Tailoring Nanoscale Light-Matter Coupling with Polaritons

Niclas S. Mueller

Emmy Noether Group Leader, Department of Physics, Freie Universität Berlin

Nano-optics is a unique tool to characterize materials at the smallest length scales and to strongly enhance light-matter interaction. Central to this field are polaritons, hybrid light-matter quasiparticles, that emerge from dipolar excitations, including phonons, excitons, and plasmons. The ability to tailor this interaction using 2D materials, cavities, and artificially structured metasurfaces has made polaritons a rapidly growing research field over the past decade [1]. This opens new pathways for extreme confinement of light, novel optoelectronic devices, and photonic engineering of materials.

In the first part of my talk, I will show how polaritons in different material platforms intrinsically reach the ultrastrong coupling regime, typically explored with complex cavity setups [2,3]. This coupling is particularly pronounced for phonon polaritons. I will demonstrate how ultrastrong coupling of hyperbolic phonon polaritons in Hf-based van der Waals materials enables extreme confinement of THz light down to UV-wavelength scales [4].

In the second part, I will introduce advanced nonlinear optical characterization techniques to image polaritons and characterize 2D materials. Nonlinear mixing of mid-infrared and visible lasers via sum-frequency generation enables sub-diffractional imaging of polaritons in SiC metasurfaces, as well as visualization of crystal orientation and stacking in typically invisible hexagonal boron nitride layers [5,6].

[1] Abajo, …, NSM et al. *Roadmap for Photonics with 2D Materials*, ACS Photonics 12, 3961-4095 (2025) - link

[2] NSM et al. *Deep strong light–matter coupling in plasmonic nanoparticle crystals*, Nature 583, 780 (2020) - link

[3] NSM et al. *Ultrastrong Light-Matter Coupling in Materials*, arXiv 2505.06373 (2025) - link

[4] Kowalski*, NSM* et al. *Ultraconfined THz Phonon Polaritons in Hafnium Dichalcogenides*, Nature Materials, in press (2025) - link

[5] Niemann*, NSM* et al. *Spectroscopic and Interferometric Sum-Frequency Imaging of Strongly Coupled Phonon Polaritons in SiC Metasurfaces*, Advanced Materials 36, 2312507 (2024) - link

[6] NSM*, Fellows* et al. *Full Crystallographic Imaging of Hexagonal Boron Nitride Monolayers with Phonon-Enhanced Sum-Frequency Microscopy*, arXiv 2504.15939 (2025) - link