# Generation of Electromagnetic Doughnut Pulses with a Singular Metamaterial Converter

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**Abstract:** We present the first experimental demonstration on the generation of "Flying Doughnuts", space-time inseparable toroidal electromagnetic excitations, by converting ultrashort transverse optical pulses in a singular metamaterial converter. Unique properties of toroidal pulses are discussed.

We demonstrate for the first time the experimental generation and full characterization of toroidal pulses with non-separable space- and time- dependence, termed "Flying Donuts" (FDs).

FD pulses propagate in free-space at the speed of light and interact with matter in unique ways, such as non-trivial field transformations upon reflection from metallic and dielectric interfaces. On the other hand, the topological similarity of FD pulses with the toroidal dipolar excitations in matter allows to excite strong toroidal response in dielectric particles, as well as to engage anapole modes, non-radiating configurations consisting of co-located electric and toroidal dipoles. Moreover, it has been suggested that the longitudinal field components could be employed for charged particle acceleration. We recently introduced a generation scheme based on metasurfaces that exhibit spatially gradient dispersive response, which allows for complex manipulations of the spatial and temporal structure of electromagnetic pulses. A schematic of our approach is presented in Fig. 1a, where an incident linearly polarized Gaussian pulse is converted to a Flying Doughnut. Here we present an experimental implementation of the scheme and a full characterization of the generated pulses in the spatial and temporal domain, and demonstrate that the generated pulses exhibit the unique characteristics of the FD pulse, including toroidal topology and space-time non-separability. In our experiment, a ~10 fs linearly polarized pulse with center wavelength at 800 nm is incident on a segmented waveplate that provides a radially polarized pulse and then to a metasurface which consists of concentric plasmonic rings with a width that varies along the radial direction and provides the required spatiotemporal coupling (see Fig. 1b). The spatial variation of geometric properties leads to shorter (longer) wavelength transmission resonances close to (away from) the center of the metasurface. The spatial and temporal profiles of the pulse emerging from the metasurface are characterized through interference with a known reference pulse. At the same time, a spatially resolved frequency decomposition of the generated pulse as it emerges from the metasurface reveals a gradient frequency spectrum with lower (higher) frequencies dominating the outer regions (close to the center) of the pulse, Fig. 1c. In contrast to the linearly polarized input pulse, the generated pulse is radially polarized according to the toroidal topology of the FD pulse, as it can be seen by the absence of intensity in the center of Fig. c. We expect that the generated FD pulses will be employed as novel spectroscopic tools in the study of toroidal and anapole excitations in matter and will find applications in new schemes for information and energy transfer.

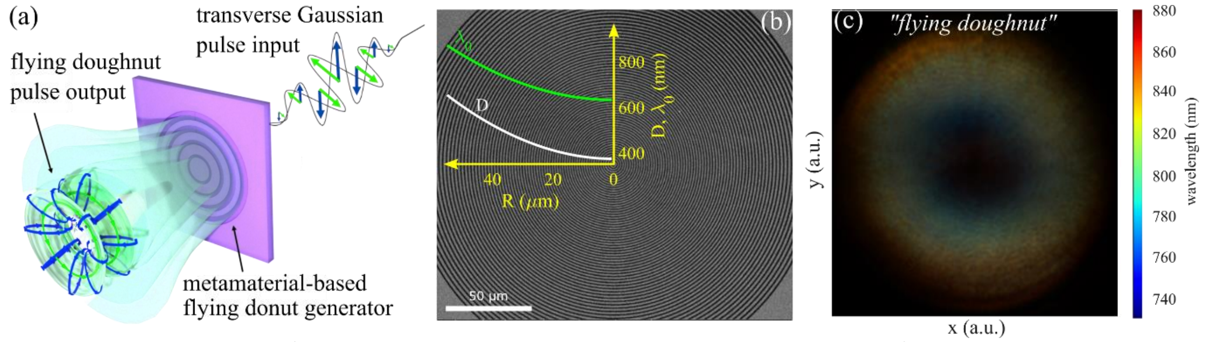

Fig. 1: (a) Pulse generation scheme for Flying Doughnut pulses. A metamaterial-based pulse converter transforms an incident linearly polarized Gaussian pulse to an FD. (b) Scanning electron microscopy picture of the FD generating metasurface. The metasurface is cylindrically symmetric and consists of an array of concentric plasmonic rings with unit cell (white line in inset) increasing from D~350 nm at the centre of the metasurface to above 600 nm at the periphery of the array, while the resonance wavelength (green line in inset) shifts from $\boldsymbol{\lambda_0}$~600 nm to ~900 nm. (c) False color image of the generated pulse. The high frequency components close to the center of the pulse are indicated by the blue-green color, while the red color in the periphery of the pulse correspond to the lower frequency components.