Abstract

This thesis presents a comprehensive study on the nonlinear light-matter interactions facilitated by plasmonic nanoantennas and metasurfaces, employing theoretical and numerical modeling as primary research methods. The investigation focuses on various plasmonic nanoantenna and metasurface configurations designed to enhance nonlinear optical processes, such as surface-enhanced Raman scattering, coherent anti-Stokes Raman scattering, light interactions with polar molecules, and multi- and two-photon absorption processes.

Key achievements include the design of plasmonic nanoantennas and metasurfaces that not only amplify these nonlinear processes but also enable the control of resonance frequencies through the application of a gate voltage to a graphene layer in the terahertz band. This capability allows for the tunable enhancement of multi-photon absorption processes, supporting two-, four-, six-, eight-, and ten-photon absorption with a fixed nanoantenna geometry by modulating the gate voltage. Additionally, coupling graphene disks with silver bars facilitates the control of terahertz emission from polar quantum systems. In these processes, the integration of silver and gold nanobars with graphene layers results in two distinct and tunable resonances ranging from the terahertz to the visible regimes. These novel nanoantenna structures can be utilized for their applications in multi-photon fluorescence and optomechanical cavities.

The thesis also explores the design of two metasurfaces with distinct optical response for enhancing Raman scattering. The first metasurface features a metal-insulator-grating configuration, which is tunable and supports multiple resonances that can be adjusted by altering the incident angle, enabling the detection of three Raman shifts in Rhodamine molecules. The second metasurface, with a metal-insulator-metal configuration, overcomes the limitations of the first by offering ultra-broadband resonance and significant electric field enhancement, thereby supporting a wide range of Raman shifts and molecules in both Raman scattering and coherent anti-Stokes Raman scattering processes.

Furthermore, the research proposes a tunable nanoantenna with dual plasmonic modes—bright and dark—that can be tuned by coupling these modes and adjusting the polarization, targeting the near-infrared and visible regimes. The quantum description of the two-photon absorption process reveals different regimes determined by molecular saturation level where orthogonal strategies for signal enhancement should be applied.

In summary, this thesis demonstrates the potential of plasmonic nanoantennas and metasurfaces for substantial enhancement of various nonlinear light-matter interactions through their coupling to atomic systems, advancing the understanding and

control methods of these complex processes.