Interaction of Flying Electromagnetic Doughnut with Nanostructures

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

[1]*Optoelectronics Research Centre and Centre for Photonic Metamaterials, University of Southampton, Southampton SO17 1BJ, UK*
[2]*DSTL, Salisbury, SP4 0JQ, UK*
[3]*Centre for Disruptive Photonic Technologies, Nanyang Technological University, Singapore*

Abstract: We report on the electromagnetic properties of the single-cycle "flying doughnut" electromagnetic permutations in the context of their interactions with nanoscale objects, such as dielectric and plasmonic nanoparticles.
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"Flying doughnut" (FD) pulses are finite-energy electromagnetic perturbations with a unique spatiotemporal structure that resembles a doughnut. Although they travel with the speed of light, as conventional electromagnetic pulses do, and can be focused in the same way, they exhibit a number of exciting properties: Within a FD pulse the magnetic (or electric) field in the centre of the perturbation is oriented along the direction of propagation, not perpendicular to it, as in a conventional electromagnetic pulse. Moreover they exist only as one-cycle pulses whose spatial dependence cannot be separated from the temporal dependence. In spite of the intriguing properties predicted over a decade ago [1,2], so far FD pulses have remained theoretical curiosities. Here we present the first comprehensive study of the propagation properties of such pulses and their interactions with nanostructured dielectrics and plasmonic metals.

As non-space-time separable solutions to Maxwell's equations, FD pulses can be classified in TE and TM field configurations, with the electric and magnetic fields in cylindrical coordinates *(ρ,θ,z)* for the TE case given by:

$$E_\theta = -4if_0\sqrt{\frac{\mu_0}{\varepsilon_0}}\frac{\rho(q_1+q_2-2ict)}{[\rho^2+(q_1+i\tau)(q_2-i\sigma)]^3},\ H_\rho = 4if_0\frac{\rho(q_2-q_1-2iz)}{[\rho^2+(q_1+i\tau)(q_2-i\sigma)]^3},\ H_z = -4f_0\frac{\rho^2-(q_1+i\tau)(q_2-i\sigma)}{[\rho^2+(q_1+i\tau)(q_2-i\sigma)]^3}, \qquad (1)$$

where $\sigma=z+ct$, $\tau=z-ct$, q_1 represents an effective wavelength for the pulse, q_2 quantifies the Rayleigh range and f_0 is an arbitrary normalization constant. Further separating real and imaginary parts of Eq. (1) yields two families of pulses, a 1 ½ cycle pulse and a single-cycle pulse, respectively. The TM solutions are readily obtained by interchanging electric and magnetic field components.

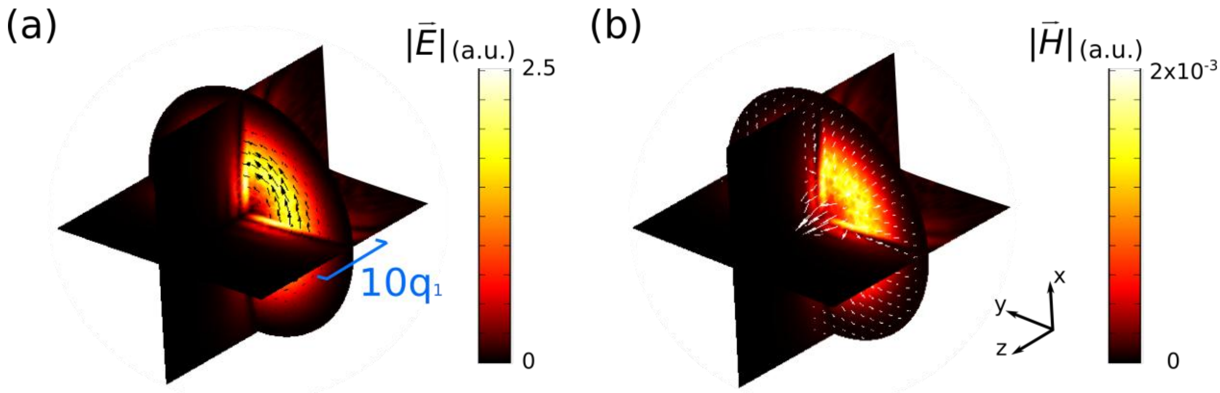

Figure 1: Field configuration of a single-cycle FD pulse propagating in free-space along the positive z-axis direction with $q_2=100q_1$. Colour maps are obtained by a commercial finite element solver and correspond to the modulus of the electric (a) and magnetic (b) field, while arrows mark the respective orientation of the fields.

Figure 1 presents a characteristic case of a TE single-cycle pulse propagating along the z-axis. Here the toroidal topology of the FD pulses is evident: the electric field is confined in a torus with its a axis parallel to the propagation direction and vanishes at the centre of the pulse. Within the torus, the electric field is azimuthally polarized aligned with the equatorial lines. On the other hand, the magnetic field is mainly concentrated at the central area of the pulse where it is oriented along the propagation direction. Off-axis, the magnetic field follows the meridians of the torus and circles around the electric field lines.

Due to the non-trivial field configuration of the (FD) pulses including circulating and longitudinal field components, single-cycle broadband nature, as well as non space-time seperability, it is expected that FD pulses can lead to unique light-matter interactions [2]. We have studied the propagation of FD pulses in dispersive and discontinuous media including dielectrics and metals. Of particular interest, is the interaction of FDs with plasmonic and dielectric interfaces and nanoparticles (see Fig. 2), where peculiar phenomena are expected. The intricacies and non-trivial manifestations of such interactions will be illustrated with the results of our simulations and discussed at the time of conference.

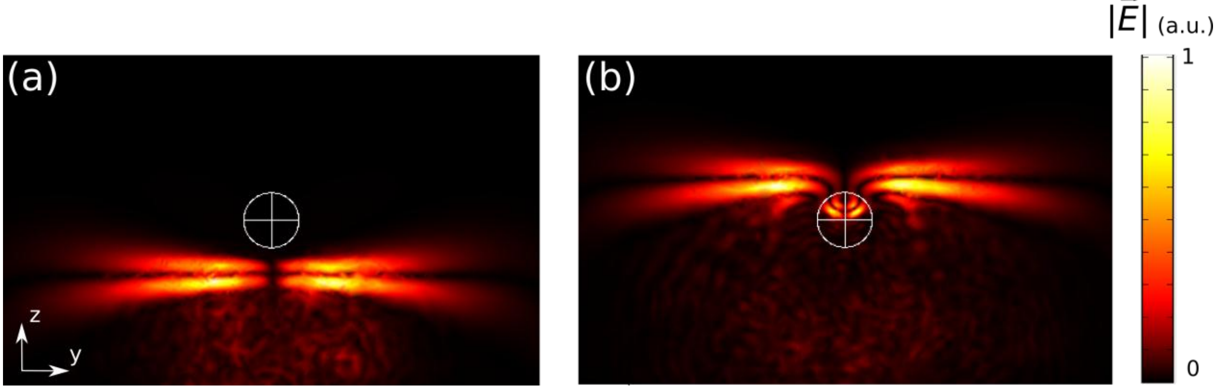

Figure 2: Finite element modeling of a single-cycle focused doughnut pulse interacting with a dielectric nanoparticle. Snapshots of the electric field modulus before the pulse reaches the nanoparticle (a) and while the pulse emerges from the nanoparticle (b). The parameters of the pulse are q_2=100q_1. The dielectric nanoparticle is described by a dispersion-less refractive index n=2. The pulse propagates along the positive y-axis.

References

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