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Demonstration of propagation-invariant 3D space-time wave packets

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Abstract. We present the first demonstration of propagation-invariant space-time (ST) wave packets localized in all dimensions - 2D space and 1D time. By introducing orbital-angular-momentum into the wave packets, we produce propagation-invariant ST-OAM wave packets traveling at arbitrary group velocities. Our results show 4× improvement in propagation distance of 3D ST wave packets compared with a separable Bessel beam having similar spatial bandwidth.

1 Introduction

Creating a localized bundle of energy overcoming diffraction and dispersion has been a long-standing challenge in optics [1]. Previous solutions include optical solitons that require a nonlinear medium, or waveguides that combat diffraction but introduce dispersion [1]. Hence, there has been a significant interest in so-called 'propagation-invariant' optical fields that propagate freely without suffering diffraction or dispersion [3]. In 1983 Brittingham proposed 'focus wave modes' (FWM) – a self-similarly propagating pulsed field in free space traveling ata group velocity equal to the speed of light c [2], which led to subsequent discoveries of other propagation-invariant wave packets. However, synthesizing such wave packets requires introducing spectrally precise non-differentiable angular dispersion (AD) in two transverse dimensions, a capability that has eluded optics to date. Consequently, with the exception of X-waves that are AD-free, no propagation-invariant optical wave packets that are localized in all dimensions have been observed in free space [3]. The challenge of introducing arbitrary AD into a generic pulsed beam along *one* transverse dimension has enabled the realization of space-time (ST) wave packets in the form of light sheets [4], which exhibit a broad host of sought-after effects [5]. Here, we demonstrate a spatio-temporal spectral modulation strategy that efficiently produces arbitrary yet precise AD in two transverse dimensions, and thus yields ST wave packets localized in all dimensions [6].

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2 Concept

Space-time (ST) wave packets are pulsed beams in which each spatial frequency is assigned to a single wavelength, thus resulting in propagation invariance at an arbitrary group velocity [4–6]. The spectral support for a propagation-invariant ST wave packet is a 1D conic section at the intersection of the light-cone $k_r^2+k_z^2=(\frac{\omega}{c})^2$ with

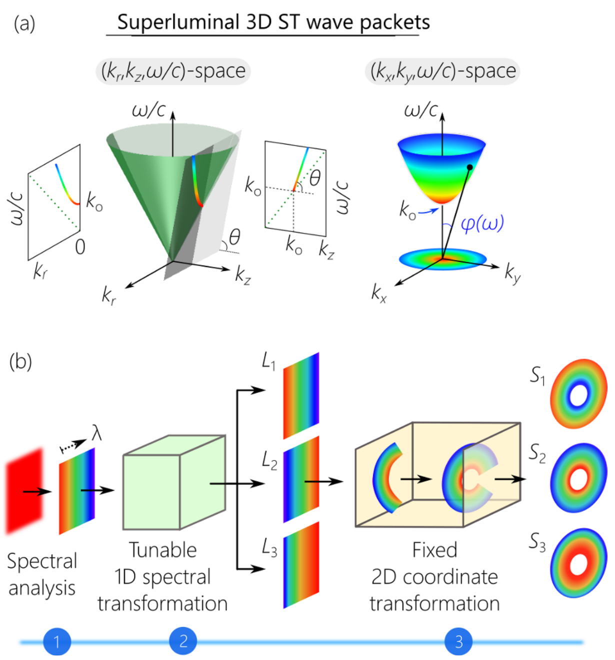

Figure 1. (a) Visualization of the spectral support domain for 3D ST wave packets on the surface of the free-space light-cone. (b) Three-stage synthesis scheme for 3D ST wave packets.

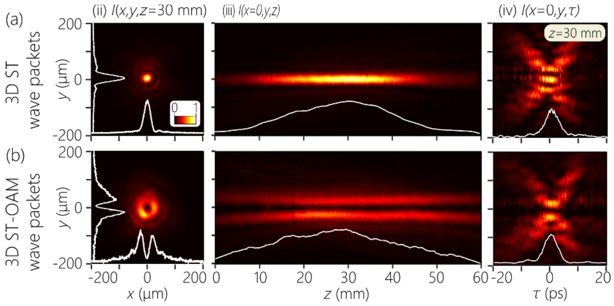

Figure 2. Measurement results for (a) superluminal 3D ST wave packets ($\widetilde{v} = 1.8c$) and (b) for a superluminal ($\widetilde{v} = 1.3c$) wave packet endowed with the OAM mode $\ell = 1$. In the first column, we plot the measured transverse intensity $I(x, y, z)$ at $z = 30$ mm, in addition to sections through $x = 0$ and $y = 0$ (white curves); and, in the second, we plot the measured intensity in a meridional plane $I(0, y, z)$. The white curve at the bottom of the panel in the third column is the on-axis intensity $I(0, 0, z)$ in (a) and $y = 30\,\mu$m in (b). In the third column we plot the measured $I(0, y, z; \tau)$ at $z = 30$ mm; For both cases, $\Delta\lambda = 0.3$ nm, the pulse width is ≈ 6 ps and the transverse beam size is $\approx 30\,\mu$m.

a spectral plane $\Omega = (k_z - k_o)c\tan\theta$, whose projection onto the $(k_z, \frac{\omega}{c})$-plane is a straight line making an angle θ (the spectral tilt angle) with the k_z-axis; here $k_r = \sqrt{k_x^2 + k_y^2}$ is the radial component of the transverse wave vector, k_z is the axial wave number, and ω is the angular frequency; $\Omega = \omega - \omega_o$, ω_o is the central frequency, and $k_o = \frac{\omega_o}{c}$ is the corresponding wave number [Fig.1(a)]. A wave-packet incorporating such a spatio-temporal spectral structure is localized in all dimensions and travels rigidly in free space.

3 Experimental setup

The synthesis scheme for 3D ST wave packets is implemented in three stages [Fig. 1(b)]. In the first stage, the spectrum of a generic plane-wave pulse from a Ti:Sapphire laser (100-fs pulse at $\lambda = 800$ nm) is spatially resolved along one dimension after a double-pass through a volume chirped Bragg grating (OptiGrate, L1-021) [7]. In the second stage, a spectral transformation ‘reshuffles’ the wavelengths into a prescribed sequence, which is performed by making use of a pair of spatial light modulators (SLM, Meadowlark 1920×1152 series). In the third stage, a log-polar-to-Cartesian conformal coordinate transformation converts the spatial locus of each wavelength from a line into a circle [8]. A lens finally converts the spectrally resolved wave front into a 3D ST wave packet localized in all three dimensions. By modulating the spatio-temporal spectral structure, we realize group velocities extending from the subluminal to the superluminal regimes over the range from $0.7c$ to $1.8c$.

Moreover, by providing access to both transverse dimensions in a ST wave packet, degrees of freedom that cannot be accessed in only one transverse dimension, such as orbital angular momentum (OAM), can now be included. We characterize the synthesized field first in the Fourier domain (k_x, k_y) by scanning the fiber tip connected to spectrum analyzer along the radial direction. Then we record the axial evolution of the time-averaged intensity measurements by scanning a CCD camera along the propagation axis z. Moreover, the time-resolved wave packet envelope is reconstructed using linear interferometry with the initial pulses used as a reference [5]. Finally, the complex field profile is recorded by exploiting off-axis digital holography (see [6] for more details).

4 Results

In Fig. 2(a) we present the measurement results for 3D ST wave packets travelling at a superluminal group velocity $\widetilde{v} \approx 1.8c$. The measured transverse intensity profile $I(x, y, z = 30$ mm) shown in column (i) confirms the localization along both transverse spatial dimensions. The measured axial evolution of the time-averaged intensity $I(x = 0, y, z)$ depicted in column (ii) confirms the diffraction-free propagation over a distance of $L_{\max} \approx 55$ mm, which corresponds to a 4× improvement compared with the separable Bessel beam and a 60× improvement compared with a Gaussian beam of the same spatial bandwidth. Lastly, in column (iii) we plot the time-resolved measurements $I(x = 0, y, \tau, z = 30$ mm), which reveal clearly the expected X-shaped profile that remains invariant over the propagation distance $L_{\max}$. We observe a similar behavior for a superluminal ST-OAM wave packet ($\widetilde{v} = 1.3c$) with $\ell = 1$ in Fig. 2(b).

5 Conclusion

In conclusion we have presented the first experimental demonstration of ST wave packets localized in all dimensions. In addition, we demonstrate propagation-invariant pulsed OAM wave packets with controllable group velocity in free space. Such 3D ST wave packets that are fully localized in all dimensions have potential uses in areas such as free-space optical communications, imaging, and nonlinear optics.

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