Flying Electromagnetic Toroids: propagation properties and light-matter interactions

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Abstract: We report on the study of the time-space localized solutions to Maxwell's equations with toroidal topology that have intriguing properties and interact with interfaces and nanostructures in a peculiar fashion.

The 'Focused Doughnut' (FD) pulse is an exact, finite-energy electromagnetic perturbation with a unique spatio-temporal structure that is toroidal in character (Fig. 1) [1]. In contrast to conventional electromagnetic pulses, the FD pulse exists purely in a single-cycle form with 3-dimensional, polynomial energy localisation. The single-cycle nature of the pulse results in an ultra-broadband pulse spectrum. Moreover, the spatial dependence of the pulse is inseparable from its temporal dependence. In addition, the toroidal topology of the pulse gives rise to significant longitudinal field components at the pulse centre aligned parallel to the axis of propagation, which has been shown to have potential for particle acceleration [1]. Although the FD pulse has remained a theoretical curiosity since their first prediction [1,2], successful experimental realisation could lead to its use in a variety of applications, such as microscopy, communications, directed energy transfer, spectroscopy and particle trapping and acceleration. A further point of interest is the topological similarities between the FD pulse and the near-field configuration of the toroidal dipole – a burgeoning field in electrodynamics [3]. As such, here we present the comprehensive study of the FD pulse, utilising finite-element modelling for the first time to examine the properties and propagation dynamics of these pulses (Fig. 2).

The complex field topology of the FD pulse, encompassing transverse and longitudinal fields and space-time non-separability, is expected to result in unique light-matter interactions [1]. We provide a full evaluation of the transformations the pulse undergoes when interacting with dielectric and metallic interfaces. This has revealed the intriguing behaviour of both the TE and TM pulses under reflection, with respect to the reversal of the azimuthal and radial field components. Furthermore, the interactions of FDs with small dielectric and plasmonic particles are considered, where the broadband nature and complex field topology of the pulses is expected to play a significant role in mode excitation. Possible experimental realisations of these complex electromagnetic perturbations resulting from the theoretical/computational treatment presented here will be discussed.

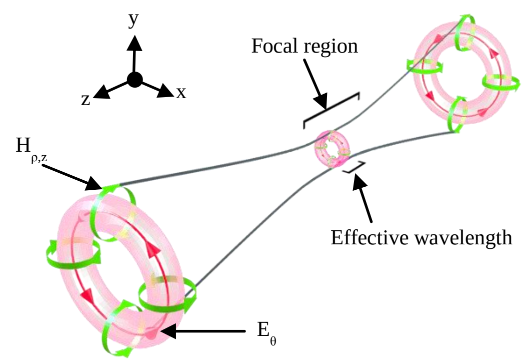

Fig. 1. Illustration of the field topology and focusing properties of the TE FD pulse. The pulse propagates along the *z* direction.

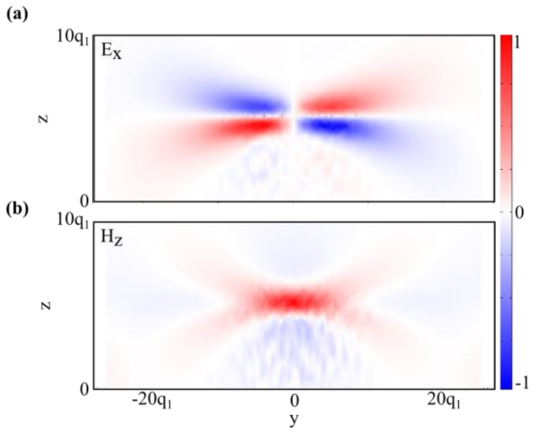

Fig. 2. The E_x (a) and H_z (b) fields of the TE FD pulse from finite element modelling (normalised to peak value). The parameter q_1 gives the effective wavelength.

References
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