Vertical cavity surface emitting laser transverse mode and polarization control by elliptical hole photonic crystal*

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(Received 4 June 2012; revised manuscript received 30 July 2012)

The polarization of traditional photonic crystal (PC) vertical cavity surface emitting laser (VCSEL) is uncontrollable, resulting in the bit error increasing easily. Elliptical hole photonic crystal can control the transverse mode and polarization of VCSEL efficiently. We analyze the far field divergence angle, and birefringence of elliptical hole PC VCSEL. When the ratio of minor axis to major axis $b/a = 0.7$, the PC VCSEL can obtain single mode and polarization. According to the simulation results, we fabricate the device successfully. The output power is 1.7 mW, the far field divergence angle is less than 10°, and the side mode suppression ratio is over 30 dB. The output power in the Y direction is 20 times that in the X direction.

Keywords: photonic crystal, vertical cavity surface emitting laser (VCSEL), elliptical holes, single mode, polarization control

PACS: 42.55.Px, 42.55.Tv, 42.62.Fi **DOI:** 10.1088/1674-1056/22/2/024205

1. Introduction

Compared with traditional laser, vertical cavity surface emitting laser (VCSEL) has many advantages, such as low threshold current, better longitudinal mode, and output characteristics. It is widely used in high-speed fiber optic data communication, free space optical interconnects, and modulation spectroscopy. Several structures have been developed to obtain single mode VCSELs, such as surface relief, multi-hole,[1] and photonic crystal structure. For single mode with high output power and lower threshold current, photonic crystal VCSEL has developed rapidly in recent years. In the photonic crystal (PC) VCSEL, the injected current and output light are restricted by oxide aperture and photonic crystal respectively. For the large oxide aperture, the PC VCSEL can operate at high output power meanwhile the photonic crystal pattern can raise the couple efficiency. However, the polarization of PC VCSEL is complicated. If the current or temperature changes, the polarization will change easily. It will cause the bit error rate (BER) to increase. For applications such as 10-Gbit/s-class high-speed modulation and free-space interconnect using polarization-dependent optical components, a pinned polarization gives better performance. In order to control the polarization, people have developed some methods such as the use of a polarizer, injection of non-uniform current or changing the growth direction of the VCSEL.[2–5] However, these methods are not perfect and still have some room for improvement.

According to the theory of photonic crystal fibers,[6–8] because of the symmetric structure of photonic crystal, the direction of polarization is unstable. The symmetry of usual photonic crystal is six-fold rotation symmetry (C_{6v}) and the defect mode is doubly degenerate. In order to obtain the stable linearly polarized light, we can change the circular air holes into elliptical air holes and the symmetry of photonic crystal turns into two-fold rotation symmetry (C_{2v}). The defect mode can be resolved into two nondegenerate polarization modes which have different values of Q factor. This method can give consideration to both transverse mode selection and polarization selection, and has easier manufacturing process. The research in this respect has been carried out. The study by Song *et al*.[9] indicates that elliptical air hole photonic crystal can control the polarization of VCSEL, and the polarization controlled single mode PC VCSEL has been obtained.[9] In our study, we find that elliptical air holes are in favor of polarization control but damage the mode characteristic of VCSEL. We analyze the elliptical air hole effect on far field divergence angle, spectrum and birefringence, optimize the structure of photonic crystal, and manufacture steady polarization and single mode PC VCSEL successfully.

2. Simulations of PC VCSEL

The criteria for single mode PC VCSEL are spectrum and far field divergence angle. In general, if the far field divergence angle is less than 10°, the side mode suppression ratio

*Project supported by the National High Technology Research and Development Program of China (Grant No. 2008AA03Z402), the Beijing Municipal Natural Science Foundation, China (Grant Nos. 4092007, 4112006, 4102003, and 4132006), the National Natural Science Foundation of China (Grant Nos. 61076044, 61036002, 61036009, and 60978067) and the Doctoral Fund of the Ministry of Education of China (Grant No. 20121103110018).

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(SMSR) is greater than 30 dB and the full width at half maximum (FWHM) is less than 0.1 nm, the light emitted by the VCSEL can be considered to be in the single mode.[10] We use FDTD solutions to simulate different size elliptical air hole PC VCSEL. The lattice constant of photonic crystal is 4 μm, each of the air holes is 2.3-μm deep, each of the elliptical air holes has a major axis of 2 μm and the minor axes of the holes are 1.0 μm, 1.2 μm, and 1.4 μm.

First, we calculate the far field divergence angles of different structures. The smaller the far field divergence angle, the better the single mode characteristic of the device is. As shown in Fig. 1, compared with circular air hole photonic crystal, three elliptical air hole structures have better far field characteristics; the horizontal and vertical far field divergence angles are both less than 10°. The horizontal divergence angles for minor axes 1.0 μm and 1.2 μm are about 5°, for the minor axis 1.4 μm, the angle is 6°. With the rise of the minor axis, the far field divergence angles increase gradually. In the vertical direction, the divergence angles for minor axes 1.0 μm and 1.2 μm are also about 5°, but faint light spots appear on the edge. The angle for the minor axis 1.4 μm is 6°, and there are a few light spots appearing.

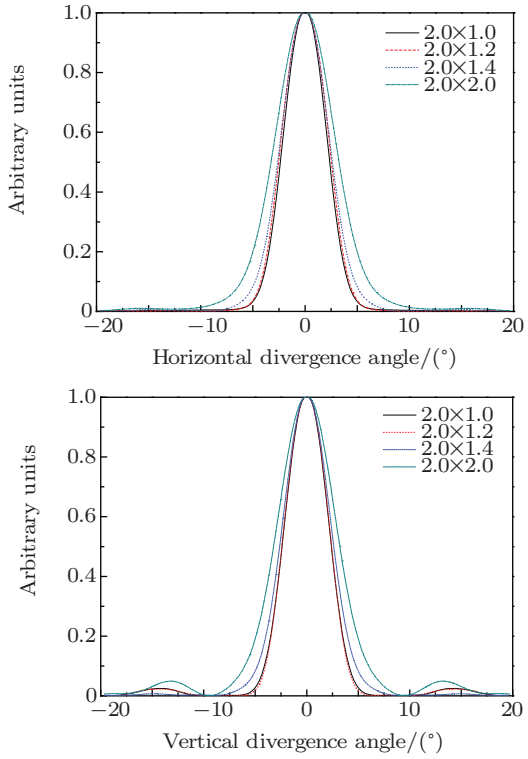


Fig. 1. (color online) Far field divergence angles of VCSEL with different size elliptical holes.

Then we analyze the spectra of elliptical air hole PC VCSELs. The higher the relative peak of the main peak near 850 nm and the lower the other peaks, the easier the other mode is suppressed and the better the single mode characteristic is. Therefore, at first we normalize the spectrum in order to compare different devices. The result as shown in Fig. 2: the spectrum of minor axis 1.0 μm is close to that of minor axis 1.2 μm and the spectrum of minor axis 1.4 μm is superior to those of the others. But compared with the circular air hole photonic crystal, the three structures are degraded to various extents. In general, the shape of the elliptical air hole is closer to being circular, and PC VCSELs have better spectra.

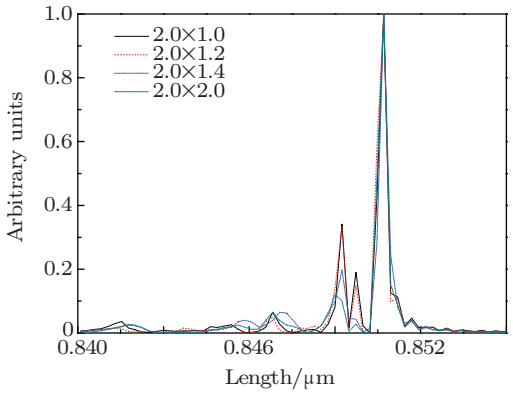


Fig. 2. (color online) Effects of different size elliptical holes on the VCSEL spectrum.

Generally speaking, the shape of the elliptical air hole is closer to being circular. PC VCSELs have larger far field divergence angles, but the spectra of VCSELs will be improved. Both factors (far field divergence angle and spectrum) must be taken into consideration to obtain a single mode device.

The most important parameter of polarization is birefringence. It is the difference in effective index between two polarization modes. We use the MODE solutions to simulate the birefringence of elliptical air hole PC VCSEL. As shown in Fig. 3, the birefringence increases with wavelength rising and the increase in the speed of birefringence quickens with wavelength increasing. The mode restriction from air holes is enhanced with wavelength increasing, so the birefringence increases with it.

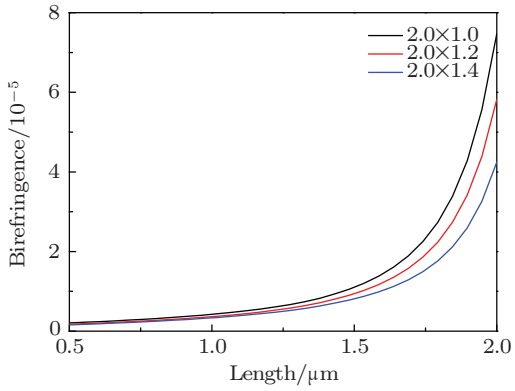


Fig. 3. (color online) Curves of birefringence versus wavelength.

Because of the contrast in refractive index between GaAs and air holes of cavity, birefringence is determined by the difference in number ratio between GaAs and air holes in two

perpendicular directions. Let the major axis of the elliptical air hole be called a, and the minor axis denoted as b, then the ratio of minor axis to major axis will be b/a. As shown in Fig. 4, the birefringence will increase when b/a is reduced. Theoretically, the polarization characteristic will improve with birefringence increasing, but considering the conditions of single transverse mode, the ratio of minor axis to major axis cannot be too low. Our experiments indicate that when $b/a = 0.7$, PC VCSEL can obtain single mode and polarization.

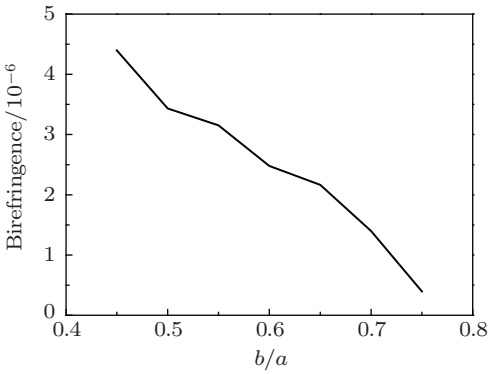


Fig. 4. Birefringence versus b/a.

using plasma enhanced chemical vapor deposition (PECVD). We use the electron beam lithography and inductive coupled plasma (ICP) etching to obtain the elliptical hole graphics on the SiO_2 film. After removing the photoresist and etching top distributed Bragg reflector (DBR), the PC VCSEL is obtained as shown in Fig. 5. The real structure is the same as the designed. The spacing between air holes is 4 μm. The elliptical air holes are all 2.0 μm (major axis)×1.4 μm (minor axis) in dimension. The depths of air holes are all 2 μm.

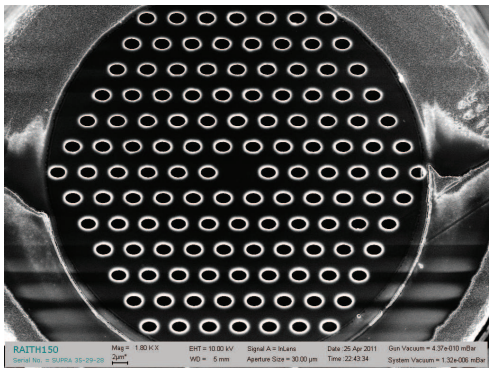


Fig. 5. Top view SEM image of the elliptical hole PC VCSEL.

3. Device fabrication and test

In this study, an 850-nm wafer is used to fabricate PC VCSEL. First, we make the VCSEL by lithography, etching, wet oxide regularity, and so on. The diameter of the oxide hole is 10 μm. Then SiO_2 film is deposited on the VCSEL by

As a contrast, we fabricate circular air hole photonic crystal VCSEL on the same wafer which has identical lattice constant, and the depths and the diameters of air holes are all 2.0 μm. Figure 6 shows the *P–I–V* and far field characteristics of PC VCSELs.

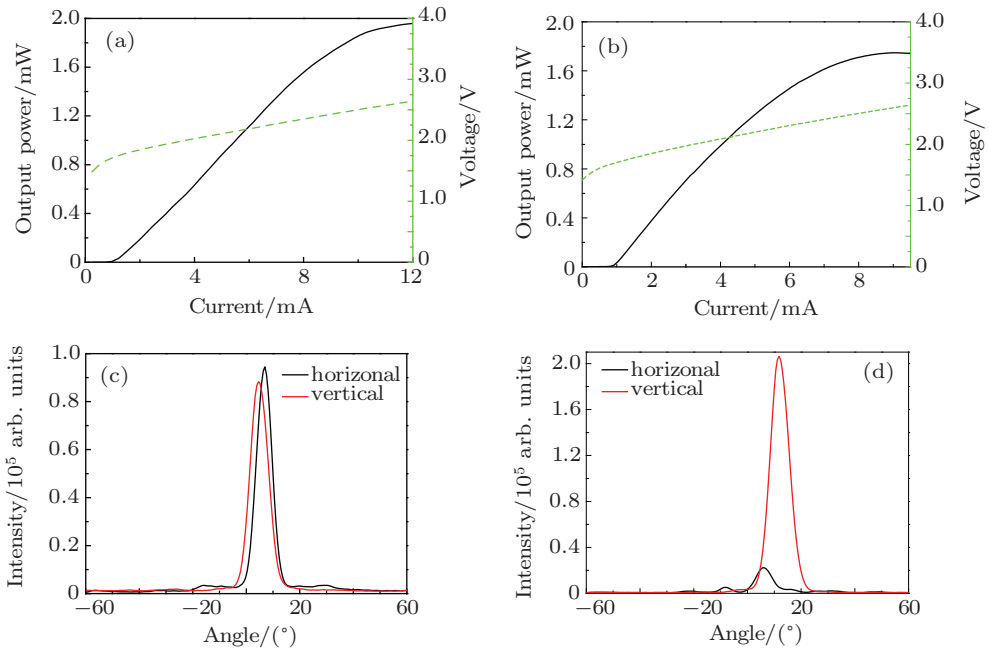


Fig. 6. (color online) The *P–I–V* characteristics and far field divergence angles of PC VCSEL.

Figures 6(a) and 6(b) show the *P–I–V* characteristics of the circular air hole PC VCSEL and the elliptical air hole PC VCSEL. As the polarization mode in the *Y* direction is restrained, the output power of the elliptical air hole PC VCSEL is a little lower than that of the circular air hole, but they are not very different. Figures 6(c) and 6(d) show the far field divergence angles of PC VCSELs. Both of them are less than 10° and have only one narrow peak. Because of the polarization characteristic of the elliptical air hole PC VCSEL, there is a great difference in intensity between horizontal and vertical directions and this phenomenon cannot occur in the circular air hole PC VCSEL.

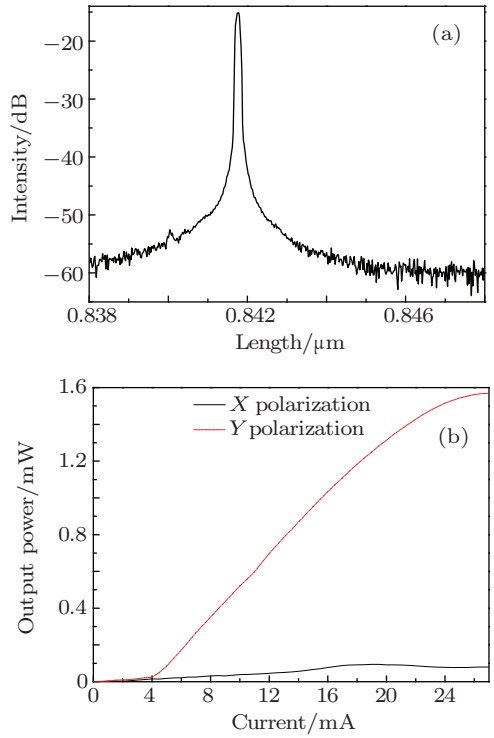


Fig. 7. (color online) (a) Lasing spectrum taken at maximum power, and (b) *P–I* characteristics of polarizations in the *X* and *Y* directions.

The spectrum of the elliptical air hole PC VCSEL is shown in Fig. 7(a). The FWHM is less than 0.1 nm, the SMSR is about 33 dB, and the device output is in the single transverse mode.

We insert a polarizer into the *P–I* test system for testing the polarization characteristic of the elliptical air hole PC VCSEL and obtain the output power in the *X* direction and *Y* direction. As shown in Fig. 7(b), the output power is only 0.08 mW in the *X* direction and 1.57 mW in the *Y* direction. The power difference is 20 times. The polarization mode is restrained in the *X* direction and has almost no loss in the *Y* direction. The elliptical hole PC VCSEL can select the polarization mode successfully.

4. Conclusion

In this paper, we simulated the effect of different dimensions of elliptical holes on the output modes of PC VCSEL. Our simulation and experiment show that the dimensions of elliptical holes can affect the far field and spectrum in the opposite manners, which must be taken into consideration in order to obtain a single mode device, both of the factors (far field and spectrum) must be considered. Theoretically, the ratio of minor axis to major axis 0.7 is optimal. We fabricate an elliptical hole PC VCSEL of steady polarization and single mode. The SMSR is 33 dB, output power is 0.08 mW in the *X* direction and 1.57 mW in the *Y* direction.

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