Spin-Orbit Coupling in Polariton Graphene: 
Optical Spin Hall Effect and Z Topological Insulator

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Abstract-We show that the TE-TM splitting of planar cavities leads to a special type of spin-orbit coupling for polariton graphene, a honeycomb superstructure formed by pillar microcavities, transforming into an emergent field with Dresselhaus symmetry at the Dirac points of the Brillouin zone. This transformation can be evidenced by the Optical Spin Hall effect. Under an applied magnetic field, polariton graphene behaves as a Z topological insulator with chiral surface states, which can be evidenced by direct resonant excitation.

Exciton polaritons – the quasiparticles formed from the strong coupling of a quantum well exciton and a cavity photon in planar microcavities – are a subject of active research since the demonstration of their Bose-Einstein condensation in 2006 [1]. Their most important properties include light effective mass, two spin projections, and strong spin-anisotropic interactions. They can be created by non-resonant excitation, allowing to study condensation, or by quasi-resonant excitation, allowing to precisely control the wavefunction, which can then be fully analyzed by studying the photons, decaying from the cavity.

The main origin of the spin-orbit coupling for polaritons is the TE-TM splitting, arising from the difference in the reflection coefficients of the cavity for TE and TM polarizations, which is enhanced by a difference in the exciton-photon coupling. The TE-TM splitting is at the origin of the Optical Spin Hall effect [2,3,4], consisting in the spatial separation of opposite spin projections.

Polaritons can be confined in an in-plane potential, engineered by patterning the microcavity [5], by applying surface acoustic waves [6], by using the interactions with the reservoir excitons [7], or by using natural disorder. Many important results were obtained in all these configurations, including the Josephson oscillations [8] and the observation of bonding and anti-bonding state in a pair of coupled pillars [9]. The TE-TM splitting is usually enhanced by the in-plane confinement and the strain. More complicated structures include a polariton benzene molecule (6 coupled pillars) [10] and, finally, polariton graphene [11]: a large hexagonal array of overlapping pillar cavities etched from a larger planar cavity. The presence of the spin-orbit coupling was experimentally and theoretically demonstrated by its dramatic effects in the benzene molecule, while the polariton graphene was proven to have a band structure similar to that of the electronic graphene, including the Dirac points. The major difference with the electronic graphene arises from the original type of the spin-orbit coupling in polariton graphene. Unlike the well-known Rashba or Dresselhaus fields, or the Kane-Mele term acting as an out-of-plane magnetic field in monolayer graphene [12], the TE-TM splitting presents a double rotation, with the direction of the field rotating twice faster than the polar angle.

In our recent works, we have shown that the TE-TM effective field leads to a strong modification of the band structure of polariton graphene [13]. While it does not open a band gap on its own, it leads to the trigonal warping – a transformation of a single Dirac cone into four, with two branches being split off. At the same time,
the reduced symmetry of the Dirac point affects the field, which transforms into the Dresselhaus field close to
the Dirac point, changing the pattern of the Optical Spin Hall Effect from a four-fold in the Gamma point into a
two-fold in the Dirac point.

Moreover, the degenerate eigenstates at the crossing of the branches exhibit spin asymmetry, being a
combination of opposite spins on two distinct atoms, and this combination is exactly the opposite in the two
different Dirac points K and K'. Therefore, a magnetic field, whose main effect when applied to polaritons is the
Zeeman splitting, acts in an opposite way on these points, leading to the opening of a gap, whose eigenstates are
inverted between K and K'. By calculating the Chern numbers, we have shown that due to the spin-orbit
coupling, in presence of a magnetic field the polariton graphene becomes a Z topological insulator [14], with
integer band Chern numbers equal ±2. The bulk-to-boundary correspondence predicts the existence of chiral
states on the surface of such insulator, which we have demonstrated, confirming their one-way nature and their
topological protection from backscattering.

All these results were obtained first in the tight-binding model, where the TE-TM splitting leads to a
difference in the tunneling coefficients for two linear polarizations. We have obtained both the band structure
and the corresponding eigenstates for the infinite 2D polariton graphene and for a finite graphene ribbon,
demonstrating the existence of the surface states. We have also carried out full numerical simulations of
polariton graphene on a 2D grid by solving a spinor Schrödinger equation with TE-TM splitting and a potential,
corresponding to the pillar confinement.

We acknowledge the support of ITN INDEX (289968) and ANR Labex GANEX (ANR-11-LABX-0014).

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