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Ultra-strong light–matter coupling and superradiance using dense electron gases

Couplage ultra-fort lumière–matière et superradiance avec un gaz dense d'électrons

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ABSTRACT

The physics of the interaction between a dense two-dimensional electron gas and a microcavity photonic mode is reviewed. For high electronic densities, this system enters the ultra-strong coupling regime in which the Rabi energy, which measures the strength of the light–matter coupling, is of the same order of magnitude as the matter excitation. The ultra-strong coupling has been experimentally demonstrated by inserting a highly doped semiconductor layer between two metal plates that produce a microcavity, with extreme sub-wavelength confinement of the electromagnetic field. A record value at room temperature (73%) of the ratio between the Rabi and the matter excitation energies (the relative Rabi energy) has been measured together with a very large photonic gap induced by the polariton splitting. The ultra-strong coupling is a manifestation of a huge cooperative dipole, which is proportional to the number of electrons participating in the interaction. Such a phenomenal interaction with light appears also in the absence of a microcavity and, for a dipole coupled with free space, it gives rise to superradiance.

RÉSUMÉ

Nous passons en revue la physique de l'interaction entre un gaz bidimensionnel d'électrons et un mode photonique de microcavité. Pour des densités électroniques suffisamment grandes, le système rentre dans le régime de couplage ultra-fort, dans lequel l'énergie de Rabi, qui mesure l'intensité du couplage lumière–matière, est du même ordre de grandeur que l'excitation dans la matière. Le couplage ultra-fort a été démontré expérimentalement en insérant un semiconducteur fortement dopé entre deux couches métalliques, qui forment une cavité avec un confinement très sub-longueur d'onde du champ électro-magnétique. À température ambiante, une valeur record (73 %) du rapport entre l'énergie de Rabi et celle de l'éxcitation électronique (l'énergie de Rabi relative) a été mesurée, ainsi qu'une large bande interdite photonique induite par l'anticroisement entre les branches polaritoniques. Le couplage ultra-fort est une manifestation de l'existence d'un dipôle coopératif, proportionnel au nombre d'électrons qui participent à l'interaction avec la

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lumière. Ce très fort couplage apparaît aussi en l'absence d'une microcavité et, dans le cas d'un dipôle couplé à l'espace libre, donne lieu au phénomène de superradiance.

1. Introduction

Ultra-strong light–matter coupling is a regime of cavity quantum electrodynamics, reached when the light–matter coupling energy, the Rabi energy E_R, is of the same order of magnitude as that of the matter excitation, E_{matter}, or of the cavity photon, E_c [1]. In this case, the routinely invoked rotating wave approximation is no longer applicable and the light–matter interaction Hamiltonian has to include anti-resonant and quadratic terms. As a consequence, new quantum phenomena and fascinating effects appear, ranging from dynamical Casimir effect [2,3] to superradiant phase transitions [4,5], efficient light emission [6–8], modified photon blockade [9], extraordinary conductance [10–12], cavity-assisted chemical and thermodynamic effects [13].

The first experimental observation of the ultra-strong coupling regime has been obtained by coupling an electronic excitation between confined levels in a quantum well (intersubband excitation) and a microcavity mode [14,15]. The quasi-particles issued from this coupling are called intersubband polaritons [16,17]. Thanks to the versatile engineering of the doping and of the electronic confinement, intersubband polaritons can display high values of the relative Rabi energy, i.e. the ratio between the Rabi and the matter excitation energies, E_R/E_{matter}. As a matter of fact, ultra-strong coupling regime has been demonstrated with intersubband polaritons in both the mid-infrared [14,18–22] and the THz range [15,23,24], by using different cavity geometries, from planar microcavities based on a dielectric confinement, to plasmonic microcavities displaying a highly subwavelength photon confinement.

Today, the ultra-strong coupling regime with a microcavity mode has been observed in several other material systems: superconducting circuits [25,26], cyclotron transitions [27], and cyclotron plasma [28], Frenkel molecular excitons [29,30], dye molecules [31,32].

In this review article, we will focus on intersubband polaritons, which are a system of choice for studying the fundamental properties of the ultra-strong coupling regime and its applications in photonics. That can be found in devices operating in the strong and ultra-strong coupling regime, where intersubband quantum engineering merges with photonic confinement to realize, for instance, quantum-well infrared photodetectors [33,34] and electrically pumped emitters [35–39]. Moreover, in this class of devices, there is a still underexplored link between electronic transport and quantum optics, which is now the object of investigation for organic systems coupled in plasmonic structures [10].

Another property of our system that has attracted much attention in the past few years is the bosonic character of intersubband polaritons [40]. Indeed, their interaction with optical phonons [38] may be exploited to realize devices based on stimulated emission of polaritons [40,41], following the same operation principle as exciton polariton lasers [42,43].

Finally, it must be pointed out that intersubband transitions in quantum wells are also suitable to be strongly coupled with the modes of plasmonic metasurfaces [44–46], giving rise to giant non-linear susceptibilities [47,48]. Coherent perfect absorption has been also observed in a photonic crystal resonator in the presence of a coupling with intersubband excitations [49].

Here we will review the basic concepts and some of the experimental results on the ultra-strong coupling between intersubband excitations in highly doped quantum wells and cavity modes. In sections 2 and 3, we will discuss the main properties of intersubband transitions and their coupling with cavity modes. Then, in section 4 we will present the properties of photon confinement in metal–dielectric–metal microcavities and we will justify why these cavities are particularly suitable for the observation of the ultra-strong coupling regime with intersubband excitations. The observation of the ultra-strong coupling regime with record values of the relative Rabi energy (73%) at room temperature will also be reviewed. The origin of such a high value of the relative Rabi energy can be ascribed to the fact that intersubband excitations in highly doped quantum wells display an extremely large collective dipole that almost perfectly overlaps with the photonic mode. We will show in section 5 that another way to probe the large dipole of collective intersubband excitations is the study of their decay into free-space radiation: a phenomenon called superradiance, recently observed in highly doped quantum wells [50]. Finally, we will discuss some perspectives in the field of intersubband polaritonics in the ultra-strong coupling regime.

2. Collective electronic excitations in quantum wells

Our system, conversely to those discussed in most of the articles of this issue, is based on *n*-doped semiconductor quantum wells, in which doping produces excess electrons. The left-hand part of Fig. 1 presents a sketch of the conduction band profile of a quantum well, confining electrons in the growth direction. As electrons are free in the layer plane, they display an approximately parabolic dispersion as a function of the in-plane momentum, as shown in the right-hand part of

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