Generation of Self-Dual Lorentz-Invariant Axionic Toroidal Light Pulses

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We report on the generation and characterization of self-dual Lorentz-invariant optical pulses of toroidal topology exhibiting spin-orbit coupling and $\boldsymbol{E} \cdot \boldsymbol{B} \neq \mathbf{0}$, that are of interest to axion electrodynamics, telecommunications, spectroscopy, and particle acceleration.

Axion electrodynamics is attracting growing research interest as it provides a framework for searching for the axion, a potential candidate for dark matter that could also solve the strong CP problem in quantum chromodynamics. The proposed axions couple to exotic electromagnetic fields with parallel electric and magnetic field components, which could allow for their detection through interactions with light.

Here, we demonstrate experimentally toroidal optical pulses exhibiting parallel longitudinal electric and magnetic fields resulting in a non-zero fundamental Lorentz invariant $\boldsymbol{E} \cdot \boldsymbol{B}$. Such field configurations are ideal for probing magnetoelectric phenomena and axion electrodynamics, where $\boldsymbol{E} \cdot \boldsymbol{B}$ can act as an axion source. Further, the generated pulses carry orbital angular momentum (OAM) and are self-dual with electromagnetic fields related by $\boldsymbol{E} = \pm i\boldsymbol{B}$. Thus, they are invariant under electromagnetic duality ($\boldsymbol{E} \leftrightarrow \boldsymbol{B}, \boldsymbol{B} \leftrightarrow -\boldsymbol{E}$), as well as under rotation-free Lorentz transformations (boosts) along the propagation direction.

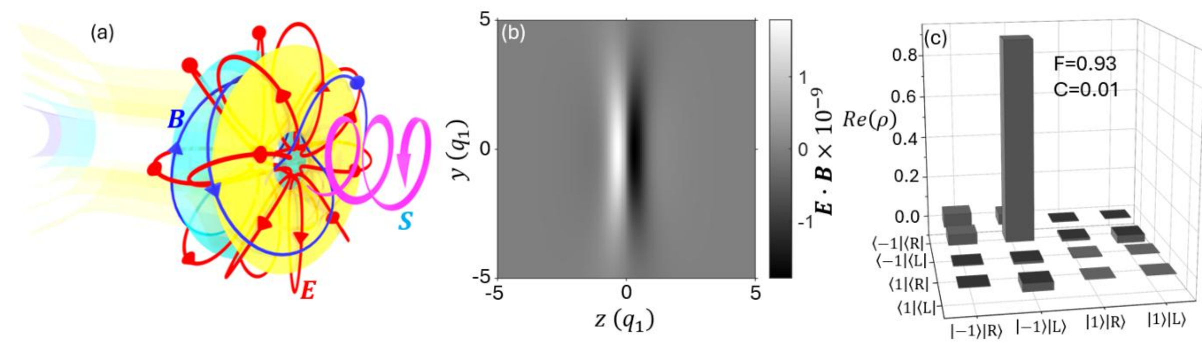

Fig. 1. (a) Conceptual illustration of a self-dual toroidal pulse. Red arrows represent the electric field, $\boldsymbol{E}$, blue arrows represent the magnetic field, $\boldsymbol{B}$, and the magenta helical arrow represents the Poynting vector, $\boldsymbol{S}$. (b) Plot of $\boldsymbol{E} \cdot \boldsymbol{B}$ at x=0, t=0. (c) Experimental density matrix for generated self-dual toroidal pulse with orbital angular momentum $\ell = -1$. The fidelity, 0<F<1, with respect to the ideal pulse is F=0.93, indicating high similarity. The concurrence is C=0.01, indicating very low space-polarization nonseparability.

The generation scheme for self-dual toroidal pulses was based on the conversion of near-infrared 10 fs laser pulses (centered at 800 nm) upon propagation through a segmented waveplate. The axes of the waveplate crystal vary along its circumference (over 8 segments), which allows the conversion of incident horizontally (vertically) linearly polarized pulses to radially (azimuthally) polarized toroidal pulses. Incident circularly polarized pulses result in a superposition of radially and azimuthally polarized pulses and thus to the generation of self-dual toroidal pulses with longitudinal electric and magnetic fields. The generated pulses were characterized by space-polarization tomography decomposing the pulse into a series of modes with different polarization and orbital angular momentum states. Experimental results showed that the generated pulse corresponded very closely to that of ideal self-dual toroidal pulse with a fidelity of F=0.93.

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