Review Article

Recent Advances in Light Matter Interactions in Temporal Media

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ABSTRACT

In this review, the progress on the research development in the field of electromagnetic wave propagation through temporal/time-varying media is presented. Temporal/time-varying media refers to materials or environments, whose properties change over time. Therefore, unlike spatial waveguides that manipulate light based on spatial configuration of the structure, the temporal waveguides focus on the evolution of light pulses over time. Understanding temporal media is essential for developing advanced communication protocols, efficient waveguides, and accurate simulations of physical systems, ultimately improving the design and performance of various applications in science and technology. As the controlled light matter interactions in the time domain offers numerous advanced applications for secured optical communication, information processing and ultrafast optics in the realm of quantum technology. The recent advances in light-matter interactions in temporal media have opened exciting avenues for manipulating light at unprecedented levels, leading to novel applications in fields like quantum computing, telecommunications, and material science.

Keywords: Temporal media, Time-varying media, Light matter interactions, Electromagnetic wave propagation

1. INTRODUCTION

Recently, the research in photonics has made revolutionary advancements in ultra-fast optical fiber communication, energy-efficient technologies for sensing, and imaging, miniaturised lab on chips, and quantum computing (Novotny and Hecht, 2012; Saleh and Teich, 1991). The integrated photonic devices are paving the way for sub-wavelength optical components and devices. The Terahertz and laser technologies are pushing the frontiers of medical diagnostics and material analysis. Additionally, photonic crystals and meta-materials are enabling new optical materials with unprecedented capabilities for light manipulation (Pendry (2000); Iyer et al., 2020). Further, the temporal media or time-varying media, are one of the emerging concepts in the field of photonics, primarily aimed at controlling and guiding light pulses over time, rather than in space (Galiffi, et. al., 2022; Sacha and Zakrzewski, 2017; Budko, 2009; Felsen, and Whitman, 1970; Koutserimpas and Fleury, 2018; Xiao et. al., 2014; Fante, 1971; Fante, 1973; Mendonc, et. al, 2003; Engheta, 2021). Such temporal media refers to materials whose properties change over time, such as those exhibiting dynamic optical characteristics, which can be used to control light behaviour. These media are artificially engineered materials, exhibiting time dependent permittivity and permeability. So, the electromagnetic waves can interact with rapidly varying material properties, allowing achieving phenomena like ultrafast pulse shaping, enhanced signal processing, and real-time control of light propagation. Advances in temporal media have enabled the development of sophisticated technologies, including ultra-fast modulators, time-varying meta-materials, and light-based communication systems that can operate at much higher speeds and efficiencies. These breakthroughs are not only pushing the boundaries of fundamental science but also driving the future of high-performance optoelectronics and quantum technologies.

In this review article, we aim to present the historical overview of the progress in the field of temporal media. We believe that this work shall provide a motivation for carrying out research in this field.

2. HISTORICAL BACKGROUND OF RESEARCH IN TIME-VARYING MEDIA

The concept of time-varying media has evolved significantly over the past century, with the contributions from diverse fields such as electromagnetism, acoustics, and fluid dynamics. While the theoretical groundwork for understanding how waves interact with changing media dates back to the early 20th century, the practical realisation and detailed study of time-varying media have gained momentum in recent decades due to technological advancements and the discovery of new materials.

(i)Early Foundations: The notion of wave propagation in time-varying media can trace its roots to classical physics, particularly the study of how waves behave when the properties of the medium are not constant. In the 19th century, physicists like Augustin-Jean Fresnel and James Clerk Maxwell laid the groundwork for understanding how electromagnetic waves propagate through different media. However, in these early formulations, the properties of the medium were assumed to be constant. It wasn't until the mid-20th century that researchers began to focus on how time-varying properties, such as variable permeability or permittivity, influenced wave behaviour (Novotny and Hecht, 2012; Saleh and Teich, 1991).

(ii)Development of Time-Varying Electromagnetic Theory: In the 1940s and 1950s, the study of time-varying electromagnetic fields gained prominence, especially during the development of radar and communication technologies. Maxwell's equations, which describe how electric and magnetic fields evolve and propagate, were adapted to account for time-varying media. The development of radar systems, which involved signal transmission through dynamic environments, became a driving force in understanding how electromagnetic waves interact with time-varying materials.

By the 1960s, the study of electromagnetic wave propagation in time-varying media expanded to include the effects of conductors and nonlinear materials, particularly with applications in communications and radar. The theoretical framework for time-varying dielectric media started to emerge during this period, with pioneering works on the modulation of wave properties due to time-dependent fields (Felsen, and Whitman, 1970; Morgenthaler, 1958; Veselago, 1967; Ginzburg, and Tsytovich, 1973; Ginzburg, and Tsytovich, 1979).

(iii)The Rise of Nonlinear Optics and Metamaterials: The 1980s and 1990s witnessed a surge in research related to nonlinear optics and metamaterials, both of which can be regarded as forms of time-varying media. Nonlinear optical materials, where the refractive index changes in response to high-intensity light, became a focal point for researchers exploring the dynamic control of light propagation. These materials are essential in modern technologies such as fiber optics, laser systems, and optical switching (Novotny and Hecht, 2012; Saleh and Teich, 1991).

The concept of meta-materials: Materials engineered to have properties not found in naturally occurring materials was also gaining momentum during this time. Early work on meta-materials in the late 1990s and early 2000s primarily focused on static properties such as negative refractive index (Saleh and Teich, 1991; Pendry, 2000; Alù, et. al., 2007 (a)). However, as the field matured, researchers began to explore time-varying meta-materials. This opened the door for the development of dynamic meta-materials that could be tuned in real-time for applications in adaptive optics, invisibility cloaks, and beam steering.

(iv)The Emergence of Time-Varying Media in Meta-materials and Plasmonics: With the rise of plasmonics in the early 21st century, the exploration of time-varying media took on new significance. The coupling of electromagnetic waves with collective oscillations of free electrons (plasmons) in metallic nanostructures created new possibilities for manipulating light at the nanoscale (Maier, 2007; Saleh and Teich, 1991). The potential to create time-varying plasmonic systems, where the material properties could be altered at very high frequencies, further broadened the scope of time-varying media.

Around the same time, the field of time-varying metamaterials emerged as a rapidly growing area of research. Advances in material science, particularly with transparent conducting oxides (TCOs) like, indium tin oxide (ITO) and epsilon-near-zero (ENZ) materials, began to reveal the extraordinary potential for dynamically controlled media. These materials enabled the experimental realisation of time-varying effects, where the dielectric properties could be actively modulated, leading to novel applications in smart materials.

(v) Recent Advancements and the Role of Modern Technologies: In the past two decades, there has been an explosion of interest in time-varying media, driven by advances in material science, nanotechnology, and meta-materials. The development of highly nonlinear and tunable materials has made it possible to actively manipulate the properties of media in real time, leading to new frontiers in optical switching, communications, and energy harvesting (Budko, 2009; Felsen, and Whitman, 1970; Koutserimpas and Fleury, 2018; Xiao et. al., 2014; Fante, 1971; Fante, 1973; Mendonc, et. al, 2003; Engheta, 2021; Maier, 2007). The ability to design materials that respond dynamically to electromagnetic, optical, or acoustic signals has catalysed breakthroughs in technologies such as smart textiles, adaptive lenses, and programmable waveguides.

Moreover, advances in computational modelling and simulation tools have provided with the ability to explore complex time-varying systems in unprecedented detail. Techniques such as finite difference time domain (FDTD) and finite element analysis (FEA) have enabled the precise modelling of wave propagation in time-varying media.

Table 1 presents the timeline of research progress related to time varying media in chronological order, along with the key developments in wave propagation and time-varying media.

3. THEORETICAL ANALYSIS

Mathematical modelling of time-varying photonic media involves studying the electromagnetic wave propagation in temporal media by solving the following Maxwell's equations:

$$\nabla \cdot \mathbf{D} = \rho_{free} \quad 1(a)$$

$$\nabla \cdot \mathbf{B} = 0 \quad 1(b)$$

$$\frac{\partial \mathbf{B}}{\partial t} = -\nabla \times \mathbf{E} \quad 1(c)$$

$$\frac{\partial \mathbf{D}}{\partial t} = -J + \nabla \times \mathbf{H} \quad 1(d)$$

Here, **D, B, E, H** are the electric displacement, magnetic field , electric field, and magnetic flux density respectively [1-2]. In time-varying media, the constitutive relations between **D** and **E**, and **B** and **H** get modified. Further, it is well known that the refractive index of a temporal medium is defined as

$$n(t) = \sqrt{\varepsilon(t)\mu(t)} \quad (2)$$

Therefore, by solving Eq. (1a-d), the time-dependent wave equation is given as:

$$\frac{\partial^2 E}{\partial t^2} - \frac{c^2}{\varepsilon(t)\mu(t)}\nabla^2 E = 0 \quad (3)$$

This equation accounts for both the spatial and temporal variations of the medium's properties.

Further, for a plane wave $\left(E = E_0 e^{i(\omega t - \beta z)}\right)$ with short spectral width, propagating along *z*-direction inside a medium of refractive index $n(\omega)$ (at frequency ω) having propagation constant $\beta(\omega)$ which can be Taylor-expanded around the central frequency ω_0 is given as follows (Plansinis, et. al., 2016).

Table I: Timeline of research progress

Time Period	Topic	Key Developments
1950s–1960s: Early Theoretical Foundations		
1958	Morgenthaler's Work on Velocity Modulation	F.R. Morgenthaler published the first theoretical analysis of wave propagation in time-varying media, focusing on velocity modulation of electromagnetic waves. This work laid the groundwork for understanding temporal boundaries and scattering in time-varying systems (Morgenthaler, 1958).
1960s	Plasma Physics and Ionization Fronts	Researchers explored wave propagation in rapidly ionizing plasmas, where permittivity changes abruptly due to ionization. E. Yablonovitch and others studied frequency conversion and self-phase modulation in time-varying plasmas (Yablonovitch, 1973; Yablonovitch, 1974).
1970s–1980s: Temporal Boundaries and Nonlinear Optics		
1970s	Temporal Boundary Conditions	R. Fante and others derived boundary conditions for electromagnetic waves at temporal discontinuities, analogous to spatial boundaries, establishing the mathematical framework for analysing wave propagation in time-varying media (Fante, 1971; Fante, 1973).
1980s	Nonlinear Optics and Parametric Processes	The field of nonlinear optics explored parametric amplification and frequency conversion in time-varying systems. J.T. Mendonça and others developed the theory of photon acceleration in time-varying media (Mendonc, et. al, 2003).
1990s–2000s: Emergence of Metamaterials and Time Crystals		
1990s	Metamaterials and Spatiotemporal Modulation	The rise of metamaterials inspired interest in spatiotemporal modulation. Researchers began exploring the combination of spatial and temporal modulation for exotic wave phenomena.
2000s	Photonic Time Crystals (PTCs)	The concept of photonic time crystals (PTCs) was introduced, where the refractive index varies periodically in time. F. Wilczek proposed the idea of time crystals in condensed matter physics, sparking interest in temporal periodicity (Wilczek, 2012).
2010s: Experimental Realizations and Technological Applications		
2010s	Experimental Demonstrations	Experimental demonstrations of time-varying effects in photonic and plasmonic systems became possible due to advances in material science and ultrafast optics. A. Alù, and others demonstrated time-refraction and frequency conversion in epsilon-near-zero (ENZ) materials (Alu, et. al., 2007).
~2015	Nonreciprocal Devices	Researchers explored time-varying media for nonreciprocal wave

Time Period	Topic	Key Developments
		propagation, enabling isolators and circulators without magnetic fields. S. Taravati demonstrated nonreciprocal devices using spatiotemporal modulation (Taravati, et. al., 2017).
~2019	Temporal Metasurfaces	Temporal metasurfaces were introduced, where the surface impedance is modulated in time to control wavefronts. A. M. Shaltout and others demonstrated spatiotemporal light modulation using time-varying metasurfaces (Shaltout, et. al., 2019).
2020s: Advances in Topology, Non-Hermitian Physics, and Quantum Systems		
2020	Topological Time Crystals	Researchers explored topological phases in time-varying systems, including temporal edge states and synthetic dimensions. E. Lustig and M. Segev demonstrated topological phenomena in photonic time crystals (Lustig, et. al., 2018).
2021	Non-Hermitian Time-Varying Media	The interplay between time-varying media and non-Hermitian physics was investigated, leading to exotic phenomena such as exceptional points and gain-loss balance. R. Fleury and others studied non-Hermitian time-Floquet systems for nonreciprocal gain and mode steering (Bossart and Fleury, 2021).
2022	Quantum Time-Varying Media	Time-varying media were extended to quantum systems, enabling control of quantum states and entanglement. W.J.M. Kort-Kamp and others proposed space-time quantum metasurfaces for quantum light manipulation (Kort-Kamp, et. al., 2021; Gaur and Mishra, 2024).

$$\beta(\omega) = \beta_0 + \beta_1(\omega - \omega_0) + \frac{\beta_2}{2}(\omega - \omega_0)^2 \qquad (4)$$

where β_1 is the inverse of the group velocity and β_2 is the group velocity dispersion parameter.

As the refractive index of the temporal media changes across a temporal boundary, say at $t=t_b$, the propagation constant also changes across the interface, and it is given by:

$$\beta(\omega) = \beta_0 + \Delta\beta_1(\omega - \omega_0) + \frac{\beta_2}{2}(\omega - \omega_0)^2 + \beta_b(t) \qquad (5)$$

here $\Delta\beta_1$ is a measure of the speed relative of the optical pulse at the interface and $\beta_b(t)=k_0\Delta n(t)$, ($k_0$: free space wave-vector) is the change in the propagation constant arising due to the time-dependent index change $\Delta n(t)$.

Now, using Maxwell's equations and under slowly varying envelope approximation, we obtain the following equation:

$$\frac{\partial\psi}{\partial z} + \Delta\beta_1 \frac{\partial\psi}{\partial t} + \frac{i\beta_2}{2}\frac{\partial^2\psi}{\partial t^2} = i\beta_b(t)\psi \qquad (6)$$

Where $\psi(z,t)$ is the pulse envelope at distance z. Therefore, depending on the structure of the temporal waveguide the above-mentioned wave equation is solved by the applying the appropriate spatial and temporal boundary conditions.

4. THE FUTURE OF TIME-VARYING MEDIA

Today, time-varying media are at the forefront of emerging technologies. As new materials and fabrication techniques continue to evolve, the possibilities for designing and controlling time-varying media are vast. Few of the future directions are given below:

(i) Ultrafast Modulation and Nonlinear Effects

Exploring ultrafast temporal modulation for high-speed signal processing and nonlinear wave phenomena. This involves studying rapid changes in media properties to manipulate signals and waves, paving the way for advanced communication and information processing.

(ii) Integration with Quantum Technologies

Applying time-varying media to quantum communication, computing, and sensing. This direction focuses on enhancing the capabilities of quantum systems through dynamic media, potentially leading to more efficient and robust quantum technologies.

(iii) Synthetic Dimensions and Topological Physics

Investigating higher-dimensional topological effects in time-varying systems. This research aims to understand how time-varying properties can create synthetic dimensions and influence the topological behaviour of materials, potentially leading to new discoveries in fundamental physics.

(iv) Energy Harvesting and Amplification

Developing time-varying media for efficient energy harvesting and amplification. Researchers are looking into how dynamic changes in media properties can be used to capture and amplify energy more effectively, which could have significant implications for renewable energy technologies.

(v) Experimental Platforms

Expanding experimental platforms to include acoustics, plasmonics, and 2D materials. This direction emphasises on the development of new experimental setups and techniques to study time-varying effects in different types of materials, broadening the scope of applications and potential discoveries.

5. CONCLUSION

Temporal waveguides represent a fascinating frontier in optical science, combining aspects of ultrafast optics, quantum mechanics, and advanced materials science. While the field is still in its early stages, the potential applications—especially in high-speed communication, quantum technologies, and nonlinear optics—are highly promising. As technology advances, temporal waveguides could play a crucial role in reshaping the future of optical information processing. The historical trajectory of research in time-varying media shows a steady progression from theoretical foundations to practical implementations, with exciting new challenges and opportunities ahead.

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Conflict of Interest

The authors further declare that there are no financial or non-financial interests that are directly or indirectly related to the work submitted for publication, and the authors declare no conflicting interests.

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