Anisotropic Fluorescence Enhancement near Semiconducting Carbon Nanotube Metasurfaces

M. D. Pugh[1], SK Firoz Islam[1,2], and I. V. Bondarev[1]

[1]*Department of Mathematics and Physics, North Carolina Central University, Durham, NC 27707, USA*
[2]*Department of Physics, Jamia Millia Islamia (A Central University), New Delhi 110025, India*

ibondarev@nccu.edu

We report a theoretical study of the directionality effects in spontaneous emission (SE) and resonance fluorescence of a quantum two-level dipole emitter (DE) near an ultrathin closely packed periodically aligned semiconducting single-wall carbon nanotube (SWCN) film [1]. Such films present an example of highly anisotropic metasurfaces with tunable optical properties [1-5] that are now available experimentally [6-8]. Near-field SE and far-field fluorescence intensity profiles are derived analytically and computed numerically as functions of the DE excitation energy and parameters of the film such as SWCN composition and thickness. The nanotube alignment is shown to provide an extra measure for quantum control of dipolar SE and resonance fluorescence in such systems, in addition to film thickness and composition parameters such as tube diameter, chirality and translational period. The processes studied are shown to be highly anisotropic, being enhanced by orders of magnitude in the direction perpendicular to the alignment and metasurface plane (Fig.1), contrasting with the commonly believed viewpoint of their uncontrollably random directionality. The model system we study mimics a single-atom detector or a single-photon source device. Knowledge of the features we predict is advantageous for the new application development with SWCN metasurfaces for solid-state single-photon source and single-atom detector engineering.

This work is supported by the U.S. Army Research Office under award No. W911NF2310206 (I.V.B.).

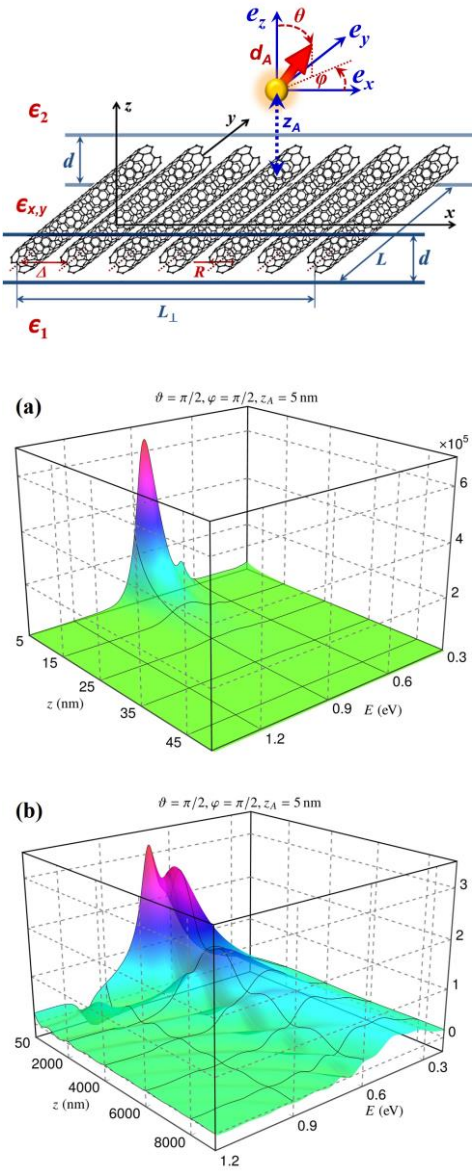

Fig.1. Short- (a) and long-distance (b) anisotropic fluorescence intensity (relative to vacuum) as functions of the DE transition energy and point of observation, computed for a DE near the 10 nm thick weakly inhomogeneous SWCN film (sketch on top) with electromagnetic response reported previously [2,8]. The strongest intensities are shown in the direction perpendicular to film plane.

References

[1] M. D. Pugh, SK Firoz Islam, and I. V. Bondarev, submitted (*under review; see arXiv:2402.17102*).
[2] I. V. Bondarev and C. M. Adhikari, Phys. Rev. Appl. **15**, 034001 (2021).
[3] P. Rodriguez-Lopez, D.-N. Le, I. V. Bondarev, M. Antezza, and L. M. Woods, Phys. Rev. B **109**, 035422 (2024).
[4] I. V. Bondarev, M. D. Pugh, P. Rodriguez-Lopez, L. M. Woods, and M. Antezza, Phys. Chem. Chem. Phys. **25**, 29257 (2023).
[5] C. M. Adhikari and I. V. Bondarev, J. Appl. Phys. **129**, 015301 (2021).
[6] P.-H. Ho, D. B. Farmer, G. S. Tulevski, S.-J. Han, D. M. Bishop, L. M. Gignac, J. Bucchignano, P. Avouris, and A. L. Falk, Proc. Natl. Acad. Sci. USA **115**, 12662 (2018).
[7] S. Zhu, W. Li, S. Yu, N. Komatsu, A. Baydin, F. Wang, F. Sun, C. Wang, W. Chen, S. C. Tan, H. Liang, Y. Yomogida, K. Yanagi, J. Kono, and Q. J. Wang, Adv. Mater. **35**, 2304082 (2023).
[8] J. A. Roberts, S.-J. Yu, P.-H. Ho, S. Schoeche, A. L. Falk, and J. A. Fan, Nano Lett. **19**, 3131 (2019).