Polariton spin Faraday rotation dynamics in a GaAs microcavity

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I. INTRODUCTION

High quality $Q(\nu/\delta\nu)$ semiconductor microcavities have been used to study spin polarization dynamics of the exciton-polariton in microcavities. These bosonic particles can condense into to a polariton final state and can present interesting effects on the spin polarization dynamics or beats. Polariton spin properties can be analyzed by polarization of the scattered light from the microcavity, by measuring the circular polarization degree $\rho = (I^+ - I^-)/(I^+ + I^-)$, where $I^+/I^-$ is the intensity for the $\sigma^+$/\$\sigma^-$ component (right/left circularly polarized), i.e. the pseudospin order parameter. In the resonant excitation process, the generated polariton spin (created by the excitation light polarization) relax by exciton-polariton scattering and exchange interactions. These relaxation processes are inherent to the Faraday rotation effect in the microcavity. Also, in the resonant excitation circularly polarized there is a larger polariton splitting (TE and TM), which can generate a spin quantum beat without external magnetic field. The effect of the Bose-Einstein condensation (BEC) of the polaritons in the polarization properties can be analyzed in terms of the pseudospin order parameter, where the pseudospin dephasing comes from the Larmor precession time. The polariton spin splitting dependence with the cavity detuning shows us a unique way to control the spin relaxations and the polariton light emission polarization helicity, performing one spin controlled optoelectronic device.

In this communication, we show experimental results about the lower polariton (LP) spin Faraday rotation in a GaAs microcavity. We measured the photoluminescence (PL) using a resonant excitation of the LP using the pump-probe technique, i.e. the photoluminescence spectrum with time resolution. The integrated PL spectrum presents one intensity peak as a function of the time delay (between the two excitation pulses). We measured one strong emission in a zero delay and also a second emission after a Faraday rotation delay, coming out due to the probe light Rayleigh scattering. This emission delay (time interval between the two emission peaks) corresponds to the interval for polariton spin precession around the induced magnetic field in the cavity normal direction. We have observed this rotation dynamics as a function of excitation power density, and also the dependence with the cavity resonance detuning, i.e. when we change the lowest energy polariton light nature from $\sigma^+$ (right) to $\sigma^-$ (left).

II. EXPERIMENTAL

The Fig. 1 shows the experimental setup. We used a 100 Å GaAs single quantum well (SQW) embedded in the center of a Al$_{0.3}$Ga$_{0.7}$As cavity, with 26.5 (24) AlAs/Al$_{0.3}$Ga$_{0.7}$As pairs for the bottom (upper) DBR mirrors. The cavity was grown by molecular beam epitaxy with a tilt in the cavity length in order to have a detuning in the cavity resonance energy with the position. The polariton emission behavior was reported previously. The sample was cooled down to 10 K in a cold finger cryostat and the experimental setup was mounted as the usual pump-probe system, using a Ti:Sapphire 50 fs laser. The fs pulse pass through a beam splitter (2/3), creating a pump and probe pulses and the delay $\delta t$ between the pulses was controlled with a motorized linear stage (0.06 µm step, or 0.2 fs in time resolution) controlled by a computer.

The LP emission spectrum was measured for each delay by the 1800 l/mm 64cm spectrometer, which means time and spectral high resolution for this luminescence measurement. Both pulses were focused in to the sample with a $\theta = 12^\circ$ (the magic angle, when the parametric amplification was achieved) in relation to the cavity normal direction as illustrated in Fig. 1. Both the excitation pulses are linearly polarized, therefore the states $\sigma^+$ and $\sigma^-$ can be populated from the linear combination of linearly polarized states. The LP emission was collected from the sample normal direction where the polariton...
wavevector is null, \(k=0\).

**III. RESULTS**

The Fig. 2(a) shows a three dimensional plot with a series of LP emission spectrum for each delay (between the pump and probe), with variation up to 250 ps. A weak laser emission peak is observed for zero delay (the emission peak decay \(\sim 10\) times when we cut the probe beam at this zero delay) and a second strong emission peak appear after a 43.4 ps delay in the probe pulse. No more strong emission peaks are observed for any delay, only a constant background emission due to the two uncorrelated pulses. In the zero delay we see the LP laser emission due to both excitation pulse (pump and probe), and after 43.4 ps delay in the probe pulse we see the second emission peak due to the Rayleigh scattering of the polaritons aligned with the probe pulse polarization direction. This delay corresponds to the Faraday rotation time, i.e. the spin polarization precession time around the effective magnetization \(B_{eff}\) in the cavity normal direction. Since the scattered polaritons (not emitted on zero delay time) with a spin polarization correlated to the pump light spin, will precess around the cavity normal direction (pump and the probe are opposite in direction) before being scattered out from the cavity by the probe pulse. This rotation time \(\tau = (2\pi h/n_0 V\rho)\) depends on the energy splitting between the circularly polarized eigenstates \(n_0 V\rho\), where \(n_0\) is the average number of polariton and \(V\) is the interaction strength.

The Fig. 2(b) shows a contour plot of the emission peak surface curve, showing a precession time of 43.4 ps and also a \(\sim 40\) \(\mu\)eV blue shift in the second emission relative to the zero delay peak. Data on the left in Fig. 3 shows the integrated spectrum for a positive detuning \(\delta=0.36\) meV (\(\delta = E_c - E_x\), where \(E_c\) and \(E_x\) is the uncoupled cavity resonant energy and the exciton energy respectively). We see here higher emission power for the negative detuning (Fig. 3(a)) compared to the emission power at zero delay, which is a surprising result, since the LP laser emission at zero delay should be a stronger process.

Linear polarization Faraday rotation effect in a resonant light passing through a semiconductor has been observed many years ago. The resonant excitation generate polariton population fluctuation in the spin up \(\sigma^+\) and spin down \(\sigma^-\) transitions, which is the equivalent physic system with a magnetic field proportional to this population imbalance in this two level energy condensed states. This energy splitting mechanism is related to the longitudinal/transversal modes for the spin up/down. Nowadays, similar effect has been observed by many groups in excited polaritons in a microcav-
ity with a magic angle, which is one of the necessary conditions for those spin population imbalance. In our pump-probe with PL experiment, we excite polaritons with the pump light in a linear horizontal polarization direction. Most of the excited polaritons relax within its recombination time \( \tau_r \), however part of those polaritons form the BEC state, precessing around the Faraday magnetic field \( B_{eff} \), until the next probe pulse hit the cavity, scattering out the rotated polaritons aligned with the probe light polarization direction. The blueshift (\( \sim 40 \mu \text{eV} \)) in the second emission peak is related to the higher energy of the final polaritons condensed states.

In Fig. 4(a) we show the integrated LP photoluminescence for three different pump power (0.38 W to 0.50 W), showing a rotation delay variation from 46.9 to 60.5 ps for the peak intensity. All data set in this Fig. 4(a) were measured for one fixed cavity resonance energy, and each data point corresponds to an integration of one PL spectrum for the corresponding delay. We observed one strong emission peak at zero delay and a second strong peak after a Faraday rotation delay of 46.9/49.6/60.5 ps with the corresponding pump power (0.50/0.42/0.38 W) and 0.3 meV cavity detuning. Note here the smaller Faraday rotation time for higher excitation pump power. These measurements show us higher amplitude ratio between the two integrated PL peaks for higher pump power. Also a secondary mode structure is observed in the integrated PL intensity for lower pump powers. The insert in Fig. 4(a), shows a rough exponential dependence for the rotation time (\( \ln(\tau) \)) with pump power. The Faraday rotation time dependence with the pump power is related to the polariton density and also to the population imbalance in the two polarization state. Similarly, the Zeeman splitting depends on the spin states population density and on the circular polarization degree \( \rho \).

Figure 4(b) left axis shows the LP spin Faraday rotation time delay dependence with the cavity detuning \( \delta \). For this measurement, we fix a sample position for each pump-probe measurement, so moving the sample around 4.5 mm in direction \( x \) parallel to the SQW plane, we detuned the cavity resonance around 6 meV. In other words, we did PL with the pump-probe measurement for several points on the LP dispersion curve, showing the polariton spin Faraday rotation time dependence with the cavity detuning. We saw a increase on the rotation time from 35 ps to 65 ps when we tune the cavity resonance from lower to higher energy, passing through exciton resonance energy. The Fig. 4(b) right axis shows the integrated emission intensity difference for the first and second strong emission peak for each position in the sample (step of 0.5 mm for the corresponding detuning). This tuning of the cavity resonance energy, change the polariton lower energy photon state from spin up (lower
energy $\sigma^+$ to spin down (higher energy $\sigma^-$) particle. In the inserted Fig. 4(b) we have estimated the pseudospin precession frequency $\omega = 2\pi/\bar{T}$ calculated from the Faraday rotation time for a half precession period $\bar{T}/2$. These data show a monotonic behavior for the splitting energy, however there is a discontinuous behavior in the emission intensity difference $\Delta I$ (estimated from the intensity difference between the two strong emission peak), as highlighted on the discontinuous guide line $\Delta I$.

The TE-TM splitting energy depends on the detuning in relation to the polariton dispersion curve, so the cavity detuning made here is one equivalent way to detune the splitting in the polariton dispersion curve, which have been calculated by Kavokin for a CdTe microcavity.\(^3\)

### IV. DISCUSSION

We investigated here the spin dynamics of two correlated condensate by the resonant linear polarization pump light. The spin relaxation is measured varying the polariton density and also by cavity detuning. We did not consider here the thermal polarization decay time, since for the linear polarization, the thermal dephasing time ($\sqrt{\hbar/nqV}$) would be much shorter.\(^4\) The measured delay support an exponential relation with the polariton density, which is in agreement with the effective $B_{eff}$ dependence with the polariton density.

The time delay $\tau$ observed in this pump-probe emission experiment corresponds to a half Faraday precession period $\bar{T}/2$, whose frequency variation are in the range of 48 GHz to 93 GHz (estimated from Fig. 4(b)), when we tune over the polariton energy dispersion curve by moving the sample position around 4.5 nm. The exponential behavior observed here has correlation with the TE-TM splitting energy calculated previously by Kavokin.\(^4\)

In this work, the measured delay $\tau$ between the laser emission pulse (zero delay) and the Rayleigh scattered pulse at delay $\tau$, differ from the previous work about measurement of the polariton spontaneous emission,\(^10\)\(^11\) i.e. the excitation pump is always above the threshold intensity regime. Essentially, the second emission peak (Rayleigh scattering) is not limited by the polariton spontaneous recombination time. So, the pseudospin precession is a rough model adopted here to interpret the Faraday rotation time observed in this work. The intensity difference data “discontinuity” (Fig. 4(b)) were the amaz-

ing observation on these data. The transition occur for $\delta > 1$ meV (Fig. 4(b)), however this may happen for zero detuning considering the error for the $E_x$ value evaluation for this sample. So, the intensity difference discontinuity may happen when the polariton spin change from $\sigma^+$ to $\sigma^-$ passing throw the linear polarization. It means one transition in the lifetime in a part of the polariton numbers, which is manifest in this pseudospin polariton dynamics measurement.

The excitation pulse power control showed that the condensed LP present in the linear polarization excitation, has a smaller relaxation time of 38 ps for the highest pump power, and for lower pump power we observe a kind of double pulse scattered by the probe pulse. Such behavior can be the spin relaxation time related to the exciton and or BEC-lower polariton, however the determination of that structure is not the matter of this paper.

In summary, we have addressed pseudospin related cavity quantum electrodynamic effects in solid state by measuring the Faraday rotation time in a SQW - GaAs microcavity. We observed the dependence of this rotation time with the polariton density, as well with the cavity detuning in relation to the exciton energy. The linear polarization resonant pump experiment using the pump-probe configuration to measure the PL and Rayleigh scattered polariton light emission, show us one unique technique to determine the precession time for photon-polariton ($\sim 35$ ps) and or for the condensed exciton-polariton ($\sim 60$ ps).

New measurements of the pseudospin rotation times as a function of the pump polarization degree would bring better analyses of the polariton emission coherent or thermal degree, since it corresponds to measure the circular polarization degree. Therefore it would be one direct measure of the second order coherence degree $g_2$.\(^11\)

Those measurements show the Faraday polarization rotation control, i.e. a polariton spin dynamic control in picoseconds regime scale, which show the potential of such effect for optical switching as well as for spintronic devices.

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