Self-Consistent Modeling of Coupled Maxwell-Bloch Equations with the Finite-Difference Time-Domain Method

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Project Type: Semester, Master project (or a combination or all)

Context: Understanding the interaction between electromagnetic fields and quantum emitters is fundamental to nanophotonics and quantum optics. A rigorous approach requires combining the classical Maxwell equations with the Bloch equations that govern the dynamics of quantum systems. However, bridging these two descriptions in a numerically stable and efficient way is challenging, as it demands handling disparate spatial and temporal scales while preserving self-consistency in the coupled dynamics. Accurate computational frameworks that address these challenges provide critical insight into phenomena such as spontaneous emission, absorption saturation, and strong light-matter coupling.

Project overview: This project focuses on a self-consistent modeling framework for the coupled Maxwell-Bloch equations using the open-source finite-difference time-domain (FDTD) software MEEP [1]. By extending MEEP's capabilities to integrate the Bloch equations alongside electromagnetic field evolution, the approach enables the simulation of realistic scenarios where light dynamically influences quantum emitters and, in turn, emitters alter the electromagnetic fields [3]. The framework will allow for the study of single and collective emitter dynamics in complex photonic environments, enabling investigations into coherence phenomena, and energy transfer at the nanoscale. The resulting tool will provide both methodological advances and practical guidance for the design of nanophotonic and quantum technologies.

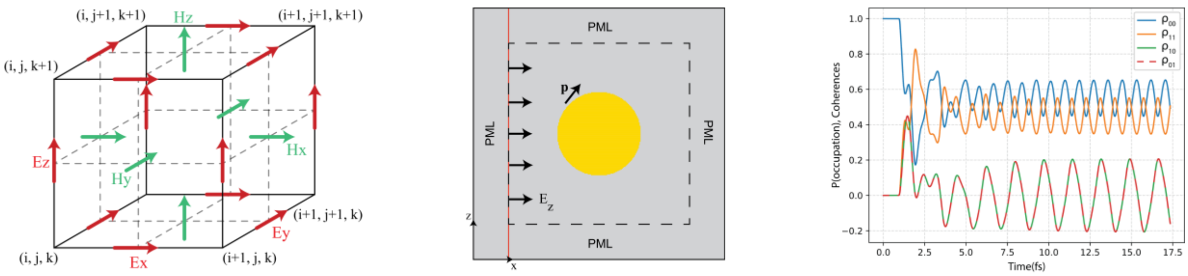

Figure. Left: Electric and magnetic field components on a cubic Yee cell [2]. Center: 2D cross section of a molecule (dipole) and plasmonic (gold) nanoparticle 3D geometry [4]. Right: Occupation probabilities and coherences for the two-level quantum system (molecule) [4].

What the student will do: The project will begin with an introduction to the FDTD method and an exploration of the physics underlying the master equation through a selection of papers from the literature. No prior knowledge of FDTD is required; however, a solid background in electromagnetism and a basic understanding of quantum mechanics are expected. Using the resources available in the group, the dynamics of selected physical systems will be studied, with a particular focus on the interaction between plasmonic resonances and quantum emitters. As part of the project, the student will learn to interpret results and gain an appreciation of how the self-consistent solution of the equations governing electromagnetism and quantum mechanics provides a powerful semiclassical description of light-matter interaction, one that goes beyond traditional frequency-domain approaches.

Benefits. This project is situated in the highly active research area of nanophotonics and offers valuable insight into current developments in the field. It provides hands-on experience with the numerical framework available in the group, enabling the study of the coupled dynamics of both electromagnetic fields and quantum systems within the Maxwell-Bloch formalism. The work involves analyzing and interpreting results, thereby fostering both technical expertise and research intuition. In addition, the student will have the opportunity to work closely with two doctoral assistants with complementary expertise in electromagnetism and quantum mechanics. This collaboration will support the project's progress and cultivate a strong sense of teamwork and scientific exchange.

References.

1. A. Oskooi *et al., Computer Physics Communications* **181**, 687-702 (2010)
2. A. Taflove, and S. C. Hagness, *Computational Electrodynamics: The Finite-Difference Time-Domain Method*, Artech House (2005)
3. G. Slavcheva *et al., Phys. Rev. A* **66**, 063418 (2002)
4. P. Mavrikakis *et al.*, PIERS, Abu Dhabi, UAE, 3A9a (2025).