Propagating Electromagnetic Skyrmions

Yijie Shen[1], **Nikitas Papasimakis**[1], **Nikolay I. Zheludev**[1,2]

1. Optoelectronics Research Centre & Centre for Photonic Metamaterials, University of Southampton, Southampton SO17 1BJ, UK

2. Centre for Disruptive Photonic Technologies & TPI, SPMS, Nanyang Technological University, Singapore 637371, Singapore

Abstract: We report on a new family of light pulses of toroidal topology - the exact solutions of Maxwell's equation - with skyrmionic field structure, termed Supertoroidal Light Pulses.

We recently demonstrated the generation of the Flying Doughnut, a few-cycle pulse of toroidal topology with space-time non-separable structure, discovered by Hellwarth and Nouchi in 1996. Here we show that a generalized family of toroidal pulses, termed Supertoroidal Light Pulses (STLPs) [2], of which the Flying Doughnut is the fundamental member, allows for skyrmion-like electromagnetic field configurations in propagating pulses. We demonstrate different types of skyrmionic fields of different topological numbers within a single focused STLP.

The propagation dynamics and topological structure of STLPs are controlled by the effective wavelength q_1, Rayleigh range q_2, and a real dimensionless parameter $\alpha \geqslant 1$. A typical example is shown in Fig. 1(a) for an STLP with α=5 and q_2=100q_1 coming in and out of focus. At focus, the STLP presents a complex topological structure with multiple magnetic field singularities including vortex rings and saddle points (see Fig. 1(b)). The combination of saddle points with vortex rings results in multiple skyrmionic patterns in the transverse plane (xy-plane in Fig. 1). Examples of such patterns are shown in Fig. 1(d), where two distinct types of skyrmionic configurations can be observed. We characterize the topology of such configurations by the topological charge s, vorticity m and helicity γ, which are typically used to describe skyrmions. The topological numbers of the skyrmionic fields of Fig. 1d are (s,m,γ) = (1,1,π) and (1,1,0) for left and right panels, respectively. At different positions of the pulse we can observe additional skyrmionic configurations with (s,m,γ) = (1,1,π), (-1,1,π), (-1,1,0) and (1,1,0), respectively. The evolution of the skyrmionic patterns and the role of space-time non-separability will be discussed at the conference.

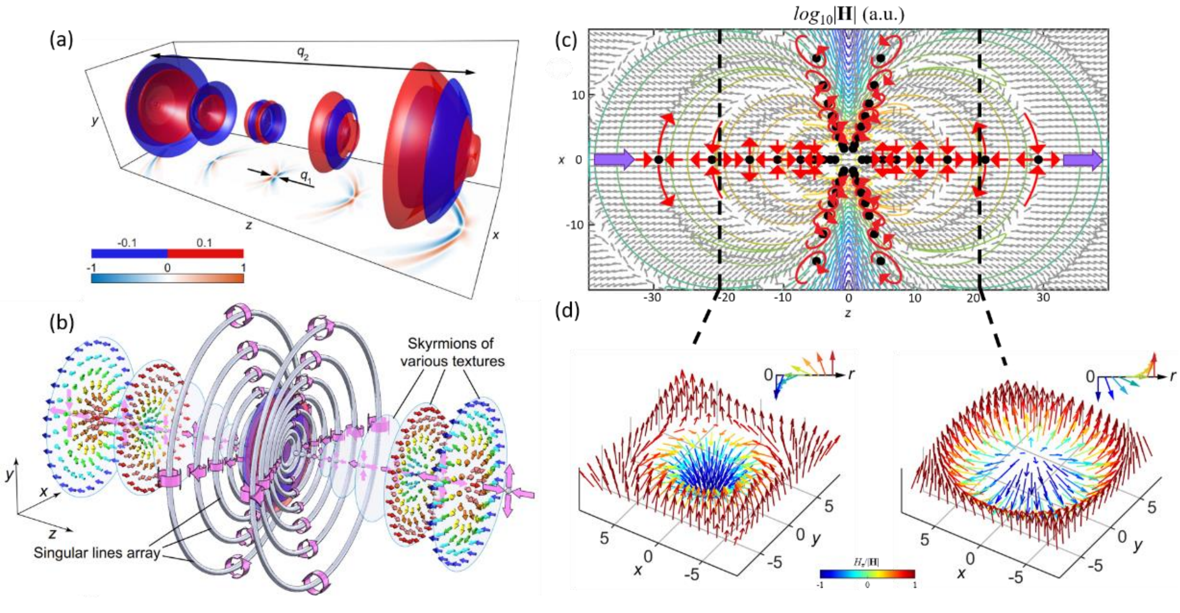

Fig. 1 (a) Isosurfaces for the electric field of a STLP with α=5 and $q_2 = 100q_1$, at t = 0, $\pm q_2/(4c)$, and $\pm q_2/(2c)$. Projections on the xz-plane correspond to cross-sections of the electric field at y = 0. (b) Illustration of the topological structure of the STLP at focus. Gray dots and rings represent singularities (saddle points and vortex rings) in magnetic field, while large magenta arrows indicate magnetic field direction. Colored arrow patterns show skyrmion patterns of the magnetic field on the transverse plane. (c) Magnetic field amplitude (contour plot) and direction (arrow plot) in the *x-z* plane at focus for a STLP with α=10. Black dots mark magnetic field singularities, while red arrows indicate singularity type (saddle or vortex). Purple arrows show the direction of pulse propagation. (d) Skyrmionic patterns in the transverse plane of the STLP presented in (c) at z=±20. Unit of length is q_1.

References

[1] A. Zdagkas, Y. Shen, C. McDonnell, J. Deng, G. Li, T. Ellenbogen, N. Papasimakis, N. I. Zeludev, "Observation of toroidal light pulses," arXiv:2102.03636 [physics.optics] (2021).

[2] Y. Shen, Y. Hou, N. Papasimakis, and N. I. Zheludev, "Supertoroidal light pulses as electromagnetic skyrmions propagating in free space," Nat. Commun. 12, 5891 (2021).