Terahertz Spatiotemporal Wave Control in Complex Media

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Abstract

Controlling electromagnetic wave propagation in scattering media presents a contemporary and intriguing challenge in modern physics. Contrary to the common assumption that multiple scattering phenomena lead to an irreversible loss of information, recent advancements reveal a more nuanced perspective (1). With its deterministic spatiotemporal dynamics, the scattering process offers a fertile ground for wave manipulation and enables desired field distribution tailoring at the output by structuring the input wavefront incidents upon a scattering media (2). Such insight opens the door to a range of transformative applications, such as focusing and imaging through scattering media, where complexity is not a hindrance but a resource to be harnessed (3). In this direction, researchers have pioneered wavefront shaping techniques to compensate for scattering-induced distortions in imaging systems (4,5). Potential strategies include iterative optimization techniques, which adjust the output by modulating the input with spatial light modulators and digital-light-processing mirrors (6). Alternatively, deterministic methods have been developed to assess the scattering transfer matrix by decomposing it into an orthogonal set of inputs, enabling the direct estimation of the scattered field for a given input (7). More recently, with the advent of broadband sources, significant research has focused on harnessing scattering as a tool - shaping and functionalizing scattered light to achieve target spatial and temporal field distributions (8,9).

Achieving complex field-wavefront synthesis hinges critically on the ability to directly measure the instantaneous electric field. In other words, generating specific temporal field dynamics necessitates resolving the absolute electromagnetic phase - a formidable challenge, particularly in the optical domain. Even if the scattering matrix of a medium is fully characterized, one could argue that without accurate knowledge of the absolute phase of the incident field, arbitrary wave synthesis and control of the output waveform remain elusive (10). In this context, Terahertz Time-Domain Spectroscopy (THz-TDS) has emerged as a well-established technique, uniquely capable of accessing the temporal waveform of broadband THz pulses, offering a robust platform for addressing this limitation.

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Knowledge of the spatiotemporal field transient at a sub-picosecond time scale creates a prominent conceptual difference from stabilized wavefront shaping methodologies in the optical domain. For instance, for each spatial illumination wavefront, the corresponding scattered space-time waveform can be directly measured, allowing the entire spectrum of possible output fields to be immediately known and can be expressed as a linear superposition. Therefore, controlling spatiotemporal wave interactions in complex media using a field-based optimization strategy is reduced to determining the coefficients without prior knowledge of the source or needing to form a complete orthogonal set (10). In this way, even for an iterative optimization approach, specific target parameters such as peak field position, field polarity, and pulse chirp at any order become readily accessible (11). Moreover, considering the deterministic approach, when the broadband transfer matrix of a scattering object is desired, spatiotemporal field measurements offer a direct means of extracting its complex-valued elements through simple projections, utilizing both the input structured wavefronts and output scattered fields. This approach bypasses the need for more complex notions, such as the spectral coherence of the scattering medium. Built upon this, we present a comprehensive review of our recent numerical and experimental work in THz spatiotemporal wave control within complex media. We showcase deterministic and iterative approaches, focusing on applications in THz wavefront shaping, pulse manipulation, and imaging through scattering media.

Our methodology leverages the nonlinear conversion of ultrafast, wavefront-shaped optical light into structured terahertz radiation, which is further used to probe complex media placed in close proximity to the nonlinear crystal (10–12). This process effectively enables sub-wavelength spatial sampling (a constraint typically imposed by the long THz wavelengths) of modulated THz wavefronts and overcomes the generally limited availability of broadband waveform shaping devices at THz frequencies (13). As a deterministic approach, illustrated in Figure 1a, a sequence of Walsh-Hadamard patterns are projected, and transmitted spatiotemporal fields are captured using a near-field TDS imager (Figure 1b). Through this, the complex-valued elements of the broadband transfer matrix are resolved and characterized by distinct spectral correlations, as shown in Figure 1c. By applying constrained inversion techniques, we compute the optimal input wavefront, achieving a spatiotemporal focus at the output of the medium (Figure 1d), demonstrating deterministic spatial and spectral control over the transmitted terahertz field. By leveraging the retrieved transfer matrix, we also show the ability to reconstruct objects concealed behind complex media. On the other hand, a typical example of an iterative optimization process is shown in Figure 1e. This approach integrates with single-pixel field-sensitive detection enabled by the TDS sensor to collect transmitted THz pulses at a target spatial location on the output surface of the scattering media, revealing the significant distortion in the pulse evolution. To overcome this, a feedback-based genetic algorithm is deployed to maximize the peak field at the target spatial location while simultaneously flattening the spectral phase (Figure 1f). The iterative approach enables comprehensive control over phase, time shift, and chirp of the THz pulse, as shown in Figure 1g. We will present detailed insights into both the theoretical framework and experimental validation of our findings.

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