State Tomography of Complex Electromagnetic Pulses

Luka Vignjevic[1], **Yijie Shen**[1], **Shankar Pidishety**[1], **Nikitas Papasimakis**[1], **Nikolay Zheludev**[1,2]
1. *Optoelectronics Research Centre & Centre for Photonic Metamaterials, University of Southampton, SO17 1BJ, UK*
2. *Centre for Disruptive Photonic Technologies, Nanyang Technological University, Singapore 637371, Singapore*

We present a new approach to characterising complex transient electromagnetic excitations and experimentally demonstrate it on light pulses of toroidal topology quantifying their space-polarization and space-frequency nonseparability and fidelity with respect to theoretical expectations.

Spurred by recent advances in topological optics and in our ability to control the spatiotemporal structured light, topologically structured pulses are attracting growing attention promising applications in the fields of spectroscopy, information and energy transfer, and manufacturing-by-light to name a few. Such electromagnetic waveforms are non-separable with coupling between different degrees of freedom, which is inherently linked to their topological structure. For instance, vector beams exhibit space-polarization non-separability, while the skyrmion-like Toroidal Light Pulses (termed also Flying Doughnuts) are non-separable both in terms of space-polarization and space-time (or equivalently space-frequency). Here, we introduce a state tomography technique that allows to characterize the space-frequency and space-polarization non-separability of toroidal pulses and quantify their quality with respect to their ideal form.

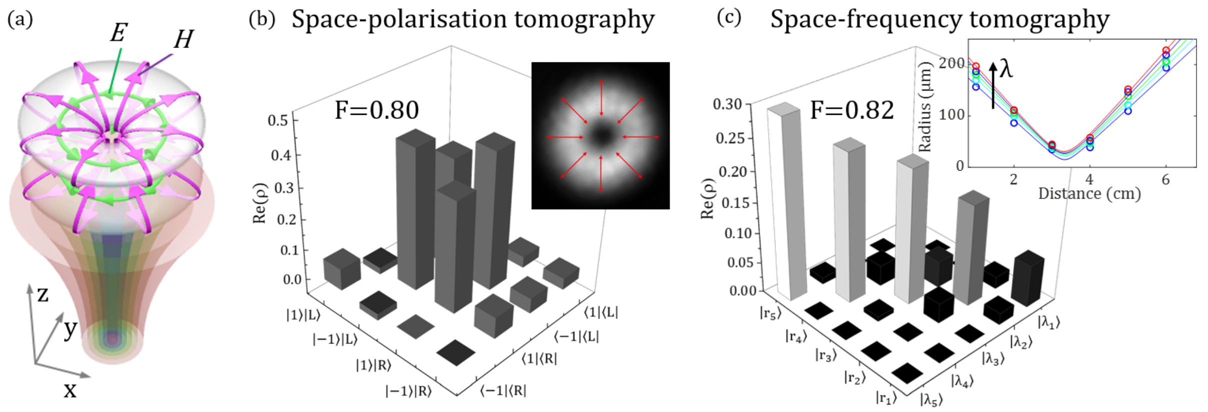

Fig. 1 (a) Schematic of toroidal light pulse field topology. (b) Density matrix in space and polarisation degrees of freedom of a toroidal light pulse. Inset: Experimentally characterized toroidal pulse with red arrows indicating polarization. (c) Density matrix in space and frequency degrees of freedom. Inset: Propagation of monochromatic components of the pulse as represented by the position in the transverse plane of the corresponding intensity maxima.

The tomography technique presented here decomposes a toroidal light pulse to monochromatic radially polarized beams (Fig.1a) and characterizes the polarization and propagation properties of each component, which in turn allows to evaluate the space-polarization and space-frequency non-separability respectively. We applied this tomography approach to experimentally generated radially polarized doughnut-shaped pulses centered at 800 nm with a bandwidth of 100 nm. Firstly, we used bandpass spectral filters (bandwidth in the range 5 to 10 nm) to isolate the monochromatic components of the pulse. Then, a pair of waveplates and a linear polariser were used to perform polarization projections onto orthogonal polarisation states, while a digital micromirror device was used for spatial mode projections. Based on the measured results of an overcomplete set of intensities recorded from these tandem projections, we can reconstruct a density matrix to characterize the full information of the vector beam component and calculate the fidelity (F=0.80) with reference to the ideal form of the pulse (Fig.1b). In parallel, space-frequency coupling was investigated by tracking the transverse position of monochromatic components of the pulse upon propagation (Fig.1c). In the case of space-frequency, the fidelity was 0.82 indicating high degree of similarity to the ideal pulse.