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Polariton spin dynamics in III–V semiconductor microcavities

G. Baldassarri Höger von Högersthal[*1], **A.J.D. Grundy**[1], **J.J. Baumberg**[1], **D. Sanvitto**[2], and **M. Skolnick**[2]

[1] Department of Physics and Astronomy, University of Southampton, SO17 1BJ, United Kingdom
[2] Department of Physics and Astronomy, University of Sheffield, S3 7RH, United Kingdom

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Time resolved measurements have been performed on a III–V semiconductor microcavity in a two beam configuration. Resonant excitation of the lower polariton branch in the parametric amplification regime is provided by a CW laser impinging at 16.5º and the system is subsequently perturbed via a pulsed laser for different angles of incidence. The polarization state of the emission at $\boldsymbol{k}_{\parallel} = 0$ is investigated for different polarization combinations of the CW and pulsed laser. We discuss the interplay between these beams in affecting the polariton spin dynamics.

1 Introduction Recent interest in microcavities arises from the possibility of harnessing the half-matter half-particle nature of polaritons and from the strong non linearities which are visible under high excitation intensities and correspond to a macroscopic occupation of a limited number of states in energy-momentum space [1]. Polarization selection rules for circularly and linearly polarized light, both in the linear and the non linear (OPO) regime, have been the subject of intense research in view of their possible exploitation in spintronic-based devices. Experimental results obtained in the non linear regime by several groups show fast and peculiar spin dynamics, both in the non resonant and the resonant excitation regime [2-4]. In particular, in this latter case unexpected spin dynamics can be envisaged, since combining, for example, a horizontally-linear-polarized pump with a circularly-polarized probe leads to a signal (idler) emission which has a diagonal (vertical) polarization [4]; interestingly, for linearly polarized CW excitation only, the emitted signal at $\boldsymbol{k}_{\parallel} = 0$ is unpolarized. Initially these results have been ascribed to a spin-sensitive parametric scattering [4], while subsequent work confirms the dominant mechanism to be a Faraday rotation effect due to optically induced splitting of the polariton states [5]. More recently, a quantum theory of the polariton spin has been developed, where polariton fine structure and stimulated scattering are specified as the driving elements of the spin dynamics [6].

In this paper, we concentrate on the signal emission from a III–V semiconductor microcavity with a CW-driven population at $\boldsymbol{k}_{\parallel} = 0$ and we address the temporal dynamic evolution of its polarization after perturbation via a pulsed laser. We discuss the experimental results obtained for different angles of incidence and polarization of the excitation beams; finally, we present time resolved data in the case of unpolarized emission upon linearly polarized CW excitation and we investigate the possibility of resolving the temporal evolution of the fine balance between the amplitude and phase of the spin-antiparallel signal polariton populations by unbalancing them via a circularly polarized pulsed laser.

2 Experiment The sample under study is a $3\lambda_{ex}/2$, GaAs/$In_{0.06}Ga_{0.94}As$/GaAs microcavity, as described in Ref. [4]. The experiment is performed at 3.5 K. CW excitation (pump, p) above threshold for

* Corresponding author: e-mail: baldassarri@phys.soton.ac.uk, Phone: +44 23 8059 3930, Fax: +44 23 8059 3910

self-stimulated parametric amplification is provided by a Ti:sapphire laser impinging at 16.5°, with the sample held at zero detuning. Pulses generated via a 100 fs mode-locked Ti:sapphire are spectrally filtered inside zero-dispersion grating compressors in order to selectively excite the lower polariton (LP) branch. The resulting ~ps pulses (with an average power of 10 mW) are set to excite the sample at +16.5° or –16.5°. A system of half- and quarter-wave plates allows us to change the polarization of either excitation beam and are pre-set to compensate for Fresnel losses at the sample surface. The signal is collected at 0°, analyzed with a similar set of wave plates, split by a cube polarizer into orthogonal polarization components and sent to a streak camera. The temporal evolution of the polarization of the signal upon perturbation of the system from the pulsed laser ('kick', k) is monitored with an overall time resolution of up to ~5 ps in the shortest time range allowed by the streak camera.

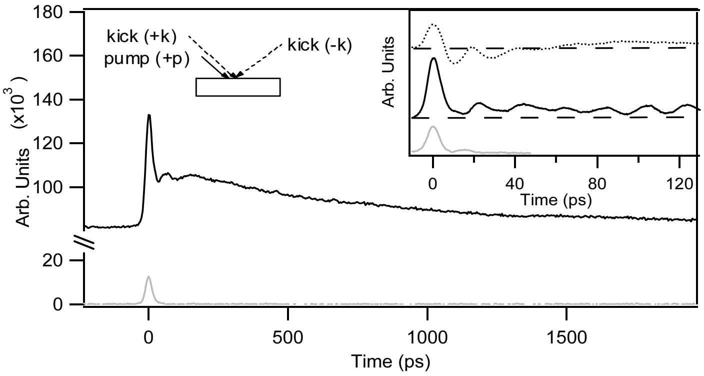

Fig. 1 Signal (black line) and kick (grey line) traces detected on a long time range. Inset: Signal (solid, dotted lines) and kick only (grey line) traces with ~5 ps time resolution; the dashed line refers to the signal level in presence of the pump alone.

3 Results and discussion We first present some general features observed in the temporal evolution of the detected signal. Figure 1 shows typical traces obtained for counter-propagating (p: –k) and co-propagating (p: +k) pump and kick in a long time range. The kick (grey line) is set to arrive at $t = 0$ and its FWHM (~25 ps) gives a measure of the temporal resolution in this time range. Before the kick ($t < 0$), the detected signal (black line) is produced by the CW excitation. Upon arrival of the kick, a sudden increase of the signal intensity is observed, which is characterized by damped oscillations with a fast decay time of a few tens of ps. At longer times the signal rises again, before dropping with a long decay time. The oscillations, resolved with a ~5 ps on a shorter time range (black lines in the inset of Fig. 1), have a period of ~16 ps and are generally visible in all the spectra, including those produced by the kick alone (grey line). We discuss their possible origin later. In some cases (dotted line in the inset), as the kick arrives, the signal intensity initially decreases, while oscillating, and reaches a minimum below the CW level, before increasing again above the CW level and following the general trend. We will address this "dip" below.

Figure 2 shows the temporal evolution of the signal intensity for circular detection. The top (bottom) trace in each panel refers to right (left) circularly polarized *detected* signal. The circular polarization state of pump and kick is (+R: +R) and (+R: +L) in panels (a) and (c), and (+R: -R) and (+R: -L) in panels (b) and (d), respectively, where the + and – signs refer to the excitation angles. The intense peak emission at t = 0 is due to parametric scattering towards the bottom of the trap by polaritons created by the kick. We will comment more on this after presenting the polarization degree in Fig. 3. An analysis of the time-resolved spectra in the (+p: +k) case yields a value of ~(730 ± 50) ps for the long decay time in the (+R: +R) configuration. This gives a measure of the time needed by the system to recover its original CW condition, after the kick has increased the co-polarized CW polariton spin population at $\boldsymbol{k}_{\parallel} = 0$. In the (+R: +L) case, one would expect no effect from the kick, since it is cross-polarized to the CW beam. However, quite surprisingly, the right polarized signal emission does show an increase. This effect is currently not understood at the moment, and is under further study. However, it is interesting to note that the decay time increases up to ~(970 ± 50) ps in this geometry, demonstrating that the recovery behaviour of the CW signal polariton population depends on the excitation conditions which perturb it. In the

(+p: -k) geometry, we obtain similar decay times, meaning that this phenomenology does not depend much on the in-plane *k* of the perturbation, but rather on the microscopic processes controlling the polariton scattering towards the bottom of the trap. In general, although the pulse of polaritons injected by the kick pulse survive only ~10 ps before reradiation, the perturbed $\boldsymbol{k}_{\parallel} = 0$ signal populations takes of order 1 ns to re-establish equilibrium.

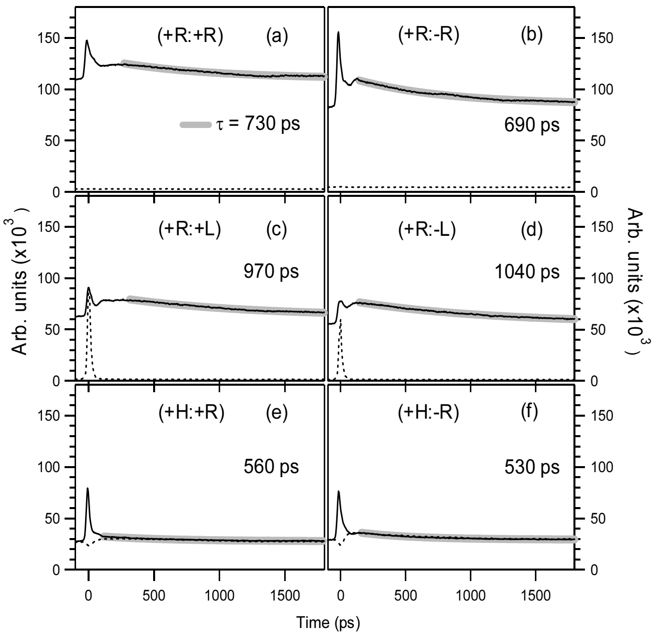

Fig. 2 Time resolved emission at $\boldsymbol{k}_{\parallel} = 0$ for different excitation configurations: left (right) panels refer to pulsed kick exciting at +16.5° (–16.5°), with the CW at +16.5°. The continuous (dotted) trace in each panel is the right- (left-) circularly-polarized *detected* emission. Grey lines are fit of a single exponential decay to the data; the decay time τ has an error of ±50 ps.

More intriguing is the case of linearly-polarized CW excitation combined with a circularly polarized kick, i.e., (+H: +R) and (+H: –R) in panels (e) and (f) of Fig. 2, respectively. At $t = 0$ the circularly polarized kick arrives and strongly enhances the co-polarized signal emission. Simultaneously, the cross-polarized signal emission shows a striking intensity dip in temporal coincidence with the kick arrival. The dip suggests that during its stimulated scattering the kick is able to partially drive the CW polariton population at the bottom of the trap towards its injected polarization state. After the dip, the temporal evolution is similar for both signal polarizations, with a decay time of ~500 ps. Such a reduced decay time may arise due to the existence of two spin anti-parallel polariton populations at $\boldsymbol{k}_{\parallel} = 0$.

In order to get a better insight into the temporal evolution of the signal polarization, for each configuration we consider the three Stokes components of the polarization vector on the Poincaré sphere $S_z = (I_R - I_L) / (I_R + I_L)$, $S_x = (I_V - I_H) / (I_V + I_H)$ and $S_y = (I_D - I_d) / (I_D + I_d)$, respectively [4], and we plot them in Fig. 3. In the (+R: ±R) cases of panels (a) and (b), S_z is constant and close to 1, while the remaining S_i components are almost close to zero; this shows that the polarization of the system remains basically circular. For crossed polarizations of pump and kick, as in panel (c) and (d) for the (R: ±L) cases, the kick perturbs the system mainly around $t = 0$, leading to an overall unpolarized condition, from which the system evolves collecting polaritons at $\boldsymbol{k}_{\parallel} = 0$ by following the CW polarized pump. Finally, when two CW populations are present at the same time as in panels (e) and (f), the pulse “kicks” the system towards its own polarization state. These results show the ability of the kick to act as a polarization switch with the possibility of exploitation in spintronic-based devices.

Finally we briefly discuss the dynamic oscillations observed with ~5 ps time resolution: they are present in most spectra, independent of polarization and angle, and do not show a marked dependence on either the average injected power or on detuning. Since they are visible already from the kick pulse alone, this suggests they are related to some intrinsic effect taking place in the sample. Converting their period into energy, we would get ~0.3 meV, which would be the splitting between two states involved in the creation of beats; these, in turn, might arise because of an additional energy renomalization induced by the presence of the pulse. Another possibility would be in terms of pump-signal-idler system overdriven by the pulse; however, this does not account for the oscillations being independent of the kick power. Alternatively, roundtrip oscillations of the signal emitted at $\boldsymbol{k}_{\parallel} = 0$ between the sample faces initiated by the additional polaritons generated by the kick, could give a similar timescale: 16 ps would correspond to a "cavity" thickness of ~0.7 mm, comparable to the 0.5 mm thickness of the whole sample. Thus further work is ongoing to determine the origin of these dynamical features.

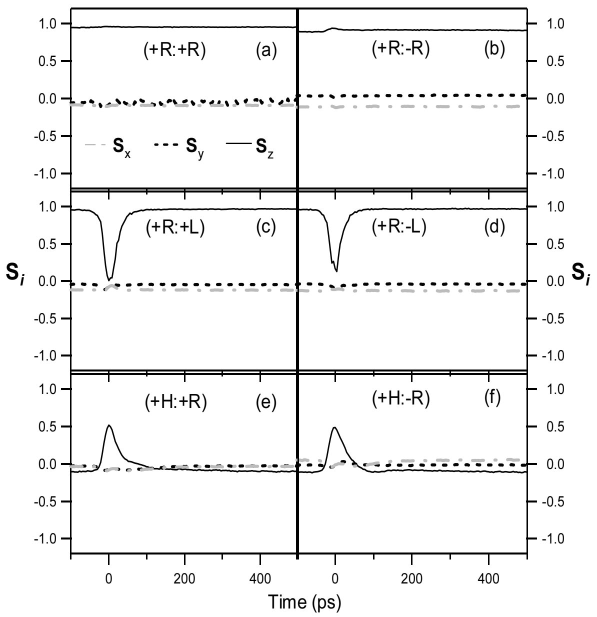

Fig. 3 Time resolved Stokes components S_i ($i = x,y,z$) of the polarization state vector of the signal for different geometries and polarizations of the excitation beams, as indicated in each panel.

4 Conclusions In conclusion, time resolved measurements of the signal polarization of a III–V microcavity excited by a CW laser in the non linear regime and perturbed via a ~ps pulse have been performed for several polarization combinations and excitation angles. We find time decays of the signal in the range of 0.5 to 1 ns, depending on the polarization of the excitation beams. Moreover, we show that the kick can act as a polarization switch. Finally, we reveal the presence of intensity beats with a period of ~16 ps, whose origin is not yet clear. Possible interpretations include multiple internal reflections of the signal collected orthogonal to the sample surface or pulse-induced overdriving of the coupled pump-signal-idler system. This work enriches the ever-growing scenario of spin dynamics in microcavities with new interesting phenomena and represents a first step towards the investigation of a local superfluid phase in the condensed polariton 2D system (Kosterlitz-Thouless transition).

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