Optimum design of anti-resonant reflecting photonic crystal vertical-cavity surface-emitting lasers

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Anti-resonant reflecting photonic crystal structure in vertical-cavity surface-emitting lasers (VCSELs) to achieve photon confinement in lateral direction is introduced. This kind of design is proposed to support large aperture single-mode emission. A proper method to fabricate the proposed structure has also been discussed. Firstly a spacer layer will be fabricated between the active layer and pDBR layer. A hexagonal array of high-index cylinders will be designed by etching and re-growth on the spaced layer. The transverse modal property of the proposed structure has been investigated. An optimum design for the minimum radiation loss by considering of the cylinder diameter has been discussed in this paper.

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There are increasing demands with the design of vertical-cavity surface-emitting lasers (VCSELs) for larger aperture and higher continuous output powers. In the past years, high power, single mode VCSELs have attracted significant interest[1−4]. A built-in positive-index waveguide in the conventional VCSEL structure is one way to support a single fundamental mode. However single mode operation for such a VCSEL is normally obtained with small emission apertures. This characteristic will limit the maximum output power at last. To get the high output power, large output aperture is needed. However, multiple modes will exist in such large aperture waveguide. One of the solutions to get the high output power by maintaining large aperture is to increase the modal discrimination and make the devices favor 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 size as large as 8–12 μm. The cladding of the ring-type ARROW VCSEL is composed by a stack of high- and low-index Bragg reflectors. Average refractive index of the stack is higher than core index. Such waveguide can achieve single mode operation with large output aperture due to its strong leakage discrimination on high-order modes. 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 Song *et al.*[5]. 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 would bring a difficult fabrication process.

Anti-resonant reflecting photonic crystal optical waveguides are another way to get single mode operation with large aperture[6,7]. In this paper, optimum design has been done with the structure proposed in Ref. [8]. 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 though cylinder dimension is relatively big as compared to cylinder-to-cylinder distance since high order modes suffer excessively large loss in this structure.

The proposed ARPC-VCSEL is shown in Fig. 1(a). As stated in Ref. [8], one proper way to get the APRC-VCSEL structure is by fabricating a thin GaAs-GaInP spacer layer between the active layer and p-DBR layer firstly. The GaAs-GaInP spacer layer is then selectively etched with a photomask whose pattern matches 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 the proposed structure is converted to Hardley's effective index model[9], the waveguide adopted can be schematically shown in Fig. 1(b). Background region is of lower index. Black regions represent high-index rods that run along the waveguide's axial direction. As the average index of cladding is higher than that of core, index-guiding is dismissed in such waveguide. In fact, photonics crystal (PC) is formed by the hexagonal array of rods in cladding region reflecting light strongly at certain wavelength ranges. Photonic band gap (PBG) is formed in this kind of structures. Such light confinement in low-index core region is attributed to Bragg reflections at cylinder boundaries along any propagation direction in the entire transverse plane.

The cross section of the ARPC-VCSEL is shown in the Fig. 1(c). d is the diameter of the high index cylinders and Λ is the pitch of the cladding PC. In our design,

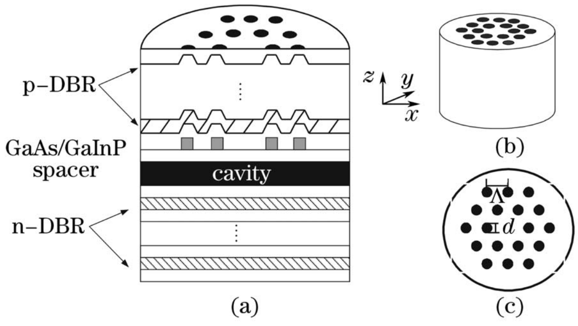

Fig. 1. (a) Schematic of ARPC-VCSEL. (b) Waveguide incorporated in ARPC-VCSEL after Hardley model. (c) Cross section of the ARPC-VCSEL, the black regions represent high index cylinders.

the effective refractive indices of cylinder n_{cylinder} (black areas) and n_{core} core (or the background region, white areas) are assumed to be 3.35 and 3.3, respectively. Λ is chosen at 6.36 μm, and the diameter of the cylinder d=2.96 μm. The emission wavelength is 0.98 μm.

Multipole method[10] has been adopted to simulate the proposed two rings of high index cylinders ARPC-VCSEL. The n_{eff} of different modes and the results are obtained by the above processes and the effective refractive index of the first three modes is given in the following Table 1. It was shown that the high order mode has large modal loss comparing with those low order modes.

The field distributions of HE_{11}^{x}, HE_{11}^{y}, TE_{01} and TM_{01} modes of ARPC-VCSEL are calculated, as shown in Figs. 2–5, respectively. We also have investigated the modal confinement losses with the change of the diameter of the high index cylinders. The modal losses of HE_{11} are calculated over a range of diameters from 2 to 6 μm and the results are shown in Fig. 6. From the figure we can see that the model loss changes periodically with the variation of the diameter of the high index cylinders. This could be explained by the fact that when the diameter of the high index cylinders has been changed.

Table 1. Mode Effective Refractive Index for the First Four Modes

$\Re(n_{\mathrm{eff}})$	$\Im(n_{\mathrm{eff}})$	Mode Description
3.29873540105	$1.48944903979\times10^{-5}$	HE_{11} Mode
3.29789257652	$54.86763200018\times10^{-5}$	TE_{01} Mode
3.29788880881	$4.87628676138\times10^{-5}$	TM_{01} Mode

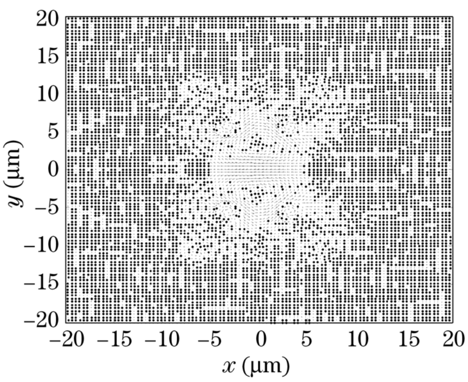

Fig. 2. Transverse electric field of HE_{11}^{x} mode.

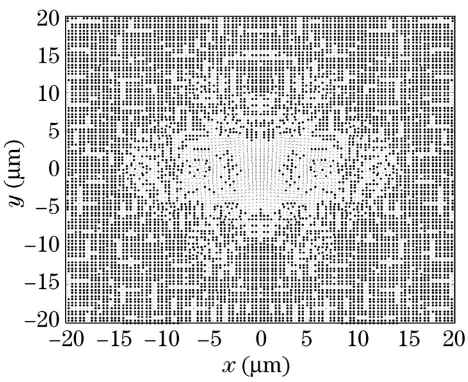

Fig. 3. Transverse electric field of HE_{11}^{y} mode.

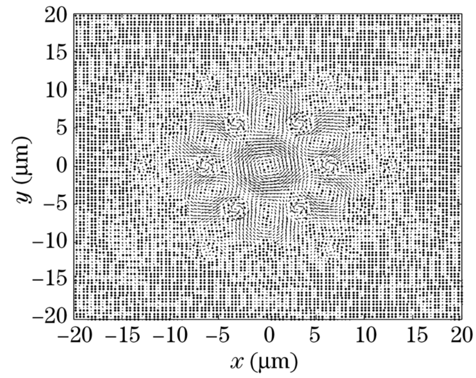

Fig. 4. Transverse field of TE_{01} mode.

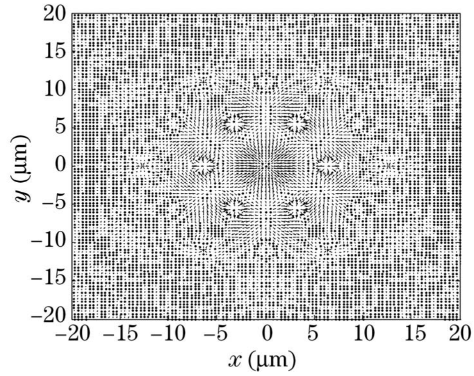

Fig. 5. Transverse field of TM_{01} mode.

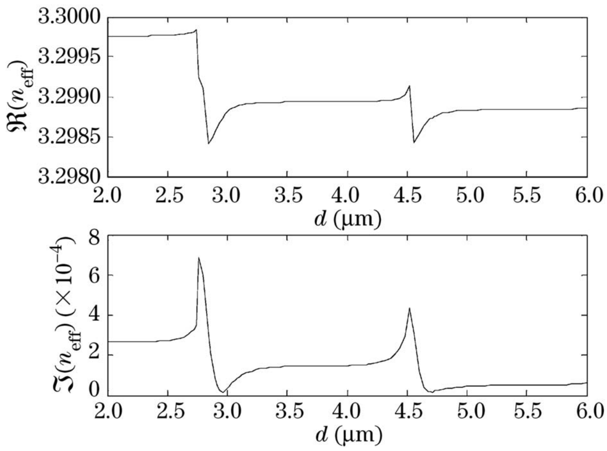

Fig. 6. Fundermental loss with change the diameter of the high index cylinders.

the band gap of the cladding will be changed also. Thus the investigated mode will experience different loss. From Fig. 6 we can choose the propel diameter of the cylinders to get the proposed loss.

In conclusion, anti-resonant reflecting photonic crystal structure has been introduced in vertical cavity surface emitting lasers VCSELs to achieve large aperture single-mode operation. The modal loss property of the proposed structures with two rings of high index cylinders has been investigated. It was found the loss properties of the modes are varied periodically with the diameter of the high index cylinders. The optimum design regarding the diameter of the high index cylinders is also discussed.

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