Single-fundamental-mode photonic-crystal vertical-cavity surface-emitting lasers

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A photonic-crystal vertical-cavity surface-emitting laser (PC-VCSEL) is proposed and demonstrated. The 850-nm-PC-VCSEL shows single-mode continuous-wave operation in the entire current range. The side-mode suppression ratio is 35–40 dB for the sample with the hole pitch (A) 5 μm and the hole diameter (a) 3.5 μm. The guiding effect of the single-defect triangular-lattice two-dimensional photonic crystal structure is experimentally observed and is explained by the effective index model. © 2002 American Institute of Physics. DOI: 10.1063/1.1481984

Single fundamental mode VCSELs have been an attractive research subject due to their potential applications such as data transmission in optical network, optical interconnects, optical storage, and laser printing. However, single transverse mode operation of VCSELs over an entire pump range is difficult to achieve due to spatial hole burning and thermal lensing. Up to date, many approaches have been reported such as long monolithic cavity VCSELs, shallow surface relief VCSELs, and hybrid ion implanted/selectively oxidized VCSELs.

In this letter, we report the single mode operation of “photonic-crystal VCSELs” (PC-VCSELs). The PC-VCSELs are similar to standard VCSELs except that they have photonic crystal defined by holes in the top mirror region. The two-dimensional photonic crystal structure has a single defect as shown in Fig. 1. In fact, we borrow the concept of the endless single-mode from photonic crystal fibers (PCF) to the VCSEL structure. By introducing the single defect photonic crystal to the VCSEL, a waveguide is expected to be formed around the central defect region where the effective index is larger than the surrounding region. It is worth pointing out that this index guiding scheme can be adapted to any long-wavelength VCSEL structure that has no appropriate guiding mechanism.

To understand the VCSEL with lateral structural variation, the effective index model is used. According to the effective index model, the number of guided mode of an oxide aperture VCSEL is determined by V value which have the form:

\[ V^2 = (h_{\text{core}}^2 - h_{\text{clad}}^2) d^2 \approx (\varepsilon) (k_{\text{clad},z}^2 - k_{\text{core},z}^2) d^2, \]

where \( k_{\text{core},z} \) and \( k_{\text{clad},z} \) are longitudinal resonance wave vectors of core and cladding region, respectively, and \( h_{\text{core}}, h_{\text{clad}} \) are transverse wave vector in the medium. \( d \) is a diameter of the core. The \( \varepsilon \) represents the dielectric constant weighted by the longitudinal standing wave. For the PC-VCSEL shown in Fig. 1, the resonance wavelengths would be different for the central core region and the surrounding region. This situation is approximated as a simple step-index waveguide as shown in Fig. 2(a). With the aid of this model, the difference of effective indices in the two regions can be estimated by measuring the resonant wavelengths in the core and surrounding regions. The overall effects of the etch, diameter, and pitch of the holes show up experimentally as the shift of the resonant wavelength. This may be written compactly as

\[ \Delta n_{\text{eff,core} - \text{clad}} / n_{\text{eff,core}} \approx \Delta \lambda_{\text{core} - \text{clad}} / \lambda_{\text{core}}. \]

First, typical mesa structures with diameter of 80–86 μm are

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**FIG. 1.** (a) Schematic of the 850 nm PC-VCSEL. Note that the first generation PC-VCSEL structure has no oxide current aperture. The oxide aperture is added to the second generation devices for current confinement; (b) top view image of the PC-VCSEL; (c) scanning electron microscope image of an etched hole.

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formed on an 850-nm-VCSEL wafer by optical lithography and chemical assisted ion beam etching (CAIBE) method. The photonic crystal holes are then defined with another photomask. Out of 24 Al_{0.15}Ga_{0.85}As/Al_{0.95}Ga_{0.05}As pairs in the top distributed Bragg reflector (DBR), top most 14–17 pairs are CAIBE etched to form the photonic crystal pattern. The first generation PC-VCSEL has no current-limiting aperture. The hole pitch \( L \) and the ratio of the hole diameter to the hole pitch \( a/L \) are 5–10 \( \mu \)m and 0.3–0.6, respectively. The resonance wavelength is measured from the photoluminescence (PL). A commercial 780-nm-laser diode is focused to a 6 \( \mu \)m-spot with 8-mW-incident power to take the PL spectra. The resonance wavelength observed at the central core region of photonic crystal differs from those of the neighbor regions as shown in Fig. 2(a). The \( V \) values of the PC-VCSELs with \( a/L = 0.6 \) and \( \Lambda = 5 \mu \)m, 10 \( \mu \)m are larger than the cutoff value of 2.4 [Fig. 2(b)]. Hence multimode operation is expected from these PC-VCSELs whereas the single mode is expected from the PC-VCSEL with \( a/L = 0.3 \) and \( \Lambda = 5 \mu \)m.

These first generation structures are tested with 100 ns-pulses with 5% duty. The PC-VCSEL with \( \Lambda = 5 \mu \)m, \( a/L = 0.6 \) exhibits single fundamental mode lasing over the entire current range of operation with the side-mode suppression ratio (SMSR) of over 35 dB as shown in Fig. 3(a). The CCD images of Fig. 3(a) demonstrate the unambiguous index guiding occurring at the central defect region. The dim spots in the background correspond to the etched air holes. The large outside circle is the image of the circumference. According to our analysis, the \( V \) value (2.67) of this structure is slightly larger than the cutoff value, based on the simple uniform step-index model. We believe the reduced reflectivity of the etched holes surrounding the core region helps the suppression of the higher order modes that overlap more with this lossy region. However, the PC-VCSEL of \( \Lambda = 10 \mu \)m, \( a/L = 0.6 \) is not able to support the single mode condition sufficiently as shown in Fig. 3(b). The devices with \( \Lambda = 5 \mu \)m, \( a/L = 0.3 \) and \( \Lambda = 10 \mu \)m, \( a/L = 0.3 \) do not lase because of the weak index guiding. Generally the operating currents of the first-generation devices are large because of the no current confinement.

For the second generation devices, oxide current apertures are formed in the PC-VCSELs as shown in Fig. 1(a) to achieve the efficient carrier confinement and the continuous wave (cw) operation. The oxide aperture is made before the formation of photonic crystal. The diameter of the oxide aperture is about 4\( \Lambda \). \( \Lambda \) and \( a/L \) of the fabricated devices are 5–15 and 0.4–0.7 \( \mu \)m, respectively. Figure 4 shows cw light output and the near-field images of the lasing modes for the devices of \( \Lambda = 5 \mu \)m. The broad bright background of the
below threshold near-field image shows the oxide aperture of 19 μm. The photonic-crystal core is slightly misaligned with respect to the center of the aperture. The single mode operation is observed from the PC-VCSELs of $\Lambda = 5 \mu m$, $a/\Lambda = 0.6, 0.7$ with the mode size of about 10 μm. On the other hand, the device of $\Lambda = 5 \mu m$, $a/\Lambda = 0.5$ shows multimode operation from the beginning with large threshold current. In this case, the whole aperture area participates in the multimode lasing operation, indicating insufficient index guiding effect.

The spectra of the two devices of $\Lambda = 5$ and $a/\Lambda = 0.6, 0.7$ μm show the single transverse mode operation with SMSR of over 40 dB (Fig. 5). The device of $a/\Lambda = 0.6$ shows the slightly larger mode size and the higher maximum output of 0.57 mW compared with that of the device of $a/\Lambda = 0.7$. The mode sizes are estimated from the near-field profiles assuming Gaussian beams. The diameters are 9.7 and 7.6 μm for devices of $a/\Lambda = 0.6$ and 0.7, respectively. The holes of the larger $a/\Lambda$ gives the stronger index step and results in the smaller mode size and the smaller output power. In this structure, only 25% of the total current overlaps with the mode. The current leakage limits the maximum single mode output power. The devices of $\Lambda = 6$ and $a/\Lambda = 0.7$ μm operate in the single mode with the SMSR of 30 dB at the current of 15 mA. The other devices with pitches larger than 6 μm show the multimode operation.

In summary, we have realized PC-VCSELs with strong mode selection. The effective index model is used to estimate the index difference between the core and cladding regions. The PC-VCSELs operate in the single fundamental mode over a wide dynamic range with the maximum SMSR of 45 dB. We expect this PC-VCSEL to become a prospective high-power single-mode source. In fact, this index guiding based on the photonic crystal can be adapted to any VCSEL structure independent of material systems.

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