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Ultrafast magnetic field induced by anisotropy in carbon nanotubes irradiated by intense laser fields

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Abstract. We report an unexpected result of the anisotropy of the nonlinear optical response of carbon nanotubes, inherent to their chirality. Using a model based on the resolution of the semiconductor Bloch equations, we theoretically demonstrate that, upon irradiation with an intense linearly polarized laser pulse along the axial direction, chiral nanotubes exhibit an oscillating azimuthal current that is absent in achiral species. This current induces a magnetic field parallel to the axis of the nanotube that radiates like a loop antenna.

1 Introduction

Carbon nanotubes (CNTs) exhibit remarkable responses to intense laser fields, revealing their unique optical and electronic properties. Under such conditions, these allotropic forms of carbon can undergo processes such as ultrafast carrier dynamics [1], optical absorption [2], photoluminescence [3], and nonlinear optical effects, among others. A notable nonlinear response is high-order harmonic generation (HHG), where the laser field drives the emission of harmonics with frequencies that extend up to the extreme ultraviolet regime [4, 5].

Understanding the complexities of carbon nanotube interactions with intense laser fields, particularly in the context of high-order harmonic generation, holds promise for applications ranging from ultrafast photonics to advanced optoelectronic devices. In this context, this contribution focuses on an unexpected result of the anisotropy of the nonlinear optical response of carbon nanotubes, inherent to their anisotropy.

2 Interaction scheme and methods

We conduct simulations to explore HHG in single-walled carbon nanotubes based on solving the two-band semiconductor Bloch equations (SBEs). The unit cell of the nanotube is regarded as a cylinder of diameter $|\mathbf{C}_h|/\pi$ and height $|\mathbf{T}|$ containing N carbon atoms, where $\mathbf{C}_h$ is the chiral vector and $\mathbf{T}$ represents the translational period. These parameters are uniquely determined by the chiral indexes (n_1, n_2) that define each CNT. The driving laser field employed in our simulations consists of a 28 fs FWHM mid-infrared pulse with a wavelength of $3\,\mu$m and a peak intensity of 5.0×10^{10} W/cm^2, linearly polarized along the nanotube axis.

Fig. 1 illustrates the conceptual framework of the interaction model. As depicted, the interaction with the laser field induces two distinct currents, aligned with the axial (‖) and azimuthal (⊥) directions of the nanotube. These currents are given by the first time-derivative of the expectation values $\langle\Psi|e\hat{x}_{\parallel,\perp}|\Psi\rangle$, where e represents the elemental charge, Ψ denotes the wave function of the Bloch electron, and $\hat{x}_{\parallel,\perp}$ are the axial and azimuthal components of the position operator, respectively. The axial current oscillates along the nanotube axis, leading to the emission of harmonics polarized parallel to it [4]. Conversely, the oscillating azimuthal current circulates around the perimeter of the nanotube. Consequently, the nanotube unit cell can be conceptualized as a spire supporting a current, thereby inducing a varying magnetic field that oscillates in the axial direction. This magnetic field radiates like a loop antenna, emitting harmonics polarized in the direction perpendicular to the nanotube axis. Noteworthy, since the laser pulse is polarized along the axial direction, this phenomenology appears as a consequence of the anisotropy of carbon nanotubes.

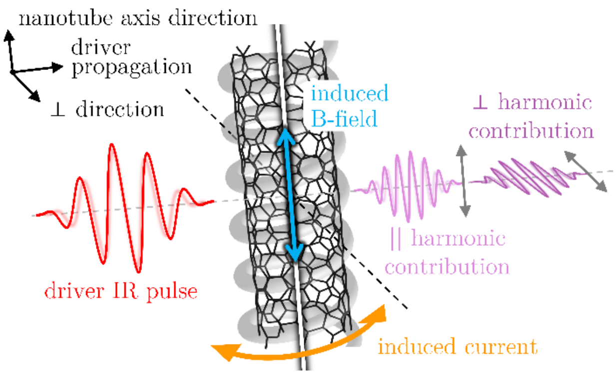

Fig. 1. Scheme of the interaction between a mid-infrared laser beam and a carbon nanotube. The total harmonic response consists of two distinct contributions, characterized by their polarization directions relative to the nanotube axis.

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3 Results

Our simulations encompassed a range of nanotube configurations, with different diameters, chiralities or metallicities. Notably, our findings consistently reveal that the azimuthal current is present across all examined chiral configurations, while absent in the achiral species. As an example, we show in Fig. 2 the magnetic moment (m) induced by the driving laser in the unit cell of the chiral nanotube (8,4). The pronounced ultrafast oscillatory behavior of m observed in this chiral configuration is completely absent in armchair or zigzag achiral species.

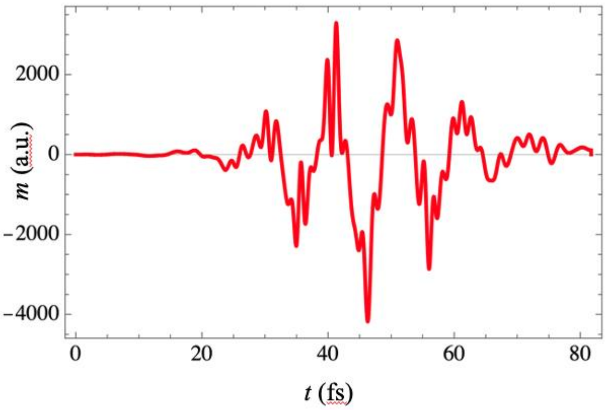

Fig. 2. Magnetic moment induced in the unit cell of the chiral nanotube (8,4) by a 3μm wavelength laser pulse with peak intensity of 5.0×10^{10} W/cm^2.

Fig. 3 illustrates the harmonic response of the semiconducting chiral nanotube (8,4) in both the azimuthal and axial directions. Interestingly, the spectral intensity of the higher harmonic orders is similar in both cases. This observation has been consistently found in all calculations performed in semiconducting species. Conversely, for metallic CNTs the azimuthal response is almost negligible in comparison to the axial response. Noteworthy, in panel (a) is clearly observed that the harmonic efficiency of the azimuthal component is higher for the higher harmonic orders. Since this phenomenology is related to the anisotropy of the target, the results obtained are in agreement with findings reported for graphene in previous studies, where it was shown that the anisotropic response is enhanced in the high-order harmonic regime [6].

4 Conclusion

We theoretically demonstrate that, upon irradiation with an intense linearly polarized laser pulse along the axial direction, chiral nanotubes exhibit an oscillating azimuthal current that is absent in achiral species. This current induces a magnetic field parallel to the axis of the nanotube that radiates like a loop antenna.

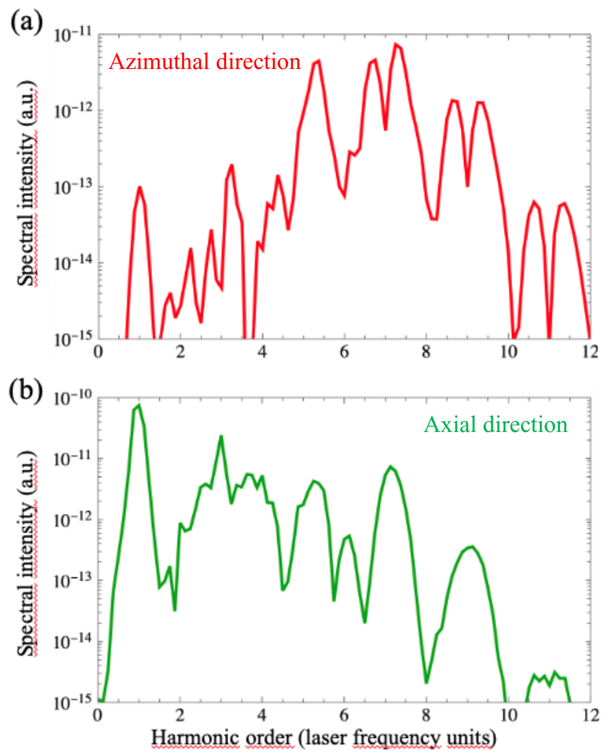

Fig. 3. Harmonic yield from a (8,4) chiral nanotube induced by the (a) azimuthal and (b) axial currents. The parameters of the driving laser are the same as in Fig. 2.

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