Coherent oscillations between polariton vortex and anti-vortex states in an elliptical resonator

G. Nardin, Y. Léger, B. Pietka, F. Morier-Genoud, B. Deveaud-Plédran^a

^aLaboratoire d'Optoélectronique Quantique, École Polytechnique Fédérale de Lausanne (EPFL), Station 3, CH-1015 Lausanne, Switzerland.

ABSTRACT

In this experimental work, we optically excite the eigenmodes of an elliptical resonator in a semiconductor microcavity. Using a pulsed excitation, we create a superposition of eigenmodes, and image the time evolution of the coherent emission pattern. Oscillations between vortex and anti-vortex states are observed, and remarkably well described within the Poincaré sphere representation for an eigenmode containing an orbital angular momentum. A semiconductor quantum well is embedded in the microcavity structure. The system is operated in the strong light matter coupling regime, where the eigenmodes are hybrid half-photon half-excitonic quasiparticles called exciton polaritons.

Keywords: Semiconductor microcavity, exciton, polariton, vortex, coherent superposition, ultra-fast dynamics, digital holography

1. INTRODUCTION

Generation of optical vortices has been demonstrated in different types of lasers like ring resonators,¹ diode lasers² and Vertical Cavity Surface Emitting Lasers (VCSELs).³ They have been identified as the transverse modes of cylindrically symmetric optical resonators and often called the TEM_{01} “donut” mode, which can be obtained as a superposition of the TEM_{10} and TEM_{01} modes.^{4–7} In semiconductor microcavities, the strong coupling between the optical modes of the planar microcavity and the excitonic resonance of an embedded quantum well (QW) gives rise to hybrid quasi-particles partly made of light, partly made of matter, called exciton polaritons,⁸ whose unique properties have triggered interest in fundamental physics^{9,10} as well as for the implementation of novel all-optical logic gates.^{11,12} The generation of optical vortices strongly coupled to the excitonic resonance (or polariton vortices) has been demonstrated in a patterned microcavity.^{13,14} The vortices were resulting from a coherent superposition of eigenmodes of an elliptical polariton trap, excited using a continuous wave (*cw*) laser. In the present work we are considering the case where the confined polariton states are not continuously driven by the laser frequency (like a forced oscillator), but are excited with a laser pulse and let free to evolve. In this situation, when a superposition of states is excited, their phase oscillations at different frequencies will give rise to a time evolution of the emission pattern.

2. SAMPLE

The sample under scrutiny is the same as in Refs.^{13,14} It is a patterned GaAs cavity¹⁵ with one embedded InGaAs QW, sandwiched between two semiconductor distributed bragg reflectors (DBRs). The QW exciton emission wavelength is 835.15nm , corresponding to an energy of $E_x = 1.4845\text{eV}$. The signature of the strong coupling between the exciton and the fundamental cavity mode is a normal mode splitting (or Rabi splitting) of 3.5meV . The polariton traps consist of nearly circular mesas that were etched on the microcavity spacer (see

Further author information: (Send correspondence to G.N.)

G.N.: E-mail: gael.nardin@epfl.ch, Telephone: +41 21 693 54 49

Y.L.: E-mail: yoan.leger@epfl.ch

B.P.: E-mail: barbara.pietka@fuw.edu.pl, Present address: Institute of Experimental Physics, University of Warsaw, ul. Hoza 69, 00-681 Warsaw, Poland

F.M.G.: E-mail: francois.morier-genoud@epfl.ch

B.D.P.: benoit.deveaud-pledren@epfl.ch

Ultrafast Phenomena in Semiconductors and Nanostructure Materials XV,
edited by Kong-Thon Tsen, Jin-Joo Song, Markus Betz, Abdulhakem Y. Elezzabi, Proc. of SPIE
Vol. 7937, 79371Y · © 2011 SPIE · CCC code: 0277-786X/11/\$18 · doi: 10.1117/12.885513

Figure 1. (a) Scheme of the microcavity sample with mesa (not to scale, only a few DBR pairs are shown). (b) Scheme of the normal mode splitting (or Rabi splitting) arising from the strong coupling between the quantum well excitonic resonance and the transverse photonic modes resulting of the confinement by the mesa. It results in discrete confined transverse modes for the upper and the lower polariton branches. (c) Spatially resolved photoluminescence spectrum of the polaritons confined by a mesa of $10\mu\text{m}$ mean diameter, under non-resonant pumping. Energy is plotted with respect to the bare exciton energy ($E_x = 1.4845\text{eV}$). Discrete confined states are visible for the lower (below E_x) and upper (above E_x) polariton branches. The white arrow points on the first excited state of the lower polariton branch. All measurements presented in this paper are performed on this confined state.

Fig. 1a). Discrete confined polariton states result of the strong coupling between the optical modes of the nearly cylindrical resonator and the exciton (Fig. 1b). The transverse mode patterns of these 0D polariton states have been observed in traps of different sizes.¹⁶ A spatially resolved spectrum of the photoluminescence emitted by the confined states in a $10\mu\text{m}$ mean diameter trap under non-resonant pumping is shown in Fig. 1c. Discrete eigenstates can be observed for the lower polariton branch (below the bare exciton energy E_x) and the upper polariton branch (above E_x). The linewidth of these states is of the order of $80\mu\text{eV}$. All further measurements presented in the paper were performed on the first excited state of the lower polariton branch (indicated by a white arrow in Fig. 1c), and for a detuning of $\delta \sim 0\text{meV}$ between the confined photonic mode and the excitonic resonance E_x .

3. POINCARÉ SPHERE REPRESENTATION OF AN EIGENSTATE CONTAINING ORBITAL ANGULAR MOMENTUM

In circular coordinates, confined states can be described by two numbers (n, m) , the well known radial and orbital quantum numbers. In cylindrically symmetric systems, there is a twofold degeneracy between states $|m_+\rangle \propto e^{+im\phi}$ and $|m_-\rangle \propto e^{-im\phi}$, which carry an integer orbital angular momentum. Similarly to light beams,⁷ the coherent superpositions of the $|m_+\rangle$ and $|m_-\rangle$ can be placed on a Poincaré sphere (Fig. 2a - for the quantum numbers $(n = 1, m = 1)$). Equally weighted superpositions give rise to standing wave patterns with $|2m|$ lobes, whose alignment depends on the phase relation between $|m_+\rangle$ and $|m_-\rangle$. For example, the states shown in Fig. 2a can be obtained as $|x\rangle = |m_+\rangle + |m_-\rangle$, $|y\rangle = |m_+\rangle - |m_-\rangle$, $|d\rangle = |m_+\rangle + i|m_-\rangle$ and $|d'\rangle = |m_+\rangle - i|m_-\rangle$. Reversibly, the $|m_+\rangle$ state can be obtained as a superposition of $|x\rangle$ and $|y\rangle$, and so on. However, it has been shown that the polariton traps on the sample under scrutiny are slightly elliptical.^{15,17} This has for effect that the $|m_+\rangle$ and $|m_-\rangle$ are no longer eigenstates of the trap. The new eigenstates are, for the $(n = 1, m = 1)$ case, the $|x\rangle$ and $|y\rangle$ states showed on Fig. 2a. Spatially resolved spectroscopy^{16,18} allowed to measure an energy splitting between $|x\rangle$ and $|y\rangle$ of $\Delta E = 50 \pm 25\mu\text{eV}$. These eigenstates can be selectively excited using resonant *cw* excitation. Their phase and amplitude patterns can be imaged thanks to an interferometric method (detailed in the next section). Near field patterns are shown in Fig. 2b, 2c, 2d and 2e, where the two-lobe structure as well as the π -phase between the two opposite lobes can nicely be observed. Using a *cw* excitation also allowed to selectively create any kind of superpositions of $|x\rangle$ and $|y\rangle$.^{14,17}

4. EXPERIMENTAL SETUP

In order to obtain the amplitude and phase structure of the polariton modes shown in Fig 2, we have used a homodyne imaging setup.¹³ Polariton states were excited from the back side of the sample (held in a cold-finger

Figure 2. a) Poincaré sphere representation of the degenerate ($n = 1, m = 1$) state. Coherent superpositions (with equal weights) of the integer orbital angular momentum states $|m_+\rangle$ and $|m_-\rangle$ yields to a two-lobe pattern, whose orientation depends of the relative phase between $|m_+\rangle$ and $|m_-\rangle$. For this $m = 1$ state, the same Poincaré sphere can be used to represent the case of an elliptical trap, for which $|x\rangle$ and $|y\rangle$ are the new eigenstates. (b) Amplitude of the near field emission pattern of $|y\rangle$, measured using the interferometric method described in section 4. (c) Corresponding phase structure, showing a π -phase shift between the lower and upper lobes. (d)-(e) Same as (b)-(c), but for the $|x\rangle$ state. Amplitude patterns are in a linear gray scale from minimal (black) to maximal (white) intensity. Phase patterns are in a linear gray scale from 0 (black) to 2π (white).

cryostat at a liquid helium temperature). The coherent emission of the polariton state was collected from the front side of the sample, and interfered on a CCD with a reference laser beam. Digital off-axis filtering¹⁹ allowed then to retrieve the amplitude and phase information of the emission pattern. When using a pulsed excitation instead of a *cw* one, the situation is very different, as the created coherent superposition is let free to evolve. We use a mode-locked Ti:Sapph laser, which provides 12nm-broad, 80fs-long pulses at a repetition rate of 80MHz. Creating a polariton population with the excitation pulse, we can probe the polariton dynamics by varying the delay τ between the excitation and reference pulses. Indeed, the reference pulse will interfere on the CCD only with the coherent emission emitted at delay τ . The time resolution of the setup is given by the temporal length of the reference pulse. In order to selectively excite the trapped polariton states, the excitation pulse is tailored to a nearly Gaussian pulse of 140μeV FWHM using a pulse shaper. The corresponding pulse duration is 13ps, which provides the time resolution of the interferometric measurements.

5. RESULTS: OSCILLATIONS BETWEEN VORTEX AND ANTI-VORTEX STATES

We use the 140μeV broad pulse obtained from the pulse shaper to excite a superposition of the $|x\rangle$ and $|y\rangle$ eigenstates resulting of the slight ellipticity of the 10μm mean diameter trap. It is very convenient to represent again the superposition in a Poincaré sphere (Fig. 3a). We place the eigenstates $|x\rangle$ and $|y\rangle$ on the vertical axis, and their possible superpositions on the equator of the sphere. As the two eigenstates oscillate with different frequencies, their relative phase will constantly change with time, leading to an evolution of the emission pattern. This evolution can be very easily pictured in the Poincaré sphere representation as a rotation of the state vector of the system (in purple on Fig. 3a) around the eigenaxis at a frequency $\omega = \frac{\Delta E}{\hbar}$. This periodical oscillation is analogous to the Rabi oscillations observed when a superposition of upper and lower polaritons is created, or to the spatial oscillations observed between two coupled wells when a superposition of the symmetric and antisymmetric eigenstates is created.

Once a polariton population is injected by the excitation pulse, the time evolution of the coherent emission can be probed by scanning the delay τ between excitation and reference pulses. We record on a CCD the resulting interference patterns which arise due to a slight tilt of the reference phase front with respect to the image plane. From the recorded interferograms, digital off-axis filtering allows to extract the amplitude and phase of coherent emission pattern emitted at the delay τ . We show on Fig. 2b the spatially integrated amplitude $\langle E \rangle$ of the coherent emission with respect to the interferometer delay. It can be seen that after the injection by the $\sim 13ps$ long pulse, the emission intensity $\langle E^2 \rangle$ decays with a characteristic decay time of $\tau = 15.7 \pm 0.3ps$. This time corresponds to the polariton lifetime, which is a combination of the cavity photon escape rate and the exciton

Figure 3. (a) Poincaré sphere representation of the nearly degenerate ($n = 1, m = 1$) state in a nearly circular trap. The eigenstates resulting of the trap ellipticity correspond to the poles of the sphere, and their equally weighted superpositions are located on the equator. The type of superposition depends of the phase difference between the eigenstates. The most typical superpositions, which are the vortex, anti-vortex and diagonal states are shown on the picture. The time evolution of a superpositions can be pictured as a rotation of the state vector (in purple) around the eigenaxis, at a frequency $\omega = \frac{\Delta E}{\hbar}$, where ΔE is the energy splitting between the eigenstates $|x\rangle$ and $|y\rangle$. (b) Amplitude $\langle E \rangle$ of the polariton coherent emission field, spatially integrated over the whole polariton emission, versus time. The time zero is given by the estimated zero delay between excitation and reference pulses. In blue: a mono-exponential fit allows to extract the decay time 2τ of the emission field amplitude $\langle E \rangle$. It gives a decay time τ for the emission field intensity $\langle E^2 \rangle$ of $\tau = 15.7 \pm 0.3$ ps. The fringes of the recorded interferogram (in a saturated color scale) are displayed in (c), the emission field amplitude in (d) and the emission field phase in (e). The different columns show snapshots of the time evolution of the emission pattern, at times indicated by vertical black lines and a corresponding letter (i)-(v) in (b). This evolution is very well explained by a rotation of the system state vector along the equator of the Poincaré sphere shown in (a). The movie corresponding to (c) can be found as a supplementary multimedia file.

lifetime. Images of the coherent emission amplitude, at the delays indicated by vertical black lines and letters (i)-(v) in Fig. 3b, are shown in Fig. 3c, 3d and 3e. The fringes of the interferogram (in a saturated color scale) are displayed in 3c, the emission field amplitude in 3d and the emission field phase in 3e.

In the first column (i) the polariton injection is shown. It displays a diagonal state $|d\rangle$, indicating that

a well balanced (i.e. with similar weights) superposition of $|x\rangle$ and $|y\rangle$ is created. Columns (ii) to (v) show the free evolution of the polariton field emission pattern, with an interval between each picture of $\sim 25ps$. A decrease of the signal intensity is observed with time, due to the finite polariton lifetime measured in Fig. 3b. In the second column (ii), the polariton emission pattern shows an integer orbital angular momentum state (or vortex state) $|m_{-}\rangle$, characterized by a donut shape. The interferogram displays a fork-like dislocation oriented downwards, indicating the presence of a phase singularity. A 2π -phase shift is visible in the phase structure when circumventing the donut core. The third column (iii) shows a $|d'\rangle$ state (orthogonally aligned with respect to the $|d\rangle$ state of (i)), featuring a π -phase difference between its two lobes. An anti-vortex state $|m_{+}\rangle$ (rotating counterclockwise, with a fork-like dislocation oriented upwards) is visible in (iv), and a diagonal state $|d\rangle$ again in (v). The system state vector has therefore made a full rotation along the Poincaré sphere equator. The rotation period is $T \sim 4 \times 25ps = 100ps$ (with a $\sim 13ps$ resolution), corresponding to an oscillation frequency of $\sim 10GHz$. It allows to estimate for this trap the energy splitting between $|x\rangle$ and $|y\rangle$: $\Delta E = \hbar\omega = \hbar \frac{2\pi}{100} = 41 \pm 5\mu eV$, in agreement with the $50 \pm 25\mu eV$ generally measured using spatially resolved spectroscopy.

6. CONCLUSION

In conclusion, we have shown in this work the imaging of the time evolution of a coherent superposition of light-matter polariton states in a semiconductor microcavity. In particular, a periodical oscillation between vortex and anti-vortex states has been evidenced in the elliptical polariton trap. The observed phenomenon is remarkably well described by a rotation of the system state vector around the eigenaxis in the Poincaré sphere representation of an integer orbital angular momentum state. The measured oscillation frequency of $\sim 10GHz$ corresponds to the energy splitting between the eigenstates of the elliptical trap.

ACKNOWLEDGMENTS

The authors would like to thank O. El Daïf for the design and fabrication of the sample. We acknowledge support by the Swiss National Research Foundation through the “NCCR Quantum Photonics”.

REFERENCES

1. M. Brambilla, F. Battipede, L. A. Lugiato, V. Penna, F. Prati, C. Tamm, and C. O. Weiss, “Transverse laser patterns. i. phase singularity crystals,” *Physical Review A* **43**, p. 5090, May 1991.
2. Y. F. Chen and Y. P. Lan, “Transverse pattern formation of optical vortices in a microchip laser with a large fresnel number,” *Physical Review A* **65**, p. 013802, Dec. 2001.
3. F. B. De Colstoun, G. Khitrova, A. V. Fedorov, T. R. Nelson, C. Lowry, T. M. Brennan, B. G. Hammons, and P. D. Maker, “Transverse modes, vortices and vertical-cavity surface-emitting lasers,” *Chaos, Solitons & Fractals* **4**, pp. 1575–1596, Aug. 1994.
4. J. E. Epler, S. Gehrsitz, K. H. Gulden, M. Moser, H. C. Sigg, and H. W. Lehmann, “Mode behavior and high resolution spectra of circularly-symmetric GaAs-AlGaAs air-post vertical cavity surface emitting lasers,” *Applied Physics Letters* **69**(6), p. 722, 1996.
5. C. Degen, W. Elsässer, and I. Fischer, “Transverse modes in oxide confined VCSELs: influence of pump profile, spatial hole burning, and thermal effects,” *Optics Express* **5**(3), pp. 38–47, 1999.

Figure 4. Video 1: Video corresponding to the snapshots of Fig. 3c. <http://dx.doi.org/doi.number.goes.here>

6. M. Padgett, "An experiment to observe the intensity and phase structure of Laguerre-Gaussian laser modes," *American Journal of Physics* **64**(1), p. 77, 1996.
7. M. J. Padgett and J. Courtial, "Poincaré-sphere equivalent for light beams containing orbital angular momentum," *Optics Letters* **24**, pp. 430–432, Apr. 1999.
8. C. Weisbuch, M. Nishioka, A. Ishikawa, and Y. Arakawa, "Observation of the coupled exciton-photon mode splitting in a semiconductor quantum microcavity," *Physical Review Letters* **69**, p. 3314, Dec. 1992.
9. A. Amo, J. Lefrère, S. Pigeon, C. Adrados, C. Ciuti, I. Carusotto, R. Houdré, E. Giacobino, and A. Bramati, "Superfluidity of polaritons in semiconductor microcavities," *Nature Physics* **5**(11), pp. 805–810, 2009.
10. K. G. Lagoudakis, T. Ostatnický, A. V. Kavokin, Y. G. Rubo, R. Andre, and B. Deveaud-Plédran, "Observation of Half-Quantum vortices in an Exciton-Polariton condensate," *Science* **326**(5955), pp. 974–976, 2009.
11. T. C. H. Liew, A. V. Kavokin, and I. A. Shelykh, "Optical circuits based on polariton neurons in semiconductor microcavities," *Physical Review Letters* **101**(1), p. 016402, 2008.
12. T. K. Paraïso, M. Wouters, Y. Léger, F. Morier-Genoud, and B. Deveaud-Plédran, "Multistability of a coherent spin ensemble in a semiconductor microcavity," *Nat Mater* **9**(8), pp. 655–660, 2010.
13. G. Nardin, Y. Léger, B. Pietka, F. Morier-Genoud, and B. Deveaud-Plédran, "Phase-resolved imaging of confined exciton-polariton wave functions in elliptical traps," *Physical Review B* **82**, p. 045304, July 2010.
14. G. Nardin, K. G. Lagoudakis, B. Pietka, F. Morier-Genoud, Y. Léger, and B. Deveaud-Plédran, "Selective photoexcitation of confined exciton-polariton vortices," *Physical Review B* **82**(7), p. 073303, 2010.
15. O. El Daïf, A. Baas, T. Guillet, J.-P. Brantut, R. I. Kaitouni, J. L. Staehli, F. Morier-Genoud, and B. Deveaud, "Polariton quantum boxes in semiconductor microcavities," *Applied Physics Letters* **88**(6), p. 061105, 2006.
16. G. Nardin, R. Cerna, T. K. Paraïso, B. Pietka, Y. Léger, O. E. Daif, F. Morier-Genoud, and B. Deveaud-Plédran, "Probability density tomography of microcavity polaritons confined in cylindrical traps of various sizes," *Superlattices and Microstructures* **47**(1), pp. 207–212, 2010.
17. R. Cerna, D. Sarchi, T. K. Paraïso, G. Nardin, Y. Léger, M. Richard, B. Pietka, O. El Daif, F. Morier-Genoud, V. Savona, M. T. Portella-Oberli, and B. Deveaud-Plédran, "Coherent optical control of the wave function of zero-dimensional exciton polaritons," *Physical Review B* **80**, p. 121309, Sep 2009.
18. G. Nardin, T. K. Paraïso, R. Cerna, B. Pietka, Y. Léger, O. E. Daif, F. Morier-Genoud, and B. Deveaud-Plédran, "Probability density optical tomography of confined quasiparticles in a semiconductor microcavity," *Applied Physics Letters* **94**(18), p. 181103, 2009.
19. T. Kreis, *Handbook of holographic interferometry : optical and digital methods*, Wiley-VCH, 2004.