

The interaction of light with matter is one of the most fundamental phenomena, leading to effects such as absorption, scattering, reflection or emission, which allow us to study and exploit the properties of matter. One prominent example is the interaction of light with quantum emitters (QEs), such as atoms or excitons in semiconductors, causing spontaneous emission, which is the basis for a wide range of light sources, from fluorescent lamps to lasers.

The strength of the light-matter interaction can be drastically increased by placing the QE in an optical cavity (OC), which can significantly improve spontaneous emission. The strength of the interaction depends on several factors, such as the number of oscillators in the cavity, the oscillator strength related to the absorption/emission linewidth of the material, and the volume of the effective mode, i.e. the space occupied by the light confined in the cavity. When the emission frequency of the material matches the resonant frequency of the cavity, the strength of the interaction can exceed the energy dissipation in the system, leading to the so-called strong coupling regime. In this case, instead of one mode, two hybrid modes appear, which can be seen as two maxima in the absorption measurements. The difference in their frequency positions is called Rabi splitting. In this case, depending on the type of matter, several desirable phenomena can occur, such as room-temperature Bose-Einstein condensation and superfluidity. These phenomena can be exploited for ultralow-threshold lasing, single-photon switches, all-optical logic systems, and control of chemical reactivity. Although very promising for basic and applied science, achieving the strong coupling regime requires a high coupling strength and/or narrow QE-OC lines. This limits the range of media to materials exhibiting extremely narrow emission lines, such as dye molecules or quantum dots, and additionally forces the use of high-quality optical cavities, which is often a technical challenge.

These problems can be overcome by using cavity metal nanostructures – a distinctive class of surfaces that can capture and amplify light in areas with dimensions of several nanometers (one millionth of a millimeter). This is possible by inducing the so-called localized surface plasmon resonance, during which the incident light forces the collective oscillations of free electrons in the metal at the edges of nanogaps, which are strongly coupled to the surface electromagnetic mode. The properties of the resonantly scattered light, such as frequency, polarization state, or direction of propagation, can be easily tuned based on the material composition, the geometry of the nanostructure, and the material parameters of the surrounding medium.

Another class of materials ideal for studying strong photon-exciton couplings are quasi-2D organic halide perovskites. These materials are formed in octahedral structures formed by metal ions, such as lead (Pb) or tin (Sn), surrounded by six halide anions (I, Br, or Cl). The remaining space of the structure is occupied by organic cations. Individual layers or a few-layer structure are separated by long organic chains. The separation of the layers leads to the formation of a natural quantum well. This results in strong excitonic absorption and narrowband emission, where the band gap energy can be controlled by adjusting the atomic composition and structural parameters of the material.

The combination of cavity plasmonic nanostructures with quasi-2D organic halide perovskites will enable the creation of a new class of supertunable surfaces for studying and exploiting the strong coupling regime. In particular, for the development of a new class of efficient light sources with controllable color and polarization of the emitted radiation.

The aim of this project is to understand and explain the physics involved in the synthesis of these materials and the range of their functionality in terms of achievable Rabi splitting and emissivity that these hybrid perovskite-plasmonic materials can exhibit. Our goal is to answer the following questions: (a) How does the architecture of plasmonic nanostructures affect the growth rate, crystallographic structure, dimensionality, and optical and electrical properties of selected quasi-2D perovskites that are uniformly synthesized both on the entire surface of the nanostructure and in the plasmonic nanocavity? (b) How does the quality, dimensionality, and geometry of quasi-2D perovskite thin films and nanocrystals affect their optical properties, including the complex refractive index and emissivity? (c) How do the geometry and material composition of the hybrid perovskite-plasmon structure affect the interaction strength in the strong coupling regime? (d) How does the geometry of the nanogap structure affect the properties of the emitted light, especially the emission direction and polarization? (e) What is the performance of the lasing system based on the hybrid quasi-2D perovskite-plasmonic structures in terms of the lasing threshold, polarization state, and spatial and temporal coherence of the emitted light?

The project aims to answer these questions, which will not only shed light on the physical foundations involved in the fabrication of such materials, but also satisfy the current need for large-area and low-cost platforms for fundamental research on strong coupling and pave the way to efficient, economical, and tunable light sources for a wide range of applications, including quantum technologies, imaging, sensing, and photonics.