# Effects of transverse mode coupling and optical confinement factor on gallium-nitride based laser diode*

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We have investigated the transverse mode pattern and the optical field confinement factor of gallium nitride (GaN) laser diodes (LDs) theoretically. For the particular LD structure, composed of approximate 4 $\mu$m thick n-GaN substrate layer, the maximum optical confinement factor was found to be corresponding to the 5th order transverse mode, the so-called lasing mode. Moreover, the value of the maximum confinement factor varies periodically when increasing the n-side GaN layer thickness, which simultaneously changes and increases the oscillation mode order of the GaN LD caused by the effects of mode coupling. The effects of the thickness and the average composition of Al in the AlGaN/GaN superlattice on the optical confinement factor are also presented. Finally, the mode coupling and optimization of the layers in the GaN-based LD are discussed.

## 1. Introduction

The GaN-based laser diodes (LDs) have attracted a lot of attention as light sources at short wavelength in recent years. Currently, the room temperature stimulated emission by pulsed current emission has been demonstrated for the InGaN/GaN multiple quantum-well (MQW) based laser diodes by our group in Peking University.[1] However, the high threshold current and the short lifetime are still the main problems in these lasers. One of the major causes for the drawback is the anti-guided-like behaviour of waveguide mode associated with the n-GaN buffer layer.[2−5] Since the refractive index of the top p-GaN contact layer and the thick n-side bottom GaN layer is higher than that of the cladding layers, in this case, both the n-side buffer and p-side top GaN layer will introduce passive waveguides which compete with the waveguide formed by the active layer of laser structure. Thus, the GaN-based LD structure actually consists of multiple optical waveguides in the direction perpendicular to the junction plane. The so-called 'ghost-mode' phenomenon is used to describe the existence of these parasitic optical modes in the adjunction waveguides.[2] In GaN laser, the waveguide of the active region and the one formed in the buffer layer are not isolated. They are coupled to each other, which is also called 'transverse mode coupling'.[5−10] Because of the ghost mode or optical mode coupling, the lasing mode is usually the higher order mode of this multi-layer waveguide for GaN LD. The optical confinement factor is also very low even for the lasing mode (about several percents). This leads to high lasing threshold. For the worst case, if the waveguide structure supports strong ghost-mode, the GaN laser would not operate even if the active region quantum well (QW) is perfect. Design of the waveguide for InGaN–AlGaN–GaN laser system is of great importance as compared to other

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laser systems. Therefore, this work is to provide a guideline for optical design. If we can optimize the optical waveguide structure and the maximum confinement factor, the lasing threshold current can also be greatly reduced. Furthermore, the mode optimization also can improve the laser lifetime and the far-field optical pattern from two spots (anti-guide) to the single spot, as observed in Ref.[8].

In this paper, we analyse the transverse modes and the optical confinement factor in the GaN LD through mode calculation. Firstly, we describe the layered structure of the InGaN–GaN–AlGaN laser and the numerical technique for optical field calculation. Secondly, the calculation results are discussed. We show that the mode of different orders has different optical confinement factor. In most cases, the GaN LD lases at the higher order mode. We also investigate our current laser design margin by minimizing the substrate ghost mode in order to obtain low threshold lasers. Finally, we analyse p-superlattice (SL) and n-SL effects on the LD lasing mode.

## 2. Optical field calculation theory

We study the waveguide structure of InGaN/GaN-based MQW laser with separated confinement heterostructure (SCH) at an emission wavelength around 400 nm, which is shown in Table 1. Our primary goal for this work is to analyse the transverse mode pattern and optical field confinement factor $\Gamma$. We use a one-dimensional (1D) laser model for simplicity. Moreover, the model is good enough to reveal important optical characteristics of MQW. Although a thin electron-block layer with quite low refractive index of the above MQW is involved in our laser diode, it has negligible influence on the optical characteristics.

**Table 1.** The layer structure and parameters of the laser diode.

| Layer | Thickness/nm | Refractive index |
|---|---|---|
| p-GaN(contact) | 50 | 2.55 |
| p-$Al_{0.12}Ga_{0.88}N$/ GaN p-SL (cladding) | 500 | 2.53 |
| p-GaN (waveguide) | 100 | 2.55 |
| p-$Al_{0.35}Ga_{0.65}N$(e-block) | 20 | 2.42 |
| n-GaN | 15 | 2.55 |
| $In_{0.1}Ga_{0.9}N$/GaN (5QWs) | 67 | 2.685/2.55 |
| n-GaN (waveguide) | 100 | 2.55 |
| n-$Al_{0.12}Ga_{0.88}N$/GaN n-SL (cladding) | 800 | 2.53 |
| n-GaN (Substrate or buffer) | 4000 | 2.55 |
| Sapphire | 4000 | 1.77 |

We analyse the optical field and explore the design optimization. There are several simulation methods described in Refs.[11] and [12]. In our model, the light propagation in the laser is determined by the solution of Maxwell equations. The optical field is expanded in terms of eigen-modes, and the intensity in these modes is described by photon rate equations, which are solved fully coupled with the electro-thermal transport. The internal transfer matrix and Ritz iteration are used to carry out mode calculations, providing an optimal choice for our LD structure. In the simulation, the index profile in propagation direction is given by the layer sequence. In addition the field around a material interface can be decomposed into forward and backward propagating plane waves. The boundary conditions for the TE and TM waves determine the coefficients in one layer as a function of the amplitudes in the prior layer, which are written in matrix form. And the transfer matrix for the whole structure is given by the product of transfer matrices for the individual elements. This problem has been simplified by assuming a strong index guiding and by approximating Maxwell's equation with scalar Helmholtz equation, resulting in real and symmetric matrices. The eigen-vectors can be solved efficiently by subspace iteration using the Ritz subroutine;[13] and the simulation model is shown in Fig.1.

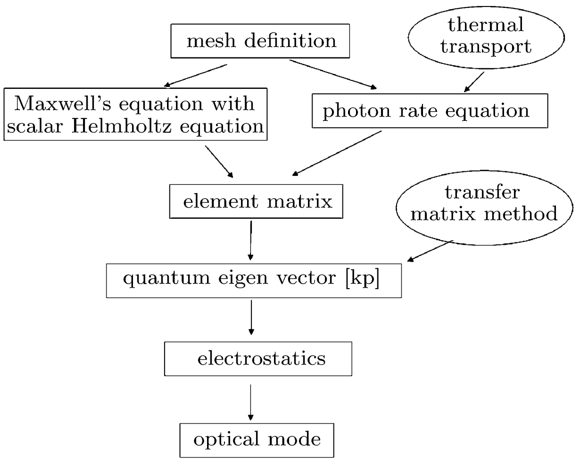

**Fig.1.** A flowchart representing the GaN LD simulation model.

The first few transverse modes are the solutions of the below scalar Helmholtz equation:[14]

$$\left[\frac{\partial^2}{\partial x^2}+\frac{\partial^2}{\partial y^2}+k_0^2(\varepsilon(x,y)-n_{\rm eff,m}^2)\right]E_{\rm m}(x,y,z)=0, \tag{1}$$

$$E_{\rm m}(x,y,z)=E_{\rm m}(x,y){\rm exp}({\rm i}k_0 n_{\rm eff,m}z), \tag{2}$$

where $k_0$ is the free-space wave vector, $x$ is a direction normal to the layer plane, and $\varepsilon(x,y)$ is the dielectric constant profile of the multilayer laser structure. The eigen-values of Eq.(1) are the effective index $n_{\rm eff,m}$ solved for each optical transverse mode of the order of m. Because the laser emission from InGaN QW is predominantly of linear TE polarization, we only considered the TE modes.[10] Optical confinement factors are expressed by the fraction of the optical mode, which overlaps with that of the QWs. The largest optical confined mode will be the lasing mode of the laser system. Most parameters used in the simulation agree with the currently published, such as those in Refs.[4] and [10].

## 3. Calculation results and discussion

The structure of our GaN LD, as shown in Fig.2(a), has a multilayer optical waveguide. There are additional two passive waveguides above and below the active region, which support their own systems of guided passive modes. The QW of our LD is located at $Y$=0 in the simulation. Figures 2(b)–2(g) show the optical field distribution of the first six modes in the GaN laser, respectively. The ripples in the mode amplitude appear at the n-type GaN buffer layer for most modes. This behaviour is called anti-guide or ghost modes. Some of those modes may interact and couple with the active layer mode, which determines the lasing mode and lasing condition. Figures 2(b)–2(f) show that the first five orders of the transverse optical modes are the guided modes in the buffer GaN passive waveguide. We also note that the fifth-order mode in Fig.2(g) has a peak intensity at zero with a maximum overlap with the MQW region. Obviously, this fifth-order mode should be the lasing mode for our current GaN LD design indicated in Table 1. Because of the co-existence of the lasing and ghost modes, the none-lasing modes will consume a great portion of injected electrons for undesired photon emission, which require more current injection into the GaN LD to achieve the same optical power output as in usual case. We also calculate all the transverse modes in the current GaN LD design, as shown in Fig.3. The optical confinement factor for the 0th order mode (the fundamental mode)

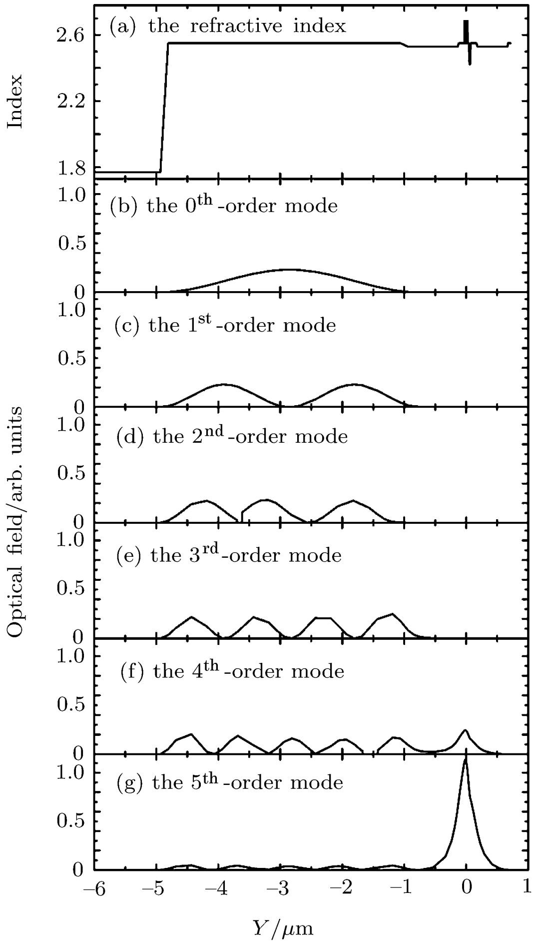

**Fig.2.** The calculated effective refractive index and the optical fields for the first six lasing modes as functions of $Y$.

is only 0.00002%, while the 5th mode has the greatest overlap of optical field with the QW, indicating that our LDs oscillate at a higher order mode (the 5th mode). Its optical confinement factor is 5.64%, which agrees with those in Refs.[3] and [8]. However, there is still a strong leakage optical field (ghost mode) in the buffer layer of the 5th order mode distribution as shown in Fig.2, which agrees with our experimental result for laser threshold. Our designed laser has a very high threshold because we did not effectively limit the ghost mode. If we can reduce the optical field in the buffer layer, the lasing threshold will greatly reduce and our laser performance will be improved.

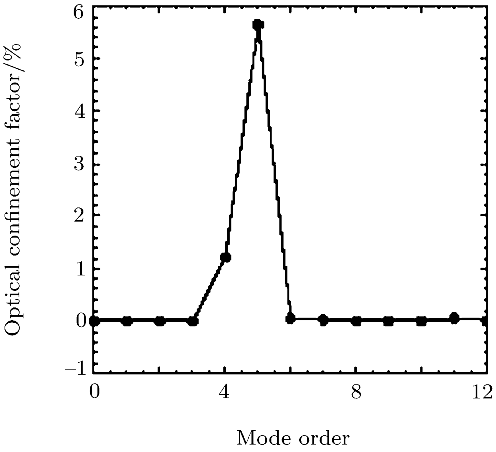

**Fig.3.** The optical confinement factor versus the mode order.

Secondly, we only vary the n-GaN substrate layer thickness, and keep all the other parameters the same as those in Table 1 to analyse the transverse mode distributions. Figure 4 shows the optical confinement factor $\Gamma$ as a function of the GaN buffer layer. It is very important to show that all the modes should exist in the laser cavity with one mode dominant, depending on which mode has the highest optical confinement factor. According to the figure, when the thickness of n-side GaN layer increases, the value of the maximum confinement factor of the oscillating mode drops periodically, accompanied by the increase of the oscillating mode order, which agrees with that in Refs.[5] and [9]. The drop of $\Gamma$ corresponds to the resonance between two adjacent modes, which demonstrates the resonant transverse mode coupling effect in GaN Lasers.[2,5,9,10] Therefore, we need to avoid the optical confinement factor dropping in our LD structures design. Besides, we also label the detailed order of the lasing mode in Fig.4, which is the mode order for the maximum optical confinement factor $\Gamma$. In general, starting with the fundamental mode (0th), the lasing mode order increases with the thickness of substrate layer. In other words, the lasing mode is not represented by a single mode at different GaN substrate thicknesses, but by a sequence of modes, with the mode order increasing by one at each subsequent transverse mode coupling.[9] The variation period of $\Gamma$ or the intervals of the maximum is a constant, which is about 0.8 $\mu$m in our case. References [5] and [9] give the interval about 0.6 $\mu$m. Actually, the exact interval should be determined by the LD structure, such as the thickness of each layer or the concentration of Al.[5] Figures 2, 3, and 4 provide the transverse modes analysis and mode coupling in the GaN-based LD research. Our data directly show the transverse mode coupling in the structure and provide clearer physics picture of waveguide modes in the laser. This is our design guideline for GaN LD in order to reduce the anti-guide modes and avoid the resonance of mode coupling.

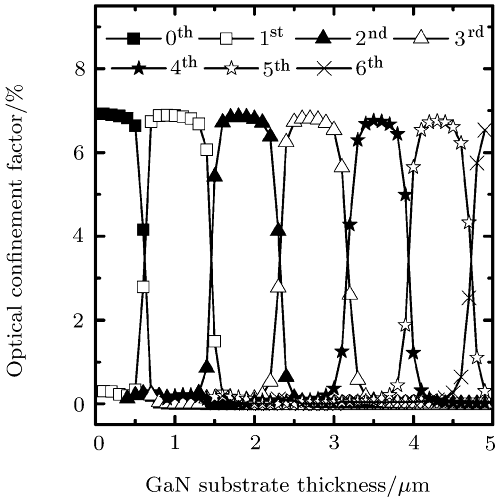

**Fig.4.** The optical confinement factor for different GaN substrate thickness.

For our current fabrication technique, it requires that the GaN substrate be at least 3 $\mu$m thick to reduce the defect number in the device. Therefore, if our GaN substrate is 3.5 $\mu$m thick, the 4th order mode will be the dominant lasing mode. All the other modes are very weak compared with the lasing mode. When we increase the GaN substrate thickness, the electrons available for lasing action will be redistributed among all the modes and more electrons will be coupled into the fifth mode for lasing action. At about 3.9 $\mu$m, the 4th and 5th order modes co-exist and together dominate the lasing action. This will be an unstable mode-competition and mode coupling stage, which should be totally avoided by the designer. If we further increase the GaN thickness, the $5^{\text{th}}$ order mode finally takes over the lasing action from all the other modes and becomes the lasing mode. In our GaN LD design, the substrate thickness is $4\,\mu$m. Figures 2, 3 and 4 show that the lasing mode is the $5^{\text{th}}$ order mode, and the $4\,\mu$m n-GaN substrate is not the optimized design because the optical confinement factor is only 5.64%. The maximum confinement factor in this design is about 7%. Our current LD structure is almost at the borderline of lasing and not lasing. As a result, our current GaN LD has high threshold and short lifetime. We need to design the n-GaN buffer layer having a thickness around $4.5\,\mu$m to achieve the maximum value of optical confinement factor and improve laser optical characteristics.

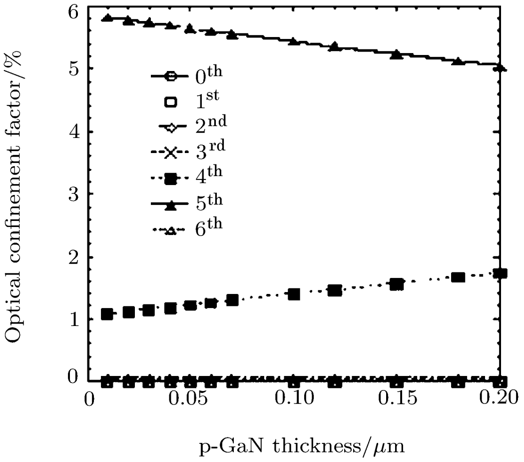

**Fig.5.** The optical confinement factor for different p-GaN thicknesses.

Thirdly, we only vary the p-GaN contact layer thickness and keep all other parameters the same as Table 1 to observe the optical mode transition or coupling. The results are shown in Fig.5. We find that the $5^{\text{th}}$ mode is still the dominate mode or lasing mode for the LD waveguide structure for p-GaN with a thickness below $0.2\,\mu$m. Usually, the p-GaN contact must be very thin in order to control the series-resistance and provide reasonable injection current for lasing action. Although such a thin p-GaN layer has a higher refractive index value compared with that of GaN, it is very hard for it to give any noticeable contribution to the lasing mode or shift the lasing mode. Therefore, p-GaN contact layer has less effect on the determination of the transverse lasing mode order for GaN lasers as compared with n-GaN substrate.

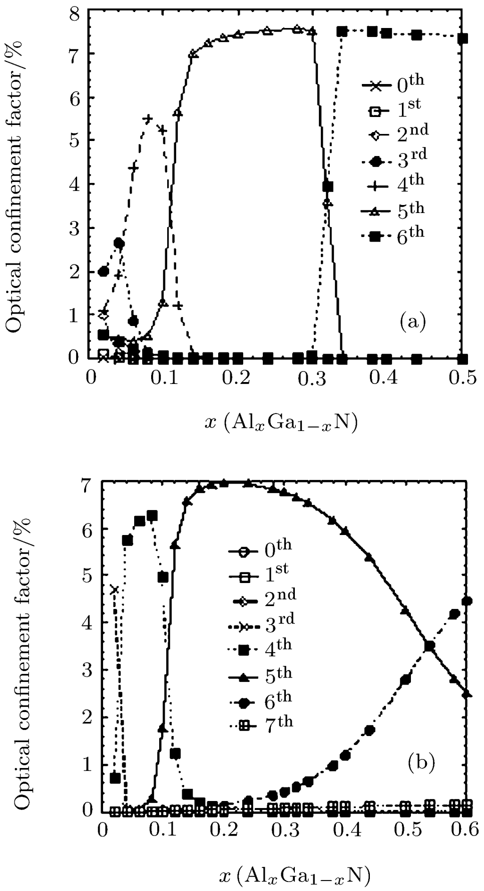

**Fig.6.** (a) The optical confinement factor for the n-SL with a thickness of $0.8\,\mu$m. Here $x$ in $\mathrm{Al}_x\mathrm{Ga}_{1-x}\mathrm{N}$ is varied from 0.04 to 0.5. For $0.3 > x > 0.12$, the $5^{\text{th}}$ order mode is the lasing mode. (b) The optical confinement factor for the p-SL with a thickness of $0.5\,\mu$m. Here $x$ of $\mathrm{Al}_x\mathrm{Ga}_{1-x}\mathrm{N}$ is varied from 0.04 to 0.6. The $5^{\text{th}}$ mode is the lasing mode when $0.12 < x < 0.54$.

Finally, we investigate laser modes by varying one of the parameters of the n-superlattice (n-SL) and p-superlattice (p-SL) and still keep other parameters constant according to Table 1. We also observe the transverse mode coupling when we design the n-SL and p-SL, as shown in Fig.6. We find that the n-SL thickness should be above 1200 nm. For n-SL, our current design parameter $x$=0.12 is also right on the edge of the transverse mode coupling. Therefore, the current design has low optical confinement factor. From Fig.6(a), we can realize the maximum optical confinement factor above 7%, for example, the $x$ of $\mathrm{Al}_x\mathrm{Ga}_{1-x}\mathrm{N/GaN}$ should be chosen to be $0.1 > x > 0.05$ for the $4^{\text{th}}$ mode, $0.3 > x > 0.12$ for the $5^{\text{th}}$ mode, or $x > 0.34$ for the $6^{\text{th}}$ mode. The mode transition region of $0.12 > x > 0.08$ and $0.34 > x > 0.3$ should be carefully avoided in the design. However, $x > 0.3$ is very hard to achieve in fabrication. In our design it is better to take the $4^{\text{th}}$ or $5^{\text{th}}$ mode as the highest mode. We also calculate that the p-SL thickness should be below 600nm and p-SL $Al_xGa_{1-x}N/GaN$ is optimized around $0.08 > x > 0.03$ for the $4^{th}$ mode or $0.54 > x > 0.1$ for the $5^{th}$ order transverse mode, as shown in Fig.6(b). Asymmetry design is preferred for current InGaN/GaN LD design: to have a thick n-SL and a thin p-SL.

## 4. Conclusion

In this paper, we have used a 1D real-matrix simulation to study the transverse mode pattern and the optical field confinement factor of GaN laser diodes. The calculation method is very simple compared with 2D or complex-matrix simulation. However, our results agree with other group's results.[10,15] Moreover, we can explain the physical picture of the optical mode coupling in the GaN laser easily and clearly.

We have calculated the transverse mode distribution of InGaN/GaN laser diodes, which were carried out at Peking University, Beijing, China. It is found that the n-GaN buffer thickness is an important parameter in the lasing-mode design, and it is also pointed out that the maximum optical confinement factor variation is due to the transverse mode coupling. Our current design is close to an optimal design, but still has a lot of room to increase the optical confinement factor, reduce the lasing threshold, and further improve laser performance, such as lifetime and far-field pattern.

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