Polaritons in Nanomaterials

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Polaritons are quasiparticles that result from strong coupling between electromagnetic waves and electric/magnetic dipoles. As electromagnetic eigenmodes, they are self-sustained and can propagate with larger wave vectors than that of bare light waves of the same energy. Therefore, polaritons can beat the diffraction limit of classical optics by confining light into regions that are much smaller than its wavelength and lead to advances in nanophotonics by enabling manipulation of photons at nanoscale.

Since the resonance frequency of magnetic dipoles is usually considerably lower than optical frequency, polaritons in nanophotonics are almost exclusively electric-dipole-type, which include plasmon polariton resulting from coupling between collective electron oscillations and a photon, phonon polariton resulting from coupling between lattice vibrations and an infrared photon, and exciton polariton resulting from coupling between a bound electron-hole pair and a visible light photon. All these three polaritons have been extensively studied in conventional materials such as noble metals, polar dielectrics, and semiconductors, and spawned many important applications in sensing, imaging, spectroscopy, integrated nano-optics, and optoelectronics.

During the last decade, a plethora of new polaritons have been discovered in nanomaterials, especially in two-dimensional (2D) van der Waals (vdW) materials, such as the plasmon polaritons in graphene, the phonon polaritons in hexagonal boron nitride (*h*-BN), and the exciton polaritons in transition metal dichalcogenides (TMDCs). These polaritons in 2D vdW materials dwarf their counterparts in conventional materials with ultrahigh degree of field confinement, ultralow transmission loss, extreme anisotropy, electrical tunability, and strong interaction in heterostructures. These extraordinary properties are promising in realizing new nanophotonic devices, therefore, polaritons in nanomaterials especially in 2D vdW materials have become a "hotspot" in nanophotonic research. Many proof-of-concept applications including ultra-small footprint phase modulator using graphene plasmon polaritons, directional control of light propagation using phonon polaritons in molybdenum trioxide, and graphene plasmon enhanced infrared spectroscopy have been successfully demonstrated. The rapid evolution of this area necessitates a periodic summary of the progress in the past years and an insightful outlook into the future, which is the aim of this special issue themed on "Polaritons in Nanomaterials". The issue contains a collection of 15 papers with a diverse range of topics that are detailed below.

To excite and detect polaritons is always a challenging task, especially for the highly confined polaritons in nanomaterials.

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Herein, there are four papers involving this technical aspect. The contribution by Xiaoxia Yang and co-workers[1] gives a comprehensive summary of the experimental characterization methods for polaritons and compares their relative merits for specific applications. Time resolved imaging and spectroscopic techniques are crucial in understanding the dynamic properties of polaritons in nanomaterials. The progress report by Mengkun Liu and co-workers[2] concentrates on this subject and reviews the ultrafast nanoimaging and nanospectroscopic applications of the scattering-type scanning near field optical microscopy (s-SNOM) within a broad frequency range. The synchrotron infrared nanospectroscopy (SINS) technique which combines s-SNOM with the ultrabroadband synchrotron source is introduced together with its applications in the study of key attributes of polaritons in 2D Materials by Raul O. Freitas and co-workers[3] In the communication by Xiaoji G. Xu and co-workers,[4] the mechanical detection of polaritons using peak force infrared microscopy is demonstrated by imaging the canonical phonon polaritons in *h*-BN.

Plasmon, phonon, and exciton polaritons are the three most important categories of polaritons in nanomaterial. There are three papers dealing with each of them respectively and one paper discussing the characteristics of all polaritons in general in this issue. The contribution by Hugen Yan and co-workers[5] details the in-plane anisotropic optical properties and hyperbolic plasmons of black phosphorus while Siyuan Dai and co-workers[6] review the transport properties and applications of hyperbolic phonon polaritons in vdW crystals. The contribution by Fengrui Hu and Zhe Fei[7] discusses the recent studies of exciton polaritons in group-VI TMDCs. The progress report by Zhiwen Shi and co-workers[8] summarizes the advances on the scaling and reflection behaviors of strongly confined polaritons in three representative low-dimensional material systems.

With new materials and properly designed structures, novel polaritonic phenomena can be expected. Alexander Paarmann and co-workers[9] report the discovery of s-polarized waveguide modes with polariton-like properties in $Ge_3Sb_2Te_6$ thin films. A multi-mode metal–dielectric–metal plasmonic antenna, which can simultaneously operate in two different spectral bands, is presented by Alexey Y. Nikitin and co-workers[10] The contribution by Yu Luo and co-workers[11] investigates the strong plasmon–exciton interaction in a nanoantenna array–monolayer WS_2 hybrid structure, while the chiral coupling of valley excitons and light in hybrid TMDCs–nanophotonic systems is reviewed by Dangyuan Lei and co-workers.[12]

Applications of polaritons in nanomaterials are of special interest, and three papers in this issue deal with this aspect in detail. The applications of localized polaritons in structured metals and 2D materials are highlighted (see the work by Yongmin Liu and co-workers[13]), while an extra emphasis is placed on the applications of both propagating and localized polaritons in vdW crystals in the mid-infrared region by Min Seok Jang and co-workers.[14] Another contribution by Sanshui Xiao and co-workers[15] stresses the application of polaritons in the strong coupling regime of light–matter interactions.

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