Enhanced directional lasing by the interference between stable and unstable periodic orbits

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We demonstrate the idea of surface-assisted microstructures to tailor the modes and resulting emission from a dynamical localized vertical cavity surface emitting laser at room temperature. With a slightly mismatch between the surface structure and the native oxide cavity layer, near field intensity images corresponding to the spontaneous emission patterns, whispering-gallery modes (WGMs), dynamical localized modes (DLMs), and unidirectional light emissions are measured and identified in experiments and simulations. Moreover, the coherent superposition of WGM and DLM, i.e., stable and unstable periodic orbits, respectively, is reported to provide an alternative and general method to control lasing characteristics as well as to study quantum chaos in mesoscopic system. © *2009 American Institute of Physics*. [DOI: 10.1063/1.3148682]

Microcavities have provided a controllable confinement and manipulation of photons in all three spatial dimensions. Intense research studies based on microcavities have been carried out in the past decades,[1,2] with emphases on ultralow threshold lasing, single-photon emitting, cavity quantum electrodynamics, and mesoscopic quantum optics. Confined by the total internal reflection at the interface, almost grazing incidence patterns known as whispering-gallery modes (WGMs) have been demonstrated in microdisks,[3] microspheres,[4] and microtori[5] with the feature of a small mode volume and a recorded ultrahigh quality factor $Q > 10^5$.[6] For state-of-the-art semiconductor technologies, vertical cavity surface emitting lasers (VCSELs) confined by high reflective Bragg mirrors in the vertical direction are a natural choice for lasers with controllable transverse behaviors and an optical output emitted vertically from the surface.[7]

Due to the rotational symmetry in the transverse cavity geometry, the in-plane WGM emission in these microcavities is isotropic. But with a nonintegrable deformation, partially chaotic mode patterns were introduced and demonstrated in the semiconductor microlaser resonators.[8,9] In general, nonintegrable and chaotic shapes of cavity can also support lasing modes, which has a common signature of the localized eigenstates of the wave equation, coined as scar modes.[10] Unlike WGM with stable periodic orbits, in this scenario, an infinite number of unstable periodic orbits is needed to construct each wave function for there are no stable periodic orbits in a fully chaotic cavity. Recently, various directionality of light emitting can be achieved by smoothly deformed the cylindrical cavities.[11–13] In this letter we extend the concept of using surface structures to design optical deformed microcavities in VCSELs to study the directional lasing. Instead of breaking the symmetry in the transverse shape, a surface ring cavity is fabricated on top of the VCSEL with a slightly mismatch between the surface structure and the native oxide layer. Experimental observation of WGMs supported by the native oxide layer is reported at low injection currents. By increasing the injection current, a hybrid lasing mode is identified, resulting in an enhanced directional lasing with counter-clockwise field distribution inside the cavity. Experimental observations are verified with directly numerical simulations by changing the relative phase between the WGM and dynamical localized mode (DLM). The experimental and numerical investigations in this work also provide an effective state for studying quantum chaos in mesoscopic system by using microstructured semiconductor lasers.

The schematic diagram of our microstructured VCSEL used in experiments is shown in Fig. 1(a), The epitaxial layers of the VCSELs are grown by metal-organic chemical-vapor deposition on a n^+-GaAs substrate, with graded-index separate confinement heterostructure active region formed by undoped triple-GaAs-AlGaAs quantum wells placed in 1λ cavity, where the emitting window is designed as 20 μm in

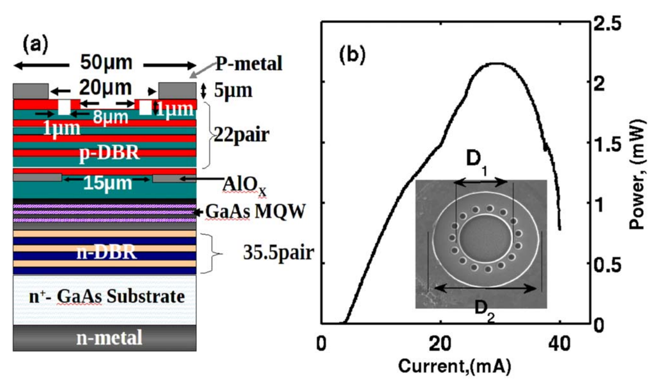

FIG. 1. (Color online) (a) Schematic diagram of the device structure. (b) The *L-I* curve for our VCSEL with a surface microstructure. The inset shows the top-view SEM image, with the geometric diameters $D_1 = 8$ μm and $D_2 = 15$ μm.

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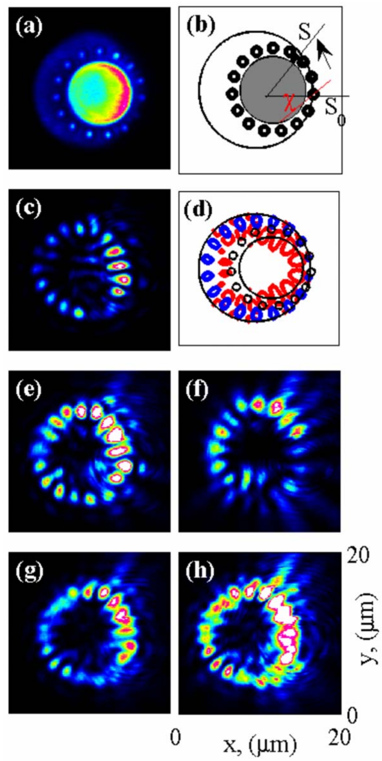

FIG. 2. (Color online) Near field intensity distributions on the surface of aperture of our microstructured VCSEL at different injection currents, i.e., (a) 3.5 mA, (c) 17 mA, (e) 19 mA, (f) 19 mA (defocus), (g) 24 mA, and (h) 30 mA. The schematic mismatched lateral boundary defined by the surface and the oxide layer is shown in (b). And the illustration of two lasing modes are shown in (d), with blue and red colors corresponding to the WGM and DLM, respectively.

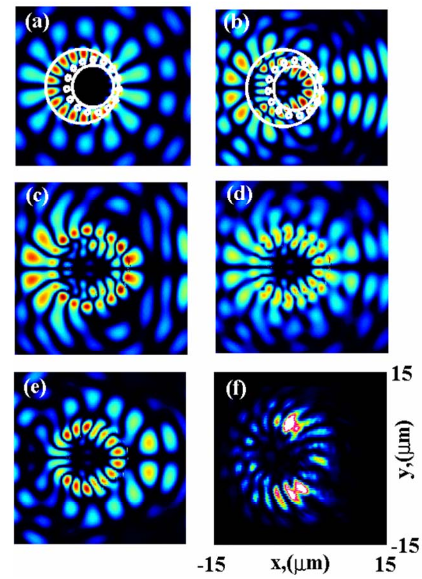

FIG. 3. (Color online) Simulations of the field distribution for the eigenmodes as a WGM (a) and a DLM (b), respectively. Superpositions between these WGM and DLM are shown with different relative phases for (c) $\Delta\phi=\pi/2$, (d) π, and (e) 0. (f) Experimental data for a clearly symmetry-breaking near field intensity distribution collecting at the injection current 7.5 mA.

diameter and the oxide-confined emitting aperture is 15 μm in diameter. On emitting window, a ring with 8 μm in diameter and 1 μm in depth is etched by focus ion beam (FIB). Moreover, 15 small holes etched by FIB with 1 μm in diameter and 0.5 μm in depth are defined along the circumference of the outside ring, in order to suppress lower-order cavity modes by destroying their vertical reflectors. Detail device parameters and lasing characteristics can be found in our previous publication on a similar VCSEL device but with different surface structures.[14] From the scanning electron microscope (SEM) image, as the inset in Fig. 1(b), one can see the top view of the surface structure formed by the annular cavities and 15 small holes. But the center position of our surface annular cavity is shifted with a displacement to the oxide aperture, which is confirmed later by the spontaneous emission pattern through collecting the near field intensity, as shown in Figs. 2(a) and 2(b) with the experimental measurement and schematic illustration, respectively. The *L-I* curve, light versus current, of the surface-structured VCSEL is shown in Fig. 1(b). The threshold current of the device is about 4 mA. The dependence of the output power to the injection current becomes nonlinear around 17 mA, with distinct kinks at 19 and 24 mA. Such kinks are believed to be the onset of a second lasing mode, as those observed in other deformed microlasers.[9] Above 30 mA, the output power decreases as the injection current increases.

Figure 2 shows the near field images on the surface of emitting window at different injection currents. While the VCSEL is operated below the threshold current, at 3.5 mA, spontaneous emission pattern just reflects the overlap of surface structure and oxide-confined emitting aperture in the VCSEL. The mismatch between the emitting window and the oxide layer is clearly shown in Fig. 2(a), resulting in a deformed microcavity. Figure 2(b) shows the schematic mismatched lateral boundary defined by the surface and the oxide layer, which is used as the cavity geometry in our numerical simulations later. Light emissions from the shifted inner disk and 15 surface holes are clearly identified. Above the threshold current, at 17 mA in Fig. 2(c), a clear high-order WGM with multiple (18) lobes is directly observed due to that some pairs of distributed Bragg reflector mirrors are destroyed. The number of lobes m in the azimuthal direction is consistent with the simple resonance condition for a ring cavity, i.e., $2\pi R = n_{\mathrm{eff}} m\lambda$, with the lasing wavelength $\lambda = 0.85$ μm, the effective index $n_{\mathrm{eff}}=3.0$, and the radius of the outer ring $R=7.5$ μm. At a higher injection current, 19 mA in Fig. 2(e), transverse patterns in forms of WGM as well as some strongly localized field patterns, which we believe is a dynamical localized resonance mode, become more and more clear.[14] Moreover in Fig. 2(f), we show the image with the same injection current but under the defocus condition. With the comparison in Figs. 2(e) and 2(f), clear two lasing modes are demonstrated in our experimental measurement. In Fig. 2(d) we illustrate the coexistence of WGM (blue color) and DLM (red color) obtained from directly numerical simulations in Fig. 3. At a critical current, 24 mA in our experiment, a unidirectional lasing emits at the mismatched boundary between the surface emitting window and the oxide-confined aperture, as shown in Fig. 2(g). By increasing the current to 30 mA, in Fig. 2(h) a clearly directional lasing mode is observed at room temperature.

To explain the wave nature and the interference effect in our optical resonator, we perform a two-dimensional mode solver based on the standard finite element method for electromagnetic waves to calculate the corresponding eigenmodes of this chaotic cavity.[15] The calculated eigenmode (a TE mode) for the wavelength at 853.252 nm is shown in Fig. 3(a), which is a whispering-gallery-like mode in the outer ring with the same number of lobes (18) in the azimuthal direction as the experimental data. Figure 3(b) shows the eigenmode at the wavelength of 853.327 nm, also with 18 lobes, resulting in a DLM with the bright spots located along the inner ring cavity, as shown in the experimental observation.

With the supported transverse eigenmodes, it can be clearly seen that the field distribution outside the outer ring is highly radically symmetric for the WGM in Fig. 3(a), while strongly directional for the DLM in Fig. 3(b). It is only the interference between these two modes that can contribute a unidirectional lasing in the right-hand side. In Figs. 3(c)–3(e), we numerically demonstrate the control of directional lasing by changing the relative phase, i.e., $\Delta\phi=\pi/2$, π, and 0, between the WGM and DLM. The overall field distributions outside the cavity can be strongly modified, resulting in a unidirectional lasing either in the left- or right-hand side. Moreover, the field distribution inside the cavity can also be tilted in the clockwise or counter-clockwise direction. Since in our designed surface structure the supported two modes have a strong overlap at the interface in the right-hand side, transverse locking of these two eigenmodes makes the total radiation pattern in a coherent superposition, i.e., $\Delta\phi=0$, as shown in Fig. 3(e). In Fig. 3(f) we report the observation of such an interference enhanced lasing mode when slightly moving the focus length of the near field microscope away from the surface emitting window. Symmetry-breaking radiation patterns are demonstrated for a hybrid WGM and DLM lasing at the injection current 7.5 mA.

In conclusion, we report a general way to control unidirectional lasing from VCSELs at room temperature with the assistance of a surface structure. Combined with the advantages of stable and unstable periodic orbits, we propose and demonstrate the idea to control directional lasing by changing the relative phase between the whispering-gallery and dynamic localized modes, which should provide a very important concept for wave formation in laser cavities, as well as for the electronic structure of atoms and the transport of electrons in resonant tunneling diodes.

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