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# 980nm Photonic Microcavity Vertical Cavity Surface Emitting Laser

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## 1. Introduction

Vertical-Cavity Surface-Emitting Laser (VCSEL) is a type of semiconductor laser with laser beam perpendicular to the surface of the semiconductor substrate, as shown in Fig.1(a) [1]. VCSEL has many advantages, such as non-divergence output beam, fabrication and test on wafer, easy two-dimensional integration, and single longitudinal mode work. VCSEL is composed of an active region sandwiched between top and bottom highly reflective DBR mirror [2,3]. Generally high power VCSEL could be realized through large emission window, but suffers multi-mode operation due to the inhomogeneous current distribution across the active region. On the other hand single-mode operation is required in many applications including optical communications. Single-mode can transport longer distance and meet the requirements of high-speed data transmission [4,5]. Several approaches such as confined aperture less than 3μm, proton implantation, oxide and proton implantation mixed structure have been reported to achieve single-mode VCSEL. Due to the small aperture of emission window, these VCSELs are lasing at low output power. Besides the requirements of high output power and single mode operation, the wavelength range of VCSEL is broadened by applying InAs quantum dots or InGaAsN quantum well of the wavelength range of 1300nm and nitride quantum well of the blue light range for the applications of fiber communication and display.

In the past few years photonic crystal materials became of a great interest due to their powerful properties allowing for previously unknown flexibility in shaping the light. On the contrary to conventional edge emitting laser, the cavity length of VCSEL is of the size of optical wavelength. This brings VCSEL actually into microcavity field, where spontaneous emission is believed not to be an intrinsic atomic property anymore. Spontaneous emission can be enhanced or inhibited by tailoring the electromagnetic environment that the atom can radiate into. In a conventional edge emitting laser made of large cavity, most of the spontaneous emission is lost to free space as radiation modes and only a small fraction couples to the resonant mode of the cavity formed by the mirrors. Therefore, significant stimulated emission output can only be obtained when the input power crosses a threshold to overcome the free-space loss. In a wavelength-sized microcavity, the photon-mode density develops singularities, just as in the case of carrier confinement in quantum well. In this case, a single spectrally distinct mode can receive most or all of the spontaneous emission, indicating threshold-free stimulation. The rate of spontaneous emission is enhanced in such a microcavity, due to the change in the mode density. Photons whose energies lie within the band gap of photonic crystal cannot propagate through the structure. A point defect in the photonic crystal structure will generate localized state inside the band gap and form a microcavity. All the photons corresponding to the wavelength of the defect can propagate in the crystal. An example of such microcavity is DBR with high-reflectivity mirrors in the direction of the guided modes.

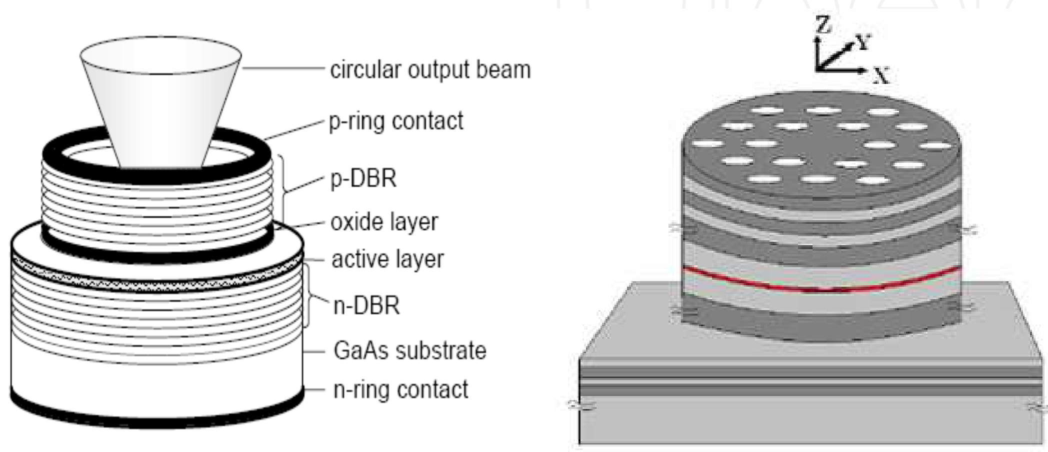



Fig. 1. VCSEL structure ((a): conventional VCSEL, (b): PhC-VCSEL)

The localization of electromagnetic models in single or multiple defects enabled to build photonic-crystal fibers, photonic planar waveguides, filters, splitters etc. Among these novel photonic crystal structures, photonic crystal-based VCSEL (PhC-VCSEL), as shown in Fig.1(b), is becoming an alternative approach and attracting more and more attention. These devices have strong potential due to their unique properties, which make them a perfect choice for many applications. These properties include stable single-mode operation [6], high-speed modulation [7] and polarization control [8]. However, to guarantee the efficient use of photonic crystals one needs careful consideration of the photonic crystal structure, which actually form a microcavity to modulate the spontaneous emission characteristics of VCSEL. Typical PhC-VCSELs consist of a classical VCSEL cavity surrounded by Distributed Bragg Reflectors (DBRs) of high reflectivity. The photonic crystal has a form of cylindrical holes located in various parts of the device. In the simplest case—and therefore the most popular one—the holes are etched in the top DBR. However, there are other possibilities like drilling the whole structure or placing the holes solely in the cavity, which can improve some properties of PhC-VCSEL but although constitutes a technological challenge. Photonic crystal structure with defects at the center was incorporated into the top layer to form microcavity, which provide lateral light confinement and also the modulation to the photon mode. However, large optical loss due to deeply-etched air holes still remains as a problem. The large optical loss is undesirable because it increases not only threshold current but also operating current level. High operating current can limit maximum single-mode output power via heating problem and lead to higher electrical power consumption.

Traditional VCSELs suffer a major drawback of the instability of the polarization, which generally attributed to the symmetric device structure. The polarization of a VCSEL tends to randomly follow one of the crystal axes and fluctuates with current. For applications such as 10-Gbit/s-class high-speed modulation1 and free-space interconnect using polarization-dependent optical components, a pinned polarization gives better performance. The competition between the modes with orthogonal polarizations can lead to polarization switching and mode hopping [9,10]. Such behavior is unacceptable for many practical applications such as intra-cavity frequency doubling, where other elements are polarization-dependent. Several approaches for polarization control have been reported based on the introduction of anisotropy to either gain or losses. These approaches include asymmetric shape resonator, metal-semiconductor gratings, or sub-wavelength grating by directly etching the top surface. In order to make use of the PhC structure for polarization control in VCSELs, PhC with elliptic air holes has been reported with polarization mode suppression ratio (PMSR) of over 20 dB in [11]. Triangular lattice PhC has been implemented with air holes elongated either along CK or CM directions. Disadvantages of etching photonic crystal holes include increased resistance and optical losses leading to higher threshold currents and voltage.

In this paper two-dimensional photonic crystal structure of hexagonal lattice of air holes on the top DBR reflector was introduced in VCSEL to suppress higher order mode operation. Defect structure of photonic crystal was created by filling one air hole ($H_1$ microcavity) or seven air holes ($H_2$ microcavity) to investigate the mode characteristics of VCSEL. With the proper selection of hole depths, diameters, and arrangement, this index confinement can be exploited to create single mode photonic crystal defect VCSELs that have the potential for low threshold currents and high output powers. The specific parameters of hexagonal lattice were optimized to achieve high Q factor of the microcavity.

## 2. Model and calculation

### 2.1 Photonic crystal micro-cavity VCSEL model

The active region of 980nm VCSEL was composed of three 8nm thick $In_{0.2}Ga_{0.8}As$ quantum well layers with 10nm thick GaAs barrier layer. $Al_{0.98}Ga_{0.02}As$ layer is incorporated between the P-type DBR and the active region to form lateral oxidation and provide both current and optical confinements. The reflectors were DBR mirrors with the reflectivity higher than 99%. In this work a periodic arrangement of air holes on the top DBR reflector was designed to form two-dimensional photonic crystal structure. Two kinds of lattice defect were produced to evaluate the Q factor of the microcavity. Schematic diagram of the structure was shown in Fig. 2.

Generally there were two types of two-dimensional periodic arrangement of photonic crystals: hexagonal lattice and square lattice. Under the similar lattice parameters of hole depth, diameter and distance, hexagonal lattice was suggested to obtain photonic band gap easily than the square lattice does. Once the photonic band gap was created, the band gap of hexagonal lattice was wider than that of square lattice. Therefore hexagonal lattice was often used in the design of PhC-VCSEL. When one or several holes were removed from the lattice, the periodicity of the lattice structure was destroyed. The simplest way is to remove one air hole from the center of the lattice. This created the H1 cavity, shown in Figure 3(a). The second photonic crystal defect structure, H2 microcavity, was to remove seven air holes from the center, as shown in Figure 3(b). In our simulation the air hole was etched through the top DBR and stop above lateral oxidation layer. The period of air holes was chosen to be 5.5μm for the easiness of fabrication.

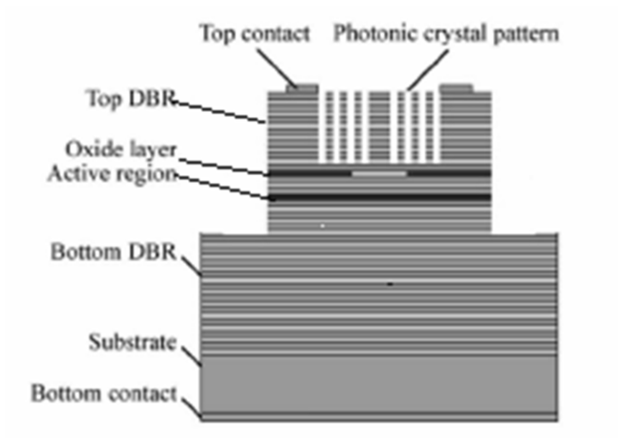
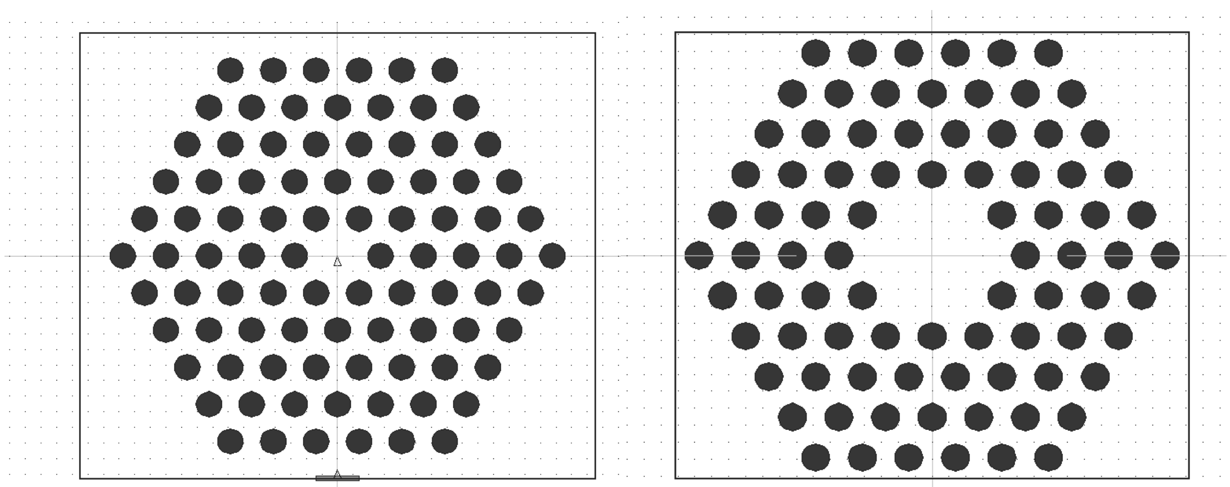



Fig. 2. Photonic crystal microcavity VCSEL



(a) (b)

Fig. 3. Photonic crystal micro-cavities (a: H1 microcavity and b: H2 micro-cavity)

### 2.2 Analysis of single-mode condition

Photonic crystal defect structure with several holes missing at the center was similar to photonic crystal fiber where the solid center was surrounded by periodic arrangement of air holes, as shown in Figure 4. The characteristics of microcavity was only determined by the arrangement of air holes and the configuration of defect. There is no active material in the PhC structure. Therefore, the theory of photonic crystal fiber was used to investigate the normalized frequency of PhC defect structure in this work.

In the theory of photonic crystal fiber, the normalized frequency was expressed as following:

$$V_{eff} = (2\pi a / \lambda)(n^2{}_0 - n^2{}_{eff})^{1/2} \quad (1)$$

Where $a$ is the lattice period, $\lambda$ is the wavelength, $n_0$ is the refractive index of the cavity center, $n_{eff}$ is the external refractive index of the photonic crystal cladding.

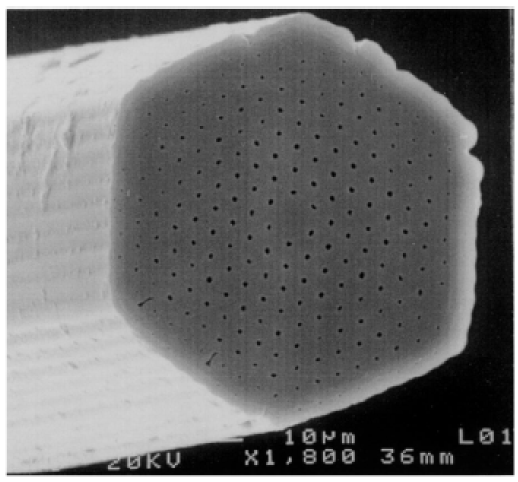



Fig. 4. Photonic crystal fiber

According to photonic crystal theory, the following requirement of normalized frequency should be met to achieve single-mode operation.

$$V_{eff} < 2.405 \quad (2)$$

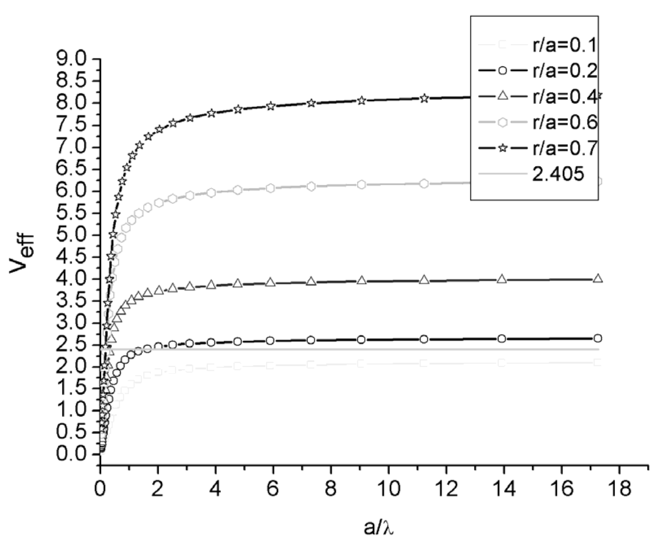



Fig. 5. Normalized frequencies $V_{eff}$ of H1microcavity at different filling ratio

According to the analysis above, the normalized frequency of H1 photonic crystal microcavity was calculated. The filling ratio *r/a* of 0.1, 0.2, 0.4, 0.6 and 0.7 was suggested for the calculation of normalized frequency, as presented in Fig.5. It was shown that H1 photonic crystal micrcavity meets the requirement of single-mode operation when the filling ratio was less than 0.1. Obviously, smaller filling ratio was beneficial to single-mode operation. But too small filling ratio would cause additional difficulty in the fabrication process of photonic crystal structure. In the above calculation the hole depth was set to be infinite. However, the thickness of VCSEL chip is reasonably around 150μm like conventional edge emitting diode laser chip. It is very difficult, if required small filling ratio, to etch through the entire chip. And the mechanical strength of the device and the electrical properties would be deteriorated significantly. So the reliable hole depth was limited, which was not the case of identical photonic crystal fiber. Therefore the calculation above based on the theory of photonic crystal fiber should be modified as follows:

$$V_{eff} = (2\pi a / \lambda)\left[ n^2{}_0 - (n_0 - \gamma\Delta n)^2) \right]^{1/2} \tag{3}$$

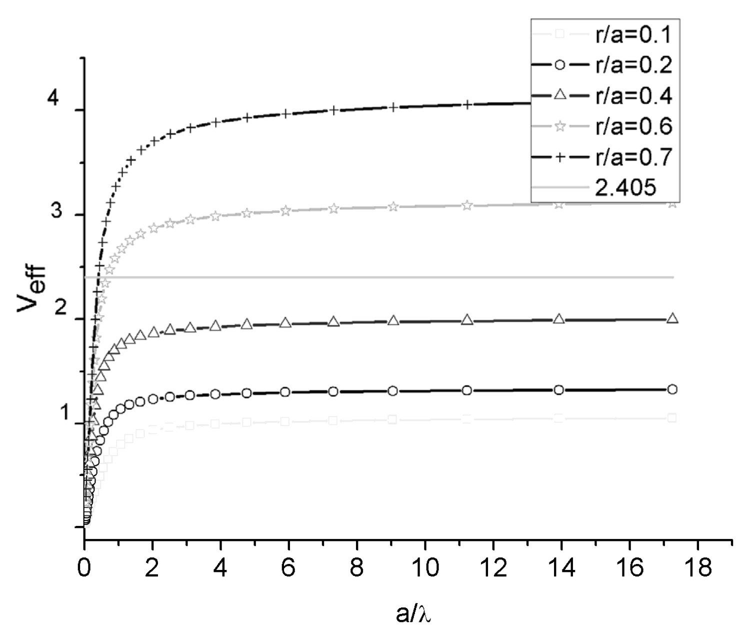



Fig. 6. Normalized frequencies $V_{eff}$ of H1microcavity at different filling ratio based on modified calculation

The normalized frequencies $V_{eff}$ of H1microcavity were calculated based on the modified model of equation (3) for different filling ratio, as shown in Fig.6. The corresponding etching depth factor γ was 0.3. Comparing Fig.5 and Fig.6 carefully, it was observed that single mode operation was realized for a filling ratio of 0.4. Though this filling ratio corresponds originally to multi-mode operation when the hole depth was set to be infinite as shown in Fig.5. This enables the fabrication of H1 microcavity much more easily while single mode operation was still maintained.

Similar to the above analysis, H2 microcavity with seven holes in the center missing was calculated, as shown Fig.4. The normalized frequencies was as following

$$V_{eff} = (2\pi\sqrt{3}a / \lambda)\left[n^2{}_0 - (n_0 - \gamma\Delta n)^2)\right]^{1/2} \tag{4}$$

For single mode operation, the normalized frequency of H2 microcavity was smaller than that of H1 microcavity. At a filling ratio of 0.1, the output is single mode. This result might caused by relatively weak confinement of H2 microcavity compared with H1 microcavity.

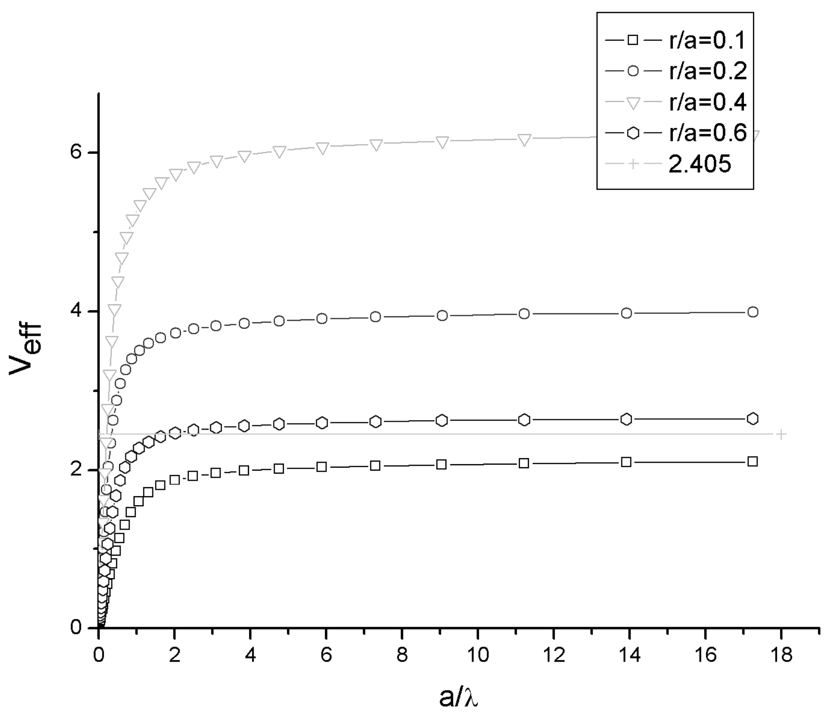
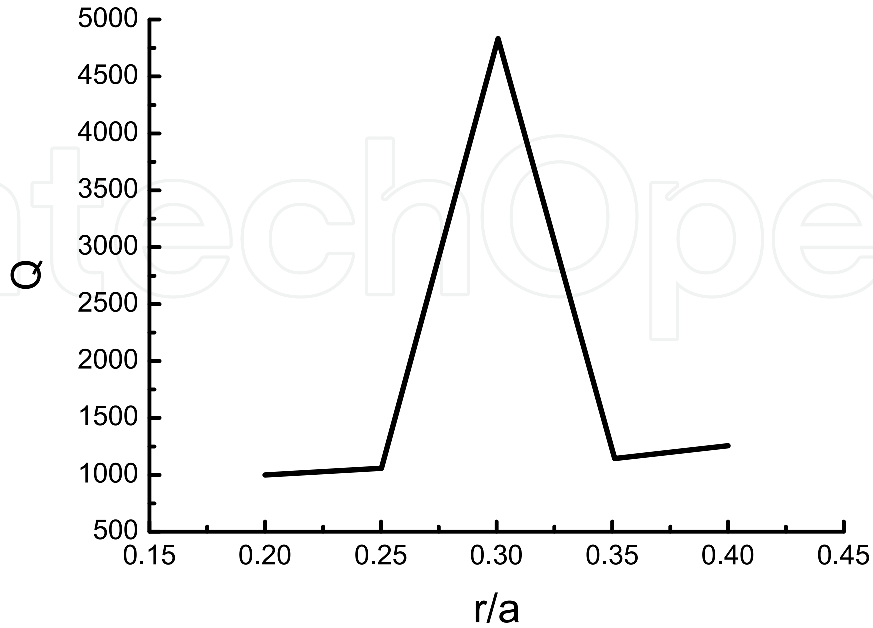



Fig. 7. Normalized frequencies $V_{eff}$ of H2 micro-cavity at different filling ratio

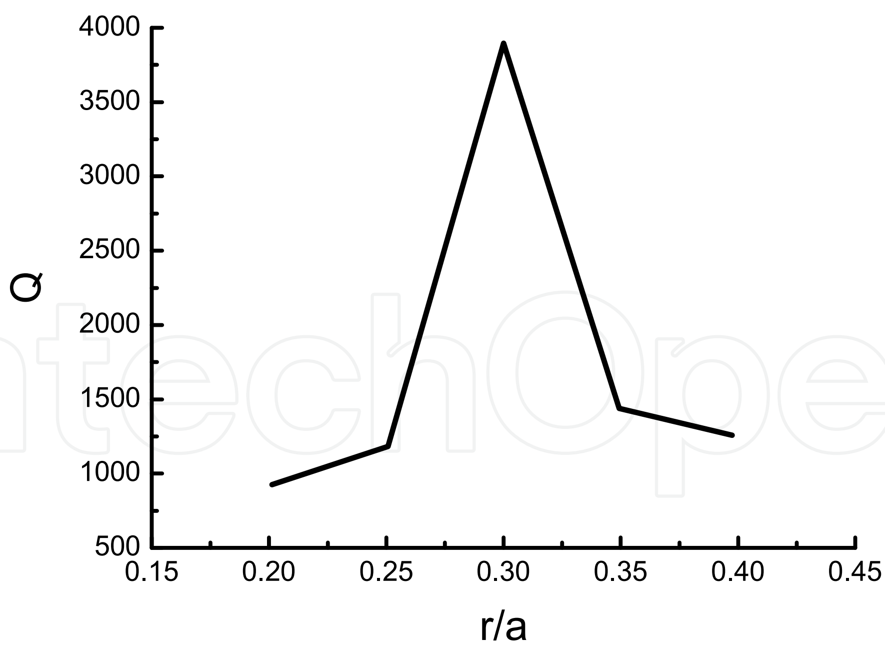
### 2.3 Quality factor *Q* of microcavity

The cavity mode volume was reduced greatly in a photonic crystal microcavity, which improved the coupling of light field with the cavity mode. High quality factor of microcavity could be realized due to the light confinement provided by the photonic band gap in the lateral direction.

Cavity quality factor *Q* was an important parameter for evaluating photonic crystal VCSEL. Quality factor implies the ability of a microcavity to store energy. Obviously a photonic crystal microcavity with high Q was the purpose of an ideal design. *Q* was defined as:




(a)




(b)

Fig. 8. Quality factor of microcavity at different filling ratio (a: H1 microcavity, and b: H2 microcavity)

$$Q = 2\pi \frac{qh\nu}{\left(-\frac{dh}{dt}\right)h} \tag{5}$$

Where $q$ is the total number of photon in microcavity, $h$ is Planck constant, $\nu$ is the resonant frequency. Now the quality factors $Q$ of H1 and H2 microcavity were calculated for different filling ratio, as shown in Fig.8.

It was shown that the Q value reach a maximum of 4832(H1) and 3931(H2) when the filling ratio was 0.3.

## 3. Conclusion

Photonic crystal micro-cavity VCSEL with hexagonal lattice of air holes was discussed in regarding the quality factor and the requirement of single mode operation. The normalized frequencies of two types of microcavities (H1 and H2) were calculated based on modified theory of photonic crystal fiber. A filling ratio of 0.4 for $H_1$ microcavity was considered to be a good choice for single mode operation when the etching depth factor was 0.3. For $H_2$ microcavity, the filling ratio less than 0.1 were necessary for single mode operation. The difference between the filling ratios for $H_1$ and $H_2$ microcavities might suggest weak confinement of $H_2$ microcavity. Quality factors $Q$ of two microcavities were calculated to be 4832($H_1$) and 3931($H_2$) respectively.

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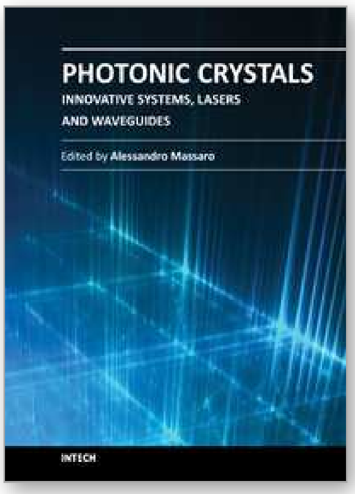


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The second volume of the book concerns the characterization approach of photonic crystals, photonic crystal lasers, photonic crystal waveguides and plasmonics including the introduction of innovative systems and materials. Photonic crystal materials promises to enable all-optical computer circuits and could also be used to make ultra low-power light sources. Researchers have studied lasers from microscopic cavities in photonic crystals that act as reflectors to intensify the collisions between photons and atoms that lead to lazing, but these lasers have been optically-pumped, meaning they are driven by other lasers. Moreover, the physical principles behind the phenomenon of slow light in photonic crystal waveguides, as well as their practical limitations, are discussed. This includes the nature of slow light propagation, its bandwidth limitation, coupling of modes and particular kind terminating photonic crystals with metal surfaces allowing to propagate in surface plasmon-polariton waves. The goal of the second volume is to provide an overview about the listed issues.