Thesis Changes Log

Name of Candidate: Ivan Gnusov

PhD Program: Physics

Title of Thesis: Spinor and vorticity control in polariton condensates

Supervisor: Prof. Pavlos Lagoudakis

Co-supervisor: Assistant Prof. Sergey Alyatkin

The thesis document includes the following changes in answer to the external review process.

Dear Jury Members, I am grateful for your valuable feedback regarding my work. I appreciate your time and effort in reviewing the thesis material. I have carefully reviewed your comments and recommendations and provided detailed responses to each. Please find them below, together with the corresponding modifications in the final version of the text.

Reviewer: **Assistant Professor Yurii Gladush**

Comment: On the sample sketch (Figure 3-6), several pairs of quantum wells are located in antinodes with distance of lambda between each other. In this situation, it is important to discuss if the beam is focused only on one pair or integral signal from several pairs is measured. What focus length was used and does PL from other out of focus QWs contribute to the signal measured.

Answer: *The 50X objective (Mitutoyo M Plan APO NIR B 50X) is used for the excitation of polaritons. It has a depth of field of 1.6 μm, comparable with the cavity's optical thickness. Thus, only one pair of the quantum wells is in the maximum of the excitation optical field; for the other two, the field intensity is at least twice less. Consequently, condensation occurs only in the pair of wells for the low pumping power. The PL from the other quantum wells is significantly less and poorly collected by the objective and does not affect the measurements.*
This explanation is now added to the Chapter 3.2.

Comment: The rotating potential experiment relies on the beating of two independent lasers, thus their mutual coherence is required. I would appreciate the discussion of their mutual coherence time and its influence on the measurement results especially in case of slow rotation .

Answer: *The mutual coherence of two lasers dictates the stability of the beating frequency and, ergo, the stability of the rotation frequency f of the optical trap. Even though the linewidth of lasers is narrow (less than a few MHz) and the emission frequency of both is stabilised with the wavemeter, the frequency jitter and instant shifts can affect their mutual coherence. The beating signal of the excitation laser detuned by several MHz is presented in Figure 6-4 (a) in the thesis. There, the instant changes in the beating frequency are evident on the time scale of 40 microseconds. During the measurement time, the periodicity of the oscillations is changed*

several times. The Fourier transform of the beating signal depicted in Figure 6-4 (b) shows that the beating harmonics have a finite width $\Delta\nu$. Consequently, the mutual coherence time over the 40 μs measurement window is calculated as $1/\Delta\nu$ and equals ≈2.8 μs. Given that the excitation laser pulses have a width of 2 μs, the optical trap rotation frequency for one realisation of the condensate in average, stays unchanged.
However, the mutual coherence of two lasers measured over a larger time window is significantly less due to accumulated frequency jitter. In the experiments, we use the HBT setup described in Chapter 3, and one measurement with this apparatus takes over ten minutes (millions of realisations of the condensate). To characterise the stability of the lasers at such a timescale, we use the same HBT intensity correlation setup and, overlap two excitation lasers (frequency-detuned by 1 GHz) and measure the g(2) at big time-delays. The results are presented in Figure 6-4 (b). The auto-correlation of the beating lasers demonstrates the decay at longer time delays of the HBT interferometer. The decay time there is around (142 ± 8) ns, which is the mutual coherence time of two excitation lasers over the measurement time. Nevertheless, even that does not prevent the intensity correlation measurements since usually GHz rotation speed is required for the experiments, which is significantly higher than the inverted mutual coherence time.
This explanation and the Figure 6-4 is now added to Chapter 6.2.

Reviewer: **Dr. Dario Ballarini**

Comment: I only recommend a thorough review for any typographical errors and English grammar issues.

Answer: *The thesis has now been carefully proofread.*

Comment: it would be beneficial to provide a clearer and more in-depth explanation and discussion of the compensation for experimental setup optical retardance described in section 5.6.

Answer: *The Section 5.6 has now been rewritten.*

Reviewer: **Associate Prof. Dr. Nina Voronova**

Comment: I note that it would certainly benefit from some careful proofreading, as it contains quite an amount of misprints, especially in the first three Chapters, some being obvious typos like missing or misplaced letters, brackets, or spaces.

Answer: *The thesis has now been carefully proofread.*

Comment: "tree" instead of "three" or "conforming" instead of "confirming".

Answer: *This has now been corrected.*

Comment: The only logical flaw that I noticed is that the detailed description of the Stokes calculus for polarisation is introduced much later in the thesis (end of Chapter 3) than referring to it in the context of polariton pseudospin (Chapter 2).

Answer: *This reference to Section 3.3.6 with the definition of Stokes calculus has now been added to Section 2.8.*

Comment: 1. Since the spin coherence described in Chapter 4 is guaranteed by the vanishing overlap of the polariton condensate with the reservoir created by the pump, one would expect the same behaviour from the condensate ballistically expanding out of the excitation spot (such as shown in the left column of Fig. 2-6), since there polaritons also propagate away from the reservoir so they will avoid spin dephasing. Therefore, could it be said that the same conclusions about the transfer of circular polarisation from the pump and pinning of linear polarisation for the case of linearly-polarised pump apply also to radially expanding polariton fluids created by tight Gaussian spots?

Answer: *In fact, the overlap of the exciton reservoir and polariton condensate in the case of the excitation with the Gaussian spot is significant since the condensate is forming atop the pump spot (see Figure 2-6). In this regard, the spin properties of the condensate for the tight Gaussian excitation are similar to the small optical trap (see Figures 4-12 (c) and (d)). As it is stated in Section 4.5: "For all sizes of the excitation ring as well as for Gaussian excitation, we observe the optical orientation effect and condensate that is co-circularly polarised with the excitation laser". The major part of the condensate overlaps with the reservoir, and increased interactions destabilise the condensate spinor, effectively lowering the integrated DOP (see Figure 4.13 (p)) compared to the confined condensate. Moreover, for the linearly polarised excitation, the condensate PL is unpolarised (DOP = 0). It should be noted that most of the emitted light coincides with the spot area for the measurements with a Gaussian excitation spot. Any light away from the spot, possibly adopting nontrivial polarisation textures [E. Kammann et al., Phys. Rev. Lett. 109, 036404 (2012)], has a negligible contribution to the averaged measurements. This discussion has now been added to the Sections 4.5 and 4.8.*

Comment: 2. For the linear polarisation pinning, since the local birefringence is position-dependent, one could expect domains of orthogonal linear polarisations separated by some domain walls (boundaries along which DLP = 0). Was this observed? If yes, could one say anything about the behavior of the condensate phase along those lines separating the domains?

Answer: *Yes, these boundaries have been observed in experiments. Scanning the position of the optical excitation, the change of the polarisation of the condensate emission was observed. On the border of two pinning regions, the integrated condensate emission has a low degree of polarisation DOP, and the pump power dependence of the Stokes components is similar to the one depicted in Figure 5-2(a). The spin of the condensate flips between linearly polarised states during the excitation pulse resulting in low averaged polarisation.*
The position of the sample, in general, does not affect the phase of the condensate. Given that no structural defects of the cavity are near the excitation spot, the phase of the condensate would be the same both in and on the boundary of the polarisation pinning region. This is explained by the fact that the timescale of spin flips is a few ns [Baryshev et al., Phys. Rev. Lett. 128, 087402 (2022)], which is significantly higher than the condensate coherence time (less than ns). This pinning boundary could affect the coupling (and the phase) of two (or more condensates), but it is yet to be studied.

Comment: 3. While it is written that the reported results do not depend on the exciton-photon detuning, from Fig. 4-10, it seems that the linear polarisation "island" is bigger and more pronounced for a more negative (photonic) detuning. Is it expected to vanish completely when one goes to positive (excitonic) detunings? And if so, why would a bigger exciton fraction preclude the formation of this pattern?

Answer: *In the range of exciton-photon detunings from -5 to -2 meV accessible on the experimental setup, the spin behaviour of the condensate is indeed qualitatively similar (see Fig. 4-10). The observed change of the linear polarisation "island" is rather connected with the strength of the position-dependent birefringent field. For different positions on the sample, the strain-induced birefringence varies not only in direction but in the amplitude of the resulting effective magnetic field. That is analogous to the value of the energy splitting between two linear polarisation components – the larger the splitting, the larger the effective magnetic field. In this regard, the shape of the polarisation "island" is defined by the interplay of the self-induced Larmor precession under slightly elliptically polarised excitation and linear polarisation pinning. The "island" shape change could also be caused by disorder in the sample. This discussion is now added to the Section 4.4.*

However, I agree that the more positive detuning and bigger exciton fraction will preclude the formation of the linear polarisation "island" for the given size of the trap. It will be dictated by the increased interactions between polaritons and exciton reservoir. The polariton-polariton interaction strength grows quadratically with the exciton fraction [Y. Sun et al., Nat. Phys., 13 (2017)], so the interactions will eventually destabilise the polariton spin, and in integrated measurements, the linear polarisation "island" probably disappears. However, the increased interactions and decreased mobility of polaritons will probably affect the confinement of the condensate and the overlap between the reservoir and condensate. In this regard, to draw a definite conclusion on the spin properties of the condensate at more positive detunings, it is necessary to conduct an experiment and/or simulations.

Comment: 4. I find it a really curious result that the asymmetry of the harmonic trap creates an analog of the TE-TM splitting for polaritons with k = 0 (at least that is what I understood from Sec. 5.7.1). How does the trap affect the already existing TE-TM splitting for polaritons with nonzero k?

Answer: *In fact, both the asymmetry of the trap and cavity inherent TE-TM splitting create the effective magnetic field (see Equation 5.8). The condensate in the elliptical trap has a distribution of the wave vectors (see Figure 5-1 (e)); they are close but not equal to zero. That is why the condensate is affected by the already existing TE-TM splitting. The effective field for the condensate in the elliptical trap is dictated by the k-space distribution of the condensate, which is, in turn, defined by the elliptical shape of the condensate.*

Comment: 5. Why is the difference in intensities of the two overlapping counter-rotating pump beams is needed to perform the polarization (spinor) rotation in Chapter 5? And why, on the contrary, it is important to have equal intensities in the "rotating bucket" experiment of Chapter 6?

Answer: *Two lasers of different intensities were used for the spinor rotation experiment to create an optical trap similar to the one utilised in Chapter 5 (see Figure 6-1 and 5-1 (a,b)). It allowed us to realise slow MHz spin precession because such a pattern formed a confining potential for polaritons even under slow rotation.*

On the contrary, the "rotating bucket" experiment required higher rotation frequencies (up to 10 GHz) to investigate the vortex appearance's frequency dependence. As discussed in the thesis, GHz rotation speed is comparable with the lifetime of the exciton reservoir, so at fast rotations, the reservoir smears out and does not induce torque to the condensate. In order to increase the range of investigated rotation frequencies, it is practical to use lasers of equal intensities because they create a more non-uniform excitation profile. Such a profile will result in a uniform reservoir at higher stirring frequencies. The corresponding discussion is now added to the Section 7.2. It is worth noting that it is possible to both realise the driven spin precession with equal laser intensities and the "rotating bucket" experiment with different ones.

Comment: 6. What is the minimum trap size that can host a vortex, given that the stirring frequency is in the right window? What is it defined by?

Answer: *Unfortunately, the trap size dependence of a vortex formation in the rotating trap was not investigated. However, the minimal size would depend on the pumping power above the threshold. The bigger the pumping power at the right rotation frequency window, the bigger optical trap is required to host a vortex, which is straightforward from Figure 7-12 in the thesis.*

Overall, the minimum required trap size is defined by the possibility of the trap to host the second excited state. For the very small traps, the second excited manifold of the trap will not be confined, and condensate will form in a ground state. Thus, the minimum trap size would depend on the height of the repulsive potential, which is defined by the interactions of polaritons with exciton reservoir. Moreover, the minimum trap size is dictated by the effective mass of polaritons, which defines their mobility. The effective mass is defined by the photon-exciton detuning.

Comment: 7. Is it possible to directly extract from measurement the healing length of the polariton fluid by looking at the intensity profile of a formed vortex? In Fig. 7-7 unfortunately the white scale bars in panels (a), (c), (e) are not explained (the size is not given), but assuming that the trap is 14 μm in diameter, by naked eye it looks like the healing length of the vortex in panel Fig.7-7(c) is of the order of 2 μm. Could this be used as a rather exact way to measure the polariton interaction constant, and to study its dependence on e.g. photon-exciton detuning, polariton density, etc?

Answer: *The healing length ξ of the vortex in the uniform media is defined* as follows:

$$\xi = \frac{\hbar}{\sqrt{2m\alpha n}}$$

where m is polariton effective mass, α is polariton interaction strength (interaction constant), n is the bulk density of polaritons. In this regard, it is straightforward to extract the interaction constant α . m is calculated from the polariton dispersion ($12.12*10^{-35}$ kg = $1.33*10^{-4}$ m_e), the density n can be extracted from the real-space images of the condensate intensity. However, our vortex is trapped, that affects the shape of the vortex. However, in the limit of weakly interacting polaritons the aforementioned estimate for healing length still holds. From the experiment ξ can be extracted from the cross-section of the vortex density distribution. We find $\xi \approx 1.5$ μm. $n \approx 100$ μm^{-2} . The estimate gives $\alpha \approx$ $1.24 \mu eV \mu m^2$ that is close to the common values of polariton-polariton interaction strength.

Comment: i. It is quite confusing that in the introductory section 3.4. devoted to the general shape of the Gross-Pitaevskii equation (GPE), it is given in the coordinate-dependent form (containing the nabla operator and spatial pump distribution), while later in the main Chapters of the dissertation all GPEs except Eq. (5.8) are only time-dependent, and there is absolutely no comment about them being different from the "general shape" given in the introduction. Are these equations used for simulations written for one fixed point in space? But then, how do they account for the shape of the pump? If, on the other hand, the variable r is assumed to be there but is omitted for the sake of brevity, then where did the nablas go?

Answer: *The simulations for the spin properties of the condensate (carried out by Dr Helgi Sigurdsson) were done using the 0D Gross-Pitaevskii equation, which can be derived from Eq. (3.17). It can be done by projecting the order parameter on only the lowest trap state (ground state). Then, $\psi_\pm(t)$ describes polaritons only in the ground state and neglects contribution from higher energy modes. That is why the spatial degree of freedom is also neglected in this*

simulation, so it, in general, does not account for the shape of the pump. However, the trap shape (size) change is reflected in the change of some parameters of equations, like exciton-polariton interaction (see Section 4.6). The corresponding discussion is now added to Section 4.6.
Also, for the sake of clarity and as per the request from the other Jury Member, Eq. (5.8) and the non-linear model in Section 5.7 have now been removed from the thesis.

Comment: In particular, in Eq. (5.10) one sees a constant ω_0 appearing in the equation for the condensate wavefunction. Physically it should mean the energy level of the condensate, but it did not appear in any previous equations introduced. Is it some specifics of the two-spot configuration?

Answer: *ω0 is the condensate intrinsic energy; this is now added to Section 5.10. It was introduced for the case of coupled condensates because a suitable rotating reference frame cannot be chosen for time-delayed coupling between condensates.*

Comment: Further, looking at Eqs. (6.4a-c) makes one completely puzzled: in all the previous text there was a mentioning of effective magnetic field components Ωx, Ωy, Ωz, but here the equations contain some mysterious quantities Ωσ and nothing is commented about their meaning. From the shape of the Eq. (6.4c) I can deduce that these are the energies of the two condensate components blueshifts, but then again the constant G appearing in this equation is not defined anywhere.

Answer: *Ωσ denoted the polariton-polariton and polariton-reservoir interactions energies, but now, for clarity, this notion was removed. Equation (6.4c) has now been incorporated into Equation (6.4a). G denotes the same-spin polariton-reservoir interaction strengths (this line has now also been added to Section 6.8).*

Comment: The legends of Fig. 6-7(b,c) read "linear pump" and "elliptical pump". I understand it should be rather "linear polarization" and "elliptical polarization", otherwise it sounds confusing.

Answer: *The image has been corrected.*

Comment: In page 126, it is written "in the vicinity of 8 deg. of QWP, the condensate eventually adopts the external stirring..". I understood that it's the polarization that starts rotating, not the condensate, so I would be careful here and reformulate.

Answer: *Now, it reads as follows "the condensate spinor eventually adopts the external stirring".*

Comment: In page 137, a bold statement is given: "As it was shown in Section 2, polaritons are shown to be superfluid". The Author should be careful when making such statements. In fact, polaritons are shown to be superfluid only for the case of non-resonant excitation, as it's the only scenario in where they spontaneously choose the condensate phase thus breaking the U(1) symmetry.

Answer: *Now, it reads as follows: "under certain pumping conditions polaritons are shown to be a superfluid."*

Comment: In page 148 while discussing the active and inactive reservoirs, it is written that the active reservoir is that of bright excitons with spin 1, and the inactive is the population of dark excitons with spin 2. Clearly this cannot be correct which is seen even by looking at the equations (7.4)-(7.6). If this would be the case, it would mean that the pump is only populating the dark exciton reservoir which then spin-flip at a rather high rate to fill the reservoir of bright excitons. I suggest that the statements in parentheses about the spin of excitons in the reservoirs are removed.

Answer: *These statements have been removed.*

Comment: In Figs. 7-7, 7-13 the scale bars are undefined and the horizontal and vertical axes contain no labels or ticks, which makes it difficult to judge anything about sizes.

Answer: *The length of the scale bars is now specified in Figures' 7-7, 7-13 captions.*

Reviewer: **Assistant Professor Fabrice P. Laussy**

Comment: The text has also not be carefully proofread (the 2nd sentence of the abstract already lacks a verb).

Answer: *The thesis has now been carefully proofread.*

Comment: "polariton blue-shift due to polariton-polariton integration" is understood as involving "interaction" instead.

Answer: *This has now been corrected.*

Comment: "*" for instance is not used in a scientific text for multiplication, as it is in an email or computer code, but the times product ($\times$ in LaTeX) should be used.

Answer: *This has now been corrected.*

Comment: The way figures are labeled, with a – instead of a . is also a bit confusing as one use – to refer to ranges so Fig. 3-4 evokes two figures (Fig. 3.4).

Answer: *Figures labels are formatted according to the official Skoltech thesis template.*

Comment: References should also be looked at more closely. Some are repeated (e.g., 38 & 105), proper names not always accentuated (e.g., bose-einstein), etc.

Answer: *The references have now been checked, the repeating ones were deleted.*

Comment: When the Author mentions the control of spin through light, this is short of what the topic is about as this too-broad definition describes mere polarization optics, so details on the issues at stakes are missing here.

Answer: *A more detailed description of spinoptronics is now introduced in Section 2.8. The corresponding text has now been added to this Section: The spinoptronics is a branch of spintronics where the control over spin is planned to be realised by virtue of light. The spinoptronics combines the study of spin and optical polarisation effects in solids to create quantum optoelectronic devices.*

It focuses on encoding information carried by photon polarisation into spin states of carriers, manipulating them on the nanoscale with light, and retrieving the information as polarised photons. Spinoptronics leverages well-controlled carrier interactions occurring in nanostructures. It also mitigates the challenges of carrier spin relaxation or decoherence, a common limitation in traditional semiconductor-based spintronics. Spinoptronics holds potential for a wide range of applications, including information storage, optical communication, quantum computing, and enhanced sensing technologies.

Comment: The spin algebra and properties of the Bloch sphere are subtle and interesting enough to have deserved more illustrations and discussions, e.g., of the typical possible configurations and how they manifest through the Stokes vectors.

Answer: *The correspondence of the spin states and Stokes vectors is now added to Section 2.8 as follows: In this regard, the spin-up polaritons correspond to the right-circular polarisation of the emission and $S = (0,0,1)^T$. The spin-down polaritons are detected as left-circular polarisation $S = (0,0,-1)^{T.}$ The other spin states are the linear combinations of the aforementioned states. Consequently, the representation of the polariton spin measured as PL polarisation on Poincare sphere is analogous to the classical representation of particle spin on the Bloch sphere."*

Comment: Whether independent landscapes of experimentally obtained components of the Stokes vector which are plentiful in the work, always provide a physical result or if there is some redundancy that can be used to validate or further constrain the measurement. Measuring polarization is indeed a sort of quantum tomography and problematics of state reconstruction are both relevant and unexplored.

Answer: *The polarimeter used in the measurements (see Section 3.3.6) was calibrated to the laser source emission with the known polarisation state and at the condensate emission wavelength. This significantly decreases the measurement error for reconstructing the polarisation state of the PL. However, the noise in the experimental setup results in minimal variation of the experimental data. The Author took it into account, for example, in Figure 5-5. Moreover, the polarisation of the PL could change while travelling through the optical setup via reflection from mirrors or propagation through cryostat glass and lenses. This was also taken into account as a rotation of the raw data Stokes vector in order to compensate for these detrimental effects of the setup optics (see Section 5.6).*

Comment: No spatial coordinate x is used in Eq. 3.2 for instance where the variable is defined.

Answer: *This has now been corrected.*

Comment: Given how important the SLM shaping of potential is for the full thesis, this could have been there better explained and in a more pedestrian fashions.

Answer: *This chapter has now been reworked.*

Comment: Calling "desired" a field distribution seem to imply that it is known (as it is wanted) so the discussion on how to compute.

Answer: *This "desired" has now been replaced with "target".*

Comment: *The sketch in Fig. 3.12 appears to be missing a BS in the first branching of the signal.*

Answer: *This has now been corrected.*

Comment: The functional form of the stimulated scattering term R in the GPE is never explained, not even broadly

Answer: *R is a monotonically growing function of n_R. This has now been added to the Section 3.4.*

Comment: Optical orientation is introduced but too briefly.

Answer: *Optical orientation is introduced in Section 4.3.*

Comment: The mechanism of condensation is also little addressed, overlooking for instance works such as Phys. Rev. Lett., 103:096404, 2009 that highlight the role that polarization plays in its characterization

Answer: *The mechanism of the polariton condensation under non-resonant excitation is described in Section 2.4.2 of the thesis. The relation between the condensation and acquisition of the defined polarisation state by the condensate is now discussed in Section 4.3. The suggested reference has now been added to the thesis.*

Comment: Basic questions that are seen in passing, such as the alleged no-condensation in 2D in absence of trapping, could also be given more importance.

Answer: *The condensation in 2D is discussed in Section 2.4.2. The zero DOP for the linearly polarised excitation is explained by stochastic condensate spin flips within the excitation pulse (see Figures 4-5(a), 4-6 (b)). Note that despite the flips, the polaritons are condensed in this regime.*

Comment: For instance, Fig. 4.12 shows the loss of polarization with smaller sizes of the trap.

Answer: *Note that DOP is zero only in the time-integrated measurements.*

Comment: The Gaussian case … would also presumably correspond to the limit of infinitely large traps, so how all this is consistent and support the narrative could be interesting.

Answer: *This is not the case in our system. Indeed, the overlap of the reservoir and condensate is maximal for the Gaussian excitation since the condensate is formed atop the pump spot. On the contrary, in the case of the large trap, the overlap is significantly less since the condensate is forming inside the trap. It decreases the interactions and decoherence coming from the reservoir.*

Comment: It is also unclear why the the simulations there do not tackle the Gaussian case.

Answer: *As the Reviewer correctly pointed out, the Gaussian excitation can be treated as the case of the very small trap. The simulations performed by Dr. Helgi Sigurdsson did not take into account the spatial distribution of the condensate. Thus, in this 0D simulation, it is not possible to distinguish between the trapped and freely propagating condensate. The change of the trap size just changed some parameters in the model (as described in Section 4.6). As a result, the Gaussian excitation in this model can be treated as a small trap with a big reservoir-condensate overlap. In order to take into account the effect of the excitation potential shape, it is necessary to model the system with the 2DGPE equations, which, unfortunately, was not performed in this* *study. Note that even the 0D model findings corresponds very well with the experimental results (see Figure 4-12).*

Comment: One would also expect a discussion of how much bigger the trap could be and maybe some connection to works such as Phys. Rev. Lett., 118:215301, 2017 that tackled very extended condensates (not for their polarization though).

Answer*: The bigger trap would result in the condensate forming at excited states of the confining potential [Phys. Rev. B , 92:035305, 2015]. Unfortunately, the polarisation properties of the condensate in this case were not studied for our sample. This investigation is planned for further research. This intent is now stated in the conclusions of Chapter 4 and in Chapter 8.*

We also did not observe the condensation in the ground state for the ballistically propagating condensate. On the contrary, the condensate at the Gaussian spot excitation acquires high k-vectors (see Figure 2-6 (e)). However, in this case, the non-trivial polarisation patterns appear through the optical spin Hall effect [Phys. Rev. Lett 109, 036404 (2012)]. It is now noted in Section 4.5 that this effect plays a minor role in the integrated measurements. Overall, it would be interesting to investigate the polarisation in the suggested regime of expanded condensate. The suggested article has now been added to the thesis.

Comment: I did not get well from this Chapter what is universal and fundamental, and what is specific to their case and sample (or class of samples).

Answer*: Section 4.8 with conclusions on this study has now been reworked.*

Comment: I was interested to see that cross H-V photon counting exhibit oscillations that look very much of the Rabi oscillation type and wonder if more information could be extracted on the self-induced Larmor precession from this beautiful result, e.g., in the amount of antibunching and dephasing, or the small asymmetry in time.

Answer*: The details on the Larmor precession properties like spin dephasing time retrieved from g(2) are discussed in Chapter 6.*

Comment: One case of 8 spots is considered to provide an elongated potential which is an interesting but fairly abrupt deviation from all the other cases, and maybe a more careful discussion on the realm of possibilities is in order here.

Answer*: The Section 5.5.2 has now been rewritten.*

Comment: A Chapter on "optical retardance" explains how this was accounted for: here the Author should not forget to introduce what this is in the first place

Answer*: The optical retardance is now introduced in Section 5.6.*

Comment: why this affects this configuration but not the previous one.

Answer: *Indeed, this affects both elliptical and annular optical trap experiments. The correction for the annular case was not crucial since it considers the vertical polarisation of the condensate, which comes through the setup unchanged. For the annular excitation, the corrections were not applied, but now the effect of the optical retardance is stated in Chapter 4 as well. The following remark is now added to Section 4.4:*
"Note that the S2 polarisation component (see Figure 4-4 (e)) for the elliptically and circularly polarised excitation arises due to optical retardance of the detection part of the optical setup. The circular polarisation of the condensate emission becomes elliptical while travelling through the optical elements (lenses, mirrors, etc.) in the setup. The value of the corresponding optical retardance is estimated in Section 5.6. This detrimental effect can be corrected for by the Soleil-Babinet compensator or by the post-processing rotation of the experimental Stokes vectors. We underline here that this retardance does not affect the conclusions on the spin physics of the condensate made in this Chapter."

Comment: I do not see the link between Eqs. (5.1) [formal] & (5.2) [numerical]. It looks like delta should be zero but it is arccos(0.8838).

Answer: *The Section 5.6 has now been rewritten for clarity.*

Comment: The discussion on the two coupled condensates also reads a bit hurried and disconnected from the state of the art.

Answer *The Section 5.9 has now been worked on for clarity.*

Comment: The choice for the 26.5 and 27.5 microns distances should be explained.

Answer: *The values of the separation distance (26.5 μm and 27.5 μm) are chosen to more vividly demonstrate the distinctive polarisation regimes. This line has now been added to the thesis.*

Comment: The "vital" character of S1 is perplexing (another possible example where English maybe confusing).

Answer: *This word has now been replaced.*

Comment: There is an interesting link to some time-delayed physics although brief and with some unclear elements, e.g., the time delay is given by the phase velocity (as opposed to group velocity) bringing questions of what is being delayed (not information, apparently).

Answer: *Indeed the Equation (5.13) is written for the phase velocity, since the phase is important for the coupling.*

Comment: I would again recommend the Author to contrast their approach to other closely related proposals, e.g, relying not on an external potential but internal Rabi oscillations (cf. Light: Sci. & App., 4:e350, 2015, Phys. Rev. Res., 3:013007, 2021 and other similar works) that furthermore span not the equator only but the full Poincaré sphere.

Answer: *It is worth noting that the approach of the external driving is different to the one already implemented for control of polaritons spin. For example, the ultra-fast spin evolution spanning various states on the Poincare sphere was realised relying on the Rabi oscillations between upper and lower polariton branches in the study [Light: Sci. & App., 4:e350, 2015]. The difference is the excitation scheme - CW non-resonant time-periodic excitation in our case and pulsed resonant one in [Light: Sci. & App., 4:e350, 2015] Furthermore, the mechanisms of the evolution of the spin vary - the resonance of the external drive with the self-induced Larmor precession in our study and Rabi oscillations of two induced cross-polarised populations of polaritons in the linear regime in Ref. It would be interesting to explore the interplay of the complex polarisation patterns and the time-periodic drive in future research.*
This text has now been added to the thesis.

Comment: I was unclear as to the possible reason for the revival of correlations after the breaks as observed in Fig. 6.9, which seems a technical, possibly normalization issue (namely, why are correlations larger when they are restarted as compared to where one would expect them to be from where they have been left before the gap).

Answer: : *It is an artefact of the HBT measurements apparatus. It can be attributed to the non-linearity of time to amplitude converting electronics of the SPC card. This line is now added to the Section 6.6.*

Comment: Maybe mentions of still other alternatives, e.g., SAW, could be considered.

Answer: *The approach for the modulation of potential for polaritons with surface acoustic waves (SAW) is now added to the discussion in Section 3.1.3:*
"It is worth noting that this all-optical technique allows the achievement of high GHz time-modulation frequency for polaritons and does not require any modifications made for the sample. In contrast, the periodic modulation technique using surface acoustic waves (SAW) previously implemented for polaritons [125, 126], operates at frequencies in the hundreds of MHz range and requires specific samples."

Comment: The manuscript itself reflects that although it is still in demand of some attention, proofreading

Answer: *The thesis has now been carefully proofread.*

Reviewer: **Professor Vassili Fedotov**

Comment: …though in some places the clarity of writing and English need improving as per my suggestions in the attached copy of the thesis.

Answer: *The thesis has now been carefully proofread. The comments made in the copy of the thesis were implemented. The ones that require a response from the Author are clarified below.*

Comment: The candidate chose to refer to himself throughout the thesis using "we". While "we" is perfectly acceptable for an ordinary scientific publication (which is typically authored by more than one person), a thesis can have only one author and so the use of "we" does not seem appropriate.

Answer: *There are no official requirements from the Skoltech Education department regarding the use of pronouns, that is why the thesis was written using "we". In accordance with the Jury Member's comment, the Author now tried to minimise the usage of "we" and change to the passive voice where possible. However, the corrected version of the thesis is still written in active voice; the Author believes that the usage of this pronoun does not diminish the findings discussed in this thesis. The Author hopes that the rewritten disclaimer put now at the beginning of each chapter will clarify the input made by the Author to the discussed results regardless of the usage of "we".*

Comment: Besides, "we" is completely unacceptable in those parts of the thesis where the candidate happens to present the research carried out by his colleagues.

Answer: *"We" is now removed from the Sections discussing the simulation results.*

Comment: Perhaps, the candidate could improve the beginning of his introduction by highlighting and illustrating the global roles that photonics and solid-state physics play in the 21st century… and then introduce polaritonics as a scientifically interesting and technologically promising product of the two fields of science and technology…

Answer: *The beginning of the introduction has now been rewritten accordingly.*

Comment: Also, Disclaimer sections appear too late and provide too little information on the actual contribution of the candidate to the work presented in respective chapters.

Answer: *The Disclaimer sections are now removed from the thesis. The Author's contribution is now stated at the beginning of each investigative Chapter.*

Comment: Therefore, I recommend the candidate to avoid using Disclaimer sections and, instead, clearly identify and acknowledge at appropriate places in the main text (and figure captions) any contributions that were made by his colleagues to the presented research.

Answer: *The contribution from the colleagues is also stated in the respective Sections in the thesis.*

Comment: I was somewhat surprised to come across some fairly large chunks of other people's work (even though properly acknowledged by the candidate), which were integrated into the thesis sometimes in the form of complete sections. I wonder why in those cases the candidate elected to include every detail of someone else's work, including problem statement, model description, equations derivation and solving, analysis of the results. In other words, why was it not sufficient to include just the results (which, I suppose, could aid the candidate's discussion or analysis) but provide references to other people's publications (like the candidate did in other cases)? Since this thesis (in first place) is a testament to the candidate's personal contribution to the field of polaritonics, such instances appear very unusual and must be properly justified.

Answer: *The parts of the other people's work that the Jury Member refers to are the numerical simulations of the experimental results made by the Author and discussed in the thesis. These simulations were made by Dr Helgi Sigurdsson and Dr Stella Harrison and are published in the same papers with the Author's authorship. From the point of view of the Author, these simulations complement the discussion and explain the experimental results. Without them, the thesis would be incomplete. Now, the motivation for including each of the simulation parts is stated in the thesis. The 2D GPE simulation of the polariton condensate in the elliptical trap (Section 5.7.2) that indeed did not bring much new information to the discussion (given the linear model also described there) has now been removed from the thesis.*

Comment: The candidate does not have to (and, in fact, should not) refer to his papers in the thesis as if they represent some additional sources of information. This thesis is not a review of the candidate's publications – it is the primary source of information for the work the candidate did in the course of his postgraduate research.

Answer: *These references have now been removed from the thesis.*

Comment: Correspondingly, rather than referencing his papers in the thesis, the candidate should refer to relevant chapters instead.

Answer: *This has now been corrected.*

Comment: I expect the candidate to use in the thesis his original plots and diagrams (i.e., created by him), in which case he does not need to refer to his publications in figure captions (i.e., "adopted from Ref. []"). If, instead, the candidate requires to reproduce certain figures or diagrams from either his publications (say, because they were created by other co-authors) or papers published by other groups (e.g., Figure 2-8), it is my understanding that the candidate needs to obtain copyright permissions from the publishers of those works. Once permissions have been granted (it maybe just a matter of checking copyright statements of respective publishers, who often allow the re-use of figures in one's thesis), the candidate should add to figure captions the corresponding statements along with justifications/reasons for including in his thesis someone else's results/creations.

Answer: *The experimental figures in Chapters 4-7 had been produced by the Author. However, according to the policies of the publishers of journals where the corresponding papers with the Author as a first author were published (APS, AAAS, ArXiv), it is necessary to acknowledge the source near the figure (in the caption). Therefore, the utilisation of figures from the Author's papers is granted by the corresponding publishers. This is now also stated at the beginning of each experimental Chapter.*

Figures from the other groups were utilised in the thesis, mainly in the theoretical Chapters and Sections, to showcase the current state-of-the-art research with polaritons and highlight the studies that are relevant to the thesis. The license for the use of these figures was now obtained by the Author (see below), and they are now properly referenced as per the requirements from the publishers.

Figure number	License number
Figure 2-3	RNP/23/SEP/070762
Figure 2-5	5638130392459
Figure 2-7 (a,b)	5631991502396
Figure 2-7 (c,d)	RNP/23/SEP/070406
Figure 2-8 (a)	5632011210651
Figure 2-8 (b)	5632011457044
Figure 2-8 (c,d)	RNP/23/SEP/070408
Figure 2-8 (g)	5632020600255
Figure 3-6	5638131083418
Figure 3-8	RNP/23/SEP/070413
Figure 7-1 (a-l)	RNP/23/SEP/070409
Figure 7-1 (o)	RNP/23/SEP/070410
Figure 7-2 (a)	RNP/23/SEP/070412
Figure 7-2 (b-g)	RNP/23/SEP/070411
Figure 7-2 (h)	5632030797868

Comment: Make sure the formatting of all titles is consistent (in some titles you use small first letters).

Answer: *All titles are now written in the same style.*

Comment: Can you show this point [the "bottleneck"] in Figure 2-4 (or use another figure)?

Answer: *Figure 2-4 has now been changed accordingly.*

Comment: In Figure 3-6b it looks more like 4*lambda microcavity, no?

Answer: *It is 2 lambda microcavity, because the Figure 3-6(b) shows the intensity distribution of the field, this is now stated in the Figure caption.*

Comment: Sounds as if you had to use more than 2 lenses in the setup. Were two lenses not enough?

Answer: *More than two conjugated lenses were used to make the necessary size of the condensate on the imaging camera.*

Comment: Figure 5-12 appears too far down from here. Initially I thought it was missing all together...

Answer: *This has now been corrected.*

Comment: So, you polarimeter operates in k-space, does it not? If so, it was not clear when you described it design earlier. Moreover, this means the polarimeter integrates over k|| from -1 to +1 um-1. Is this what you want or don't care about (if so, why?) ... or something you simply have to live with?

Answer: *The k-space filtering was performed in order to cut the emission from the incoherent polariton reservoir. It was done by the iris put at the entrance of the polarimeter. However, the polarimeter itself does not characterise spatial or momentum distribution of the condensate PL, but measures the integrated (time- and space-averaged) polarisation.*

Comment: Why does spin make two revolutions for a rotation period? It was not the case for slow rotation, was it? Can you elaborate on this?

Answer: *The value of the spin projection is defined by the orientation of the elliptical condensate, as described in Chapter 5. During the rotation period of the trap the condensate have the same orientation of the long axis twice, since the shape of the trap at t = 0 and t =T/2, where T is rotation period are identical. That is why the spin is making two revolutions per a rotation period. This holds for both slow and fast rotation. This note is now also added for the case of the slow rotation in Section 6.3.*

Comment: On the other hand, if the principle does matter then, of course, it needs to be discussed but then one also needs to explain why this particular principle of SLM operation was important (compared to other SLMs).

Answer: *The phase-only spatial light modulator is the preferred choice for these experiments due to its high efficiency and versatility in creating various optical patterns. Deformable mirrors, which are an alternative for beam shaping, usually have fewer active elements than SLMs, which limits their ability to create optical patterns with many features. This text is now added to Section 3.1.2.*