PHYSICAL REVIEW B VOLUME 61, NUMBER 20 15 MAY 2000-II

Coherence effects in light scattering of two-dimensional photonic disordered systems: Elastic scattering of cavity polaritons

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(Received 3 March 2000)

Resonant scattering by cavity polaritons in a semiconductor microcavity is investigated. The bidimensional photonic behavior is well shown by the angular spread of the Rayleigh scattered light on the elastic cone. Moreover, the strong coupling between the excitonic oscillator and the cavity mode enables the simultaneous observation of both (i) universal properties of disordered systems such as coherent backscattering over a large angular width, and (ii) scattering anisotropy due to the microscopic nature of the scatterer.

Interference and coherence effects in elastic light scattering from disordered systems have been the focus of wide interest due to their importance in many domains of physics.[1] They have also been revived by the analogies that could be made with theories and experiments developed for the propagation of electrons in disordered systems, such as the weak and strong localization regimes.[2] For electron systems, such studies have been seen as direct evidence of the quantum nature of the electron and resulted in the breakdown of classical transport descriptions such as the diffusion equation or the Boltzmann equation.

For photons, coherence effects also led to the reexamination of radiative transfer equations.[1] Of paramount importance was the observation for electrons or photons of weak localization in the form of coherent backscattering (CBS), which provides an unambiguous signature of phase coherence in the system.[1] The latter experiments are usually carried out in a large variety of physical systems (thin films, dielectric spheres, rods, etc.), where the disorder is due to fluctuations of the real part of the effective refraction index originating in either composition or size fluctuations of the scatterers. These systems allow one to adjust the scatterer density to yield a favorable ratio of light wavelength (λ) to light mean free path (l^*).[3]

In other light scattering experiments the light frequency is resonant with an elementary electronic excitation. In such studies the disorder being observed is the one acting on the resonant electronic excitations.[4–8] The light reemitted by the system consists of (i) a coherent, elastic part due to *static* disorder, called resonant Rayleigh scattering (RRS); (ii) an incoherent, elastic part called resonant hot luminescence, involving inelastic scattering events such as phonon scattering; (iii) partially or completely thermalized contributions called photoluminescence (PL). These emissions yield information on the energy level scheme and nature of these levels, as well as on their dynamics. This is well demonstrated in two-dimensional (2D) semiconductor quantum wells (QW's): early work on RRS demonstrated exciton localization effects and the existence of a mobility edge[9] while more recent studies dealt with the dynamics of RRS,[10,11] and the speckle spectroscopy of disorder.[12]

In this paper, we report on resonant elastic light scattering in a 2D system where the light-matter interaction is in the strong-coupling regime. We use semiconductor microcavities, where the 2D QW excitons are strongly coupled to the 2D photon states of a high finesse planar Fabry-Pérot cavity.[13] The resulting coupled-mode excitations are called cavity polaritons.[14]

There are a number of original features in this system which impact on light scattering: First consider what happens for *nonresonant* 3D disordered systems in microcavities (the disorder is considered small enough for a cavity mode to develop). In a first approximation, the scattered far-field light is distributed on the Fabry-Pérot cones. Such cavity-based features of nonresonant disorder have been observed and modeled only in the small cavity finesse case (thin films).[15,16]

First consider resonantly excited excitons in 2D quantum wells: one deals with a quasi-two-dimensional electronic system, in which ideally elastically scattered excitons lie on a constant energy ring in k space. However, multiple scattering leads to a randomization of the scattered photon wave vector, with energy being conserved only between initial and final photon states.[17]

This occurs due to the low exciton dispersion on the scale of the photon wave vector. Therefore, the RRS intensity is isotropic and does not reflect the bidimensionality of the excitons.[4,8,11,18] Investigating RRS of a quantum well in a microcavity in the weak-coupling condition, one mainly expects a cavity filtering of the scattered light and therefore a featureless ring of scattered light.

In contrast, a microcavity in the strong coupling regime is an almost ideal 2D photonic system: when photon loss through the cavity mirrors is negligible (a good approximation in our high-finesse cavity[19]), the coupled exciton-photon

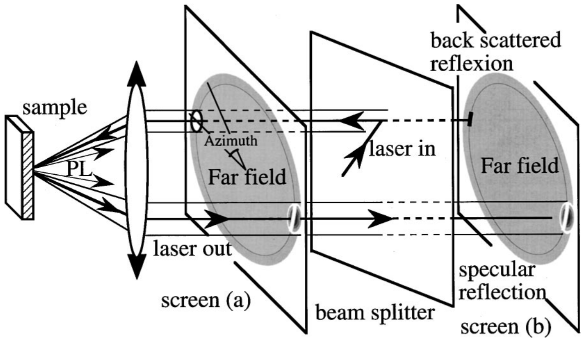

FIG. 1. Far field emission pattern setup, screen (a) is used in most measurements, screen (b) is used for backscattering measurements.

states (cavity polaritons) are a perfect 2D system and the 2D dispersion curve exhibits a significant curvature. It is therefore expected, and indeed observed that scattering events occur on the quasielastic ring of resonantly excited states, showing the coherent and noncoherent effect of the microscopic exciton disorder and its anisotropy.

The experimental setup consists of a Ti:sapphire laser beam impinging at the edge of a $f/2$ lens (Fig. 1). The beam is focused on the sample with an incidence angle of $9°$ and angular aperture of $1°$. The same lens is used to collect the light emitted from the sample. The spot is 100 μm in diameter and impinging intensity is kept at a low value of 100 mW/cm^2. The collected light either forms an image of the far field pattern on a visualization screen (Fig. 1) or is coupled into a monochromator. The screen is located either in front of or behind a beam splitter when the exact backscattered direction is observed. A movable diaphragm after the collection/excitation lens allows spectral measurements to be taken as a function of emission angle. In all cases, the excitation is resonant with the lower cavity-polariton branch and the sample temperature is between 1.5 and 4.2 K.

The sample consists of a high finesse microcavity formed from GaAs/AlAs distributed Bragg reflectors (21, 24 pairs front and back, respectively) around a 2λ GaAs cavity containing three $In_{0.04}Ga_{0.96}As$ quantum wells, one at each cavity antinode. The sample has a Rabi splitting energy of 5.1 meV and linewidths in the 100 μeV range.[20] The cavity-exciton detuning varies from $+8$ to -4 meV (negative for cavity energies smaller them the exciton) as a function of sample position due to a designed variation in the cavity length. Angular measurements show the now-standard cavity-polariton dispersion curve. The quality of the sample is such that disorder plays a small role in the spectral properties of this system.

Figure 2(a) shows the far-field image of the microcavity emission and scattered light as a function of angle. The excitation laser spot is in resonance with the lower polariton branch. In this image, a narrow ring of resonantly scattered light can be seen showing some structure along the ring. The exciting beam covers a finite range of incidence angles larger than the cavity-polariton angular width. A neutral density filter has been used to reduce the intensity of the reflected spot in Fig. 2(a). A dark arc in the reflected beam can be seen. It coincides with the ring of RRS, and represents the

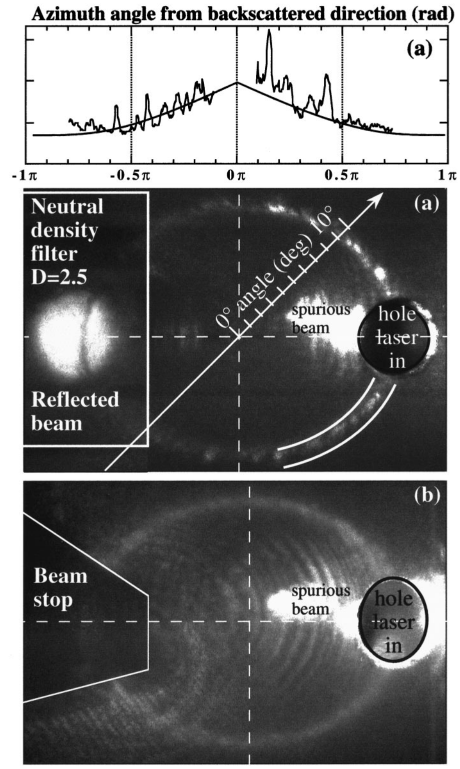

FIG. 2. Far field image observed before the beam splitter [screen (a), Fig. 1] under resonant excitation of the lower cavity polariton branch for (a) a detuning of -2.5 meV. Note the elastic Rayleigh arc of circle, its speckle, the attenuated specularly reflected spot, with the absorption beam appearing as a dark arc against an undiminished, nonresonant, reflected beam; (b) a detuning of $+1$ meV, $T=4.2$ K. In both cases the intensity emission profile on the Rayleigh circle vs the azimuthal angle is plotted above (counted from the backscattering direction). The large fluctuations present in (a) and not in (b) are due to speckle effect. The continuous line in (a) is a guide to the eye. ''Spurious'' beams found on all images originate from reflection on cryostat windows.

polariton as it would be seen in reflectivity. Careful investigations show the following: (i) The scattered ring is only observed when resonantly exciting the lower polariton branch and for all accessible negative and positive detunings up to $\delta=+2.5$ meV. (ii) At negative detunings, it conserves the linear polarization of the incident photon. (iii) The intensity variations along the ring resemble speckle features. They are very sensitive to any variation in position, angle, or wavelength of the laser. (iv) The emission is spectrally identical to the laser. (v) The intensity of the ring is strongly temperature dependent. At higher temperatures (20 K) the intensity vanishes and the ring becomes a featureless ring of *unpolarized* light. (vi) Due to the limited dynamic range of the camera, other effects are not visible in the figure, which will be discussed below.

There is PL inside the circle. The PL is nonresonant with the laser, shows the same linewidth as the lower polariton branch, changes wavelength as a function of observation angle, and follows the cavity-polariton dispersion curve.[14] Although the unambiguous proof of coherence can only be done by interferometric methods,[21] the presence of speckle [Fig. 2(a)] is already a very good indication of the coherence of the elastic ring. We can therefore explain features (i) through (v) in the following way: the speckled, polarization preserved ring observed at low temperatures, on the lower polariton branch and negative detuning is due to RRS,[22] and the weak unpolarized featureless ring at high temperatures or positive detuning to hot photoluminescence. This Rayleigh scattering corresponds to in-plane momenta contributions which span a region in k space much larger than the reciprocal size of a polariton state (of the order of inverse microns). It might be difficult to reconcile the observation of Rayleigh scattering with well-defined polariton states, as observed in reflectivity or absorption experiments, or even measure a 2D dispersion curve.[14] Due to the strong curvature of the cavity-polariton dispersion (10^4 larger than for excitons), intermediate states in multiple scattering remain near the polariton dispersion curve. As a consequence it can be shown[23] that weak disorder tends to break the vectorial in-plane momentum polariton dispersion, while still preserving the absolute value of the in-plane momentum. Therefore, while $k_\parallel=(k_x,k_y)$ is not a good quantum number anymore, $|k_\parallel|$ remains a good one. The polariton states are then complex coherent superpositions, with cylindrical symmetry, of ideal polariton states of different azimuthal orientation.

A Rayleigh scattering experiment can then be understood as the excitation of a subset of the whole eigenstate which then reemits over its whole extension in k space, or alternatively as the excitation of a wave packet which then spreads on the elastic ring. However, such a wave packet evolution model leads to a Rayleigh emission centered around the initial creation in-plane wave vector (i.e., around the *reflected* beam). A remarkable feature observed in Fig. 2(a) is that the reflected intensity is stronger in the backscattered direction, showing that additional effects do occur. The favored backscattered direction is a feature consistently observed under various conditions of excitation and detuning. As seen in Fig. 2(a), the line shape shows an enhancement of a factor of 2 in the backscattered direction, with respect to the forward direction, exactly as is expected from CBS. However, the angular linewidth of CBS typically reported is in the range of a few mrad (both for 3D and 2D systems). In our observation the angular linewidth is around 90°, leading to a λ_{db}/l^* value close to 0.2 where λ_{db} is the de Broglie wavelength of the polariton.[24] It is significantly below the Ioffe-Regel limit ($\lambda \approx l^*$) for optical Anderson strong localization and is a regime never observed up to now (to the best of our knowledge) where line shape modification of the CBS is expected.[25] To obtain a quantitative analysis of the present CBS phenomena is clearly beyond the scope of this paper as it requires a new formulation of CBS in strongly coupled systems.

Figure 3 shows a far field image as recorded with a beam splitter [screen (b) in Fig. 1] allowing the observation of the exact backscattered direction. The bright spot in the exact back scattered direction [Fig. 3(a)] is much too intense to be attributed to CBS (up to 10 times that of the speckle averaged background). If the excitation beam is rotated with respect to the crystallographic axis of the sample three spots can be seen. Each one follows a vertical and horizontal mirror symmetry [Fig. 3(b)]. It is well known from optical experiments[26] or direct measurements[27–29] that molecular beam epitaxy (MBE) grown QW's display microscopic anisotropic fluctuations with island structure elongated in the $\{110\}$ direction. Significant scattering anisotropy due to these microscopic fluctuations has never been reported in bare quantum wells.

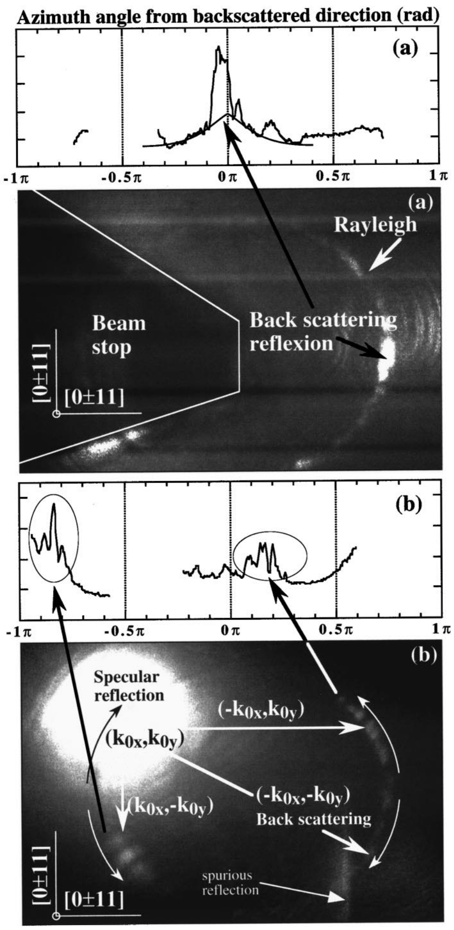

FIG. 3. Far field image observed after the beam splitter [screen (b), Fig. 1], displaying the backscattered intensity, for excitation in a plane of incidence $\{110\}$ (a) or about 30° off (b). In both cases, intensity emission profile vs azimuthal angle are plotted above. The arrows in (b) show how the scattered spots move with respect to the incident laser beam and the substrate crystal orientation. The third peak is hardly seen due to the spurious reflection but is clearly observed when moving the incident beam.

Here the anisotropic disorder is probed in a different way due to the polariton nature of the system leading to a macroscopic manifestation of a microscopic anisotropy. While the CBS discussed previously is a general property of disordered systems, the anisotropy is due to the precise nature of the scatterer.

In conclusion, we have shown that elastic scattering of light in a situation of strong light coupling in a semiconductor system yields detailed information on the eigenstates of the 2D cavity-polariton system, in addition to providing a prototype of a 2D system to study light scattering. The coherence of the scattered light for negative detuning, and its transformation to hot luminescence for positive detuning is strong proof of the phase memory associated with disorder scattering. The 2D photonic behavior is well shown by the angular spread of the Rayleigh scattered light on the elastic cone. Moreover, the strong coupling between the excitonic oscillator and the cavity mode enables the simultaneous observation of both (i) universal properties of disordered systems such as coherent backscattering over a large angular width, and (ii) scattering anisotropy due to the microscopic nature of the scatterer. Such experiments provide a bridge between light scattering experiments in disordered systems and the physics of strongly coupled microcavities, opening eventually towards quantum disorder effects.

We thank Vincenzo Savona for many discussions on disorder effects on excitons and cavity polaritons. This work was supported by EPFL (Switzerland) and the Swiss National Priority Program for Optics.

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