Full 3D FDTD analysis of Electromagnetic Field in Photonic Crystal VCSEL

LIU Fa*, XU Chen, XIE Yi-Yang, ZHAO Zhen-Bo, ZHOU Kang, WANG Bao-Qiang, LIU Ying-Ming, SHEN Guang-Di
Key Laboratory of Opto-electronics Technology (Beijing University of Technology), Ministry of Education, Beijing University of Technology, 100 Ping Le Yuan, Chaoyang District, Beijing 100124, China

E-mail: liufa20719@126.com

Abstract. The effect of etch damage to the mode characteristics of photonic crystal vertical cavity surface emitting lasers was simulated in this paper. The devices simulated in this paper are 850-nm GaAs-based VCSELs with photonic crystal. And the devices were simulated by using finite difference time domain (FDTD) method. Limited to the computer resource, the top DBR was simulated only, and the traverse size was smaller than the real size. In order to highlight the impact of the etch damage, several kinds of light sources and photonic crystal structures were simulated separately, and each situation is calculated in the condition of ideal photonic crystal and photonic crystal with etch damage respectively. All parameters of device and light feature are referred to the real condition.

1. Introduction

The vertical-cavity surface-emitting lasers (VCSELs) are the key light sources used in telecommunication and the local networks [1-2]. During the fabrication of photonic crystal (PHC) lasers, the defects of cylindrical air holes are always generated in etching process. So, it’s necessary for us to study the affection of defects to the PHC laser modes [3-4]. A group from MIT reported that the band gaps were not sensitive to the defects in the photonic crystals [5]. In this paper, finite difference time domain (FDTD) algorithm was developed and applied to investigate the affection of defects to the distribution of EM fields and laser mode characteristics. In order to contrast the results, the distribution of EM fields in the ideal structure and nonideal structure was simulated separately.

2. Methodology

Respecting the FDTD method is a classical numerical method [6-7], the introduction to it is omitted in this paper. Apparently, the mode characteristics rely on the reciprocity of the active region,
DBR and photonic crystal structure, etc. In this paper, to simplify the simulation, we deal with the model as that the laser light projects vertically into photonic crystal and then detect the emergent light on the other side of photonic crystal. Via the comparison of the distribution of electromagnetic fields between the perfect device and the defective one, the influence of defect to the model could be estimated.

3. Device structure and Simulative domain

Owing to this paper is serviced for laser research in our lab, so photonic crystal structure and the defect in this paper imitate entirely the real device and etching defect. In this Letter, the VCSELs were fabricated from a 3-inch n-type wafer with epitaxial structure consisting of a bottom n-type (Si-doped) 34 pairs DBR, an undoped active region with three GaAs quantum wells, and a similar top (C-doped) 22 pairs DBR. The DBR are formed by graded heterojunction of AlxGa1-xAs, the unit period of bottom and top DBR mirrors consisting of 4 layers of AlxGa1-xAs (x: 0.9-0.12), Al0.12Ga0.88As, AlxGa1-xAs (x: 0.12-0.9), Al0.9Ga0.1As. In addition, a 30 nm Al0.98Ga0.02As oxidization layer was inserted between the top DBR and the active region. The structure is shown in Figure 1(a). The operation wavelength of the device is designed at 850 nm. The top 22 pairs DBR is the disquisitive object, we assume that the laser is emitting from the active region into the top DBR, and we could detect the light field on the upper surface.

![Figure 1. (a) Structure of the selectively oxidized VCSEL (b) The actual device photo (c) Simulating area on the xoy plane](image)

The photonic crystal pattern is shown in Figure 1 (b). In this pattern, the diameter of the etched air circular holes is 0.01 μm; the distance of two adjacent circular centres is 0.02 μm. In the centre of the device, there is a region of 7 holes unetched. The light is well confined into or radiate out from this extent, we could see the area as the device aperture. In the region of far away from the aperture, the optical intensity decline rapidly, almost all energy is centralized in the aperture and the vicinity. So, it is enough to have a simulating region with three centre circle air holes. As shown in Figure1(c), the whole simulating district in XOY plane is 1000×1000 grids, represented 20 μm × 20 μm. The depth of the air holes is 1.6 μm, about 12 pairs of DBR. Figure 2 (a) shows a cross section of a real device with much of etching injury and Figure2 (b) shows the cut plane of ideal photonic crystal. For made the study object clearly, two kinds of defect are defined and researched in this paper. The first
one is the diameter of air holes decreases gradually along with the increases of etching depth. This
defect is caused by the bombarding rate of reacting ion decreases along with the increases of depth. In
virtue of the unit period of DBR mirror consisting of four different layers, so the radius of etching
holes on each layer is different and alters periodically. Therefore, the other sort of defect is the
diameter of holes changed periodically along with the depth. Accordingly, the same photonic crystal
structure with several state of defection as shown in Figure 3(a) – (e) was simulated. It needs to pay
attention to the dimension, the abscissa scale direction is -10 μm to 10 μm, the vertical direction is
only about 3 μm. For distinguishing the impact of DBR structure on the simulation result, the
photonic crystal with DBR and without one is simulated respectively. Finally, a special defect
configuration is simulated for much more approaching the shape in Figure 2(a). The affection of
defect to the laser mode can be obtained through compare the distribution of near field between the
ideal photonic crystal and the defective one.

Figure 2. (a) Air holes with etching defect                          (b) The ideal photonic crystal

Figure 3. (a) The cut plane of simulative device without defect or DBR

Figure 3. (b) The cut plane of simulative device with defect but no DBR
4. Optical Source Selection

A field source must be selected in the method of FDTD simulation. Considering Gauss beam is the fundamental mode of many sorts of lasers, so this light source is used in this paper mainly. The size of Gauss light is consulted the real device completely, and selected several size for simulation. Due to the spot size in real device is confined by the device aperture and oxide-hole [8-9], the area of real light can not much larger than aperture.

Then the style of electromagnetic wave should be considered. In this paper transverse electric and magnetic field (TEM) is simulated. In the semiconductor laser the form of electromagnetic field is not strict TEM, but the transverse size of VCSEL device much greater that the area of emitting, so it can be treated approximately. Finally, continuous sine wave is used in simulation.
Figure 4. (a) The $r_0$ is 1.6 $\mu m$  
(b) The $r_0$ is 2.4 $\mu m$

Figure 5. (a) Result in ideal device  
(b) Result in nonideal device

Figure 6. (a) Result in ideal device  
(b) Result in nonideal device
5. Results and Discussion

In this paper, we used the FDTD method to simulate the performance of the photonic crystal VCSEL, by our FORTRAN code with 3000 time step and $4 \times 10^8$ grids. Once process needs memory 2.24 GB and 10 hours upwards. For the usage of symmetry in x axis and y axis, the analytical space was expanded to $20 \mu m \times 20 \mu m \times 3 \mu m$ and the DBR is arranged. They are still a little smaller than the actual device due to the limitation of computer resources. We considered, however, that origins of the fundamental mode could be estimated.

For evaluating the influence of defect on the light field, we define $w_e$ as $\varepsilon \times E^2$ to describe the energy intensity on the given plane. If the distribution of output power in near field of device is more centralized, it is can be considered as more being close to fundamental mode. Apparently, the more percentage of energy in center zone is closer to what we need. We define $r_0$ as the half bandwidth of Gaussian light, and the distance to the centre of device smaller than $r_0$ is defined as center zone. So, energy of any point in the center area and in the whole plane is added separately, and the ratio (expressed as $k$) of center power in the whole output power could express the modal characteristic. The figure on the finally time step of each simulative process is shown in figure 5-8.

Figure 5(a), (b) shows separately the simulative result of the ideal photonic crystal without DBR and the defective one, and the $r_0$ equal to 1.6 $\mu m$ as shown in figure 4(a). In the Figure 5(a), the total energy of relative magnitude $1.1988 \times 10^4$ is a little larger than $1.1987 \times 10^4$ which shown in figure 8, however, the ratio $k$ 0.8750 in ideal photonic crystal is smaller than 0.8626 that in the defect.
Figure 6(a), (b) shows the similar simulative condition with the Figure 5(a) and (b), but the difference is that $r_0$ is altered to $2.4 \, \mu m$ as shown in figure 4(b). The total power is $2.8929 \times 10^4$ and $2.8902 \times 10^4$; ratio $k$ is 0.8750 and 0.8769. The varietal tendency is similar with that of the last 2 figures.

The two pairs of results simulated hereinbefore are the photonic crystal without DBR, now the results with DBR will be shown. As shows in Figure 11 and 12, the total power in the ideal and nonideal is $2.2371 \times 10^3$ and $2.2367 \times 10^3$; the ratio $k$ is 0.8315 and 0.8318. The half bandwidth $r_0$ is 1.6um in this group of result.

The final group of result is shown in Figure 8(a) and (b). The structure of photonic crystal with DBR is shown in Figure 3(e), and $r_0$ is $2.4 \, \mu m$. Figure 3 shows the etched defective style. The total power of relative magnitude in the ideal and the defective one is $3.6518 \times 10^3$ and $3.6363 \times 10^3$; and ratio $k$ is 0.8086 and 0.8152. Apparently, as can be seen in this group, the total power in the ideal is little larger than in the nonideal, and the ratio $k$ in the ideal is a little smaller.

An obvious law could be discovered from all the simulative data. The total output power of relative magnitude in the ideal photonic crystal is little higher than in nonideal, the ratio of the variety to the total is less than 1%. However, the ratio of $k$ in the ideal is less after a sort, less than 1% also.

The reason of these phenomena could be considered as the defect caused by etching technology enlarged the dispersion of EM wave, more power is scattered than in ideal structure; however, the centre aperture is unetched, so the fringe energy is more strongly suppressed than the centre [10]. Besides, the inconspicuous trend can be explained by the too small variety of defects.

6. Conclusion

We adopted FDTD method to analysis the 850-nm GaAs-based photonic crystal VCSELs. The impact of defect to the laser mode with varied light size and with and without DBR is simulated in this paper. Via these simulative data, it can be observed that, the defect in the photonic crystal should depress the output power and heighten the modal characteristic, but these trends are not obvious. The farther of the research is expanding the size of defect in simulation and comparing the results with experiment.

7. References

[1]. T Czyszanowski, M Dems and K Panajotov 2007 J. Phys. D: Appl. Phys. 40 2732–2735
[2]. Aaron J. Danner, James J. Rafillery, Jr., Paul O. Leisher, and Kent D. Choquette 2006 APPLIED PHYSICS LETTERS 88, 091114
[3]. Xie Yi-Yang, Xu Chen and Kan Qiang 2010 Chin. Phys. Lett. 27 024206
[4]. Delai Zhou L. J. Mawst and Zheng Dai 2002 IEEE JOURNAL OF QUANTUM ELECTRONICS, 652-664, 38
[5]. Shan hui fan 1997 MIT Doctoral Dissertation 30
[6]. Jason S. Ayubi-Moak, Stephen M. Goodnick, Dan Stanzione, and Gil Speyer 2008 DoD HPCMP Users Group Conference of IEEE 319-326 85
[7]. K. Sheikhi · and N. Granpayeh 2008 Opt Quant Electron 991–1003
[8]. Anjin Liu, Mingxin Xing, Hongwei Qu, Wei Chen, Wenjun Zhou, and Wanhua Zheng 2009 APPLIED PHYSICS LETTERS 94, 191105
[9]. Tomasz Czyszanowski, Robert P. Sarzala, Lukasz Piskorski, Maciej Dems, Michal Wasiak, 2007 IEEE JOURNAL OF QUANTUM ELECTRONICS, 1041-1047 43
[10] Kosuke Morito, Daisuke Mori, Eichi Mizuta and Toshihiko Baba 2005 Proc. of SPIE Vol. 191-200 5722