Introduction to the Feature Section on Cavity Solitons: An Overview

SINCE the mid-1990s, there has been a lively interest in the topic of cavity solitons (CSs) (see [1]–[3] and references quoted therein). These belong to the wide class of spatial solitons [4]–[6], but arise in a dissipative environment, in contrast to standard spatial solitons, which emerge in the framework of reversible Hamiltonian dynamics. For this reason, CSs exhibit characteristic properties of their own. For example, CSs are rigid, in the sense that, once the values of the system parameters are fixed, all their properties (e.g. their height, width, their spatial profile) are simultaneously fixed. The interest in CSs arose especially from the fact that they can be manipulated (i.e., written and erased) individually by external control beams, which makes them appropriate for application to optical information processing. Such manipulation is possible because CSs are independent of one another provided that they are not too close to each other and are independent of the boundary, provided that they are not too close to the boundary. In addition, it is possible to control the location and the velocity of CSs by introducing phase or amplitude gradients in the background in which CSs are embedded.

The idea is to consider the transverse planes, orthogonal to the propagation direction of the beam, as a blackboard on which light spots can be written and erased in any desired location and in a controlled way. Transverse optical patterns [1] typically display an array of light spots, for example, with a hexagonal shape. However, they are not suitable for this task because the intensity peaks are strongly correlated to one another so that if, by any means, one introduces a change into one element of the array, either the entire array is affected, or the system spontaneously restores the original configuration of the array. This task becomes possible, instead, using cavity solitons.

The name "cavity solitons", which has been introduced relatively recently in the literature, is very appropriate to distinguish this topic in the framework of the field of spatial solitons. We will use this name in a broad sense to designate this topic, but it is convenient to keep in mind that, from a theoretical standpoint, this area is based on two distinct theoretical approaches, the mutual relations of which are not yet completely understood. One approach was developed by Rosanov and collaborators [7], [8] with the name "diffractive autosolitons". This phenomenon develops in nonlinear optical systems which display bistability between two stationary solutions which are homogeneous in the transverse plane. In the case of one transverse dimension, switching fronts may connect the two solutions. The autosolitons form from the locking of two switching fronts under conditions determined by a Maxwell rule. They are bright spots which correspond to a portion of the higher intensity solution localized in the lower intensity solution background. A general theory of front locking in one dimension has recently been formulated by Coullet and collaborators [9]. Related to this approach is the phenomenon of localized domain formation, theoretically described for $\chi^{(2)}$ media [10]–[13], in which there is bistability between two homogeneous solutions with opposite phase, under conditions such that the Maxwell rule is automatically satisfied. Again, the bright spot is an unmodulated solution localized by locked fronts in a background corresponding to another solution. The same phenomenon occurs in a vectorial Kerr-medium model as a consequence of field polarization [14].

The second theoretical approach is based, instead, on the general phenomenon of localized structures, which has been previously described for nonoptical systems [15], [16]. Even if often in the optical case this phenomenon arises in the presence of plane-wave bistability, the latter is not necessary. Instead, the presence of a modulational instability is necessary, i.e. a portion of the homogeneous stationary branch must be unstable against the formation of a spatial pattern. Localized structures arise under conditions of coexistence (i.e. bistability), in a nonlinear dynamical system, of a stable homogeneous stationary solution and a stable patterned stationary solution (technically speaking, this coexistence requires that the modulational instability arises *via* a subcritical bifurcation). Coexistence means that for the same values of the system parameters, according to the initial condition, the system may approach a configuration which is uniform in space or a pattern configuration. In this case, one may meet the phenomenon of localized structures, which are solutions intermediate between the homogeneous and the pattern solutions, in the sense that they coincide with the pattern solution in a certain restricted region of the plane, and with the homogeneous solution in all the rest of the physical region occupied by the system. Under conditions of translational invariance, the presence of localized structures implies that the system displays the coexistence of a continuous infinity of coexisting solutions, because the structure can be located in arbitrary positions. A CS corresponds to a localized structure with a single peak, which sits over the pedestal of the stable homogeneous stationary solution and displays a tail with more or less pronounced oscillations. The first example of CS formation following the localized structure scheme was provided by Tlidi et al. [17], [18] and was followed by other theoretical papers by Firth and Scroggie [19] and Brambilla *et al.* [20], which demonstrated the plasticity and the manipulation of CSs. Precursors for these theories can be considered the works of Moloney, Newell, and McLaughlin [21]–[23] and McDonald and Firth [24].

CSs are usually produced by means of optical resonators containing nonlinear materials (see Fig. 1). The energy is provided to the system by a broad-area coherent and stationary holding beam which is injected into the cavity and, in the case of semiconductor amplifiers, also by an electric current. The device is

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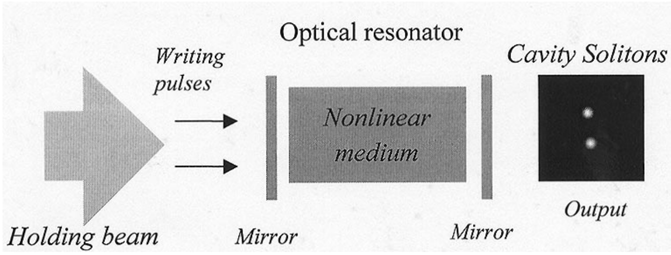

Fig. 1. A coherent, stationary, quasiplane-wave holding field drives an optical cavity containing a nonlinear medium. The injection of narrow laser pulses creates persistent localized intensity peaks in the output (cavity solitons).

operated under parametric conditions such that the output is basically uniform. However, by injecting a localized laser pulse, one can write a CS where the pulse passes. It is very important that the CS persists even after the pulse, until the holding beam is kept on [20]. In this way, by injection of several pulses one can write a number of CSs. They can be subsequently erased by again injecting pulses in the locations where CSs lie; in most cases, the erasing pulses must be coherent and out of phase with respect to the writing pulse [20], [25]. Very important are the properties of CSs concerning their mutual interaction and their motion with respect to gradients in the holding beam. Two CSs do not interact provided that their distance is larger than a certain minimal distance [20], [26]. Below this minimal distance, there is the possibility that the two CSs reach an equilibrium distance determined by the locking of their tails. Actually, there may be more than one equilibrium distance. This circumstance opens the possibility for the formation of clusters [27], [28]. Finally, when the distance is below a certain critical minimum, the two CSs fuse into a single CS which has the same characteristics (width, height, etc.) of the original CSs. Under conditions of translational invariance in the transverse plane, a CS can move in presence of noise, performing a slow random walk which, of course, is undesired for applications. Another cause for the motion of CSs is the presence of amplitude or phase gradients in the holding beam. Under the influence of an amplitude gradient, CSs tend to move to the nearest local maximum of intensity. For example, if the holding beam has a Gaussian configuration, all CSs move to the top so that, finally, only one soliton remains [25]. This effect is also undesired for applications. Under the influence of a phase modulation, CSs move toward the nearest local maximum with a velocity proportional to the gradient [19]. Phase gradients are very useful for applications, and can be used to neutralize the negative effects arising from amplitude gradients and from noise. For instance, by introducing a periodic phase modulation in the holding beam, it is possible to create an array of equilibrium positions for CSs, in which solitons can be set on or off by injecting laser pulses. This constitutes a reconfigurable array of binary pixels.

The prediction of CSs, initially limited to $\chi^{(3)}$ materials, was extended to $\chi^{(2)}$ media [29]–[32]. For an overview of both cases, see [33].

Experimental observations of localized structures in macroscopic cavities have been obtained in photorefractive resonators [34] and lasers with saturable absorbers [35], [36]. Similar phenomena have been observed in other systems with feedback [37]–[41]. In particular, the results of [39]–[41], obtained in sodium vapor with a single feedback mirror show the main functionalities of CS and belong to what might be considered one of the most systematic and beautiful set of experiments in the field of optical pattern formation.

Most interesting for practical applications is the realization of CSs in semiconductor microresonators because of the miniaturization and the fast response of the material. However, such small and temporal scales make this realization a difficult and challenging task. Theories which predict CSs in semiconductor devices were formulated in [42]–[45] and [25], [26]. Optical patterns in semiconductor cavities have been observed in [46]–[50]. Interesting precursors of CSs [47] and soliton-like structures [51]–[54] have been identified by Taranenko, Weiss, and Kuszelewicz in passive (i.e. without population inversion) semiconductor microcavities, but they are boundary dependent, because the Fresnel number is too small to distinguish between self-confinement and boundary confinement. In addition, most of the observations are affected by thermal effects [54]. A recent experiment by Tredicce, Barland, and Giudici [55] attained a clear-cut observation of CSs using a broad-area driven vertical-cavity semiconductor microlaser slightly below threshold. In particular, two CSs are first written with the help of an address beam and subsequently erased by flipping the phase of the control beam by π. This demonstrates that the two are independent of one another and the large Fresnel number ensures the independence of the boundary, as it must be for CS. The experimental findings agree well with the theoretical/numerical predictions, which provided a guideline for the experiment. In particular, the connection with a modulational instability and with the presence of a pattern is clear.

This Feature Section of the IEEE JOURNAL OF QUANTUM ELECTRONICS gathers a number of papers from some of the main contributors of the field. They, in part, review previous results and in part publish new results. Hence, they provide a convenient meeting forum for newcomers. An article by the Muenster group reports on experimental results which illustrate the properties of feedback mirror solitons in a single-mirror experiment. The remaining papers are theoretical.

The case of semiconductor microcavities is studied in two contributions. One arises from a collaboration between the Laboratoire de Photonique et Nanostructures (France) and Bari Polytechnic (Italy), and discusses optical patterns and CS in quantum-dot microresonators. The other is contributed by Bari Polytechnic and the University of Strathclyde (U.K.), and provides a general discussion of the link between patterns and CS in semiconductor microcavities. Two contributions deal, instead, with the case of $\chi^{(2)}$ materials. The first originates from a collaboration between the University of Palma de Mallorca (Spain) and the University of Strathclyde, and analyzes the topics of stable droplets and dark-ring cavity solitons in optical parametric oscillators and, in parallel, in vectorial Kerr media. The second is contributed by Jena University (Germany) and discusses quadratic CSs generated by second harmonic generation.

Results on two-dimensional stationary and oscillatory solitons in a wide-aperture laser with a saturable absorber are presented by University of St. Petersburg (Russia).

Finally, general issues in the interface between optical patterns and CS are discussed in a paper contributed by a collaboration between the Free University of Brussels (Belgium) and the University of St. Petersburg.

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