



Feature issue introduction: temporal and spatiotemporal metamaterials

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Abstract: Temporal modulation of material parameters provides a new degree of freedom for metamaterials, metasurfaces and wave-matter interactions as a whole. In time-varying media the electromagnetic energy may not be conserved, and the time reversal symmetry may be broken, which may lead to novel physical effects with potential applications. Currently, theoretical and experimental aspects of this field are rapidly advancing, expanding our understanding of wave propagation in such complex spatiotemporal platforms. This field promises novel possibilities and directions in research, innovation and exploration.

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Time-modulated metamaterials, whose optical parameters such as the electric permittivity are dynamically modulated in time via an external mechanism, have recently emerged as a new paradigm for wave manipulation [1,2,3]. They naturally break some of the fundamental barriers present in conventional media such as reciprocity and wave energy conservation. The goal of this feature issue is to present some representative research lines in the area of electromagnetic (EM) waves in time-varying metamaterials.

“Temporal interfaces” are created when the optical parameters of a medium change rapidly in time. The scattering of EM waves off temporal boundaries is ruled by momentum conservation (in contrast to conventional spatial interfaces which are ruled by energy conservation). As a consequence, a temporal interface generates time-reflected and time-refracted waves at frequencies that differ from the incident frequency. This has enabled the generation of time-reversed waves, as well as broadband frequency shifts, to name some examples. New insights over temporal interfaces are offered by Yin et al., who study *chiral* temporal interfaces. Dual to spatial interfaces between chiral media, the authors show that a chiral time-interface splits a propagating wave into two orthogonal circular polarization waves at different frequencies [4]. Such temporal analogue of optical activity adds a new building block to the field of temporal metamaterials.

Phased modulation of the optical parameters in space as well as in time generates a spatiotemporal modulation. The presence of a linear bias breaks reciprocity, as is the case in physically moving (or rotating) media. An example of this is considered by Yang et al., who show how a subwavelength spinning cylinder generates nonreciprocal frequency shifts [5]. This realization of non-reciprocity does not require an applied static magnetic field, and it may provide paths to compact nonreciprocal devices such as optical isolators. A detailed investigation on the performance of nonreciprocal wave propagation under spatiotemporal modulations is given by Sotoodehfar et al. [6].

Compact on-chip isolators based on two or three coupled resonators subject to phased temporal modulations are presented by Mock [7]. This design implements a spatiotemporal modulation, resulting in nonreciprocal wave propagation. A realization of these devices using photonic crystal nanobeam resonators is presented and high performance for optical isolation is shown. Another promising property of temporal modulations is the generation of synthetic dimensions that offer new pathways for non-reciprocity and optical isolation. Wu et al. introduce a dynamically modulated waveguide array that generates a synthetic two-dimensional space where unidirectional edge modes exist [8].

A hallmark system in time-modulated media is the photonic time crystal. Novel physical phenomena can emerge when the refractive index of a material undergoes rapid and periodic modulations in time. Remarkably, their dispersion relation is characterized by momentum gaps – instead of the more familiar frequency gaps – which results in an exponential amplification of the waves that travel in the medium and extract energy from the modulation. Amplification of normally incident waves on a dielectric slab subject to a periodic temporal modulation is studied by Salehi et al. [9]. Furthermore, Lustig et al. review the progress on fundamental aspects of light-matter interactions in photonic time crystals. Interestingly, light amplification in photonic time crystals is predicted to be non-resonant, eliminating the constraint of phase-matching. In particular, the emission of a point source (a quantum emitter, or a nano-antenna) in a photonic time crystal is exponentially amplified, independent of its resonance frequency. Photonic time crystals hold this and other exciting prospects such as tunable lasing [10].

A key challenge to experimentally realize a photonic time crystal at optical frequencies is the need for a rapid change in refractive index and observation of time reversal. In order to generate detectable time reflected light and to realize a photonic time crystal, unity-order refractive index modulations in a time scale of a single optical cycle are needed. Saha et al. discuss experimental progress in materials and mechanisms along this direction. Transparent conducting oxides stand as a very promising platform because they enable order of unity changes in the refractive index at picosecond time scales. As discussed by Saha et al, the palette of materials available for large modulations of the optical response is increasing [11].

Another fundamental aspect of light-matter interactions in time-dependent media is discussed by Pendry. By considering a spatiotemporal modulation, Pendry shows that time-dependent systems, which are open systems, and hence do not conserve electromagnetic energy, can nevertheless conserve the total number of photons at the same time. While these two conservation laws come together in static systems and it may seem paradoxical to observe gain with a fixed photon number, Pendry discusses how time dependence decouples energy and photon conservation. Thus, amplification can be observed even in systems with real eigenvalues, originated by a fixed number of photons climbing up a frequency ladder [12].

Adding time modulations to the toolbox of metamaterials opens the door to four-dimensional metamaterials (4D), where the more conventional spatial variations of optical parameters in three dimensions is complemented by a temporal variation [13]. This has enabled time reversal, nonreciprocity or temporal aiming [14], among other examples [1–3]. In the microwave regime, temporal variations can be realized electronically with coding metasurfaces, as Yang et al. exploit to obtain dynamic radiation steering in a transmission-type coding metasurface [15].

On the other hand, Garg et al. detail a theoretical framework based on T-matrix to study the optical response of 4D metamaterials consisting of a periodic arrangement of time-varying scattering particles in up to three dimensions [16]. Starting from the T-matrix of an individual scatterer, which is characterized by a Lorentz model with a time varying electron density, an effective T-matrix is constructed for a metasurface. With this semi-analytical approach, Garg et al. are able to compute all the optical properties of a space-time metasurface, including reflection and transmission coefficients for each frequency and for each diffraction order. For instance, results for a time-modulated Huygens' metasurface shows that zero backscattering is suppressed

under the temporal modulation, while negative absorption is possible, associated to the lack of electromagnetic energy conservation in these systems. This method adds a very valuable computational tool to the set of theoretical methods available to study space-time metamaterials.

In summary, temporal and spatiotemporal metamaterials are emerging as a fruitful platform to realize new and rich features in wave propagation and light-matter interaction. The research results presented in this feature issue exemplify many of the current approaches in this active field. We thank all the authors who have contributed to this issue.

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