# Design and Analysis of Spatio-temporal Modulation based Non-reciprocal Filters, Antennas, and Metasurfaces using FDTD

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***Abstract*—This work explores space-time-modulated structures for compact, non-magnetic nonreciprocal devices, including filters, antennas, and metasurfaces. We developed an FDTD-based framework to model wave propagation in time-varying transmission lines, addressing resistive and dielectric losses. A novel FDTD-based simulator is introduced for nonreciprocal bandpass filters, validated against harmonic balance simulations. Additionally, we propose a multifunctional metasurface enabling tunable frequency-selective transmission, reflection, and on-air frequency mixing. Simulation and experimental results confirm the effectiveness of space-time modulation for advanced RF applications in communication, radar, and sensing.**

***Index Terms*—Finite-Difference Time-Domain (FDTD), Frequency-selective surfaces (FSS), filters, Metasurfaces, Non-magnetic non-reciprocity, Non-reciprocal devices, Space-time modulation, Time-varying transmission lines (TVTLs).**

## I. Introduction

NON-MAGNETIC, non-reciprocal electronic devices have gained attention due to their shift from ferrite-based designs to spatiotemporal modulation for breaking reciprocity. This transition enables the development of compact, efficient components for beam scanning, frequency translation, and filtering antennas [1], [2]. Recent advances in time-modulated circuits have led to nonreciprocal microstrip filters, filtering antennas, and multifunctional components like mixer-duplexer antenna systems [1]. Metasurfaces further enhance non-reciprocity in applications such as one-way screens, radar absorbers, and illusion cloaks, while engineered space-time responses enable innovations like nonreciprocal Bragg gratings and optical waveguide isolators.

Despite decades of research, modeling time-modulated circuits remains challenging, as traditional linear time-invariant (LTI) methods cannot capture frequency translation effects [3], [4]. Commercial EM solvers like CST and HFSS struggle with time-varying components, requiring specialized numerical methods.

This work focuses on designing nonreciprocal filters, antennas, and metasurfaces using space-time modulation. By integrating antennas with nonreciprocal filters, we aim to enhance power transmission and suppress unwanted signals. Our in-house Finite-Difference Time-Domain (FDTD) simulations overcome the limitations of existing solvers, enabling accurate modeling of time-varying media for communication, radar, and sensing applications.

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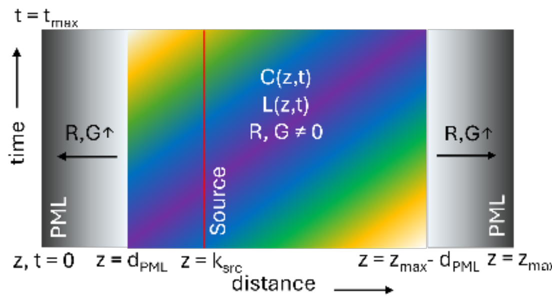


Fig. 1. Schematic representation of a lossy TL with space-time-varying capacitance $C(z,t)$ and inductance $L(z,t)$, nonzero resistance $R$ and conductance $G$, a wave source, and PML boundaries with exponentially increasing $R$ and $G$ to suppress reflections.

## II. FDTD Analysis of Wave-Propagation in TVTLs

To model wave propagation in lossy transmission lines with space-time-varying parameters, we employ the FDTD method, extending previous research on temporal and spatio-temporal modulation effects [2], [3], [5]. This study examines frequency translation, nonreciprocity, and energy dissipation while accounting for resistive and dielectric losses [6]. A novel perfectly matched layer (PML) is introduced to minimize reflections at boundaries. Key parameters such as modulation frequency, modulation index, and loss effects are analyzed to optimize nonreciprocal wave behavior. These findings provide a foundation for designing advanced nonreciprocal components, including isolators, frequency mixers, and energy harvesters, while also paving the way for further investigation into nonlinear effects and experimental validation.

## III. FDTD-Simulator for Non-Reciprocal Circuits

Building on the FDTD modeling framework, we introduce a novel approach for simulating nonreciprocal bandpass filters (BPFs) [7]. This method is based on modified Telegrapher's equations, adapted to facilitate FDTD modeling of discrete time-invariant and time-variant $L$, $C$ components, and $LC$ resonators for RF component design. We apply this technique to the design of nonreciprocal BPFs using time-variant resonators, demonstrating its efficacy through two filtering examples compared against harmonic balance simulations in

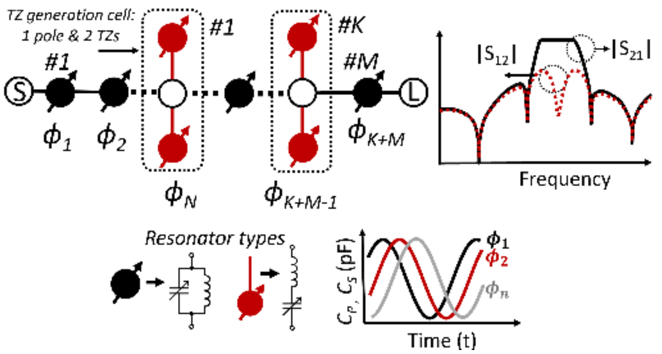


Fig. 2. Generic CRD of an NR-BPF, comprising $M$ time-modulated in-line resonators and up to $K$ time-modulated TZ generation cells. When unmodulated, it exhibits a transfer function shaped by $M$+$K$ poles and 2$K$ TZs. Nonreciprocity is introduced by modulating the resonators with progressively phase-shifted low-frequency AC signals.

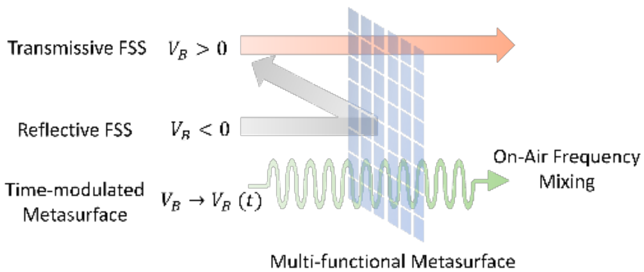


Fig. 3. Conceptual illustration of the multifunctionality of the proposed metasurface: Transmissive mode for 'ON' state (bias voltage, $V_B > 0$), Reflective mode for 'OFF' state ($V_B < 0$), and on-air frequency mixing for the transient state ($V_B \rightarrow V_B(t)$).

Keysight ADS. These include a three-pole BPF and a three-pole/two-transmission zero (TZ) nonreciprocal BPF, showcasing the potential of our FDTD approach for high-accuracy circuit modeling.

## IV. Multi-Functional Time-Modulated Metasurface

Expanding the application of time-modulated systems, we propose a multifunctional metasurface capable of operating as a narrowband transmissive/reflective frequency-selective surface (FSS) and an on-air frequency mixer [8]. The metasurface consists of unit cells with square and circular metallic loops connected by PIN diodes controlled by a bias source. Unlike conventional wideband FSSs, the proposed structure achieves a narrow 0.55 GHz stopband (27.5% fractional bandwidth) at 2 GHz in the OFF-state bias, which can be tuned by adjusting the reverse bias voltage. Under forward bias, the metasurface transitions to a passband response, alternating between transmissive and reflective modes based on bias conditions. The design is compact, angularly stable, and polarization-insensitive for both TE and TM polarization. A prototype was fabricated, with experimental results correlating well with FDTD-based simulations. Furthermore, on-air frequency mixing through the metasurface was demonstrated, with parametric studies conducted via FDTD simulations and experiments to assess the effects of various parameters.

## V. Conclusion

This paper presents an FDTD-based approach for modeling space-time-modulated nonreciprocal devices, demonstrating its accuracy in wave propagation analysis. The proposed simulator successfully designs nonreciprocal filters, validated against simulations. A multifunctional metasurface enabling tunable transmission, reflection, and frequency mixing is experimentally verified. These findings highlight the potential of space-time modulation for compact RF components. Future work will explore nonlinear effects and further optimization of FDTD techniques.

## VI. IMS 2024 Impressions, Fellowship Impact and Career Plan

IMS 2024 in Washington, DC, was an invaluable experience, offering engagement with top researchers and industry experts. The technical sessions refined my research focus, while networking opportunities broadened my academic and industry perspectives. Thanks to the MTT-S fellowship, I fully immersed myself in this enriching environment, strengthening my commitment to innovative research and collaboration.

The IEEE MTT-S Graduate Fellowship has been a pivotal milestone, providing both financial support and motivation. It has reinforced my goal of an academic career in RF and microwave engineering, focusing on space-time metamaterials and next-gen wireless systems. I aim to mentor young researchers and actively contribute to the IEEE MTT-S community through research collaborations and technical advancements.

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