Nonlinear localized modes in bandgap microcavities

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We study experimentally an electrically pumped GaAs-based bandgap structure based on a vertical cavity surface emitting laser (VCSEL). We demonstrate that a microcavity embedded into this bandgap VCSEL structure supports localized optical modes without any holding beam. We propose a model of surface-structured VCSELs based on a reduced dissipative wave equation for describing electromagnetic modes in such semiconductor cavities and analyze a crossover between linear and nonlinear solitonlike cavity modes. © 2010 Optical Society of America

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The study of spatially localized structures in optical systems is a rapidly growing research area with many promising applications in physics and technology [1,2]. In particular, with the existence of bandgaps in photonic crystals (PhCs), a unique way of controlling light by employing guided-light modes has shown potential applications in photonics, such as optical memories and signal processing [3]. More recently, nonlinear effects in PhCs were shown to play an important role in achieving all-optical operations in switching devices and in the formation of self-trapped localized states [4,5], but only a few recent works [6–8] have considered their role in the formation of dissipative nonlinear structures.

Because they have large transverse lasing area compared to the cavity length, vertical cavity surface emitting lasers (VCSELs) are recognized as a natural platform for the study of dissipative solitons and the generation of optical patterns in mesoscopic systems; for example, self-organized linear and nonlinear optical modes were demonstrated in semiconductor microresonators, from chaotic scar modes [9,10] to cavity solitons with external holding beams [11] and without an external injection beam through mutually coupled semiconductor microcavities [12,13], and delayed or frequency-selective feedbacks [14,15].

In this Letter, we study experimentally a type of two-dimensional (2D) bandgap microstructures based on a VCSEL geometry. Pumping this structure electrically, we observe, by using near-field scanning optical microscope (NSOM) technology, the generation of self-organized optical modes due to a surface bandgap structure. By increasing the injection current, we analyze transitions between linear defect modes supported by a cavity in the PhC and nonlinear optical patterns resembling clusters of dissipative solitons existing without any holding beam. We develop a simplified model and demonstrate that numerical results based on a reduced dissipative nonlinear wave equation are in a good agreement with the experimental data.

First, we discuss our experimental results. A schematic diagram and scanning electron microscope (SEM) image of the microstructured VCSEL used in our experiments are shown in Figs. 1(a) and 1(b). Instead of using shallow surface microstructures, as in the case of chaotic optical modes [9,10], to study an interplay between nonlinear and bandgap effects, we fabricate a deep hexagonal lattice of holes with a cavity (defect) in the center by employing a focused ion beam. The deep holes are made by punching the upper 14–16 layers of the distributed Bragg reflector structure, resulting in a periodic modulation of the refractive index to the intracavity field. The lattice constant of the hexagonal lattice in this PhC-structured VCSEL is 1 μm, and the diameter for the surrounding holes is 500 nm. To have a clear illustration of the theoretical model and the experimental demonstration, two small extra holes in the core region are added to break the rotational symmetry of the corresponding cavity modes. The diameter for these two extra holes is 100 nm. With this kind of symmetry-breaking geometry, we can view the cavity as a quasi-one-dimensional system along the horizontal direction.

Figure 2(a) shows the experimental results for the cw light-current dependence measured for our GaAs-based PhC-structured VCSEL. The threshold current for lasing is about 32 mA, below which only spontaneous emission is registered [16]. After the VCSEL is turned on, we use NSOM operated at the collection mode to measure the electromagnetic intensity distribution on the aperture surface. Above the threshold current, we record a series of three-dimensional (3D) and top-view images for the

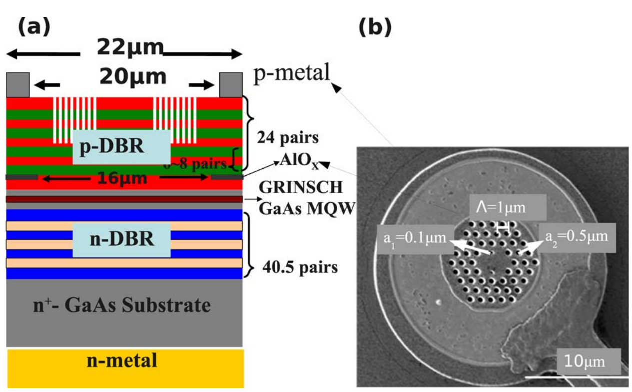

Fig. 1. (Color online) (a) Structure of VCSEL with a surface PhCl cavity; (b) top-view SEM image.

optical fields inside the hexagonal PhC structure and present them in the first and second columns of Figs. 3 [Figs. 3(a)–3(h)], respectively. By increasing the injection current from 33 to 37 mA, we observe that the radiation patterns not only grow in intensity, but also become sharper at the center of the lasing area. The size of these optical "nonlinear pixels" becomes less than 6 μm $\times$ 6 μm. When the operation current is selected well above the threshold and the cavity effects are considered, nonlinearity plays a crucial role in the formation of the transverse optical patterns, and the observed structure itself resembles a cluster of solitons. This is confirmed by the subsequent theoretical analysis summarized below.

The complex spatiotemporal dynamics of broad-area semiconductor laser cavities has been theoretically analyzed for the filamentary behavior [17]. To study theoretically the stationary spatiotemporal state in a semiconductor laser cavity, we derive a reduced dissipative wave equation for the electromagnetic waves in a semiconductor microcavity [11,18]:

$$i\partial_\tau E + \frac{1}{\alpha}\bar{\theta}E - \left(1+i\frac{1}{\alpha}\right)\left[-(1+\eta)+\frac{2C(I-1)}{1+|E|^2}\right]E + \left(1-i\frac{1}{\alpha}d\right)\partial_\xi^2 E = 0, \qquad (1)$$

where C is the saturable absorption coefficient scaled to the resonator transmission, η is the linear absorption coefficient in the cavity, $\bar{\theta}$ is the cavity detuning, d is the diffusion constant of the carrier scaled to the diffraction coefficient, and I is the external injection current. The coordinates are defined with respect to the corresponding line-width enhancement factor α as $\tau = \alpha t$ and $\xi = \sqrt{\alpha} r$. When $\alpha \gg 1$, the proposed Eq. (1) can be approximated by the generalized nonlinear Schrödinger equation [19], where modulation instability is known to lead to the formation of nonlinear patterns and solitons [20].

To support our experimental results and model a PhC cavity with a defect, we modify Eq. (1) by introducing a spatial-dependent cavity loss $\eta + V(\xi)$, where $V(\xi)$ has real and imaginary parts to describe both periodic loss and phase modulations. The solid curves in Fig. 2(b) show the first four linear eigenmodes inside the lossy periodic cavity. Similar to linear defect modes in a high-quality cavity, the number of peaks for these modes is one for the ground state and two or more for the higher-order modes (almost degenerate, but far separated). In such a structure, the fourth-order linear mode has a profile with three peaks in the cavity region and additional two peaks in the periodic regions, owing to the leakages outside a finite cavity. By introducing the current above the threshold condition, for example, 36 mA in Fig. 2(b), we can apply our model to study the corresponding nonlinear cavity modes, shown by the dashed curves, which are found to be more localized than their linear counterparts.

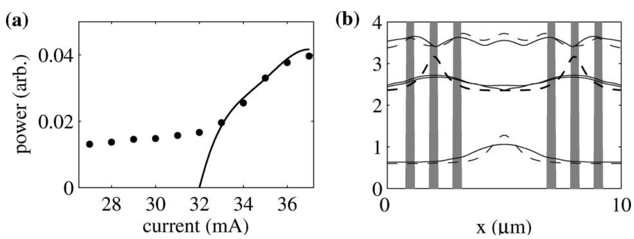

Fig. 2. (a) Dependence of the output lasing power on the injection current, measured experimentally (marked as •) and calculated from a theoretical model (solid curve). (b) Four low-order linear eigenmodes (solid curves) in a lossy cavity with periodic modulations of $V(\xi)$ (shaded areas) and the corresponding nonlinear cavity modes (dashed curves) calculated at the injection current $I = 36$ mA. The modes are normalized, and a constant level is added to the real part of their eigenvalues.

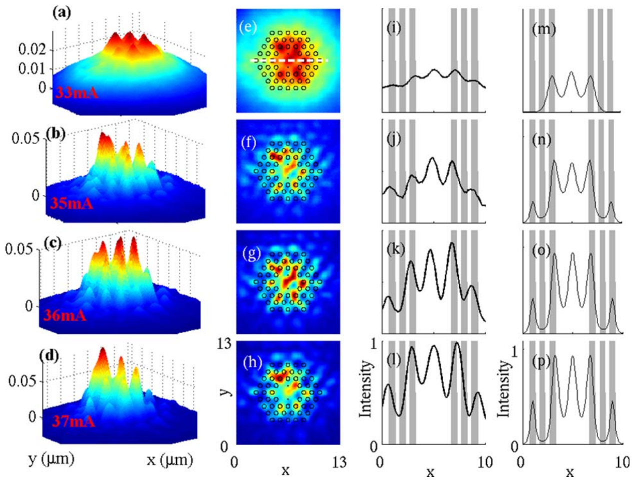

Fig. 3. (Color online) Experimental demonstration of soliton lattices with 3D and 2D NSOM images (first and second columns). The injection currents are 33, 35, 36, and 37 mA, respectively. The third column shows the mode profile along the horizontal direction, i.e., along the dashed line in (e). The shaded areas mark a periodic lattice. The corresponding theoretical results are presented in the fourth column, for the parameters $\eta = 5$, $C = 2$, $\alpha = 5$, and $d = 0.0001$.

To describe the experimental data presented in Fig. 3, we employ the localized defect modes to match the structure observed in the experiment. Then we add nonlinearity and find numerically the spatial intensity distribution for nonlinear modes in our model for different injection currents by applying Eq. (1) with the real one-dimensional lattice potential in the experiment, shown by a dashed line in Fig. 3(e). Just above the threshold current of 33 mA, the field outside the defect cavity is almost suppressed, resulting in a profile with three peaks, as shown in Figs. 3(i) and 3(m). As the injection current increases, not only the three peaks in the defect center, but also the two peaks outside, become higher, supporting our observation that the generated structures can be linked to the corresponding nonlinear modes. In Fig. 3, the simplified one-dimensional intensity distributions from the calculations (fourth column) resembles those extracted from experimental data (third column). Moreover, with the threshold current fitted from the experimental data, the simulation results also reflects a good correspondence with the experimental light-current dependencies above the threshold, as shown by the solid curve in Fig. 2(a).

As a VCSEL device, PhC structures have been proposed to tailor the radiation modes and enhance the lateral confinement of the fundamental modes [21]. The basic idea is to reduce losses by applying a photonic-defect cavity instead of a typical cavity boundary defined by oxide compounds. In our study, we demonstrate that not only the specific PhC structure but also the nonlinear response are crucial in supporting the coherent structures. As a comparison, we apply the optical confinement factor, i.e., optical power confined in the PhC over the total power emitted from our PhC-structured microcavity VCSEL. Using the value of 36 mA, the corresponding optical confinement factors are defined as 0.7033 and 0.9714 for the fourth-order linear mode in Fig. 2(b) and the nonlinear mode in Fig. 3(o), respectively. In the presence of nonlinearity, the optical confinement factor is expected to be greatly improved, in order to reduce the required threshold current for the excitation of a higher-order lasing mode.

In conclusion, we have studied a combined action of nonlinearity and bandgap localization on the structure of transverse optical modes in electrically pumped GaAs-based PhC-structured VCSELs. We have observed the generation of localized defect modes and solitonlike nonlinear modes at room temperature. With a specific design of the bandgap cavity, we have demonstrated a crossover between linear defect PhC modes and nonlinear modes resembling a cluster of dissipative spatial solitons. We have developed a theoretical model based on a reduced dissipative nonlinear wave equation and demonstrated good agreement between the experimental data and the numerically obtained dissipative modes. Such PhC-structured VCSELs represent a novel type of nonlinear dissipative system, and they may provide a background for the study of many different bandgap effects in the nonlinear dynamics of semiconductor cavities.

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