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TOPICAL REVIEW — Nanolasers

Semiconductor photonic crystal laser*

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By combing artificial micro–nano structures, photonic crystals (PCs), with traditional semiconductor laser material to realize the dynamic collaborative control of photonic states and confined electrons, the band engineering of the PC has been confirmed. This brings new development space for the semiconductor laser, such as for low threshold and high efficiency. Based on a series of works by Zheng's group, this paper has reviewed kinds of PC lasers including electrical injection PC vertical cavity and lateral cavity surface-emitting lasers, and PC high beam quality lasers, to show that the PC is vital for promoting the continuous improvement of semiconductor laser performance at present and in the future.

Keywords: semiconductor laser, photonic crystal, complex cavity

PACS: 42.55.Px, 42.70.Qs, 42.60.Fc **DOI:** 10.1088/1674-1056/27/11/114211

1. Introduction

The invention and development of lasers have changed human production, life, and science and technology. Over the past 40 years, lasers from gas lasers to solid and liquid laser to semiconductor lasers have been continuously researched by scientists in regards to working materials, laser cavities, and pumping mode. impelling the rapid development of laser. Different types of lasers play important roles in different fields. In particular, semiconductor lasers are widely used in the fields of optical communications, optical computing, optical storage, display, and pumping sources because of their miniature size and good cost performance.

The photonic crystal (PC) belongs to a kind of functional material with artificial micro–nano structures. Based on a periodic or quasi-periodic distribution of dielectric permittivities, the PC provides new material systems and physical principles for people to manipulate light. The concept of the PC was formulated independently by Yablonovitch[1] and John.[2] Since then, photonic bandgap material has greatly drawn people's attention because of its special dispersion. When the period of the dielectric material is wavelength-scale, the theory has a formal analogy to the quantum mechanics of electrons in crystals, thus making the dispersion characteristics of the PC display a band structure. Between these bands, there possibly exists a photonic bandgap in analogy to the semiconductor bandgap in solid-state physics, within which the transmission of light is strictly inhibited. However, at the band edge, modes usually have a large-area resonance.[3] PCs can be fabricated as waveguides or microcavities by introducing line or point defects[4] to open up bandgaps and produce defect states. By very flexible design for photonic band engineering, various integrated photonic devices have emerged in the past decade.

Through the combination of PCs with traditional semiconductor laser materials to realize dynamic collaborative control of photonic states and confined electrons, the semiconductor PC laser was born. In 1999, Painter *et al.* developed the first PC laser.[5] The dipole mode of a triangular lattice defect cavity was employed to realize a 1.55 μm PC microcavity laser at room temperature. By using the coupling between the microcavity and line defect waveguide, PC edge-emitting lasers can be obtained. In 2004, Sugitatsu *et al.*[6] achieved an edge-emitting laser by the slow-light effect of the PC waveguide band edge. In 2008, Watanabe and Baba[7] reported an edge-emitting laser through the coupling between a PC microcavity with high Q and a defect waveguide. Based on a lateral p–n junction realized by ion implantation and thermal diffusion, in 2013 Takeda *et al.* developed current-driven lambda-scale embedded active region PC lasers, with a low energy consumption of 4.4 fJ·bit^{-1} at a bit rate of 10 Gb·s^{-1} and a detectable output power of 2.17 μW.[8] In recent years, Zheng's group has also proposed a series of PC lasers, e.g. electrical injection PC vertical cavity and lateral cavity surface-emitting lasers, PC high beam quality lasers, etc. to improve the performance of the semiconductor laser. In this paper, the relative progresses are reviewed.

2. Optically pumped PC surface-emitting laser

Early in 1946, Purcell[9] discussed the modulation effect of the microcavity on the coupling between the electromag-

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netic field and materials. The spontaneous emission is enhanced in the cavity with the size of wavelength; this is called the Purcell effect. The Purcell factor is proportional to the quality factor (Q) of the microcavity and inversely proportional to the mode volume (V). Because of the reduction of V, the number of modes supported by the microcavity is decreased, resulting in an increase in the spontaneous emission coupling coefficient, even up to 1.[10] It is beneficial to achieve a laser with an ultra-low threshold. Vertical cavity surface emitting laser (VCSEL) is designed to be the first type of laser that compresses the size of the optical mode to the scale of the optical wavelength and maintains a low loss.[11] The microdisk laser also has an optical microcavity with a high Q and a small V of the cubic wavelength.[12] By utilizing the band gap property of the PC, a higher Q and a smaller V can be obtained. For example, three-dimensional (3D) PCs completely restrict light in three dimensions of space. Theoretically, the defect structure of this type can be used to achieve thresholdless lasers.[13,14] The 3D PC is difficult to fabricate, but based on a relatively simple 2D PC, a variety of active and passive devices already show application potentials in the field of photonic integration, which is one of the research hotspots at present. The microcavity laser based on a 2D PC slab has the advantages of high Q and small V, and can also be finely tuned the laser wavelength by slightly changing the geometry of the lasers; thus, it has important applications in on-chip integrated light sources.[15–18]

To obtain the single mode and high Q, Zheng *et al.*[19] deformed the overall lattice of the H1 cavity (see Fig. 1(a)), resulting in the symmetry change of the triangular lattice and the separation of the degenerate dipole mode into x- and y-pole modes. The average pump power threshold was approximately 1.6 μW, and the peak wavelength was about 1540 nm, i.e. the y-pole mode, which had a polarization ratio as high as 51:1. Zheng *et al.*[20] also studied the 2D PC slab laser with an H3 cavity. In the perfect PC structure, 19 airholes near the center were removed, forming the H3 defect cavity (see Fig. 1(b)). Under the mean pumping power of 90 μW, the laser with the peak wavelength of 1500 nm was obtained. The side mode suppression ratio (SMSR) reached 13.8 dB, and the mean threshold pumping power was about 51.7 μW. As shown in Fig. 1(c), the triangular cavity was achieved by removing three adjacent airholes at the center. The single longitudinal mode lasing was realized at room temperature, with the laser wavelength and the corresponding line width of 1454.4 nm and 0.6 nm, respectively. The average pump power threshold was 3.5 μW.

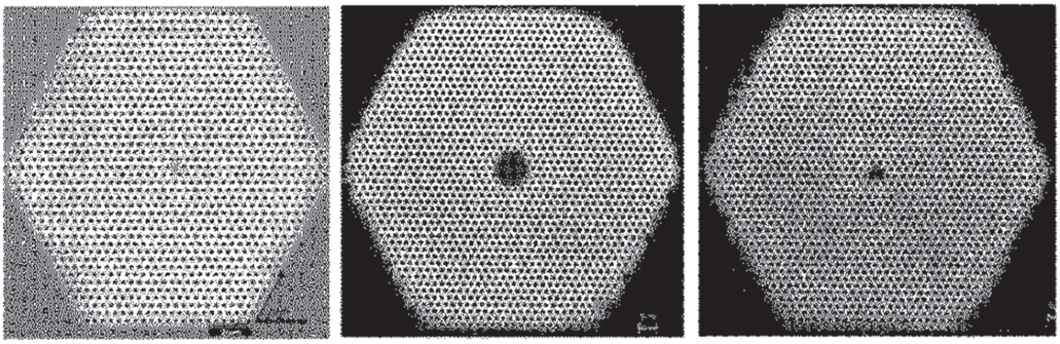


Fig. 1. (a) PC H1 cavity laser (tensile lattice along the vertical direction),[19] (b) PC H3 cavity laser,[20] and (c) PC triangular cavity laser.

3. Optically pumped PC edge-emitting laser

The PC laser may serve as an effective light source in photonic integration, of which the edge-emitting type can be easily integrated with other coplanar photonic devices. There are two ways to achieve an edge-emitting PC laser. One is to use the low group velocity of guided wave modes at high symmetry points of the active PC waveguide[6,21,22] to achieve slow light resonance and lasing. The other way is using the coupling of a high-Q microcavity with a waveguide to couple out the microcavity mode. The high-Q cavity can be directly obtained from the point defect microcavity[23–25] and also be made by introducing a heterojunction structure in the waveguide.[26–28]

So far, people have proposed various kinds of PC laser structures at a single wavelength, whereas multiwavelength lasers are only limited to the structure of the array.[29,30] Zheng *et al.*[31,32] realized multiwavelength lasing based on one PC laser (see Fig. 2(a)). The slow light line defect waveguide structure was adopted to minimize the whole size to tens of micrometers. As shown in Fig. 2(b), one of the waveguide ends was sealed with a complete PC lattice structure, whereas the middle structure was the tunable part, in which the radii of the nearest neighbor airholes were reduced from left to right. Therefore, the band varied with the position of the waveguide, and so did the slow light frequency. However, the radii remained unchanged in the output waveguide after the tuning structure. In the experiment, when different positions were pumped (see Fig. 2(a)), five laser peaks were obtained, which are shown in Fig. 2(c). The tuning range reached 57 nm.

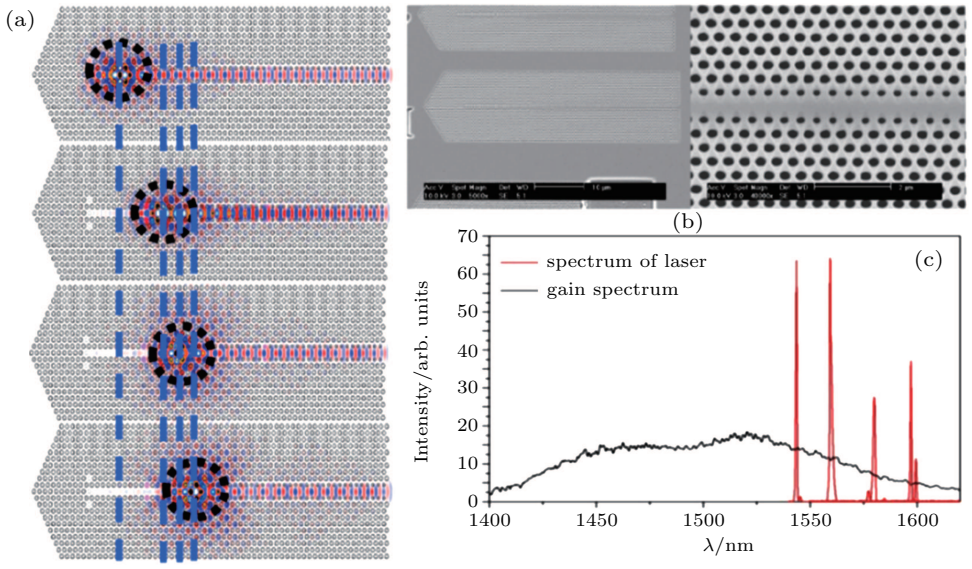


Fig. 2. (color online) (a) Steady magnetic field distribution in the PC waveguide for lights with different frequencies at different pumping positions. (b) SEM images of the whole tunable edge-emitting microlaser and only the tunable part. (c) Lasing spectrum of the tunable edge-emitting microlaser. The broad line shows the gain spectrum of the material.[31,32]

4. Electric injection PC-VCSELs

VCSELs are demanded for several applications, including optical communication, localization sensing, high-speed laser printing, display, and novel cesium atomic clocks. To achieve single-mode high-power VCSELs with small divergence angles, many structures have been proposed based on the principle of separated confinement, and significant progress has been made. Due to the out-of-plane band, a PC can be used to control the guide mode of the PC fiber[33] and to realize an "endless" single mode. This feature sets a theoretical basis for the control of the transverse mode of VCSELs. By introducing longitudinal waveguide structures similar to the PC fiber into the top distributed Bragg reflection (DBR) of oxide-confined VCSEL to select the mode and modulate its field distribution, people have opened up a new research field: PC-VCSEL.[34,35]

In 2008, Zheng *et al.* proposed the point defect PC-VCSEL (see Fig. 3(a)), and obtained a single-mode operation at all currents, with an SMSR over 30 dB.[36] The smallest measured divergence angle was only 5.1°. Zheng *et al.* continually studied two different ring defect PC-VCSELs, i.e. structures A and B (see Fig.s 3(b) and 3(c)). Structure A was formed by removing the six nearest neighbor airholes while keeping the central airhole, thus constructing one ring defect as the optical aperture;[37] structure B was constructed by removing a round of the next nearest neighbor airholes around the central point defect to form a point/ring defects composite optical aperture.[38] Compared with the point defect PC-VCSEL, the continuous wave (CW) output power of device A was greatly improved to as high as 4.6 mW. When the current was less than 15 mA, only the out-of-phase mode was lasing. In the case of a current higher than 15 mA, an in-phase mode became lasing at a shorter wavelength. The far-field pattern (FFP) was quasi-Gaussian, and the divergence angle was approximately 7.2°. The maximum output power of device B was 4.3 mW, and the differential resistance was only 32 Ω. There were at most three modes over the entire operating current range, including the in-phase supermode with the shortest wavelength and the out-of-phase supermode with the longest wavelength. The measured FFP had an approximate Gaussian distribution at a current of 33 mA with a divergence angle of only 5.4°. Zheng *et al.*[39,40] also proposed a single-mode-integrated microlens VCSEL based on a petal-shaped holey structure (see Fig. 3(d)), not only with high power and a low divergence angle but also with a simple fabrication without second epitaxy. The maximum output power reached 7.9 mW, and the SMSR exceeded 30 dB. The average divergence angles remained in the range of 3.2°–3.6° throughout the drive current range.

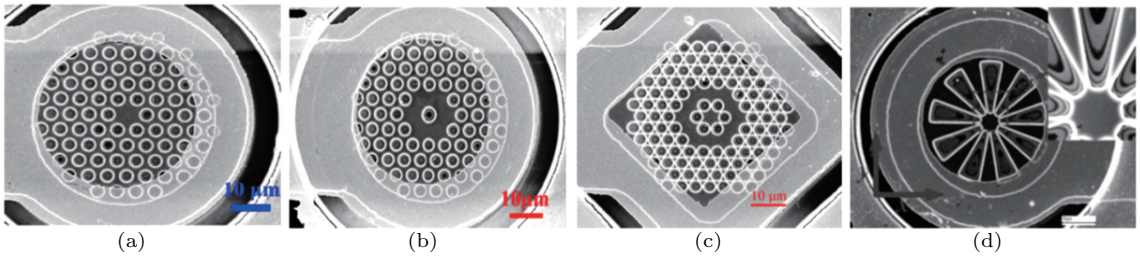


Fig. 3. (a) Point defect PC-VCSEL.[36] (b) Ring defect PC-VCSEL A.[37] (c) Ring defect PC-VCSEL B.[38] (d) Petal-shaped holey VCSEL.[39,40]

5. Electric injection lateral cavity PC surface-emitting laser

The band edge surface-emitting laser has a symmetrical beam spot, small divergence angle, single-mode function, and so on, which can be used in optical communication, distance measurement, optical tweezers, surgery, printing, mouse, optical storage, etc. Noda's group has done a lot of groundbreaking work in this field. In 1999, they realized the first room temperature electric injection PC edge-emitting laser.[41] In 2001 by adjusting the unit cell structure of a 2D PC and achieved polarization control.[42] In 2006, various beam shapes (circular, ring, petaloid, etc.) were obtained at small divergence angles.[43] In 2015, the output direction of the beam was successfully controlled.[44] In 2014, the CW output power over 1 W, divergence angle smaller than 1°, SMSR larger than 60 dB, and beam spot close to the Gaussian distribution were simultaneously realized, broadening the application of surface-emitting lasers into materials processing, laser medicine, and nonlinear optics.[45] By breaking the C2 symmetry with triangular air holes to allow some radiation into the normal direction, the lasing mode was not a strict symmetry-protected bound state in the continuum (BIC) at the Γ point, but a quasi-BIC.[46]

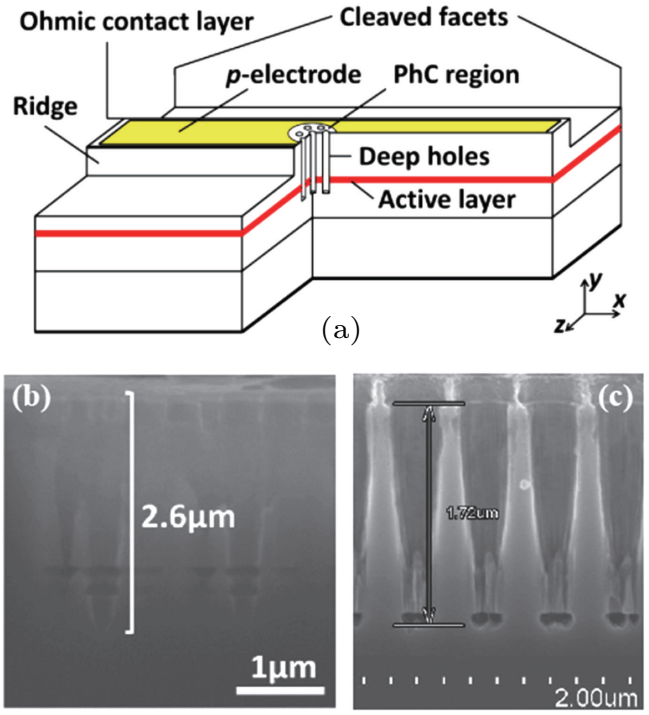


Fig. 4. (color online) (a) Schematic structure of the lateral cavity (LC)-PCSEL. (b) and (c) SEM images of PC air holes for the first type and the second type, respectively.[47,48]

Since 2008, Zheng *et al.* have studied PCSELs based on commercial epitaxial wafers without DBRs and wafer bonding (see Fig. 4(a)), providing potential values for the mass production of electric injection PCSELs. The defined PC area was much less than that of Noda's PC laser, which had a diameter of 490 μm, and thus the exposure time was shortened. Two types of PCSELs were designed: one with cylinder air holes etched through the active layer with a depth of 2.6 μm (see Fig. 4(b))[47] and the other with cone-like air holes etched near the active layer with a depth of 1.7 μm (see Fig. 4(c)).[48] The PC area of the former was 50 μm×50 μm, and that of the latter was 12 μm× 20 μm. The PC area was so small that not enough horizontal feedback of the mode could lead to lasing. Consequently, the FP cavity was used as the LC to provide sufficient lateral Γ2-1 feedback as well as a large area for the current injection. For the second type of LC-PCSELs, highly reflective coating was introduced on the cleaved facets of the FP cavity.

The measured threshold current of the first type was 400 mA; thus, the threshold current density was estimated to be approximately 667 A/cm^2, which was ultralow compared with other groups' results.[42,49] The center wavelength and the full width at half maximum (FWHM) of the surface-emitting mode Γ2-1 were 1553.8 nm and 0.4 nm, respectively. The Q factor was 3884 according to $\lambda/\Delta\lambda$, and the SMSR was 10 dB. The mechanism of the PC directly modulating the active layer not only inhibited spontaneous radiation of photons with nonresonant frequency and increased the inner quantum efficiency but also turned the multiple longitudinal modes in the traditional Fabry–Perot cavity into the Γ2-1 resonant mode, which output vertically. The divergence angle was 5.5° in the lateral direction and 7.5° in the longitudinal direction. For the second type, the threshold current was 200 mA, half of that of the first type due to the highly reflective coating of FP cavity facets. If the injected current was increased to 480 mA, the laser power reached 1.8 mW, much larger than that of the first type. Under a current of 400 mA, the measured center wavelength and FWHM of the surface-emitting mode Γ2-1 were 1575 nm and 0.1 nm, respectively. The Q factor was as high as 15750, and the SMSR reached 29 dB. The divergence angle was 10.7° in the lateral direction and 4.5° in the longitudinal direction. For the LC-PCSEL of the second type, the air holes were etched artificially with a cone-like shape for two reasons: one was that the effective refractive index of PC changed gradually from bottom to top, forming the index microlens effect beneficial to a decrease in divergence angle; the other was that it helped reduce the FP-like effect when the light in the compound cavity transmitted along the vertical direction, and thus increased the output efficiency.

In 2016, based on the platform of LCSEL, Zheng *et al.* designed a lateral cavity leaky coupling PC array surface-emitting laser (see Fig. 5(a)).[50] A pulsed power of 2.3 mW and CW power of 0.5 mW at 1545 nm, SMSR of 26 dB, FWHM of 0.12 nm, and small divergence angle less than 4.8° were obtained. In 2017, a lateral cavity random PC surface-emitting laser with random apertures under electric injection at room temperature was realized (see Fig. 5(b)).[51] The introduction of a stochastic structure reduced the lasing threshold, and the multiple scattering processes led to different local

states and extended states, and eventually a wide output spectrum. This means of reducing laser coherency in the frequency domain has contributed to the development of directly speckle-eliminated technology for semiconductor laser displays.

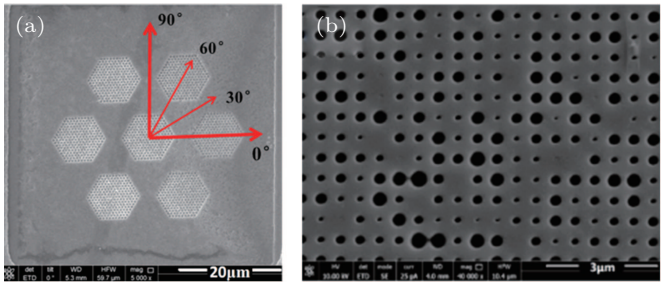


Fig. 5. (color online) SEM images of (a) a leaky coupling PC array[50] and (b) a random PC.[51]

6. PC lasers with high beam quality

Recently, edge-emitting laser diodes with high power and low divergence have been widely applied, such as in optical storage, laser display, and erbium-doped fiber amplifiers. Many attempts have been made to improve the output power, including broad-area lasers,[52] master oscillator power amplifier (MOPA) lasers,[53] and phase-locked diode laser arrays.[54,55] However, broad-area lasers always show multimode in the lateral direction and hence need an additional structure as a filter. Because of in-cavity gratings, MOPA structures require a complicated fabrication process. In addition, the lasers are very sensitive to gain spatial hole-burning and thermal gradients because they do not have built-in positive refractive index steps. As a result, they are not suitable for operating at the fundamental mode. Compared with these structures, phased-locked laser arrays use the effective index difference between the injection region and the etching region to achieve the modulation of lateral modes. Additionally, their structures are compact and easy to be fabricated. However, they always display a two-lobe FFP. Known approaches to solve this problem include utilizing antiguided laser arrays[56] and Y-junction laser arrays.[57] The former needs a complicated epitaxial growth process, and the latter shows large radiation loss.

Phase-shift structures, such as an external phase-shift plate[58] or an integrated phase-shift facet coating,[59] have been applied to phase-locked laser arrays to convert a two-lobe pattern into a single-lobe one. Zheng *et al.*[60] developed a laser that contained a coupling region and a mode conversion region. As shown in Fig. 6, the structure provided less mode mismatch and a more effective phase-shift function with a simpler design. The device was operated at 910 nm, and stable single-lobe FFP was achieved in the slow axis. The total CW output power reached 0.93 W, and the lateral divergence angle was only 2.4° (FWHM) with a lateral beam quality of 2.9. Such a device shows a promising future for high-brightness applications.

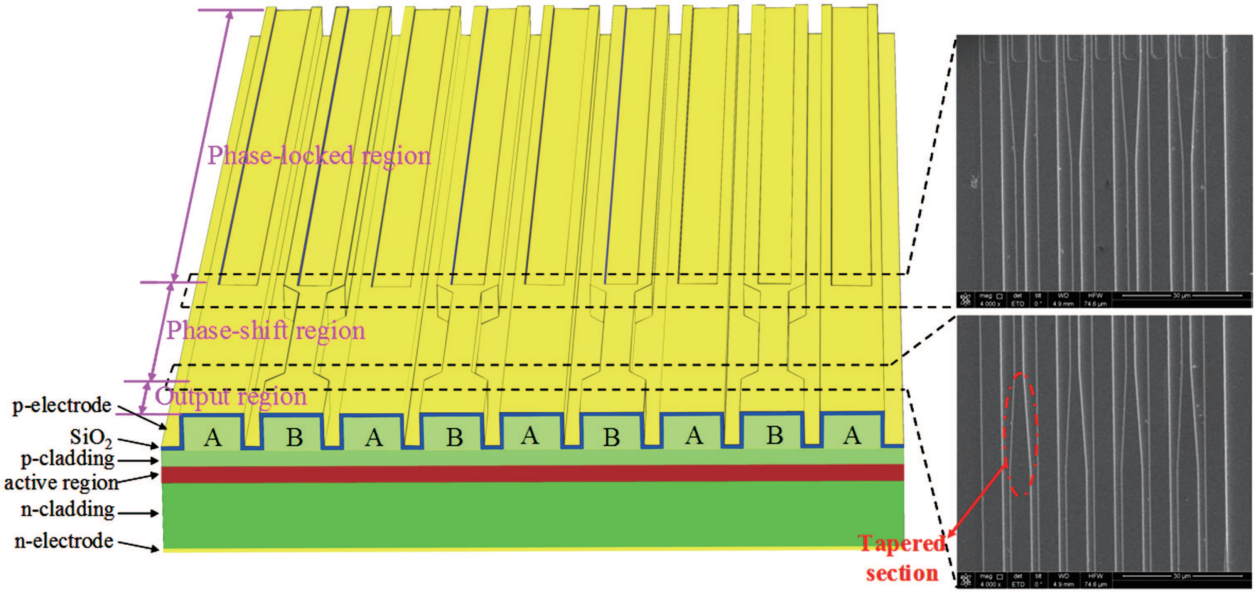


Fig. 6. (color online) Schematic of the device's structure. SEM images (inset) show the zoomed-in view of the tapered sections in the phase-shift region.[60]

Single transverse mode ridge waveguide (RW) lasers are one of the most promising ways to achieve high beam quality. For stable lateral fundamental mode emission, a sufficient index step between the ridge and etched area is required. This results in a high facet load and thus catastrophic optical mirror damage (COMD) at low power. Since the ridge width cannot be enlarged, expansion of the mode in the vertical direction is required to reduce the facet load. This also results in decreased vertical divergence, which advantageous for focusing and fiber coupling. Zheng *et al.*[61] developed 980 nm high-power single transverse mode RW lasers based on the design of the PC for low vertical divergence (see Fig. 7). 3 mm long

RW lasers with a 7 μm wide ridge achieved kink-free 2 W output power limited by COMD, and a maximum power conversion efficiency (PCE) of 59%. The laser showed divergence angles of 7.2° in the lateral direction and 10.3° in the vertical direction at FWHM.

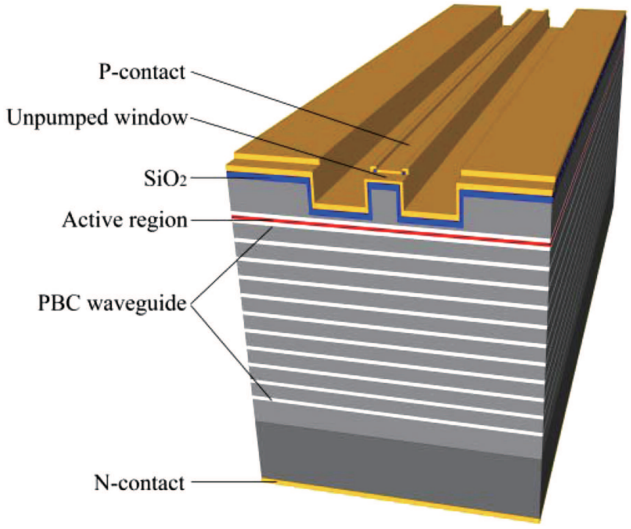


Fig. 7. (color online) Schematic structure of the RW laser based on the PC.[61]

The research of the angled cavity laser has decades of history. It has been used for stable and narrow divergence in the slow axis[62,63] and improving spectral purity combined with Bragg gratings[64,65] or 2D PCs.[66–68] Zheng *et al.*[69] proposed an angled cavity laser diode with a 2D tilt based on a longitudinal PBC waveguide[70,71] (see Fig. 8(a)). The laser was operated at 905 nm. Tilts in sidewalls along the lateral and longitudinal directions were used to enlarge the transverse mode size, and hence stable and narrow divergence angles were achieved in the fast and slow axes simultaneously. Reducing the transverse angle by 44% as well as narrowing the lateral angle to be only two times larger than the diffraction limit was demonstrated in Ref. [67]. The obtained CW output power reached 1.26 W. Zheng *et al.*[72] also designed a 980 nm angled cavity longitudinal PBC laser diode with asymmetrical high-order surface gratings (aHSGs) (see Fig. 8(b)). Experimentally, a continuous-wave output of 0.85 W/facet, a low divergence of 1.5° × 10.6°, and a narrow spectral width of 0.07 nm were achieved. The lateral beam quality was superior with an M2// of 1.96.

In order to solve the bottleneck problem of the decrease in laser output efficiency, the instability of the laser mode, and the difficulty of increasing the output power caused by the introduction of the longitudinal PC, Zheng *et al.* increased the coupling of material carrier recombination with the laser oscillation mode by placing the semiconductor gain layer at a specific position in the longitudinal PC defect region (see Fig. 9(a)). They realized that the divergence angle was greatly reduced and the beam quality was improved while maintaining a high power output.[73] A CW output power of 5.75 W, quasi-CW output power of 10.3 W, vertical divergence angle of 10.5°, and horizontal divergence angle of 5.7° were achieved in the 905 nm PC edge emitting laser. Compared with the completely periodical longitudinal PC laser, the vertical divergence angle with 95% power content was reduced by 57%.

Tapered lasers consisting of a straight ridge waveguide and a tapered section are expected to achieve a high output power while keeping a high beam quality. However, the vertical beam divergence of conventional tapered lasers is usually large. In order to reduce the vertical far-field divergence and further increase the wall-plug efficiency, Zheng *et al.* demonstrated 4 mm long tapered lasers based on PC structures, in which single InGaAs quantum wells emitting in the 980 nm range were designed in the defect layer as the core region[74] (see Fig. 9(b)). Output powers of 7.3 W in the CW mode and 17 W in the pulsed mode, and a maximum wall-plug efficiency of 46% in the CW mode and 49.3% in the pulsed mode were obtained. At an injection current of 3 A, the beam divergences were 11.1° and 6.3° along the vertical and lateral directions, respectively. The device had a vertical M2 value of 1.97 and a lateral M2 value of 1.34 at a current of 0.7 A, indicating a nearly diffraction-limited beam quality.

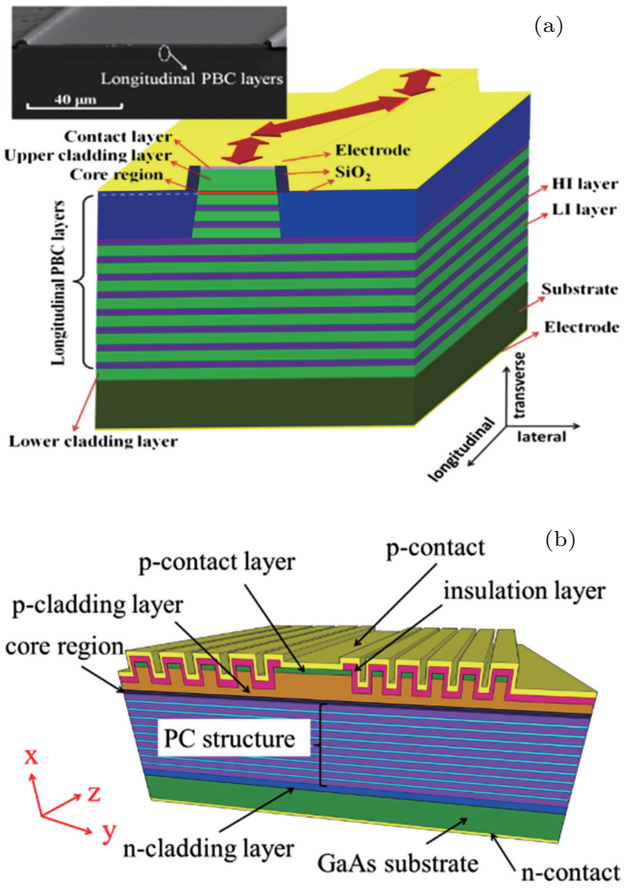


Fig. 8. (color online) Schematic structures of (a) the 2D tilt[69] and (b) aHSGs[72] longitudinal PBC lasers. The SEM image (inset in (a)) shows the waveguide at the facet.

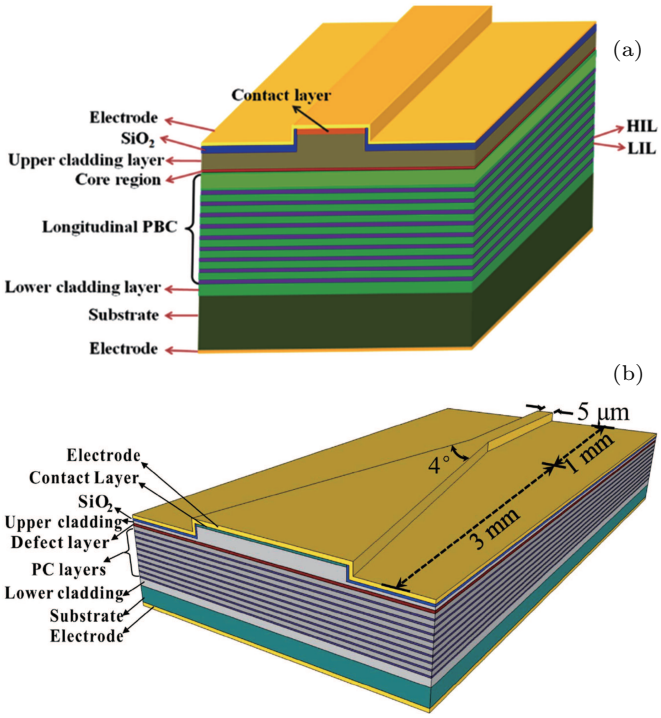


Fig. 9. (color online) Schematic structures of (a) the quasi-periodic stripe[73] and (b) tapered[74] longitudinal PBC laser diodes.

7. Silicon-based hybrid laser

The key problem in the development of silicon-based photoelectric devices is to choose the right light source. The InP/Si hybrid laser is expected to be the most promising and suitable for high-density integration.[75–91] It was first studied by Intel and the University of California, Santa Barbara in 2004 and succeeded in lasing in 2006. They first bonded the SOI-based waveguides with III–V epitaxial materials, then removed the InP substrate and fabricated lasers with micro/nanotechnology. Light was coupled to the lower SOI waveguides through evanescent field coupling. The electrical injection was realized by coplanar electrodes in the III–V material layer. To date, many groups have developed new kinds of lasers based on silicon hybrid structures, and some lasers are almost in practical use but their fabrications are so complicated and have high costs.

By etching slots on a silicon waveguide and using III–V materials as the gain medium, Zheng *et al.*[92] demonstrated a hybrid silicon laser; it is shown in Figs. 10(a) and 10(b). It not only utilized evanescent field coupling of the silicon waveguide but also employed the microstructure to choose the single longitudinal mode. The silicon waveguide and microstructure could be fabricated in one common photolithography. The CW single longitudinal mode laser was achieved at 210 K with an SMSR above 20 dB. Later, the mode choosing mechanism was etching slots periodically on the silicon waveguide (see Fig. 10(c)),[93] further realizing the single longitudinal mode lasing at room temperature with an output power of 0.62 mW and SMSR above 20 dB.

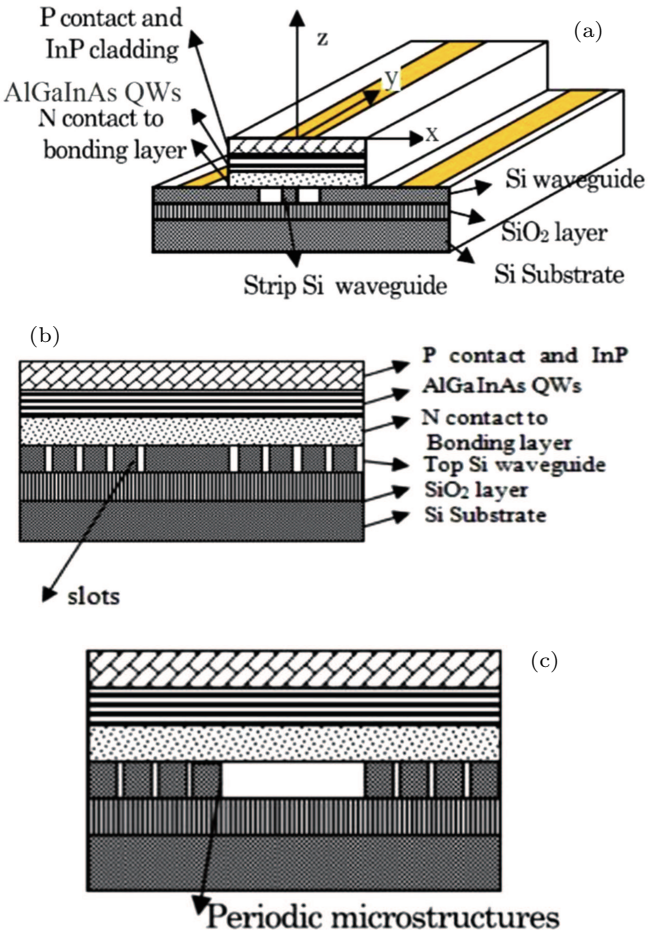


Fig. 10. (color online) (a) Schematic structure of the laser, (b) y–z cross section of the slotted single mode hybrid laser,[92] and (c) y–z cross section of the hybrid laser with periodic microstructures.[93]

8. Summary and outlook

The strong capability of photon manipulation in the wavelength scale has been demonstrated in different PC lasers. The study of a PC-integrated chip similar to the electronic-integrated chip has become an important direction of research efforts. As the core device, PC lasers, with regard to the field of information-oriented applications, will gradually develop toward having high speed, multichannel [x], narrow linewidth, and frequency stabilization, and being tunable; these are in addition to having lower power consumption, higher efficiency, and better repeatability. Meanwhile, the PC-integrated circuits that generate and manipulate single-photon quantum states will be a new focus.

By combining the light field control of the PC with the photo-electron regulation in the quantum structure, it has been confirmed that band engineering of the PC brings new development space for the semiconductor laser, such as that regarding low thresholds, high efficiency, high beam quality, etc. Adjusting the photon energy band to realize high beam quality output of the semiconductor laser is of interest to both scientific research and industrial applications across the world. Future research will dig deeper into the kinetic mechanism of energy conversion based on the combination of photons and

electrons, and break through the performance bottleneck of traditional optoelectronic devices. Future work will also make the PC laser obtain higher efficiency, a lower lasing threshold (or even no threshold), a higher output power, and higher beam quality. Finally, the PC will enable continuous improvement of semiconductor laser performance.

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