Photonic Crystal Vertical Cavity Lasers With Wavelength-Independent Single-Mode Behavior

Ansas M. Kasten, *Student Member, IEEE*, Meng Peun Tan, *Student Member, IEEE*, Joshua D. Sulkin, *Student Member, IEEE*, Paul O. Leisher, *Member, IEEE*, and Kent D. Choquette, *Fellow, IEEE*

***Abstract*—We report on two-dimensional photonic crystal designs in vertical-cavity surface-emitting lasers that yield single-transverse mode operation over a wide range of wavelengths (780, 850, and 980 nm). These single-mode photonic crystal designs are consistent with predictions of a theoretical model that considers design parameters such as hole diameter, lattice constant, and etching depth. The single-mode lasers demonstrate side mode suppression of $>$ 35 dB and $>$ 1 mW output power using the same photonic crystal pattern.**

***Index Terms*—Oxide-confined photonic crystal vertical-cavity surface-emitting laser (VCSEL), single-mode operation, vertical-cavity surface-emitting laser (VCSEL).**

I. Introduction

VERTICAL-CAVITY surface-emitting lasers (VCSELs) have been widely deployed in short-haul optical data communication and sensing applications. Conventional VCSEL designs typically lead to operation in multiple transverse modes because the VCSEL lateral dimension is usually much larger than the effective cavity length in the longitudinal direction. Single-mode VCSELs are necessary for high-speed (low dispersion) optical communication, high precision sensing, optical imaging, and atomic clocks. Several methods for achieving single fundamental mode VCSEL operation have been demonstrated, include increasing loss to higher order modes [1] and properly designing the transverse index profile for single-mode confinement [2]–[4]. However, these methods require unique designs with specific dimensions (for example cavity diameter) correlated to the emission wavelength. Recently, the use of a photonic crystal (PhC) pattern introduced into the top facet of a VCSEL has been shown to create single-mode VCSELs [5]–[7].

In this letter, we report designs of single-mode photonic crystal VCSELs that produce output power $>$ 1 mW and side-mode suppression ratio $>$ 35 dB over a wide range of wavelengths (780 to 980 nm). Endlessly single-mode photonic crystal studies have been reported by Birks *et al.* where incorporating two-dimensional arrays of air holes into an optical fiber was used to achieve single mode [8]. Similar to the situation in photonic crystal fibers, single-mode operation in PhC VCSELs is partially created by the radial refractive index profile produced by the photonic crystal which surrounds a defect. However, in contrast to fiber studies, the etch depth of the air holes in PhC VCSELs cannot be assumed to be infinite [9]. Higher order modes experience optical loss induced through the photonic crystal holes partially etched into the top distributed Bragg reflector (DBR) mirror [10]. PhC design parameters considered in this study are: etch depth of the circular air holes, pitch between the holes, and diameter of the air holes.

II. Analysis

To analyze the modal properties of VCSELs we employ the V-parameter obtained from optical fiber theory [11]. Thus, the modal properties of a PhC VCSEL operating at a wavelength λ_o can be estimated using the V_{eff}-parameter which is given by [9]:

$$V_{\text{eff}} = \frac{\pi D}{\lambda_o}\sqrt{n_m^2 - (n_m - \gamma \Delta n_m)^2}. \quad (1)$$

The defect diameter $D = 2a - b$, where a is the lattice constant and b the hole diameter, is a function of the photonic crystal design. The effective refractive index of the cladding photonic crystal region is calculated from the out-of-plane photonic band diagram which can be computed using the plane-wave expansion method [7]. Each DBR layer in the photonic crystal region is modeled by a single layer of constant refractive index, described by $n_m - \gamma\Delta n_m$ where n_m is the material refractive index of a DBR layer and Δn_m is the index reduction induced by the PhC air holes in the cladding region. The finite etch depth of the air holes can be taken into account with the etch depth dependence factor γ, where $0 < \gamma < 1$ [9]. The etch depth dependence factor γ can be understood qualitatively as proportional to the integrated optical power distribution inside a VCSEL along the longitudinal direction.

For V_{eff} values smaller than 0.6, the optical loss induced through the PhC is larger than the available gain resulting in devices that do not lase [12]. For larger V_{eff} values greater than 0.6 and less than 2.4, the devices are expected to only operate in the fundamental mode [11]. To obtain stable single-mode operation, V_{eff} should be close to 2.4 to overcome any external perturbations such as carrier-injection or thermal effects. Increase of the b/a ratio results in bigger hole diameters, deeper

Manuscript received June 21, 2008; revised August 27, 2008. First published October 31, 2008; current version published November 21, 2008. This work was supported in part by the National Science Foundation under Award DMI 0328162 and in part by the U.S. Defense Advanced Research Projects Agency under Award 317271-7830.

A. M. Kasten, M. P. Tan, J. D. Sulkin, and K. D. Choquette are with the Department of Electrical and Computer Engineering, University of Illinois, Urbana, IL 61801 USA (e-mail: akasten@illinois.edu; mengtan@illinois.edu; sulkin@illinois.edu; choquett@illinois.edu).

P. O. Leisher was with the Department of Electrical and Computer Engineering, University of Illinois, Urbana, IL 61801 USA. He is now with nLight Corporation, Inc., Vancouver, WA 98665 USA (e-mail: paul.leisher@nlight.net).

Color versions of one or more of the figures in this letter are available online at http://ieeexplore.ieee.org.

Digital Object Identifier 10.1109/LPT.2008.2006003

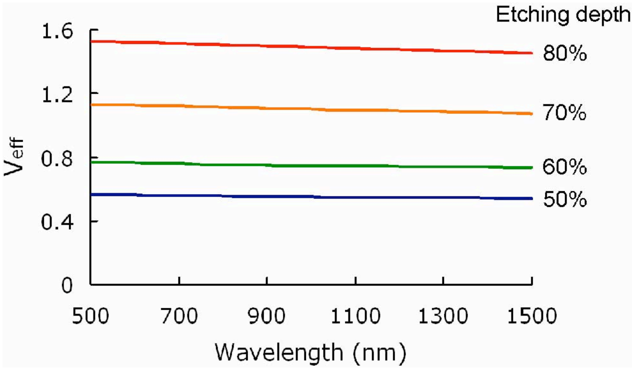


Fig. 1. Variation of V_{eff} over a range of wavelengths for $b/a = 0.7$, $a = 4.5\ \mu$m and varying etching depth ranging from 50% to 80% into the top DBR.

etch depths, and larger defect diameters, which eventually will lead to V_{eff} values larger than 2.4 producing multimode operation.

Fig. 1 shows the calculated V_{eff} as a function of wavelength. The etch depth of the PhC air holes from 50% to 80% into the top DBR corresponds to a range of γ factors from 0.25 to 0.4, respectively. As shown in Fig. 1, V_{eff} remains constant over a wide range of wavelengths since the change in refractive index difference between the core and the photonic crystal compensates for the change in normalized diameter of the core (D/λ). This property, called the endlessly single-mode condition, is well known in photonic crystal fibers [8] and enables a unique PhC VCSEL design to yield single-mode emission regardless of lasing wavelengths.

III. Experiment

Three different but conventional epitaxial structures grown by metalorganic vapor phase epitaxy are used for the fabrication of oxide-confined photonic crystal VCSELs. The 780-, 850-, and 980-nm VCSELs have 30-, 22-, and 22-period p-type top DBR mirrors, respectively. A high aluminum content layer $(Al_{0.98}Ga_{0.02}As)$ is placed above the active region for fabrication of an oxide aperture. Photonic crystal patterns are defined by standard optical lithography and are etched into the top DBR by inductively coupled plasma reactive ion etching. The PhC and the oxidation trench are simultaneously patterned by optical lithography but etched separately. This results in self-alignment of the PhC defect to the oxide aperture. Various photonic crystal patterns with a hole diameter to lattice constant ratio $b/a = 0.7$ are considered in this work. Etch depths of the photonic crystal holes vary from 40% to over 100% into the top DBR. Approximately 70 different PhC designs are evaluated at each of the three VCSEL wavelengths. A cross-sectional sketch and optical image of a single-mode photonic crystal VCSEL are shown in Fig. 2.

IV. Results

The light versus current and voltage as well as spectral properties are measured for the VCSELs under continuous wave operation at room temperature. In general, PhC VCSELs tend to exhibit higher threshold voltage due to the increase in series resistance from etching in the top DBR. In addition, optical loss introduced by the photonic crystal will discriminate against higher order modes that overlap the PhC region to enhance single-mode operation.

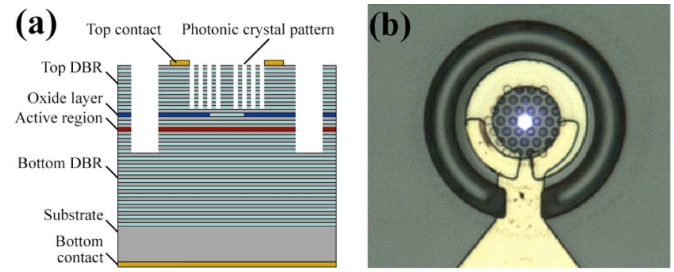
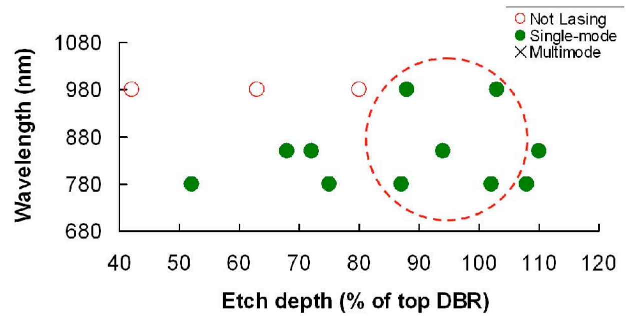
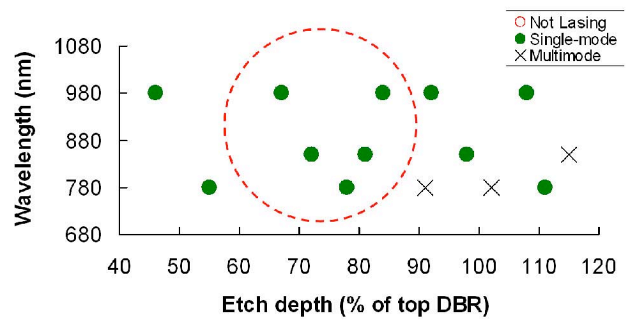


Fig. 2. (a) Cross-section sketch and (b) near-field optical microscope image of an oxide-confined PhC VCSEL lasing in the fundamental mode.



(a)



(b)

Fig. 3. Modal properties of PhC VCSELs. Designs that are independent of wavelength are shown in dashed circles: (a) $b/a = 0.7$, $a = 4\ \mu$m, oxide aperture $= 12\ \mu$m and (b) $b/a = 0.7$, $a = 4.5\ \mu$m, oxide aperture $= 12\ \mu$m.

In this letter, we define single fundamental mode operation as side mode suppression ratio greater than 35 dB from threshold through maximum output power. Two example single-mode designs yielding single-mode operation for all three wavelengths (780, 850, and 980 nm) are presented in Fig. 3. These two PhC designs have periods of 4 and 4.5 μm. Fig. 3 also shows the range of etch depths for which these designs operate in the single fundamental mode (indicated by the dashed circles). Note that etch depths $< 60\%$ correspond to $V_{\mathrm{eff}} \leq 0.8$, which may not be sufficient for single-mode operation [12]. Etch depths varying from 60% to 80% and 70% to 100% of the top DBR thickness for PhC designs with $b/a = 0.7$, $a = 4\ \mu$m, and $b/a = 0.7$, $a = 4.5\ \mu$m, respectively, allow for single-mode operation. In some cases, single-mode operation is also observed for PhC VCSELs with deeply etched holes. This arises from our definition of single mode, since single-mode operation from threshold

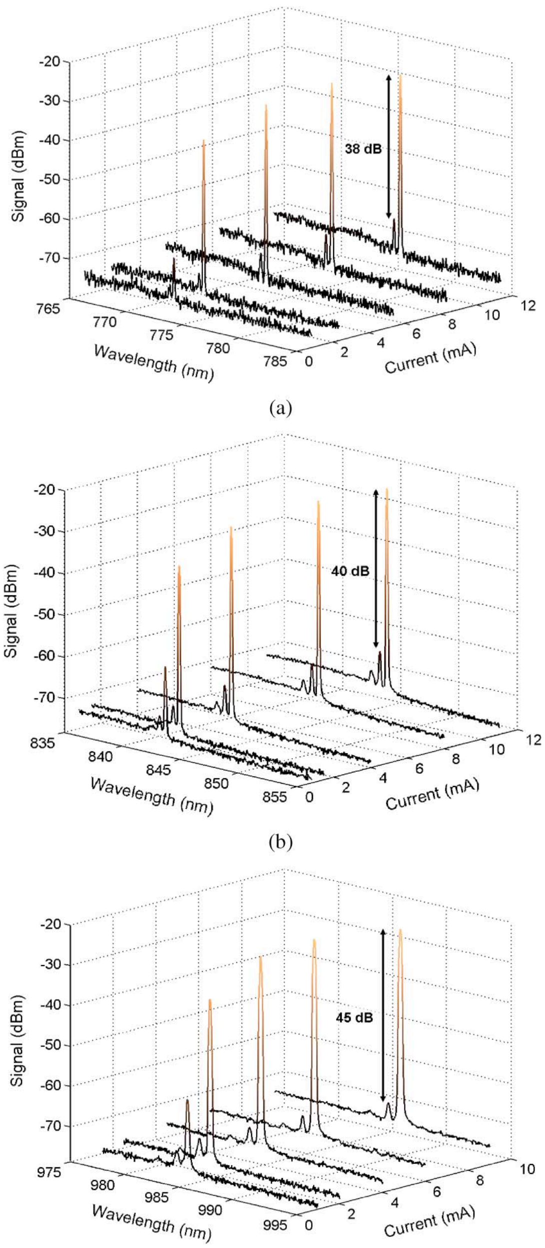


Fig. 4. Spectral properties of PhC VCSELs for various injection currents at three different wavelengths: (a) 780 nm, (b) 850 nm, and (c) 980 nm.

through maximum output power is observed in some low power VCSELs with large V_{eff} values. Three emission spectra of PhC VCSELs with $b/a = 0.7$, $a = 4.5$ μm, oxide aperture of 12 μm, and etch depth of 80% into the top DBR are shown in Fig. 4. The side mode suppression ratio of all VCSELs is well above 35 dB from threshold through rollover.

Other PhC designs with different b/a ratios yield single-mode operation for a subset of the etch depths considered or for a limited wavelength regime. The etch times used for the creation of PhC holes are aimed towards larger b/a ratios such as 0.6 and 0.7. The large hole diameter of these PhC designs allows for easier fabrication and results in V_{eff} values close to 2.4. Smaller hole diameters for designs with b/a ratios of 0.4 and 0.5 do not result in deep enough holes to sufficiently overlap the longitudinal optical power distribution. Large b/a ratios combined with lattice constants bigger than 4.5 μm result in V_{eff} values well above 2.4 and thus cause defect confined multimode operation.

V. Summary

We demonstrate single-mode photonic crystal designs that are independent on the VCSEL emission wavelength. The fabrication was based on a high-tolerance conventional manufacturing process only using optical lithography. Since a wide range of different etch depths resulted in single-mode emission etch depth uncertainty during manufacture can have a minimal influence on mode properties. Universal PhC designs that produce single-mode operation over a wide range of wavelengths could lead to simple manufacture of single-mode VCSELs operating at different wavelength regimes.

References

[1] H. Martinsson, J. Vukusic, M. Grabherr, R. Michalzik, R. Jager, K. Ebeling, and A. Larsson, "Transverse mode selection in large-area oxide-confined vertical-cavity surface-emitting lasers using a shallow surface relief," *IEEE Photon. Technol. Lett.*, vol. 11, no. 10, pp. 1536–1538, Oct. 1999.

[2] E. W. Young, K. D. Choquette, S. L. Chuang, K. M. Geib, A. J. Fischer, and A. A. Allerman, "Single transverse mode vertical cavity lasers under continuous wave and pulsed operation," *IEEE Photon. Technol. Lett.*, vol. 13, no. 6, pp. 927–929, Jun. 2001.

[3] A. Haglund, J. S. Gustavsson, J. Vukusic, P. Modh, and A. Larsson, "Single fundamental-mode output power exceeding 6 mW from VCSELs with a shallow surface relief," *IEEE Photon. Technol. Lett.*, vol. 16, no. 2, pp. 368–370, Feb. 2004.

[4] A. Furukawa, S. Sasaki, M. Hoshi, A. Matsuzono, K. Moritoh, and T. Baba, "High-power single-mode vertical-cavity surface-emitting lasers with triangular holey structure," *Appl. Phys. Lett.*, vol. 85, no. 5161, 2004.

[5] D. S. Song, S. H. Kim, H. G. Park, C. K. Kim, and Y. H. Lee, "Single-fundamental-mode photonic-crystal vertical-cavity surface-emitting lasers," *Appl. Phys. Lett.*, vol. 80, p. 3901, 2002.

[6] N. Yokouchi, A. J. Danner, and K. D. Choquette, "Vertical-cavity surface-emitting laser operating with photonic crystal seven-point defect structure," *Appl. Phys. Lett.*, vol. 82, p. 3608, 2003.

[7] N. Yokouchi, A. J. Danner, and K. D. Choquette, "Two-dimensional photonic crystal confined vertical-cavity surface-emitting lasers," *IEEE J. Sel. Topics Quantum Electron.*, vol. 9, no. 5, pp. 1439–1445, Sep./Oct. 2003.

[8] T. Birks, J. Knight, and P. Russell, "Endlessly single-mode photonic crystal fiber," *Opt. Lett.*, vol. 22, p. 961, 1997.

[9] N. Yokouchi, A. J. Danner, and K. D. Choquette, "Etching depth dependence of the effective refractive index in two-dimensional photonic-crystal-patterned vertical-cavity surface-emitting laser structures," *Appl. Phys. Lett.*, vol. 82, p. 1344, 2003.

[10] J.-H. Baek, D.-S. Song, I.-K. Hwang, K.-H. Lee, and Y. H. Lee, "Transverse mode control by etch-depth tuning in 1120-nm GaInAs/GaAs photonic crystal vertical-cavity surface-emitting lasers," *Opt. Express*, vol. 12, p. 859, 2004.

[11] B. E. A. Saleh and M. C. Teich, "Fiber Optics," in *Fundamentals of Photonics*, J. W. Goodman, Ed. New York: Wiley, 1991, pp. 278–282.

[12] A. J. Danner, J. J. Raftery, Jr, N. Yokouchi, and K. D. Choquette, "Transverse modes of photonic crystal vertical-cavity lasers," *Appl. Phys. Lett.*, vol. 84, p. 1031, 2004.