Exploiting quantum coherence of polaritons for ultra sensitive detectors

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(Dated: May 3, 2014)

Besides being superfluids, microcavity exciton-polariton condensates are capable of spontaneous pattern formation due to their forced-dissipative dynamics. Their macroscopic and easily detectable response to small perturbations can be exploited to create sensitive devices. We show how controlled pumping in the presence of a peak-dip shaped potential can be used to detect small externally applied velocities which lead to the formation of traveling holes in one dimension and vortex pairs in two dimensions. Combining an annulus geometry with a weak link, the set up that we describe can be used to create a sensitive polariton gyroscope.

PACS numbers: 03.75.Lm, 71.36.+c,03.75.Kk, 67.85.De, 05.45.-a

Microcavity exciton-polaritons are two-dimensional half-light half-matter quasi-particles that result from the hybridisation of quantum well excitons and photons in a planar Fabry-Perot resonator. At low enough densities, they behave as bosons and if the temperature is lower than some critical value they undergo Bose-Einstein condensation [1, 2]. Recent experiments have investigated exciton-polariton condensation and the phenomena associated with it, such as pattern formation [3, 4], quantised vortices and solitons [5, 6], increased coherence and the cross-over to regular lasing; recent reviews of the field can be found in [7, 8]. These discoveries have opened a path for new technological developments in optoelectronics (ultra-fast optical switches, quantum circuits), medicine (compact terahertz lasers) and power production (hybrid organic-inorganic solar cells). However one fundamental property of exciton-polariton condensates, their ability to flow without friction at moderate velocities [9, 10], has never been considered for technological use. The existence of frictionless flow in polariton condensates sets them apart from other solid-state quantum systems and links them to cooperative fluids, such as superfluid helium or atomic condensates. In this letter we propose an idea that may lead to a new generation of ultra-sensitive devices based on the quantum coherence and superfluidity of exciton-polariton condensates. The important ingredients of this novel technology come from the unique properties of polariton condensates: (1) they are non-equilibrium systems capable of pattern formation; (2) their dynamics is controlled by the balance between gain, due to continuous pumping, losses and non-linearity; (3) polaritons condense at relatively high (even room) temperature thanks to their very small effective mass; (4) one can easily engineer any external landscape and vary pumping in space and time; (5) polariton condensates form quantised vortices in response to slight changes in the environment: when flow exceeds the critical velocity, when fluxes interact, when pumping powers exceed a threshold for pattern forming instabilities, when the magnetic field exceeds a threshold, etc. These properties allow one to prepare the system in a state slightly below the criticality for vortex formation, so that a tiny external perturbation will take it over the criticality, leading to a macroscopic and easily detectable response. Similar principles underpin superconducting single photon detectors, biased just below their transition temperature. Therefore, we propose exploiting superfluid properties and sensitivity to vortex formation of polariton condensates to create sensitive devices that respond to slight changes in rotation rate, gravity or magnetic field. We will illustrate the main principles using the example of an exciton-polariton gyroscope.

Superfluid helium gyroscopes have already been shown to provide sensitive means for detecting absolute rotations [11, 12], but required very low temperature for operation. A superfluid in an annulus (ring) that is slowly rotated remains motionless as there is no friction with boundaries. But if a partition with a small opening (weak link) is inserted in the annulus, a flow in the direction opposite to the rotation will be generated through it. To leading order [12], the velocity $U$ across the opening is

![FIG. 1: (color online) Schematic of the experiment: pumped polariton condensate channel with a weak link. If the flow across the link is high enough, vortices are generated.](https://example.com/figure1.png)
related to the angular speed of rotation $\Omega$ by the relation
$U = \Omega R^2/\delta$, where $R$ ($\delta$) is the width of the annulus
(opening). When $U$ exceeds some critical value, which is
of the order of the Landau critical velocity $U_c$, vortices
are generated and detected as phase slips. For the case of
superfluid He$_4$, $U_c \sim 50$ m/s, $R \sim 0.1$ m, $\delta \sim 100$ nm,
allowing accurate detection of the Earth’s daily rotation
rate. It was also established that superfluid rotation
sensors, similar to atomic beam gyroscopes, belong to
the same class of quantum interference effects as Sagnac
light-wave experiments [13]. The same principles can be
applied to a polariton gyroscope, schematic of which is
given in Fig. [1] which offers the advantage of potentially
operating at room temperatures. The critical velocity for
vortex formation in polariton condensates [10] is three-
four orders of magnitude higher than that in superfluid
He$_4$, a fact that would reduce the sensitivity of the
polariton gyroscope. However, the pattern forming proper-
ties of polariton condensates allow one to severely reduce
the velocities needed for the vortex formation to occur
and to use pumping intensity as the control parameter.
We propose to insert a peak-dip shaped potential, which
will further accelerate the flow, at the position of the
weak link. Such a potential can be prepared either using
a combination of etching [14-16] and stress induced
traps [1], or directly defining blue-shifted trap potentials
via spatial light modulators [3]. Even in the absence of
any externally applied flow, velocity fluxes connecting re-
gions where the density is low (at the potential peak) to
regions where the density is high (at the potential dip)
will be generated; in between them will be a point
where the condensate speed takes its maximum value.
Close to such a point, the density has a local minimum
(Bernoulli effect). A slight change of external conditions,
e.g. an increase of the potential strength, or a decrease of
the pumping intensity, will further lower the density.
If the perturbation is large enough, the density minimum
will reach zero and a vortex pair will be emitted, as we
illustrate below using a mean-field model of polariton
condensates. The scheme for measuring rotations then
becomes quite straightforward: having prepared a po-
tential such that the system is in a slightly subcritical
configuration for the range of rotation speeds that one
intends to measure, the strength of the pumping intensity
is varied, recording the moment when vortices start
to nucleate. From this one deduces the back-flow through
the aperture and, therefore, the rotational velocity.

Polariton condensates at temperatures much lower
than the critical temperature for condensation can be
effectively described using the complex Ginzburg-Landau
equation (cGL) [19] [20]. If a condensate is flowing with
bulk speed $U$ along the $x$ axis, the cGL in a frame co-
moving with the condensate takes the form

$$2(\eta - i)\left(\partial_t + U \partial_x\right) \psi = \left[\nabla^2 - V(x, y) - \mid \psi \mid^2 - i(\alpha - \sigma \mid \psi \mid^2)\right] \psi$$

(1)

where $V(x, y)$ describes an external potential, $\alpha$ is a
pump rate, $\sigma$ is a nonlinearity which causes pumping
to reduce as density increases and $\eta \sim 0.1$ is an energy
relaxation term [21] which causes the evolution towards
states of lower energy. Linear losses are included in $\alpha$.
Eq. (1) is stated in harmonic oscillator units, assuming
that $V = \omega^2/2$ and measuring energy in units of $\hbar \omega/2$,
length in units of the oscillator length $l = \sqrt{\hbar/m}$, and
time in units of $\omega^{-1}$, where $\omega$ is the oscillator frequency
of the trapping potential. For $m$ and $\hbar \omega$ we take the
values found by Ballivi et al [1] [23]: $\hbar \omega = 0.066$ meV,
m $= 7 \times 10^{-5}$ m, and for $\alpha$ and $\sigma$ we follow estimates
given in Refs. [19] [22]: $\alpha = 0.3$, $0 < \alpha < 10$.

In order to illustrate the main principles of the vor-
tex formation mechanism, we consider first the simpler
1D case, with an external potential of the form $V(x) = V_0 \exp(-(x-x_0)^2) - \exp(-(x+x_0)^2))$. The peak-dip
shape of this potential allows for a better acceleration of
the condensate than a single bump; moreover, in 2D the
dip has also the useful role of temporarily trapping vor-
tices and making their detection easier. After perform-
ing a Madelung transformation setting $\psi = \sqrt{\rho} \exp(i\phi)$, equation (1) in a frame at rest ($U = 0$) and for a sta-
tionary state becomes the system

$$\partial_t (\rho \phi) = (\alpha - \sigma \rho - \eta \mu) \rho$$

(2)

$$\mu = \rho + u^2 + V(x) - \rho^2 \sqrt{\rho}/\sqrt{\rho}$$

(3)

where $\mu$ is the chemical potential. The speed $u = \nabla \phi$
takes its maximum at some point between $-x_0$ and $x_0$,
the maximum and minimum of the potential. It follows from Eq. (3), which is a generalized version of Bernoulli’s
equation, that close to the maximum of the speed, den-
sity has a local minimum. The numerical results displayed in Fig. [2] show that max$(u)$ is an increasing
function of $V_0$ and min$(\rho)$ a decreasing one. This can
be verified analytically deriving an approximate solution
as follows. For very small $V_0$ it is natural to expect a
dip-peak density profile; however, for higher values of $V_0$,
there will be an additional minimum due to the Bernoulli
effect. Therefore we take a density ansatz of the form
$p = \alpha/(\sigma + \eta) + B \exp(-b(x - x_0)^2) + C \exp(-c(x - x_1)^2) - Q \exp(-q(x - x_2)^2)$, where $b, B, c, C, q, Q, x_1, x_2, x_3$ are
free parameters. Substituting in (2) and integrating one has:

$$\rho u = \frac{\sqrt{\pi} \sigma}{2\sqrt{\mu}} \left[ \frac{Q}{\sqrt{\mu}} \text{erf}(\sqrt{3} \sigma \xi_3) - \frac{B}{\sqrt{b}} \text{erf}(\sqrt{2} \xi_3) - C \sqrt{\frac{C}{\nu}} \text{erf}(\sqrt{3} \sigma \xi_3) \right]$$

$$- \frac{\sqrt{\pi} \sigma}{2} \left[ \frac{B^2}{\sqrt{b}} \text{erf}(2 \sqrt{2} \xi_1) + \frac{C^2}{\nu} \text{erf}(\sqrt{2} \xi_2) + \frac{Q^2}{\sqrt{q}} \text{erf}(\sqrt{2} q \xi_3) \right]$$

$$+ \sqrt{\pi} \sigma \left[ -E(B, C, b, c, x_1, x_2) + E(B, Q, b, q, x_1, x_3) \right. \left. + E(C, Q, c, q, x_2, x_3) \right]$$

$\text{erf}$ denotes the error function.
where \( \tilde{x}_j \equiv x - x_i, x_{ij} \equiv x_i - x_j \) and

\[
E(B, C, b, c, x_i, x_j) = \frac{BC}{\sqrt{b+c}} e^{-\left(\frac{b+c}{b+c}\right)} \text{erf}\left( \frac{h \tilde{x}_j + c \tilde{x}_j}{\sqrt{b+c}} \right)
\]

The potential \( V(x) \) is then determined from \( H \) and contains the unknown parameters \( B, C, Q, b, c, q, x_1, x_2, x_3 \). The values of these parameters can be fixed requiring \( V(x) \) to fit the original potential \( V(x) \). A comparison of the analytical and numerical solutions for \( u \) is shown in panel (a) of Fig. 2, while numerical solutions for \( \rho \) are shown in panel (b). The behavior of \( \max(u) \) and \( \min(\rho) \)

**FIG. 2:** (color online) (a) Numerical (black dashed line) and analytical estimates (red solid line) of velocity profiles as \( V_0 \) is increased from 1 to 4. (b) Numerical solutions for \( \rho \) with \( V_0 = 1.4, 2.0, 2.6, 3.2, 3.8, 4.4 \). Higher values of \( V_0 \) correspond to lower values of \( \min(\rho) \). In both figures \( x_0 = 1.5 \).

with \( V_0 \) is mostly linear up to \( V_0 = 4 \), see Fig. 3 panel (a). A deviation from the linear regime leads quickly, for \( V_0 > 4.4 \), to the loss of stability of stationary solutions. The time dependent solutions found for \( V_0 > 4.4 \) are characterized by the periodic emission of traveling holes [21], which travel for a short time before dissipating, see Fig. 4. The density hits zero when the hole is emitted.

In two dimensions we take a similar potential: \( V = V_0 \left( \exp\left(-\left((x - x_0)^2 + y^2\right)\right) - \exp\left(-\left((x - x_0)^2 + y^2\right)\right) \right) \). The dynamics is similar to that of the 1D case: \( \min(\rho) \) is again a decreasing function of \( V_0 \), with a linear behavior for small values of \( V_0 \), see Fig. 3 panel (b). When \( V_0 \) exceeds a critical value, stationary solutions become unstable and vortex pairs form. If the system is close enough to criticality, the drop of \( \min(\rho) \) to zero and consequent onset of vortex nucleation can also be started by a small increase of the external velocity \( U \) or decrease of the pumping strength \( \alpha \). The process is shown in Fig. 5 where the onset of vortex nucleation is due to an increase of \( U \). Representatives of critical and subcritical states are shown in Fig. 6. There is, however, one notable difference with the 1D case: while in the latter the emission of traveling holes sets in at a finite value of \( \min(\rho) \), in 2D there are stationary solutions all the way down to \( \min(\rho) = 0 \), see the right panel of Fig. 4. An example calibration curve is shown in Fig. 7, where the critical values of \( \alpha \) which start vortex nucleation are recorded for fixed \( V_0 \) and different values of \( U \). The boundary \( U(\alpha) \) between subcritical and critical behavior is, for a bulk speed \( U < 0.5 \), nearly linear, hence the sensitivity of the apparatus scales linearly with \( \alpha \) or, equivalently, with the bulk density \( \alpha/\sigma \) of the condensate. In the numerical simulations that we performed, the system showed a clear transition between subcritical and critical states at velocities of the order of \( 10^{-4} \) of the critical velocity \( U_c = \sqrt{\mu/m} \) for this system.
the parameters $U$ and $\alpha$ for $V_0 = 14$, $x_0 = 1.5$. The inset has been obtained with a different values of the potential, $V_0 = 16.8$, $x_0 = 1.5$ and gives an idea of the attainable resolution for small values of $U$.

This puts the sensitivity of polariton gyroscopes in the same range as that of superfluid helium gyroscopes, but at the advantage of potentially operating at room temperature.

In summary, we proposed an idea for creating polaritonic sensitive devices, such as a superfluid gyroscopes, based on their macroscopic response to small perturbations. We studied the mechanism of the formation of traveling holes in 1D and vortex pairs in 2D in an externally imposed peak-dip shaped potential when the height of this potential (the difference between maximum and minimum) exceeds the threshold.

G.F. acknowledges funding from Marie Curie Actions ESR grants. All authors acknowledge funding from EU