Exciton-Polariton Oscillations in Real Space

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We introduce and model spin-Rabi oscillations based on exciton-polaritons in semiconductor microcavities. The phase and polarization of oscillations can be controlled by resonant coherent pulses and the propagation of oscillating domains gives rise to phase-dependent interference patterns in real space. We show that interbranch polariton-polariton scattering controls the propagation of oscillating domains, which can be used to realize logic gates based on an analogue variable phase.

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Introduction.— Rabi oscillations are well-known for their role in nuclear magnetic resonance devices and underly proposals for quantum computing [1, 2]. Following the archetypical example of coherent and reversible energy transfer between atoms and light in electromagnetic cavities [3], Rabi oscillations have been achieved at the quantum level in a variety of systems, including: Josephson junctions [4–6]; electron spins in quantum dots [7–9]; nuclear spin systems [10]; and molecular magnets [11].

Rabi oscillations were also observed in planar semiconductor systems, such as quantum wells containing excitons [10], and semiconductor microcavities containing exciton-polaritons [11]. Conversion of spin-polarized excitons into circularly polarized photons and vice versa in microcavities results in magnetization oscillations with terahertz frequencies [12]. Planar microcavities also allow the ballistic transport of energy in space [13], with exciton-polaritons covering distances on the order of hundreds of microns [14, 15]. While Josephson oscillations [16, 17] and other spatially dependent oscillations [18] were reported recently, the study of exciton-polariton Rabi oscillations has been typically kept separate from the study of spatial dynamics. This is likely due to the fact that Rabi oscillations are short-lived, surviving only a limited number of cycles due to the short polariton lifetime (a few tens of picoseconds in state-of-the-art samples). Nevertheless propagating polaritons have been progressing steadily toward the realization of optical circuits, where their light effective mass and strong nonlinear interactions have allowed several implementations of optical switches [19–21] and transistors [22–23].

To overcome the limited duration of Rabi oscillation, one can consider the amplification [24] of polaritons by a non-resonant excitation. This creates a reservoir of hot excitons, which can undergo stimulated scattering into polariton states. The result is an effective incoherent pumping or gain mechanism of polariton states, which can compensate polariton decay [24]. Using a Ginzburg-Landau type model [25], we show that this results in sustained Rabi oscillations, which brings new opportunities for their control, manipulation, and application.

Exciton-polaritons also have a rich spin dynamics [26], allowed by their two-component spin degree of freedom. We show that the propagation of polariton spin oscillations induced by Rabi oscillations [12] in space can be influenced by applied magnetic fields, as well as transverse electric-transverse magnetic (TE-TM) splitting of the modes. We show that Rabi oscillations can be further controlled by applying additional pulses to the system, which may enhance or suppress oscillations, where the pulse phase becomes a control variable.

Finally, we consider oscillations between exciton-polariton states with different momenta (i.e., different in-plane wavevectors), where propagating domains in real space are distinguished by their phase. In analogy to previous studies of domain wall propagation [27], the domains act as information carriers and logic gates can be realized from the combination of domains at engineered points of space. However, unlike previous work, the phase of the domains is a free continuous variable, opening an area of analogue information processing in polaritonics.

Theoretical Model.— To describe a coherent state of excitons and cavity photons, we introduce the mean-field wavefunctions [28] of spin-polarized excitons, χσ, and photons, φσ. The index σ = ± accounts for the two possible spin projections of (optically active) excitons and photons on the structure growth axis. The evolution of the mean-fields is described by complex Ginzburg-Landau equations [25, 29]:

\[
i\hbar \frac{\partial \chi_\sigma}{\partial t} = (E_X + \sigma \Omega_Z + i \left( P_\sigma - \Gamma_X - \Gamma_{NL} |\chi_\sigma|^2 \right) + \alpha |\chi_\sigma|^2) \chi_\sigma + \Omega \phi_\sigma,
\]

\[
i\hbar \frac{\partial \phi_\sigma}{\partial t} = \left( -\frac{\hbar^2}{2m_c} \nabla^2 - i \Gamma_C \right) \phi_\sigma + \Omega \chi_\sigma + F_\sigma.
\]

Here \( E_X \) represents the exciton-photon detuning and we neglected the dispersion of excitons, which is flat compared to the parabolic photon dispersion given by the light photon effective mass \( mc \). In a magnetic field excitons experience a Zeeman splitting [26], given by \( 2\Omega_Z \).
The incoherent pumping of the system is described by the polarized pumping strength \( P_\sigma \), which is saturated at high densities due to non-linear losses characterised by \( \Gamma_{\text{NL}} \). We also allow for a coherent resonant pumping with amplitude \( F_\sigma \). \( \Gamma_X \) and \( \Gamma_C \) are the decay rates of excitons and photons, respectively. Non-linear interactions between excitons with parallel spins are introduced in Gross-Pitaevskii form and described by the scattering strength \( \alpha \). For simplicity, we neglect the much weaker interactions between excitons with opposite spins. Finally, \( \Omega \) is the Rabi coupling strength between the excitons and photons.

**Homogeneous Solutions.**—To gain some understanding of the states supported by Eqs. (1) and (2), let us first consider a spatially homogeneous incoherent pumping and no coherent pumping \((F_\sigma = 0)\). For simplicity, let us also first neglect the Zeeman splitting and polariton-polariton interaction terms \((\Omega_Z = 0; \alpha = 0)\). For pump powers exceeding a threshold \( P \geq \Gamma_C + \Gamma_X \), stationary homogeneous states exist:

\[
\phi_\sigma = \frac{\Omega X_\sigma}{\hbar \mu + i \Gamma_C}, \quad \chi_\sigma = \sqrt{\frac{P_\sigma - \Gamma_C - \Gamma_X}{\Gamma_{\text{NL}}} e^{-i \theta_\sigma}} \tag{3}
\]

where \( \hbar \mu = \sqrt{\Omega^2 - \Gamma_C^2} \). Since there are no terms coupling \( \sigma^+ \) and \( \sigma^- \) polarized states in Eqs. (1) and (2), we effectively have two scalar problems. This would not be the case in the presence of a polarization splitting. Note that the incoherent pumping does not fix the phase of the solutions, given by \( \theta_\sigma \), which would be set by initial excitation conditions. The stability of the stationary solution can be checked by considering the spectrum of elementary excitations. While the solution is stable, it is not the only possibility.

We may also consider oscillating solutions of the form \( \chi_\sigma(t) = \chi_{\sigma,1} \sin(\omega t) \) and \( \phi_\sigma(t) = i \phi_{\sigma,1} \sin(\omega t) + i \phi_{\sigma,2} \cos(\omega t) \), where \( \chi_{\sigma,1}, \phi_{\sigma,1}, \phi_{\sigma,2} \) are taken to be constants. Substituting into Eqs. (1) and (2), and collecting terms oscillating as \( \cos(\omega t) \) and \( \sin(\omega t) \), we obtain the approximate solution:

\[
|\chi_{\sigma,1}|^2 = \frac{2}{3} \left( \frac{P - \Gamma_C - \Gamma_X}{\Gamma_{\text{NL}}} \right), \quad \hbar \omega = \pm \sqrt{\Omega^2 - \Gamma_C^2} \tag{4}
\]

Here we neglected fast oscillating terms proportional to \( \sin(3\omega t) \), appearing in the expansion of the term \( \sin^3(\omega t) = (3 \sin(\omega t) - \sin(3\omega t)) \). A comparison with the direct numerical solution of Eqs. (1) and (2) is shown in Fig. 1. To place the system in an oscillating state a pulse \( F_\sigma(t) \) was applied to the photon evolution according to Eq. (2). The Rabi oscillating solution is metastable. The phase difference between the exciton and photon component is \( \pi/2 \) at any moment of time for this solution. Fluctuations of the phase difference away from this value will lead to decay of oscillations. However, the amplification provided by the continuous incoherent pump ensures that the oscillations are sustained long after the pulse has passed.

Given that the two spin polarized components are decoupled, it is possible to prepare them in different states. Pairing a linearly polarized incoherent pump \((P_+ = P_-)\) with a circularly polarized pulse \( F_+(t) \) excites Rabi oscillations in the \( \sigma^+ \) polarization, while the \( \sigma^- \) polarization achieves the stationary state given by Eq. (3). Such a situation is shown in Fig. 1a, and is qualitatively unchanged even in the presence of a magnetic field \((\Omega_Z \neq 0)\). In this way, the presence of Rabi oscillations also manifests in oscillations in the circular polarization degree \( \rho \) (see Fig. 1a, and a circular rotation of the pseudospin vector on the Poincaré sphere (Fig. 1b). In contrast to common expectations, this pseudospin rotation is not related to any polarization splitting.

**Spatial Propagation of Rabi Oscillations.**—If the applied coherent pulse is not homogeneous in space, but rather localized, then one can consider the resulting prop-
Parametric Oscillations and Analogue Logic in Real Space. — To allow for oscillating domains that propagate in all directions, we make use of the potential parameter scattering \[\text{between polariton modes},\] allowed by the simultaneous coherent excitation of the bottom of the condensate. An initial pulse at \(t = 0\) ps. The pulses set the phase of their respective domains, and the resulting interference pattern of the domains differs depending on whether the pulses arrive in-phase (Fig. 3a, b) or out-of-phase (Fig. 3c, d).

This phase sensitivity of interfering polaritons has previously been appreciated as an ingredient for polaritonic information processing \[\text{32}.\] The spreading of Rabi oscillating domains is also reminiscent of spin polarized domains, which can be used to realize binary logic gates \[\text{27}.\] However, a limitation of the propagation shown in Fig. 2 is that it occurs only in one direction – the one set by the wavevector of the applied pulse. For the construction of cascadelable logic gates, one typically needs to have signals capable of travelling in a variety of directions in the microcavity plane.

**Parametric Oscillations and Analogue Logic in Real Space.** — To allow for oscillating domains that propagate in all directions, we make use of the potential parametric scattering \[\text{33}.\] between polariton modes, allowed by the nonlinear \(\alpha\)-dependent term in Eq. 4. Considering the simultaneous coherent excitation of the bottom of the arrows and vertical dashed lines. The first pulse induces Rabi oscillations in the system, which reach a fixed maximum amplitude (as seen before in Fig. 1). The second pulse can either amplify or suppress the oscillations, depending on whether it is in-phase or out-of-phase with the oscillations. In the former case, the amplification decays quickly, on the order of the polariton lifetime. In the case of an out-of-phase second pulse, the Rabi oscillations in the system can be suppressed for an extended period, with careful tuning of the pulse amplitude.

**Future Directions.** — With such a remarkable richness of dynamics already observed in the two-pulse excitation scheme, it is clear that the potential for future investigations is immense. It is to be expected that the amount of controllable functionality will increase significantly as the physics of polaritons is better understood and exploited. The work presented here opens new avenues for the realization of complex quantum systems, making it a promising field for further investigation.
the lower and upper polariton branches, one can expect scattering to non-zero wavevector states on the lower polariton branch \[ k \approx 10 \, \text{um}^{-1} \], as demonstrated in Fig. 5 (this requires a positive exciton-photon detuning; \( E_X = 3 \text{meV} \)).

By the spatial patterning of the pumping field \( F(x) \), one can confine polaritons along channels and we consider a “Y”-shaped channel in Fig. 5. Applied pulses localized in the left-hand channels trigger the parametric scattering and also set the phase of the resulting signal states. Figure 5a shows the polariton intensity 200ps after the pulses arrive, which are chosen to have the same phase (for simplicity, we consider only a single spin component here). A weak spatial modulation of the polariton density is associated with the scattering in reciprocal space shown in Fig. 5c. Filtering of the polariton field around the signal wavevector \( (k_s \approx 10 \, \text{um}^{-1}) \) clearly shows that the signal has propagated into the right-hand output channel.

In contrast, when pulses excite signals in the channels with opposite phase, they interfere destructively at the point where channels join, suppressing the propagation.

A further advantage of this scheme is that the signal wavevector can be tuned near the point of maximum group velocity of the lower polariton dispersion. In principle, this allows repetition rates of the order of tens of gigahertz, which could be further improved by reducing the dimensions of the channel pattern. On the other hand, oscillating parametric polariton solitons [33, 34] with very different spatial profiles and frequencies can be obtained operating near a flatter exciton-like region of the dispersion.

**Conclusion.**— We considered the generation of exciton-polariton Rabi oscillating domains in semiconductor microcavities subjected to coherent pulses. A continuous wave incoherent pump compensates the polariton lifetime, giving rise to sustained oscillations. The spin polarization of oscillations can be selected via the pulse polarization, which also allows the generation of terahertz frequency oscillations in the polariton spin degree of freedom. The oscillations remain in the presence of magnetic fields or TE-TM splitting, and can be further controlled by the application of additional pulses.

An important property of the Rabi domains is that their phase can be varied, which gives a continuous variable for encoding information. By making use of interbranch polariton-polariton scattering, the propagation of oscillating domains can be controlled along channels by patterning the incident optical field. A logical phase-dependent behaviour is observed from the interference when domains collide. This opens a route for analogue
architectures in polaritonic devices.

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SUPPLEMENTARY INFORMATION

Influence of TE-TM splitting on propagating spin-Rabi oscillations.— Many semiconductor microcavities exhibit an additional k-dependent polarization splitting, mainly due to the different energies of transverse electric (TE) and transverse magnetic (TM) photonic cavity modes. This splitting is well-known to influence the spin dynamics and resulting spatial patterns formed by propagating polaritons (see e.g., [15, 26] and references within).

Theoretically, the TE-TM splitting can be accounted for by adding a wavevector dependent term that couples the two spin components to the right hand side of Eq. (2):

\[ i\hbar \frac{\partial \phi_{\sigma}}{\partial t} = \ldots + \frac{\Delta_{LT}}{k_{LT}} \left( i \frac{\partial}{\partial x} + \sigma \frac{\partial}{\partial y} \right) \phi_{-\sigma} \tag{S1} \]

where \( \Delta_{LT} \) determines the strength of the TE-TM splitting at the in-plane wavevector \( k_{LT} \).

For typical parameters, we obtain the result shown in Fig. S1. The basic phenomenology of propagating spin-Rabi oscillations remains, however, the TE-TM splitting breaks the mirror symmetry of the system about the horizontal axis. This gives rise to assymmetric patterns in the distribution of the circular polarization degree.

FIG. S1. (color online) Influence of TE-TM splitting, giving rise to an asymmetric spatial distribution of Rabi oscillations. Images show the same as in Fig. 3, accounting for TE-TM splitting. Parameters: \( \Delta_{LT} = 0.1 \text{meV}, k_{LT} = 1 \mu\text{m}^{-1}, \Omega_Z = 0 \text{meV}. \)