Generation of Flying Electromagnetic Doughnuts via Spatiotemporal Conversion of Transverse Electromagnetic Pulses

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Abstract: We introduce a new class of metamaterials that allow simultaneous spatial and temporal control of electromagnetic waveforms and present for the first time the generation of flying doughnuts, single-cycle pulses of toroidal topology.

Flying doughnut (FD) pulses are exact solutions to Maxwell's equations, distinguished by a doughnut-like configuration of electric and magnetic fields, strong longitudinal field components along the propagation direction, and unique spatiotemporal coupling [1,2]. They are single-cycle, wide bandwidth pulses that propagate in free-space with the speed of light. In contrast to other families of pulses, their spatial and temporal dependence cannot be separated. FD pulses interact with matter in unique ways, including non-trivial field transformations upon reflection from interfaces and the excitation of strong toroidal response in dielectric particles [3].

Here we introduce a scheme for the generation of FDs based on spatially gradient metamaterial arrays. We employ a cylindrically symmetric metamaterial array (see schematic representation in Fig. 1a), reflecting the toroidal topology of the Flying Doughnut pulse. The spatiotemporal coupling is provided by varying the properties of the metamaterial elements across the array according to the parameters of the targeted FD pulse, the effective wavelength, q_1, and Rayleigh length, q_2. We consider illumination by a transverse, short, Gaussian pulse and calculate numerically the emitted electromagnetic fields. Similarly to ideal FD pulses, the generated pulse is of single-cycle duration and toroidal topology, as indicated by the electric field intensity profile of Fig. 1b. Importantly, the emitted pulse exhibits coupled spatial and temporal structure, with a spatially varying frequency spectrum (see inset to Fig. 1b).

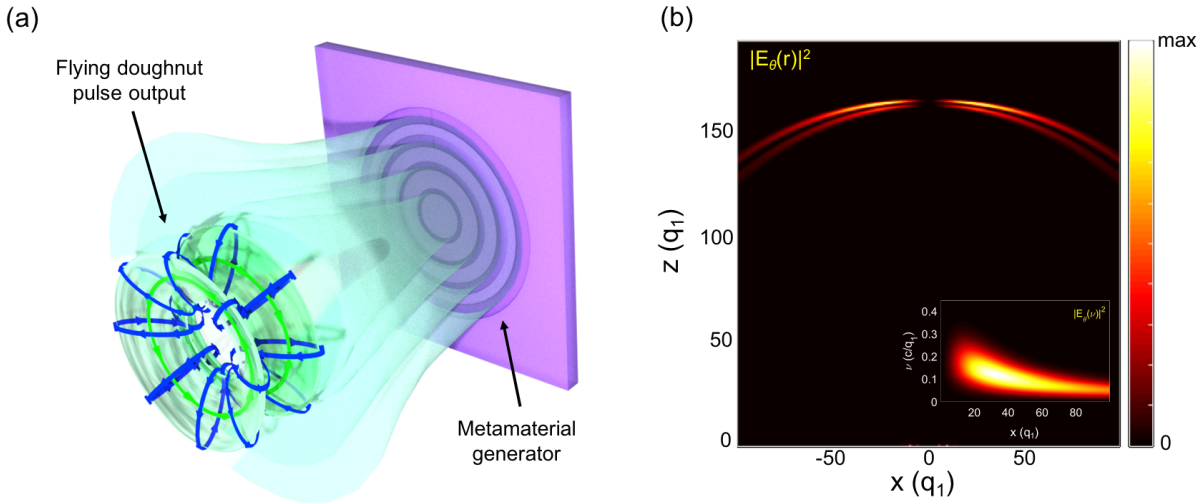

Fig. 1 (a) Schematic representation of the flying doughnut generation scheme. A cylindrically symmetric metamaterial array excited by a transverse electromagnetic pulse emits a flying doughnut pulse. (b) The azimuthal electric field intensity of the metamaterial-generated FD pulse in a cross-section normal to the y-axis. The generating metamaterial array is in the z=0 plane. The inset shows the corresponding Fourier transform highlighting the radially gradient spectral content with low frequencies occupying the outer regions of the pulse, and higher frequencies close to its centre. All units are normalized to q_1, which is the effective wavelength of the FD pulse [2].

In summary, we demonstrate a practical scheme for the generation of FD pulses based on metamaterial arrays with simultaneous spatial and frequency dispersion. Possible applications include new schemes for information and energy transfer, as well as new forms of spectroscopy.

References

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