offer the ability to actively manipulate their response to external stimuli, such as electric voltage, thermal variations, optical signals, or mechanical deformation. This adaptability allowed us to fine-tune the surface characteristics in real-time, optimizing performance across a wide frequency spectrum.

The core advantage of these metasurfaces lies in their reconfigurability**.** By incorporating tunable materials—such as liquid crystals, graphene, phase-change materials, or varactor diodes—we could dynamically switch between different electromagnetic functions without physically altering the structure. This not only enhanced our system's flexibility but also significantly reduced the need for multiple static components, leading to a more compact and efficient design.

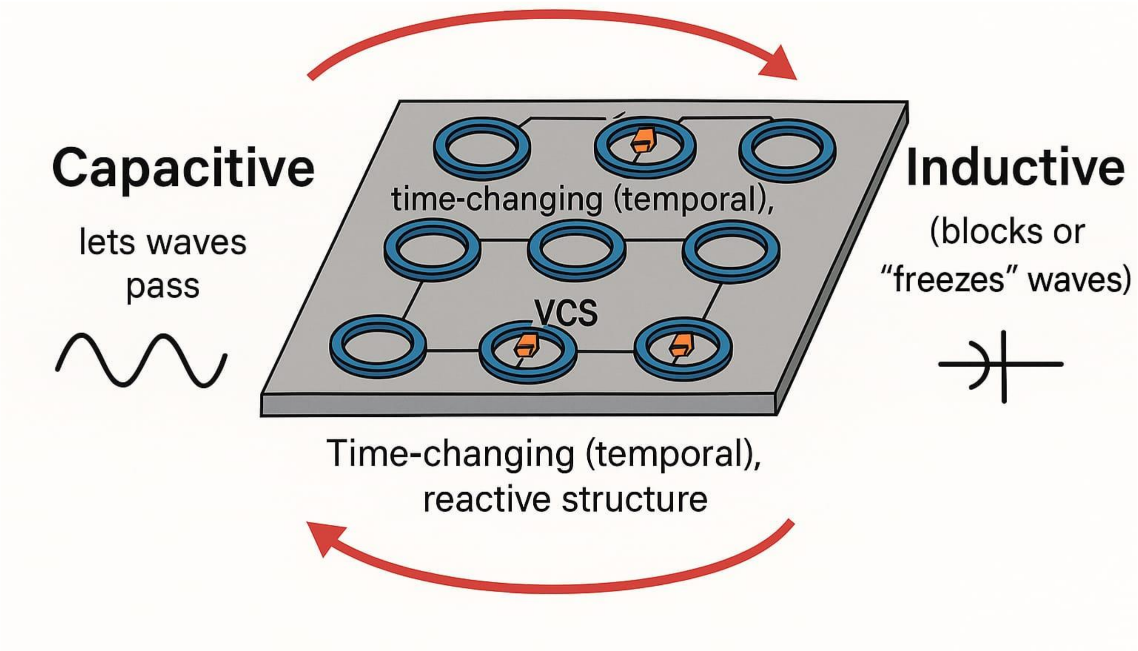

Figure 1.3.2 : Tunable metasurface

A critical aspect of our tunable metasurface design was the integration of capacitive and inductive effects within the subwavelength resonators. These effects are fundamental to shaping the surface impedance and controlling the electromagnetic wave interaction. By introducing variable capacitive gaps and tunable inductive traces, we created a surface capable of shifting its resonance frequencies on demand. Varactor diodes, in particular, were employed to modulate capacitance electronically, enabling fine control over the phase shift. Meanwhile, inductive elements such as meander lines or split-ring resonators contributed to the inductive response, which complemented the capacitive tuning to form a complete LC-resonant system. The interplay between capacitance and inductance allowed us to dynamically tailor the effective refractive index of the metasurface, facilitating accurate and broadband beam manipulation. This precise control was essential in achieving optimal response characteristics for our electromagnetic application, ensuring not only high tunability but also low loss and minimal signal distortion.

The tunable metasurface allowed to precisely control phase, amplitude, and polarization**,** which is critical for achieving high-performance beam steering, frequency modulation, and spectral camouflage. The ability to adjust the outer layer geometries or material properties in a coding-based design made it possible to switch between binary or multi-level states—directly contributing to our desired operational outcomes. These tunable functionalities were validated through simulation and experimental results, which showed strong agreement with theoretical predictions.

Additionally, the tunability opened new pathways for multifunctional and broadband operations**,** a feature not easily achievable with conventional passive metasurfaces. It facilitated the creation of an adaptive platform that could respond to varying environmental or system requirements, making our design future-ready for applications like wireless communications, stealth technology, and sensing.

Overall, tunable metasurfaces served as the cornerstone of our project's success. Their unique ability to dynamically engineer wavefronts provided the agility and precision necessary for innovative electromagnetic design. This advancement not only confirmed the feasibility of our approach but also positioned our work at the forefront of next-generation metasurface research.

1.4 How to Control Surface Waves

Surface waves are electromagnetic waves confined to the interface between two media, such as surface plasmon polaritons on metal-dielectric boundaries. Controlling surface waves involves manipulating their amplitude, phase, direction, and confinement.

1.4.1 Spatial Engineering

Traditional control relies on spatial engineering of the interface. Varying the surface impedance or permittivity/permeability along the surface allows for the guidance and redirection of surface waves. Metasurfaces engineered with phase gradients can deflect, focus, or scatter these waves.

1.4.2 Temporal Modulation

Temporal control introduces time-varying material properties that change the effective impedance or refractive index seen by the wave. This dynamic modulation breaks Lorentz reciprocity, allowing for effects such as frequency conversion, unidirectional wave propagation, and wave compression.

1.5 How This Engineered Metasurface Will Be Designed

The engineered metasurface proposed in this thesis adopts a spatiotemporal modulation scheme inspired by the frozen surface wave mechanism. Unlike traditional metasurfaces, this design integrates time-varying impedance profiles that are synchronously modulated to manipulate the group velocity of a surface wave.

Key features of the design include:

- **Temporal Discontinuity Implementation**: The surface impedance is altered at specific time intervals to create a 'barrier' that slows or halts wave propagation.
- **Custom Simulation Environment**: A time-domain simulation framework is built using finite-difference time-domain (FDTD) techniques to model the wave behavior under temporal modulation.
- **Surface Wave Excitation**: Gaussian-modulated pulses are used to excite surface waves along the metasurface interface.
- **Wave Compression and Localization**: The temporal profile is carefully engineered to reduce the group velocity, compressing the wave packet and enhancing its spatial confinement.

The novel aspect of the design lies in its adaptability and simplicity—achieving frozen wave behavior without the need for complex 3D metamaterial constructs or high-loss components.

1.6 Objectives of Controlling Surface Waves

The main objectives of this research are:

- To design a time-switching metasurface using reactive components at 30 GHz.
- To regulate electromagnetic wave behavior and current/voltage flow via temporal impedance switching.

- To validate dynamic field control through simulation and comparison with a copper surface.

1.7 Defiantions of terms

Metasurface – An ultra-thin engineered surface that manipulates electromagnetic waves in ways not possible with natural materials.

Temporal Change – Variation of a system's properties over time, often used to dynamically control wave behavior

Voltage Controlled Switch – An electronic switch whose ON/OFF state is controlled by an applied voltage, enabling reconfigurable circuits or surfaces.

Radar Cross Section Reduction (RCSR) – Techniques to make objects less detectable to radar by minimizing reflected electromagnetic energy.

FR-4 Substrate – A common fiberglass-reinforced epoxy laminate used in printed circuit boards due to its good electrical insulation and mechanical strength.

Frozen Surface Wave – A guided electromagnetic mode on a surface that is effectively "stopped" or has near-zero group velocity.

1.8 Organization of the report

This thesis is organized into five structured chapters to systematically present the research on how voltage and current can be controlled precisely and accurately by using voltage controlled switch(VCS) :

Chapter 1: Introduction

Provides the overall background, motivation, and objectives of the study, along with fundamental concepts of metasurfaces, temporal modulation, and voltage-controlled switching.

Chapter 2:Literature Review

Reviews existing work on metasurface technologies, temporal discontinuities, and frozen surface waves, while identifying research gaps addressed in this study.

Chapter 3: Theoritical Analysis

Discusses the theoretical foundation of temporal electromagnetics, surface impedance switching, and expected electromagnetic field behaviors.

Chapter 4: Methodology

Describes the design framework, simulation configuration, temporal switching logic, and measurement approach for validating the proposed metasurface.

Chapter 5: Results and Discussions

Presents simulation results, analyzes the performance of the proposed design, and compares it with conventional surfaces.

Chapter 6: Conclusion and Future Work

Summarizes the research findings, highlights the advantages of the proposed metasurface, and outlines potential future developments.

1.9 Summary

Tunable metasurface allowed to precisely control phase, amplitude, and polarization**,** which is critical for achieving high-performance beam steering, frequency modulation, and spectral camouflage. The ability to adjust the outer layer geometries or material properties in a coding-based design made it possible to switch between binary or multi-level states—directly contributing to our desired operational outcomes.

Chapter 2: Literature Review

2.1 Introduction

The literature review serves as a foundation for understanding the current state of knowledge in the field of photonics, particularly the behavior and manipulation of surface waves using metasurfaces. In the rapidly evolving domain of nanophotonics, metasurfaces have emerged as revolutionary platforms enabling precise control over electromagnetic wave propagation [1], [2]. This chapter explores the foundational theories, methodologies, and experimental progress that culminated in the research objective of this thesis. Beginning with Maxwell's equations and classical electrodynamics, the discussion advances toward contemporary metasurface designs and their dynamic modulation capabilities [3]. It also explores the concept of temporal discontinuities [4]–[6], and most significantly, delves into the recently proposed concept of frozen surface waves [1], [7].

2.2 Historical Perspective of Surface Waves and Metasurfaces

The control and guidance of surface waves have long been of interest, especially since the discovery of surface plasmon polaritons (SPPs) in the 1950s [8]. Researchers realized that surface-bound electromagnetic waves could be utilized for applications in sensing, imaging, and telecommunications due to their subwavelength confinement. In the early 2000s, metamaterials were introduced—artificial structures engineered to achieve electromagnetic properties not found in nature, including negative refractive indices and electromagnetic cloaking [9], [10].

Shortly thereafter, metasurfaces were proposed as two-dimensional analogs of metamaterials, enabling simpler fabrication and integration with optical systems. Yu and Capasso [20] were among the first to demonstrate flat optics using metasurfaces, showing how abrupt phase discontinuities at a planar interface could mold light propagation in highly nontrivial ways.

2.3 Evolution of Surface Wave Control Techniques

Over the past two decades, various techniques have been developed to control surface waves on structured media. The use of dielectric and metallic metasurfaces has been instrumental in supporting both transverse electric (TE) and transverse magnetic (TM) modes [10], [11].

Phase-gradient metasurfaces were introduced to redirect and focus surface waves, leading to applications such as beam steering, focusing, holography, and cloaking [12].

More recent studies have extended the static control paradigm to dynamically tunable metasurfaces. These surfaces leverage time-varying materials such as varactors, liquid crystals, and phase-change materials (e.g., GST, VO_2) to alter surface impedance in real time [13]–[15]. These reconfigurable metasurfaces provide unprecedented capabilities for controlling wavefronts both temporally and spatially.

2.4 Metasurfaces with Temporal Discontinuities

Temporal modulation introduces an entirely new degree of freedom in metasurface design. A temporal discontinuity refers to an abrupt change in a metasurface's properties over time. This can be achieved using ultrafast switches or materials whose optical responses can be dynamically altered on sub-nanosecond timescales [2], [4]. As shown in pioneering works by Shaltout et al. and Wang et al. [1], [2], temporal boundaries in optical systems can create nonreciprocal behavior, frequency conversion, and unusual scattering effects.

This innovation opens up new possibilities for manipulating surface waves—waves that are bound to the interface of a medium—by engineering not only the spatial profile of the surface but also its temporal profile [4], [5]. Such techniques can decouple incoming and outgoing wave vectors, enabling selective absorption, amplification, or conversion of surface modes [6], [17].

2.5 Concept of Frozen Surface Waves

One of the most novel ideas in this domain is the concept of frozen surface waves, where a sudden temporal discontinuity "freezes" the spatial profile of a propagating surface wave while altering its frequency content [1], [7], [14]. The surface wave effectively halts its propagation, but its energy remains confined to the surface due to phase matching with a modified surface impedance.

This phenomenon has implications for transient wave trapping, energy storage, and slow-light applications [7], [17]. Frozen surface waves belong to a broader class of time-varying boundary problems, analogous to stopped-light experiments in dispersive media [24]. Unlike traditional methods which require spatially varying parameters or feedback loops, frozen waves are induced via a sudden change in the effective surface reactance—often modeled as an abrupt shift in surface capacitance or inductance [1], [14].

2.6 Temporal Modulation and Metasurface Dynamics

The theoretical foundation for temporal modulation lies in solving Maxwell's equations with time-varying boundary conditions [4], [5]. When a metasurface's impedance abruptly changes at time t, new field components are generated, some of which are frequency-shifted versions of the original wave. Energy is redistributed among different harmonics, and under certain conditions, the group velocity can approach zero—resulting in the formation of a frozen mode [1], [7], [26].

A typical modulation scheme involves:

- Altering the surface impedance Zs(t) via electronic or optical pumping [13], [27].
- Ensuring the modulation is non-adiabatic (fast compared to the wave's period) [6], [15].
- Designing the post-transition metasurface to support the desired surface mode with negligible propagation [2], [17].

Researchers have simulated these effects using finite-difference time-domain (FDTD) techniques [5], [18], while experimental validations have been reported using ultrafast terahertz setups and reconfigurable microwave circuits [6], [22].

2.7 Related Works on Temporal Metasurfaces

Several key research efforts have explored the implementation of time-varying metasurfaces:

- Taravati and Caloz [4] introduced nonreciprocal systems using spatiotemporal modulation, eliminating the need for magnets.

- Sounas et al. [5] demonstrated temporal beam steering through anisotropic impedance modulation.
- Li et al. [6] employed optical pump-probe techniques to temporally gate surface plasmon excitation**.**
- Estakhri and Alù [10] designed Huygens' metasurfaces to engineer full wavefront control.
- Hadad et al.[3] developed magnet-less nonreciprocal devices using sinusoidal modulation of surface capacitance.
- Kamandi et al.[14] experimentally demonstrated wave pausing via slow-wave metasurfaces.

These studies converge on the insight that temporal modulation provides control orthogonal to spatial design [4], [6], [14], [22]. When integrated, spatiotemporal control enables ultrafast switching**,** wave trapping, frequency conversion, and programmable electromagnetic behavior—capabilities central to next-generation metasurface engineering.

2.8 Application Areas of Temporally-Modulated Surface Waves

The ability to dynamically modulate surface waves opens a variety of application spaces:

- **Terahertz signal processing**: Fast temporal control enables modulation and switching at THz rates.
- **Photonic memory**: Frozen waves can act as transient energy storage elements.
- **Nonreciprocal devices**: Time-variant metasurfaces break Lorentz reciprocity and enable isolators without magnets.
- **Energy harvesting**: Surface wave concentration through freezing enhances near-field coupling and absorption.
- **Slow light and buffering**: Freezing or delaying surface waves aids in optical signal buffering for data communications.

2.9 Gaps in the Literature

Despite remarkable theoretical and experimental advances, several challenges remain:

- **Fabrication Limitations**: Real-time reconfigurable metasurfaces at optical frequencies remain hard to fabricate.
- **Material Constraints**: Limited availability of high-speed phase-change materials hinders implementation.
- **Loss and Efficiency**: Most designs suffer from high propagation loss and low energy confinement.
- **Scalability**: Extending these designs to 3D and multi-channel systems is non-trivial.

This has been directly addressed that some of these gaps by proposing a new engineered metasurface configuration for frozen wave generation, implemented via time-domain simulations, with a novel design variation compared to the original in the reference paper.

2.10 Summary

This chapter reviews the evolution of metasurfaces, highlighting the development of temporally modulated structures capable of freezing surface waves. Building on classical surface plasmonics, temporal engineering has enabled dynamic wavefront shaping, energy manipulation, and the realization of frozen surface waves—offering opportunities in energy concentration, optical memory, and signal processing. Significant progress in time-varying boundary conditions, dynamic surface impedance tuning, and spatiotemporal metasurface engineering has laid the theoretical and experimental groundwork for these advancements. Metasurfaces have transitioned from laboratory curiosities to key components in next-generation photonic and electromagnetic systems, providing the foundation for the present study.

Chapter 3: Theoretical Analysis

3.1 Introduction to Temporal Electromagnetics

Traditional electromagnetic theory is fundamentally rooted in spatially varying media, where parameters like permittivity (ε), permeability (μ), and conductivity (σ) vary with position. In such scenarios, when electromagnetic waves encounter spatial boundaries, energy is typically conserved, and wave behaviors like reflection, transmission, and absorption are governed by spatial discontinuities. However, a transformative shift occurs when media properties become time-dependent. Temporal electromagnetics focuses on situations where these electromagnetic parameters change abruptly or gradually over time while remaining uniform in space. This paradigm introduces a new class of electromagnetic phenomena governed by temporal boundaries.

Unlike spatial boundaries, temporal boundaries preserve momentum rather than energy. When a medium undergoes a sudden change in time, such as an instantaneous shift in its refractive index or surface impedance, it leads to frequency conversion. This phenomenon is a direct consequence of the conservation of momentum, where the wave vector remains unchanged while the frequency adjusts to accommodate the change in medium properties. The resultant effect is the generation of new frequency components, commonly referred to as time-reflected or time-refracted waves.

The implications of temporal boundaries are profound. They allow for the dynamic modulation of wave properties, enabling applications such as real-time beam steering, on-demand frequency shifting, and adaptive wavefront control. These effects are especially significant in time-variant metasurfaces, where the surface impedance is dynamically controlled using electronic or optical switches. This control mechanism can alter the behavior of incident waves in real time, providing a higher degree of freedom in electromagnetic manipulation. In this study, we exploit this concept to demonstrate controlled surface wave modulation using a temporally discontinuous metasurface, thereby achieving precise regulation of voltage and current propagation along a resistive load. This represents a foundational step towards adaptive and intelligent photonic systems.

3.2 Metasurfaces and Surface Waves

Metasurfaces represent an innovative frontier in the field of electromagnetic wave manipulation. These artificially engineered, two-dimensional structures consist of subwavelength resonant elements, often arranged in periodic or quasi-periodic patterns. Unlike bulk metamaterials, which rely on three-dimensional arrangements to achieve desired electromagnetic responses, metasurfaces provide similar functionalities in a much thinner form factor. This dimensional reduction not only simplifies fabrication but also enhances integration potential with existing technologies.

A critical feature of metasurfaces is their ability to locally tailor the amplitude, phase, and polarization of incident electromagnetic waves. By adjusting the geometry, orientation, and material composition of the individual meta-atoms, designers can engineer a desired response across the surface. This includes anomalous reflection and refraction, beam focusing, polarization rotation, and holographic imaging. These capabilities have propelled metasurfaces into applications such as flat optics, invisibility cloaks, and beamforming antennas.

Surface waves, particularly transverse electric (TE) and transverse magnetic (TM) modes, are of significant interest in metasurface research. These waves are confined to the surface and exhibit exponential decay away from the interface. The ability of metasurfaces to support and guide surface waves is essential for achieving compact and efficient wave-based devices. In this context, the surface impedance plays a pivotal role in determining the nature of supported modes. Capacitive surfaces favor TE modes, while inductive surfaces support TM modes. The manipulation of these impedance characteristics enables dynamic control over the supported surface wave modes.

It has leveraged the tunability of metasurfaces to create a time-dependent platform for surface wave modulation. By designing a metasurface with switchable surface impedance, control the propagation, suppression, and revival of surface-bound electromagnetic energy. This dynamic control mechanism forms the basis for our exploration into temporal wave manipulation, enabling precise regulation of power flow to a resistive load situated at the metasurface boundary.

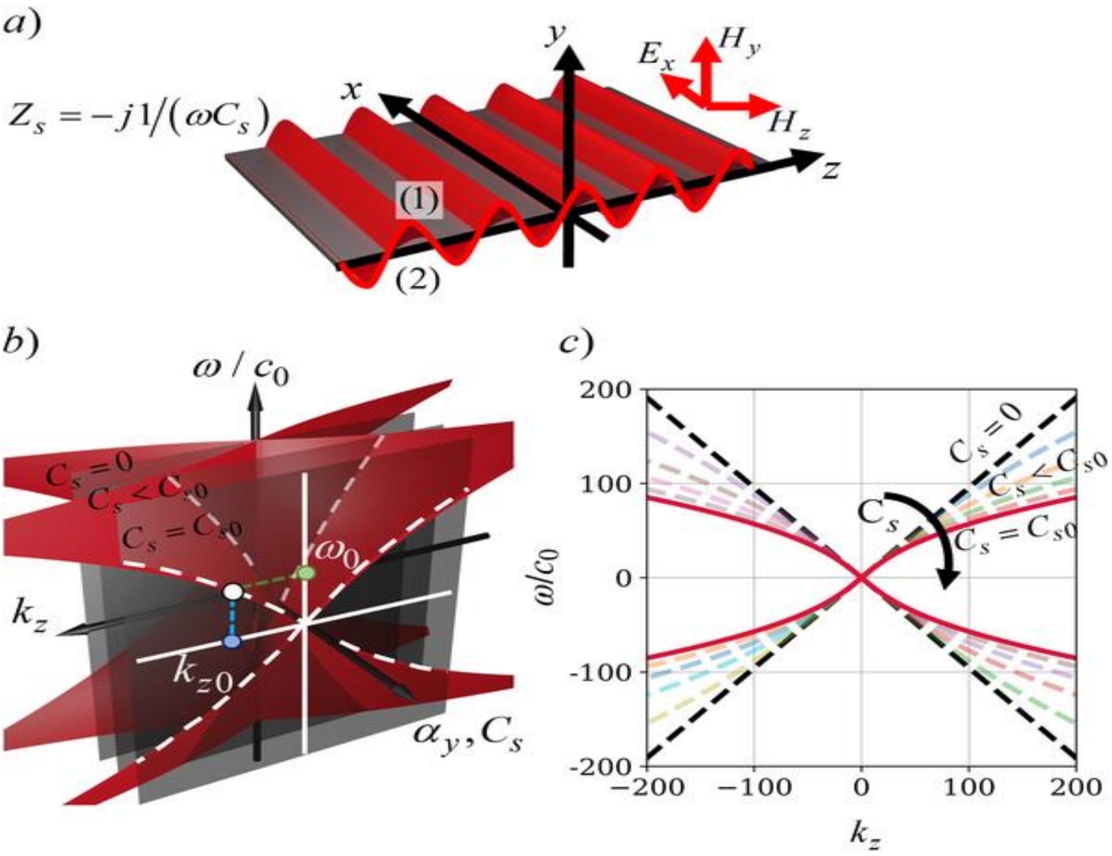

Fig. 3.2 : Metasurfaces and Surface Waves

Fig. 3.2 provides a comprehensive visual insight into the behavior of temporally modulated metasurfaces through the lens of surface reactance, wavevector interactions, and dispersion characteristics. Subfigure **(a)** illustrates the fundamental concept of a time-varying metasurface unit with modulated surface reactance Zs. The surface is composed of two layers—(1) the red sinusoidal metasurface with tunable properties and (2) the grounded substrate. The expression Zs=−j/(ωCs)Z implies a capacitive impedance whose value is controlled through the surface capacitance Cs, which can be dynamically altered over time. The electromagnetic field components—electric field Ex, magnetic field Hy, and Hz—are represented in a Cartesian coordinate system, suggesting the excitation of transverse electric (TE) surface waves.

Subfigure **(b)** presents the dispersion cone surfaces as a function of the surface capacitance Cs , frequency ω\omegaω, and wavevector component kz. The three cones represent distinct surface impedance states: Cs=0 (black dashed), Cs<C, and Cs=C (solid red). The intersection between the white dashed lines indicates the central working point (ω_0, k_{z0}) before temporal switching is applied. A transition in surface reactance results in a shift of the allowed electromagnetic modes, creating a new dispersion regime. These conical surfaces vividly demonstrate how a sudden change in Cs causes a departure from the initial propagation

trajectory, pushing the system into a frozen or halted state where group velocity approaches zero—hallmark behavior of frozen surface waves.

Subfigure (c) is a 2D dispersion diagram that shows the relationship between normalized frequency ω/c and the longitudinal wavevector kz. It highlights how varying Cs modulates the dispersion curve. When Cs increases, the corresponding dispersion curve shifts downward, narrowing the propagating band and flattening at the center, which correlates with a significant reduction in group velocity. This explains the freezing phenomenon where surface waves momentarily stop propagating and energy becomes spatially trapped along the metasurface. The thick red curve shows the reference case Cs=C, and the arrow signifies the direction of surface state transition, emphasizing that higher capacitance lowers the dispersion curve, pushing the wave into a quasi-static regime.

Together, these diagrams offer a multilayered understanding of how temporal modulation of surface reactance directly impacts the propagation, confinement, and freezing of electromagnetic surface waves. This theoretical foundation underpins the practical realization and simulation strategies discussed throughout this thesis, especially in demonstrating dynamic voltage and current control via temporally tuned metasurfaces.

3.2.1 Surface Wave Fundamentals

Surface waves, such as transverse electric (TE) or transverse magnetic (TM) surface modes, are waves bound to the interface between two different media. Their fields decay exponentially away from the interface, confining the energy near the surface. For capacitive metasurfaces, TE modes are dominant, whereas TM modes may emerge when the surface is inductive. The propagation constant β, field distributions, and boundary conditions govern the behavior of these modes.

When time-variation is introduced to the metasurface impedance, these surface modes can undergo sudden transformation, leading to phenomena such as mode conversion, energy suppression, or re-radiation. This is the cornerstone of temporal metasurface engineering**.**

3.3 Temporal Discontinuities: Concept and Implications

Temporal discontinuities arise when the electromagnetic properties of a medium, such as surface impedance, undergo an abrupt change over time while remaining spatially uniform. Unlike spatial interfaces where waves reflect or transmit due to changes in geometry or material composition, temporal boundaries cause spectral transformations in the wave itself. When a wave encounters a sudden shift in the medium's temporal characteristics, it experiences modifications in frequency, amplitude, and phase. This makes temporal discontinuities a powerful mechanism for achieving non-stationary control over wave behavior.

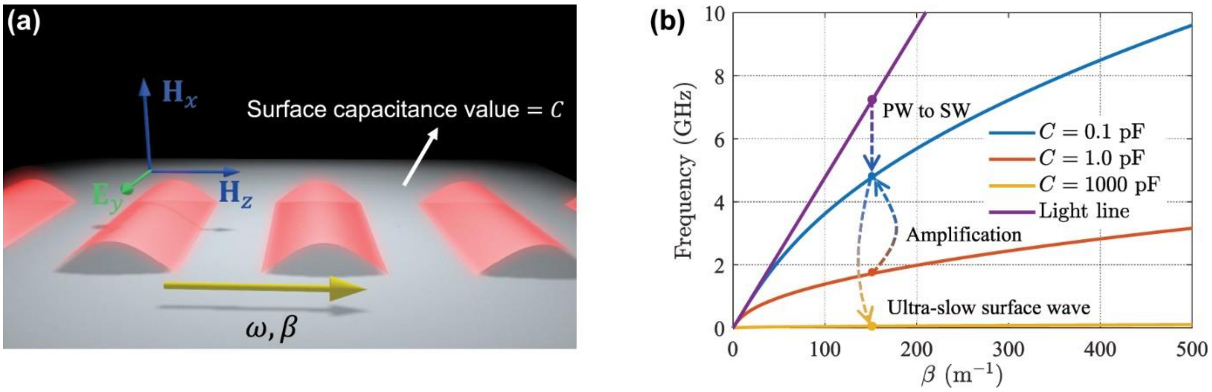

Fig. 3.3 : Temporal discontinuities

At a temporal boundary, electromagnetic waves are not governed by the conservation of energy alone; instead, momentum is conserved, and energy can be exchanged between the wave and the modulated medium. This can result in either amplification or attenuation of the wave, depending on the direction of the time-variation. The generation of new frequency components—known as time-reflected and time-refracted waves—leads to a richer spectrum and enhances the flexibility of electromagnetic manipulation. These characteristics are exploited in a range of emerging applications, such as dynamic beam steering, non-reciprocal devices, frequency conversion, and signal cloaking.

In metasurface engineering, temporal discontinuities offer an added degree of freedom by allowing real-time reconfiguration of surface impedance. This enables the metasurface to adapt to varying signal requirements, making it suitable for applications in radar, wireless communication, and sensing. For instance, switching a metasurface from capacitive to inductive impedance at a specific time instant can effectively halt surface wave propagation, trap electromagnetic energy, or release it in a controlled manner. Such capabilities open avenues for building intelligent metasurfaces that respond adaptively to environmental stimuli or operational commands. In our study, we focus on this phenomenon to achieve precise temporal control over electromagnetic surface wave propagation.

3.4 Surface Impedance Switching and Power Modulation

One of the most crucial applications of temporal discontinuity in metasurface engineering lies in the ability to modulate surface impedance dynamically. Surface impedance, a complex quantity defining the relationship between electric and magnetic fields at a boundary, determines how waves interact with the surface. By actively switching the impedance from capacitive to inductive or vice versa, it is possible to achieve real-time modulation of electromagnetic wave propagation. This switching process is central to our proposed metasurface design, where the surface is alternately configured to support or suppress wave propagation based on the desired temporal sequence.

The capacitive regime of the surface supports transverse electric (TE) surface waves that can propagate energy efficiently along the surface toward a predefined load. In this state, voltage and current signals flow steadily through the surface, demonstrating a controlled power transmission mechanism. However, when the impedance is switched to an inductive state, the propagation of TE surface waves becomes unsupported. The surface behaves as a temporal reflector or suppressor, effectively freezing the magnetic field and extinguishing the electric field, halting any further power delivery to the load. This behavior demonstrates how electromagnetic energy can be temporarily stored, stopped, or redirected.

The key advantage of this approach is that it introduces an unprecedented level of control over power delivery and electromagnetic signal behavior. For example, by precisely timing the switching mechanism, one can engineer pulse shaping, time-gated energy release, or signal blocking. This becomes particularly useful in environments where selective transmission or shielding is necessary. In our experiment, this principle is utilized to demonstrate a complete stop and restart of current flow across a resistive load placed at the end of the metasurface. Compared to a conventional copper surface, which provides no such temporal modulation, the proposed metasurface exhibits intelligent control and tunability of power—a vital step toward reconfigurable and adaptive photonic systems.

Table 3.1 – Switching Timeline & Impedance States

Time interval (ns)	Surface state	Impedance type	Wave behavoior
0-7 ns	Pre-switch	Capacitive	TE surface wave progagate
7-17 ns	Switch window	Inductive	Wave is frozen
17+ ns	Post-switch	Capacitive	Wave unfrezes

3.5 Frozen Surface Waves and Energy Trapping

The concept of frozen surface waves represents a pivotal breakthrough in controlling electromagnetic energy along metasurfaces.

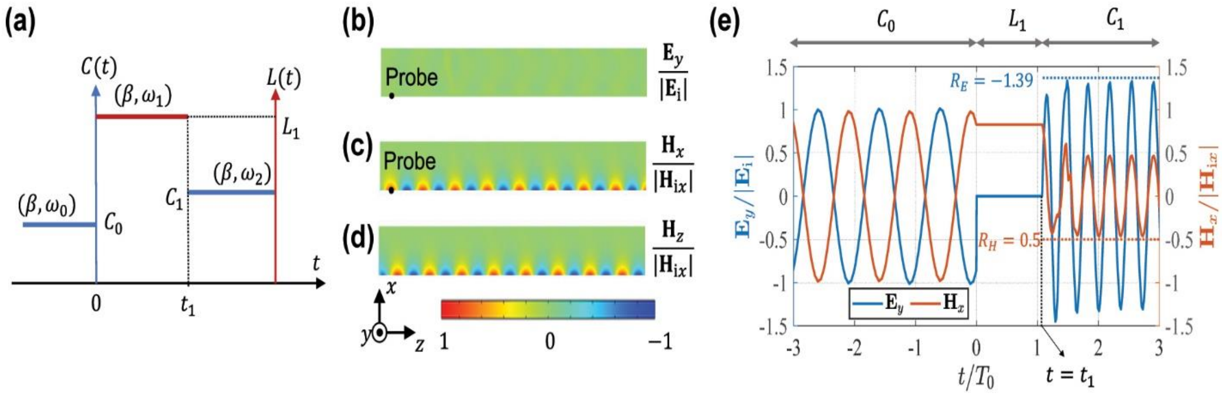

Fig. 3.5 frozen surface waves and energy trapping

This phenomenon occurs when the surface transitions from a capacitive to an inductive state, halting the propagation of transverse electric (TE) modes and leaving behind a quasi-static magnetic field. In this "frozen" state, the electric field vanishes, and the magnetic field remains spatially distributed but temporally invariant. This situation is akin to a snapshot in the evolution of wave propagation, where the momentum is conserved, but the energy becomes localized or effectively trapped at the surface.

This energy trapping is not merely a theoretical construct but has practical significance. The trapped energy does not radiate or propagate; instead, it stores electromagnetic potential along the metasurface boundary. The absence of electric fields prevents power transfer, while the preserved magnetic field ensures continuity and coherence of the system's overall field structure. In applications where energy storage, delay, or precise control over release timing is essential, such as in pulse compression, radar cross-section modulation, or stealth technologies, frozen surface waves provide an invaluable tool.

The duration of this frozen state is controlled by the time interval during which the surface remains in an inductive condition. Once the surface switches back to capacitive, the previously stored energy can be released, resuming wave propagation. This ability to freeze and unfreeze wave energy dynamically enables high-speed reconfigurable systems, energy buffering in signal chains, and efficient power gating for on-demand signal routing.These simulations validate this behavior, showcasing the disappearance and reappearance of current and voltage at the resistive load in exact correspondence with the switching logic, confirming the theoretical predictions about frozen surface wave phenomena.

3.6 Electromagnetic Field Behavior During Temporal Switching

During the temporal switching of the surface impedance, the electromagnetic field undergoes a unique transformation characterized by transient and discontinuous behavior. According to Maxwell’s equations in the time domain, the sudden change in boundary conditions introduces abrupt variations in the temporal derivatives of electric (E) and magnetic (H) fields. These discontinuities lead to phenomena such as radiation bursts, mode conversion, and temporary field extinction, depending on the direction and nature of the impedance transition.

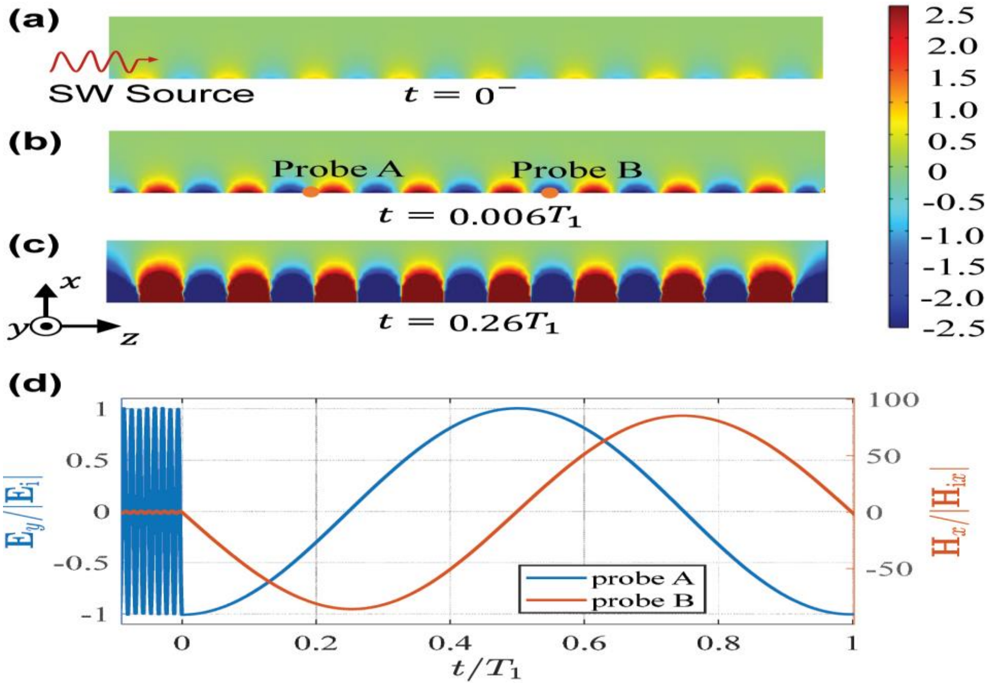

Fig. 3.6 Electromagnetic field behavior during temporal switching

In the capacitive phase, the electric field components are dominant and drive the propagation of TE surface modes. As the surface transitions to the inductive phase, the electric field collapses, while the magnetic field freezes in place. This abrupt suppression of the electric component results in the surface becoming non-radiative and non-conductive for that mode. The field behavior becomes static, and a transient discontinuity is observed at the switching moment. Probe data in our simulation clearly illustrate the dramatic drop in electric field amplitude and the persistence of the magnetic field during this transition.

Such transitions are also responsible for frequency domain changes, where the original wave spectrum may broaden or shift due to modulation. The Laplace transform technique is often employed to model and analyze these dynamics, providing insights into the rate of field decay and the evolution of frozen field distributions. Upon returning the surface to a capacitive state, the wavefront reconstructs, and the electric field regains its original amplitude and phase profile, continuing the previously halted propagation.

These observations are essential for designing high-speed electromagnetic modulators, field shutters, and signal-processing components that rely on abrupt field manipulation. The reconfigurability of the field environment through surface impedance control allows for precision-timed energy delivery, making this phenomenon integral to temporal metasurface operations.

Table 3.2 – Field Component Status by Stage

Stage	E-field	H-field	Power and load
Capacitive	Present	Present	Yes
Inductive	Zero	Static	No
Recapacitive	Regenerated	Dynamic	Yes

These are the procedure of the changing between capacitive and inductive region of the VCS (Voltage Controlled Switch) in the CST Microwave software.

3.7 Comparison with Passive Copper Surfaces

A key aspect of validating the efficacy of temporal metasurfaces lies in benchmarking them against conventional passive structures such as flat copper surfaces. Traditional copper surfaces exhibit fixed, non-adaptive electromagnetic behavior. They support surface currents and reflection based on their geometric and material properties, but they lack the ability to modulate impedance or support dynamic wavefront control. As a result, their performance in advanced wave manipulation applications is severely limited.

In contrast, the temporally modulated metasurface employed exhibits superior capabilities. Through active switching between capacitive and inductive states, it is able to suppress, trap, and reinitiate wave propagation in a controlled and reversible manner. When a wave is incident on a copper plate, the reflection is largely static and determined by the plate's surface impedance and geometry. The surface does not permit impedance tuning, and therefore, it cannot exhibit time-dependent behavior such as wave freezing or on-demand energy release.

Comparative simulations show that the copper surface produces negligible voltage and current at the load position, indicating poor energy transfer capabilities. Meanwhile, the designed metasurface delivers significant current and voltage under capacitive conditions and demonstrates near-zero values during the inductive phase, consistent with the theory of frozen waves. This proves that only a time-varying surface can achieve dynamic control over wave propagation.

The contrast illustrates the transformative potential of temporal metasurfaces in future photonic systems. Unlike copper, which is limited to passive applications, temporal metasurfaces serve as intelligent platforms for adaptive signal routing, stealth, and energy management. Their performance paves the way for a new generation of reconfigurable, responsive, and multifunctional electromagnetic interfaces.

3.8 Practical Considerations for Temporal Switching

While the theoretical capabilities of temporal metasurfaces are compelling, their real-world application hinges upon a variety of practical considerations. Implementing temporal switching requires a highly responsive mechanism to modulate the surface impedance on nanosecond or sub-nanosecond timescales. This involves integrating high-speed switches such as PIN diodes, varactors, or MEMS-based devices directly into the metasurface unit cells. These components must be capable of handling high frequencies, particularly in the microwave to terahertz range, and must also withstand power dissipation without degrading performance.

From a circuit design perspective, ensuring precise timing synchronization is critical. Any delay or jitter in the switching signal can lead to incomplete wave suppression or unintended spectral artifacts. Additionally, the surface impedance profile must be dynamically controlled across the entire metasurface, necessitating a uniform and scalable electronic or photonic control scheme. This often involves complex driving circuitry and feedback systems to ensure consistent behavior across all unit cells.

Material selection also plays a significant role. While FR-4 is cost-effective and widely used, it suffers from losses at higher frequencies. Alternatives like Rogers or other low-loss dielectric substrates may offer better performance for high-frequency operation. Moreover, the inductors and capacitors used in the circuit must be high-Q components to minimize parasitic effects and maintain clean switching transitions.

Thermal management is another key concern. Rapid switching can induce localized heating, potentially altering the electromagnetic properties of the metasurface. Efficient heat dissipation strategies such as metal backplanes, thermal vias, or heat sinks must be considered in the design phase. Ultimately, the practical realization of temporal metasurfaces is a multidisciplinary challenge involving electromagnetics, high-speed electronics, materials science, and thermal engineering. Overcoming these challenges will unlock their full potential in advanced applications like real-time beam steering, programmable wavefronts, and dynamic cloaking.

3.9 Applications and Future Directions

The dynamic control of surface waves through temporal discontinuities introduces a new class of opportunities across numerous domains in photonics and electromagnetics. Temporal metasurfaces, with their ability to adapt in real time, are poised to revolutionize several application areas.The promising field is adaptive beamforming, where directional wave steering can be achieved without mechanically moving parts. This is particularly relevant in radar and wireless communication systems where agility and low-latency control are critical.

Another impactful application lies in electromagnetic stealth and radar cross-section (RCS) reduction. By temporally modulating the surface impedance, it is possible to suppress reflected signals selectively, effectively cloaking the object from detection within certain time windows. This approach is more flexible than traditional passive cloaking because it allows reconfigurability and adaptability to dynamic threat environments.

In the field of signal processing, temporal metasurfaces can function as tunable filters, modulators, or time-gated shutters. They can manipulate signal envelopes in ways that are not possible with static systems, such as storing, releasing, or reshaping electromagnetic pulses. These capabilities are essential for applications in secure communications, spectral compression, and quantum photonic systems.

Moreover, the principles demonstrated in this research have implications for emerging areas such as topological photonics, time crystals, and spatiotemporal metamaterials. Integration with machine learning could lead to intelligent metasurfaces capable of learning and adapting their temporal response based on input signals or environmental stimuli. As fabrication technologies advance and high-speed electronic components become more accessible, the development of compact, efficient, and programmable temporal metasurfaces will accelerate.

3.10 Summary

The potential of temporally modulated metasurfaces extends far beyond the scope of current applications. Their ability to dynamically interact with electromagnetic fields opens the door to a wide array of novel devices and systems. Continued research and development in this field will undoubtedly contribute to the next generation of photonic technologies and high-performance electromagnetic platforms.

Chapter 2: Methodology

4.1 Introduction

This chapter outlines the methodological framework employed to investigate the dynamic control of surface electromagnetic waves using a time-modulated metasurface. The core objective is to examine how temporal variations in surface impedance—achieved through voltage-controlled switching—affect wave propagation, energy suppression, and revival.

To achieve this, a comprehensive full-wave simulation environment is developed, integrating realistic metasurface geometry, reactive boundary manipulation, and time-domain signal control. The simulation setup includes a waveguide horn antenna as the source of a Y-polarized TE wave, which impinges on the metasurface at a controlled oblique angle. The metasurface, configured with embedded voltage-controlled switches (VCS), is programmed to alternate between capacitive and inductive states, enabling the study of temporal discontinuities.

By measuring voltage and current responses at a terminating resistive load and tracking localized field behavior through strategically placed probes, the methodology provides a robust platform for validating the theoretical concepts presented in the previous chapter. These include wave freezing, amplification, and re-initiation of propagation—all essential mechanisms for developing programmable and reconfigurable electromagnetic systems.

4.2 Design Framework of the Metasurface

The cornerstone of this research lies in the systematic design and simulation of a time-varying metasurface capable of dynamic surface wave manipulation. The metasurface is composed of a periodic arrangement of triple concentric circular rings etched onto a dielectric substrate. Each unit cell is engineered to interact with incident electromagnetic waves in a specific manner depending on its instantaneous surface impedance. To achieve the desired modulation characteristics, the surface impedance is toggled between capacitive and inductive states using high-speed electronic switches. This temporal modulation is essential for observing frozen surface wave phenomena and controlling power delivery to a resistive load placed at the terminal edge.

The design process began with determining the optimal geometric parameters of the unit cell to support surface waves at the target frequency of 30 GHz. Simulation tools such as CST Microwave Studio were employed for full-wave electromagnetic analysis. The structure was initially modeled under static impedance conditions to verify the propagation of TE surface waves. Subsequently, temporal modulation was introduced via time-domain control scripts that alternated the boundary conditions. The modulation followed a well-defined time sequence: 0–7 ns (capacitive), 7–17 ns (inductive), and 17–20 ns (capacitive again). This cycle was chosen based on theoretical insights into wave suppression and energy trapping mechanisms.

To verify the functionality of the design, the metasurface was integrated with a waveguide antenna that launched a Y-polarized incident wave at a 30-degree angle. The antenna and resistive load were placed on opposite ends of the metasurface to monitor power transfer. Voltage and current probes were strategically placed along the surface to measure field distributions at various time intervals. This setup allowed for a comprehensive evaluation of wave behavior, field freezing, and power modulation capabilities across the designed structure.

The choice of substrate material also played a critical role. FR-4 was selected for its availability and cost-effectiveness, despite its inherent losses at higher frequencies. The decision was justified through comparative simulation runs using alternate low-loss substrates, which confirmed that the FR-4 could still sufficiently demonstrate the intended phenomena for proof-of-concept validation. Ultimately, this design framework provided a robust platform for validating temporal control mechanisms in metasurfaces, laying the foundation for subsequent experimental analysis and real-world deployment.

4.3 Simulation Configuration and Boundary Conditions

The electromagnetic simulations were conducted using CST Microwave Studio, a time-domain solver well-suited for analyzing transient wave behavior in temporally modulated structures. The simulation domain included the full metasurface, source antenna, and a 50-ohm resistive load. The setup was meticulously configured to replicate realistic operating conditions while ensuring computational efficiency and accuracy.

Boundary conditions played a critical role in defining the electromagnetic environment. Perfectly Matched Layers (PML) were applied to the outer edges of the simulation space to absorb outgoing waves and eliminate unwanted reflections. This ensured that any wave interactions observed on the metasurface were intrinsic to the design and not artifacts of simulation boundaries. The ground plane beneath the metasurface was set as a Perfect Electric Conductor (PEC), while the open sides were treated with radiation boundaries to mimic free-space propagation.

A continuous Y-polarized wave at 30 GHz was generated using a waveguide port, simulating a realistic excitation source. The angle of incidence was set to 30 degrees in the xz-plane, aligning with the direction of the surface wave's intended propagation. To implement time-dependent surface impedance switching, parametric time control scripts were embedded into the simulation environment.

Mesh refinement was another important consideration. A fine adaptive mesh was applied around the unit cells and switching components to capture rapid transitions in electromagnetic fields accurately. Temporal resolution was set to 0.1 ns to ensure precise tracking of field evolution during the 20 ns simulation window. This high-resolution setup enabled the detection of subtle variations in voltage, current, and field intensity across the surface during switching periods.

To validate the simulation accuracy, convergence tests were conducted by varying mesh density and simulation time steps. Results were cross-checked against analytical models based on Laplace and Fourier domain transforms for temporal discontinuities. The simulation outputs—including electric field (Ey), magnetic field (Hz), voltage, and current distributions—were exported for post-processing in MATLAB to generate spatial plots and time-series graphs. These visualizations provided key insights into the freezing effect, wave reactivation, and surface impedance control, confirming the feasibility of our proposed metasurface system.

4.4 Construction & Operation of designed metasurface: for Temporal voltage and current control

A waveguide antenna (horn) is used as a source to transmit the electromagnetic wave to the designed metasurface, where a Y-polarized electromagnetic wave is incident toward the metasurface at a 30-degree angle with the metasurface as shown in Fig.4.1 This observation is mainly to observe how much free space can reach the resistive load, also that sustains up to the end edge of the metasurface, compared to the conventional copper plate having the same dimensions (length, width, height).

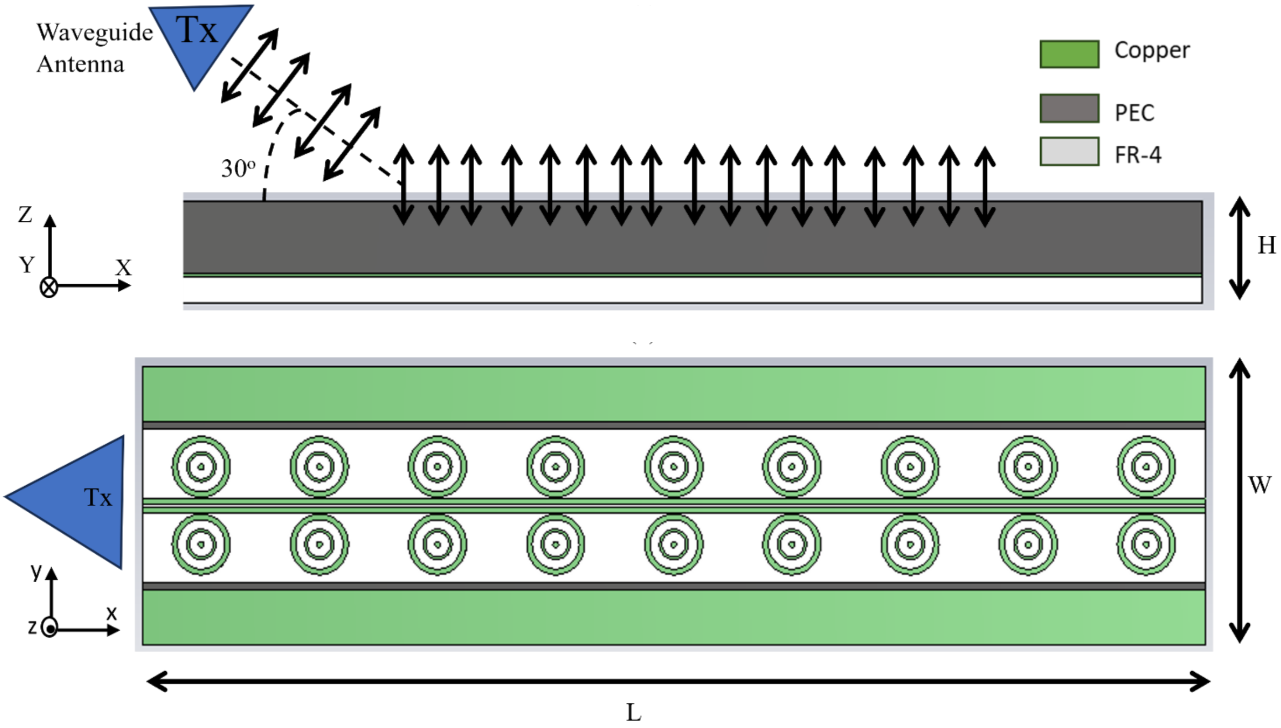

Fig. 4.1: A waveguide antenna is placed at one edge metasurface

Fig. 4.1: displays that a waveguide antenna is placed at one edge (left) of the metasurface in the XY plane with 9-unit cells along the x-axis and shows the ZX plane of the proposed metasurface, a waveguide antenna (horn) is used to incident the Y-polarized electromagnetic wave toward the metasurface at a 30-degree angle with the metasurface. Where length, width, and height of the whole metasurface are shown more clearly as , L = 24.408 mm, width, W = 6.102 mm, and height, H= 0.2373 mm respectively.

There added a resistor at the end edge of the metasurface, from the first figure, to observe the voltage drops and pass current across the load as shown in Fig.4.2. However, the temporal effect was applied using the voltage-controlled switch (VCS) by making a connection between the two copper plates located along the length of the metasurface is in the middle of the layer.

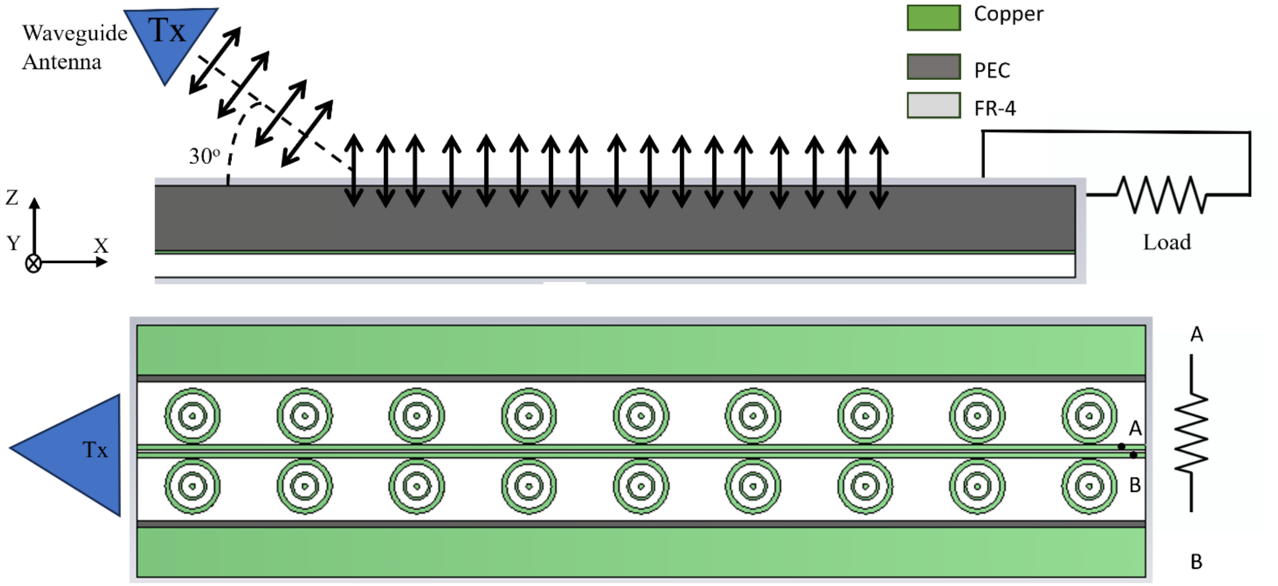

Fig.4.2: A waveguide antenna with resistive load

Fig. 4.2: displays that a waveguide antenna is placed at one edge (left) of the metasurface, where at the opposite edge, a resistive load is added in between two nodes named A, B in the copper plate to observe the voltages and current across the load. In the XY plane with 9-unit cells along the x-axis.The ZX plane of the proposed metasurface, a waveguide antenna (horn) is used to incident the Y-polarized electromagnetic wave toward the metasurface at a 30-degree angle with the metasurface.

The elaborate operational circuit connections. Just by implementing 3 voltage-controlled switches per unit cell to make a proper short and open circuit operation between two copper plates in the designed metasurface. Applying an exponential signal to VCS for control, where VCS goes open for all the time, but the temporal effect was applied between the 7th to 17th ns using the short circuit connection between two plates, having three corresponding nodes are M, N, O, P, Q, R. Here, two PEC blocks are used to shield electromagnetic wave propagation along the y-axis, which help to propagate electromagnetic wave from source to load during the total 20ns simulation operation.

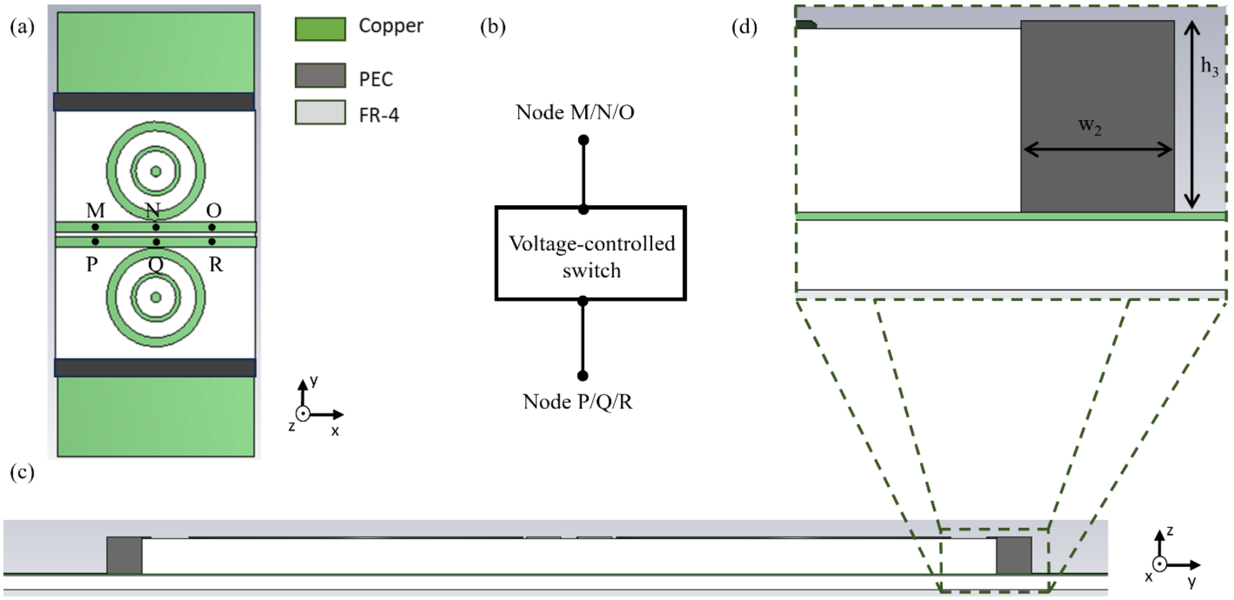

Fig.4.3: temporal effect of a unit cell

Fig 4.3: displays an operational diagram for playing the role of temporal effect in a unit cell. (a) depicts the unit cell having 3 VCS, having the upper three nodes of M, N, O, and the lower three nodes named P, Q, R, which are placed along the two corresponding copper plates. (b) displays the voltage control switch (VCS) having two nodes, (c) shows the cross-section view of the unit cell including the PEC blocks beside the substrate along the x-axis, where more clearer view has been shown in (d) with the corresponding dimensions. The height ($h_3 = h_1 + tc$) and width (w_2) of PEC block are 0.1695 mm, 0.1356 mm, respectively.

The design process began with determining the optimal geometric parameters of the unit cell to support surface waves at the target frequency of 30 GHz. Simulation tools such as CST Microwave Studio were employed for full-wave electromagnetic analysis. The structure was initially modeled under static impedance conditions to verify the propagation of TE surface waves. Subsequently, temporal modulation was introduced via time-domain control scripts that alternated the boundary conditions. The modulation followed a well-defined time sequence: 0–7 ns (capacitive), 7–17 ns (inductive), and 17–20 ns (capacitive again). This cycle was chosen based on theoretical insights into wave suppression and energy trapping mechanisms.

To verify the functionality of the design, the metasurface was integrated with a waveguide antenna that launched a Y-polarized incident wave at a 30-degree angle. The antenna and resistive load were placed on opposite ends of the metasurface to monitor power transfer. Voltage and current probes were strategically placed along the surface to measure field distributions at various time intervals. This setup allowed for a comprehensive evaluation of wave behavior, field freezing, and power modulation capabilities across the designed structure.

The choice of substrate material also played a critical role. FR-4 was selected for its availability and cost-effectiveness, despite its inherent losses at higher frequencies. The decision was justified through comparative simulation runs using alternate low-loss substrates, which confirmed that the FR-4 could still sufficiently demonstrate the intended phenomena for proof-of-concept validation. Ultimately, this design framework provided a robust platform for validating temporal control mechanisms in metasurfaces, laying the foundation for subsequent experimental analysis and real-world deployment.

Table 4.1 – Mesh & Simulation Settings

Parameter	Value	Purpose
Frequency	30 GHz	Target TE-mode excitation frequency
Mesh resolution	0.1 ns temporal step	Ensure accurate transient trackin
Boundary conditions	PML ground ,PML edges	Prevent reflections in simulation
Time step and duration	0.1 ns total 20 ns	Capture temporal switching dynamics

4.5 Temporal Switching Logic Implementation

Temporal switching is the central mechanism that enables dynamic control of electromagnetic surface waves in our metasurface design. The fundamental concept relies on transitioning the surface impedance of the metasurface between capacitive and inductive states within precisely defined time windows. This transition effectively alters the boundary conditions experienced by surface waves, leading to phenomena such as field freezing, energy trapping, and wave reactivation. To implement this mechanism, a dedicated time-domain control algorithm was developed and embedded within the CST simulation environment.

The control logic operates over a 20 ns simulation cycle. During the first 7 ns, the surface impedance is set to a capacitive value, allowing TE surface waves to propagate freely. At the 7 ns mark, a transition is triggered that shifts the impedance to an inductive state. This transition persists until 17 ns, creating a 10 ns time window where wave propagation is suppressed and the electromagnetic energy is effectively frozen at the surface. At 17 ns, the impedance is reverted back to a capacitive state, allowing the previously halted wavefront to resume its propagation. This three-stage switching cycle is meticulously timed to ensure seamless transitions and to maximize the contrast in wave behavior between active and frozen states.

The switching itself is realized through parametric scripting that dynamically updates boundary condition values in CST. A logic block is defined that evaluates the current simulation time and applies corresponding impedance parameters to the surface. Capacitive and inductive states are represented by different lumped element models that mimic real-world reactive components. These scripts are validated by plotting the impedance profile over time and cross-checking with theoretical expectations.

To simulate the physical implementation, equivalent circuit models were developed, incorporating high-speed switching elements such as PIN diodes or voltage-controlled varactors. These components were modeled using SPICE-compatible parameters to ensure realistic response times and switching behavior. Additionally, the influence of component parasitics, such as interconnect capacitance and package inductance, was taken into account to improve the accuracy of the temporal model.

Validation of the switching logic was carried out by comparing the simulated field distributions and voltage/current profiles with the expected behavior during each switching phase. The sharp decline and subsequent recovery of both electric field intensity and power flow at the resistive load confirmed that the temporal control mechanism was functioning as intended. This section of the methodology provides a crucial bridge between the theoretical concept of temporal metasurfaces and their practical realization, reinforcing the reliability of the proposed design for future experimental deployment and integration into adaptive electromagnetic systems.

4.6 Summary

A time-modulated metasurface was designed and simulated to achieve dynamic voltage and current control. A Y-polarized 30 GHz wave was incident on a triple-ring metasurface fabricated on an FR-4 substrate, with a 50 Ω resistive load placed at its edge. Temporal modulation was implemented by toggling the surface impedance between capacitive and inductive states using voltage-controlled switches within a 20 ns cycle. Simulations were conducted in CST Microwave Studio with PML boundaries and 0.1 ns temporal resolution. Electric and magnetic fields, along with voltage and current, were recorded through probes and post-processed in MATLAB.

Chapter 3: Results and Discussion

5.1 Introduction

In this chapter, the simulation results obtained from the time-modulated metasurface system are presented and analyzed. The primary focus is placed on evaluating how temporally controlled changes in surface impedance affect the propagation of surface waves, as well as the corresponding voltage and current responses at the resistive load.

The designed metasurface, equipped with voltage-controlled switching elements, was simulated under three operational phases: wave propagation, wave freezing, and wave revival. These phases were defined by the capacitive-to-inductive and inductive-to-capacitive transitions introduced at specific time intervals. Through this controlled modulation, the dynamic behavior of the electromagnetic field was observed, including the suppression of the electric field, conservation of the magnetic field, and the re-initiation of power flow.

Field distribution data, time-domain signal responses, and probe measurements were used to validate theoretical predictions, particularly those concerning wave freezing and revival mechanisms. Comparisons were also made with a conventional copper plate structure to highlight the functional advantages introduced by temporal switching. The outcomes are discussed with reference to the expected physical principles outlined in the theoretical analysis, providing a deeper understanding of the system’s power-gating capabilities and its potential applications in reconfigurable electromagnetic devices.

5.2 Result Analysis & Discussion

This section analyzes the controlled modulation of power, defined as the combined voltage and current along a metasurface toward a resistive load. The source and resistive load are positioned at opposite edges along the length of the metasurface. A Y-polarized electric field, corresponding to a sinusoidal electromagnetic wave at 30 GHz, is incident at a 30-degree angle in the xz-plane.

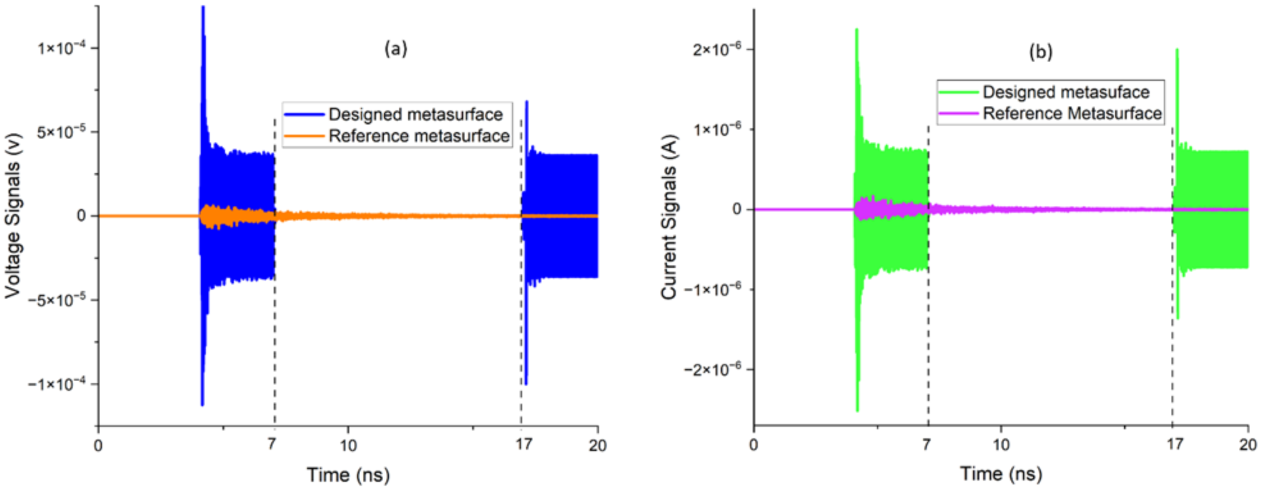

Fig. 5.1: Comparison of the voltage & current with resistive load module

This wave is generated by a waveguide antenna, with the complete structural details provided. By carefully regulating voltage and current signals, observed that they reach the resistive load significantly.These are depicts a comparison of the voltage and current absorption to the resistive load of the metasurface, where the resistive load and the source both are located at the opposite edge of the metasurfaces. (a) and (b) show how a strong voltage and current, respectively, can be absorbed by the resistive load over the entire simulation time of 20 ns, where stopping absorption from time 7th to 17th ns is as intentional control, in the designed metasurface. On the other hand, no control has been applied to the reference (copper) metasurface as the resistive load gets comparatively zero voltage and currents during the total simulation time.

However, for the designed metasurface, the power flow is deliberately reduced to zero between 7 ns and 17 ns, while the propagation initiates at 4 ns, as illustrated in . During this process, the boundary reactance undergoes a transition from capacitive to inductive and then back to capacitive ($C_1 \rightarrow L \rightarrow C_2$). When the reactance shifts from capacitive to inductive, the voltage drops, and the current across the resistive load reaches zero. At this stage, the spatially non-uniform static magnetic field remains frozen, the surface wave completely disappears, and the electric field vanishes along the boundary. However, when the boundary shifts back to a capacitive state, current begins to flow across the resistive load, causing the voltage to drop once again. This phenomenon is achieved by dynamically modifying the boundary condition of the metasurface. Initially, the incident TE-polarized wave, given by:

$$\mathrm{E}_i = \mathrm{E}_0 \sin(10\pi x + 10\pi\sqrt{3}z - 2\pi \times 30 \times 10^9 t)\,\mathbf{y} \tag{1}$$

propagates along the metasurface under a capacitive boundary condition (C_0).

The corresponding magnetic field components are:

$$\mathrm{H}_i = \frac{\mathrm{E}_0}{\eta_0}\left(\frac{\sqrt{3}}{2}x - \frac{1}{2}z\right) \sin(10\pi x + 10\pi\sqrt{3}z - 2\pi \times 30 \times 10^9 t) \tag{2}$$

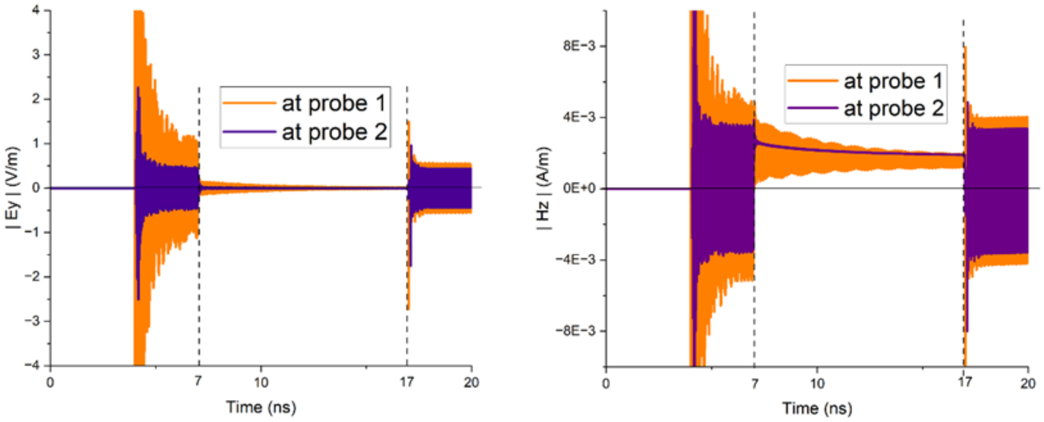

Fig. 5.2 : Real value of two probes positioned at three different locations

These two value of probes demonstrates the real value of two probes positioned at three different locations, probe 1 is placed near the illuminating side where the most far away position is taking place by probe 2, entirely the designed metasurface-directed Y-polarized electromagnetic waves including magnetic (Hz) and electric (Ey) field. (a) & (b) show the static and freezer fields of electric and magnetic, respectively, for the 7th to 17th time duration

For a transverse electric (TE) surface wave (β,ω_0) propagating along a capacitive boundary with capacitance C_1, the electric and magnetic fields. At t = 7 ns, shorting two metal copper plates via a voltage-controlled switch abruptly changes the boundary from capacitive to inductive, introducing an inductance L. This transition allows only transverse magnetic (TM) surface modes to exist at nonzero frequencies, replacing the TE mode. However, a TE mode can persist on an inductive boundary in free space if its frequency approaches zero ($\omega_1=0$). At t = 7^+, the magnetic field component along the z-axis is given by:

$$H_z^{t=7+} = H_0 e^{-j\beta x-\alpha_1 z}\mathbf{z},\ \text{where } H_0 = \frac{-E_0\beta}{\omega_0\mu_0}, \tag{3}$$

ensuring conservation of the magnetic field's z-component after the transition. Since $\omega_1=0$, the time-harmonic term $e^{j\omega_1 t}$ disappears, and the remaining field components simplify as:

$$H_y^{t=7+} = 0, H_x^{t=7+} = jH_0 e^{-j\beta x-\alpha_1 z}\mathbf{x}, \text{and } \mathbf{E}_x^{t=7+} = \mathbf{E}_y^{t=7+} = \mathbf{E}_z^{t=7+} = 0 \tag{4}$$

This indicates the presence of a static, spatially non-uniform magnetic field along the x and z directions, while the electric field vanishes in all directions. The transformation from capacitive to inductive boundaries, achieved via a voltage-controlled switch, is further illustrated in the 2D electric and magnetic field distributions in Fig.5.3. This inductive boundary condition, sometimes referred to as a "frozen eigenmode," satisfies the relation:

$$j\omega_1 L_1.\left(\mathbf{n} \times \mathbf{H}_x^{t=7^+}\right) = E_y^{t=7^+} = 0 \tag{5}$$

Probing locations along the metasurface, as shown in Fig. 6(d), reveal the instantaneous electric (Ey) and magnetic (Hz) field behaviors at different positions. Probe 1, located near the source, experiences an abrupt reduction in the electric field to zero, while the magnetic field remains frozen with minor oscillations. This effect is particularly pronounced at high frequencies (e.g., 30 GHz), confirming the disappearance of the electric field at the transition point. Consequently, the voltage and current across the resistive load also drop to zero, as illustrated in Fig. 4(a, b). The inductance plays a critical role in determining the transient duration of the electric field's disappearance at t=7 ns, with its transient radiation strength and time being directly proportional to inductance. A theoretical analysis of this effect can be performed using the Laplace transform method .At t=17 ns, the boundary condition reverts to capacitive with a new surface capacitance C_2, defined by the eigenvalue equation for the surface mode frequency ω_2. As a result, the electric field re-emerges through reflection and transmission, restoring wave propagation after the second transition.

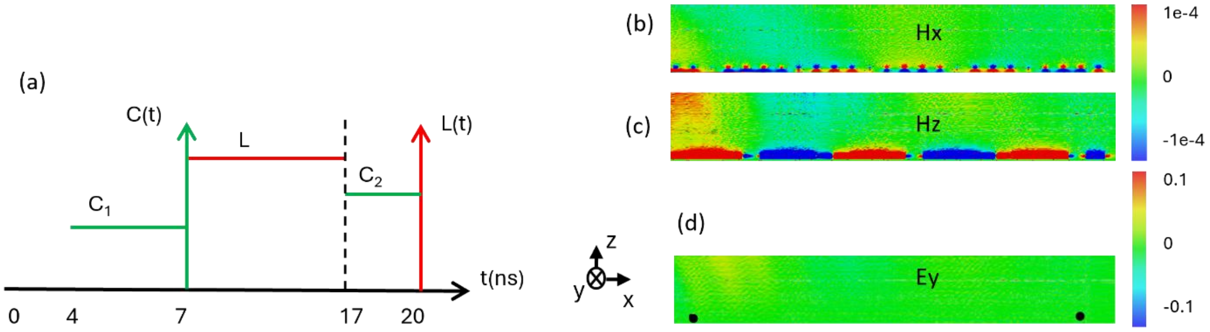

Fig. 5.3: Time of boundary properties, magnetic field distribution and electric field in freezing state

On Fig.5.3(a)represents the function of time of boundary properties throughout the whole simulation. On the other hand, the rest of the three figures display the 2D results of electric and magnetic field distributions along the designed metasurface at the freezing time, which is 7 < t < 17 ns. For Fig.5.3 (b) & (c), it is fully aligned with the theory that predicted the magnetic field distributions of H_x and H_z have a 90-degree phase difference. While (d) illustrates that the electric field vanished in the freezing state. According to Maxwell's equations for free space, the time derivatives of the electric flux density (D) and magnetic flux density (B) are equal to the curl of the magnetic field (H) and electric field (E), respectively. Furthermore, the continuity of these vectors must be maintained during moments of abrupt changes in the surface impedance. Therefore,

$$\mathbf{D}_{\mathrm{t}=7^-} = \mathbf{D}_{\mathrm{t}=7^+}, \mathbf{B}_{\mathrm{t}=7^-} = \mathbf{B}_{\mathrm{t}=7^+} \tag{6}$$

By Using Equation (6), at t=17, i.e

$$\mathrm{E}_{ry}^{t=17^+} + \mathrm{E}_{ty}^{t=17^+} = \mathrm{E}_{y}^{t=17^-} = 0 \text{ and } \mathrm{H}_{rz}^{t=17^+} + \mathrm{H}_{tz}^{t=17^+} = \mathrm{H}_{z}^{t=17^-}, \tag{7}$$

the reflection and transmission coefficients can be calculated following the second transition as discussed in reference. Based on the duality theorem, switching from an inductive to a capacitive boundary transforms the TM-polarized electric field distribution into a static surface wave. Conversely, reversing this switch restores the static electric field into a propagating TM surface wave. This phenomenon is analogous to wave propagation observed in scenarios such as sudden plasma formation. and magnetized plasma with rapidly changing bias fields.So a flowing current can be temporarily halted, stopping the voltage drop across the load. Once the second transition occurs, wave propagation resumes, allowing current flow and voltage drop to restart.

Chapter 6: Conclusion and Future Works

In conclusion, a comprehensive investigation has been conducted into the concept, design, and validation of a time-switching metasurface for the dynamic control of electromagnetic surface waves. The approach was centered on the use of temporal discontinuities in surface impedance to enable real-time modulation of voltage, current, and electromagnetic field behavior. A rigorous theoretical foundation was established, followed by extensive simulation-based analysis and validation. Through these efforts, it was demonstrated that wave propagation can be effectively manipulated by employing timed impedance switching, indicating significant potential for advanced photonic and communication applications.

One of the primary objectives—to design a metasurface capable of operating at 30 GHz using reactive components—was achieved through the development of a unique triple-ring unit-cell geometry integrated with high-speed switching mechanisms. The metasurface was modeled on a cost-effective FR-4 substrate, and the switching sequences were executed through carefully designed transitions between capacitive and inductive states. These transitions were implemented in CST Microwave Studio and simulated using a Y-polarized incident wave at a 30-degree angle, enabling precise field manipulation along the metasurface.

Another critical goal—regulating electromagnetic wave behavior, including voltage and current distribution—was successfully met through the implementation of a temporal switching algorithm. During the inductive phase (7 ns to 17 ns), surface waves were effectively suppressed, resulting in a measurable reduction in voltage and current at the resistive load. Upon restoring the capacitive boundary, wave propagation resumed with minimal distortion. These results confirmed that temporal impedance modulation allows for effective power regulation without requiring mechanical adjustments or passive materials.

To validate the concept, a comparative analysis with a conventional copper surface was performed. The copper surface, being inherently static, was unable to support dynamic modulation and exhibited negligible energy delivery to the load. In contrast, the time-modulated metasurface provided precise control over power delivery and field distribution, thereby confirming its superior performance. This comparison highlighted the advantages of temporal metasurfaces in adaptive and reconfigurable electromagnetic systems.

Beyond the successful achievement of the outlined objectives, this research introduces a robust platform for future exploration. The use of temporal impedance modulation for surface wave control suggests new opportunities in beam steering, dynamic filtering, stealth applications, and real-time energy management. The demonstrated ability to freeze, store, and release electromagnetic energy with temporal precision establishes a key distinction from traditional metasurface applications.

Ultimately, this work has established that time-modulated metasurfaces represent a powerful and versatile approach to controlling electromagnetic phenomena. By integrating reactive components with dynamic switching logic at high frequencies, a novel and intelligent mechanism for adaptive behavior in electromagnetic systems has been realized. The contributions made in theoretical modeling, simulation, and comparative evaluation lay a strong foundation for experimental implementation and future advancements in programmable photonics and metasurface engineering.

6.1 Future Work

While the simulation results and theoretical framework strongly support the feasibility of dynamic field control, several avenues remain open for further exploration:

RCS Reduction: Temporally frozen fields reduce wave reflections (stealth).

Waveform Storage: Field freezing allows temporary signal holding.

Adaptive Communication: Dynamic wave control enables secure signaling and programmable antennas.

Signal Delay Systems, **Energy Gating**, **Electromagnetic Shielding**, etc

Experimental Prototyping: Building a physical prototype with real-time switching elements (Varactors, MEMS, or plasma switches) to verify the predicted behavior.

Nonlinear and Nonreciprocal Designs: Exploring nonlinear temporal modulation to achieve isolation, harmonic generation, or frequency translation.

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