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Innovative Approaches to Luminescence: Exciton-Polariton Lasers and Quantum Confinement in 2D Materials

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Abstract

The phenomenon known as luminescence occurs when an external energy of any kind excites a substance's electronic state, and the excited energy is released as light. Luminescence is the absence of heat produced by light emission. Luminescence comes in a variety of forms, including thermoluminescence, bioluminescence, and chemiluminescence. Examples of luminescence include flat-screen TVs, LED lights, and bioluminescent phytoplankton. The measurement of the emission spectrum produced when previously excited atoms or molecules return to their ground state is the foundation of luminescence techniques. Different forms of luminescence are always the result of an energy input of some kind causing light to be emitted. Emissive displays, fluorescent lights, LEDs, and systems that detect X-rays or γ-rays—used in medical imaging, for instance—are among the major applications. In the latter type of applications, high-energy photons excite luminescent materials, and a portion of the excitation energy is converted to visible light. He study delves into exciton lasing fluorophores, emphasizing the potential of plasmon-exciton-polaritons (PEPs) to achieve laser-like emission at low threshold powers. The unique properties of PEPs, facilitated by strong light-matter coupling in metallic nanostructures, are examined, highlighting their potential integration with photonic circuits and metamaterial technologies. Additionally, the article reviews hybrid light-matter lasers, where polariton lasing occurs without the need for population inversion, offering significant benefits over conventional lasers, particularly in terms of operating thresholds.

Keywords: Luminescence, Plasmon-exciton-polaritons (PEPs), Photonic circuits, Hybrid light-matter, lasers Energy, conversion

INTRODUCTION

In recent years, the exploration of light-matter interactions has ventured into the realm of quantum phenomena, revealing new dimensions of control over photonic processes. One particularly intriguing development is the harnessing of hybrid light-matter states, such as exciton-polaritons, to achieve unconventional lasing mechanisms. These quasi-particles, formed by the coupling of excitons with confined electromagnetic fields, offer a unique pathway to coherent light emission at remarkably low thresholds. This approach challenges the traditional boundaries of laser physics, enabling the realization of compact, efficient light sources that operate under conditions where conventional lasers would struggle. The integration of these

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hybrid systems into nanoscale photonic circuits promises to revolutionize the landscape of optoelectronics, paving the way for new applications in areas such as quantum computing, advanced sensing, and energy-efficient lighting. As research continues to unfold, the potential of exciton-polariton systems to drive innovation in photonics becomes increasingly apparent, offering a glimpse into the future of light-based technologies.

Exciton Lasing Fluorophores

Metallic nanostructures offer an array of tools for coherent light generation below the diffraction limit. Plasmonic-based lasing is based on the population inversion of emitters, including organic fluorophores, and the feedback provided by plasmonic resonances. In this weak light-matter coupling regime, the radiative properties of the system can be understood in terms of the Purcell effect. Hybrid quasi-particles called plasmon-exciton-polaritons (PEPs) arise when molecular excitons and the electromagnetic field generated by plasmonic devices exhibit a strong light-matter connection. Due to the quasi-particle structure of exciton-polariton condensation, laser-like emission can occur at significantly lower threshold powers than in traditional photon lasers. Here, we observe PEP lasing through an optically pumped organic system including a low threshold array of metallic nanoparticles. Interestingly, even though the active material's quantum efficiency decreased, These findings demonstrate a novel room-temperature platform for studying the physics of exciton-polaritons in an open-cavity design and open the door for the integration of this on-chip lasing device with current photonics and active metamaterial planar technologies. Exciton-polaritons, hybrid light-matter quasi-particles produced by strong exciton-photon interaction, have prompted almost 20 years of extremely interdisciplinary research. Since the first observations of Bose-Einstein Condensation (BEC) and superfluidity in optics were made in semiconductor microcavities, the study of polariton physics has primarily focused on these cavities due to the strong nonlinearities caused by quantum well excitons and the high-quality factor cavities made possible by state-of-the-art epitaxial techniques. One of the most important early ideas in the discipline was the polariton laser, which provided the prospect of creating a coherent light source. As efforts are made to lower thresholds and improve operating parameters, polariton lasers have remained the subject of proof-of-concept studies and have not yet been widely used. Recently, several researchers have focused on organic materials in an effort to circumvent some of the material-related restrictions impeding applications of exciton-polaritons and to investigate novel light-matter states linked to various types of excitons. Despite the fact that organic systems are typically disordered, their optical transitions have the potential to have large transition dipole moments, which allows them to couple to light strongly at room temperature. Numerous separate studies have already documented polariton lasing/BEC and nonlinear interactions with organic excitons in microcavities.

Plasmonic systems have been found as a possible alternative platform to study exciton-polaritons in an open architecture. Exciton-polariton devices can now be integrated with integrated photonics circuits, since the multilayer dielectric stack that formerly defined the resonator's "cavity" is no longer present. These plasmonic structures, which have been shown to be extremely appropriate for photon lasing, allow the excitonic material in Figure 1 to be easily incorporated through solution processing. The quality factors of plasmonic resonances are significantly lower than those of their dielectric microcavity counterparts. Nonetheless, the subwavelength field enhancements generated by resonant metallic nanostructures can greatly boost the light-matter connection. History of strong plasmon-exciton couplinghowever previous attempts to produce plasmon-exciton-polariton (PEP) lasing were unsuccessful due to the saturation of strong coupling at large pumping fluences and the inefficient relaxation mechanism of PEPs [4–7]. Figure 1 Regarding the optically pumped array of silver nanoparticles coated in a thin layer of organic molecules, respect demonstrated low-threshold PEP lasing at ambient temperature. Strong interaction between the excitons in organic molecules and the collective plasmonic resonances of the array produces PEPs. The descriptive problem observed a sharp emission intensity threshold and spectrum narrowing as optical pumping increases the PEP density. Apart from these general lasing features, our system exhibits two relatively special features. Initially, PEP lasing threshold power is lowered in tandem with a drop in the perspective of traditional laser physics, this counterintuitive behavior is closely linked to the onset of strong coupling and the appearance of new eigenstates, or PEPs. The support for both dark and bright modes provided by the nanoparticle array is a second distinctive quality of our PEP laser. When a mode initially approaches the lasing threshold, it is genuinely dark below the threshold. Though dark-mode photon lasing has attracted much interest in the plasmonic world for several years, Scheme gave the first report of lasing from a dark mode in a highly coupled plasmon-exciton system.

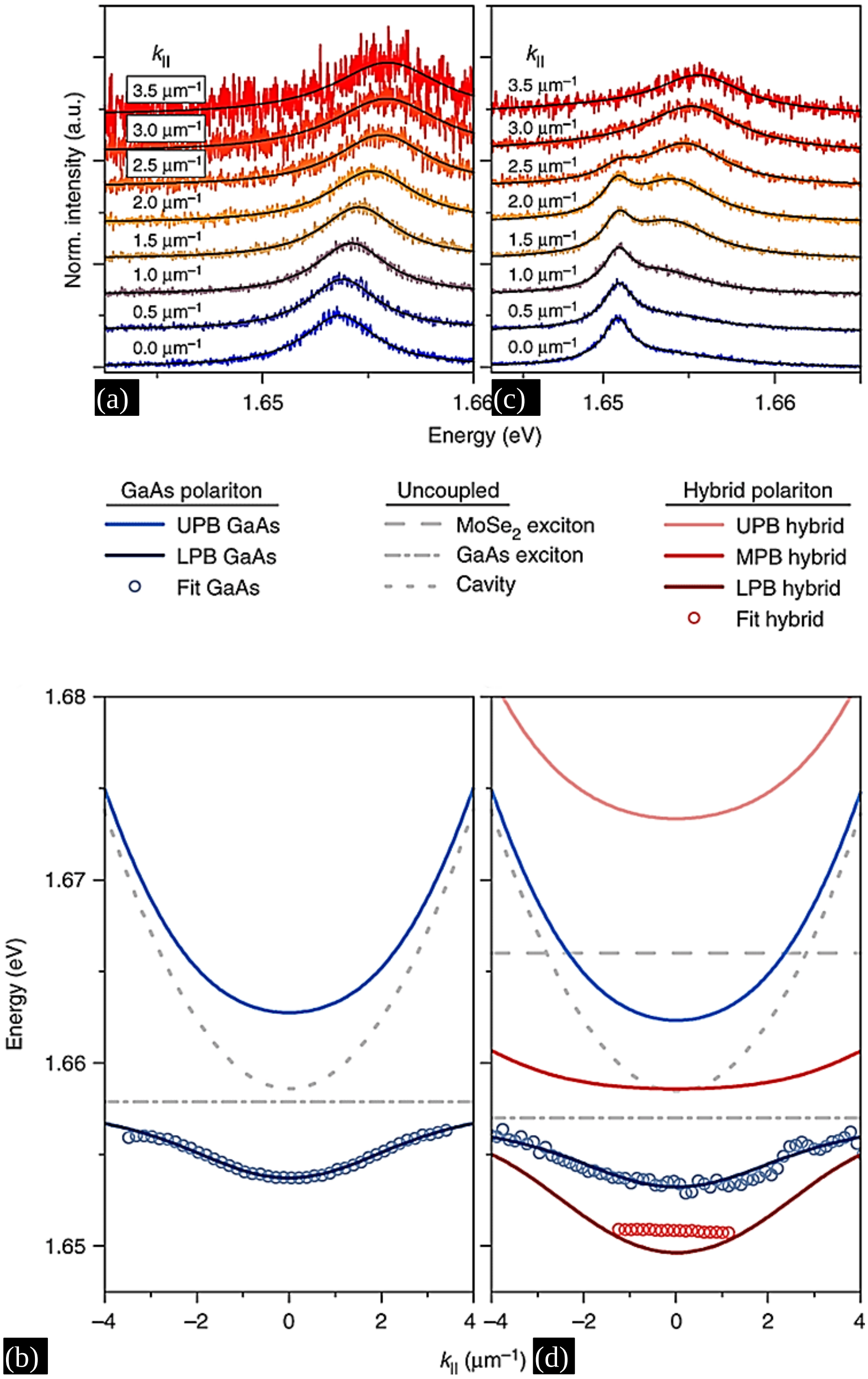

Figure 1. (a–d) Luminescence of GaAs exciton-polaritons and hybrid polaritons.

Hybrid Light–matter Laser

In coherent emitters known as polariton lasers, the fundamental particles are not photons amplified by a gaining medium but rather hybrid quasi-particles known as polaritons. This review covers the key subjects in the field of polariton lasing, beginning with an introduction to the concepts of polaritons and the strong coupling regime. Next, it discusses the mechanism of polariton lasing and the primary obstacles to implementing it. Then, a review of some of the key findings on polariton lasing from confined structures to 2D samples is done. This latter instance will enable us to talk about some of the unique characteristics of polariton lasing in comparison to conventional lasers. The majority of polariton lasing occurs at cryogenic temperatures, but we will see that it is also possible to observe it at room temperature if the right materials are used [8–11].

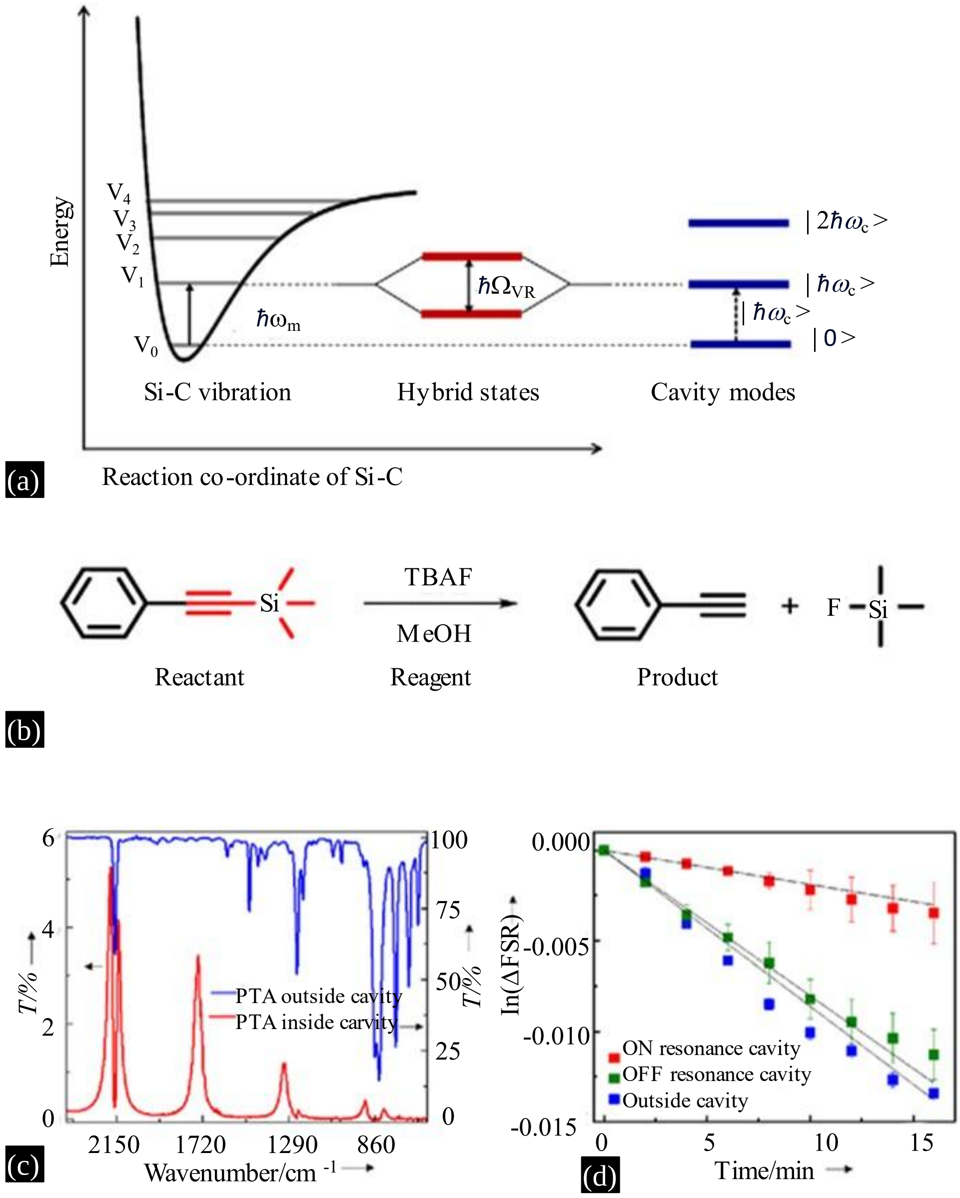

Figure 2. (a–d) Hybrid Light-Matter States

With the rapid development of advanced tools and techniques for manipulating, manufacturing, and characterizing matter at a nanoscale length scale, new alternatives for efficiently directing light propagation and confinement in solid-state materials are increasingly available. Figure 2 This can significantly improve how semiconductor materials interact with confined electromagnetic modes [12]. Applications include commercially available light-emitting diodes and laser diodes [13]. Excitons trapped in Quantum Wells (QWs) and the modes of photonic cavities are one example of strong coupling; the resulting hybrid exciton-photon quasi-particles are known as exciton-polaritons. The build-up of a significant number of polaritons in a single quantum state is known as polariton lasing. [14].

Lower symmetry 2D material

Numerous anisotropic 2D materials with a variety of band structures have been found to date. They have a wealth of optical properties, which suggests great potential for new applications in optoelectronics, photonics, and optics. In this regard, the anisotropic optical characteristics and polaritons of a wide variety of low symmetry 2D materials were investigated. An introduction to the background of anisotropic 2D semiconductors' optical properties, such as excitons, photoluminescence, band structure engineering, and interband absorption, for changing optical responses. Sophisticated tests of hyperbolic polaritons in anisotropic 2D materials comprised plasmon, exciton, and phonon polaritons. Unconventional superconductivity in magic-angle graphene superlattices, Hofstadter's butterfly and fractal quantum Hall effects, and the astounding half-integral quantum Hall effect are just a few of the astounding quantum phenomena of 2D materials that have been discovered since 4 years ago. These phenomena have made 2D materials fascinating since their inception. Furthermore, 2D materials show robust interactions between light and matter [15].

One such example is the significant interband absorption that single-layer graphene displays in the infrared (IR) regime. Surprisingly, because of the quantum confinement and decreased dielectric screening, robust excitonic absorption in monolayer Transition Metal Dichalcogenides (TMDCs) can reach up to 20% at room temperature. This allows studying the interplay of light and matter possible on a state-of-the-art platform: 2D materials. Among the remarkable optical features found in 2D materials are single-photon emission, Dirac-type plasmons, helicity of valley excitons, near unity excitonic reflection, and photoluminescence (PL) quantum yield. Furthermore, the optical properties of 2D materials are considerably enhanced by their remarkable tunability. Specifically, the non-bonding characteristic of the van der Waals (vdWs) interlayer interaction allows 2D materials to be arbitrarily stacked layer by layer to construct homo/heterostructures without a lattice matching restriction, thereby providing unlimited freedom to control optical properties.

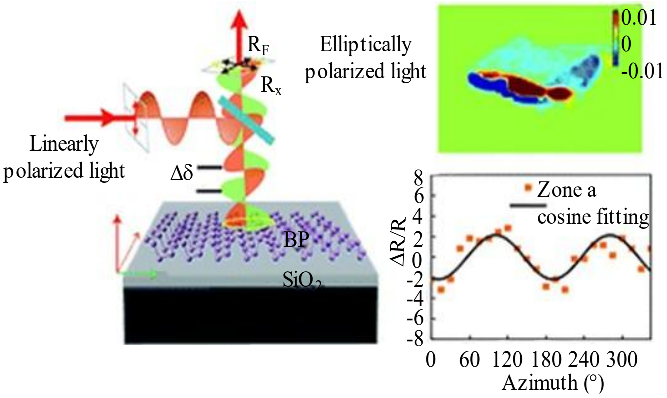

Figure 3. Resolving the optical anisotropy of low-symmetry 2D materials.

Due to the in-plane low crystal structure symmetry, a special class of 2D materials with in-plane anisotropic properties is particularly intriguing to researchers. Black phosphorus (BP) is the most representative and extensively researched one. First, BP caught people's attention because of its highly adaptable qualities and high carrier mobility, connecting graphene and TMDCs with features like a strongly thickness-dependent direct bandgap that spans the visible to the Mid-IR (MIR) regime and perfectly complements the bandgaps of both materials [17].

In the Figure 3 Electrical, optical, mechanical, and thermal properties soon after became problematic due to its anisotropic state. Anisotropy affects optical properties in a way that not only causes well-known phenomena like linear dichroism in absorption and birefringence, but also gives you more control and flexibility over how you can detect and control light. However, anisotropy results in various optical conductivities along various in-plane axes. These unique polaritons with their extraordinarily high Density of energy State (DOS) and directional propagating rays are among the most fascinating phenomena in photonics [18–21].

Momentum to capture more towards photon than electron

Fundamentally, both light emission and absorption are joint properties of the emitter and its optical surroundings. Photons have far smaller momenta than electrons do at comparable energies, therefore the optical environment usually only affects the emission/absorption rates, leaving the emitter transition frequencies almost as intrinsic properties. Here we show how surface polaritons, like graphene plasmons but also relevant for other forms of polaritons, enable significant and controllable control of the transition frequencies of a nearby quantum well, clearly breaking from the emitter-centric perspective. This finding depends critically on the enormous momenta of surface polaritons, which can approach the momenta of electrons and impart a marked non-local behavior to the quantum well. This work makes it easier to access non-vertical optical transitions in solids and supports ongoing efforts to do so in indirect-bandgap materials like silicon. It also enhances research on non-locality in photonics, which has been crucial to a number of scientific and technological breakthroughs. In fact, this idea of quantization is essential to comprehending both light emission and absorption, enabling important photonic technologies like solar cells, LEDs, and Charge-Coupled Device (CCD) photodetectors as well as lasers and other Light-Emitting Diodes (LEDs). The Purcell effect allows for highly accurate control of the relative amplitude of the different transitions by altering the local optical environment of an emitter. The Purcell effect alters the local density of photonic states by speeding up transition rates at some frequencies and slowing them down, which affects the emission/absorption spectrum.

Quantum Confinement Cavity to Expand for Mid Infra-red

The "particle in a box" concept, widely explored in semiconductor quantum dot research, was extended into mid-infrared (IR) cavity modes by means of lateral confinement in an optical cavity. Discrete cavity modes combined with molecular vibrational modes gave rise to four polariton states that can support numerous coherence states in the IR region. Descriptive issue used specialized pump pulse sequences to prepare these coherences selectively, and we confirmed the existence of multiple coherences. The simulation using the Lindblad equation demonstrated that the four polariton states were particularly resistant to decoherence brought on by variations in space because they shared a cavity [22].

Half-matter, half-light quasiparticles known as molecular vibrational polaritons have the ability to alter chemical reactions, alter energy transfer pathways, and possibly serve as an alternative platform for quantum simulation [23]. When the collective dipole coupling between cavity photon modes and molecular vibrational modes is strong enough to cause the two modes to exchange energy faster than the lifetimes of either mode, Upper and Lower Polaritons (UP and LP) are formed, and the systems enter the so-called Vibrational Strong Couple (VSC) regime. Most molecular vibrational polaritons are currently produced in the Fabry-Perot (FP) cavity, which has a corresponding cavity photon mode for every unique in-plane momentum. These modes form a continuous parabolic dispersion curve at various in-plane momentum [24.] Because of this, an FP cavity can only hold one coherence, or off-diagonal density matrix element, for any pair of UP and LP at a given in-plane momentum. Thus, under ambient conditions, UP and LP can be regarded as a single polariton qubit system [25].

CONCLUSION

The exploration of hybrid light-matter interactions, particularly through the lens of exciton-polaritons and their associated lasing phenomena, has revealed profound implications for the future of photonic technologies. By leveraging the unique properties of these quasi-particles, we can achieve efficient, low-threshold lasing, which holds the potential to significantly advance the fields of optoelectronics and quantum devices. This new frontier not only deepens our understanding of fundamental light-matter coupling but also opens up transformative applications, from ultra-compact lasers to novel quantum information systems. As research in this area continues to evolve, the integration of these advanced photonic systems into everyday technology promises to redefine the capabilities and efficiencies of next-generation devices, marking a pivotal shift in the trajectory of light-based innovations.

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