Square-lattice photonic-crystal vertical-cavity surface-emitting lasers

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Abstract: The single mode square lattice photonic-crystal vertical-cavity surface-emitting lasers (PC-VCSELs) are proposed and demonstrated. Square-lattice photonic-crystal patterns of various lattice constants are introduced on top mirrors of VCSELs having two different current apertures. The maximum single mode output power of about 1 mW is obtained from the device with lattice constant of 5.0 μm and current aperture of 16 μm. The PC-VCSEL operates in a single transverse mode in an entire operating current range with a side-mode suppression ratio of over 20 dB. The asymmetric introduction of smaller air holes improves the polarization selectivity.

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OCIS codes: (230.0250) Optoelectronics, (250.7260) Vertical cavity surface emitting lasers

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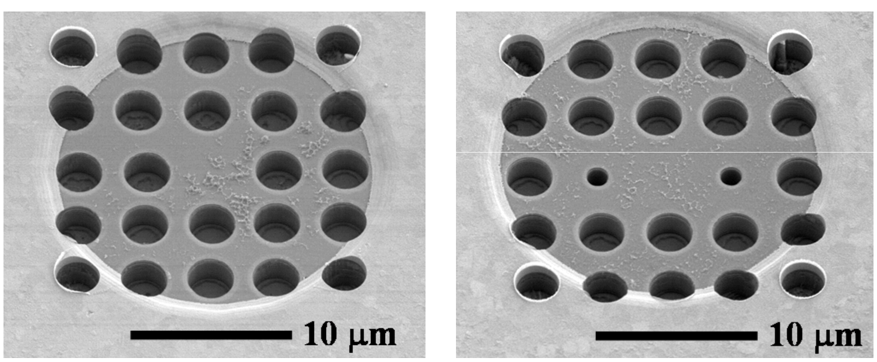
1. Introduction

The stable single mode laser with small divergence angle is advantageous for reliable high speed data transmission. Even for short-distance links, multi-mode VCSELs undergo various problems at high modulation frequencies. Therefore, controlling the transverse mode remains a crucial issue [1-3]. In addition to the single mode operation, the control and stabilization of output polarization are essential for most applications. In particular, for polarization-sensitive systems dealing with 10-Gbit/s-class high speed modulation or free-space interconnect, the stable polarization promises improved performance. Previously, photonic-crystal VCSELs have been demonstrated to be effective for transverse mode control [4-7]. And the polarization control of triangular PC-VCSELs has also been reported [8] by the modification of circular holes into elliptical air holes. However, PC-VCSELs with different photonic-crystal lattice structure have not yet been investigated.

In this paper, we have introduced square lattice photonic-crystal patterns in the top mirror of VCSELs to obtain a single transverse mode. To achieve the stable single transverse mode, photonic crystal patterns with three different kinds of lattice constant are fabricated for VCSELs with two different current apertures. Furthermore, polarization properties of the square-lattice PC-VCSEL with relatively low 4-fold symmetry are investigated. Improvement of polarization selectivity is observed by the asymmetric introduction of two small air holes.

2. Design and Fabrication

The VCSEL structure has $Al_{0.92}Ga_{0.08}As/Al_{0.2}Ga_{0.8}As$ distributed Bragg reflectors (DBRs) below and above an active region with 7-nm-thick 3 GaAs quantum wells, which is designed to operate at wavelengths close to 850 nm . The top and bottom DBRs consist of 24 pairs and 35 pairs, respectively. In the top mirror, a 47-nm-thick $Al_{0.98}Ga_{0.02}As$ layer is placed to be used later as an oxidation layer. For current limiting, oxide apertures of diameters of 12 μm and 16 μm are formed by wet oxidation techniques. The current limiting oxide aperture is designed sufficiently large to decouple the unwanted index-guiding contribution. Photonic-crystal patterns of three different lattice constants are prepared; Λ=5.0 μm, 4.5 μm and 4.0 μm for current aperture of 16 μm, and Λ=4.0 μm, 3.5 μm and 3.0 μm for current aperture of 12 μm. Usually, the diameter of the air hole (a) is chosen to be a/Λ=0.7. When the ratio of the lattice constant to the air-hole size is fixed, the total number of PC-guided modes remains unchanged, although the physical size of the cavity increases with lattice constant [9,10]. Two kinds of square-lattice photonic-crystal patterns are fabricated. The first kind is the 5×5 square-lattice photonic-crystal pattern with one missing hole in the top mirror. Fig. 1(a) shows a SEM image of this regular square lattice pattern. The other is the modified photonic-crystal pattern with two small air holes on X-axis or Y-axis as shown in Fig. 1(b).



(a) (b)

Fig. 1. SEM images of square-lattice PC-VCSELs with Λ=4.0 μm and a=0.7 Λ(2.8 μm) (a) Regular PC-VCSEL, (b) Modified PC-VCSEL.

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The modified PC-VCSELs are used to study the polarization characteristics. The diameter of the small holes is chosen to be 0.3Λ. These photonic-crystal air holes are patterned with focused-ion beam etching (FEI Strata DB237M) into a SiO_2 mask layer and subsequently etched by chemically assisted ion beam etching (CAIBE) techniques. The etching depth is about 1.7 μm. This etching depth is chosen based on the previous results from the triangular PC-VCSELs [9]. Fig. 1 shows the resulting square-lattice photonic-crystal VCSEL with lattice constant of 4.0 μm.

3. Transverse mode characteristics

Optical and electrical characteristics are measured for the conventional VCSELs without air holes and square-lattice PC-VCSELs with regular air holes. The threshold current is about 2.5 mA for the conventional VCSEL with current aperture of 16μm and it functions in multi-modes. The regular square-lattice PC-VCSELs of the same current aperture show higher threshold currents of over 4mA as shown in Fig. 2(a). This increase of the threshold current is understandable because the larger optical threshold gain is required to balance the increased modal loss of the PC-VCSEL. All PC-VCSELs of three different lattice constants operate in the single mode except one device of lattice constant of 5.0 μm. The side mode suppression ratio over 20 dB is observed in the entire operating current range. Single mode output power up to 1 mW is obtained from the PC-VCSEL of lattice constant of 5.0 μm.

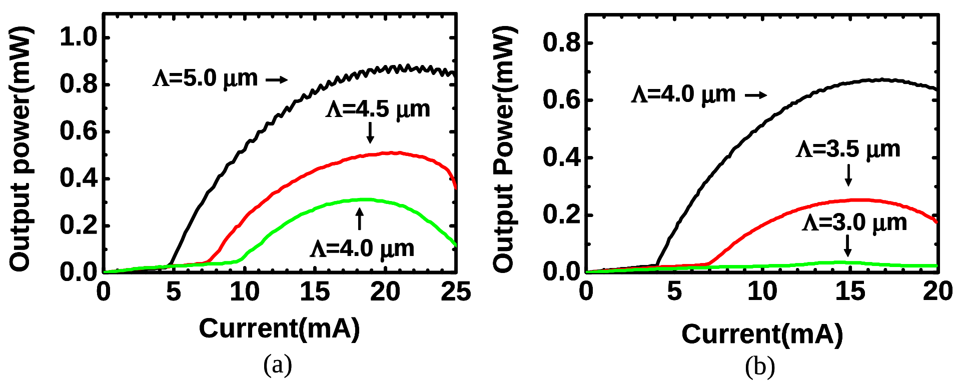

Fig. 2. L-I characteristics of regular PC-VCSELs with (a) current aperture of 16μm, (b) current aperture of 12 μm.

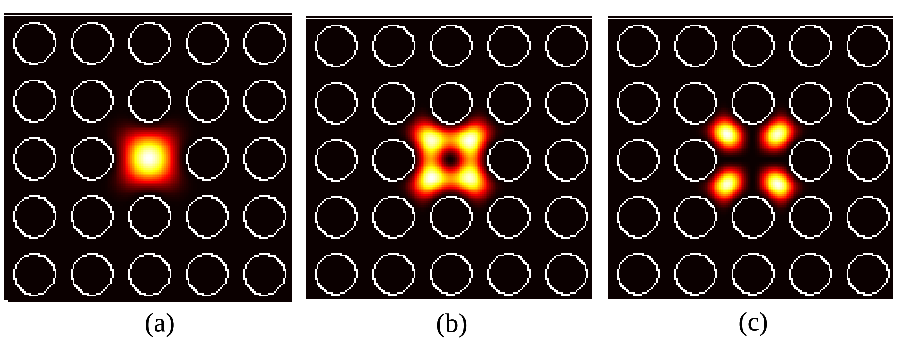

Fig. 3. PC-guided modes for a fully-drilled regular PC-VCSEL calculated by plane wave expansion method (a) fundamental PC-guided mode, (b) 2nd PC-guided mode, (c) 3rd PC-guided mode.

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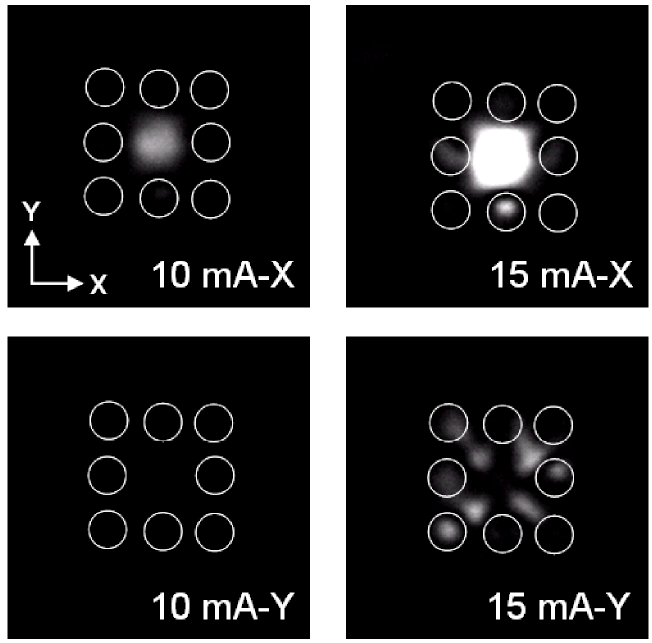
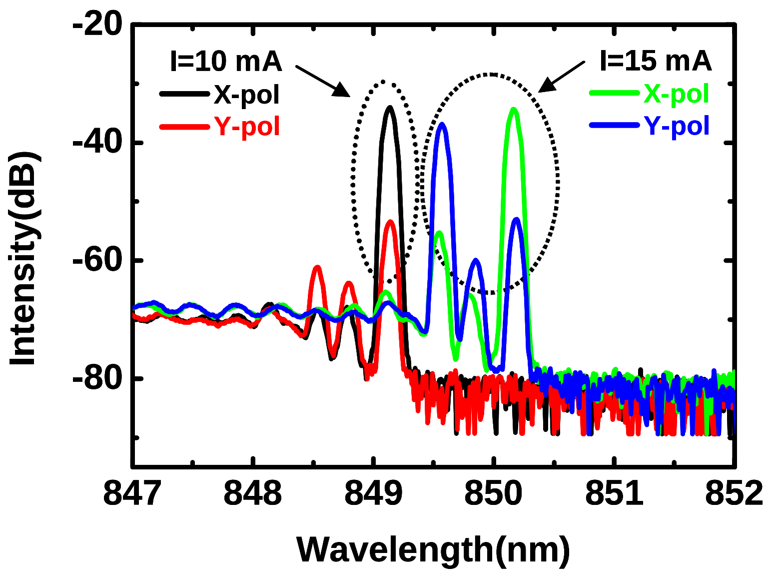


(a) (b)



(c)

Fig. 4. Polarization-resolved near-field pattern at (a) 10 mA, (b) 15 mA, (c) Polarization-resolved spectra for a regular PC-VCSEL with current aperture of 16µm, lattice constant (Λ) of 5.0 µm.

The PC-VCSELs of current aperture 12 μm show characteristics similar to those of PC-VCSELs of current aperture 16 μm. The results for the devices with current aperture of 12 μm are summarized in Fig. 2(b). In this case, the maximum single mode output power is 0.7 mW when the lattice constant is 4.0 μm. The output power can be further improved by optimizing parameters such as current aperture, lattice constant, etch depth and hole size.

We compute the photonic-crystal-guided (PC-guided) modes by the plane wave expansion method employing an infinite 2-dimensional structure with an index of 3.28 [9, 10]. A total of three PC-guided transverse modes with 2, 4, 2-fold degeneracy are identified as shown in Fig. 3(a)-(c). Therefore, one can expect a maximum of three PC-guided transverse modes in the partly-drilled real PC-VCSEL structure. The calculated spectral separation between the fundamental PC-guided mode and the 2^{nd} PC-guided mode is 3.6Å. The spectral separation measured near threshold is 2.4 Å. The difference is attributed to the finite depth of the air holes in the real structure.

Polarization-resolved near-field images and spectra are analyzed to identify the PC-guided modes. Figure 4 shows the polarization-resolved near field patterns at two different operating currents and polarization-resolved spectra of the PC-VCSEL with lattice constant of 5.0 μm, current aperture of 16 μm. The black and red curves in Fig. 4(c) represent the X-polarized and Y-polarized spectra, respectively, at operating current of 10 mA. Here, the polarization suppression ratio is about 20 dB. The X-polarized near field pattern at 10 mA resembles the calculated fundamental PC-guided mode in Fig. 3(a). The green and blue curves in Fig. 4(c) correspond to the X- and Y-polarized spectra, respectively, at 15 mA. Note that the weak Y-polarized near field pattern of Fig. 4(b) corresponds to the third blue peak near 849.5 nm. This pattern resembles the 3^{rd} PC-guided mode in Fig. 3(c). Here, the 3^{rd} PC-guided mode arrives at threshold earlier than 2^{nd} PC-guided mode. This happens because the 3^{rd} PC-guided mode overlaps less with the fundamental PC-guided mode as shown in Fig. 3.

4. Polarization characteristics

For square-lattice PC-VCSELs with regular air holes, over 80% of fabricated devices operate in a single polarization state without switching in the entire operating current range. Generally, the conventional VCSELs have no preferential polarization direction due to the isotropic optical gain and the cylindrically symmetry. In previous works, elliptical or rectangular air holes are introduced in triangular-lattice PC-VCSELs to control the state of polarization [8]. On the contrary, the square-lattice PC-VCSELs show better polarization characteristics even with circular air holes. Although the full mechanism of the polarization selection is yet to be understood, it is interesting to test whether the introduction of a simple asymmetry along X-axis or Y-axis could further improve the polarization stability. In fact, we introduce two small air holes. These modified PC-VCSELs prefer the polarization aligned with the direction of the small air holes. Figure 5(a) shows a polarization-resolved L-I curve with 16 μm-current aperture, lattice constant of 4.0 μm and small air holes along X-direction. The device functions in a single mode until the maximum output power with an extinction ratio over 20 dB as shown in Fig. 5(b). We observe the perfect polarization selection from both X- and Y-oriented modified PC-VCSELs independent of the crystallographic orientation.

For comparison, we compute the photonic-crystal-guided modes for the modified PC-VCSELs by the plane wave expansion method. Here, we find four PC-guided transverse modes as shown in Fig. 6(a)-(d). The fundamental mode is split into two modes of different polarizations. The original 2^{nd} PC-guided mode with 4-fold degeneracy (Fig. 3(b)) is now split into two different modes (Fig. 6(b), (c)) with 2-fold degeneracy due to the asymmetric lattice structure. The spectral separation of the fundamental mode and the 2^{nd} PC-guided mode is 2.2 Å. The experimental value is 1.8 Å at threshold current, which is smaller than that of the regular PC-VCSEL. Fig. 7 shows the near field patterns at different operating currents and the polarization-resolved spectra of the modified PC-VCSEL with lattice constant of 4.0 μm, current aperture of 16 μm and small air holes in Y-direction. From the near filed pattern and spectrum at 10 mA, the dominant rightmost peak on the Y-polarized spectrum (red curve)

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corresponds to the fundamental guided mode. However, the dominant peak of X-polarization changes at 15 mA. The second green peak at 849.8 nm corresponds to the 2nd PC-guided mode in Fig. 6(b).

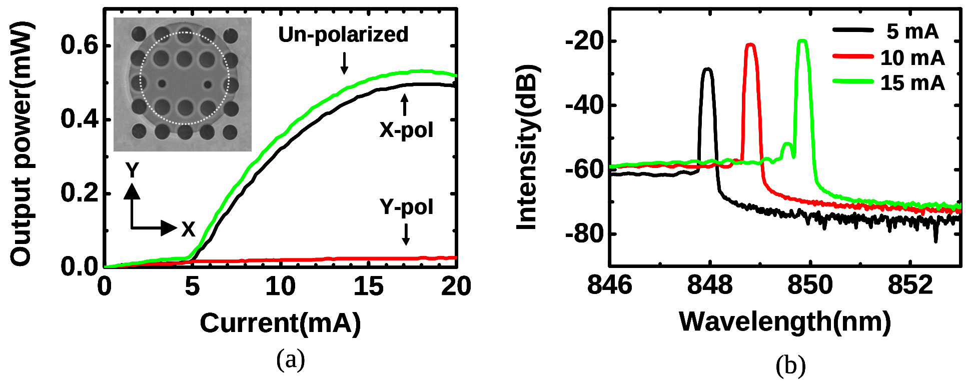

Fig. 5. (a) Polarization-resolved L-I characteristics (b) The spectra at various operating currents for a modified PC-VCSEL with small air holes of 0.3Λ in X-direction, current aperture of 16 μm and lattice constant of 4.0 μm.

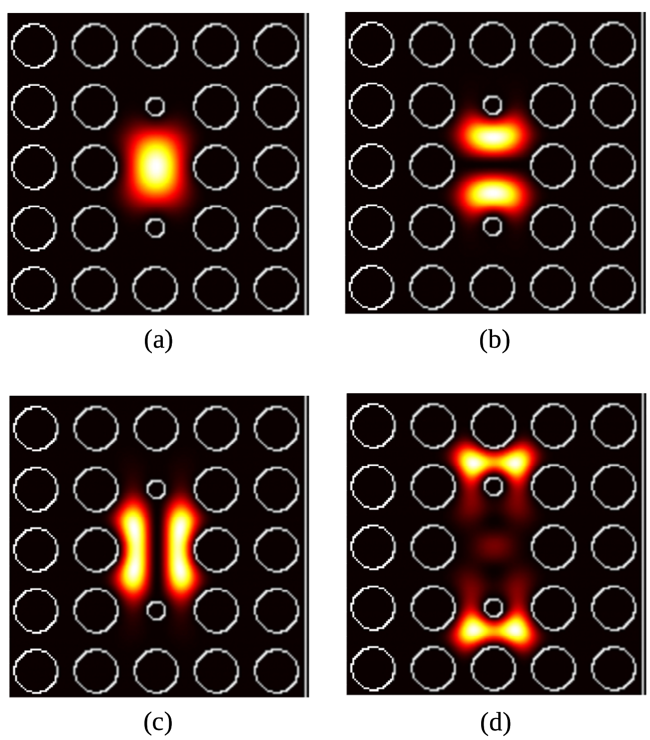

Fig. 6. PC-guided modes for a fully-drilled modified square-lattice PC-VCSEL calculated by plane wave expansion method (a) fundamental PC-guided mode, (b) 2nd PC-guided mode, (c) 3rd PC-guided mode, (d) 4th PC-guided mode.

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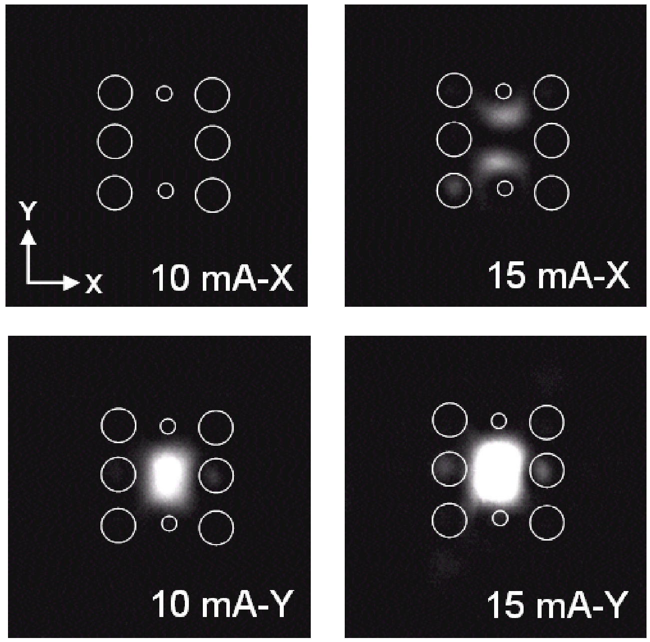
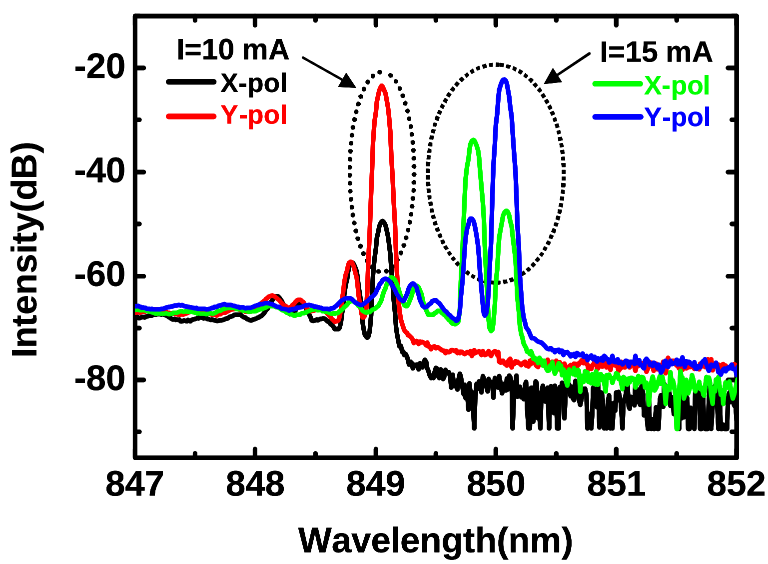


(a) (b)



(c)

Fig. 7. Polarization-resolved near-field patterns at (a) 10 mA (b) 15 mA (c) Polarization-resolved spectra for a modified PC-VCSEL with small air holes of 0.3Λ in Y-direction, current aperture of 16μm and lattice constant (Λ) of 4.0 μm. All the dimensions of this PC-VCSEL are identical to those of Fig. 5. For comparison purposes, both PC-VCSELs of Fig. 5 and Fig. 7 are fabricated on the same wafer, but the orientations of small air holes are perpendicular to each other.

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5. Comparison of the regular and the modified PC-VCSELs

All regular PC-VCSELs with lattice constant of 5.0 μm and current aperture of 16 μm show the single mode operation in entire operating current range except one device. However, it is not the case for the modified PC-VCSELs. The reason is attributed to the fact that the introduction of small air holes increases the effective cavity area. As the lattice constant decreases, the modified PC-VCSEL shows better single-mode characteristics. For the modified PC-VCSEL with 16 μm-current aperture, the device with Λ=4.5 μm operates in a single mode in the low current regime, whereas the device with Λ=5.0 μm operates in multimode from the beginning. When the lattice constant (Λ) is 4.0 μm, the modified PC-VCSEL remains in a single mode. The lattice constant of 5.0 μm seems to be close to the upper limit for the single mode operation independent of the aperture diameter. All small devices with Λ=3.0 μm and 12 μm-current aperture remain comfortably in the fundamental mode with smaller output power. The modified PC-VCSEL with lattice constant of 4.0 μm and 12 μm-current aperture operates in a single mode only at low operating current. These results are summarized in Table 1 where the 20-dB criterion is used to define the single mode operation. Although the small lattice constant is preferred for the stable single mode, the output power is significantly limited by the increased modal losses and reduced modal volume. Therefore, the proper selection of lattice constant is important to achieve both the single transverse mode and the high power.

Table 1. Comparison of the regular PC-VCSEL and the modified PC-VCSEL, S; single mode operation (20 dB criterion), S→M; transition from single mode to multi-mode operation, M; multi-mode operation.

Current Aperture diameter=16 μm			Current Aperture diameter=12 μm		
Λ	Regular	Modified	Λ	Regular	Modified
5.0 μm	S or S→M	M	4.0 μm	S	S→M
4.5 μm	S	S→M	3.5 μm	S	S or S→M
4.0 μm	S	S or S→M	3.0 μm	S	S

6. Summary

In summary, we proposed and demonstrated the square-lattice photonic-crystal VCSELs. The various lattice constants were introduced to obtain effective single mode output power for the square lattice PC-VCSELs with two different current apertures (16 μm, 12 μm). Single mode output power of about 1 mW was obtained for the PC-VCSEL with 16 μm-current aperture and lattice constant of 5.0 μm. The PC-VCSEL operated in a single transverse mode over an entire operating current range with a side-mode suppression ratio of over 20 dB. Furthermore, the introduction of two small air holes was formed to be effective for the single-polarization and single mode operation. Through the polarization resolved spectra and near field patterns, we experimentally confirmed the existence of PC-guided modes calculated by the plane wave expansion method.

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