Quantum microcavities for spintronic applications

Research report of I.A. Shelykh

Project goals:

Within the frameworks of the current proposal our research was aimed at *studying one dimentional spin dependent transport in semiconductor microcavities* and *investigation of the possibilities of use of the polariton spin transport effects for realization of prototypes of 'spinoptronic' devices*. The objectives of the project were specified as follows:

Objective 1: Study of the effects of geometric phase in polariton transport
Objective 2: Study of domain well motion in polariton neurons

The goals of the proposal were fully achieved in collaboration with the members of the Mediterranean Institute of Fundamental Physics, namely Prof. A.V. Kavokin and Dr. M.A. Kaliteevskii. Moreover, we established close collaboration with Dr. M.A. Kaliteevski on the topic of his POLATOM project connected to quantum microcavities as sources of THz radiation.

Results obtained:

Objective 1

We considered the effects connected with polariton geometric phase in Optical Spin Hall effect in the nonlinear regime.

Optical Spin Hall Effec (OSHE) is analogical to the intrinsic Spin Hall Effect. The role of Rashba SOI in this case is played by TE-TM splitting of the polariton mode . It is well known that due to the long-range exchange interaction between the electron and the hole, for excitons having non-zero in-plane wavevectors the states with dipole moment oriented along and perpendicular to the wavevector are slightly different in energy. In microcavities this splitting is amplified due to the exciton coupling with the cavity mode and can reach values of about 1 meV. TE-TM splitting results in the appearance of an effective magnetic field provoking the rotation of polariton pseudospin. It is oriented in the plane of the microcavity and makes a double angle with the X-axis in the reciprocal space. This is different from the orientation of the effective magnetic field provided by Rashba SOI which makes a single angle with Y-axis. This difference in the orientations of results in different patterns of spin currents for electronic SHE and OSHE.

OSHE is a linear effect which does not imply polariton-polariton scettering. However, the natural quastion is: what will be effect of the polariton-polariton interactions and will they lead to any qualitative changes of the pattern of spin currents in the nonlinear regime? These changes can originate from spin- anisotropic nature of the polariton polariton interactions: due to the dominance of the exchange in scattering of 2D excitons, the polaritons having the same circular polarization interact much stronger then polaritons with opposite circular polarizations. Moreover, the corresponding matrix elements can have different signs, which leads to the inversion of the poalrization in polariton-polariton scattering . One can thus imagine the following scenario. The interference effects in the disordered microcavity lead to the increase of the backscattering amplitude, and then the scattered beam interacts with ingoing beam via parametric process accompanied by the inversion of the linear polarization . The spin of the final states is then rotated under the effect of TE-TM splitting. The spin currents generated in this process will be inverted as respect to those generated in OSHE in linear regime provided by simple disorder scattering.

We discovered this inversion in our numerical modeling. The corresponding results are shown at Fig. 1. One clearly sees that the increase of the intensity of the pump leads to the inversion of the domains of circular polarization in the reciprocal space, corresponding to the far field spectroscopy (upper panels). The distribution of the polarization in the real space (corresponding to near field spectroscopy) is also affected by nonlinear effects, as it is shown at lower panels of Fig. 1. Again, the effect of polarization inversion with increase of the intensity of the pump can be clearly detected.

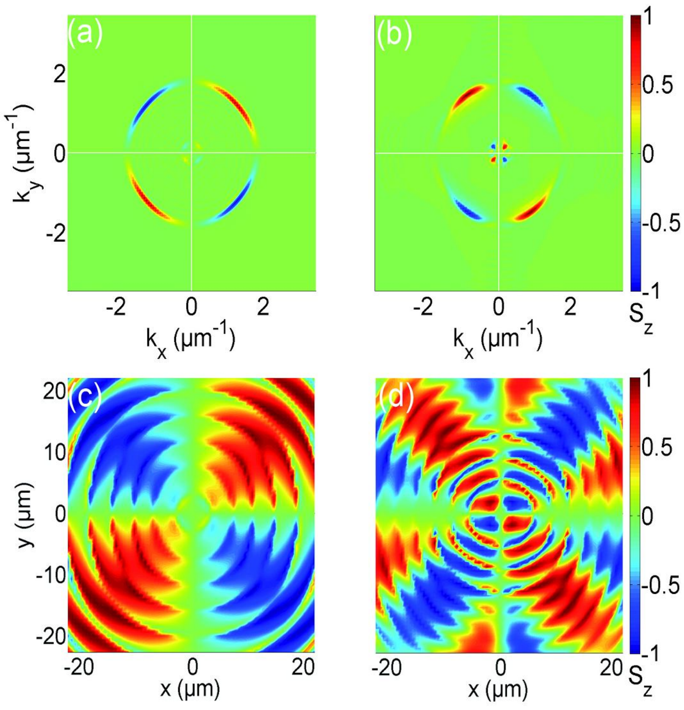

Fig. 1 The distribution of circular polarization degree in real and reciprocal spaces for linear polarized pump at normal incidence in linear((a) and (c)) and nonlinear ((b) and (d)) regimes. One clearly sees the inversion of circular polarized domains with the increase of the pumping power.

Publication on subject: H. Flayac, I.A. Shelykh and M.A. Kaliteevski, Nonlinear Optical Spin Hall Effect, in preparation.

Objective 2.

We studied the effect of temperature on bistability behavior of the polariton neuron.

In semiconductor microcavities, bistability can arise due to the interplay between a blueshift of polaritons caused by their interaction energy and enhanced resonant absorption when the polariton energy matches the energy of an optical pump. The combination of the lateral confinement of the cavity polaritons with polarization multistability allows to propose a concept of a polariton neuron, in which domain wall propagates along one dimentional channel of a given geometry, obtained e.g. by deposition of a metallic stripe. The signal propagation speed depends strongly on the intensity of the driving *cw* field and can reach the values about 1.8×10^6 m/s. It is important that individual polaritons do not move the whole distance from one end of the channel to the other; rather it is the switching of successive parts of the channel caused by very short propagation of polaritons that results in signal propagation. In this sense the channel bears a loose analogy to biological neurons. Although the polaritons have finite lifetime, this does not limit the length of signal propagation in a polariton neuron, and the signal keeps propagating as long as the background *cw* pumping persists.

Although the concept of the polariton neurons is clearly formulated, the details of the domain wall propagation, such as dependence of the propagation speed on the material of the cavity, geometry of the channel and temperature are not clear. The latter was in focus of our consideration.

Standard approach based on Gross- Pitaevsky equations is not applicable, as it neglects the prcesses of the decoherence arising from the interactions of polaritons with acoustic phonons. Therefore, we developed a fully new method of the description of the system, based on density matrix approach. The results of our calculations revealed that themperature strongly affects the bistability characteristics of the system. In particular, with increase of the temperature the bistability curve describing the concentration of the polariton system as function of the intensity of the pump becumes more narrow and disappears above some critical value determined by the material of the system as it is shown at Fig. 2

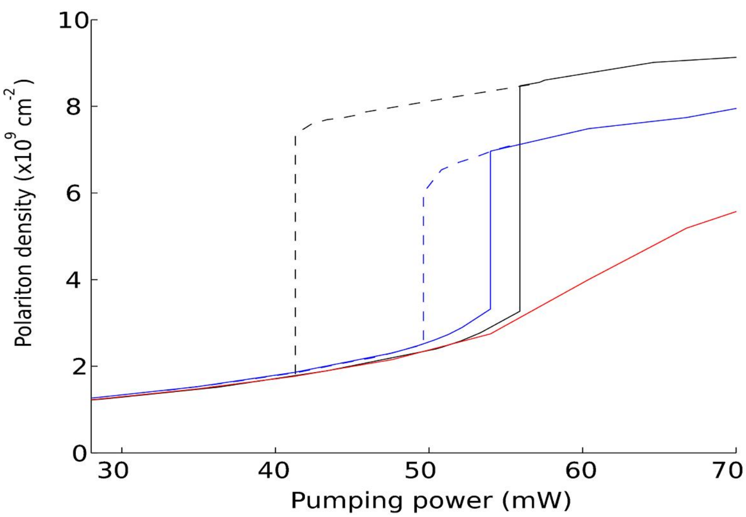

Fig. 2 The dependence of the polariton concen-tration on spatially homogeneous cw pumping intensity for various temperatures. At 10 K (black), the hysteresis curve is quite wide. At 50 K (blue), the hysteresis curve is much narrower, while at 100 K (red) it has disappeared completely. The unit of pumping is the rate of incoming photons.

The propagation of the domain wall is also temperature dependent. At low temperatures the domain wall is quite sharp and its propagation is distinct, while increase of the temperature leads to washing out of the domain wall profile and finally to disappearence of the switching when bistable behaviour disappers (Fig. 3)

<u>*Publication on Subject:*</u> E.B. Magnusson, I.G. Savenko and I.A. Shelykh, Bistability phenomena in one- dimensional polariton wires, *Phys. Rev. B* **84**, 195308 (2011)

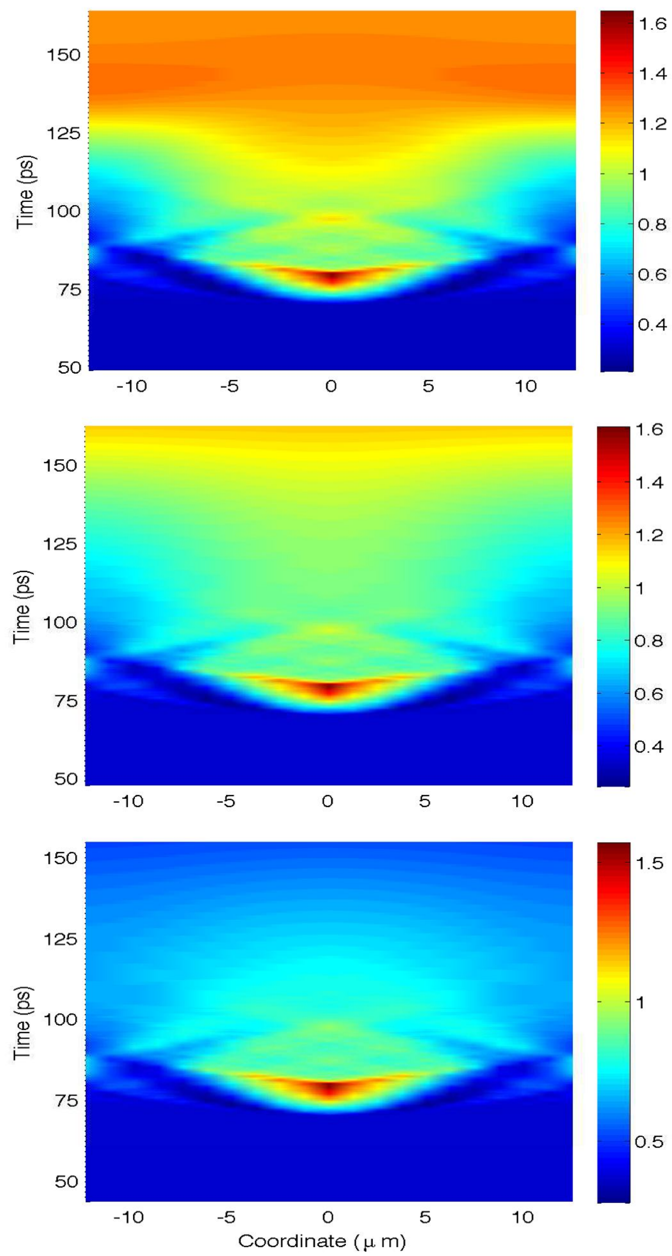

Figure 3. Neuron behavior and domain wall propagation for (top to bottom) T=15K, 20K and 25K. The plots show the polariton concentration in real space (horizontal axis) and time (vertical axis). The system is pumped non-resonantly by spatially homogenious cw laser, at 70-80ps a switching pulse arrives. At 15 K one sees the propagation of the distinctive domain wall which becomes more smeared and fully disappears at 25 K due to that there is no bistability at this pump intensity and temperature.

Objective 3 (not stated initially among the original objectives of the project):

In frameworks of POLATOM grant of Dr. M.A. Kaliteevski we investigated nonlinear Thz emission from semiconductor microcavities.

THz band remains the last region of electromagnetic spectrum which does not have wide application in modern technology due to lack of solid state source of THz radiation: compact, reliable and scalable . Fundamental objection preventing creation of such source is small rate of spontaneous emission of the THz photons: according to the Fermi Golden rule this rate is about tens of inverse milliseconds, while lifetime of the photoexcited carrier in the solid typically lies in picosecond range due to the efficient interaction with phonons. Spontaneous emission rate can be increased by application of Purcell effect when emitter of THz is placed in cavity for THz mode, but even in this case cryogenic temperatures are required to provide quantum efficiency of the order about one percent for the quantum cascade structure.

Recently it was proposed, that rate of spontaneous emission for THz photons can be additionally increased by bosonic stimulation, when the radiative transition occurs into a condensate state. The example is a transition between upper and lower polariton branches in semiconductor microcavity in the regime polariton lasing. Radiative transition, accompanied by emission of THz photon, between upper and lower polariton modes originated from exciton and cavity modes is forbidden, since initial and final exciton states of this transition are the same. Nevertheless, such radiative transition become possible if upper polariton state is mixed with exciton state of different parity. Amplification of spontaneous emission by Purcell effect together with bosonic stimulation increase the rate of spontaneous emission by many orders of magnitude, making it comparable with rate of scattering by phonon which results in effective emission of THz radiation.

It is well known that strong polariton- polariton interactions in microcavities makes possible observation of the pronounced nonlinear effects even for relatively weak intensities of the pump (orders of magnitude smaller then in other optical nonlinear systems). Among them are polariton superfluidity, bistability and multistability, soliton formation and others. One can expect that polariton-polariton interactions will as well strongly affect the process of the THz emission. However, the quasiclassical approach based on Boltzmann equations cannot provide correct description of coherent interaction of THz photons and polaritons, and development of more exact quantum formalism is needed. We built such a formalism, accounting for the following physical processes: coherent polariton- THz photon interaction, polariton- polariton interaction leading to the blueshift of the polariton modes and coupling of the polaritons with acoustic phonons. Development of such description is also timely in light of intensive studies of ultrastrong light-matter coupling, single cycle THz generation, intersubband cavity polariton and control of the phase of THz radiation.

We have demonstreted that polariton- polariton interactions result in the following intriguing phenomana in Thz domain:

1. Bistability of the Thz emission. Equilibrium value of THz population emission n as a function of the external pump P demonstrates threshold-like behaviour. For high enough temperatures, below the threshold the dependence of n on P is very weak. When pumping reaches the certain threshold value, polariton condensate is formed in the lower polariton state, radiative THz transition is amplified by bosonic stimulation, and occupancy of THz mode increases superlinearly together with occupancy of lower polariton state (Fig. 4, blue curve). This behavior is qualitatively the same as in the approach operating with semiclassical Boltzmann equations. However, lowering of the temperature leads to the onset of the bistability and hysteresis in the dependence n(P). The bistable jump appears when the intensity of the pump tunes energy offsets into resonance with cavity mode . The parameters of the hysteresis loop strongly depends on temperature (Fig.4). For 1K, it is very pronounced and broad. The increase of the temperature shifts the loop into region of higher pumps and diminishes it width, until it disappears completely at T=20K.

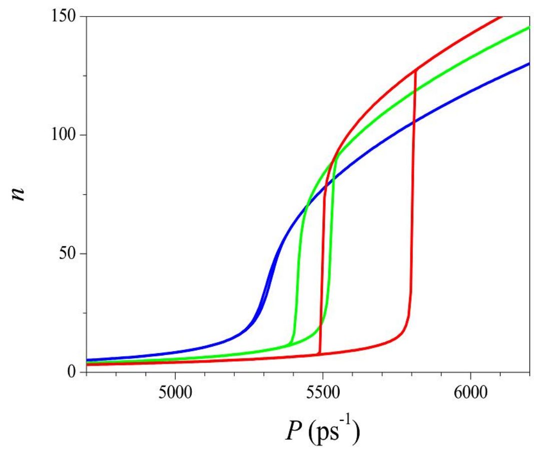

Figure 4. Dependence of occupancy of the THz mode on pump in equilibrium state for different temperatures: 1 K (red), 10 K (green) and 20 K (blue). Illustration of the bistability and hysteresis.

2. Coherent nature of the interaction beween excitons and THz photons make possible the periodic exchange of the energy between polaritonic and photonic modes and oscillatory dependence of the THz signal in time. Fig.5 shows temporal evolution of the occupancy of THz mode after excitation of the upper polariton state by a short pulse with duration of 2 ps. It is seen that the occupancy of THz modes reveals a sequence of the short pulses having duration of dozens of ps with amplitude decaying in time due to escape of THz photons from a cavity and radiative decay of polaritons. The period of the oscillations is sensitive to the initial number of the polaritons in the system N and decreases with increasing of N. Note that if the lifetime of polaritons is less than the period of the oscillations, single pulse behaviour can be observed as it is shown in the inset of Fig.5. Appropriate choice of the parameters can ultimately lead to a generation of THz wavelets composed of one or several THz cycles, which make polariton-THz system suitable for application in a sort pulse THZ spectroscopy.

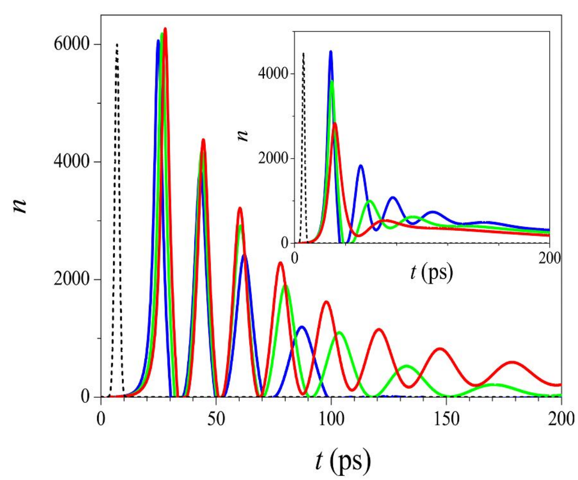

Figure 5. Terahertz photons number dynamics after a short pumping pulse for different temperatures: 1 K (red line), 10 K (green) and 20 K (blue), background pump is switched off. Lifetime 50 ps (main plot) and different on the inset: 15 ps (red), 20 ps(green) and 25 ps(blue).

<u>*Publication on subject:*</u> I.G. Savenko, I.A. Shelykh and M.A. Kaliteevski, Nonlinear terahertz emission in semiconductor microcavities, *Phys. Rev. Lett.* 107, 027401 (2011)

Future collaboration with the members of the Institute

We established the following future collaboration lines with the members of the Meditarranean Institute of Fundamental Physics:

Prof. A.V. Kavokin:

1. Theory of the spin dynamics of 4- component condensates of cold excitons
2. Theory of two- photon processes in quantum microcavities

Dr. M.A. Kaliteevski

1. On- demand generation of vortices in polariton superfluids
2. Confined states in hybrid metal- microcavity systems.