Exploring the influence of boundary shapes on emission angular distributions and polarization states of broad-area vertical-cavity surface-emitting lasers

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Abstract: We design the stadium-shaped and rectangular vertical-cavity surface-emitting lasers (VCSELs) to investigate the influence of boundary shapes on the emission angular distributions and polarization states. For the stadium-shaped VCSELs, the emission angular distribution prefers to be almost omnidirectional because the lasing mode with purely scarred structure is seldom to be excited. On the contrary, the rectangular VCSELs usually generate dominant lasing modes with the morphology of quasi-periodic linear ridges, which can make emission angular distribution to be concentrated on the certain direction. From the polarization-resolved light-current curves, the stadium-shaped VCSEL is quite prone to exhibit numerous abrupt changes (kinks) associated with polarization switching with increasing current, whereas for rectangular VCSEL there is no conspicuous kink to be seen during a wide range of current changing from near to far above lasing threshold.

OCIS codes: (140.7260) Vertical cavity surface emitting lasers; (140.3945) Microcavities; (260.5430) Polarization.

References and links

1. V. S. Ilchenko, X. S. Yao, and L. Maleki, "Pigtailing the high-Q microsphere cavity: a simple fiber coupler for optical whispering-gallery modes," Opt. Lett. **24**(11), 723–725 (1999).
2. B. E. Little, S. T. Chu, W. Pan, and Y. Kokubun, "Microring resonator arrays for VLSI photonics," IEEE Photon. Technol. Lett. **12**(3), 323–325 (2000).
3. M. Cai, O. Painter, and K. J. Vahala, "Observation of critical coupling in a fiber taper to a silica-microsphere whispering-gallery mode system," Phys. Rev. Lett. **85**(1), 74–77 (2000).
4. E. Krioukov, D. J. W. Klunder, A. Driessen, J. Greve, and C. Otto, "Sensor based on an integrated optical microcavity," Opt. Lett. **27**(7), 512–514 (2002).
5. K. J. Vahala, "Optical microcavities," Nature **424**(6950), 839–846 (2003).
6. J. U. Nöckel and A. D. Stone, "Ray and wave chaos in asymmetric resonant optical cavities," Nature **385**(6611), 45–47 (1997).
7. J. Wiersig, "Hexagonal dielectric resonators and microcrystal lasers," Phys. Rev. A **67**(2), 023807 (2003).
8. S. V. Boriskina, T. M. Benson, P. D. Sewell, and A. I. Nosich, "Directional emission, increased free spectral range, and mode Q-factors in 2-D wavelength-scale optical microcavity structures," IEEE J. Sel. Top. Quantum Electron. **12**(6), 1175–1182 (2006).
9. J. U. Nöckel, A. D. Stone, and R. K. Chang, "Q spoiling and directionality in deformed ring cavities," Opt. Lett. **19**(21), 1693–1695 (1994).
10. C. Gmachl, F. Capasso, E. E. Narimanov, J. U. Nöckel, A. D. Stone, J. Faist, D. L. Sivco, and A. Y. Cho, "High-Power directional emission from microlasers with chaotic resonators," Science **280**(5369), 1556–1564 (1998).
11. N. B. Rex, H. E. Tureci, H. G. L. Schwefel, R. K. Chang, and A. D. Stone, "Fresnel filtering in lasing emission from scarred modes of wave-chaotic optical resonators," Phys. Rev. Lett. **88**(9), 094102 (2002).
12. Q. Chen, Y. H. Hu, Y. Z. Huang, Y. Du, and Z. C. Fan, "Equilateral-triangle resonator injection lasers with directional emission," IEEE J. Quantum Electron. **43**(6), 440–444 (2007).
13. M. Choi, S. Shinohara, and T. Harayama, "Dependence of far-field characteristics on the number of lasing modes in stadium-shaped InGaAsP microlasers," Opt. Express **16**(22), 17554–17559 (2008).
14. T. Harayama, T. Fukushima, S. Sunada, and K. S. Ikeda, "Asymmetric stationary lasing patterns in 2D symmetric microcavities," Phys. Rev. Lett. **91**(7), 073903 (2003).

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15. S. Sunada, T. Harayama, and K. S. Ikeda, "Multimode lasing in two-dimensional fully chaotic cavity lasers," Phys. Rev. E Stat. Nonlin. Soft Matter Phys. **71**(4), 046209 (2005).
16. K. F. Huang, Y. F. Chen, H. C. Lai, and Y. P. Lan, "Observation of the wave function of a quantum billiard from the transverse patterns of vertical cavity surface emitting lasers," Phys. Rev. Lett. **89**(22), 224102 (2002).
17. T. Gensty, K. Becker, I. Fischer, W. Elsäßer, C. Degen, P. Debernardi, and G. Bava, "Wave chaos in real-world vertical-cavity surface-emitting lasers," Phys. Rev. Lett. **94**(23), 233901 (2005).
18. C. C. Chen, K. W. Su, Y. F. Chen, and K. F. Huang, "Various high-order modes in vertical-cavity surface-emitting lasers with equilateral triangular lateral confinement," Opt. Lett. **33**(5), 509–511 (2008).
19. M. P. van Exter, M. B. Willemsen, and J. P. Woerdman, "Polarization fluctuations in vertical-cavity semiconductor lasers," Phys. Rev. A **58**(5), 4191–4205 (1998).
20. K. Panajotov, B. Ryvkin, J. Danckaert, M. Peeters, H. Thienpont, and I. Veretennicoff, "Polarization switching in VCSEL's due to thermal lensing," IEEE Photon. Technol. Lett. **10**(1), 6–8 (1998).
21. L. Olejniczak, K. Panajotov, H. Thienpont, M. Sciamanna, A. Mutig, F. Hopfer, and D. Bimberg, "Polarization switching and polarization mode hopping in quantum dot vertical-cavity surface-emitting lasers," Opt. Express **19**(3), 2476–2484 (2011).
22. Y. Hong, P. S. Spencer, and K. A. Shore, "Suppression of polarization switching in vertical-cavity surface-emitting lasers by use of optical feedback," Opt. Lett. **29**(18), 2151–2153 (2004).
23. M. Arizaleta Arteaga, O. Parriaux, M. López-Amo, H. Thienpont, and K. Panajotov, "Polarized optical feedback from an extremely short external cavity for controlling and stabilizing the polarization of vertical cavity surface emitting lasers," Appl. Phys. Lett. **90**(12), 121104 (2007).
24. W. Wang, Y. Q. Ning, J. L. Zhang, L. Qin, Y. G. Zeng, Y. Liu, C. Z. Tong, and L. J. Wang, "Power and spectra polarization of large-aperture rectangular-shaped vertical-cavity top-emitting lasers," Laser Phys. **22**(3), 554–558 (2012).
25. M. P. Tan, A. M. Kasten, T. A. Strand, and K. D. Choquette, "Polarization switching in vertical-cavity surface-emitting lasers with anisotropic cavity geometry and injection," IEEE Photon. Technol. Lett. **24**(9), 745–747 (2012).
26. E. J. Heller, "Bound-state eigenfunctions of classically chaotic Hamiltonian systems: scars of periodic orbits," Phys. Rev. Lett. **53**(16), 1515–1518 (1984).
27. Y. T. Yu, P. H. Tuan, P. Y. Chiang, H. C. Liang, K. F. Huang, and Y. F. Chen, "Wave pattern and weak localization of chaotic versus scarred modes in stadium-shaped surface-emitting lasers," Phys. Rev. E Stat. Nonlin. Soft Matter Phys. **84**(5), 056201 (2011).
28. S. P. Hegarty, G. Huyet, J. G. McInerney, and K. D. Choquette, "Pattern formation in the transverse section of a laser with a large Fresnel number," Phys. Rev. Lett. **82**(7), 1434–1437 (1999).
29. P. O'Connor, J. Gehlen, and E. J. Heller, "Properties of random superpositions of plane waves," Phys. Rev. Lett. **58**(13), 1296–1299 (1987).

1. Introduction

Optical microcavities have been identified as attractive light sources because the generation of high-Q light emission has great potential applications in optoelectronic circuits, optical storage, and biological sensors [1–5]. Since changing cavity shape can drastically affect optical confinement of light, understanding the influence of cavity shapes on resonant mode behaviors has long been a significant issue [6–8]. From the viewpoint of practical use, it is important to generate excited modes with high emission directionality [8–12]. However, the emission angular distribution of microdisk lasers is difficult to be straightforwardly measured due to the property of the lateral radiation [13–15].

Unlike microdisk lasers, vertical-cavity surface-emitting lasers (VCSELs) have a dominant longitudinal wave vector k_z that is not only single-valued but also significantly greater than the transverse wave number. As a consequence, the relationship between the near-field spatial patterns and far-field angular distribution can be directly explored with simple optics. More advantageously, since the lateral oxide confinement of VCSELs can act as an excellently reflective boundary, the broad-area devices have been successfully employed to demonstrate the phenomena of quantum chaos [16–18]. The nice demonstration indicates that the oxide-confined broad-area VCSELs are practically convenient to be exploited to explore the influence of the boundary shape on the emission angular distribution. Furthermore, it is highly desirable to investigate the influence of the boundary shape on the polarization characteristics, since the control of the polarization state is useful for numerous applications with VCSELs [19–25].

In this works, we develop the stadium-shaped and rectangular-shaped broad-area VCSELs to explore the boundary effect on the emission angular distributions and polarization states. The transverse orders of lasing modes are widely varied with the cryogenic cooling to achieve the detuning $\Delta\omega = \omega_g - \omega_c$, where ω_g is the central frequency of the gain profile and ω_c is the frequency of the fundamental mode. For the stadium-shaped VCSELs, the emission angular distribution is experimentally found to be nearly omnidirectional. Notably, the so-called purely scarred modes [26] related to the unstable periodic orbit in ray optics are seldom observed. On the other hand, the near-field patterns of lasing modes in the rectangular-shaped VCSELs display the morphology of quasi-periodic linear ridges that leads to the emission angular distribution to be concentrated on the direction parallel to the long sides of the device shape. We believed that the results can provide a valuable prospect in designing a microcavity laser with directional emissions. Moreover, it is also found that the polarization characteristics of the VCSELs are strongly dependent on the boundary shape. The stadium-shaped VCSELs tend to exhibit numerous abrupt changes associated with polarization switching in the polarization-resolved light-current (L-I) curves, whereas the polarization instability is experimentally confirmed to be rather weak in the rectangular-shaped VCSELs.

2. Experimental setup

Figure 1 illustrates the schematic diagram of the VCSEL devices and the experimental setup. The aperture size for the rectangular VCSEL is about 47 × 22 μm^2. For stadium-shaped VCSELs, it has been confirmed that the aperture size plays a key role for the mode selection between chaotic and scarred modes [27]. Here we fabricated stadium-shaped VCSELs with aperture sizes of 45 × 22 μm^2 and 60 × 30 μm^2 to perform investigations. The device structures of the oxide-confined VCSELs were similar to those described in [28]. The emission wavelengths of the VCSELs were approximately 780 nm. The VCSEL devices were placed in a cryogenic system with a temperature stability of 0.1K in the range of 200-300 K. A power supply providing current with a precision of 0.01 mA was utilized to drive the VCSELs. The laser output is collimated by an objective lens (Mitutoyo, numerical aperture 0.9) and is divided into two parts of lights with equal intensities by beam splitter (BS). One part of light is coupled into a charge-coupled device (CCD) camera (Coherent, Beam-Code) to measure near-field patterns. Using a lens to perform spatial Fourier transform, the far-field patterns can also be reimaged onto a CCD camera. The other part of light is split into two orthogonal polarized lights by passing through a polarization beam splitter (PBS) for further measurement. The light beam was identified as x-polarization (y-polarization) whose direction of polarization is along horizontal-axis (vertical-axis) of the device.

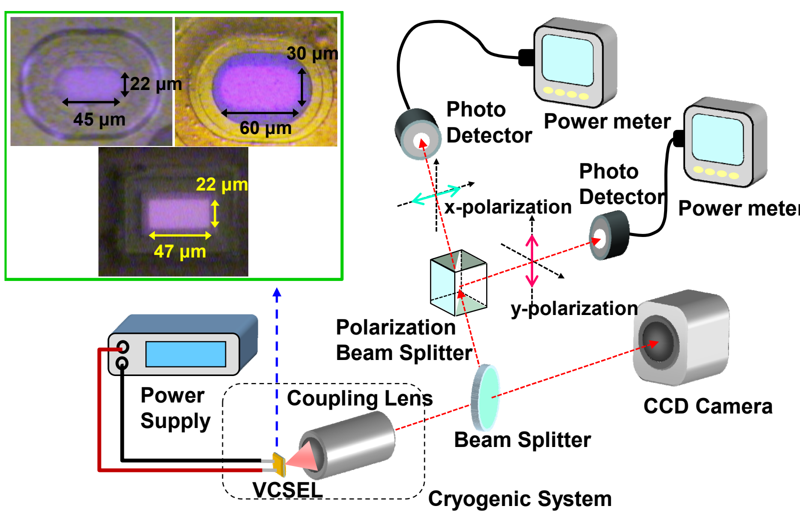

Fig. 1. Schematic diagram of the VCSEL devices and the experimental setup.

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3. Far-field characters of the lasing modes at threshold current

Figures 2(a)-2(d) depict the experimental near- and far-field patterns at lasing threshold for the stadium-shaped VCSEL with area of 45 × 22 μm^2 when the operating temperatures are held at 295 K, 250 K, 230 K, and 200 K. Their emission angular distributions are plot in Figs. 2(a')-2(d') in order to quantitatively realize the emission directionality of the lasing modes. At the operating temperature of 295 K, the lasing mode behaves like a chaotic wave that can be described by a random superposition of plane waves [29]. It can be seen in Fig. 2(a') that its far-field emission is extended over all angles and is lack of directionality. When the operating temperature was decreased to below 250 K, the lasing modes are whispering gallery modes (WGMs) with some irregular structures inside the interior region. In comparison with fully chaotic waves, such modes have larger portion of light emissions distributed in the regime of $0^o \le \theta \le 25^o$, $60^o \le \theta \le 120^o$, and $150^o \le \theta \le 180^o$, as shown in Figs. 2(b')-2(d'). However, these far-field patterns also do not present pronounced directional emissions.

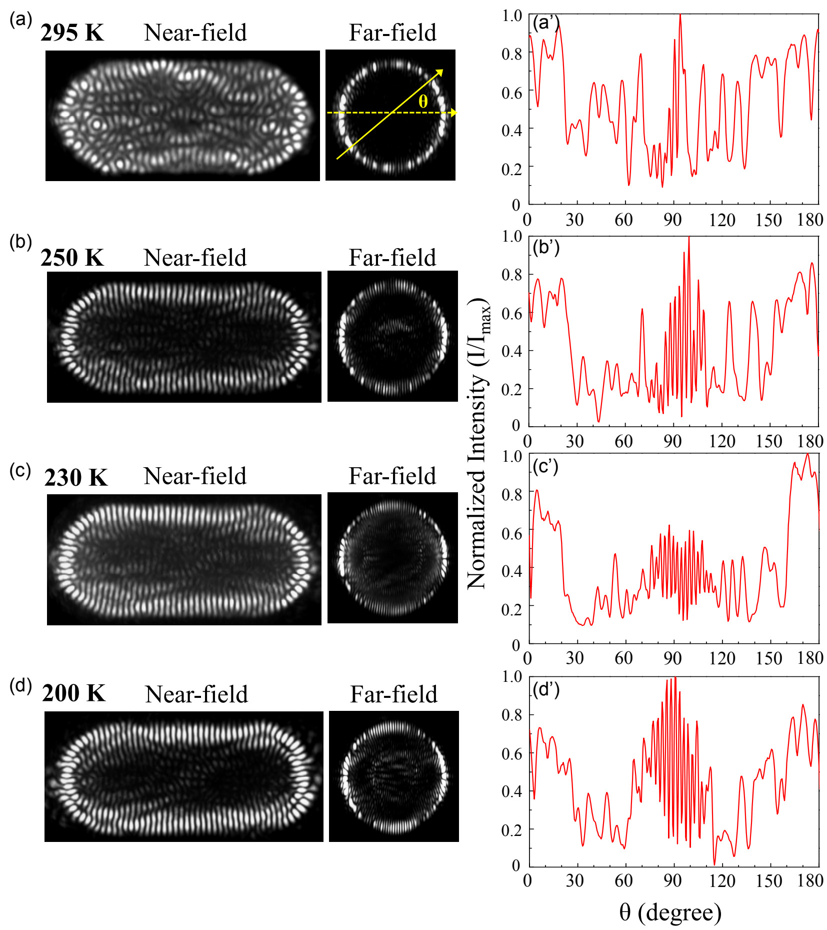

Fig. 2. Experimental near- and far-field patterns for the stadium-shaped VCSEL with area of 45 × 22 μm^2 at the operating temperature of (a) 295 K, (b) 250 K, (c) 230 K, and (d) 200 K. The emission angular distributions (a')-(d') correspond to (a)-(d), respectively.

Figure 3 illustrates the experimental results for the stadium-shaped VCSEL with larger area of 60 × 30 μm^2 at different operating temperature. It can be seen that the near-field patterns are mainly composed of two wave structures with WGMs and the scars. At the operating temperature of 290K, the scarred structure of the lasing mode exhibits the diamond

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orbit. When the operating temperature was decreased to below 260 K, the scarred structure will change to the double diamond orbit. From the emission angular distributions shown in Figs. 3(a')-3(d'), even scarred modes are spatially localized on definite geometric ray orbits, these lasing modes are found still not to exhibit remarkable directional emissions. This observation is attributed to the fact that the lasing mode is not purely scarred mode but is composed of more than one wave structures, causing the far-field emission not to be noticeably concentrated in any particular directions.

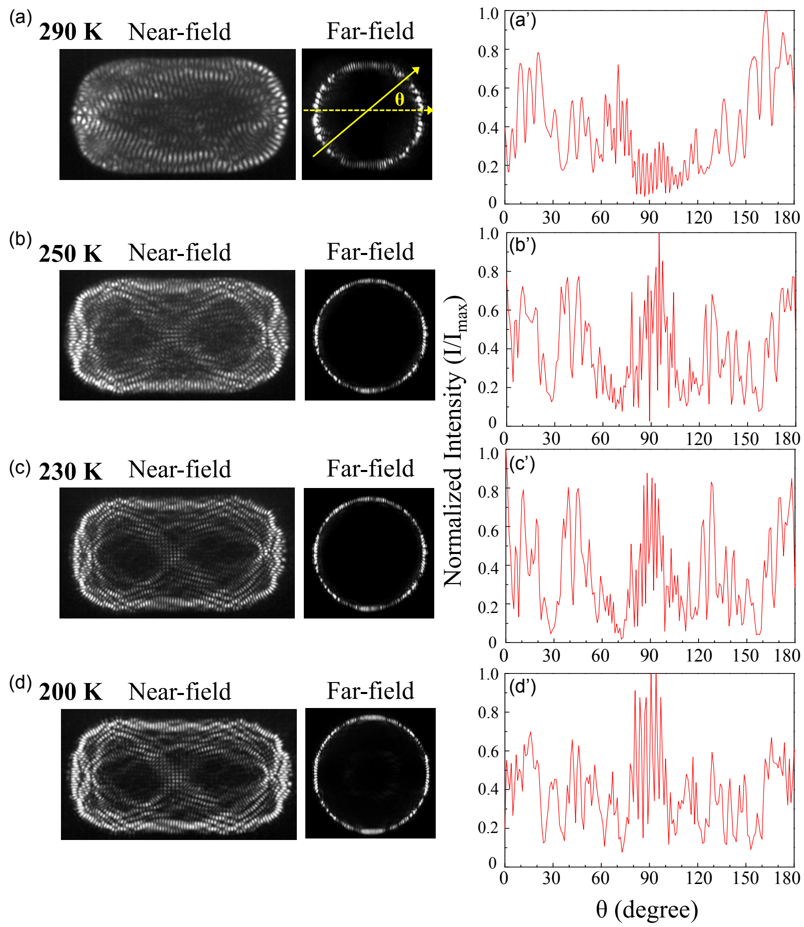

Fig. 3. Experimental near- and far-field patterns for the stadium-shaped VCSEL with area of 60 × 30 μm^2 at the operating temperature of (a) 290 K, (b) 250 K, (c) 230 K, and (d) 200 K. The emission angular distributions (a')-(d') correspond to (a)-(d), respectively.

We then explore the lasing patterns and the corresponding emission properties for the rectangular VCSEL, as depicted in Fig. 4. The lasing patterns present the morphology of quasi-periodic linear ridges from low to high transverse orders when the operating temperature was changed from 295 K to 200 K. As can be seen in the far-field patterns, such type of the lasing modes are superimposed by a number of transverse modes with $k_x \gg k_y$. The results of emission angular distributions illustrated in Figs. 4(a')-4(d') reveal that the emissions of these modes are mainly concentrated in the narrow regime of the directions around 15^o and 165^o. That is, directional emissions are clearly attained. It should be emphasized that based on the experimental results of numerous samples, the rectangular VCSELs are quite feasible to present high directionality in far-field emissions because they

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usually generate the lasing modes with structures of quasi-periodic linear ridges or other superscarred structures.

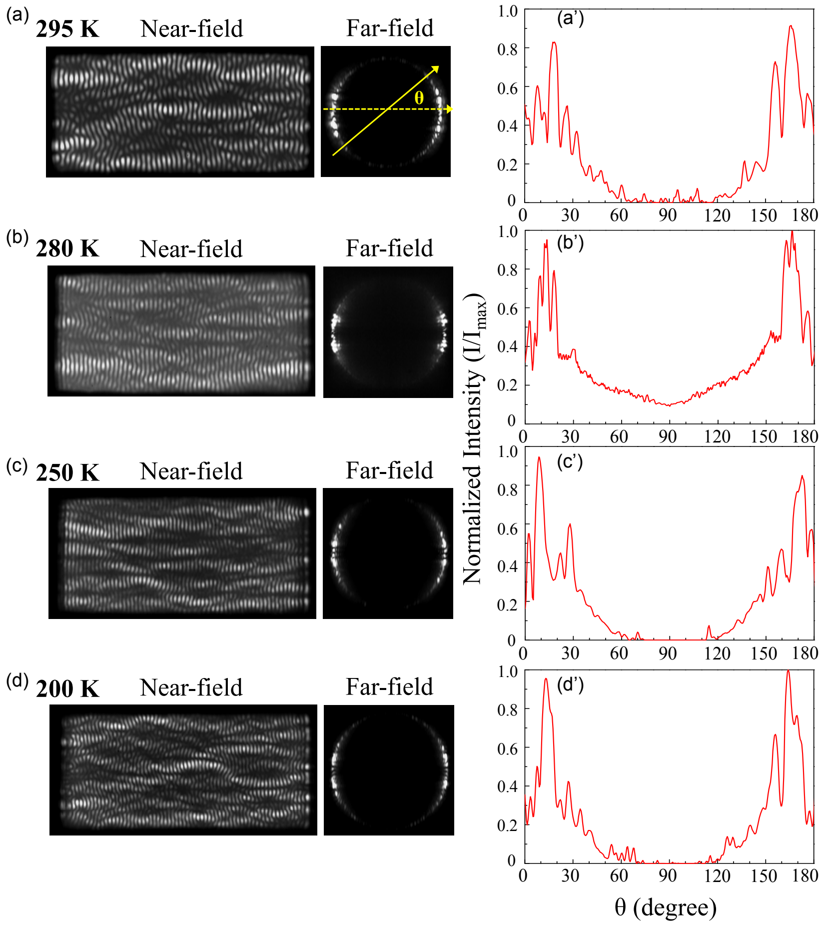

Fig. 4. Experimental near- and far-field patterns for the rectangular VCSEL at the operating temperature of (a) 295 K, (b) 280 K, (c) 250 K, and (d) 200 K. The angle-resolved far-field distributions (a')-(d') correspond to (a)-(d), respectively.

4. Characters of light emissions in the two orthogonal polarizations

VCSELs have the striking feature of polarization instability that arises from the competition between two orthogonally polarized modes. When the mode competition takes place, light emissions of VCSELs present an abrupt change (kink) in the light-current curves (L-I curves) of the two orthogonal polarizations, which is the so-called polarization switching. The suddenly power degradation in a certain polarized mode would limit the practical applications of VCSELs. It has long been an important task to study how to control or to prevent polarization switching [22–25]. Introducing cavity anisotropy has often been used to obtain the lasing modes that can retain stable linear polarization state [24, 25]. The stadium-shaped and rectangular VCSELs are such typed devices. However, for our cases, the aperture sizes of the VCSELs are so large that the generation of multiple high order transverse modes would notable affect behaviors of light emission. It is thus interesting to explore the emission properties for the two VCSELs.

Figure 5 shows the L-I curves and the lasing patterns in x- and y-polarizations at different operating temperature for the stadium-shaped VCSEL with area of 45 × 22 μm^2. At both

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cases, the VCSEL starts to lase the y-polarized modes at the threshold current and the x-polarized modes will subsequently be excited with the current slightly larger than the threshold value. When the injected current increases, numerous kinks can be seen in the slopes of the polarization resolved L-I curves. The observation indicates that the two orthogonal polarized modes undergo keen competition with varying injected current. Light emission in each polarization thus becomes very unstable. When the injected current further increases to approaches to the thermal rollover current, x-polarized modes will then dominate the output power emission and light emission in y-polarization gradually degrades to saturate. This can be explained as follows. At both temperatures, the transverse orders of lasing modes in y-polarization are obviously higher than the modes in x-polarization. As the injected current is well above threshold, due to thermal lensing effect, high-order modes will experience larger loss than high-order modes. Consequently, the saturation phenomena for y-polarized modes take place.

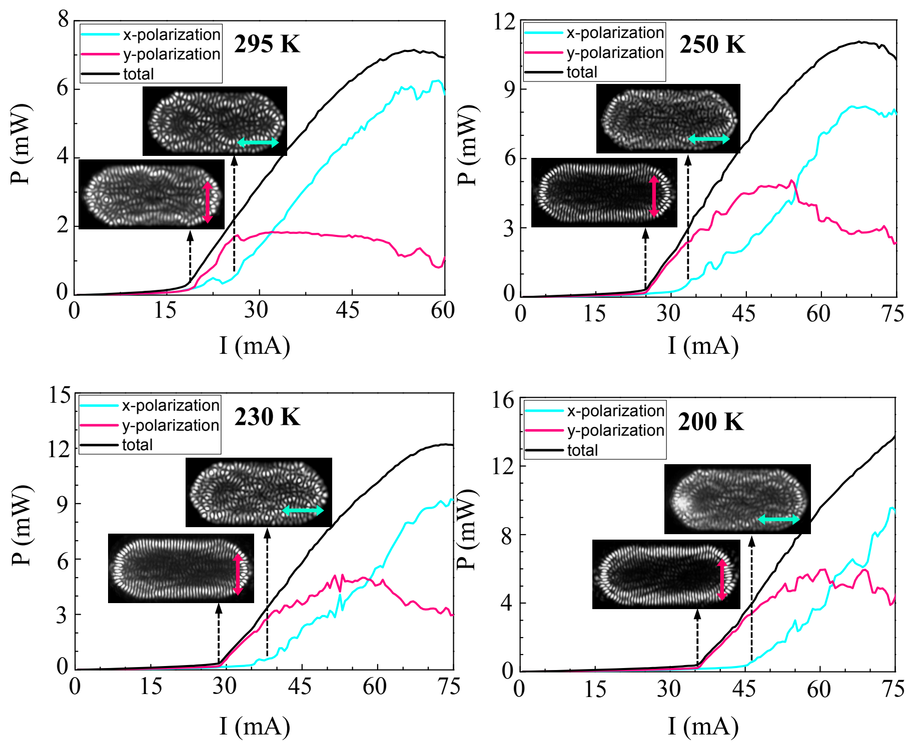

Fig. 5. The polarization resolved L-I curves for the stadium-shaped VCSEL with area of 45 × 22 μm^2 at the operating temperature of 295 K, 250 K, 230 K, and 200 K.

Figure 6 depicts the experimental results for the rectangular VCSEL. For both temperature treatments, the lasing modes are in y-polarization component at the threshold current. However, in contrast to the stadium-shaped VCSEL, x-polarized modes cannot exhibit pronounced light emission until the injected current increases to very high value, as the black circle labeled in Fig. 6. More importantly, during the current regime in which x-polarized modes have low emitted power, light emissions can increase monotonically without conspicuous kinks. Such current range will become wider with decreasing operating temperature. The kinks can only be shown when the injected current is so high that thermal effect would be considerable to affect the gain competition between the two orthogonally polarized modes. In other words, the rectangular VCSELs are more suitable to achieve light emissions without polarization switching rather than the stadium-shaped VCSELs. This

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finding also provides the meaningful evidence that cavity shape is important for affecting the tendency of polarization switching of the dominant lasing mode for broad-area VCSELs.

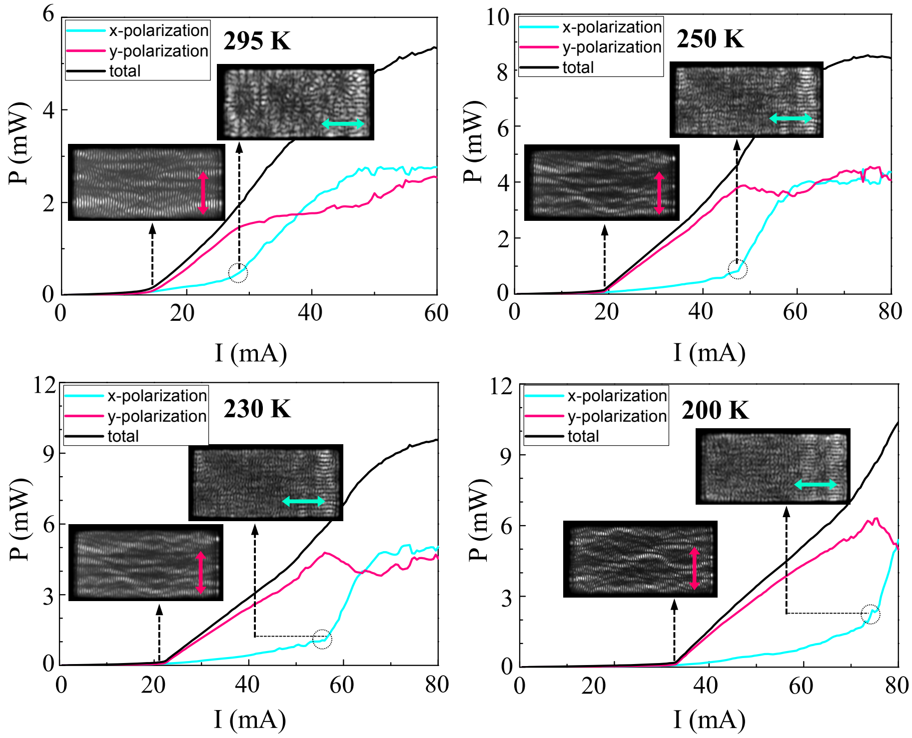

Fig. 6. The polarization resolved L-I curves for the rectangular VCSEL at the operating temperature of 295 K, 250 K, 230 K, and 200 K.

4. Conclusion

We have studied the boundary effect on the emission angular distributions and polarization states for the stadium-shaped and the rectangular VCSELs under cryogenic cooling operation. For the stadium-shaped VCSELs, since the lasing mode with purely scarred structure is rare to be generated, the emission angular distributions are usually lack of directionality. In contrast, the rectangular VCSEL is prone to excite the lasing modes with the morphology of quasi-periodic linear ridges that can obviously present highly directional emissions in the far-fields. Furthermore, polarization properties for the two types of VCSELs have also been found to be quite distinct. The stadium-shaped VCSEL has been found to exhibit numerous abrupt changes (kinks) associated with polarization switching in the polarization-resolved L-I curves. In the case of the rectangular VCSEL, light emission in the two orthogonal polarizations can increase monotonically without conspicuous kinks in the wide range of current changing from near to far above lasing threshold. In other words, the rectangular VCSELs are feasible to generate light emissions without polarization switching.

Acknowledgments

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