Bistable and Addressable Localized Vortices in Semiconductor Lasers

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We demonstrate experimentally that localized emission states in coupled broad-area semiconductor lasers can carry a finite orbital angular momentum. The resulting structures therefore possess the chirality of optical vortices together with the properties of localized structures in dissipative systems, namely, the coexistence with a low intensity homogeneous emission and the mutual independence. These results open the way to the realization of arrays of optically addressable and bistable chiral laser pixels.

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Vorticity, while most often thought of as a hydrodynamical phenomenon, has also been observed in optics, in which case it has attracted strong interest from several points of view. From a quantum perspective, the vorticity of light has been associated to the orbital angular momentum carried by even a single photon and therefore has been proposed as a means of enlarging quantum encryption alphabets ([1] and references therein). In nonlinear optics, strong emphasis has been put on the existence of nondiffracting beams seeded vorticity (see [2] and the review [3]), which are stabilized either by nonlocal coupling or partial spatial incoherence [4,5].

In parallel, spatially localized structures in dissipative systems have been a subject of intense research in different physical systems such as granular media [6], gas discharge [7] and biological [8] or optical systems (see [9] and references therein). Their fundamental properties, bistability and mutual independence (ie, several such structures can be present or not independently of others depending only on initial conditions), are related to the presence of dissipation, and therefore they often receive, in optics, the name of cavity solitons.

At the intersection between these two areas of research, theoretical works [10–12] have predicted the existence of bistable and mutually independent localized states which would be able to carry an orbital angular momentum. Such spatial structures, predicted in dissipative optical systems with competing nonlinearity such as a laser with saturable absorber, have received the name of localized vortices since they would carry vorticity, but also be bistable and mutually independent, ie, they would be able to exist in arbitrary number across the system, depending only on initial conditions. The existence of such states would enable the realization of arrays of independent and controllable vortex beams useful for advanced optical nanoscopy techniques [13], microfluidics [14], or parallel topological optical information encoding, especially if found in fast and compact sources such as semiconductor lasers.

In spite of the numerous examples of localized states reported in optical systems (see references in [9] and more recently [15–17]), no experimental demonstrations of bistable and mutually independent vortices has been given to date, even if beams with vorticity have long been observed in lasers [18]. We give here experimental evidence of the formation and control of such states in a cavity soliton laser [19–21] which is known to be able to host independent and bistable localized states [16] and possesses the required topology, as opposed to for instance a nonlinear optical amplifier or absorber with optical injection.

The experimental system consists of two optically coupled two broad-area semiconductor lasers (Vertical Cavity Surface Emitting Lasers or VCSELs), one facing the other (see Fig. 1, left). Both devices are thermally stabilized and electrically pumped. One of the devices is pumped below transparency, such that it is acts as a saturable absorber, while the other one is pumped above transparency and provides light amplification. The coupled system therefore constitutes a laser with saturable absorber (ie, a system with saturable nonlinearity and phase symmetry) in which both the amplifying and the absorbing media are inside their own cavity, which together define the resonator of the compound system. The compound cavity is such that the amplifying and the absorbing medium are imaged onto each other, contrary to what was performed in the experiment reported in [22], which allows for the formation of mutually independent spatial structures. The coupled devices are nominally identical bottom emitting vertical-cavity surface-emitting lasers provided by ULM Photonics. Their diameter is 200 μm and their effective length of a few microns for an emission wavelength slightly below 980 nm. The threshold current of uncoupled devices is around 400 mA and the transparency current value has been estimated at about 45 mA. The experiment described above has been performed for current values between 15 and 25 mA for the absorbing device and around 300 mA for the amplifying device. Coherent emission can be obtained for this current value (lower than standalone threshold) thanks to the light fed back from by the absorbing device into the amplifying one which induces an overall reduction of the losses. The substrate temperature of each device has been chosen such that they are brought into resonance via Joule heating at these current values [23].

The existence of localized states in the form of bistable localized laser beams has been established using the ex-

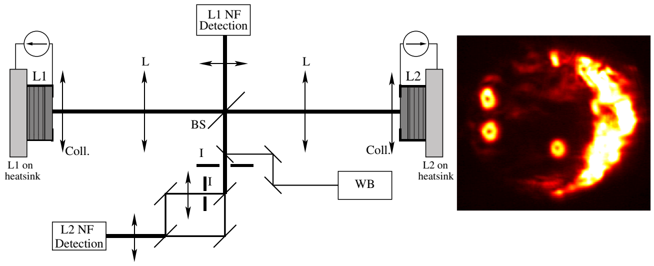

FIG. 1 (color online). Left: experimental setup. Two broad-area semiconductor lasers (L1 and L2) are coupled by imaging them onto each other via collimating optics (Coll) and lenses (L). Part of the emitted beam is extracted from the compound cavity via a beam splitter (BS) for near field (NF) detection allowing interferometric measurements and spatial filtering (I). A tiny beam from a tunable laser can be used to apply a local perturbation to the system (WB). Right: Spontaneously formed intensity rings in the near field. The two devices (200 μm diameter) are laterally shifted with respect to each other. In the spatial region where they overlap, the absorption can locally saturate and lead to the formation of several bright bistable rings.

periment in Ref. [16] for a broad range of parameters provided a few conditions in terms of relative tuning of both cavities, total gain and absorption in the system are satisfied [23]. Within this parameter regime, we also observe the spontaneous formation of several bright ringlike structures in the near field of the device (Fig. 1, right). As we shall demonstrate in the following, these structures have a number of properties which allow their interpretation in terms of localized vortices.

Independently of the presence of a phase defect, an expected property of dissipative solitons or localized structures in dissipative systems is bistability. This property results from the discrete character of the ensemble of soliton solutions in dissipative systems, as opposed to the continuous family of solitons of conservative systems [11,24]. Indeed, the spatial structures described above can appear for different parameter sets, but a consistent feature is their abrupt appearance when the pump parameter of the amplifier laser is ramped upwards, which may indicate subcriticality and therefore coexistence of multiple states. These structures can either appear from a spatially homogeneous low intensity background, or from a preexisting localized state, depending on the parameters' values. In Fig. 2 the intensity of the field emitted in a small region ($\approx$30 μm diameter) of the system as a function of the pump current of the amplifier laser shows an abrupt switch towards a two-humps structure, which switches to a ring structure upon further increase of the parameter. When the bias current is decreased, the system switches back to the two-humps shaped structure, then to a single hump one and finally back to the fundamental off state. The stability region of each of these states can be determined by appropriate scanning of the parameter. In the present case, one clearly observes the coexistence between the ring structure with both the two hump structure and the homogeneous state. Similarly, the two- and single-hump states both coexist with the homogeneous state and with each other in a certain domain. On the other hand, the stability region of the single-hump and the ring state do not clearly overlap at least in the present parameter set.

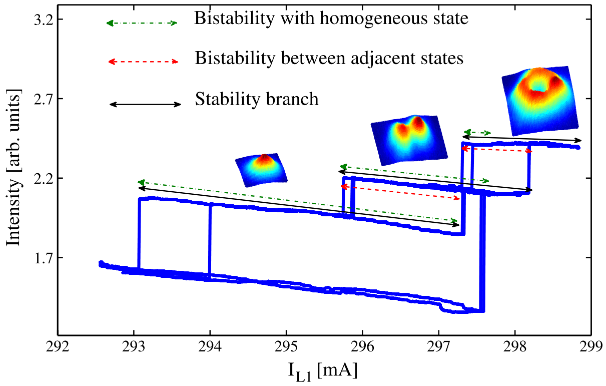

FIG. 2 (color online). Bifurcation diagram showing the spontaneous switching of the system between different solutions. The ring can coexist with an "off" state and/or with a two-humps state.

While the stability properties of the ring structures is compatible with theoretical predictions for a localized vortex [11], the spontaneous formation of localized states in the absence of any local perturbation of the system is not expected in a system with perfect translation symmetry. This spontaneous formation can occur at different positions in the device, often for slightly different parameter values [25]. As in other experiments involving localized structures, a possible explanation for this behavior is the unavoidable presence of small scale material inhomogeneities in the devices, which may act as the source of localized states [26].

Since the system composed by coupling the two devices has a total length of about 32 cm, several longitudinal resonances of the compound resonator may be involved in the radiation emitted by this laser with saturable absorber [27]. Indeed, dynamical states spanning several of these modes have been observed. However, 6 GHz bandwidth pointlike measurements have been performed and indicate that each spatial structure presented above can be stationary, ie, is a monochromatic solution of the system. The experiment has been performed with system lengths ranging from 20 to 60 cm leading to the same qualitative results.

In addition to bistability common to all stationary localized states in dissipative systems, the distinctive feature of localized vortices is the presence of a singularity in their phase front. In order to disclose the phase profile of the intensity rings shown above, we perform interferometric measurements in the parameter range where a ring structure exists. To this aim, the output beam of the system is split in two parts which are recombined on a charge coupled device camera after different propagation paths, forming a Mach-Zehnder interferometer. One of the beams is prepared such that the whole near field of the system is imaged onto the camera while the other beam passes through an additional lens in order to considerably enlarge it with respect to the other. In this way, a small spatial region of the beam profile can be selected and converted to an almost plane wave which will serve as a reference beam to build an interferogram of the system. We note that this somewhat complicated homodyne procedure is necessary to obtain an interferogram due to the absence of any phase reference in the system. On the left of Fig. 3, the reference beam has been blocked: only one beam reaches the camera, which reveals two structures in the central part of the near field. On the right panel, the reference beam which has been selected from a small part of the ring structure also reaches the camera, under the same angle of incidence. An interference pattern is generated where there is mutual coherence between the reference beam and the spatial region with which it overlaps. We note that this phenomenon is related to the absence of any phase reference in this system, in contrast with the majority of experiments regarding localized structures in optics which involve some form of coherent energy input. A remarkable feature is that the interference pattern appears only where the ring structure itself is. In particular, the neighboring structure does not interfere at all with the reference beam. This absence of mutual coherence between the fields emitted in distinct spatial areas shows the lack or extreme weakness of any coherent coupling between these two areas. This observation is compatible with the interpretation of localized states in a laser with saturable absorber as independent microlasers. The other striking feature observable on the right panel of Fig. 3 is the presence of a phase discontinuity originating in the center of the ring, which contains, therefore, a phase defect. The spiral shape of the discontinuity, which is also observed in numerical simulations in presence of localized vortices [11] and does not exist in pure Gauss Laguerre resonator modes, is a signature of the coupling between phase and amplitude of an optical field propagating in a semiconductor medium.

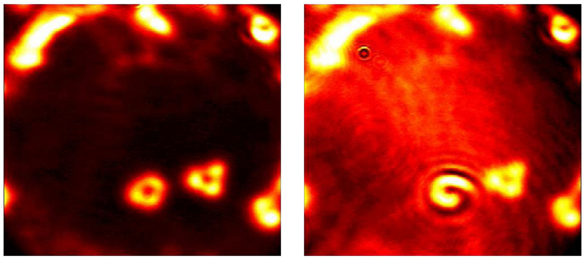

FIG. 3 (color online). Left: near field intensity of the system, showing two bright spatial structures sitting on the dark homogeneous background corresponding to nonsaturated absorption. Right: interferometric measurement. When both arms of the interferometer are aligned (a small part of the ring structure being superimposed with the whole ring structure and surrounding region), the phase profile of the ring structure is indicated by spiral like interference pattern.

While the chirality of the phase profile of the ring structure is readily apparent in Fig. 3, it can also be conveniently detected by performing an identical measurement, but tilting the two beams with respect to each other. In this case, interference fringes are detected, as shown on Fig. 4. The orientation and periodicity of the fringes is of course set by the tilt between both beams, but the presence of a dislocation in the pattern [Figs. 4(b) and 4(c)] reveals the existence of a phase defect at the core of the ring since the circulation of the phase around the center does not vanish. Even though the chirality of the ring structure appears to be very robust (it can persist for minutes in this experiment where typical time constants are of nanosecond order), we occasionally observed (with a constant parameter set) spontaneous switching between the two chirality states shown on Fig. 4(b) and 4(c). This switching can be attributed to exchange of charge with the surrounding zero solution (as was observed at the boundaries of the system in [28]).

Beyond the physical interest of localized vortices, the possibility of optically controlling the on/off state of arrays of optical vortices could enable parallel approaches to microobjects manipulation or optical nanoscopic detection techniques. This switching procedure, referred to as "hard excitation" in [12] or considered as an initial condition in [10], consists in placing the system in the suitable parameter regime in the low intensity homogeneous solution, and locally modifying the state of the system beyond a certain threshold leading to the nucleation of a localized vortex which persists upon removal of the perturbation.

As a first attempt towards such a realization, a localized optical perturbation is prepared as a small diameter laser beam tuned close to the emission frequency of the coupled laser system, with zero topological charge, applied on the absorber section. The system is prepared in the homogeneous low intensity state shown in Fig. 5(a). The tuning condition between devices and the absorption are set such that only the ring structure and the homogeneous state coexist. When the perturbation is applied, the system switches to a high intensity state, where no local minimum is observed [Fig. 5(b)], without modification of the neighboring structures. When the perturbation is removed, a

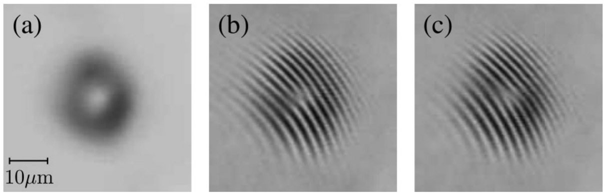

FIG. 4. (a) Near field intensity of a localized vortex. When a part of it is magnified and interferes with the whole vortex, fringes appear if both beams are tilted with respect to each other. Their orientation and periodicity is set by the tilt angle. (b), (c) The dislocation of the fringe pattern indicates the presence of a phase defect and the direction of the dislocation gives the sign of the charge.

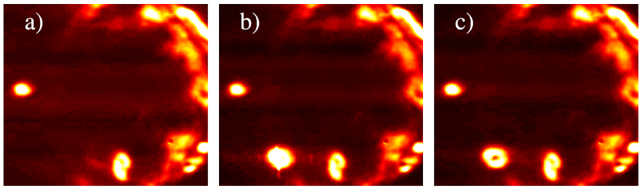

FIG. 5 (color online). A local optical perturbation can switch the system from "off" to "ring" state: (a) near field without local perturbation; (b) an optical perturbation switches the system to a high intensity state; (c) which ends up in a self-sustained localized vortex when the perturbation is removed.

localized state whose dark center hosts a phase defect remains [Fig. 5(c)]. We note that the nucleation of a structure hosting a single defect results in a surprising topological imbalance since defects are expected to be generated by pairs. This excess in the total charge has been observed in the case of two-dimensional optical chaos [28] where it has been used as a measure of boundary effects [29], attributing the imbalance to the fact that the areas of low emitted intensity at the boundaries can act as a reservoir of defects. In the present case, this imbalance is therefore to be expected, since a localized structure is by definition bounded in space and surrounded by a zero solution.

Beyond this very basic switching demonstration, a number of other manipulations could be attempted. In particular, numerical simulations [10,12] indicate the possibility to generate states with higher topological charge if the perturbation itself possesses adequate vorticity.

In conclusion, we have demonstrated that localized structures in a cavity soliton laser can bifurcate towards self-sustained and independent optical vortices which feature three among the most intriguing properties of light (all of them self-sustained): spatial localization, coherence and vorticity. Even if the experimental system in its present implementation is far from a usable device in terms of applications, we note that it is possible to grow monolithic semiconductor devices containing all the necessary features [17] for the formation of bistable and independent localized vortices. Such a robust and compact device may well prove useful for advanced microobjects manipulation such as torque measurements, state-of-the art optical nanoscopy methods, or parallel topological information encoding.

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