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Synthesis of Ultrafast Spatiotemporal Pulses

RESEARCHERS

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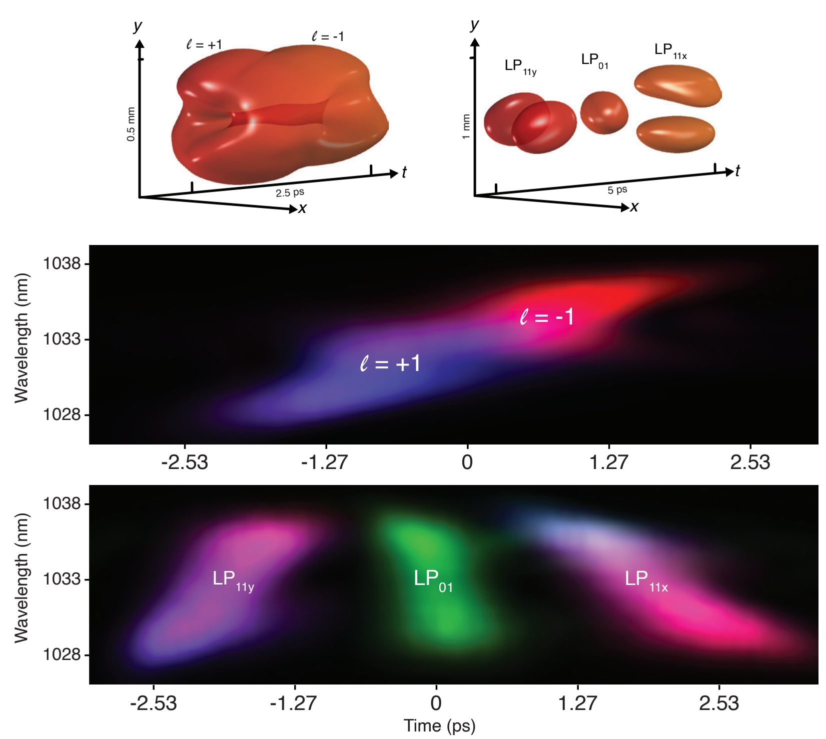
Since the inception of the laser, a long-standing goal has been control of all degrees of freedom of light at will. Until recently, spatial manipulation and temporal manipulation of light were mainly pursued independently. In recent years, space-time wavepackets have been synthesized, featuring specific correlations among the various degrees of freedom—for example, localized spatiotemporal structures that travel rigidly in free space,[1] space-time vortices,[2] pulses with topological spectral correlations[3] or time-reversed optical waves.[4] However, the ability to independently tailor all spatial and temporal dimensions remains an open challenge.

In recent work,[5] we demonstrated a versatile approach to synthesizing convoluted ultrafast light structures in which the spatial and temporal dimensions can be precisely correlated on demand. We developed an experimental platform that sequentially but synergistically shapes the temporal and spatial properties of a 180-fs laser source (approximately 6-nm FWHM) centered at around 1030 nm.

In the first stage, the initial pulse enters a 2D Fourier transform pulse shaper, enabling us to generate an array of Gaussian beams, each with an independent spectral/temporal modulation, that can be tailored on demand. In the second stage, a multiplane conversion system transforms the linear array of Gaussian beams into a set of copropagating 2D spatial modes. Each mode has an independent transverse profile that can be changed on demand. This powerful scheme maintains the spatial and temporal coherence of the electromagnetic field, thereby allowing the incoming laser pulse to be shaped in all dimensions.

To demonstrate the capabilities of our space-time pulse shaper, we generated a linearly chirped pulse with time-varying angular momentum that changed from $\ell = +1$ to $\ell = -1$ in approximately 2 ps. At the same time, we generated a sequence of three 1-ps-long pulses, each with a different transverse spatial mode, frequency chirp, central frequency and time delay. We observed the generated spatiotemporal pulses by developing a tomographic method capable of reconstructing their complex field structure in space and time. These examples constitute the first experimental demonstration of reconfigurable 3D synthesis of ultrafast optical wavepackets with on-demand tailored and correlated spatiotemporal properties.

These tailored spatiotemporal wavepackets can help control and optimize laser–matter interactions; enable pulse transmission in media with chromatic dispersion; and facilitate time-resolved studies of electronic transport in semiconductors and heterostructures. Consequently, we believe these new advances in sculpting light in space and time offer unprecedented opportunities in diverse areas of science and technology, ranging from extreme nonlinear optics and quantum networks to new families of multimodal ultrafast fiber amplifiers. OPN



Measured iso-intensity profile (top) and corresponding spectro-temporal map (bottom) of the generated spatiotemporal wavepackets.