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## Taming light in all dimensions

Pierre B ejot and Bertrand Kibler

*A combination of state-of-the-art temporal and spatial shaping techniques enables shaping pulsed laser light in all dimensions in a correlated manner, paving the way for new classes of on-demand space-time wavepackets.*

Manipulating all degrees of freedom of light at will has been a long standing aim since the early days of laser science, mainly motivated by the desire to control and optimise laser-matter interaction [1-2]. The ability to tailor arbitrary space-time optical waveforms is key in many areas of science, such as microscopy, astronomy, quantum computing, telecommunications, polaritonics and plasmonics, among others. Until recently, the manipulation of the spatial and temporal characteristics of light were mainly pursued independently. As a result, experimental efforts have mainly focused on synthesizing laser light shaped separately in time or in space (e.g., pulsed beams whose tailored spatial shapes are time-independent). Another class of tailored waves, non-separable space-time optical waveforms, has also been developed and sparked interest in the community. In this case, instead of having spatial and temporal degrees of freedom tailored separately, the packets are characterized by tight spatiotemporal correlations. These correlations provide unique features such as controllable superluminal or subluminal medium-independent group velocity [3], insensitivity to both diffraction and dispersion in bulk media or waveguides [4] and space-time optical vortices [5], but still lack the ability to independently tailor all spatial and temporal dimensions.

Now, writing in *Nature Photonics* [6], Cruz-Delgado and colleagues report on the production of full three-dimensional space-time wavepackets, a significant advance in manipulating space-time electromagnetic wavepackets in all dimensions.

Up to now, state-of-the-art spatiotemporal shaping techniques have been limited to tailoring wavepackets over two dimensions, one spatial dimension and time. Space-time light sheets [7] conical waves [8] and space-time optical vortices [9] are some examples of such 2D space-time coupled optical waveforms. The synthesis of these light structures relies on the same architecture of temporal pulse shapers. Briefly, in a standard temporal pulse shaper, the frequencies of the incoming laser pulse are first spatially dispersed by a grating and then collimated by a cylindrical lens. A one-dimensional spatial light modulator (SLM) placed in the Fourier plane of the lens applies a programmable phase modulation that tailors the spectral phase of the pulse as well as amplitude or polarization, if two SLMs are used [10]. Finally, the different spectral components are recombined. If one wants to generate 2D-shaped space-time wavepackets, the 1D SLM can be replaced by a 2D modulator, which allows independent manipulation of the vertical spatial phase of each frequency component. However, this technique suffers from a critical limitation. Since one spatial dimension is used to map the pulse spectrum, no spatial shaping can be applied over this dimension, thus restricting the setup to bi-dimensional space-time wavepacket manipulation. Consequently, a full three-dimensional space-time control is likely to remain out-of-reach with this method.

In their work, Cruz-Delgado and colleagues combine a 2D pulse shaper with a spatial mode multiplexer borrowed from telecommunication systems and based on multi-plane light conversion (MPLC) [11]. The MPLC is capable of converting a linear array of Gaussian

beams into a set of co-propagating two-dimensional spatial modes [12]. A schematic representation of the whole two-stage shaping system is displayed in Fig.1. The first module (on-demand 2D pulse shaper in Fig. 1) is composed of a diffraction grating, a cylindrical lens, and a bi-dimensional reflective SLM. This stage is used to imprint a spectral phase profile in the direction along which the pulse spectrum is spread. At the same time, this first module differentially steers the frequencies along a set of vertical positions. Thus, at the output of this module, the field is composed of a set of  $N$  temporally shaped pulses centered at different frequencies  $\omega_k$ , with Gaussian spatial distributions and evenly spread along a vertical array of given positions  $y_k$ . After passing through relay lenses, the field is sent to the second module to engineer the spatial phases and amplitudes of the  $N$  sub-pulses. When entering the second shaping device (On-demand multiplate 2D spatial mapping device in Fig. 1), the light bounces back and forth between an SLM and a mirror that face each other. At each reflection on the SLM, a spatial phase is imparted, thus gradually morphing the 2D-field. After six bounces, thanks to a careful design of the six holograms on the SLM, a Gaussian beam at any given vertical coordinate  $y_k$  is adiabatically transformed into a specific Hermite-Gaussian mode at the output of the MPLC. The fact that the combination of the two devices maintains the spatial and temporal coherence of the electromagnetic field allows engineering an incoming laser pulse in all dimensions. The generated wavepacket can be reconfigured on-demand both in time and space by modifying the spectral phases applied to the  $N$  sub-pulses and by steering them at different positions  $y_k$  with the first module.

In a series of experiments, the authors demonstrate the capabilities of their synthesizer by producing and characterizing (with a time-resolved interferometric technique) a linearly polarized pulse embedding a time-varying longitudinal angular momentum, changing from  $l = 1$  to  $l = -1$  in approximately 2 ps or a sequence of three 1 ps-long pulses, each assigned to a different linearly polarized (LP) spatial mode with a distinct frequency chirp (see inset in Fig. 1). These two examples constitute the first experimental demonstration to date of reconfigurable 3D synthesis of ultrafast optical wavepackets with tailored and correlated spatiotemporal properties.

Taming light in all dimensions opens very exciting perspectives over a wide range of photonics applications and beyond, thanks to the control of light-matter interaction or analogous wave dynamics in other branches of physics. It holds promises for unprecedented capabilities in classical and quantum optics as this tool could be useful in the next generation of smart lasers and multimodal linear/nonlinear optical systems. Tailored wavepackets can also aid in the study of nonlinear inverse-propagation studies in free-space, bulk and multimode waveguides for designing complex space-time input electromagnetic fields that optimally transform into the desired target output. In another domain, space-time wavepackets could also be used in time-resolved study of nonlocal effects, such as electronic transport properties in metal, semi-conductors, plasmas or hetero-structures.

Despite these exciting opportunities, there still remain outstanding challenges, such as a further increase of the tailoring capability of the device or a complete integration over more compact fiber or waveguide platforms. Since electromagnetic radiation is intrinsically vectorial, the polarization of light is another degree of freedom that can be tailored both in space and time. Generating space-polarization or time-polarization correlated optical fields is a very active field of research that has led to the development of concepts such as vector beams [13], optical centrifuge [14] or time-twisted linear polarization [15], to name a few. Being able to simultaneously tailor at will all degrees of freedom of vectorial optical fields in a correlated manner will be the next step in producing even “smarter” light objects in the future.

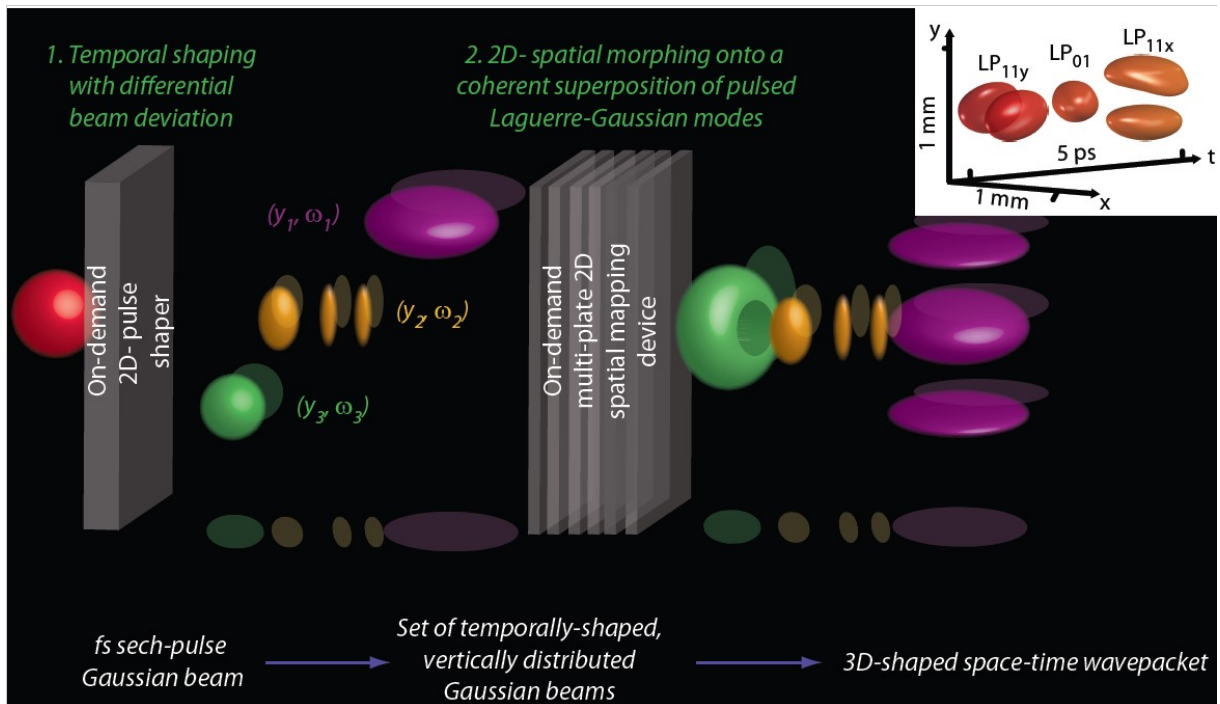


Figure 1: Schematic of the setup employed for the 3D synthesis of ultrafast optical wavepackets. The inset shows an example of space-time wavepacket generated in [6].

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#### **Ethics declaration**

Competing interests

The authors declare no competing interests