Engineering spatiotemporal metamaterials for 4D wave-matter interaction control

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Metamaterials and metasurfaces have provided scientists and engineers with unprecedented ability to manipulate and control fields and waves via their properly designed effective material parameters such as permittivity, permeability, and refractive index [1]. They have been shown to offer various applications in antennas, lenses, filters, invisibility cloaks, and circuits and sensors, to name a few [2]. The research on metastructures has been primarily conducted in the frequency domain where wave propagation is manipulated via spatial inhomogeneities using geometrical inclusions of different materials [3]. However, the temporal manipulation of their optical properties has re-gained recent attention in order to achieve a full 4D control of wave-matter interaction [4-5]. Some of the early work on temporal and spatiotemporal modulation of (ε,μ) dates back to the last century where a time-dependent $\varepsilon(t)$ following a step function was theoretically analyzed [6]. By using this temporal function of $\varepsilon(t)$, it was shown that a set of two waves, one traveling forwards (FW) and one backward (BW), was generated when changing the permittivity from an initial value ε_1 to ε_2 [7].

In our work here, to explore the novel features of time-varying media and their exciting physics and engineering properties with new potential applications, we will discuss our ongoing efforts in exploring 4D metamaterials, with focus on temporal aiming and temporal anisotropy, spatiotemporal ring resonators, anti-reflection temporal coatings, effective medium concept in the time domain, and phase conjugation, among others [8–12]. We will discuss physical insights into these results and forecast possible future research directions on these topics.

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