Thesis title: Directing Nanoscale Light-Matter Interactions with Polaritons in Low-Dimensional Systems

Abstract:

In this dissertation we analyze light-matter interactions at the nanoscale using various approaches based on analytical, semi-analytical and numerical methods. The thesis introduces a detailed theoretical description of classical plasmonics in both two- and three-dimensional systems, with special attention to plasmonic waveguides of different shapes and materials.

In the initial phase, we review fundamental aspects of classical electrodynamics, covering essential concepts crucial for the study of plasmonics. Subsequently, we utilize this foundation to describe plasmonic excitations at both single- and double-layer dielectric-metal interfaces. Following this review, the theoretical framework is extended by an examination of the linear and nonlinear optical response of graphene, triggering a comprehensive discussion on plasmonic excitations within two-dimensional systems. This discussion reveals the consequences of the interaction between modes in multiple graphene sheets, as well as the unique plasmonic spectrum of graphene nanostructures.

Next, the attention is turned to an investigation of plasmonic waveguides formed by bending a flat graphene sheet into a parabolic structure. Specifically, we derive a theoretical formalism to describe the dispersion relation and associated electric potential of the plasmons in this waveguide. Our findings indicate that the attainable field confinement in the graphene parabolic waveguide surpasses that of flat graphene sheets, thus acting as a setting for extreme subwavelength field localization. As a result of this intense confinement, we analyze the Purcell enhancement of a point dipole situated in the vicinity of the apex of the waveguide. Here, we find that an increase in the curvature of the parabola intensifies the Purcell factor of a dipole located below the waveguide, while the opposite trend is reported for a dipole above the apex.

We then proceed with a study of both the linear and nonlinear optical response of heterostructures made of parallel graphene ribbons. Specifically, we aim to optimize second- and third-harmonic generation in these geometries through ideal combinations of intrinsic and extrinsic material parameters of the ribbons. The results illustrate that the second- and third-order nonlinear responses are largest when the double- and triple-resonance conditions are satisfied, respectively. Furthermore, we analyze the effect of the second-order cascaded contribution to the total third-harmonic generation in stacked graphene ribbon dimers. This analysis elucidates the importance of an asymmetric system, which we achieve by a relative horizontal shift between the ribbons, while doping the two structures with opposite charge carrier types.

Finally, our attention shifts towards examining the generation of plasmons in thin silver waveguides. These plasmons are excited by free energetic electrons and are analyzed through the utilization of the two-dimensional boundary element method, which provides us with the linear wavevector-energy-resolved EELS map. Subsequently, we compute higher-order terms of the EELS, with a special focus on the second-order contribution, describing two-photon excitation events in the waveguide. Then, using suitable masks to pick out areas of interest in the EELS spectrum, we analyze the even pair and odd entanglement production of counter-propagating plasmons. The data reveals certain spectral ranges in which the generation of entangled plasmon pairs makes up approximately 80% of all excitation events, up to the second order. Moreover, it is found that the efficiency of entanglement generation increases when the thickness of the waveguide is decreased.