A vertical cavity surface emitting laser based on Fibonacci photon quasicrystal cavity

Xiaolin Liu, Xiaohong Sun *

1Henan Key Laboratory of Laser and Opto-electric Information Technology, School of Information Engineering, Zhengzhou University, Henan 450052, China

*Corresponding author E-mail: iexhsun@zzu.edu.cn

Abstract: In this paper, a vertical cavity surface emitting laser (VCSEL) is designed based on Fibonacci photonic quasicrystal (FPQC) cavity. This laser uses a light source with a spectral center of 460 nm. Two different FPQC structures are designed and optimized to serve as the total reflection mirror (TRM) and the transmission mirror (TM) of the resonant cavity, respectively. Compared with the distributed Bragg reflection (DBR) cavity, the designed FPQC cavity laser has smaller far-field divergence angle and relative mode field area, as well as higher brightness.

1. Introduction
Semiconductor lasers have advantages in photoelectric conversion efficiency, output power, and service life. The main application fields require lasers to have high output power, beam quality and brightness at the same time. However, the large divergence angle makes the direct coupling efficient of the optical fiber lower, which limits direct application of semiconductor laser in the industrial field. The laser that emits light from the direction perpendicular to the surface of the semiconductor substrate has the advantages of good mode, low threshold, good stability, long life, high modulation rate, high integration, small divergence angle, high coupling efficiency and low price [1].

Many researchers have adopted a large cavity structure [2] in order to reduce the far-field divergence angle of the laser by widening the thickness of the upper and lower waveguide layers or increasing the refractive index of the waveguide layer to extend mode volume for wattage output power and high conversion efficiency, and the far-field divergence angle is reduced to 10° ~ 20° [3-4]. However, the structure has problems such as an increase in the number of transverse modes and a weakening of the refractive index guide, and the final emission spectrum exhibits more harmonics. In 2002, Ledentsov of the Technical University of Berlin in Germany proposed a scheme to introduce a one-dimensional photonic crystal waveguide on the N-side of a semiconductor laser to improve the mode expansion in the direction. The theoretical and measured values of the far-field divergence angle of the laser at the same time are weakened are 6° and 8°, respectively [5]. In 2005, the Ioffe Institute of Phys and Technology in Russia used the concept of photonic crystal waveguide to realize a 20W pulse power output at 646nm in the visible light range. The output power is 2.5 times as much a conventional semiconductor laser of the same type, and the divergence angle is reduced to 8° [6]. In 2011, the Ferdinand-Brown Institute of Germany [7] used a low-refractive-index quantum barrier structure [8-9] to expand the waveguide thickness of a large cavity structure to 8 μm, and the output power obtained was watt-level, and its divergence angle was 9°. Kaspi of the US Air Force Laboratory used a large optical cavity laser with an optical pump to achieve a divergence angle of less than 10° [10]. At the same time, the German industrial university in Berlin, the Ioffe Institute of Phys and Technology in Russia
and the PBC laser company in Israel cooperated to adopt a waveguide structure that introduces one-dimensional photonic crystals laterally at multiple wavelengths (650[11], 850[12], 980[13], 1064[14]). A semiconductor laser with a low divergence angle (5°~10°) is realized. The 1060nm pulse output power achieved in 2014 is close to 20W, and the continuous output power reaches the watt level up to 9.5W [15].

In this paper, a VCSEL with FPQC cavity is designed. Two FPQC cavity mirrors are designed and optimized to decrease the far-field divergence angle and mode field area, and increase the emission intensity.

2. Structure design of VCSEL laser

The structure of the laser is shown in figure 1. The middle layer is a quantum-dot light emitting layer (white). Right side of the source is the TRM and substrate of glass (gray). Left side of the source is a transmission mirror (TM) where the laser exit. TRM and TR of the cavity are composed of Fibonacci structures [16].

![Figure 1](image-url)

Figure 1 Schematic diagram of the laser

3. Optimization of FPQC cavities

We used FDTD Solutions for simulation calculations. Considering the VCSEL cavity, a TRM is required on the bottom mirror. In order to determine the optimal number of layers of TRM, the reflectance of the 1st to 11th layers were tested while minimizing the thickness of TRM. It can be seen from figure 2 that the structure of 7-layer and above have a high reflectance of more than 90%. And after optimization, the structure which reflectance is 99.958% can be used as TRM of 460nm.
Figure 2 Reflectivity vs. number of FPQC layers

When the number of reflection mirror’s layer is fixed at 7, the thickness of TiO$_2$ and SiO$_2$ is optimized for each layer to obtain a TRM with an optimal reflectivity. Two steps are executed. First, the thickness of TiO$_2$ is fixed at 600 nm. By changing the thickness of SiO$_2$ from 300 nm to 700 nm, the reflectance is investigated, shown in figure 3(a). From the figure, we can see that the maximum reflectivity with 97.99% happens at SiO$_2$ with the thickness of 641.3 nm. Second, fixing SiO$_2$ at 641.3 nm and varying the thickness of TiO$_2$ from 300 nm to 700 nm, and the maximum reflectance of the 7-layer structure is determined (reflectance 99.958%), and the optimum thickness of TiO$_2$ is determined to be 565.31 nm, shown in figure 3(b).

Figure 3 TRM reflectivity changing with (a) the thickness of SiO$_2$ with the fixed thickness of TiO$_2$ at 600 nm. (b) the thickness of TiO$_2$ with the fixed thickness of SiO$_2$ at 641.3 nm.

The other side of the VCSEL cavity is the transmissive surface. The smaller the far-field divergence angle and the relative mode field area of the entire laser beam is, the higher the beam brightness is. The far-field divergence angle is calculated using the beam radius at 1/e of the peak intensity, which contains about 63.2% of the total energy.

We use the same light source to pass through the 0 to 9 layers structure, respectively. And we measure the far-field divergence angle and the relative mode area of these structures at the same position. As shown in figure 4, After adding the cavity, the far-field divergence angle and relative mode field area will decrease, and 7-layer of the transmission mirror structure is optimal.
We use the same method to get the thickness of the transmission mirror. When the number of transmission mirror's layer is fixed at 7, the thickness of TiO$_2$ and SiO$_2$ is optimized for each layer to obtain a transmission mirror with the smallest far-field divergence angle and the relative mode field area. First, the thickness of TiO$_2$ is fixed at 600 nm. By changing the thickness of SiO$_2$ from 300 nm to 700 nm, the divergence angle and the relative mode field area is investigated, shown in figure 5(a). From the figure, we can see that the minimum divergence angle and the relative mode field area happens at SiO$_2$ with the thickness of 525.5 nm. Second, fixing SiO$_2$ at 525.5 nm and varying the thickness of TiO$_2$ from 300 nm to 700 nm, and the minimum divergence angle and the relative mode field area of the 7-layer structure is determined, and the optimum thickness of TiO$_2$ is 550.1nm, shown in figure 5(b).

Figure 5 Transmission mirror far-field divergence angle and relative mode field area changing with (a) the thickness of SiO$_2$ with the fixed thickness of TiO$_2$ at 600nm. (b) the thickness of TiO$_2$ with the fixed thickness of SiO$_2$ at 525.5nm
Figure 6(a) shows the emission spectrum of the FPQC and source spectrum, and figure 6(b) shows the emission spectrum of the DBR cavity [17] and source spectrum. Compared with the DBR cavity, the FPQC cavity has fewer resonant waves and higher light intensity.

![Figure 6 (a) Emission spectrum of FPQC (black) and spectrum of source (red) (b) Emission spectrum of DBR (black) and spectrum of source (red)](image)

The monitors are placed at a distance of 1640 nm from the cavity surface. Figure 7 shows the far-field divergence angle of three kinds of lasers. From the figure, we can see that the angle of FPQC laser is smaller than DBR laser and the source with no cavity. It proves that FPQC laser has higher collimation.

![Figure 7 The far field divergence angle of (a) FPQC laser (b) DBR laser (c) the source with no cavity](image)

4. Conclusions

A VCSEL with FPQC cavity has been designed. By optimizing the structure of FPQC cavity, the laser has been obtained with good emission characteristics. Compared with DBR cavity laser, the laser has a smaller divergence angle of 5.7° (while the DBR cavity laser is 7.3°) and mode field area of 4.15 $\mu m^2$ (while the DBR cavity laser is 5.39 $\mu m^2$).

References

[1] Iga K. Surface-emitting laser-its birth and generation of new optoelectronics field[J]. Sel. Top in Qua. Electron IEEE J of, 2000, 6(6):1201-1215.
[2] Lockwood H F, KresSel. H, Jr H S S, et al. An efficient large optical cavity injection laser [J]. Appl. Phys. Lett., 1970, 17(11):499-502.
[3] Wenzel H, Bugge F, Erbert G, et al. High-power diode lasers with small vertical beam divergence emitting at 808 nm[J]. Electron Lett., 2001, 37(16):1024-1026.
[4] Sebastian J, Beister G, Bugge F, et al. High-power 810-nm GaAsP-AlGaAs diode lasers with
narrow beam divergence[J]. *IEEE J of Sel. Top in Qua. Electron*, 2001, 7(2):334-339.

[5] Ledentsov N N, Shchukin V A. Novel approaches to semiconductor lasers[C]. *In Asia-Pacific Opt. and Wireless Commun. Int. Soc. for Opt. and Photon.*, 2002.

[6] Maximov M V, Shernyakov Y M, Novikov I I, et al. High power GaInP/AlGaInP visible lasers (\(\lambda = 646\) nm) with narrow circular shaped far-field pattern[J]. *Electron Lett.*, 2005, 41(13):741-742.

[7] Crump P, Pietrzak A, Bugge F, et al. 975 nm high power diode lasers with high efficiency and narrow vertical far field enabled by low index Qua. barriers[J]. *Appl. Phys. Lett.*, 2010, 96(13):719803.

[8] Pietrzak A, Crump P, Wenzel H, et al. Combination of Low-Index Qua. Barrier and Super Large Opt. Cavity Designs for Ultranarrow Vertical Far-Fields From High-Power Broad-Area Lasers[J]. *IEEE J of Sel. Top in Qua. Electron*, 2011, 17(6):1715-1722.

[9] Pietrzak A, Wenzel H, Crump P, et al. 1060-nm Ridge Waveguide Lasers Based on Extremely Wide Waveguides for 1.3-W Continuous-Wave Emission Into a Single Mode With FWHM Divergence Angle of 9(°) × 6(°) [J]. *IEEE J of Qua. Electron*, 2012, 24(7):599-601.

[10] Kaspi R, Tilton M L, Dente G C, et al. Ultralow Beam Divergence and Increased Lateral Brightness in Opt.ly Pumped Midinfrared Laser[J]. *IEEE Photon. Technology Lett.*, 2012, 24(7):599-601.

[11] Novikov I I, Karachinsky L Y, Maximov M V, et al. Single mode cw operation of 658nm AlGaInP lasers based on longitudinal photonic band gap crystal[J]. *Appl. Phys. Lett.*, 2006, 88(23):1470.

[12] Posilovic K, Kettler T, Shchukin V A, et al. Ultra-high-brightness 850 nm GaAs/AlGaAs photonic crystal laser diodes[J]. *Appl. Phys. Lett.*, 2008, 93(22):751.

[13] Novikov I I, Gordeev N Y, Shernyakov Y M, et al. High-power single mode (>1W) continuous wave operation of longitudinal photonic band crystal lasers with a narrow vertical beam divergence[J]. *Appl. Phys. Lett.*, 2008, 92(10):1537.

[14] Posilovic K, Kalosha V P, Winterfeldt M, et al. High-power low-divergence 1060 nm photonic crystal laser diodes based on Qua. dots[J]. *Electron Lett.*, 2012, 48(22):1419-1420.

[15] Miah M J, Kettler T, Posilovic K, et al. 1.9 W continuous-wave single transverse mode emission from 1060 nm edge-emitting lasers with vertically extended lasing area[J]. *Appl. Phys. Lett.*, 2014, 105(15):751.

[16] Lusk D, Abdulhalim I, Placido F. Omnidirectional reflection from Fibonacci Quasi-periodic one-dimensional photonic crystal[J]. *Opt. Commun.*, 2001, 198(4):273-279.

[17] Schubert M F, Xi J Q, Kim K S, et al. Distributed Bragg reflector consisting of high- and low-refractive-index thin film layers made of the same material[J]. *Appl. Phys. Lett.*, 2007, 90(14):1385.