Superfluid Motion of Light

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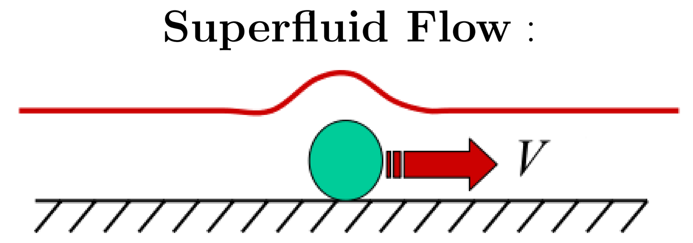
Introduction

Superfluidity, the ability of a fluid to move without dissipation, is one of the most spectacular manifestations of the quantum nature of matter. It has been observed, for instance, in liquid Helium, in the electrical transport of electrons in metals (superconductors) and in ultracold dilute atomic gases. It is at the basis of many actual and potential applications, with limitations coming mainly from the very low temperatures required for its manifestation. Here we analyze a different system, the room-temperature propagation of light in a nonlinear medium. We show that there are regimes where the motion is superfluid, e.g. the scattering from defects is suppressed. We explicitly describe an experimental realization of this new phenomenon based on the transverse motion of light through a photonic lattice. Controlling the speed of light with respect to a defect, we demonstrate that above a critical velocity superfluidity is destroyed by the emission of discrete solitons. The results open new perspectives for room-temperature superfluidity, with possible applications in transport optimization and, more generally, in controlling light propagation.

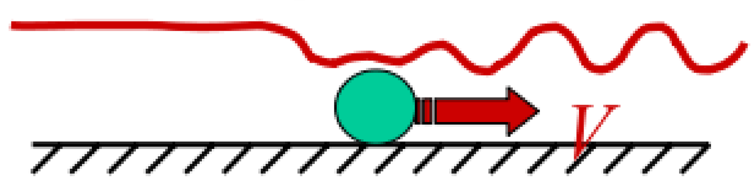
Superfluidity: basic concepts

Superfluid Flow :



- No dissipation, No drag force
- Perfect transmission

Dissipative Flow :

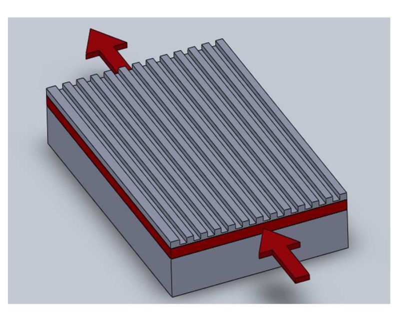


- Dissipation, non-zero drag force
- Emission of excitations

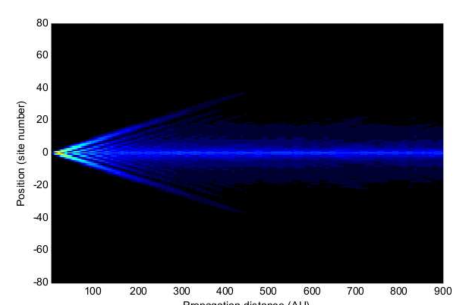
Landau critical velocity $v_c = \min(\epsilon(p)/p)$

Experiments on nonlinear photonic crystal (PC)

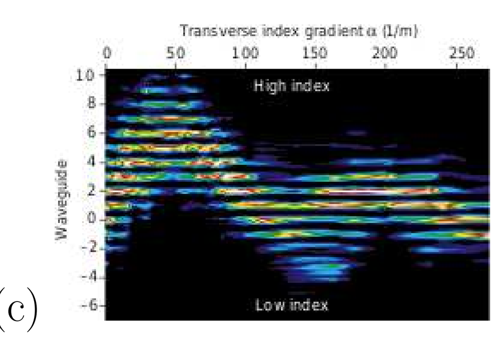
Examples of recent experiments using photonic crystals (a) to highlight Anderson localization [1] (b) , or Bloch oscillations [2] (c) .



(a) Schematic view of a photonic crystal.



(b) Localization of a light beam through a photonic crystal.



(c) Bloch oscillations in a photonic crystal.

Formal analogy with Bose-Einstein Condensate (BEC)

All these experiments come from the formal analogy between the Gross-Pitaevskii equation (eq. (1)) and the equation of propagation of light in a discrete nonlinear medium (eq. (2))[3]:

$$i\hbar\partial_t\psi(x,t) = \left[-\frac{\hbar^2}{2m}\partial_x^2 + V(x) + g|\psi(x,t)|^2 - \mu\right]\psi(x,t) \quad (1)$$

$$i\frac{\partial A_k}{\partial z} = -C\left(A_{k+1} + A_{k-1}\right) + \gamma|A_k|^2 A_k + \epsilon_k A_k \quad (2)$$

It is clear that there is an exact correspondance between equations (1) and (2), except that space is discrete in eq. (2) :

Eq. (1)		Eq. (2)
Evolution of a BEC in 1d	$\Longleftrightarrow$	Transverse propagation of light
Mean field approximation	$\Longleftrightarrow$	Paraxial approximation
t	$\Longleftrightarrow$	z
x	$\Longleftrightarrow$	k
$\Psi(x,t)$	$\Longleftrightarrow$	$A_k(z)$
$V(x)$	$\Longleftrightarrow$	ϵ_k
$g>0$	$\Longleftrightarrow$	$\gamma>0$

<u>Conclusion</u> **: As a BEC described by eq. (1) exhibits superfluidity [6, 7], eq. (2) should also show a superfluid motion for light transverse dynamics.**

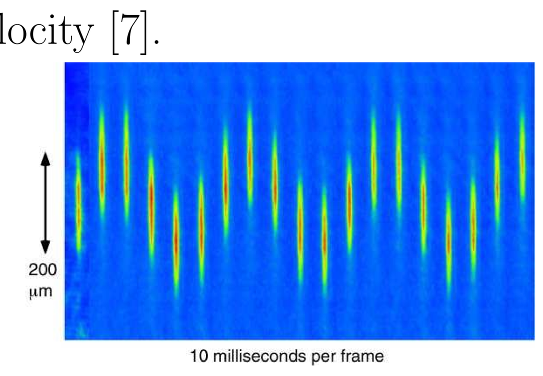
Dipole oscillations (DOs): Principle and expectations

We would like to be able to clearly single out the influence of a defect on light propagation, that is why we decide to use dipole oscillations: By modulating the width of each waveguide, we build a set of harmonic on-site "energies" $\epsilon_k = \frac{1}{2}\omega^2 k^2$. If we shine a light packet located at an arbitrary distance d from the bottom of the potential:

Without any defect :	With a defect $\epsilon_k = \frac{1}{2}\omega^2 k^2 + U_0\delta_{k,0}$:
Maximum velocity $v = \omega \cdot d$	Maximum velocity $v = \omega \cdot d$
Oscillations with frequency ω [4, 5]	Similar **if** superfluid
Wavepacket oscillates with a frozen shape	Similar **if** superfluid

Experimental DOs in BECs

Examples of experiments including DOs of a BEC in a harmonic trap. In fig. (b), the experiment aims to determine the critical velocity of a superfluid BEC. The oscillations of the condensate, which are supposed to be perfect for a superfluid, are here damped because its velocity exceeds the critical velocity [7].



(a): Dipole Oscillations of a BEC.

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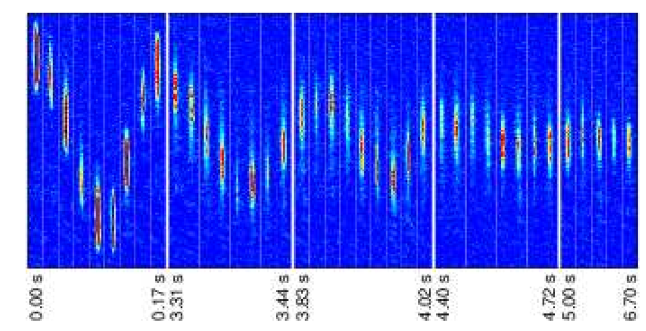
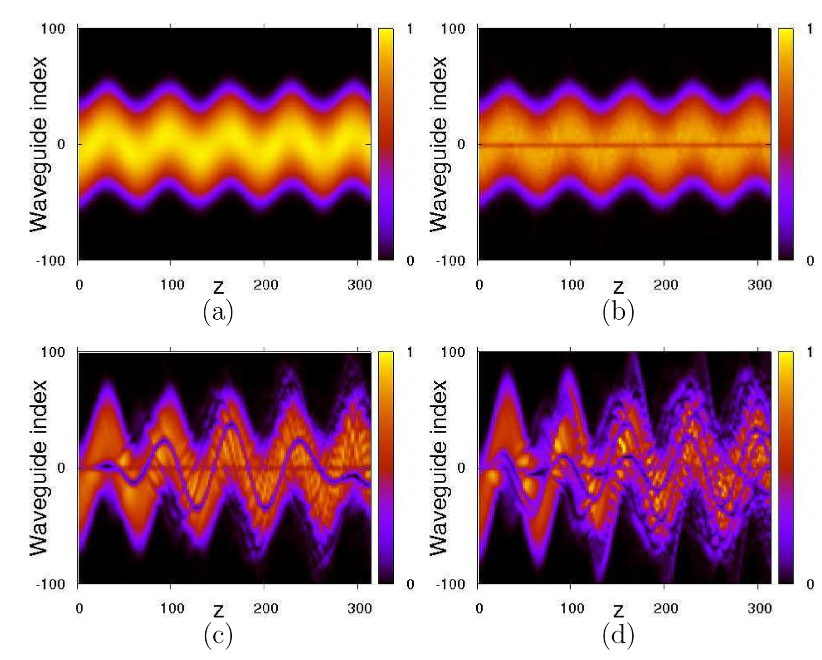
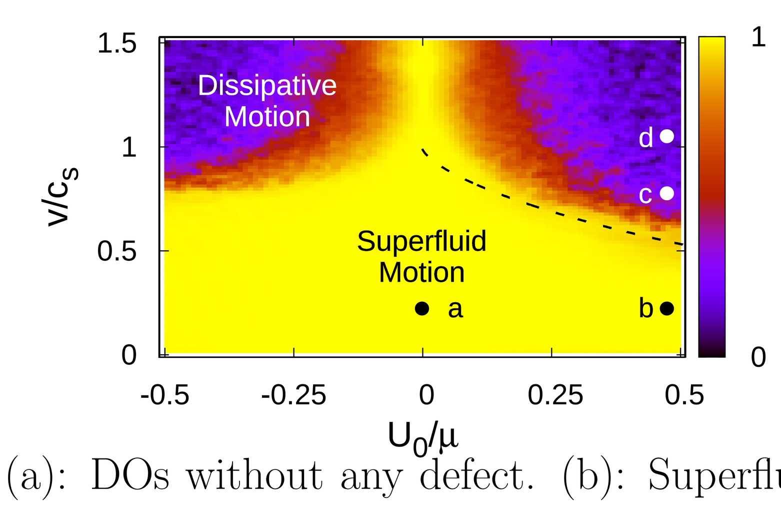


(b): Damping of DOs due to the presence of a defect in the trap.

R. Hulet's Group - Rice University

Numerical Results [8]





(a): DOs without any defect. (b): Superfluid motion, for small oscillations, i.e. slow velocity. (c): Entering in a turbulent regime. (d): Collectivity fully lost for high velocities.

The color diagram represents the amplitude of oscillations after a long time: when it goes to 1, the oscillations are undamped, whereas if it goes to 0, they are fully damped. We show that for high defect intensity, a critical velocity exists, below which the only impact of the presence of the defect is a slight modification of the intensity profile (see red horizontal line on left panel). For too high velocities, we enter a turbulent regime where the collectivity is affected by the emissions of solitons (see black curve propagating inside the wavepacket, left panel).

Conclusion and outlook

- We proposed an experimental set up, in order to highlight a superfluid motion of light, through a waveguides array.
- We numerically showed that above a critical velocity, superfluidity is destroyed by the emission of discrete solitons.
- We are now working in collaboration with an experimental group who are planning to do this experiment.
- The results may be generalized also to any type of scattering potential. For instance, it has been shown that a positive critical velocity exists for disordered potential [7].

References

[1] Y. Lahini *et al.*, Phys. Rev. Lett. **100**, 013906 (2008).

[2] D. N. Christodoulides, F. Lederer and Y. Silberberg, Nature **424**, 817-823 (2003).

[3] In eq. (2), we measure all distances in units of the incident light wavenumber.

[4] Although quite interesting, the amplitude of the oscillations used here are sufficiently small in order to ignore the impact on the dynamics due to the discrete aspects of the lattice.

[5] W. Kohn, Phys. Rev. **123**, 1242 (1961); L. Vichi and S. Stringari, Phys. Rev. A **60**, 4734 (1999).

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[7] D. Dries, S.E. Pollack, J.M. Hitchcock, and R.G. Hulet, Phys. Rev. A **82**, 033603 (2010).

[8] S. Moulieras and P. Leboeuf, Phys. Rev. Lett. **105**, 163904 (2010).