Anti-resonant Reflecting Photonic Crystal Vertical-Cavity Surface-Emitting Lasers

Hairong Liu* [a], Min Yan [b], Ping Shum [b], H. Ghafouri-Shiraz [c], Deming Liu [a], Xi Lu [a]

[a] Optoelectronic Engineering Department
Huazhong Unversity of Science and Technology,P.R.China, 430074

[b] Network Technology Research Center
Nanyang Technological University, Singapore 639798

[c] School of Electronic, Electrical and Computer Engineering
The University of Birmingham,Edgbaston, Birmingham B15 2TT, UK

ABSTRACT

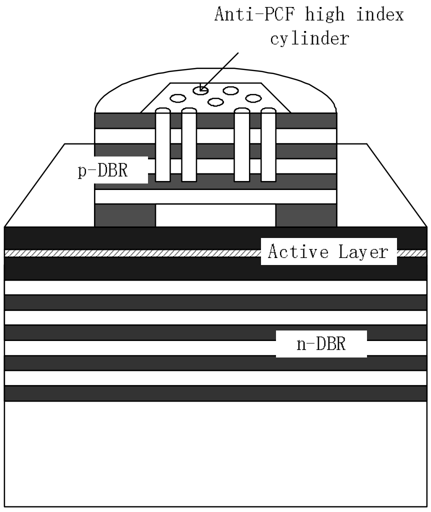
Anti-resonant reflecting photonic crystal structure is employed in vertical cavity surface emitting lasers (VCSELs) to achieve photon confinement in lateral direction. Such a design is promising in supporting large aperture single-mode emission. In the configuration, a hexagonal array of high-index cylinders which run vertically in the cladding region are introduced in the top of the VCSEL p-type DBR mirror region. The transverse modal property of the proposed structure, especially leakage loss, has been investigated. An optimum design for the minimum radiation loss while maintaining single-mode operation has been discussed in this paper.

1. INTRODUCTION

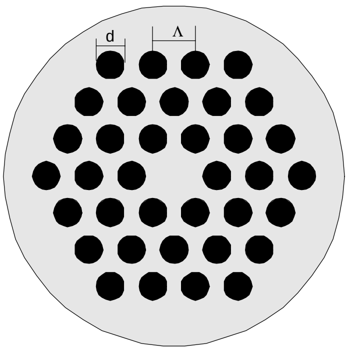
High power, single mode vertical cavity surface emitting lasers (VCSELs) have attracted significant interest in the past years [1-4]. The conventional VCSEL structure incorporates a built-in positive-index waveguide, designed to support a single fundamental mode. However single mode operation for such a VCSEL is normally obtained with small emission apertures, which will limited the maximum output power. There are increasing demands for the larger aperture and higher continuous output powers. Due to the fact that multiple modes will exist in larger aperture waveguide, one of the solutions is to increase the modal discrimination and make the devices favour fundamental mode only [3]. Recently ring-type Anti-resonant-reflecting optical waveguide (ARROW) VCSELs [4] have been reported to operate at single mode with emitting aperture

Semiconductor and Organic Optoelectronic Materials and Devices,
edited by Chung-En Zah, Yi Luo, Shinji Tsuji, Proceedings of SPIE Vol. 5624
(SPIE, Bellingham, WA, 2005) · 0277-786X/05/$15 · doi: 10.1117/12.570580

size as large as $8 \sim 12\mu m$. The cladding of the ring-type ARROW VCSEL can be approximately regarded as a stack of high- and low-index Bragg reflectors. Average refractive index of the stack is higher than core index. Such waveguide's strong leakage discrimination on high-order modes is responsible for achieving single mode operation with large aperture.
Index guiding photonic-crystal structure, a waveguide whose cladding is made of holey photonic crystal, has recently been applied in VCSEL design to get single-fundamental-mode operation by Dae-Sung Song *et al.* [5]. This kind of photonic-crystal VCSEL is expected to provide endlessly single-mode operation. However, the endlessly single mode operation can be provided only if the ratio of the hole diameter to the hole-to-hole distance stays smaller than a certain value. This threshold value could be very small if index contrast involved is relatively high, which would make fabrication a difficult process.



(a)



(b)

Fig 1 (a) Schematic of anti-resonant reflecting photonic crystal VCSEL (b) cross section of the ARRP-VCSEL

In this paper, we propose an alternative design. On the top of the p-type DBR mirror structure, hexagonal arrays of high-index cylinders are introduced in the cladding region. These high-index cylinders are tuned in dimension to strongly reflect light back to the core region. We refer to this design as anti-resonant reflecting photonic crystal vertical cavity surface emitting lasers (ARPC-VCSEL). In contrast to a positive index waveguide, the ARPC-VCSEL can operate with only a fundamental mode even cylinder dimension is relatively big as compared to cylinder-to-cylinder distance since high order modes suffer excessively large loss in this structure.

2. DESIGN OF ANTI-RESONANT REFLECTING PC-VCSEL

The schematic of a 980nm ARPC-VCSELs is shown in Fig.1. As shown in the figure, anti-resonant reflecting photonic crystals are introduced on the top of the p-type DBR mirror region. The inclusion of high-index cylinders in the cladding region gives rise to a waveguide whose core index is smaller than the effective index of its cladding. In such waveguide, light is confined in the low-index core region due to it experiences Bragg reflections at cylinder boundaries along any propagation direction in the entire transverse plane [6]. Photonic bandgap (PBG) is another explanation for the Bragg reflection mentioned here [7].

As stated in reference (Fig 2 in Ref. 4), one proper way to get the ARROW structure is by chemically etching a thin GaAs-GaInP spacer layer. Following by regrowth precess, the high- and low-index ring reflectors can be defined. Our proposed APRC-VCSEL can be realized exactly in the same way. That is, the GaAs-GaInP spacer layer is selectively etched with a photomask whose pattern matches with the array of high index cylinders. The places where the spacer layer remains (an array of circular regions in this case) are responsible for the formation of high index .cylinders after Hardley's effective index modeling [8].

Another possible process to get the antiresonant reflecting photonic crystal VCSELs can be realized by the method proposed in [5]. First, typical mesa structures are introduced on the VCSEL wafer by optical lithography and chemical assisted ion beam etching (CAIBE) method. Then photomasks are used to define the high index cylinders on the mesa. CAIBE method is used to obtain the holes on the top pDBR. After the holes are formed, regrowth of high index material for example GaAs-GaInP (in our design n=3.35) in the holes can be processed to obtain high index cylinders.

After our proposed structure is converted to Hardley's effective index model [3][8], the cross section of the ARPC-VCSELs is shown in the Fig1(b). d is the diameter of the high index cylinders and Λ is the pitch of the cladding photonics crystal. In our design, the effective refractive index of the cylinder $n_{cylinder}$ and the core (or the background region) effective refractive index n_{core} are assumed to be 3.35 and 3.3, respectively, after effective step index model approximation. Cylinder-to-cylinder distance, or period Λ sets to $5.56\mu m$. The emission wavelength is 0.98 μm.

3. RESULTS AND DISCUSSIONS

The field distributions of the LP01 and LP11 mode for three rings of 36 high index cylinders ARPC-VCSEL are analyzed. Finite-difference beam propagation method is applied in the calculation and scalar approximation is assumed since index contrast involved is very small. In the simulation, we observed that the field distributions are greatly affected by the diameter of the high index cylinders. Figures 2 and 3 show the LP01 mode field at $d = 3.38\mu m$ and $d = 2.96\mu m$, respectively. It is found that the field is well confined at $d = 3.38\mu m$. As explained later, this good confinement is due to the fact that the photonic crystal cladding is highly antiresonant at this *d* value. However, at $d = 2.96\mu m$, strong modal field exists in the cladding region. The photonic crystal cladding becomes slightly resonant with the core mode at this *d* value. The LP11 mode field at $d = 3.38\mu m$ is shown in Fig.4. Comparing with the fundament model obtained in the Fig.2, we observed in the structure the fundament mode is better confined than the high order mode. Generally speaking, higher order modes experience higher radiation loss than fundamental mode does.

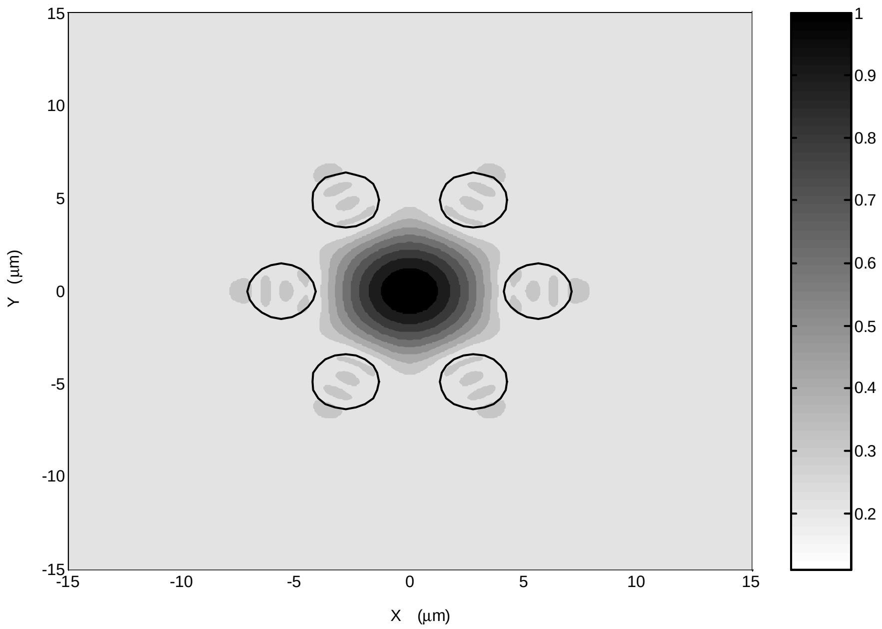


Fig. 2 the normalized LP01mode field of three rings' cylinders at d=3.38um

In order to study the effects of the diameter of the cylinders on the modal loss properties of the proposed structure, we have calculated the effective indices n_{eff} for different values of the cylinder diameter d. The relationship between the imaginary part of n_{eff} and the loss α of the modal can be written as

$$\alpha = \frac{\pi \Im(n_{eff})}{25\lambda} \qquad (1)$$

where the units for wavelength and loss α are in *m* and cm^{-1}, respectively.

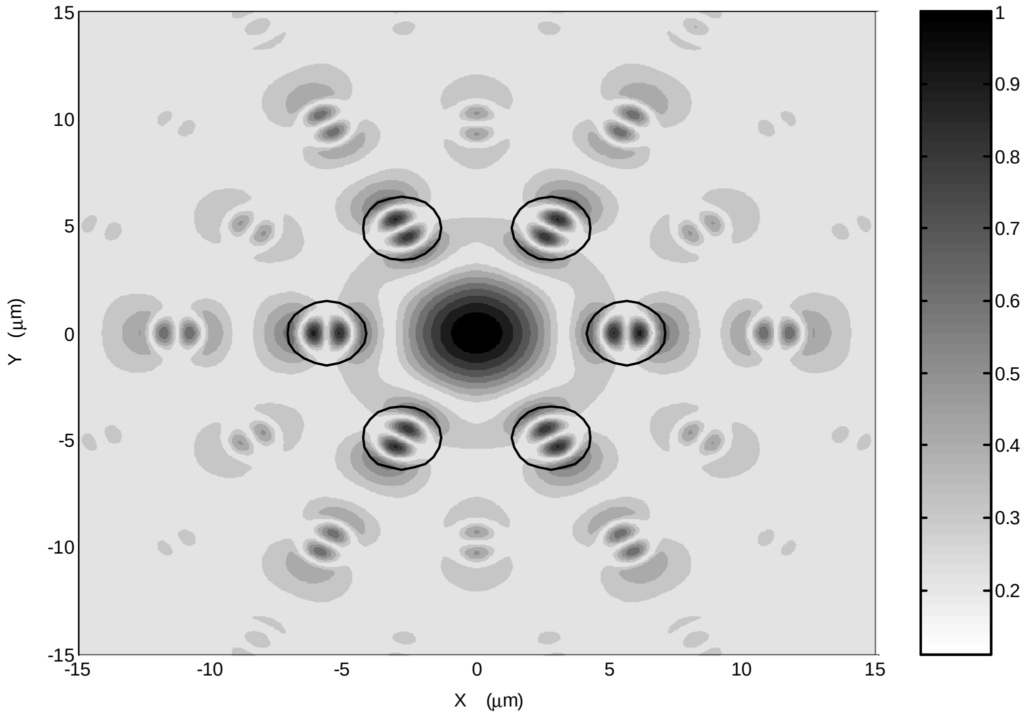


Fig. 3 the normalized LP01mode field of three rings' cylinders at d=2.96 um

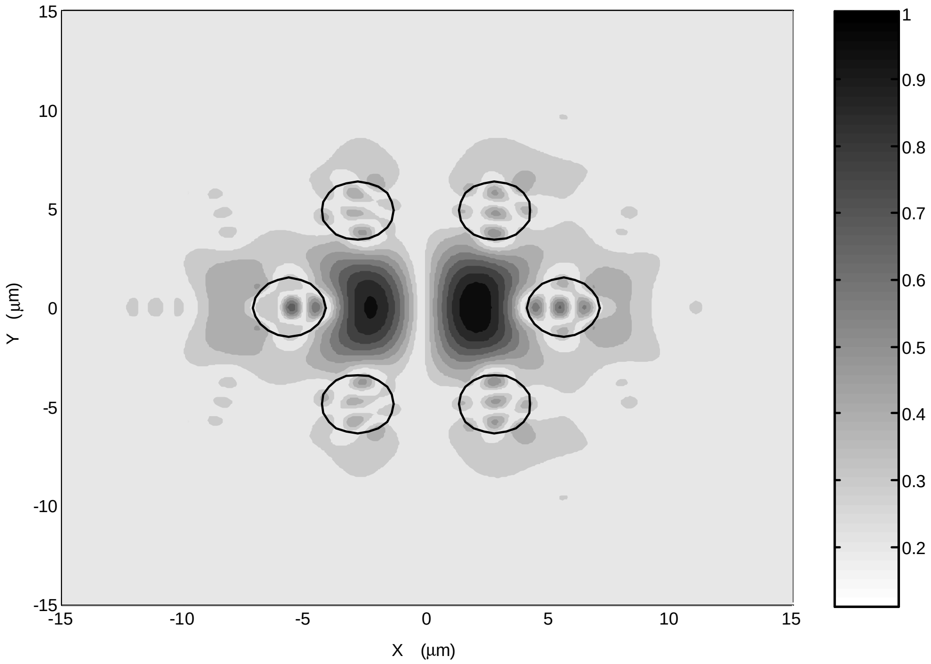


Fig. 4 the normalized LP11mode field of three rings' cylinders at d=3.38 um

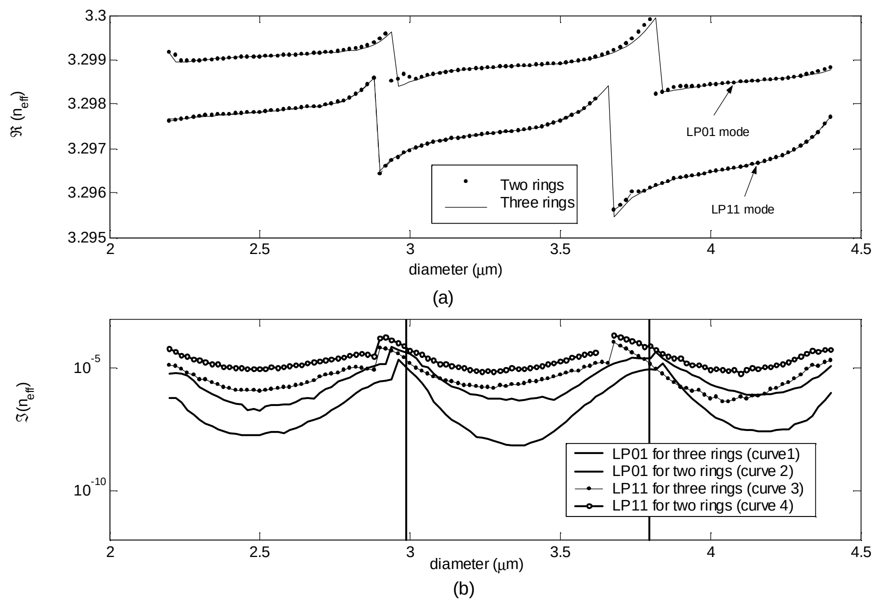


Fig 5 the properties of Modal n_{eff} with the change of the diameter of the high index cylinders

The modal effective index n_{eff} of the two structures: three rings of 36 high index cylinder and two rings of 18 high index cylinders are calculated respectively. Period is fixed at 5.56 um in all simulation. The diameter of all high index cylinders is varied from 2.2 μm um to 4.4 μm. The variation of the real part $\Re(n_{eff})$ and imaginary part $\Im(n_{eff})$ for Lp01 and LP11 modes are shown in Fig.5. Fig. 5a indicates that $\Re(n_{eff})$ curve hardly change from two rings to three rings of cylinders. However, $\Im(n_{eff})$ in Fig.5b shows large difference between of the two rings and three rings structures. We observe there are multiple peaks in the $\Im(n_{eff})$ curves, and $\Re(n_{eff})$ changes sharply at these $\Im(n_{eff})$ peaks. At each peak position, the PC cladding is in complete resonance with the core mode. At these *d* values, light cannot be confined in the core region at all. It is believed that the peaks appearance is due to the scattering properties of the individual cylinders. According to the prediction and analysis model by Natalia M. Litchinister etc. in [9], the peaks of the imaginary part of the effective mode index is determined by the cutoffs for the modes of single high index cylinders immersed in the background index material. The cutoff condition of such a high index cylinder fulfills

$$J_l(k_{ex}d) = 0 \qquad (2)$$

where k_{ex} is the transverse component of the wavevector *k* in high index region. The loss peaks with the diameter can be predicted by the following expression

$$d \cdot \frac{2\pi}{\lambda}\sqrt{n_{cylinder}^2 - n_{core}^2} = roots(J_l) \qquad (3)$$

where $roots(J_l)$ means the roots of Bessel function of order l. It is noticed that those particular diameters where loss peaks are present in Fig. 5b can be predicted very well by the equation (3) (dotted vertical lines in Fig. 5 b). But it is not necessary for every predicted loss peaks using equation (3) to appear. This is because that some predictions, especially those which are calculated using root of a Bessel function of very high order, are corresponding to weak resonances whose effect can be ignored. In Fig5b, peaks for curve 1 appear at around $d = 2.96\mu m$ and $3.80\mu m$. These values agrees well with the calculated diameter $d = 2.9862\mu m$ (corresponding to $roots(J_l)$ =5.5201, one of the roots of J_0) and $d = 3.7953\mu m$ (corresponding to $roots(J_l)$ =7.0156 , one of the roots of J_1) by using equation (3).

According the Fig.5 we can find there is an optimum ARPC-VCSEL design by choosing an appropriate diameter for high index cylinders. The modal loss difference of the LP01 and LP11 approaches to maximum for three rings structure at $d = 3.38\mu m$. To get the single mode operation, it is suggested to make $d = 3.38\mu m$ since at this point fundamental model is favored for its smaller leakage loss and the high order mode is greatly depressed.

4. CONCLUSIONS

We have introduced anti-resonant reflecting photonic crystal structure in vertical cavity surface emitting lasers (VCSELs) to achieve large aperture single-mode operation. The modal loss property of the proposed structures with three and two rings of high index cylinders has been investigated. We found that the modal discrimination is highly improved by using three rings configuration with some appropriate structure parameters. Also it was found the loss properties of the modes are varied periodically. And the maximum loss locations can be determined by analyzing the modal property of a single high index cylinder.

5. REFERENCE

1. A.J. Ficher, K.D. Choquette, W.W. Chow, A.A.Allerman, D.D. Serkland, and K.M.Geib, "High single mode power observed from a coupled-resonator vertical-cavity laser diode", *Appl. Phys. Lett.*, Vol.79,pp4079-4081, 2001

2. Y.A.Wu, G.S.Li,R.F.Nabiev,K.D.Choquette, C,Caneau, and C.J.Chang-Haisnain, "Single-mode, passive antiguide vertical cavity surface emitting laser," IEEE J. Select. Topics Quantum Electron., Vol.1, pp629-, 1995

3. Luke J. Mawst, " "anti" up the aperture", *IEEE circuits & devices magazine*, pp34-41, March, 2003

4. Delai Zhou and Luke J. Mawst, "High-power single-mode antiresonant reflecting optical waveguide-type vertical-cavity surface-emitting lasers", *IEEE J. of Quantum. Electron.* , pp1599-1605, Dec, 2002

5. Dae-Sung Song, Se-Heon Kim, Hong-Gyu Park, Chang-Kyu Kim and Yong-Hee Lee, "Single-fundamental-mode photonic-crystal vertical-cavity surface-emitting lasers", *Applied Physics Letters*, American Institue of Physics, Vol 80, No. 21, pp3901-3903, 2002

6. N.M. Litchiniser, A.K. Abeeluck, C. Headley and B. J. Eggtleton, "Antiresonant reflecting photonic crystal optical waveguides", *Optics Letters*, Vol. 27, No. 18, pp1592-1594, 2002

7. A.K. Abeeluck, N.M.Litchinister, C. Headley, and B.J. Eggleton, "Analysis of spectral characteristics of photonic bandgap waveguides", *Optics Express*, Vol 10, No.23, pp1320-1333,2002

8. G. Ronald Hadley, "Effective index model for vertical-cavity surface-emitting lasers" OPTICS LETTERS ,Vol. 20, No. 13 , pp1483-1485,1995

9. Natalia M. Litchinister, Steven C. Dunn, etc, "Resonances in microstructured optical waveguides", *Optics Express*, Vol. 11,No.10, pp1243-1251,2003.