Optical orientation, polarization pinning and depolarisation dynamics in optically confined polariton condensates

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We investigate the optical orientation, polarization pinning, and depolarisation of optically confined semiconductor exciton-polariton condensates performing a complete Stokes mapping of the condensate polarization and rotation of the polarization vector of a non-resonant optical pump both along the equator and the meridian of the Poincare sphere. We utilise a ring-shaped non-resonant optical excitation to generate an exciton-induced potential that spatially confines polariton condensates into a single mode. We observe that optical orientation of the condensate spinor parallel to the circular polarization of a non-resonant pump persists even for a small component of pump ellipticity, $S_4 \approx 0.03$. By varying the ring diameter we realise a transition from the condensate polarization being pinned along the coordinate-dependent cavity-strain axes, to a regime of zero degree of condensate polarization under linearly polarized pump. Analysis through the driven-dissipative stochastic Gross-Pitaevskii equation reveals that depolarisation stems from a competition between a sample induced in-plane polarization splitting and the condensate-reservoir overlap. An increase in the role of the latter results in weakening of the condensate fixed-point phase space attractors, and enhanced presence of limit-cycle trajectories, effectively reducing the degree of time-integrated polarization.

I. INTRODUCTION

Exciton-polaritons (from here on polariton) are quasi-particles that arise from the strong coupling between exciton and photon modes in a semiconductor microcavity. Due to their composite nature they are characterized by a low effective mass, short lifetime, and strong nonlinearity which has made them a popular candidate to explore novel nonlinear physics. Despite their short lifetime, the advantage of polaritons is manifested in the fact that when they decay their information is encoded in the emitted cavity light, including spin structure. Of interest, when polaritons condense one gains access to ultrafast nonlinear spin physics with possible applications in spinoptonic devices.

Because of their two-level spin structure, polaritons offer an exotic platform to study various non-Hermitian spin-physics. Their sensitivity to external magnetic fields, cavity mirror birefringence, along with a unique spin-orbit coupling mechanism known as the Optical Spin Hall Effect, has paved the way for the realization of polaritonic Chern insulators, polarized solitons, and half skyrmions, spin switches, spontaneous lattice ordered polarization, spin-selective filters, spin bistability, spin multistability and spin valves and measuring the quantum geometric tensor. This has also lead to the formulation of proposals for novel integrated devices like a polariton based polarization rectifier while other works have focused on synthesizing polarization sensitive potential geometries for polaritons.

Fueled by the promise of developing polariton based spinoptonic devices, nonresonant excitation schemes seem the likely direction for future applications. In such a setup, optical excitation triggers bosonic stimulated scattering and subsequent buildup of coherence and polarization as polaritons condense. This is in contrast to earlier works which relied on resonant excitation schemes to generate a coherent ensemble of polaritons. There, interplay between linear and nonlinear phenomena (e.g., optical Spin Hall effect and self-induced Larmor precession) has been studied both in the transient (pulsed excitation) and the dynamic equilibrium (continuous wave excitation) regime. However, ideally, spinoptonic devices will either completely or partially work using nonresonant excitation elements since it bypasses the need to fine tune the energy, momentum, and phase of a resonant laser. Moreover, such a device would likely operate at and above condensation threshold in order to efficiently exploit the nonlinear spin dynamics of polariton fluids. Nonlinearity is needed for a device to perform nontrivial tasks, but it can also destabilize the spin state of the condensate, potentially affecting said device performance. Recent studies have mapped out interesting regimes of polarization buildup, collapse, inversion, and hysteresis, as well as deterministic control of linearly polarized emission, but with most of the work focused on selected components of the Stokes vector. Therefore, a full characterization of the emission properties of optically confined polariton condensates, and its stability properties, is still lacking.

In this paper, we perform full-Stokes polarimetry of an optically trapped polariton condensate under nonresonant excitation. We investigate the formation and depression of strongly polarized ground-state condensate regimes as a function of incident beam polarization, power, and confinement area. We find that an interplay of strain induced in-plane polarization splitting of the photonic mode and reservoir-condensate overlap can destabilize the polariton pseudospin, resulting in a decrease of emitted polarized light. Under linearly polarized excitation we observe, with increasing power, a...
transition from an unpinned to a polarization pinned condensate\textsuperscript{38}. Our observation directly confirms the critical role of particle nonlinearity to pin the polarization of the condensate. We additionally predict regimes of condensate limit cycles where an elliptically polarized pump gives rise to a stable Larmor precession of the condensate pseudospin.

II. EXPERIMENT

The sample used is a 2λ GaAs microcavity with embedded InGaAs quantum wells, where we have previously demonstrated strong coupling and polariton condensation\textsuperscript{39}, held in a cryostat at 4K. The experiments are conducted in the strong coupling regime at a negative exciton-cavity detuning ($\Delta \approx -3$ meV). The sample is excited non-resonantly ($\lambda = 783$ nm) with a single mode continuous wave (CW) optical source, that is time-modulated at 1 kHz and 1% on-off ratio with an acousto-optic modulator, and spatially modulated with a phase only spatial light modulator (SLM) [see S1-S3 in Supplementary Material (SM) for detailed information on the experimental configuration].

Results and Discussion. Typical electron spin relaxation timescales in GaAs based systems are much longer than the relaxation time to the excitonic mode\textsuperscript{40}. As such, some of the degree of circular polarization of the continuous wave beam is transferred to the spin populations of the incoherent excitonic reservoir, residing in the bottleneck regime of the lower polariton dispersion (see Fig. 1). Above the polariton condensation threshold pump power, spin-conserving stimulated scattering of polaritons from the reservoir starts forming a mostly co-circularly condensate. In the case of linearly polarized excitation, and no pinning potential, the polarization of the condensate becomes randomly oriented on the $(S_1, S_2)$ equatorial plane of the Stokes (Poincaré) sphere since no specific condensate phase is adopted from the incoherent reservoir\textsuperscript{41–43}. However, if the structure is anisotropic due to fabrication or strain, a finite linear polarization splitting can form which pins the condensate polarization\textsuperscript{39,38,44,45}.

The polarization of the emitted light provides direct access to the condensate spin, since the two circular polarizations couple independently with spin-up and spin-down optically active exciton states in the quantum wells through angular momentum selection rules. In their condensed form, polaritons can be expressed by a spinor order parameter $\Psi = (\psi_+, \psi_-)^T$ with spin-up and spin-down polaritons $\left(\psi_{\pm}\right)$ corresponding to right- and left-circular polarized light respectively. Polariton spin physics are often conveniently described in the pseudospin formalism\textsuperscript{46} stemming from the fact that the polarization of the emitted light relates explicitly to the polariton spin structure such that the Stokes vector $\mathbf{S}$ is a measure of the polariton pseudospin. With the total particle number in the condensate written $S_0 = |\psi_+|^2 + |\psi_-|^2$, the normalized components of the Stokes (pseudospin) vector $\mathbf{S} = (S_1, S_2, S_3)^T$ are written $S_1 = 2\text{Re}(\psi_+^* \psi_+)/S_0$, $S_2 = -2\text{Im}(\psi_+^* \psi_+)/S_0$, and $S_3 = (|\psi_+|^2 - |\psi_-|^2)/S_0$.

Our measurements are conducted entirely in the regime where condensation of polaritons occurs always in the ground state of the optically induced trap at low momenta and no higher order modes are excited for the full range of condensate densities studied\textsuperscript{37}. In order to filter out residual emission from the reservoir and collect only the condensate PL, we perform $k$-space filtering of wave-vectors more than $\pm 1\  \mu m^{-1}$. Figure 2 shows the time-integrated polarization from a trapped polariton condensate for a pump ring of diameter $d = 12$ µm as a function of pump power and polarization ellipticity controlled by rotation of a quarter wave plate (QWP). Here, QWP = −45°, 45°, and 0° correspond to right-circular, left-circular, and linear polarization of the excitation laser respectively. Between those values the pump is elliptically polarized. Figures 2(a-d) show the condensate total emission intensity $S_0$, degree of linear polarization DLP $= \sqrt{S_1^2 + S_2^2}$, total degree of polarization $\text{DOP} = \sqrt{S_1^2 + S_2^2 + S_3^2}$ and circular polarization $S_3$ respectively (see three Stokes components in S4 SM). Figure 2(a), shows the threshold behavior of the condensate PL, marked by the white dashed line, revealing that the condensation threshold is higher for linearly polarized excitation (around 1.18$P_{th}$) as opposed to a circular polarized excitation which we define as $P_{th}$. This effect appears due to the same-spin Coulomb exchange interactions dominating over opposite spin interactions\textsuperscript{47,48}. A right (left) circular polarized excitation beam that results in a more spin up (down) populated reservoir of incoherent excitons will sooner reach threshold density and undergo stimulated scattering into a co-circularly polar-
Figure 2. (a) Total emission intensity $S_0$ in a.u., (b) DOP, (c) DLP, and (d) $S_3$ as a function of pump power $P$ and ellipticity (QWP angle) for a ring excitation geometry with a diameter of $d = 12 \mu m$. QWP angles $-45^\circ$, $45^\circ$, and $0^\circ$ correspond to right-, left-circular, and linear polarized excitation. White dashed lines mark the condensation threshold. (e) Condensate Stokes parameter with respect to the excitation power plotted on Poincare Sphere for left-circular (purple points), right-circular (yellow) and linear (orange). Blue and red arrows plotted on Poincare Sphere for left-circular (purple points), densate Stokes parameter with respect to the excitation power. (f) PL Stokes vector for different excitation polarization for 3 fixed powers $(1.41P_{th}$, green dots, $2.12P_{th}$, blue, $2.47P_{th}$, red). Scans positions for Figures (e), (f) are also depicted on Figures (b) and (d) in form of dashed lines with corresponding colors.

Figure 3. (a) Condensate polarization for a ring pump of $d = 12 \mu m$ at $P = 1.23P_{th}$, fine-resolved for a pump laser $S_3$ from -0.3 to 0.3. (b) Measured integrated photoluminescence (squares) and simulated $S_0$ (dots) for different trap diameters and QWP $-45^\circ$. Horizontal axis is given in $P_{th}$ corresponding to a $d = 12 \mu m$ pump.

For higher excitation powers and $\approx 99%$ linear degree of polarisation of the pump (QWP $\sim 0^\circ$), we observe the formation of a linear polarization ‘island’ (see Fig. 2(c)), which is attributed to an interplay of in-plane polarization splitting (due to sample strain/birefringence) and increased condensate nonlinearity leading to pinning of the condensate pseudospin. The absence of this polarized island at lower powers is due to low occupation of the condensate (small nonlinearity) making it weakly pinned. Stochastic noise then sets the pseudospin on a random walk on the Stokes sphere (see Fig. S7 in SM). The stochastic behavior during the excitation period that manifests in our measurements as the absence of pinning at low densities, yet above threshold, to the best of our knowledge has not been reported yet. Past experiments have shown either the immediate buildup of a pinned polarization above threshold, shot-to-shot stochastic polarization, or $S_3$ spin flips. This polariton density dependent observation brings potential into designing linearly polarized spin-switches with operational capacity.

Formally, splitting between the polariton pseudospin components can be described by an effective magnetic field $\Omega(r) = (\Omega_x, \Omega_y, \Omega_z)$ which rotates the condensate pseudospin. The direction of the pseudospin strongly depends on the location of the excitation spot (see S5 in SM).
Figure 4. DLP polarization maps as a function of pump power and QWP angle. Panels (a-c) show results for decreasing pump diameter $d = 15, 12, 9 \, \mu m$. (d) Shows the condensate DLP in the case of a Gaussian spot excitation (no confinement). (e-f) Simulated time-average condensate DLP using Eqs. (1)-(3). The star, circle and diamond markers correspond to panels (a-c) in Fig. 6. (h) Black line shows the measured condensate blueshift at QWP = 0° in a $d = 12 \, \mu m$ pump trap for increasing power. Red line is the simulated energy of the condensate.

pinned polarization island Fig. 2(c). Notably, attractors are on opposite sides of the Poincare sphere in contrast to the predictions of previous models\cite{50} that suggested they lie on the same hemisphere. The spin-imbalanced condensate and background reservoir of uncondensed polaritons, denoted $X_{\pm}$, result in an effective out-of-plane magnetic field, $\Omega_{z} = \alpha(|\psi_{+}|^{2} - |\psi_{-}|^{2}) + g(X_{+} - X_{-})$ due to polariton-polariton interactions $\alpha$, and polariton-reservoir interactions $g$. This eventually causes the condensate pseudospin to start precessing around this interaction induced out-of-plane magnetic field which suppresses the linear polarization in the time-average measurements (i.e., regimes of almost zero DLP but finite $S_{3}$). For increasing beam ellipticity the condensate starts to become pinned along the stronger $\Omega_{z}$ magnetic field, observed as an increase in $S_{3}$ (see Fig. 2(d)). We note that similar results were obtained for detunings between $-4$ meV to $-2$ meV (see Supplementary Material S6).

Interestingly, the linearly polarized island is enclosed by two depolarized streaks (see Fig. 2(b,c)) which, to the best of our knowledge have not been previously reported. These streaks correspond to the interface between the pseudospin being pinned either by the in-plane magnetic field ($\Omega_{x}, \Omega_{y}$) birefringence or the interactions-induced magnetic field $\Omega_{z}$. In-between these two pinning regimes the pseudospin is very sensitive to background white noise which can stochastically move it from precessing around one field to the other, causing the measured polarization to appear completely depolarized. In Fig. 3(b) we show results on the measured integrated condensate photoluminescence (squares) as a function of pump power, with QWP = $-45^\circ$, and for three different trap sizes. Interestingly, we observe for smaller traps a decrease in the polariton condensate occupation number.

In Fig. 4 we show that the size of the condensate confinement area (i.e., the diameter of the ring shaped pump) has a pronounced effect on the measured polarization patterns. By decreasing the diameter of the excitation ring, we observe that the aforementioned linear polarization island decreases (see Fig. 4(b)) until it vanishes completely (see Fig. 4(c)). When the condensate is excited with a Gaussian excitation spot, such that it does not experience any optical confinement, the DLP decreases even more (see Fig. 4(d)). Same behavior is seen in the DOP (see S4 in SM). This observation effectively demonstrates that increasing the overlap between the condensate and its background reservoir results in strong depolarization, as supported by numerical simulations detailed below. It should be noted that for the measurements with a Gaussian excitation spot most of the emitted light coincides with the spot area. Any light away from the spot, possibly adopting nontrivial polarization textures\cite{10,16,52}, has a negligible contribution to our averaged measurements.

By recording the condensate polarization under different linear polarization angles of the excitation, we find that the condensate $S_{3}$ and DLP at high powers is mostly invariant as a function of the linear polarization angle (see Fig. 5(a,b)). This further confirms that the pinning is not a result of transferred linear polarization from the excitation to the condensate. Moreover, the condensation threshold is uniform for all linear polarization angles of the excitation (see Fig. 5(c)). Nevertheless, we point out that the condensate polarization varies slightly when excitation switches from diagonal to anti-diagonal polarization. Just above threshold, we observe a small formation of $S_{3}$ component with different signs that is suppressed as the condensate density increases (see Fig. 5(a)). We attribute this to a small pump ellipticity induced by the optical elements of our excitation setup as well as a non-zero retardation of the excitation beam ($\delta = 0.06\pi$) due to sample birefringence (see S7 for a measurement of the sample birefringence).
III. THEORY

The destabilization of the condensate pseudospin and the consequent apparent depolarization of the system, can be modeled through a set of driven-dissipative stochastic (Langevin-type) Gross-Pitaevskii equations\textsuperscript{33} coupled to spin-polarized rate equations describing excitonic reservoirs $X_{\pm} = X_{\pm x} + X_{\pm y}$ feeding the condensate,

$$i\psi_{\alpha}(t) + \frac{1}{2}(\alpha |\psi|^2 + g(1 - \eta P_{\sigma}))(X_{\pm x} + X_{\pm y})$$

$$+ i \left[ R(1 - \eta P_{\sigma})X_{\pm} - \Omega_{\sigma} \right] \psi_{\sigma} - \frac{\Omega_{\sigma}}{2} \psi_{-\sigma}, \quad (1)$$

$$X_{\sigma} = -(\Gamma_{\sigma} + R(1 - \eta P_{\sigma})|\psi|^2) X_{\alpha},$$

$$+ \Gamma_{\sigma}(X_{\pm x} - X_{\pm y} + W X_{\sigma}'), \quad (2)$$

$$X_{\sigma}' = -(\Gamma_{\pm} + W) X_{\sigma}' + \Gamma_{\sigma}(X_{\pm x} - X_{\pm y} + P_{\sigma}). \quad (3)$$

Here, we take into account the presence of spin-polarized active and inactive reservoirs $X_{\alpha,\pm}$ respectively\textsuperscript{30,54,55}. The former satisfies energy conservation rules of particles scattering into the condensate whereas the latter does not. Here, $R$ is the spin-conserving rate of stimulated scattering of polaritons into the condensate, $\Gamma_\sigma$ is the polariton condensate decay rate, $\Omega_\sigma$ represents a birefringence induced effective magnetic field which splits the polariton $XY$ polarizations, $\Gamma_{\alpha,\pm}$ are the decay rates of active and inactive reservoir excitons respectively, $W$ is the conversion rate between inactive and active reservoir excitons, $\Gamma_\sigma$ is a spin-flip rate of excitons in each reservoir, and $P_{\pm} = P_0 \cos^2(QWP + \pi/4)$ is the total (spatially integrated) power of the non-resonant continuous wave pump. The parameter $\eta$ phenomenologically captures the sublinear dependence of the ground state energy shift and gain with increasing pumping power. Such sublinear dependence can be physically understood from the decreasing overlap between the more tightly confined condensate and the surrounding reservoir.

The correlators of the background shot noise from the reservoir $\theta_{\pm}(t)$ are written,

$$\langle \theta_{\alpha}(t) \theta_{\sigma}(t') \rangle = \frac{\Gamma + RX_{\alpha}^2}{2} \delta_{\alpha,\sigma} \delta(t - t'), \quad (4)$$

$$\langle \theta_{\alpha}(t) \theta_{\sigma}(t') \rangle = 0. \quad (5)$$

We define a time-averaged Stokes component from simulation as $S_n = \int_0^T S_n dt / T$, where $T(= 10 \text{ ns})$ is the simulated time interval. Below condensation threshold there is no buildup of a coherent polariton state and the simulated average pseudospin is zero, $S = 0$. The threshold is defined as the point where gain and losses balance against each other, written $RX_{\alpha}^2 - \Gamma = 0$. Above threshold, gain overcomes losses and a coherent polariton state $\Psi$ forms.

Decreasing the pump diameter $d$ affects some parameters of Eqs. (1)-(3). Namely, $\alpha, \Gamma, g, R$. The polariton-polariton interaction strength $\alpha$ increases because of a decreased localization of the condensates which scales as $\alpha \propto \int |\Psi|^4 \, dr$. \textsuperscript{36} Assuming that the condensate occupies the ground state of a cylindrically symmetric two-dimensional harmonic potential $V(r) = V_0 (2r/d)^2$, whose oscillator strength changes with pump diameter, we have $\Psi(r) = \sqrt{\pi} \exp[-\beta^2 r^2]/2$ where $\beta = \left(8 \pi m V_0 / d^2 \right)^{1/4}$. One then obtains that $\alpha \propto 1/d$. The change in overlap between the reservoir and the condensate $g, R \propto \int P(r) |\Psi|^2 \, dr$ is more challenging to estimate as it depends on the details of the pump shape $P(r)$. We find a good fit to the experimental results with the dependence $g, R \propto 1/d^3$. From Fig.4(a-c) it can be seen that the threshold of the condensate does not depend too strongly on the trap size. This can be attributed to an increase in the condensate decay $\Gamma$ due to the enhanced escape rate of the more energetic polaritons in smaller traps\textsuperscript{36}. We therefore adopt $\alpha \propto 1/d^3$ dependence such that the threshold condition, $RX_{\alpha}^2 - \Gamma = 0$, becomes invariant of trap diameter $d$. Parameters used in simulations: $d_0 = 15 \mu m$, $\alpha = \alpha_0 d_0 / d$, $\alpha_0 = 1.8$ ns$^{-1}$, $g = g_0 (d_0/d)^3$, $g_0 = 0.36$ ns$^{-1}$, $R = R_0 (d_0/d)^3$, $R_0 = 3.9$ ns$^{-1}$, $\Gamma = \Gamma_0 (d_0/d)^3$, $\Gamma_0 = 0.6$ ps$^{-1}$, $\Gamma_A = 0.78$ ps$^{-1}$, $\Gamma_\eta = 0.0026$ ps$^{-1}$, $\Gamma_{\sigma} = 0.1$ ps$^{-1}$, $W = 0.31$ ps$^{-1}$, $\eta = 0.18/P_0$, $\Omega_{\sigma} = 0.18$ ps$^{-1}$.

Results from simulation are shown in Fig. 4(e-g) where the DLP = $[S_1^2 + S_2^2]^{1/2}$ is plotted in comparison to experimental observations for varying pump diameters $d$, showing good agreement. Pump power in simulation is given in units of $P_0 = 2 \Gamma A (\Gamma + W) / (RW)$ which is the threshold power for $P_\sigma = P_{\sigma^c}$. In Fig. 4(h) we show the measured and simulated condensate blueshift as a function of pump power at QWP = 0° and $d = 12 \mu m$. We observe from simulation (see Fig. 4(e)) that the DLP of the polarization island, after its formation, does not decrease with increasing pumping powers. Therefore, the stability of the island is not sensitive to the monotonically increasing blueshift experienced by the condensate when pump power is increasing. Instead, for QWP = 0°, the vanishing of the polarization island is found to depend on the strength of the in-plane field $\Omega_{\sigma}$ against the polariton-polariton nonlinearity. Indeed, as the trap diameter decreases the scattering rate $R \propto 1/d^3$ increases proportionally, leading to saturation of the reservoirs $X_{\alpha}$ for smaller particle number $S_0$. Consequently, we observe in both experiment and simulation a strong decrease in $S_0$ for smaller trap sizes (see Fig. 3(b)).

This evidences that the nonlinearity of the condensate, which scales with particle number $S_0$, is the crucial mechanism along with $\Omega_{\sigma}$ in order to pin the polarization\textsuperscript{38}. This is in agreement with our experimental observations that the linearly polarized island could only form at higher pumping powers above threshold (see Fig. 2(b,c)). For elliptically polarized pumps (QWP $\neq$ 0°) the spin imbalanced reservoir and condensate start playing a role in the vanishing of the island through the pump induced component $\Omega_{\sigma}$ which tilts the net effective magnetic field. A simplified Gross-Pitaevskii model, detailed in the SM, verifies this interpretation of the island’s destabilization. We note that the results reported here do not depend
value of $\Gamma_s$ strongly on spin-anisotropic interactions, nor the precise excitation one gets $|S_1| \geq |S_2|$ which can set the condensate into a tilted limit-cycle appearing as persistent oscillations in the Stokes components. (d,e) Overlaid pseudospin phase space trajectories with $\theta_\perp(t) = 0$ but random initial conditions, corresponding to the star and circle in Fig. 4 respectively. Results show a change from one dominant attractor to two weaker ones. (f) Representation of the limit-cycle (precession) in (c) on the surface of the Stokes sphere.

Figure 6. (a-c) Dynamics of the normalized $S_1$ component from the star, circle, and diamond markers in Fig. 4 respectively. (a) For large traps the pseudospin is pinned along the effective magnetic field $\Omega_x$, (b) For smaller pump diameters the condensate blueshifts and the pseudospin starts destabilizing and fluctuates between $S_1 = \pm 1$. (c) For elliptical excitation one gets $|\Omega_1| \gtrsim |\Omega_2|$ which can set the condensate into a tilted limit-cycle with the reservoir components in our model contributing to the observed depolarization of the emission. Our results pave the way towards generating highly polarized polariton condensates using only non-resonant excitation, promising for spin-dependent opto-electronic devices.

IV. CONCLUSIONS

We have experimentally investigated and analyzed the polarization characteristics of optically trapped polariton condensates. For the case of a circularly polarized excitation we have shown a sharp (up to $DOP \approx 1$) increase of the degree of polarization above condensation threshold. The high polarization is consistent with recent observations on the extreme long coherence times of optically trapped polariton condensates. The condensate spin properties in these conditions are governed by optical orientation of the reservoir excitons mostly adopting the polarized condensate due to a pinning effect. When the pump diameter decreases overlap with the reservoir increases and we observe rapid depolarization (unpinning) of the condensate due to stochastic spin fluctuations. We also report on the presence of limit cycles in the condensate pseudospin which contribute to the observed depolarization of the emission. Our results pave the way towards generating highly polarized polariton condensates using only non-resonant excitation, promising for spin-dependent opto-electronic devices.

Interestingly, a recent report has shown that a random massive degree of circular polarization can build up for $QWP = 0^\circ$ under very similar conditions as presented here (i.e., optical trapping of polaritons). There, spin-flip scattering of polaritons into the condensate from the reservoir was treated equal to spin-conserving scattering. In our work, the spin-flip rate $\Gamma_s$ between the reservoir components in our model contributes to such mixed scattering of polaritons but we do not observe such circularly polarized states. This begs the question whether there exist conditions where the regimes of pinned linearly polarized condensates and bifurcated circularly polarized condensates can be brought together to exploit non-resonant multistable operation on the Stokes sphere in contrast to resonant schemes.
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Supplementary Material

S1. EXPERIMENTAL SETUP

Figure S1 depicts a simplified schematic of the experimental setup. An $M^2$ SolTiS CW mono-mode laser is used for the excitation of polaritons in the sample; we pump at first Bragg minimum at 783.6 nm. The experiments are performed in a quasi-CW excitation regime. Namely, the pump laser radiation was modulated with an acoustic-optic modulator (AOM) with 1 kHz frequency and 1% duty-cycle ($10 \mu s$ pulse length) to diminish heating of the sample. Then, a phase only spatial light modulator (SLM) transforms the Gaussian beam into a ring-shaped profile, which creates the optical confining potential for polaritons. We investigate the photoluminescence (PL) of the sample in a confocal configuration using a 50x objective with 0.42 NA for excitation and collection of the sample photoluminescence.

We detect real- and Fourier-space images of the sample PL. Also, we characterize the spectrum and dispersion of the PL by using a Princeton Instruments 750mm Spectrometer with a Pixis CCD. For the polarization characterization of the polariton condensate, we use specially developed full-Stokes polarimeter (see S2l). PL intensity is quite low especially below the condensation threshold, so we use lock-in amplifiers together with Si-photodiodes to measure polarization power dependence. The lock-in integration time is set to 100 ms that results in integration of the signal from approximately 100 pulses.

Figure S1. Schematic of the experimental setup and polarimeter. AOM, SLM, PBS, BS stand for acousto-optic modulator, spatial light modulator, polarized and non-polarized beam-splitter respectively.

S2. STOKES PARAMETERS MEASUREMENT

Used polarimeter (see figure S1) is based on the division of amplitude approach. Firstly, a beamsplitter (BS) 50:50 divides incoming light into two equal parts. One of them falls onto polarizing beamsplitter PBS, and the intensities of horizontal $I_1$ and vertical $I_2$ components then are registered by two photodetectors. $I_1$ and $I_2$ are then used for the calculation of $S_0$ and $S_1$ Stokes components.

To take into account the non-ideality of optical elements, polarimeter is carefully calibrated on the laser light with a known polarization state tuned to the condensate emission wavelength. The developed optical scheme can detect fast polarization change. The speed of data collection is limited just by the rise- and dead- times of the photodetectors, however, in our experiment, the limiting factor of polarimeter operation speed is lock-in amplifiers integration time (100 ms).

$$S_1 = \frac{I_1 - I_2}{I_1 + I_2},$$
$$S_2 = \frac{4I_3 - (I_1 + I_2)}{I_1 + I_2},$$
$$S_3 = \frac{4I_4 - (I_1 + I_2)}{I_1 + I_2},$$
(S1)

S3. DISPERSION AND CONDENSATION

We excite the sample non-resonantly at 783.6 nm. Below the condensation threshold, we see the lower polariton branch (LPB) on our imaging spectrometer. The bottom of the branch is at $857 \text{ nm}$ (see Fig. S2a). Further increasing the intensity of the non-resonant excitation laser, we observe blueshift of the LPB which is accompanied by condensation at close to zero wave-vectors (see Fig. S2b).

Figure S2. Dispersions of the cavity PL at excitation powers a) below and b) 20% above the condensation threshold. Colorscale for a) and b) are normalized to 1.
S4. DOP AND STOKES COMPONENTS OF CONDENSATE PL FOR DIFFERENT EXCITATION RING SIZES

Figure S3 is the follow up from Fig. 3 in the main text. It presents all Stokes polarization components and the total degree of polarization (DOP) for three studied excitation ring diameters and a Gaussian pump.

For all sizes of the pumping ring and Gaussian excitation, we observe that the circular polarization of the condensate follows the circular polarization of the pump [see Fig. S3(i-l)]. Also, for each size of ring-shaped excitation, we observe the depolarization of the PL under elliptically polarized excitation. On the other hand, under linearly polarized excitation depending on the size of the ring and consequent difference in polariton-reservoir interactions we observe the transition between unpolarized PL and pinning regimes above the condensation threshold [see Fig. S3(a-h)].

Moreover, the polarization of the linear polarization island is excitation independent [see Fig. S3(a-b)]. This set of experiments were carried out for one spot on the sample, so linear polarization splitting is fixed. So regardless excitation ring size, condensate in this place adopts vertical polarization ($S_1, 0$).

![Figure S3](image-url)

Figure S3. $S_1$ (a-c), $S_2$ (e-h), $S_3$ (i-l), and DOP (m-p) for ring excitation of diameter $d = 15, 12, 9 \, \mu m$ and Gaussian (FWHM = 4 $\mu m$ ) respectively.

S5. EXCITATION PLACE DEPENDENCE

Here we present the polarization maps for $S_1$ and $S_2$ Stokes component of the polariton PL for two different points on the sample. For the first point [see Fig. S4(a,c)] for high pump powers (> $1.4P_{th}$), we see an increase in the $S_2$ component, while the $S_1$ stays close to zero. On the other hand, for the second point [see Fig. S4(b,d)] both $S_1$ and $S_2$ component undergo growth, which corresponds to a splitting in polarization which is between linear and diagonal.

Overall, moving from point to point on the sample, we can observe any type linear polarization pinning, as strains in the sample are strongly place dependent, and dictate condensates pinned polarization.

![Figure S4](image-url)

Figure S4. $S_1$ and $S_2$ polarization maps for two different excitation point on the sample under different linearly polarized excitation. (a) and (c) corresponds to $S_1$ and $S_2$ of the PL from the first studied point, and (b) and (c) represents $S_1$ and $S_2$ for the second point respectively.

S6. DETUNING DEPENDENCE

Here we present the results of the polarimetry for two more detuning values - the most negative $\Delta = -4 \, meV$ and the most positive $\Delta = -2 \, meV$ accessible on the sample for the ring $d = 12 \, \mu m$ (See Figure S5).

The overall trend for these measurements is the same that it is in the main text. We observe optical orientation under circularly polarized pumps and formation of the linear polarization island at big excitation power, accompanied with unpolarized streaks. Linearly polarized “island” appears at the same range of the excitation powers, but the shape of it is a bit different, which could be addressed to the disorder of the sample.
Figure S5. Measured DLP and $S_3$ for the two different detuning values. DLP a) and $S_3$ c) for the detuning $\Delta = -4$ meV, DLP b) and $S_3$ d) for detuning $\Delta = -2$ meV.

S7. SAMPLE BIREFRINGENCE MEASUREMENT

To find out the sample birefringence at 4K, we consider it as waveplate with unknown birefringence. To define the birefringence, we used a set of two polarizers. Illuminating the sample with a parallel linearly polarized laser beam and using the first polarizer as linear polarization generator and the second polarizer in the detection first, we define the fast and slow axes of the sample. Further, we operate in the obtained sample basis. From the Mueller matrix for the arbitrary retarder, one could obtain that when diagonal linearly polarized light hits the retarder its retardance, $\delta$ appears to be related to the $S_2$ component of the transmitted light as follows $S_2 = \cos(\delta)$.

Thus, at the excitation wavelength 783.6 nm, the sample has $\delta \approx 0.07\pi$. This birefringence could explain small revivals of the $S_3$ component just above the condensation threshold for diagonal and anti-diagonal linearly polarized pumps (see figure 5 in the main text of the paper). The excitation having a polarization that does not coincide with fast or slow axes of the sample inherit some ellipticity due to described sample retardance resulting in the elliptically polarized condensate.

For the wavelength close to the condensation wavelength, namely the cavity mode bottom wavelength (856.6 nm), the sample has non-zero transmission. So the retardance of it at this wavelength is $\delta \approx 0.15\pi$ and $\delta \approx 0.06\pi$ in transmission and reflection respectively.

S8. NUMERICAL SIMULATIONS AND THEORETICAL DESCRIPTION

A. Full Stokes map characterization

In Fig. S6 we present the rest of the average Stokes components $\bar{S}_{1,2,3}$ as well the DOP and DLP corresponding to the simulation in Fig. 3 in the main text.

B. Condensate pinning as a function of power

In Fig. S7 we show the simulated onset of pinning at QWP = 0° for increasing pump power. Panels (a-c) correspond to pump power $P = (1.2; 1.5; 2)P_0$ with $P_0$ defined in the main text. The results show that the condensate pseudospin stabilizes when the condensate non-linearity, which scales with pump power, increases.

C. Destabilization of the pinned polarization island

In this subsection, we simplify our equations of motion [Eqs. (1)-(3) in main text] and adopt a reservoir free model [Ohadi et al., Phys. Rev. X 5, 031002 (2015)] to describe the stability properties of the polarization island. Such a model becomes accurate when the characteristic timescales of the reservoirs are shorter than that...
of the condensate.

\[ \partial_t \psi_\sigma = \theta(t) + [(1 - ig)P_\sigma - (R + i\alpha)|\psi_\sigma|^2] \psi_\sigma + i\Omega_x \psi_{-\sigma}. \]  
(S2)

Here, \( P_\sigma \) denotes the net injection rate of particles through the polarized nonresonant excitation, \( R \) saturates the condensate above threshold, \( gP_\sigma \) is blueshift originating from interactions with an excitonic reservoir scaling with the pump excitation, \( \alpha \) is the polariton-polariton interactions strength, \( \Omega_x \) is the in-plane magnetic field which couples the spin components of the condensate, and \( \theta(t) \) is a white noise term.

Let us consider the case where \( P_\sigma = P \) which corresponds to linearly polarized excitation, \( \text{QWP} = 0^\circ \). We additionally rescale the wavefunction \( \psi_\sigma = \psi'_\sigma \sqrt{P/\alpha} \) and define time in units of pump power, \( t = \tau/P \) for brevity.

\[ \partial_t \psi'_\sigma = \theta(t) + \left[ 1 - ig - (r + i)|\psi'_\sigma|^2 \right] \psi'_\sigma + i\omega_x \psi'_{-\sigma} \]  
(S3)

where \( r = R/P \), and \( \omega_x = \Omega_x/P \). In Fig. S8 we show the \( \tilde{S}_1 \) Stokes component for two slices of the three dimensional parameter space of Eq. (S3). In Fig. S8(a) we see that as \( r \) grows the averaged steady state polariton occupation \( \tilde{S}_0 = 2/r \) decreases and the \( \tilde{S}_1 \) components smears out against fluctuations. As \( |\omega_x| \) becomes stronger the polaritons are more easily pinned even for small occupation number of the condensate. In Fig. S8(b) the coupling is fixed at \( \omega_x = 0.05 \) and we vary now both \( g \) and \( R \). The results show that the diagonal shift in energy does not affect the stability of the polarization island against random fluctuations. Thus, the vanishing of the polarization island as seen in experiment at \( \text{QWP} = 0^\circ \) can be attributed purely to the balance between polariton nonlinearity and the in-plane effective field coupling the spins.

![Figure S8. Simulated \( \tilde{S}_1 \) Stokes component using Eq. (S3).](figure)

(a) Varying the coupling \( \omega_x \) changes both the sign and strength of the polarization island. As \( r \) increases the amplitude of the wavefunction (i.e., the polariton population \( \tilde{S}_0 = 2/r \)) decreases and the \( \tilde{S}_1 \) components smears out against fluctuations.

(b) Here \( \omega_x = 0.05 \) and \( g \) is varied showing that for linearly polarized excitation the blueshift coming from the pump does not change the average degree of condensate linear polarization against fluctuation.