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# APL special topic: Time modulated metamaterials

**Special Collection: Time Modulated Metamaterials**

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## I. INTRODUCTION

Metamaterials represent control over matter on a small enough scale to change the macroscopic properties, opening an enormous space of new and optimized mechanical and electromagnetic material parameters. Nevertheless, there remain immovable constraints on conventional static metamaterials. For example, static materials can never change the wave frequency nor amplify the wave amplitude. Instead, when a material changes with time, new degrees of freedom can be exploited.

Recently, there has been a growing interest in time modulated metamaterials.[1] These materials exhibit dynamic changes in their properties over time, representing a novel approach to manipulating waves and processing information. This approach goes beyond the constraints imposed by energy conservation and time-reversal symmetry. Time-switched and time-varying metamaterials, as they are also called, enable us to access the momentum and frequency of the waves, leading to a wide array of unique properties, such as time-refraction,[2] time-reversal,[3] nonreciprocal behavior,[4] wave synthesis and frequency conversion,[5,6] and amplification.[7] Time modulated metamaterials have potential for application in communication, security, sensing, and computation just to mention a few, across various wave domains from electromagnetism to acoustics and mechanics.

## II. BACKGROUND

Time modulated metamaterials exhibit a temporal variation of their wave response, for example, of their impedance, on timescales comparable with the wave oscillation period. This modulation usually originates from an external driving, either in the form of a mechanical force, a laser beam, or a mechanical load, for example. Most of the physical properties of these materials affect how waves are transported or generated within them, and therefore, many phenomena are common to many weave domains, e.g., from light waves to elastic ones, from acoustic waves to radio frequency.

In optics, despite the challenges of ultrafast switching of the refractive index, pump–probe experiments have elucidated many of the fundamental and applied aspects of time-modulated materials. Free carrier injection by femtosecond laser pulses induces Drude-like adjustments to the refractive index, enabling adiabatic frequency conversion and translation,[2,6] including for harmonics generation,[8] and the temporal analog of the Young's double-slit experiment.[9] However, the lack of deep periodic drive stonewalls most experimental realizations pertaining, for instance, to time crystals and Floquet engineering. New solutions are required to create the high-frequency periodic modulation of dielectric permittivity in the optical range.

Time-coding and space–time-coding digital metasurfaces with inherently programmable properties emerge as powerful and versatile platforms for implementing time modulation and space–time joint manipulation,[10] which have been widely explored in the microwave frequency for their potential for nonlinear harmonics controls, programmable nonreciprocity, and new-architecture wireless communications.

Time modulated metamaterials can also be harnessed to replicate complex wave phenomena and information processing techniques. Furthermore, they offer an opportunity to emulate fundamental phenomena occurring in curved spacetimes,[11] thereby extending their utility beyond traditional wave manipulation and information processing.

## III. SUMMARY OF AREAS COVERED

This Special Topic in Applied Physics Letters collects recent advances in the broad area of time modulated metamaterials. This is a broad field, and this collection has contributions that encompass time reversal, parity-time symmetry, nonreciprocity, parametric effects, subharmonic mixing, coding and inverse design, and new temporal phenomena. Here below, we have attempted to highlight some of the papers and the broad topics they address.

As exemplary results within this topic, Sadafi *et al.*[12] and Rafi *et al.*[13] provided an analytical solution for scattering from a particle composed of a material with time-varying permittivity, and temporal modulation of the material parameters can be exploited to transfer energy to high-order modes.

Gaxiola-Luna and Halevi[14] investigate the band structure $\omega(k)$ of a photonic time crystal with periodic square (step) modulation in time of its permittivity $\varepsilon(t)$. Additionally, He *et al.*[15] investigate Faraday rotation in nonreciprocal photonic time-crystals and created a link between photonic nonreciprocity and parametric gain. While Mattei and Gulizzi[16] designed space microstructures in the propagation of waves in time modulated composites and demonstrated that a pulse propagates with constant amplitude regardless of the impedance between the constituent materials.

Stefanini *et al.*[17] studied a rainbow-like scattering process taking place at the interface of a boundary-induced temporal metamaterial. They demonstrate an equivalent temporal interface that occurs between two different media by abruptly changing the conductivity of one of the two metallic plates. Therefore, the monochromatic wave propagating into the waveguide gets scattered into a polychromatic rainbow in free space.

Castaldi *et al.*[18] developed an approximate approach to model the multiple actions of time-resolved short-pulsed metamaterials systematically. Their result illustrates the potential capabilities of SPMs to serve as elementary bricks in more complex analog-computing systems.

In the context of space–time coding, our Special Topic features several exciting papers since this is an area of growing interest in the community of programmable metasurfaces and information science and technology. References 19–22 discuss some important features in this area for direction-of-arrival estimations, near-field microwave computational imaging, physics-driven intelligent autoencoder, and time-coding spoof surface plasmon polaritons. These results demonstrate that the space–time coding approach has powerful capabilities in modulating the electromagnetic waves and also expands the potential applications of programmable and information metasurfaces.

Several applications are also suggested in this Special Issue, such as switching the transmission response of THz wave,[23] secure wireless communication,[24] engineering bandwidth of small antennas,[25] and controlling the radiation of the nonlinear waves.[26]

## IV. CONCLUSION

The field of time modulated metamaterials is developing both a fundamental theoretical and experimental understanding while targeting a broad range of applications.

This Special Topic compilation offers Applied Physics Letters' diverse readership a chance to explore the latest developments in the field of time-modulated metamaterials and their practical applications. We hope that this curated assortment of articles will act as a catalyst, encouraging researchers to explore new frontiers beyond the traditional domains of electromagnetic research, photonics, and wave physics, ultimately propelling this field to greater heights.


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## AUTHOR DECLARATIONS

### Conflict of Interest

The authors have no conflicts to disclose.

### Author Contributions

**Riccardo Sapienza:** Writing – review & editing (equal). **Maxim Scherbakov:** Writing – review & editing (equal). **Daniele Faccio:** Writing – review & editing (equal). **Tie Jun Cui:** Writing – review & editing (equal). **Humeyra Caglayan:** Writing – review & editing (equal).

## DATA AVAILABILITY

The data that support the findings of this study are available from the corresponding author upon reasonable request.

## REFERENCES


1E. Galiffi, R. Tirole, S. Yin, H. Li, S. Vezzoli, P. A. Huidobro, M. G. Silveirinha, R. Sapienza, A. Alù, and J. Pendry, "Photonics in time-varying media," Adv. Photonics **4**, 014002 (2022).

2Y. Zhou, M. Z. Alam, M. Karimi, J. Upham, O. Reshef, C. Liu, A. E. Willner, and R. W. Boyd, "Broadband frequency translation through time refraction in an epsilon-near-zero material," Nat. Commun. **11**, 2180 (2020).

3S. Vezzoli, V. Bruno, C. DeVault, T. Roger, V. M. Shalaev, A. Boltasseva, M. Ferrera, M. Clerici, A. Dubietis, and D. Faccio, "Optical time reversal from time-dependent epsilon-near-zero media," Phys. Rev. Lett. **120**, 043902 (2018).

4R. Fleury, D. L. Sounas, C. F. Sieck, M. R. Haberman, and A. Alù, "Sound isolation and giant linear nonreciprocity in a compact acoustic circulator," Science **343**, 516 (2014).

5M. R. Shcherbakov, R. Lemasters, Z. Fan, J. Song, T. Lian, H. Harutyunyan, and G. Shvets, "Time-variant metasurfaces enable tunable spectral bands of negative extinction," Optica **6**, 1441 (2019).

6N. Karl, P. P. Vabishchevich, M. R. Shcherbakov, S. Liu, M. B. Sinclair, G. Shvets, and I. Brener, "Frequency conversion in a time-variant dielectric metasurface," Nano Lett. **20**, 7052–7058 (2020).

7M. Lyubarov, Y. Lumer, A. Dikopoltsev, E. Lustig, Y. Sharabi, and M. Segev, "Amplified emission and lasing in photonic time crystals," Science **377**, 425 (2022).

8M. R. Shcherbakov, K. Werner, Z. Fan, N. Talisa, E. Chowdhury, and G. Shvets, "Photon acceleration and tunable broadband harmonics generation in nonlinear time-dependent metasurfaces," Nat. Commun. **10**, 1345 (2019).

9R. Tirole, S. Vezzoli, E. Galiffi, I. Robertson, D. Maurice, B. Tilmann, S. A. Maier, J. B. Pendry, and R. Sapienza, "Double-slit time diffraction at optical frequencies," Nat. Phys. **19**, 999–1002 (2023).

10J. Zhao, X. Yang, J. Y. Dai, Q. Cheng, X. Li, N. H. Qi, J. C. Ke, G. D. Bai, S. Liu, S. Jin, A. Alù, and T. J. Cui, "Programmable time-domain digital coding metasurface for nonlinear harmonic manipulation and new wireless communication systems," Natl. Sci. Rev. **6**, 231–238 (2019).

11A. Bahrami, Z.-L. Deck-Léger, and C. Caloz, "Electrodynamics of accelerated-modulation space-time metamaterials," Phys. Rev. Appl. **19**, 054044 (2023).

12M. M. Sadafi, A. F. da Mota, and H. Mosallaei, "Dynamic control of light scattering in a single particle enabled by time modulation," Appl. Phys. Lett. **123**, 101702 (2023).

[13]R. S. Rafi, S. Fardad, and A. Salandrino, "Intermodal excitation in time-varying plasmonic structures," Appl. Phys. Lett. **122**, 041701 (2023).
[14]J. G. Gaxiola-Luna and P. Halevi, "Growing fields in a temporal photonic (time) crystal with a square profile of the permittivity $\varepsilon(t)$," Appl. Phys. Lett. **122**, 011702 (2023).
[15]H. He, S. Zhang, J. Qi, F. Bo, and H. Li, "Faraday rotation in nonreciprocal photonic time-crystals," Appl. Phys. Lett. **122**, 051703 (2023).
[16]O. Mattei and V. Gulizzi, "On the effects of suitably designed space microstructures in the propagation of waves in time modulated composites," Appl. Phys. Lett. **122**, 061701 (2023).
[17]L. Stefanini, D. Ramaccia, A. Toscano, and F. Bilotti, "Temporal rainbow scattering at boundary-induced time interfaces," Appl. Phys. Lett. **122**, 051701 (2023).
[18]G. Castaldi, C. Rizza, N. Engheta, and V. Galdi, Appl. Phys. Lett. **122**, 021701 (2023).
[19]X. Q. Chen, L. Zhang, and T. J. Cui, "Intelligent autoencoder for space-time-coding digital metasurfaces," Appl. Phys. Lett. **122**, 161702 (2023).
[20]J. Han, T. Wang, S. Chen, X. Ma, G. Li, H. Liu, and L. Li, "Utilization of harmonics in phaseless near-field microwave computational imaging based on space–time-coding transmissive metasurface," Appl. Phys. Lett. **122**, 031701 (2023).
[21]L. P. Zhang, H. C. Zhang, J. Zhang, L. Y. Niu, P. H. He, C. Wei, W. Tang, and T. J. Cui, "Reprogrammable control of electromagnetic spectra based on time-coding plasmonic metamaterials," Appl. Phys. Lett. **121**, 161702 (2022).
[22]Q. Y. Zhou, J. W. Wu, S. R. Wang, Z. Q. Fang, L. J. Wu, J. C. Ke, J. Y. Dai, T. J. Cui, and Q. Cheng, "Two-dimensional direction-of-arrival estimation based on time-domain-coding digital metasurface," Appl. Phys. Lett. **121**, 181702 (2022).
[23]Y. Huang, T. Okatani, N. Inomata, and Y. Kanamori, "A reconfigurable ladder-shaped THz metamaterial integrated with a microelectromechanical cantilever array," Appl. Phys. Lett. **122**, 051705 (2023).
[24]M. Wei, H. Zhao, Y. Chen, Z. Wang, T. J. Cui, and L. Li, "Physical-level secure wireless communication using random-signal-excited reprogrammable metasurface," Appl. Phys. Lett. **122**, 051704 (2023).
[25]M. H. Mostafa, N. Ha-Van, P. Jayathurathnage, X. Wang, G. Ptitcyn, and S. A. Tretyakov, "Antenna bandwidth engineering through time-varying resistance," Appl. Phys. Lett. **122**, 171703 (2023).
[26]X. Liu, Y. Tang, Y. Li, Z. Hu, J. Deng, and G. Li, "Continuous amplitude control of second harmonic waves from the metasurfaces through interference paths," Appl. Phys. Lett. **121**, 111701 (2022).