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All-optical control of pattern dynamics generated by Airy beams

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We study a pattern forming system driven by two counter propagating 2D Airy beams in a nonlinear single feedback configuration. When increasing the Airy beam power, modulation instability takes place but with several successive instability thresholds that correspond to destabilization of the different Airy beam satellite lobes. Most importantly, the self-organization is accompanied by a natural drifting dynamics related to the intrinsic acceleration of the Airy beam. The drifting dynamics is controlled by the Airy beam parameters. Numerical simulations reproduce the experimental findings.

Controlling light by light is of peculiar interest in modern optics. Nonlinear optics allows for example generating spontaneous light self-organized structures (patterns) that can be controlled all-optically. Examples are shown in optical nonlinear cavity [1–3] as well as in single feedback configuration [4–9]. Instead of the conventionally used Gaussian beams, we suggested in [10] to use a beam carrying an orbital angular momentum (an optical vortex) to drive the pattern forming system and resulting in what we called a vortex induced rotation dynamics of optical patterns [10]. In what follows, we propose to use the peculiar properties of another unconventional beam, an Airy beam, to induce new interesting pattern dynamics.

The Airy wavepacket was discovered for the first time, in 1979, by Berry and Balazs [11] as a solution of the Schrodinger equation describing a free particle. As it possesses an infinite energy, it was impossible to generate it experimentally. We had to wait for almost three decades before its first realization in optics [12]. Although being a truncated solution of the ideal Airy wavepacket, the optical Airy beam keeps its non-spreading, self-healing and accelerating properties over a finite distance. An optical Airy beam is generated by linear and nonlinear methods [13, 14], and are performed with different apodization technics [15] to limit its energy. Scientists were then interested to control the Airy shape, its intensity and its acceleration [16–19]. Thanks to these characteristics, Airy beams have received growing interest due to their promising applications in all-optical routing [20, 21], optical multiplexing [22], optical micromanipulation [23, 24], vacuum electron acceleration [25], plasmonic energy routing [26, 27] and soliton generation [28]. Very recently, the Airy beam has also been used in free space optical communication [29].

In the present paper, we demonstrate that an Airy beam can self organize into a pattern with an intrinsic drifting dynamics. The generated pattern is naturally drifting and originates from a multi-thresholds bifurcation scenario related to the non-simultaneous destabilization of the different lobes of the Airy beam. Then, we highlight that the intrinsic Airy acceleration is correlated to the velocity of the drifting pattern and consequently

that the transverse pattern velocity can be controlled via the longitudinal acceleration. we therefore demonstrate an all-optical control of optical pattern dynamics by tailoring the parameters of an optical Airy beam.

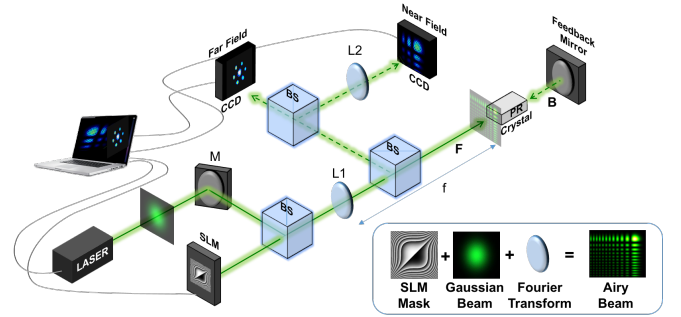


FIG. 1. Experimental set-up for pattern generation and measurements. BS, beam splitter; SLM, spatial light modulator; L1, L2, lens; M, mirror. The inset describes how the Airy beam is generated via the combination of a collimated Gaussian beam coming from the Laser, a peculiar phase profile launched onto the SLM and a Fourier transformation via the lens L1.

Our experiments (Fig. 1) are performed in a nonlinear Cobalt-doped Barium Titanate photorefractive crystal (BaTiO₃:Co) with dimensions 6*6*6 mm³. We use a 532 nm coherent linearly polarized and collimated laser beam. We generate the truncated Airy beam by applying to a Gaussian laser beam a cubic phase pattern via a spatial light modulator (SLM). The Airy beam is then created in the Fourier plane of the lens L_1 where is located the input face of the crystal. A feedback mirror is placed at the crystal's back face. Due to the two-wave mixing process arising from the forward Airy beam F and the backward Airy beam B we expect that modulation instability takes place in the resulting transverse intensity profile of the two counter-propagating beams. The orientation of the crystal is chosen to provide a maximum energy coupling between the two counter-propagating beams. Consequently the angle between the optical axis of the system and the polarization c -axis of the crystal is set to approximately 25 degrees. The large electro-optic

coefficient r_{22} of the crystal gives then a strong contribution to the photorefractive coupling strength, providing a two-wave mixing amplification process in the backward direction B [30]. In this study, the mirror is kept as straight as possible such as the forward (F) and the backward (B) beams are perfectly aligned. Observations and studies onto the near- and corresponding far-fields are realized by imaging the backward beam B , after its passage through the crystal, onto two CCD cameras (Fig. 1).

We first analyze the possibility to generate a pattern from a truncated Airy beam. We remind that the mirror is placed exactly at the back side of the crystal and it is perfectly aligned to guarantee an optimized overlap between F and B . The main lobe size of the forward Airy beam is $x_0 = 95 \mu\text{m}$ and the input power of the laser is increased gradually. Above a certain threshold ($P_{th} = 0.3 \text{ mW}$), the wavevectors associated with the lowest gain exponentially grow following the principle of a winner-takes-all dynamics. As we can see in Fig. 2(a), the bifurcation from an homogeneous state [Fig. 2(a)(1)] to a modulated one [Fig. 2(a)(2)] is sub-critical. For increasing and decreasing values of the input power (ranging from $P = 0.3 \text{ mW}$ to $P = 1.6 \text{ mW}$), the bifurcation diagram presents an area where the pattern is unstable and coexists with the homogeneous state. Such a bistability has already been observed in classical pattern forming systems using Gaussian beams interaction [31, 32], but interestingly in our configuration the different lobes of the Airy beam do not destabilize simultaneously: the bifurcation curve has as many thresholds as visible lobes onto the camera [Fig. 2(a)(1)-(4)]. This bifurcation scenario is unique and originates from the peculiar intensity distribution of the Airy profile. The second, third and fourth lobes being smaller and smaller in size, need more and more gain (input power) to satisfy the modulational instability threshold.

Similarly to Gaussian beams in this configuration, the near- and far-field patterns present an honeycomb and respectively hexagonal structures [Fig. 2(a)(1)-(4), (b)]. As we also know from previous studies [8, 9], patterns are in principle static, in the single feedback configuration, unless transverse symmetry is broken e.g. by an unintentional misalignment of the feedback mirror. The forward and backward Airy beams are supposed to be perfectly aligned in our case. Still, the patterns produced by the counter-propagating beams interaction move naturally without any external forcing. Moreover, the drift follows the bisector direction corresponding exactly to the direction of the transverse Airy beam acceleration [Fig. 2 (b)]. We may conclude that the Airy beam controls its drifting pattern, but to be sure that it is not due to a misalignment in our experimental system, we complete our study by simulating the spatio-temporal dynamics of the pattern using the equations system (Eqs. 1). To fit also with the experimental curve [Fig. 2 (a)], we simulated the bifurcation scenario. Such a configura-

tion can be modelled by the following three coupled equations [33]:

$$\frac{\partial F}{\partial z} = -iD \frac{\partial^2 F}{\partial x \partial y} + QB, \quad (1a)$$

$$\frac{\partial B}{\partial z} = -iD \frac{\partial^2 B}{\partial x \partial y} + Q^* F, \quad (1b)$$

$$\frac{\partial Q}{\partial t} = -Q + \gamma \frac{FB^*}{|F|^2 + |B|^2 + I_d}, \quad (1c)$$

where F and B stand for the forward and the backward optical fields. D is the diffraction coefficient and Q represents the complex amplitude of the photorefractive reflection grating arising inside the material. z is the normalized propagation coordinate, x and y are the transverse ones and γ is the photorefractive coupling strength. I_d corresponds to the background illumination intensity which we neglect. The forward beam F used in our simulation is defined by the initial conditions in $z=0$, as :

$$F(x, y) = Ai\left(\frac{x}{x_0}\right) Ai\left(\frac{y}{y_0}\right) \exp\left(\frac{ax}{x_0} + \frac{ay}{y_0}\right) \quad (2)$$

where a is a decay factor limiting the beam energy. x_0 and y_0 are the transverse scales in both x and y coordinates. We suppose then that $x_0=y_0$. Note that when we neglect the decay parameter ($a=0$), we find the ideal Airy beam form. By using a conventional split step Fourier beam propagation method (BPM), we integrate the master equations (Eqs. 1) using the Airy beam F (Eq. 2) and the backward beam B linked to F using a boundary condition as described in [33]:

$$B(x, y, L, t) = -\sqrt{R} T_F^{-1} \exp(i\phi_k) T_F(F(x, y, L, t)) \quad (3)$$

Where T_F is the transverse Fourier transform, L being the crystal length, R is the mirror reflectivity and ϕ_k denotes the propagation phase.

In the boundary conditions, we set the angle between the two counter-propagating Airy beams equal to 0 to simulate a perfectly aligned experimental condition. The simulations confirm that the instabilities drift towards the direction of the Airy beam transverse acceleration [white arrow in Fig. 2 (b)]. Thanks to equivalence principle, it has been demonstrated [34] that, in an accelerated frame, the Airy function presents an extra phase factor depending on the propagation variable z . Thus, the wavefront is tilted from the vertical direction ($z=0$). Hence, when we are placed on the output face of the crystal ($z=0$), we are observing an out of phase grating index of the equiphase direction, supposed to be the plane formation of the grating index. Hence, the intrinsic accelerating property of the Airy beam explains why the resulting pattern is moving. The numerical plot (Fig. 3) reproduces qualitatively well the experimental curve. It shows the normalized output intensity (intensity of the

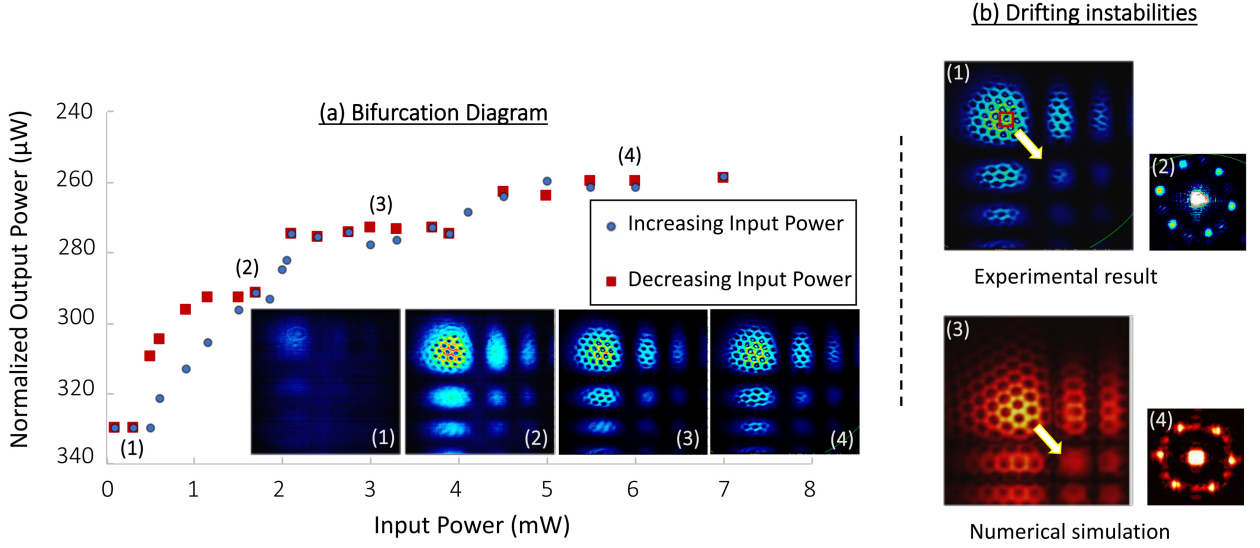


FIG. 2. (a) Experimental multi-thresholds bifurcation diagram of an Airy beam with $x_0 = 95 \mu\text{m}$, and images in the near field obtained after each bifurcation. (b-1) Experimental and (b-3) numerical near-field patterns. (b-2) Experimental and (b-4) numerical far-field. Measurements are taken at the crystal back face. The white arrow illustrates the direction of the pattern drift.

overall unstable pattern in far-field divided by the intensity of the central spot corresponding to the stable forward Airy beam) versus the photorefractive coupling strength. We clearly identify the different bistability areas and jumps referring to the successive destabilization of the different Airy lobes.

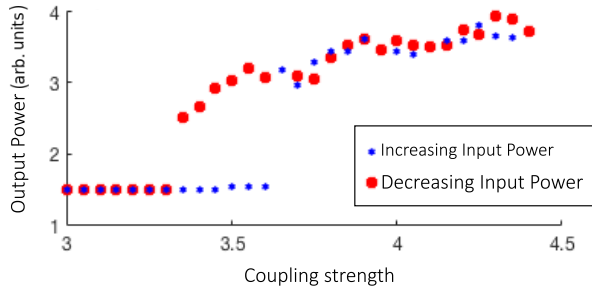


FIG. 3. Numerical multi-thresholds bifurcation diagram of a 2D Airy beam : Normalized pattern power at the crystal back face as a function of the photorefractive coupling strength γ .

Note that all the observations referring to the spatio-temporal dynamics are realized with the near-field intensity profiles. The corresponding far-fields are also accompanied by a dynamics but which is not clearly identifiable. In what follows we therefore decide to concentrate our study onto the dynamics of the near-field drifting instabilities for different Airy beam transverse accelerations. We want to identify the role played by the Airy acceleration on its pattern dynamics. Note that we can retrieve the Airy acceleration value a_{cc} from its deflection a_0 using the following equation $a_{cc} = \frac{2a_0}{z^2}$ [14]. Hence,

for a fixed z , deflection and acceleration are proportional. We have summarized in figure 4 the pattern drift velocity versus four different Airy deflections a_0 . Experimentally and numerically changing the transverse Airy deflection consists of varying the width of the Airy main lobe x_0 as they are linked by the relation $a_0 = \frac{\sqrt{2}z^2}{4k^2x_0^3}$ [14]. By knowing the distance traveled by one instability spot [red squares in Fig. 2(b)] and the time separation between two consecutive near-field pictures, one can calculate the velocity of the drift. We have normalized the size of the main lobe and kept the power of the input Airy beam constant. Deflections are normalized as well. Note that the deflection's order of magnitude in our experiments is around nanometers. We observe experimentally [Fig. 4 (a)] that the velocity of the drifting pattern grows as the deflection increases. For instance, for $a_0 = 0.58$, the pattern moves with $v = 6.87 \mu\text{m.s}^{-1}$ whereas for $a_0 = 1.57$ the pattern velocity is equal to $v = 10.49 \mu\text{m.s}^{-1}$. To ensure that the increase of velocity is essentially due to the Airy acceleration process, we performed numerical simulation and made the same analysis onto the corresponding near-field profiles for the same values of the photorefractive coupling strength γ . The numerical results [Fig. 4 (b)] are in excellent agreement with experiment [Fig. 4 (a)]. Increasing the deflection corresponds implicitly to saying that we increase the Airy phase shift [34]. Therefore, explaining why the pattern drifting velocity increases as well.

To summarize, we have explored both experimentally and numerically the formation and the control of optical pattern originating from an Airy beam in a single feed-back configuration. We find that modulation instability

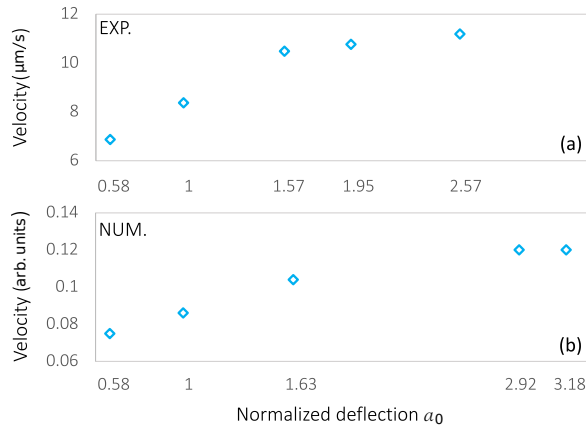


FIG. 4. (a) Experimental and (b) numerical velocity of the main lobe's Airy pattern as a function of the normalized Airy deflection a_0 at the crystal back face .

starts first in the main lobe of the Airy beam when we reach a certain value of the input power, while the others lobes still maintain their steady homogeneous state. By increasing the input power even more, we notice that the other lobes begin to destabilize, giving rise to other bifurcation thresholds. The resulting bifurcation curve, with a multi-thresholds shape, makes a signature of the Airy beam pattern formation. Furthermore, contrary to the pattern formation induced by a Gaussian beam, the Airy pattern presents a drifting dynamics in a preferential direction in absence of any external breaking of symmetry. Thus, the Airy beam translates its longitudinal acceleration into a transverse drift by the means of a phase shift. We have measured that the transverse pattern velocity is proportional to the Airy acceleration thanks to the correlation between its longitudinal phase shift and its transverse deflection. This work therefore demonstrates an all-optical control of the dynamics of optical patterns by tailoring the parameters of an accelerating beam.

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