Experimental demonstration of phase bistability in a broad-area optical oscillator with injected signal

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We demonstrate experimentally that a broad-area laserlike optical oscillator (a nondegenerate photorefractive oscillator) with structured injected signal displays two-phase patterns. The technique [de Valcárcel and Staliunas, Phys. Rev. Lett. **105**, 054101 (2010)] consists in spatially modulating the injection, so that its phase alternates periodically between two opposite values, i.e., differing by π.

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I. INTRODUCTION

Bistability is a crucial mechanism for optical information encoding and processing. When speaking of bistability one usually thinks of *intensity* bistability, i.e., the stable coexistence of two states of unequal field intensity, like the high and low transmission states of (so-called) optical bistability [1,2] or the on and off states of optical fiber solitons [3,4] or cavity solitons [5–11]. There is, however, an alternative type of bistability, namely *phase* bistability, in which two coexisting stable states of equal intensity but opposite phase are supported by the system. Phase bistability occurs in special nonlinear optical cavities, like synchronously pumped optical parametric oscillators [12]. Phase-bistable states are usually more symmetric than amplitude-bistable states, and it would be desirable for optical information processing if lasers could display such phase bistability.

The first work in that direction was proposed in Ref. [13] and demonstrated in a laserlike system (specifically, a photorefractive oscillator under nondegenerate wave mixing) in Ref. [14]: If in a laser with injected signal the phase of driving field alternates periodically in time between two opposite values (differing by π) at a sufficiently high repetition rate, the phase of the slave laser can lock to one of two possible values, with both states having the same intensity. Such driving technique was termed *rocking* because, in a mechanical analogy, that kind of injection tilts periodically (i.e., rocks) the laser potential between two extreme positions [13,15,16]. Note that the phase of the emitted signal does not lock necessarily to either of the injections, say 0 and π, but rather to some values in between, which depend on the detuning between the injection and the cavity [13,16]. The laser emission, simply speaking, avoids the action of the alternating injection, i.e., avoids the locations in phase space that are maximally affected by the alternating injection, and consequently moves to the most quiet locations. From a dynamical viewpoint such rocking is similiar to the stabilization of the topside position of the pendulum when the hanging point is vibrated in vertical direction (Kapitza pendulum).

This kind of rocking is, however, problematic in solid-state and semiconductor lasers, the so-called class-B lasers, because the relaxation oscillations characterizing those lasers limit the performance of rocking [15]. Consequently the initial concept of rocking in time was extended to rocking in space by considering the injection alternating in transverse space [17,18]. The first proposal [17] consisted of injecting a TEM_{10} mode (displaying two opposite phases at the two mode lobes) into a low Fresnel number laser, capable of emitting only on one, the lowest order, transverse mode. According to Ref. [17], the phase of the slave laser locks to one among two possible (and opposite) values, which was successfully demonstrated in a laserlike oscillator [18]. The concept was further extended to broad-area lasers [19], in which many transverse modes (a continuum of modes) play a role; it was predicted that under injection of a (monochromatic) beam displaying a spatial alternation of its phase between two opposite values across its cross section, the emission of the slave laser displays phase bistability. In this case, due to the spatially extended nature of the system, different parts of the slave laser beam cross section can take different phase values (among those special two), and phase patterns are predicted to appear, opening the way in particular to phase-bistable cavity solitons [19]. Similar to the rocking in time, where the injection must vary sufficiently rapidly as compared to the characteristic time scale of the system (the cavity lifetime), here in spatial rocking the injection must vary on a sufficiently small space scale as compared with the characteristic spatial scale of the system (diffraction length) [19]. Here we demonstrate experimentally the feasibility of this mechanism by using a photorefractive oscillator (PRO).

II. EXPERIMENT

PROs are optical cavities containing a photorefractive crystal, which is pumped by laser beams that do not resonate inside the cavity (e.g., because they are tilted with respect to the cavity axis) [20–22]. Under appropriate conditions (mainly crystal orientation and pump alignment) an intracavity light field starts oscillating via efficient wave mixing. PROs are highly versatile systems for the study of nonlinear dynamics as different wave mixings (two vs four waves, or degenerate vs nondegenerate) can be tuned by using different resonators (ring or linear) and pumping geometries (one pump or two counterpropagating pumps). In particular when the cavity is linear and a single pump is used, the oscillation occurs due

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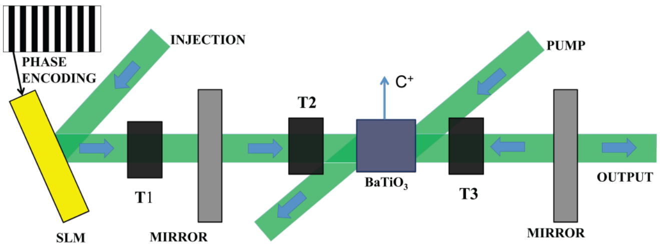

FIG. 1. (Color online) Sketch of the photorefractive oscillator with injected signal (rocking). Two mirrors form the resonator, which contains a $BaTiO_3$ crystal of $4.5 \times 4.5 \times 8.0\,\text{mm}^3$. SLM: spatial light modulator. T1, T2, T3: telescopic systems.

to a nondegenerate four-wave mixing (NDFWM) process, and the phase of the self-generated light is free, as in a free-running laser. However, the similarities between lasers and NDFWM PROs go far beyond that phase invariance: The PROs are laserlike systems also from a nonlinear dynamics viewpoint [23]. In particular, NDFWM PROs have been proven successful for the study of universal out-of-equilibrium pattern formation scenarios of phase-invariant systems, such as vortex arrays and different traveling wave patterns [24]. In order to allow for pattern formation in the experiment, the cavity Fresnel number is made very large by two telescopic systems that image the cavity mirrors close to the photorefractive $BaTiO_3$ crystal (nearly self-imaging resonator [25]); see Fig. 1. We inject a rocking beam along the cavity axis, whose phase is tailored by means of a spatial light modulator (SLM). The SLM (PLUTO-VIS-006-A, Holoeye Photonics AG) is electrically addressed and controlled by a computer in order to give sharp π-phase jumps across the beam cross section. The rocking beam, the pumping beam, and other auxiliary beams (for cavity length active stabilization and interferometry) all come from the same frequency-doubled Nd:YAG laser at 532 nm (Verdi V5, Coherent Inc.). For details about the setup, the cavity-stabilization procedure, the interferometry, and the data processing, see Ref. [26].

Owing to the small SLM pixel pitch (8 μm), large diffraction is observed on the reflected beam in such a way that only the first two spatial harmonics enter efficiently into the cavity. The injection has then a sinusoidal variation across the resonator transverse section, alternating periodically its sign (phase). This means that when the SLM is operated so that the phase changes by π every three pixel rows (as is the case in the figures we show next), the effective rocking beam profile at the SLM has the form $\cos(2\pi x/\Lambda_{\text{SLM}})$, with $\Lambda_{\text{SLM}} = 6 \times 8\,\mu\text{m}$ being the spatial period. A telescope T1 images the SLM plane onto the entrance cavity mirror, which in turn is imaged close to the crystal by the left intracavity telescope T2 with total lateral magnification of $0.5\times$; hence the effective rocking beam profile at the crystal has the form $\cos(2\pi x/\Lambda_C)$, with the transverse period $\Lambda_C = \cos(15^\circ) \times 24\,\mu\text{m} = 23.2\,\mu\text{m}$ approximately. Here we took into account the tilt of the SLM with respect to the cavity axis.

III. EXPERIMENTAL RESULTS AND DISCUSSIONS

Without injection our PRO is a phase-invariant system (any value of the phase is possible) which, because of its large

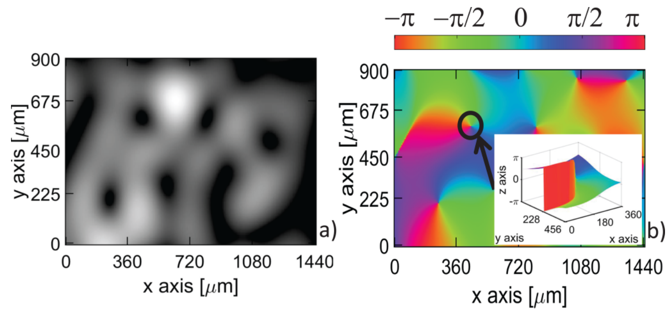

FIG. 2. (Color online) Optical vortex array forming spontaneously in the free-running PRO. Amplitude (a) and phase (b) maps of the field at the nonlinear crystal. Spatial dimensions: 1440 μm (horizontal) $\times$ 900 μm (vertical). A three-dimensional (3D) representation of the phase around one of these optical vortices is shown in the inset in panel (b), with spatial dimensions 360 μm $\times$ 450 μm; a clear 2π rotation of the phase is appreciated.

Fresnel number, leads to the spontaneous formation of optical vortices [27,28], as shown in Fig. 2. These phase singularities are characterized by a smooth rotation of the field phase by 2π on a closed loop around a core, a point of null intensity. On the contrary, when spatial rocking is applied, the phase invariance gets broken and just two (opposite) phases are preferred. In this case vortices are replaced by one-dimensional objects, so-called phase domain walls (DWs) [29,30], which separate spatial domains of opposite phase (Fig. 3). The total light field is the superposition of the rocking beam and the beam generated by the PRO. As the latter has small spatial frequencies (small divergence angle) as compared to the former, both contributions are well separated from each other in the far field [19]. In fact, the high spatial frequency

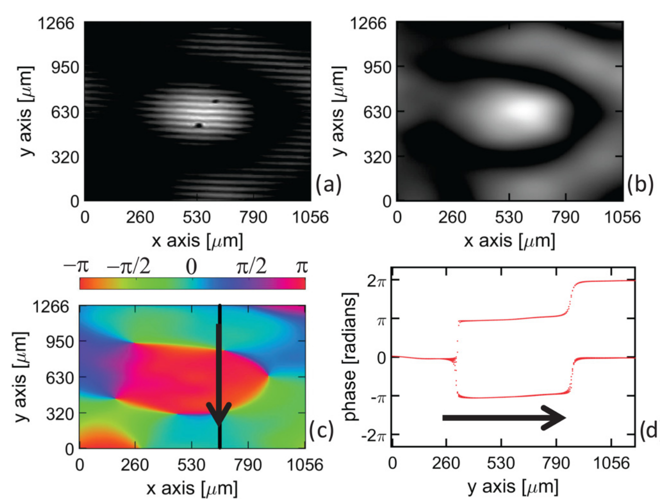

FIG. 3. (Color online) Two-dimensional (2D) phase domains formed by the action of spatial rocking. The spatial period of the rocking beam is $\Lambda_C = 23.2\,\mu\text{m}$ (not seen in the images). The spatial dimensions of all subfigures are 1056 μm $\times$ 1266 μm. The interferogram (a) exhibits horizontal fringes, which are shifted in the central domain by half a period with respect to its surroundings, indicating a π jump of the phase. (b) Amplitude map. (c) Phase map. (d) Different phase profiles around the vertical cut marked by a black vertical arrow in panel (c), evidencing π jumps across the phase domain boundary.

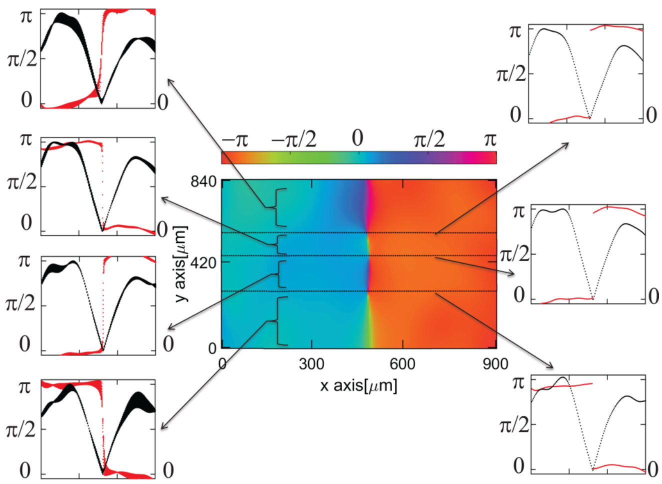

FIG. 4. (Color online) Study of the chirality of a straight domain wall. Spatial dimensions: 900 μm × 480 μm. The spatial period of the rocking beam is $\Lambda_C = 23.2$ μm (not visible in the image). The central image shows the phase map of the wall. The left column shows different phase (red [gray] dashed line) and amplitude (black dashed line) profiles along the horizontal axis, displaying $+\pi$ or $-\pi$ jumps in phase, depending on the region. The right column shows abrupt π jumps and their respective amplitude profiles, observed at three Néel points present in the wall.

of the rocking beam (around 23.2 μm^{-1}) does not appear in the figures we show here as diffraction outside the cavity filters out the large-angle components of the rocking beam. Domain walls can be such that the phase abruptly jumps by π across the boundary (Ising wall) or displays a relatively smooth variation (Bloch wall), with that terminology coming from solid-state physics [30]. The phase variation across a Bloch wall can be increasing or decreasing; i.e., the phase angle can rotate clockwise or counterclockwise across the wall, which means that Bloch walls are chiral [29,30] [see Fig. 3(d)]. Although we demonstrate the existence of DWs induced by spatial rocking (see Fig. 3), the curvature of DWs can induce an additional dynamics, which should be removed in order to separate the effects. Thus special efforts are taken to ensure a quasi-one-dimensional regime in the transverse plane [29] in order to avoid that influence of DW curvature in the observed dynamics [31,32]. Quasi-one-dimensionality is achieved by placing slits inside the nonlinear cavity, at the Fourier planes of telescopes T2 and T3 (see Fig. 1). The width of the slits is adjusted to the size of the diffraction spot in these planes. In this way, waves with large inclinations are not compatible with the diffraction constraints of the cavity. We also use another pair of slits in the near field, i.e., close to the cavity mirrors (MIRROR in Fig. 1), which allows us to select specific parts of the nonlinear crystal, e.g., particularly homogeneous regions of the crystal (see Fig. 4). In quasi-one-dimensional systems the interface separating phase domains can display positive chirality in a particular segment and negative chirality in the adjacent one, as shown in Fig. 4. By continuity, between the sections of Bloch walls with opposite chirality, a point of null chirality (a kind of Ising wall) appears. This point is a kind of bound vortex, which is the nonequilibrium analog of a Néel point in solid-state physics [33]. Usually nonequilibrium Bloch walls move according to their chirality [29,30], so that opposite-chirality walls move in opposite directions. When two Bloch walls with opposite chirality are separated by a Néel point, such as in Fig. 4, such motion generically leads to the emergence of spiral waves with center at the (static) Néel point [33,34]. In our case such effect has not been observed, due to two different causes: (i) the dynamics of the system is very slow (in previous experiments on the Ising-Bloch transition in PROs the velocity of the Bloch walls was measured to be on the order of 1 μm/s [29]) and we did not perform long-time observations, and (ii) the quasi-1D geometry affects the possible wall motion because walls ending at a boundary are not free to move but are always perpendicular to it [35].

IV. CONCLUSIONS

In this work we have given experimental evidence of phase bistability appearing in a large-Fresnel-number laserlike system submitted to spatial rocking. This agrees with previous theoretical work [19]. The large Fresnel number of the cavity allows the formation of phase patterns, which take the form of domain walls due to phase bistability imposed by spatial rocking. Such phase-bistable spatial structures can be efficiently written, erased, and moved across the transverse section of the system, as has been demonstrated in temporal rocking [35,36]. The reported theoretical results thus indicate that the recent predictions on the excitation of cavity solitons by spatial rocking in broad-area semiconductors, lasers [37], and vertical surface emission lasers [38] open the way to other types of optical information processing in semiconductor microlasers [5–7], based on phase-bistable cavity solitons.

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