Interrogating nanoparticles with focused doughnuts

T. A. Raybould[1], V. A. Fedotov[1], N. Papasimakis[1], I. Youngs[2], and N. I. Zheludev[1,3]

[1]Optoelectronics Research Centre and Centre for Photonic Metamaterials, University of Southampton, SO171BJ, U.K.
[2]DSTL, Salisbury, U.K.
[3]Centre for Disruptive Photonic Technologies, Nanyang Technological University, Singapore

Abstract—

The propagation of electromagnetic radiation in free-space is described by the source-free Maxwells equations. In contrast to conventional solutions such as infinite-energy plane waves and Gaussian pulses, there exists a family of exact solutions which represent localised transmission of finite electromagnetic energy [1]. 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 [2]. Here, for the first time we present a comprehensive study of the FD pulse: we investigate the propagation dynamics and interactions of these complex electromagnetic pulses with homogeneous and structured media.

The FD pulse exhibits a number of intriguing properties. Its purely single-cycle nature results in an ultra-broadband frequency spectrum and a well defined spatial-chirp. In fact, 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 that hold potential for particle acceleration applications [2]. Although the FD pulse has remained a theoretical curiosity since its first prediction, successful experimental realisation could lead to its use in a variety of settings, such as microscopy, communications, directed energy transfer, spectroscopy, and particle trapping and acceleration. Further interest in the FD pulse stems 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].

The intriguing light-matter interactions of the FD pulse are examined from several perspectives. We present a full evaluation of the transformations the FD pulse undergoes due to interactions with dielectric and metallic interfaces. This has revealed the unusual 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. Recent work has demonstrated broad modal excitation within the nanostructures and distinct differences between the interaction with TE and TM pulses. Possible experimental realisations of these complex electromagnetic perturbations resulting from the theoretical/computational treatment presented here will be discussed.

ACKNOWLEDGMENT

The authors acknowledge support from DSTL, the Engineering and Physical Sciences Council, U.K. and the Leverhulme Trust.

REFERENCES

1. Ziolkowski, R., "Localised transmission of electromagnetic energy," *Phys. Rev. A*, Vol. 39, 2005–2033, 1989.
2. Hellwarth, R. W. and Nouchi, P., "Focused one-cycle electromagnetic pulses," *Phys. Rev. E*, Vol. 54, 889–895, 1996.
3. Kaelberer, T. et al, "Toroidal dipolar response in a metamaterial," *Science*, Vol. 330, 1510–1512, 2010.