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Propagating toroidal electromagnetic excitations and their interactions with metamaterials and nanostructures

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***Abstract* – We report on the electromagnetic properties of 'focused doughnuts' (FD), space-time localized solutions to Maxwell's equations with toroidal topology. We show that light-matter interactions of FD pulses, include non-trivial field transformations and broadband modal excitations.**

I. INTRODUCTION

The propagation of electromagnetic radiation in free-space is described by the homogenous Maxwell's equations. Well established solutions, such as infinite-energy plane wave, are widely used as approximations across the optics community. However, there also exists a family of exact solutions to the homogenous Maxwell's equations, which represent localized transmission of finite electromagnetic energy [1]. These exact solutions have been previously described as the classical analogue of a photon.

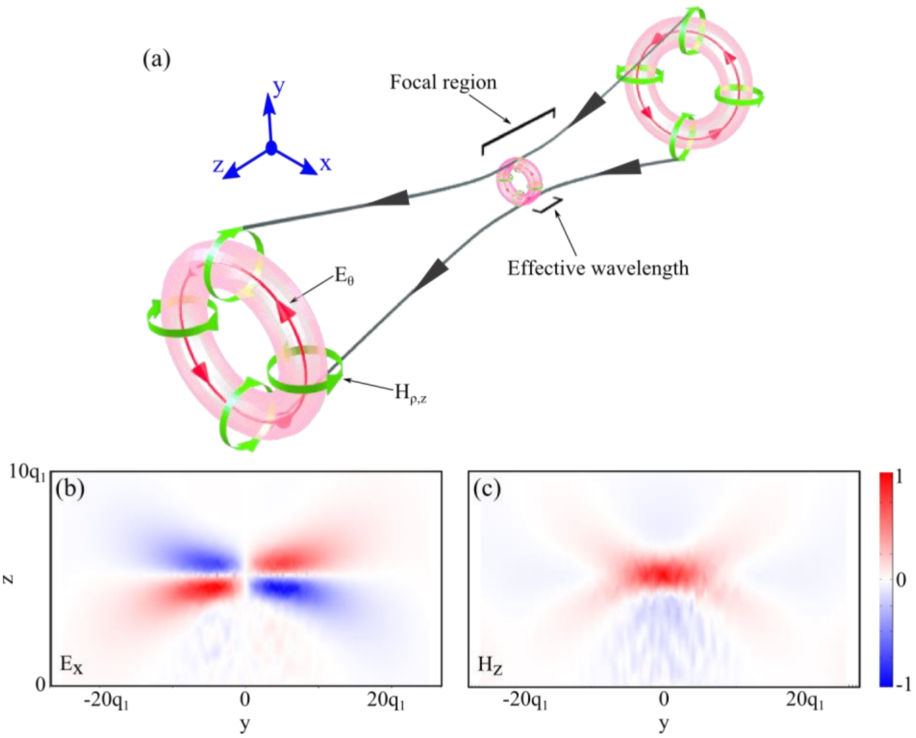

Fig. 1. (a) An illustration of the field topology and focusing properties of a TE FD pulse propagating along the *z*-axes, with the effective wavelength and focal region indicated. Panels (b) and (c) show respectively the E_x and H_z fields of the FD pulse from finite element modelling (normalised to peak value). The parameter q_1 gives the effective wavelength of the pulse.

One such solution is known as the 'Focused Doughnut' (FD) pulse – a peculiar single-cycle electromagnetic perturbation with a unique toroidal field topology and 3-dimensional, polynomial energy localisation [Fig.1 (a)] [2]. As a consequence of its single-cycle nature, the FD pulse is ultra-broadband. Furthermore, the temporal dependence of the pulse is inseparable from its spatial dependence, leading to significant variation of the frequency components across the spatial extent of the pulse. In addition, the toroidal topology of the pulse results in significant longitudinal field components aligned parallel or anti-parallel to the axis of propagation. This property has been shown to have the potential for particle acceleration [2].

An experimental realisation of the FD pulse could lead to its use in a variety of applications, including microscopy, communications, directed energy transfer, spectroscopy, particle trapping and acceleration. A different perspective arises from the burgeoning field of toroidal electrodynamics, owing to the topological similarities between the FD pulse and the near-field configuration of the toroidal dipole excitation [3]. As such, here we utilize a commercial 3-dimensional Maxwell's equation solver to present a comprehensive examination of the propagation dynamics and interactions of these complex electromagnetic perturbations with matter.

II. Simulations & Results

The simulations were conducted using the transient RF package of COMSOL 3.5a. We first show explicitly the toroidal topology, single-cycle nature and presence of longitudinal fields in our simulations of the FD. These are illustrated in Fig. 1 (b-c). We further present a full evaluation of the transformations the FD pulse undergoes when interacting with dielectric and metallic interfaces [Fig. 2 (a)]. This has revealed counterintuitive differences between the TE and TM pulses under reflection, related to the reversal of the azimuthal and radial field components.

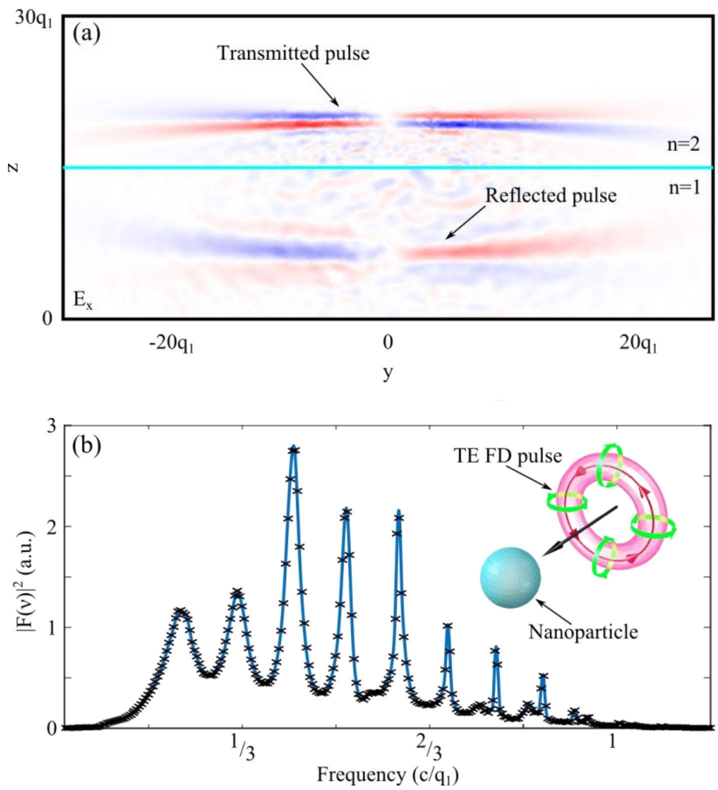

Fig. 2. Panel (a) shows the reflected and transmitted fields for a TE FD pulse after incidence on a semi-infinite dielectric boundary (n=2). Panel (b) shows the excitation spectrum for a non-dispersive, dielectric nanoparticle (r=q1) located at xyz=0, excited by a TE FD pulse at focus (z=0). The spectrum indicates a broad range of Mie modes excited within the nanoparticle.

In addition, we consider the light-matter interactions of the FD pulse when incident upon small dielectric and plasmonic nanoparticles [Fig. 2]. In this regime, it is expected that the complex field topology and the broadband nature of the pulse will play a significant role in modal excitation. Recent work has demonstrated several intriguing features of such excitations. This includes broad modal excitations within the nanostructures and distinct differences between interactions with TE and TM pulses. As a further point of interest, preliminary work has suggested the ability of these pulses to excite a non-negligible toroidal dipole mode in structures that do not possess toroidal symmetry.

III. Conclusion

We have provided an extensive study of the propagation dynamics and light-matter interactions of FD pulses including a study on the non-trivial changes in the field configurations from pulse reflection at semi-infinite interfaces, and the modal excitations of nanostructures. The excitation of more complex nanostructure geometries and the excitation of toroidal modes are a subject of ongoing investigation. Possible experimental realisations of these complex electromagnetic perturbations resulting from the theoretical/computational treatment presented here are also being investigated and will be discussed.

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