Non-diffracting speckle beam :

how to design a disordered refractive index map in a nonlinear crystal

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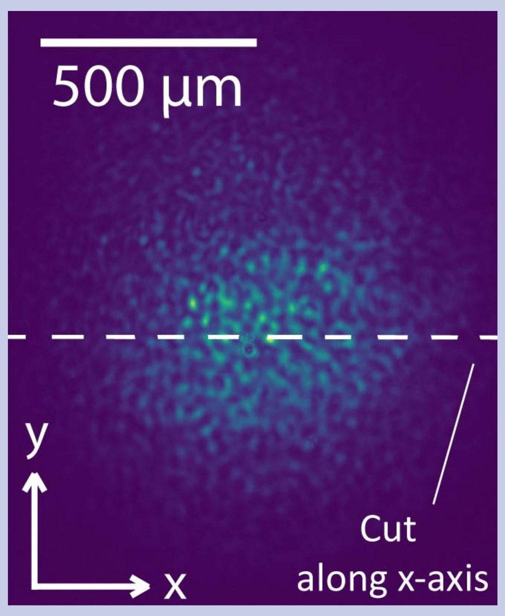
In this work, we investigate the behaviour of a light wave propagating through a 2D disordered system. First of all, we study the generation of a randomly distributed optical beam that will play the role of the disorder. After the characterisation of this so-called ''speckle beam'', we implement it in a nonlinear crystal. The main objective is to imprint a refractive index map into the crystal, via its nonlinear response, that will follow the spatial distribution of intensity of the speckle beam. We finally propagate into the crystal a secondary laser beam that will probe the effects of the disordered refractive index map.

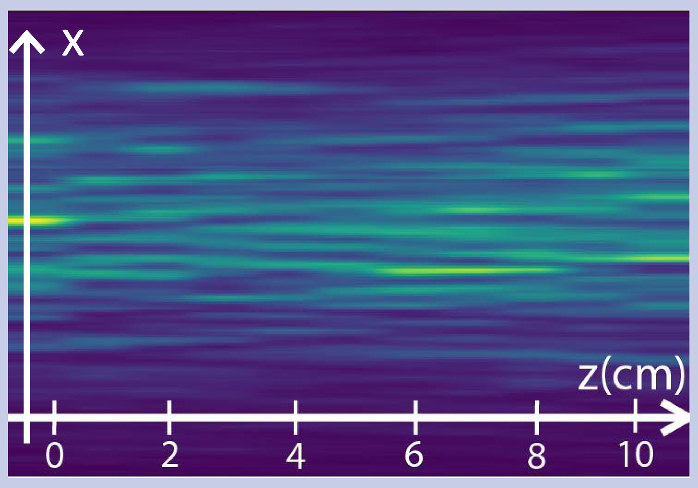
1. Creation of a randomly distributed optical beam

Speckle : randomly distributed intensity pattern



Generated by a superposition of random plane waves

Spatial evolution of a speckle along the propagation direction



Cut along x-axis

2. Analogy between time and space [1,2]

Temporal evolution of a wave function

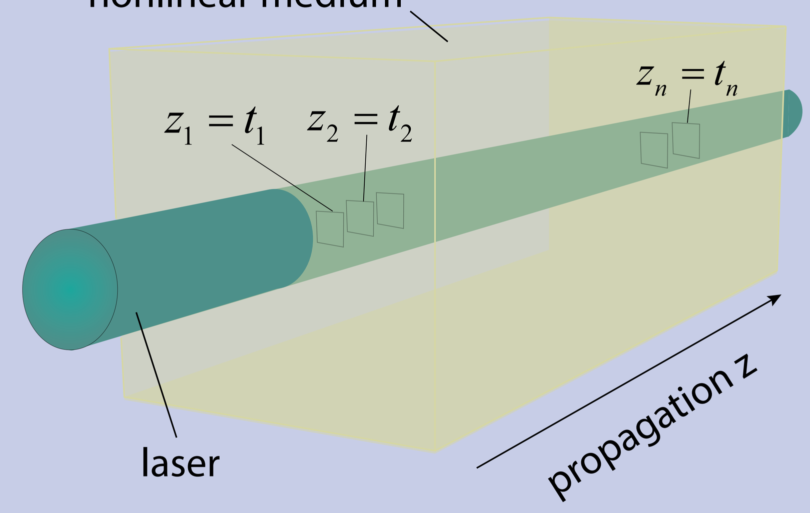
$$i\hbar\frac{\partial}{\partial t}\psi = -\frac{\hbar^2}{2m}\nabla^2\psi + V(\vec{r})\psi$$

time-independant

Spatial evolution of a optical wave

$$i\frac{\partial}{\partial z}E = -\frac{1}{2k_0}\nabla^2 E + \frac{k_0}{2n_0}(n_0^2 - n(\vec{r})^2)E$$

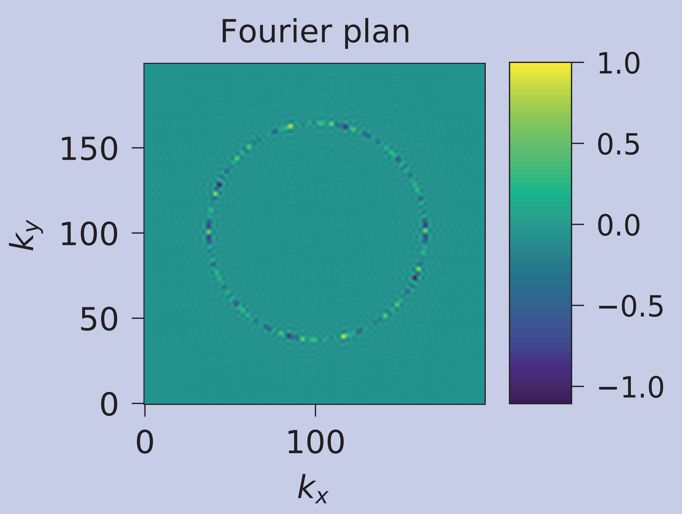
z-independant



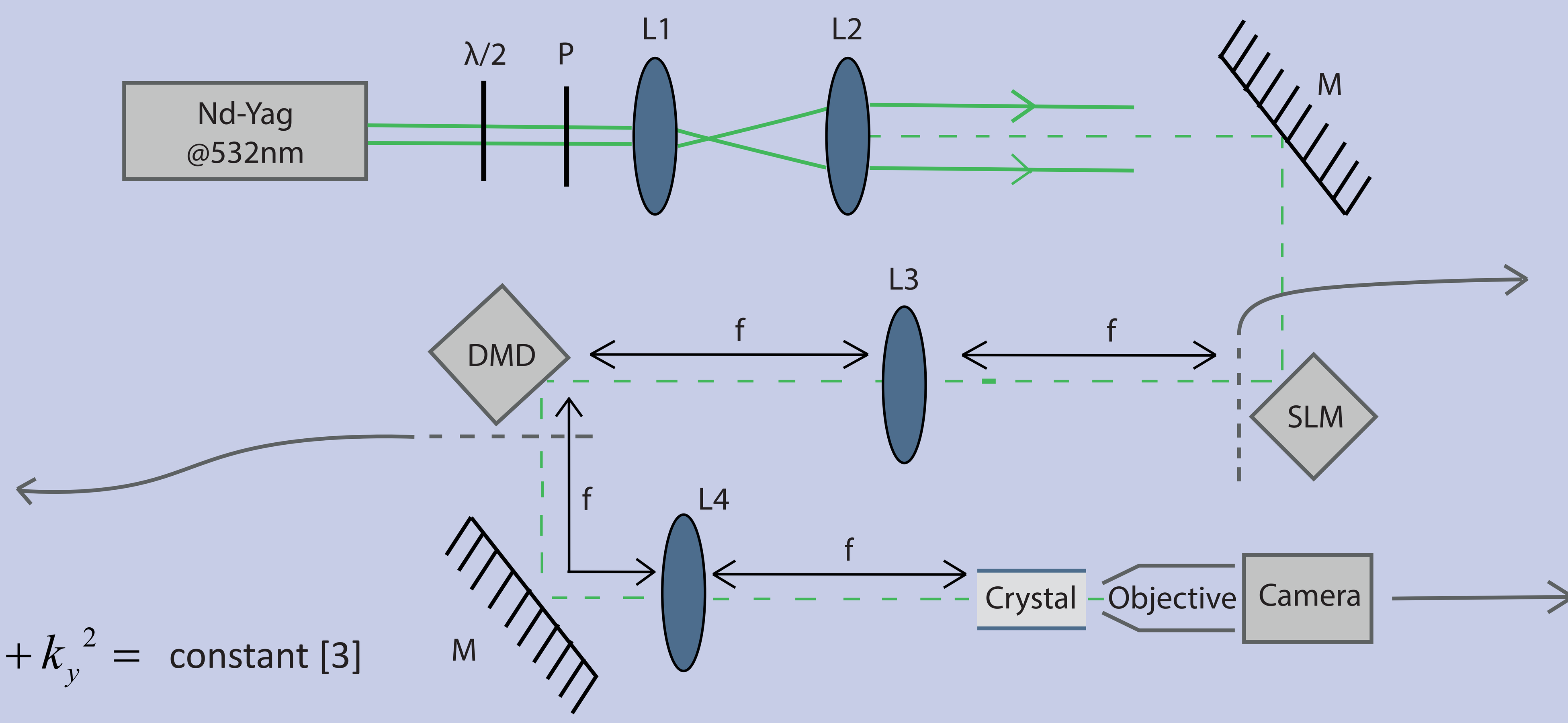
Random environment generated by a **non-diffracting speckle beam**

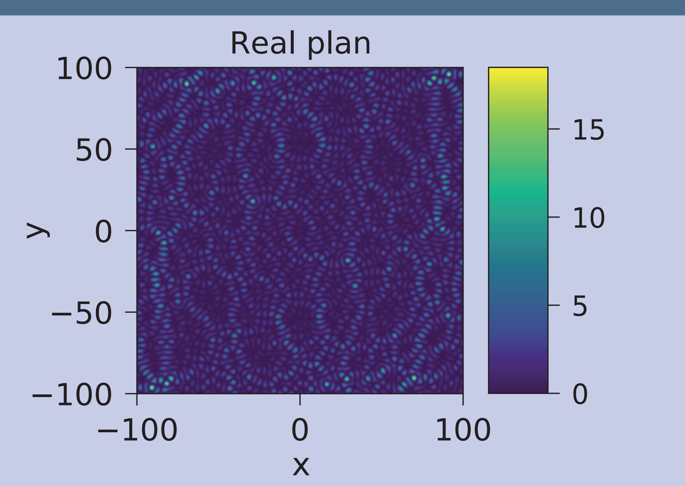
3. How to obtain a non-diffracting speckle ?

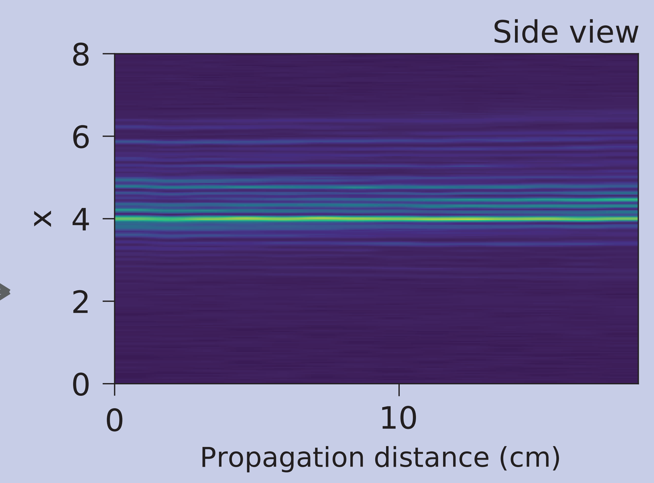
Ring



Non-diffracting condition : $k^2 = k_x^2 + k_y^2 =$ constant [3]

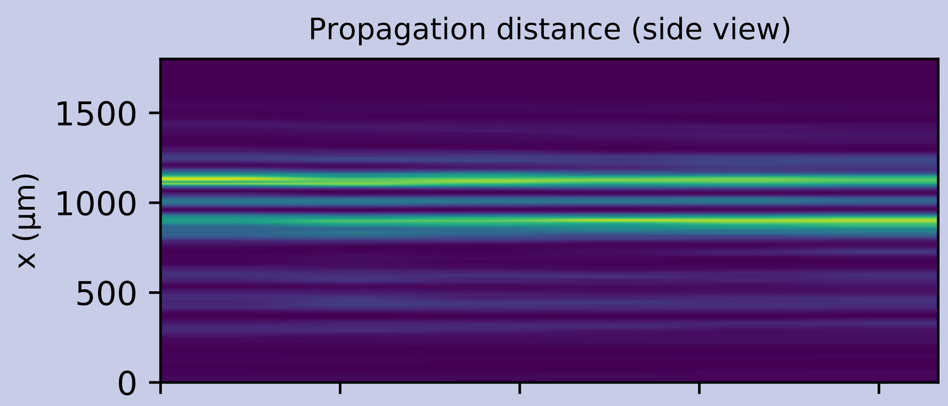


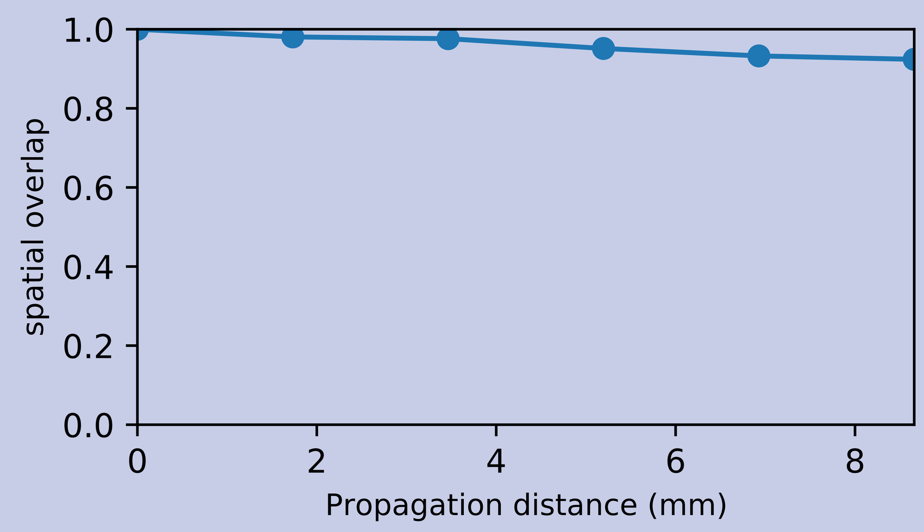


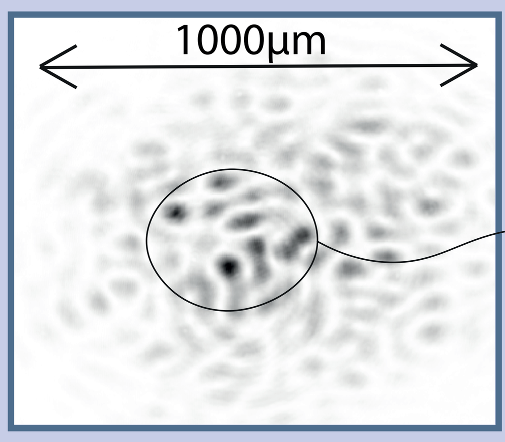


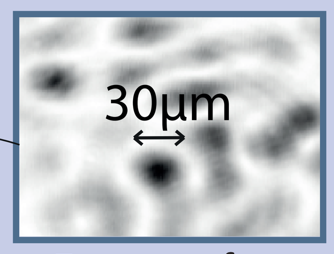
4. Non-diffracting speckle in the linear regime

Beam propagation in a crystal for a ring of width 10 pixels and inner radius 50 pixels









Zoom on few spots

Initial gaussian beam delivers 150mW

Speckle at crystal entrance 16µW

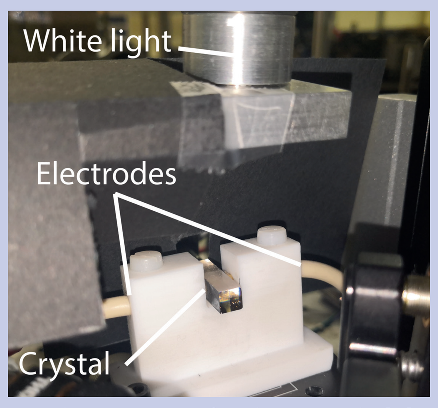
⇓

Loses : $\approx 99.99\%$

$$I_{spot} \simeq 1.8\cdot 10^{-3}\, mW / cm^2$$

Overlap method : $\dfrac{\int u_0 \cdot u_i\, dxdy}{\int |u_0|^2\, dxdy}$ with u_0 the intensity of the first image and u_i with $i \in [0, z_{max}]$ the intensity of the i^{th} image

5. The photorefractive effect



Usual parameters for this crystal : [4]

$n_0 = 2.36$ the refractive index of the crystal

$r_{33} = 250\cdot 10^{-10} cm/V$ the electro-optic coefficient

$I_{sat} \sim 300 mW/cm^2$ the intensity of saturation

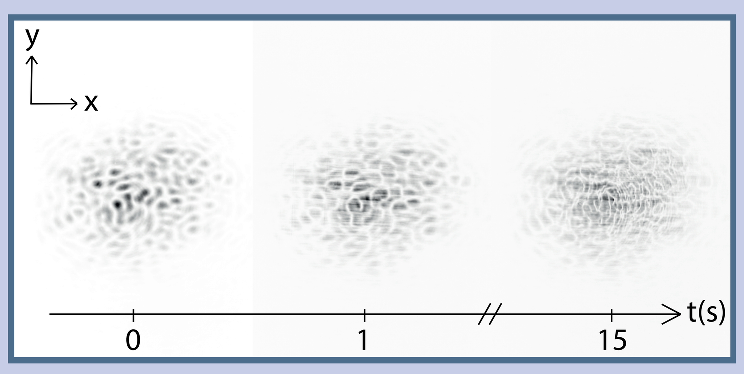
$E_0 \sim 1500 V/cm$ the external electric field

$$\Delta n(I) = -\frac{1}{2} n_0^3 r_{33} E_0 \frac{I(\vec{r})/I_{sat}}{1 + I(\vec{r})/I_{sat}}$$

$$\Delta n(I_{spot}) \simeq -1.5\cdot 10^{-9}$$

6. Enhancing the nonlinearity

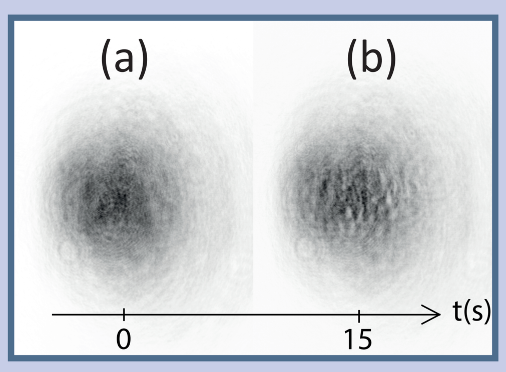
Speckle temporal evolution



White light at 1V

External electrical field at 700V

Probe temporal evolution



(a) : uniform distribution

(b) : white spots corresponding to obstacles

Perspective : higher power laser to ensure that the intensity of the speckle is high enough to realise the photo-induction of the disordered refractive index map, while keeping the non-diffracting feature.

[1] Pomeau, Y., Rica, S., C. R. Acad. Sci. Paris **397**, 1287 (1993)

[2] Hakim, V., Phys. Rev. E **55**, 2835 (1997)

[3] Phillips, D. B., Ruiqing, H., Qian C., Gibson, G. M., Padgett, M. J., Opt. Express **24**, 14172 (2016)

[4] Boughdad, O., Eloy, A., Mortessagne, F., Bellec, M., Michel, C., Opt. Express **27**, 30360 (2019)