Fluid of Light in atomic vapors

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Abstract

Since its discovery in 1995, Bose-Einstein Condensation (BEC) has been a powerful object for quantum experiments. Its coherence offers a lot of possibilities for measuring quantum phenomena. Even if BEC is well studied with ultra-cold atoms cloud, an analogy for classical waves propagating in a non-linear medium can be established and condensation of classical waves has been predicted [1].
Our experiment is based on the use of atomic vapor as a non-linear medium. By heating a Rubidium cell, we create a nonlinear medium with adjustable non-linearity. By modifing properties of the incident laser beam (shape, size, frequency, etc.) we are able to study a wide range of phenomena.
After the observation of pre-condensation of classical waves in this system [2], we turned to a study of fluids of light.

Experiment

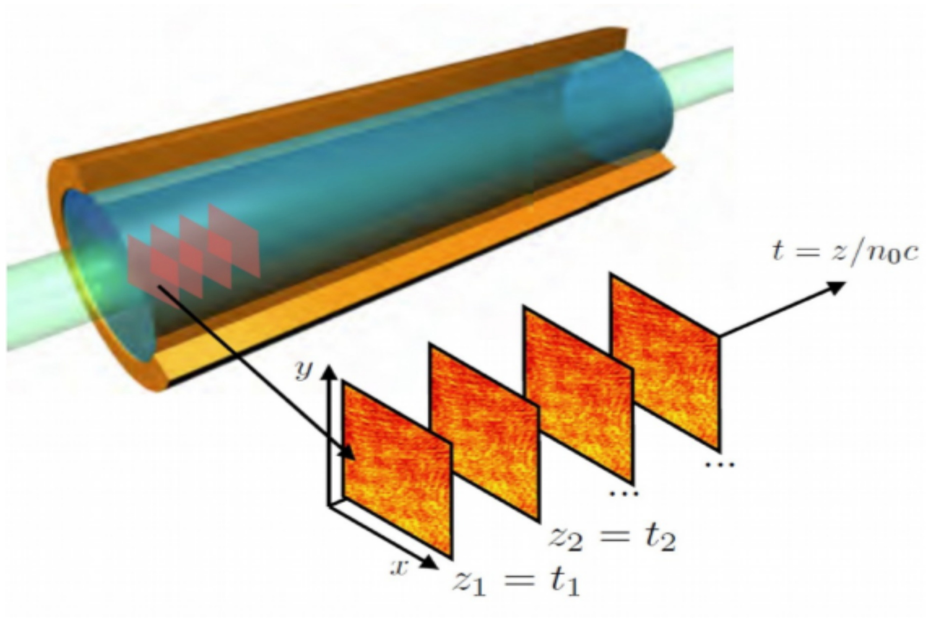

Figure 1. Beam propagation scheme.

Propagating a laser beam through an atomic vapor allows us to study a wide range of phenomena described by the non-linear Schrodinger equation (1). The propagation axis of the beam being equivalent to a time axis for our 2D fluid of light, we can study the whole evolution of each phenomenon just controlling the beam propagation in the medium.

$$i\partial_z \psi = -\frac{1}{2k_0}\nabla^2\psi + \gamma \mid \psi \mid^2 \psi \qquad (1)$$

In this equation, the second term of the right part corresponds to the non-linear interaction where the non-linear strength γ can be written as:

$$\gamma = k_0 n_2 \equiv \frac{\rho_{at}}{\Delta^3} \quad \text{whith} \quad \Delta n = n_2 I \qquad (2)$$

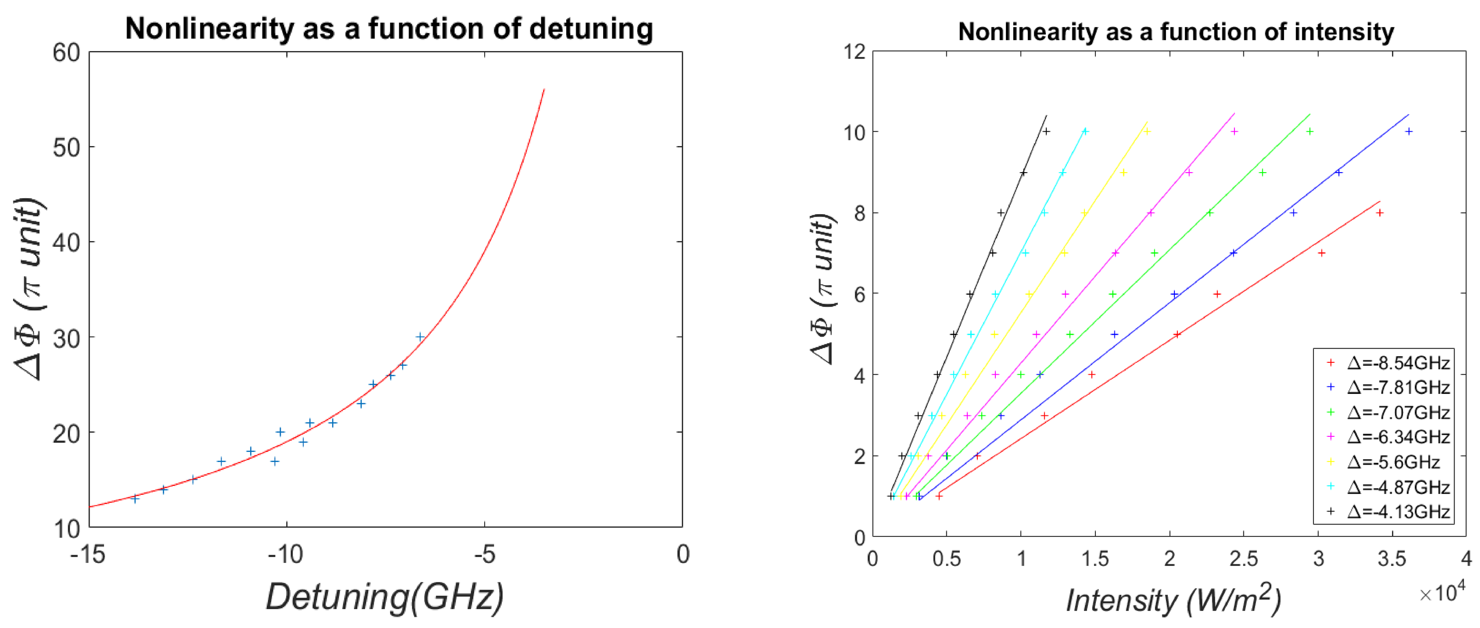

Figure 2. Left plot represents the non-linear phase-shift $\Delta\phi$ as a function of the laser detuning. Right plot represents $\Delta\phi$ as a function of the intensity.

$\Delta\phi$ is linked to the non-linearity and measuring it helps us to know the medium properties. We can define our fluid of light with a density equal to the beam intensity and a velocity proportional to the phase gradient of the beam.

Dispersive Shockwaves

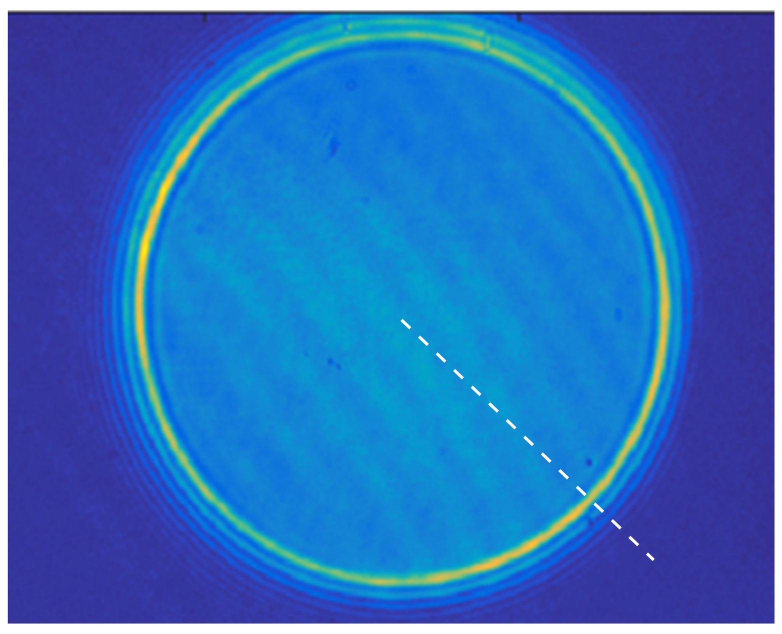

Figure 3. 2D gaussian beam after propagation through the medium.

When propagating a gaussian beam through the non-linear medium, we first observe that the beam becomes flat with sharp edges. Then, we observe riples all around edges, these are the dispersive shockwaves.
Using a second gaussian beam as a background beam can increase the contrast of these oscillations.
By taking a cut as shown in fig.3 we can study the profile of the beam.

If we set the non-linearity to a specific point of the evolution which is the shock point, it is easier to understand the different effects occuring in this phenomenon.

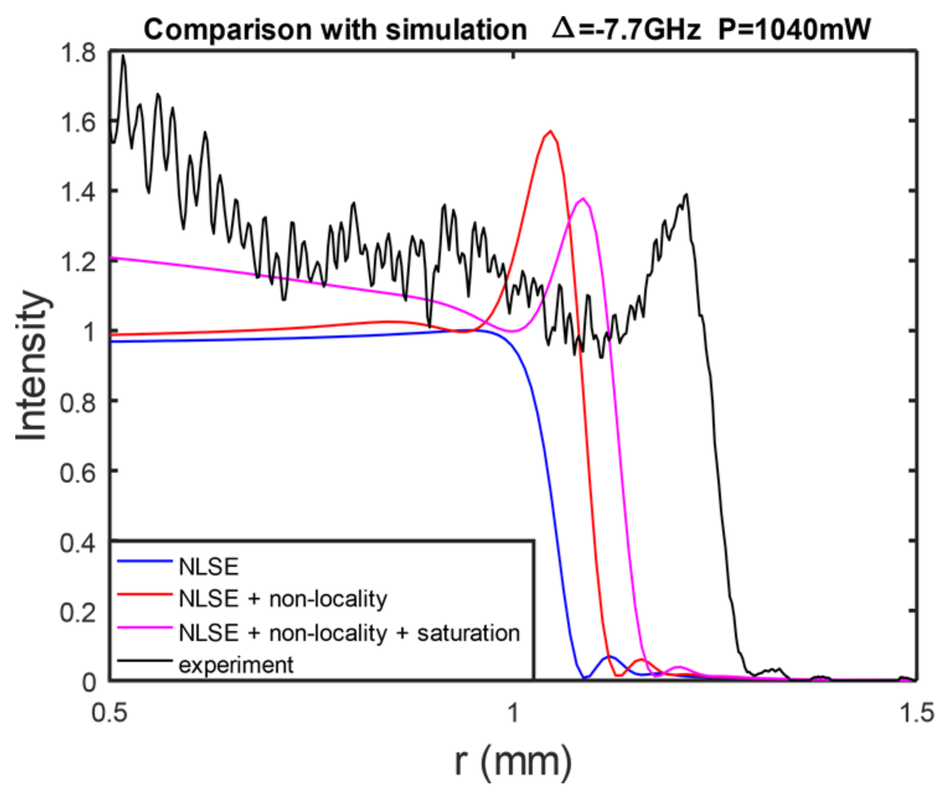

Figure 4. Comparisons between experiment and simulations.

We observe that the non-locality $V(r)$ explains the peak on top of the edge while the saturation of the non-linearity β helps better reproduce the general shape of the experiment.

$$i\partial_z\psi = -\frac{1}{2k_0}\nabla^2\psi + \frac{V(r) * \mid \psi \mid^2}{1+\beta \mid \psi \mid^2}\gamma\psi \qquad (3)$$

Other experimental studies have shown that the height of the non-local peak could change depending on several parameters. The peak grows when increasing the atomic density of the vapor. Something unexpected is that the linear absorption also increases the height of the peak.

Vortex creation

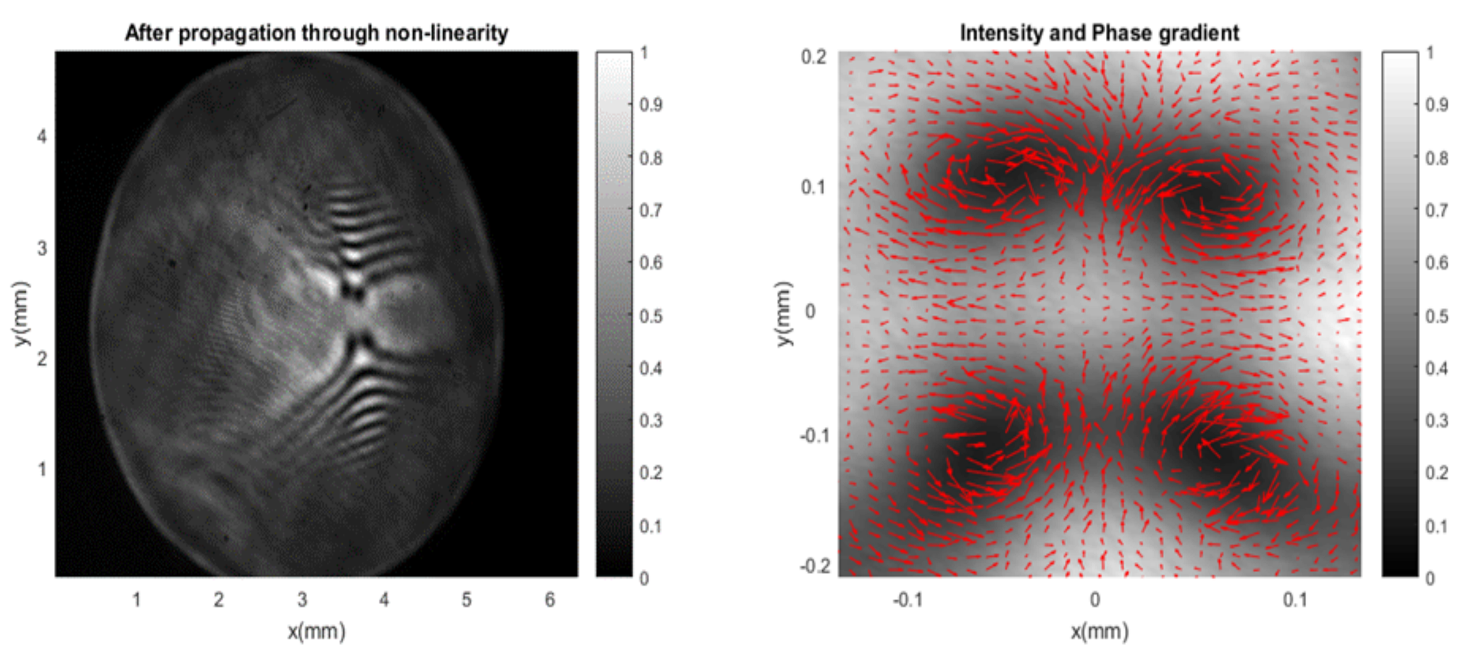

Figure 5. Left plot shows 2 pairs of vortices created after propagation through the medium. Right plot is a zoom on vortices with the phase gradient displayed as vectors

By propagating an elliptical beam in destructive interference with a gaussian background (gaussian beam with an elliptical dark soliton inside) we observe snake instabilities appearing which decay into pairs of vortices.
Using a Shack-Hartmann wavefront sensor allows us to measure the phase gradient distribution of the beam which corresponds to the velocity of our fluid of light. We observe the rotation around each intensity hole which confirmed the presence of vortices. We notice that each pair of vortices is composed of vortices with opposite topological charges.
Using specific initial conditions can accelerate vortex creation. It can even leads to vortices interactions with collision and annihilation of vortices.

Conclusion

After calibration of the non-linearity, we studied dispersive shockwaves with a distinct signature (enhanced by absorption) attributed to the non-local non-linearity of our medium. Then, we selected specific symetries to create vortices and observed their interactions.

Reference [1] C. Connaughton, C. Josserand, A.Picozzi, Y. Pomeau and S. Rica. Condensation of classical nonlinear waves. PRL, 95 2005.

[2] N. Santic, A. Fusaro, S. Salem, J. Garnier, A. Picozzi and R. Kaiser. Nonequilibrium precondensation of classical waves in two dimensions propagating through atomic vapors. PRL, 120 2018.