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Quantum information with semiconductor nanostructures

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Abstract. Integrated optoelectronic devices based on exciton-polaritons are very promising for quantum information, since they allow quantum optical effects as well as spin control and spin switching. Moreover the quantum fluid properties of exciton polaritons indicate that they are good candidates for quantum simulation.
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Integrated optoelectronic devices can provide basic functions such as switching, transport and low-level logic. At the same time, the emerging field of quantum information requires specific resources for the implementation of quantum protocols. Particularly promising are optoelectronic devices based on exciton-polaritons in semiconductor microcavities, which open the way both to operation at the quantum level and to spin based architectures. Semiconductor microcavities provide a significant step forward due to their low-threshold, polarization-dependent, nonlinear emission, fast operation and integrability. Here we show the perspectives opened by these devices as tools for quantum information processing.

Exciton-polaritons are mixed light-matter quasiparticles arising from the strong coupling between photons and excitons in a micrometer sized cavity with embedded quantum wells. They have been studied extensively since the discovery of strong light–matter coupling in these systems in 1992 [1]. Polaritons are bosons that can be created by directly shining a laser onto the microcavity. Due to momentum conservation in the microcavity plane, the angle of incidence determines the in-plane wavevector of the polaritons. The very low mass of the polaritons ($\sim 10^{-4}$ times that of the electron, inherited from their photonic component) enables their propagation over long distances at very high speeds (~1% the speed of light, on the order of 1-2 µm/ps). Their excitonic component results in strong polariton-polariton interactions giving rise to high non-linearities.

Nonlinear optical effects are due to Coulomb and exchange interactions between excitons. Owing to these features we have been able to achieve for the first time quantum noise reduction on a light beam transmitted by such a device, relying on a Kerr-like effect [2]. By using non degenerate four-wave mixing, we have demonstrated strong correlations between the two emitted beams [3].

Moreover, polaritons are spin degenerate with two possible values of the spin projection on the structure axis, either +1, or -1. These spin projections directly couple to circularly polarized light (σ+ and σ-, respectively) in both

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excitation and emission, and enable the use of polaritons in polarization sensitive devices. In microcavities in the strong coupling regime, we have observed the optical spin Hall effect, which consists in the generation of a spin current perpendicular to the charge current flow, and is a remarkable effects of spintronics [4]. For polaritons, the optical spin Hall effect [5] consists in a separation between polaritons with different transverse electric and transverse magnetic linear polarizations that takes place owing to a combination of elastic scattering of exciton–polaritons by structural disorder and an effective magnetic field coming from polarization splitting of the polariton states. The excitonic spin currents are controlled by the linear polarization of the laser pump. We have demonstrated propagation of polariton spin currents over 100 µm [6]. By rotating the polarization plane of the exciting light, we were able to switch the directions of the spin currents.

Interaction between polaritons also depends on their spins, resulting in a spin dependent scattering process between coherent polaritons. As a result, when two pumps beams illuminate the microcavity interaction, the 4-wave mixing process generating two other beams is polarization dependent. It can only occur if the two pump beams are co-polarized. Thus a polarization controlled optical gate of a micron size can be realized [7]. The spin dependence of the polariton interaction can also be used for switching. We have demonstrated a non-local, all-optical spin switch. In the presence of a sub-threshold pump laser (dark regime), a tightly localized probe induces the switch-on of the entire pumped area. If the pump is circularly polarized, the switch is conditional on the polarization of the probe [8]. The motion of polaritons results in large propagations of the switched area with a spin state determined by that of a localized probe (non-local action), potentially working at high rates due to the large polariton velocity and reduced lifetime (in the picosecond range).

Due to the interaction between polaritons, the motion of the polariton fluid injected into a planar microcavity by a nearly resonant laser can be deeply changed and become superfluid. For low enough velocities, when the pump laser intensity, i.e. the polariton density, is increased the system goes from a non-superfluid regime in which a static defect creates a perturbation in the moving fluid to a superfluid one, in which the polariton flow is no longer affected by the defect. In the supersonic regime, superfluid propagation is replaced by the appearance of a Cerenkov-like perturbation produced by the defect, in agreement with theoretical predictions [9]. This superfluid property is consistent with the polariton Bose- Einstein condensation demonstrated by other groups. Moreover, in the same way as in atomic condensates, the potential landscape seen by the polariton fluid can be engineered, using potential barriers created by polarized light beams, the shape and the height of which can be controlled at will. In such a way, the polariton fluid can be studied in two, one or zero dimensions, trapped in specific geometries or submitted to a random potential. One of the great advantages of this technique is that it allows for the dynamical modification of the potentials at high speed [10]. These novel properties of exciton polaritons and the capacity to manipulate them like cold atoms indicate that polaritons are good candidates for quantum simulation in the same way as cold atoms, with a potentially high flexibility.

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