Controlling Ultrashort Pulses in Scattering Media

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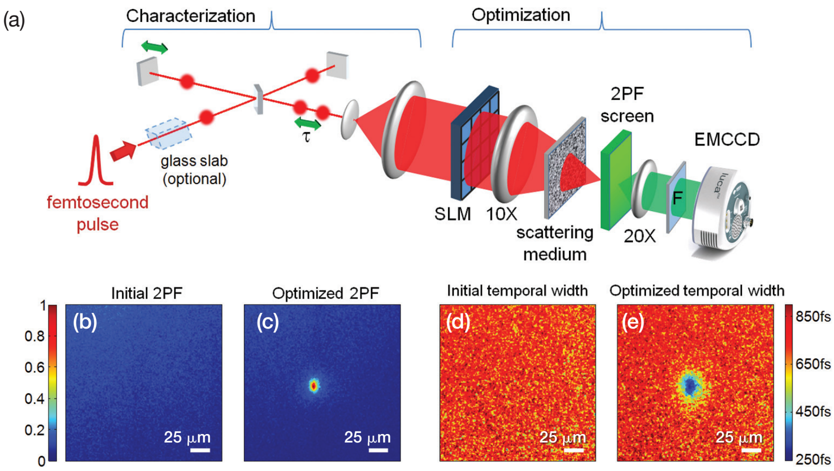
Light is randomly scattered when it passes through an inhomogeneous medium, such as biological tissue. The result is a diffused and smeared light pattern even from the most focused laser beam. Such scattering-induced distortions are one of the major limitations in many applications, from astronomy to microscopy. Focusing light through scattering media is even more challenging when ultrashort pulses are considered, as the scattering distorts the pulses in both space and time. Understanding and correcting the spatiotemporal distortions is crucial when nonlinear processes are involved, as these processes are sensitive to the pulse temporal shape. This applies to applications such as multiphoton microscopy, nanosurgery, micromachining and quantum coherent control experiments.

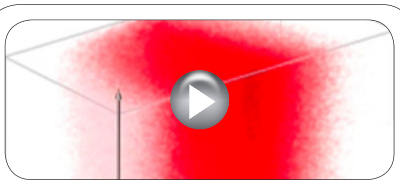
In recent years, the challenge of correcting scattering-induced spatial distortions has been the focus of many works in the fields of adaptive optics and wavefront shaping.[1,2] However, despite previous achievements, the simultaneous correction of the temporal distortions of ultrashort pulses has only been addressed this year.

In our recent work,[3] we have tackled exactly this question—namely, can one engineer an ultrashort optical pulse that will focus in both space and time through a scattering medium? In a set of experiments using 100 fs-long infrared pulses we have shown that this goal is achievable. Moreover, we have discovered that one can correct both spatial and temporal distortions by manipulating only the incident wavefront's spatial degrees of freedom. The reason behind this surprising result is that multiple scattering couples the spatial and temporal degrees of freedom by introducing path-length differences between the scattered photons, similar to how scattering from a grating couples the spatial and spectral degrees of freedom in a conventional femtosecond pulse-shaper. Such coupling is extensively utilized by time-reversal techniques in acoustics and radio frequency,[4] and has also been demonstrated this year by Aulbach et al.[5]



(a) Experimental setup for spatiotemporal focusing through scattering media;[3] a 100 fs pulse is focused through a scattering medium by controlling its wavefront with a 2-D SLM. Spatiotemporal focusing is obtained by optimizing a two-photon fluorescence (2PF) signal at a selected point behind the medium. The optimized and non-optimized pulses are spatiotemporally characterized by 2PF autocorrelation using a Michelson interferometer. Images of the 2PF from the scattered field before (b) and after (c) optimization. Maps of the 1/e-width of the pulse temporal autocorrelation, before (d) and after (e) optimization, revealing the temporal compression around the optimization point. (F-band-pass filter).

In our experiments we have used a two-dimensional spatial light modulator to focus ultrashort pulses through scattering samples.[3] To correct spatial and temporal distortions, we have optimized the wavefront spatial phase to maximize a two-photon fluorescence (2PF) signal at a selected point behind the medium (a). Optimizing such a nonlinear signal (which is widely used in multiphoton microscopy) results in a refocused pulse in both space and time, and has even resulted in a compressed pulse which was shorter than the input pulse, when the latter was not Fourier limited. To prove that our optimization results in temporal compression in addition to the spatial focusing (b-c), we have used the 2PF to measure the temporal autocorrelation of the pulses across the entire field (d-e). We have demonstrated spatiotemporal focusing through various scattering samples, from 1 mm-thick brain tissue to turbid bone samples. Our results open up new possibilities for optical manipulation and nonlinear imaging in scattering media. ▲



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Refe0rences

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