# WAVELENGTH DEPENDENCE OF TRANSVERSE MODE COUPLING WITH/WITHOUT E-BLOCK OF GAN LASER CAVITY

**By**

**KrishneelLal**

**Senior Project**

**ELECTRICAL ENGINEERING DEPARTMENT**

**California Polytechnic State University**

**San Luis Obispo**

## Abstract

Transverse mode wavelength dependence in the GaN laser cavity is a new topic. Modal analysis simulations are run to optimize the blue Gallium Nitride (GaN) based laser diode with a wavelength of 400, 430, and 460nm. It is shown that the optical confinement factor (OCF) has a strong dependence upon wavelength of emission and e-block thickness. The OCF can be changed from 4.9% at a 460nm wavelength to 7.6% at 400nm, which is a 55% difference. The effect of adding an electron block layer of different widths is also investigated with results showing that an electron block layer can change optical confinement by 14% at 460nm wavelength and 13% at 400nm wavelength. The bottom n-GaN layer thickness is optimized between 0.1 and 7μm. It is found that a thin buffer layer improves optical mode distribution by reducing the ghost mode.

**Acknowledgement**

I would first like to thank Professor Jin for introducing me to the world of lasers and this wonderful project that I've had the pleasure to be apart of for my last year at Cal Poly. You have shown me what I can truly accomplish with hard work and dedication. Secondly, I would like to thank the Peking University Physics Department for their hospitality and a chance to experience a totally new culture in what could be a once in a lifetime experience for me. Also I would like to thank the National Science Foundation for funding the program that Professor Jin has kindly put together.

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# Chapter 1: Introduction

The visible color spectrum has three primary colors, red, green and blue, from which all colors can be generated. Red and green have successfully been implemented, but blue has been the most challenging to create with a laser diode. The Gallium Nitride (GaN) material has proven to be the best option for short wavelength laser emission at the present time. Although GaN lasers have been implemented, currently they have a high threshold current and short lifetime. A major cause for these problems is the anti-guided-like behavior of the waveguide mode associated with the n-GaN buffer layer and multi-layer waveguides. This is also referred to as the "ghost mode" phenomenon [1] [2]. As a result of ghost modes, GaN lasers usually lase at a higher order mode. The optical confinement of this mode is also very low (around 5%), which contributes to the high threshold current. And high threshold currents lead to lower life expectancy [3][4]. Currently, the optical waveguide mode optimization is still a very important research topic in GaN laser diode design, such as Ref. [5] in Green GaN Laser diode. In this paper, we investigate which modes the same waveguide structure can support if the wavelength of the blue GaN LD is varied. In other words, we study the transverse modes variation in the laser cavity according to the operational wavelength.

Recently, a thin electron-block layer with quite low refractive index value placed above the Multi-Quantum Well (MQW) is involved in GaN LD design. An electron blocking (e-block) layer is put between the p-doped side and the active layer to prevent leakage of electrons to the p-doped side. It is used to confine electron/hole carrier recombination to the active region where light is most likely to result. Any recombination outside the active layer will likely not radiate or radiate at a frequency the laser is not designed for. The laser diode's lifetime is also dependent upon the number of non-radiative recombination centers [6].Therefore leakage is a problem for III-Nitride compound semiconductors because they require a relatively high injection current due to their low hole concentration [7].

Although the e-block lowers electron carrier leakage, it also increases the threshold current by adding unwanted resistance and blocks p-side holes from entering the active region [8]. It is a very important layer which improves the laser's efficiency. However, its influence on the optical characteristics of the laser cavity is not fully studied or understood. In this paper, we present some new results on how the e-block influences optical modes in the GaN laser diode cavity.

First, we present the one-dimensional optical mode analysis of the GaN laser emitting a wavelength of 460nm. These results are compared to the results of simulations run with a wavelength of 400nm and 430nm to see if the optical confinement factor has any dependence upon the wavelength. Second, the bottom n-GaN layer thickness design is studied and optimized from 0.1 to 7µm. Finally, we also explore the effect of using an e-block layer in our laser diode design throughout the paper.

**1.1 Background information on the general laser**

All lasers are constructed with 3 main components: a pump source, gain medium, and a resonating path which includes mirrors. A basic laser structure is shown in Fig 1.1.

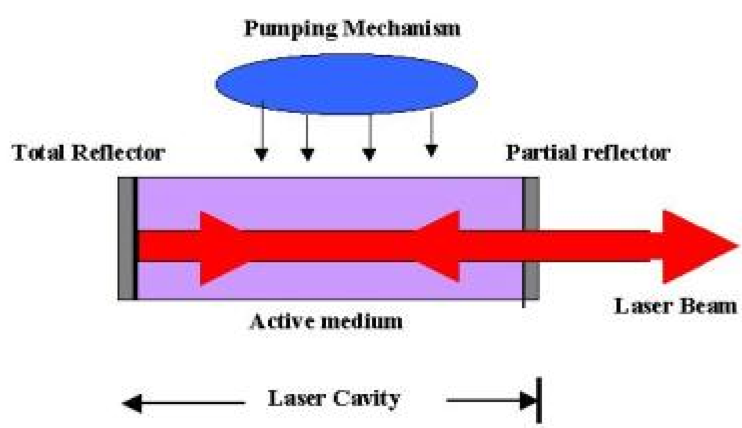



**Fig 1.1:General Laser**

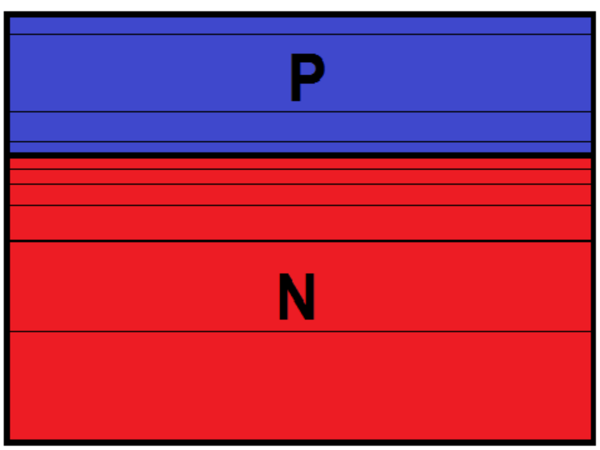
For a semiconductor gain medium such as GaN, the pumping source is a DC bias voltage. The gain medium, which is what I am optimizing, is where electrons get excited to a higher energy state and release their energy in the form of photons. The quantum wells within this medium trap these photons within the active layer. On one side of the active layer there is a total reflector which reflects the photons back into the active layer. On the other side there is a partial reflector which reflects some photons back into the active layer while allowing some photons to escape. This path between the 2 mirrors is called the resonating path.

The production of laser light is called lasing. Lasing requires a certain amount of energy which means the resonators gain must be greater than its loss. The partial reflector serves the purpose of trapping enough energy for lasing to occur while allowing the light to be outputted for use.

**1.2 Gain medium**

The gain medium is a block of different layers creating a p-n junction diode. The p and n sides both are constructed of multiple layers as shown in Fig 1.2. Table 1.1 shows the layer material along with thickness and refractive index.

**Table 1.1: Laser gain medium layers**




| Layer | Thickness (nm) | Refractive index |
|---|---|---|
| p-GaN (contact) | 50 | 2.55 |
| p-AlGaN (cladding) | 500 | 2.53 |
| p-GaN (waveguide) | 100 | 2.55 |
| p-AlGaN (e-block) | 0,20,35 | 2.42 |
| n-GaN | 15 | 2.55 |
| InGaN (5QWs) | 67 | 2.685 |
| n-GaN (waveguide) | 100 | 2.55 |
| n-AlGaN (cladding) | 800 | 2.53 |
| n-GaN (Substrate) | 4000 | 2.55 |
| Sapphire(Substrate) | 4000 | 1.77 |

**Fig 1.2: Laser Gain medium**

A wave guide is a multilayer structure which has a higher refractive index in the middle layer which allows total internal reflection to occur. Within the gain medium several wave guides are created although the active region with the quantum wells is the primary waveguide. This waveguide is what allows the light production to be centered in a specific location of the gain medium.

**1.3Quantum Wells**

In our active region there are 5 quantum wells. A quantum well is a potential well with quantized energy levels. When a biasing voltage is put across the diode, energy flows from a high potential to the lowest potential. The quantum well is put in this path and is a local potential minimum. Electrons are trapped in this well but there is a bandgap between the conduction band and the valence band. These electrons leap across this bandgap and emit photons of light. Quantum wells are not required but increase the quantum efficiency of the diode. They can be created by alternating semiconductor materials which have been doped by either electrons or holes.

# Chapter 2 Numerical Modeling

## 2.1 Simulation Method

We study the waveguide structure of InGaN/GaN-based MQW laser with separated confinement hetero-structure (SCH) at emission wavelengths of 400, 430, and 460nm, which is shown in Table 1.1. Our primary goal for this work is to analyze the transverse mode pattern and optical field confinement factor variation. We use a one-dimensional (1D) laser model for simplicity. Moreover, the model also reveals important optical characteristics of the MQW GaN laser diode. We model the laser diode resonator properties of each layer with standard material properties. The light propagation through the laser is found by solving Maxwell's equations. We assume that our structure has strong refractive index guiding; therefore we approximate Maxwell's equations with the Helmholtz equation. The strength and location of each mode of propagation are calculated by simultaneous iteration of the Helmholtz equation which then allows the optical confinement factor to be calculated.

Helmholtz equation:

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

where, $E_m(x,y,z) = E_m \exp(ik_0\, n_{eff,m} z)$, $k_0$ is the free-space vector, and $\varepsilon(x,y)$ is the complex dielectric constant profile of the multilayer structure. The eigenvalues are given by the effective refractive index $n_{eff,m}$. The frequency $k_0 = \omega_0/c$ of the mode is solved and is set to correspond to the quantum well band gap energy.

At the beginning of GaN LD development, a diode with a 405nm wavelength (ultra-violet)was developed and most laser cavity designs are focus around this wavelength, Ref. [9]. In recent years, GaN LDs around 450nmhave been studied intensively, and a similar laser cavity design is used for both 400nm and 450nm cases. Our basic simulationlaser diode structure is based on the same structure used in Ref. [9].In this paper, we simulate multiple wavelengths (400, 430, and 460nm) instead of only simulating 400nm. We reveal the optical mode variation with wavelength to identify if our current laser structure is appropriate for the blue GaN LD design.Table 2.1 lists the layers of the structure with its thicknesses and refractive indices. The basic design of the laser diode is a PN junction with an active layer between the p and n cladding layers. The active layer consists of five quantum wells where the optical gain allows the stimulated emission of light. An electron blocking layer is put in between the p-doped side and the active layer to prevent leakage of electrons to the p-doped side. The e-block is a p-doped layer itself which has a higher band gap than the adjacent layers. Any leakage current drops the efficiency of the laser because of dissipation of non-lasing energy.

**Table 2.1. Laser diode structure with variable e-block and fixed substrate width**

| **Layer** | **Thickness (nm)** | **Refractive index** |
|---|---|---|
| p-GaN (contact) | 50 | 2.55 |
| p-AlGaN (cladding) | 500 | 2.53 |
| p-GaN (waveguide) | 100 | 5.55 |
| p-AlGaN (e-block) | 0, 20, or 35 | 2.42 |
| n-GaN | 15 | 2.55 |
| InGaN (5QWs) | 67 | 2.685 |
| n-GaN (waveguide) | 100 | 2.55 |
| n-AlGaN (cladding) | 800 | 2.53 |
| n-GaN (buffer) | 4000 | 2.55 |
| Sapphire(Substrate) | 4000 | 1.77 |

## 2.2 Laser Diode Structure

Our basic laser diode structure is based on the same structure used in our study presented in Ref.[1]. The only difference is that we use a wavelength of 460nm instead of 400nm. Table 2.1 lists the layers of the structure with its thicknesses and refractive indices. The basic design of the laser diode is a PN junction with an active layer between the p and n cladding layers. The active layer consists of five quantum wells where the optical gain occurs allowing the stimulated emission of light. An electron blocking layer is put in between the p-doped side and the active layer to prevent leakage of electrons to the p-doped side. Any leakage current drops the efficiency of the laser because of dissipation of non lasing energy. The e-block is a p-doped layer itself which has a higher band gap than the adjacent layers.

The active layer will determine the lasing mode which is the mode with the highest optical confinement factor (OCF). Other modes are also present in the substrate layer because of its significantly larger width and its waveguide like properties due to smaller refractive indices of the layers besides it. One of our goals is to reduce the OCF of the non-lasing modes because they reduce the efficiency of the laser.

We also study how the e-block affects the laser. As shown in Table 2.1, we test without an e-block and with an e-block, thicknesses of 20nm and 35nm. Finally, the influence of the n-GaN substrate layer thickness is also investigated later.

# Chapter 3 Simulation Results

## 3.1 Wavelength dependence of optical mode with and without e-block

The active layer will determine the lasing wavelength. Usually the mode in the waveguide structure with the highest optical confinement factor is the lasing mode. Other modes are also present in the laser cavity and try to compete with lasing mode and reduce the laser efficiency. For example, the buffer layer has a significantly larger thickness and has waveguide like properties due to smaller refractive index of the layers beside it, which support the ghost (non-lasing) mode in the laser structure [10]. It is preferred to reduce the OCF of the non-lasing modes and improve the efficiency of the laser. Here we present new data on how the e-block affects the laser mode for the first time. As shown in Table 2.1, we simulate the transverse mode distribution without an e-block and with e-block thicknesses of 20nm and 35nm.

Our simulation is focused on maximizing the confinement of optical power from location 8.8 to 8.9µm (MQW region) from the x-axis with a 4000nm n-GaN buffer layer. This region is the designed active region where the best lasing result can occur due to the lower refractive index of the adjacent layers creating a waveguide. We desire to design a lasing mode in the active layer instead of the substrate. The optical confinement factor of a chosen mode is defined as the ratio of the total guided energy of all the modes to the energy of the chosen mode located in the active region. The optical confinement of all the modes according to the design of Table 2.1 without an e-block is shown in Table 3.1, column 1 for 460nm wavelength. We see that the 3$^{rd}$ mode is the lasing mode. Its OCF is 4.91% which agrees with the results from Ref. [8]. The field intensity contribution from each mode is shown in Fig. 3.1(a) for this case. Although mode 3 has the highest field intensity in the MQW region, mode 5 has high field intensity in the substrate as opposed to the active region. Modes found in regions outside the active region are called ghost modes [11] [12]. They are parasitic modes which occur due to the waveguide like properties of passive layers inside the structure. This ghost mode dissipates energy that could be used by the lasing mode and makes the laser less efficient. The optical confinement of all the modes in the design with an e-block of 35nm width is also shown in Table 3.1. Table 3.1, Column 2, shows that mode 5 has the best optical confinement factor of 5.01% for this case, since the lasing mode should occur between 8.8 to 8.9µm, as shown in Fig. 3.1(b). This mode has very few oscillations at 4.5µm (substrate location). The optical confinement of all the modes in the design with an e-block of 20nm width is shown in the Table 3.1 Column 3. From Table 3.1, we see that mode 5 also gives the highest optical confinement factor. It also gives the highest field intensity as shown in Fig. 3.1(c). In Fig. 3.1(a), the substrate mode intensity (at location 4.5µm) is almost equal to that of lasing mode (at location 8.8 to 8.9 µm) without the e-block, which are about $7x10^{15}$a.u.. For the structure with the e-block (Fig. 3.1b and Fig. 3.1c), the lasing mode is greatly enhanced for this case ($\sim 10^{16}$a.u.) and is much bigger that the substrate/ghost mode. The e-block actually improves the optical mode in the laser cavity for this case. However, in general, the confinement factor of all modes varieswhen the e-block was removed. It is very clear that with the e-block the lasing mode shifts to higher order mode and OCF can be changedby about 14%.

Wavelength dependence of optical confinement factor is also investigated. A total of 9 cases are presented in which the thickness of the e-block width is varied among 0, 20, and 35nm, and each of those cases is simulated with wavelengths of 400, 430 and 460nm, as shown in Tables 3.1-3.3. The results show that for any e-block width, decreasing the wavelength will increase the lasing mode's OCF. The case with no e-block produces the highest OCF at 7.6% which was almost a full percent higher than our 20nm e-block case for 400nm. The effectiveness of the e-block seems to vary with wavelength. They even have different trends for 460, 430, and 400nm wavelength cases. For the 400nm wavelength, the effectiveness of OCF improvement decreases with an increase of wavelength. Considering wavelength and e-block variation, with no e-block case, the OCF changed from 4.9% (460nm) to 7.6% (400nm), which is a 55% variation.

**Table 3.1: Optical confinement factors of each mode   = 460nm**

| Mode | Optical Confinement Factor (%) | | |
|---|---|---|---|
| | **no e-block.** | **e-block of 35nm width** | **e-block of 20nm width.** |
| (0,0) | 0.0002463 | 0.000058 | 0.000001 |
| (1,0) | 0.0015903 | 0.000297 | 0.000467 |
| (2,0) | 0.0023530 | 0.000313 | 0.000525 |
| (3,0) | 4.9179800 | 0.021712 | 0.056455 |
| (4,0) | 1.7050500 | 0.000028 | 0.000137 |
| (5,0) | 0.0001122 | 5.016970 | 5.614760 |
| (6,0) | 0.1647760 | 0.454514 | 0.294066 |
| (7,0) | 0.1138420 | 0.101090 | 0.107288 |
| (8,0) | 0.7883330 | 1.112340 | 0.971194 |
| (9,0) | 1.332770 | 1.527570 | 1.447420 |

| **Mode** | **Optical Confinement Factor (%)** | | |
|---|---|---|---|
| | **no e-block.** | **e-block of 35nm width** | **e-block of 20nm width.** |
| (0,0) | 0.000181236 | 3.47842e-005 | 5.37843e-005 |
| (1,0) | 0.00119628 | 0.000172161 | 0.000280763 |
| (2,0) | 0.00183944 | 0.000178779 | 0.000310567 |
| (3,0) | 6.48846 | 0.0116452 | 0.0314922 |
| (4,0) | 0.665776 | 1.4366e-005 | 6.22837e-005 |
| (5,0) | 6.81571e-005 | 5.46505 | 6.11234 |
| (6,0) | 0.110426 | 0.373773 | 0.219643 |
| (7,0) | 0.127324 | 0.135863 | 0.132975 |
| (8,0) | 0.707224 | 1.03036 | 0.888357 |

| (9,0) | 1.25963 | 1.49478 | 1.39863 |
|---|---|---|---|

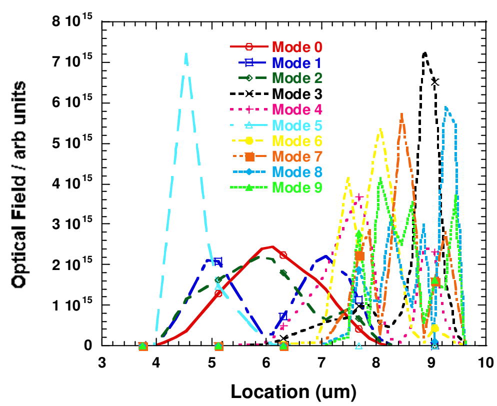
**Table 3.2: Optical confinement factors of each mode with = 430nm**

**Table 3.3: Optical confinement factors of each mode with = 400nm**

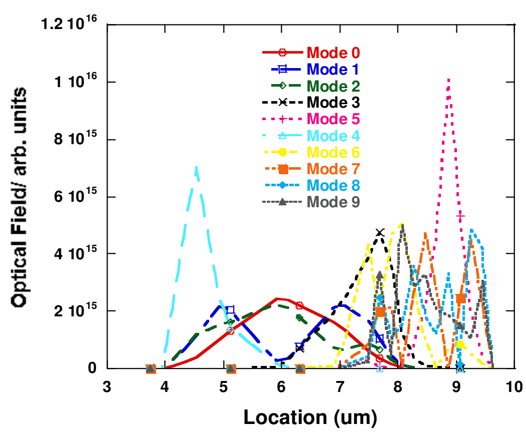
| **Mode** | **Optical Confinement Factor (%)** | | |
|---|---|---|---|
| | **no e-block.** | **e-block of 35nm width** | **e-block of 20nm width.** |
| (0,0) | 0.000139042 | 1.94146e-005 | 3.13519e-005 |
| (1,0) | 0.00096935 | 9.43627e-005 | 0.000161123 |
| (2,0) | 0.00164004 | 9.66973e-005 | 0.000176117 |
| (3,0) | 7.61901 | 0.0059375 | 0.0170242 |
| (4,0) | 0.157396 | 7.38821e-006 | 3.08794e-005 |
| (5,0) | 3.31361e-005 | 6.02678 | 6.70086 |
| (6,0) | 0.0652654 | 0.283008 | 0.147521 |
| (7,0) | 0.134202 | 0.171566 | 0.155288 |
| (8,0) | 0.615611 | 0.924631 | 0.788146 |
| (9,0) | 1.17286 | 1.4475 | 1.33585 |

**3.2 Bottom n-GaN buffer layer design**

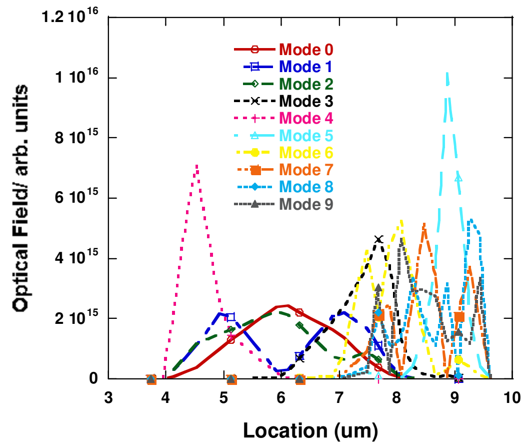
To further reduce the substrate mode and study its effects, the bottom n-GaN buffer layer thickness is optimized between 0.1 and 7µm. The goal is to find the width which creates the best optical confinement factor and the most coupling of different modes of propagation. The substrate width verses OCF of each mode from (0,0) to (9,0) are shown in Fig. 3.2. The design in Ref. [9] used a buffer layerwidth of 4µm. In here, we study how the OCF varies according to thinnerGaN buffer. The n-GaN buffer thickness is an important parameter in the lasing-mode design. The maximum optical confinement fact variation is due to transverse mode coupling.Not only that, the detailed order of the lasing mode is labeled at Fig. 3.2, which shows the mode order of the maximum optical confinement factor. Generally, starting with fundamental mode (0th), the lasing mode order increases with substrate thickness. In the other word, the lasing mode is not represented by a single normal mode at different GaN substrate thickness, but by a sequence of normal modes, with the mode order increasing by one at each subsequent transverse mode coupling. In general, the results show that the highest optical confinement is achieved with a substrate width of 0.1µm, which also provides fundamental mode lasing condition. At this width, mode (0,0) and mode (6,0) both have an OCF of 5.7267%. Our simulation results show that lower order lasing with a smaller substrate width. Because the nano-substrate will reduce the substrate mode, this has the benefit of lowering the threshold current since a wider layer increases the impedance of the diode. However, one factor that must be taken into account is the reason why we have a substrate/buffer layer. The buffer layer is added to reduce the number of defects or cracks in the layer of sapphire due to a lattice mismatch. To design an efficient GaN LD, we need to comprise between fabrication capability and theoretical optimization. Currently, new flip chip technology or nanolithography can be used for the thinner substrate to realize the optimized GaN LD performance [13] [14].




(a)



(b)




(c)

**Fig. 3.1. Field intensities of each mode through the structure at 460nm wavelength a) no e-block, b) an e-block with a 35nm width, and c) an e-block with a 20nm width.**

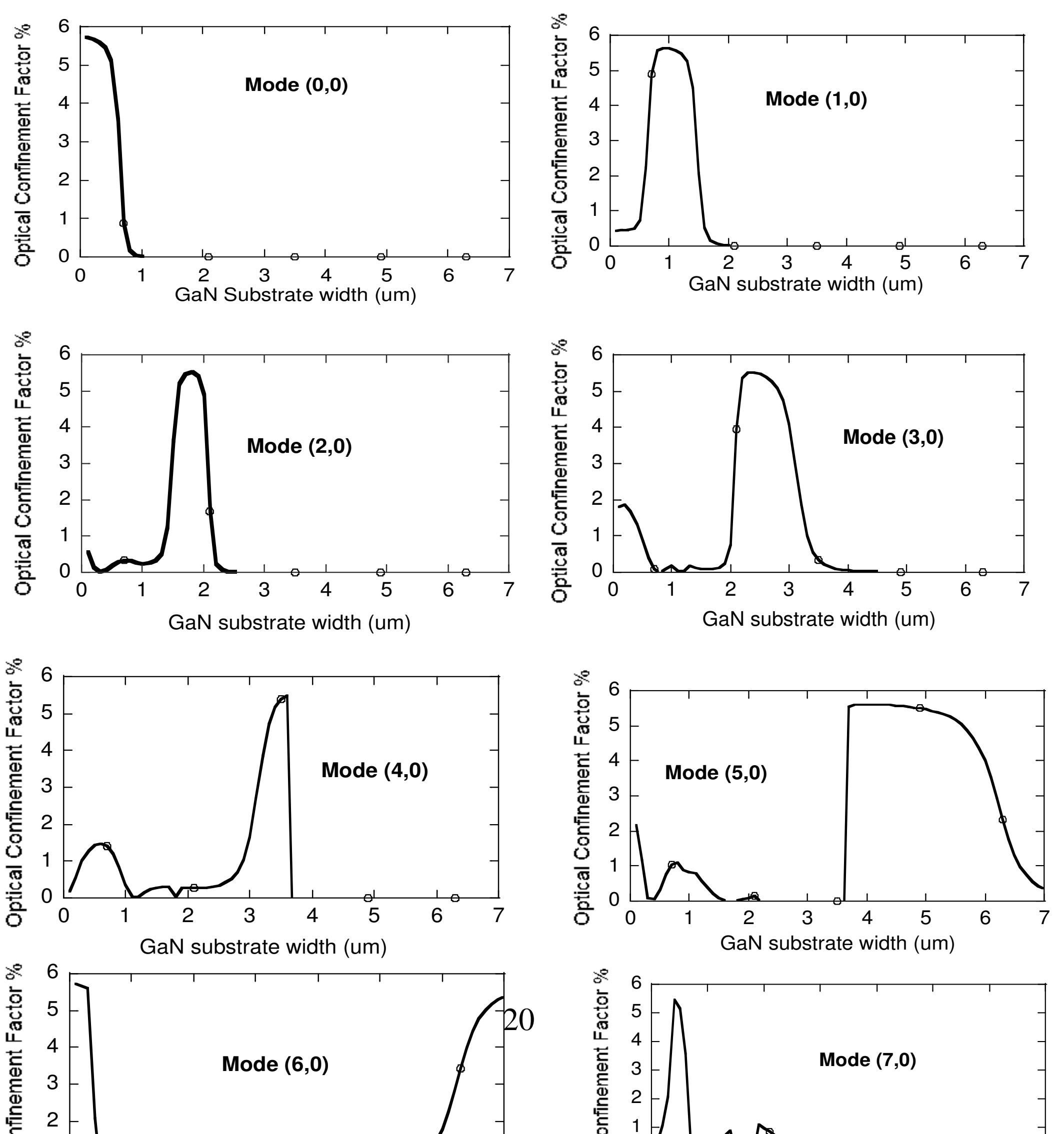


**Fig. 3.2 Optical confinement factor variation of different optical mode vs.GaN substrate thickness.**

# Chapter 4 Using RSoftLaserMod

## 4.1 Creating a Structure

Fig 4.1 shows the main screen of the cad layout with my laser structure already created. On the left top panel, the user is given the choice of different types of materials to use such as semiconductors or insulators. After a structure is laid out the properties must be set such as size, material and alignment with adjacent materials. The properties window is shown in Fig 4.2.

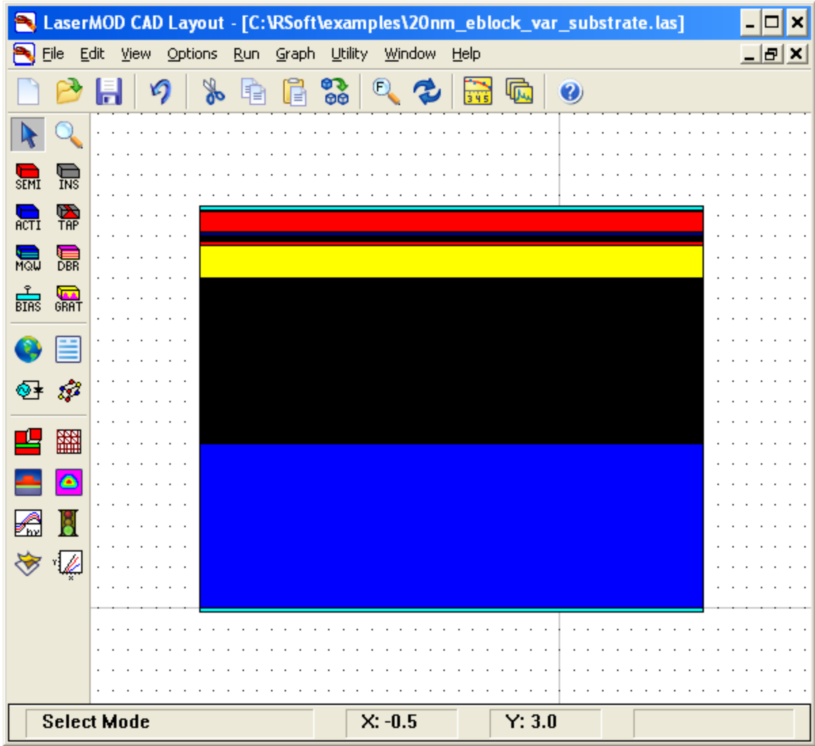



**Figure 4.1LaserMod main window**

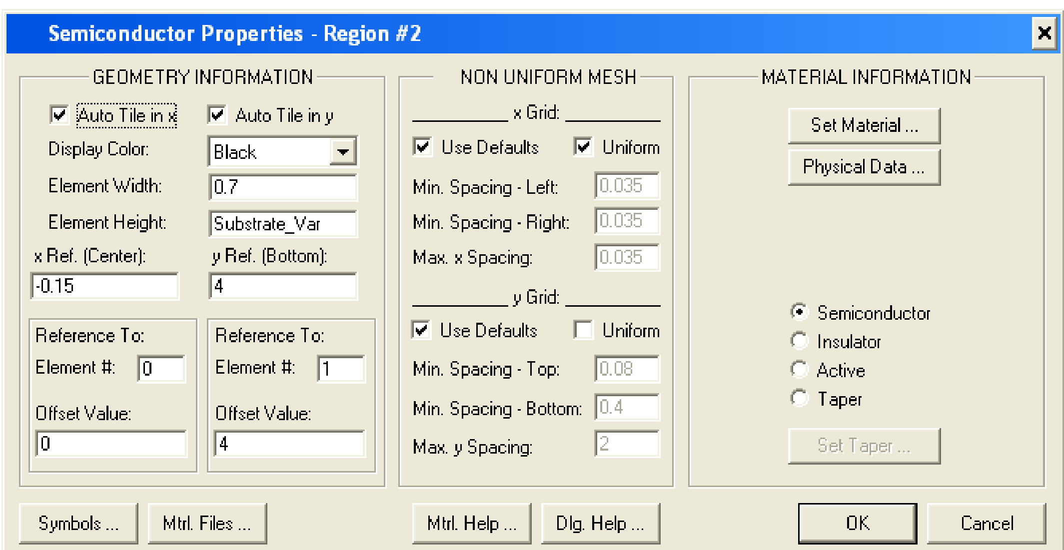



**Figure 4.2 material properties screen**

Under GEOMETRY INFORMATION each layers width and height can be set. To make sure materials are sitting flush on top of each other we can reference them to another layer and specify an offset value. In the MATERIALS INFORMATION section, the material type can be changed. We can set the specific material by clicking the Set Material button which brings a material data window shown in Fig 4.3. The material can be selected from the drop down menu labeled Material System. All of the material's properties are stored in a material file found in the directory C:\RSoft\products\lasermod\materials.

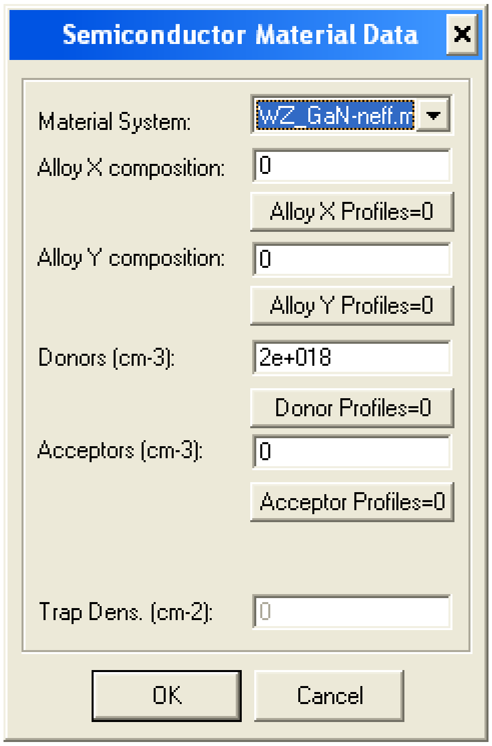



**Figure 4.3: Material data window**

### 4.2 Setting Refractive Indices

The refracted index of each material is found in the material file stored in the variable named kpmat_DIELOPT. The value stored in this variable is actually the square of the refractive index. Example: for a refractive index of 2.5, kpmat_DIELOPT =6.25. The materials file is located at C:\RSoft\products\lasermod\materials.

### 4.3 Mode Calculation

The mode calculation simulation is used to find the OCFs of the modes in the laser. The mode calculation tool is shown by the red arrow in Fig. 4.4. The simulation parameters window contains all the properties of the simulation. This is where I set the wavelength to 460nm and chose how many transverse modes to calculate.

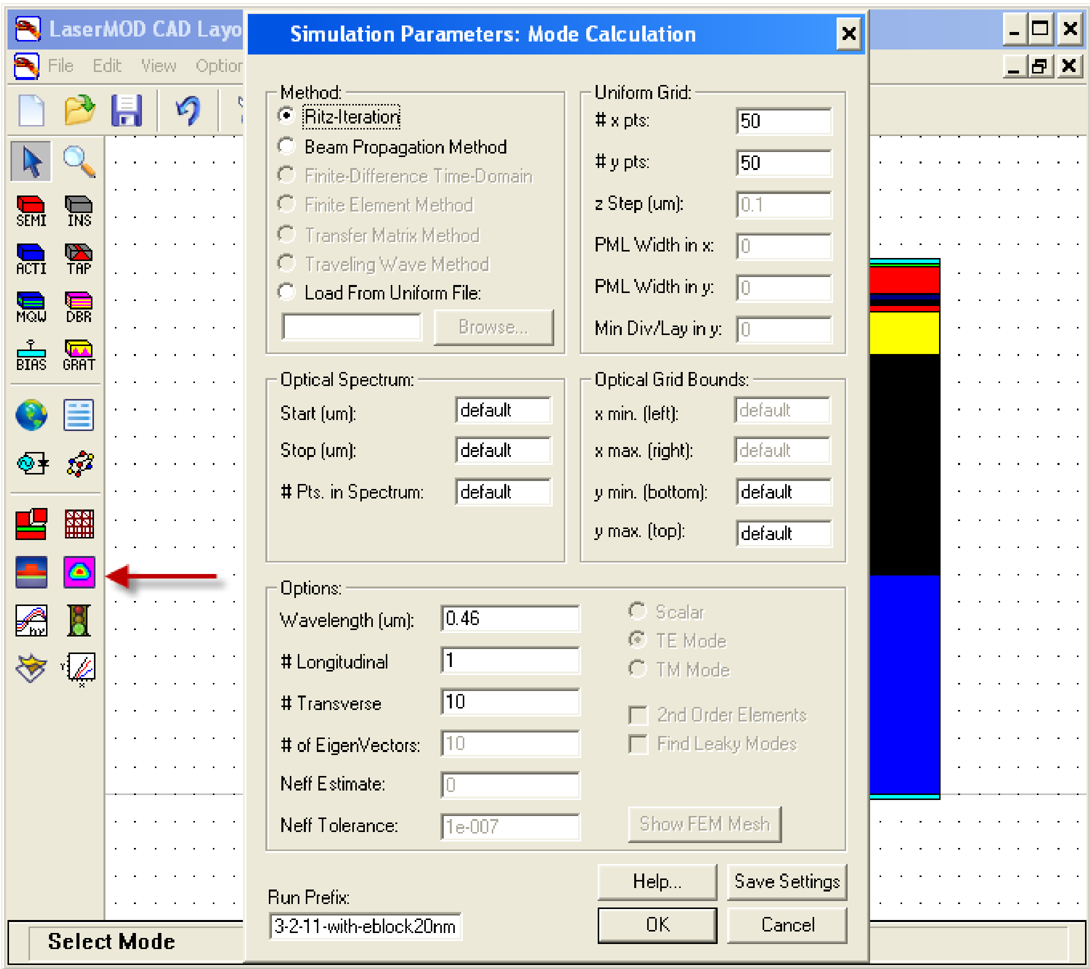



**Figure 4.4: Mode Calculation**

## 4.4 Using Parameter Scan

When optimizing a layer width it would be a tedious job to manually simulate all possible widths, therefore the use of parameter scan is recommended. The parameter scan tool is located at the bottom left of the tool kit presented on the left hand side of the screen as shown by the red arrow in Fig. 4.5. The parameter scan takes a user defined variable and runs a specified simulation at all the values of the variable defined by the input of Starting Value and Ending Value.

A variable is created by defining it in the edit symbols tool shown by the red arrow in Fig. 4.6.

A default value can be set to the variable in the Expression box. Once created, the variable can be used for any numerical property of a material. For example I used Substrate_Var for the element height in Fig. 4.2.

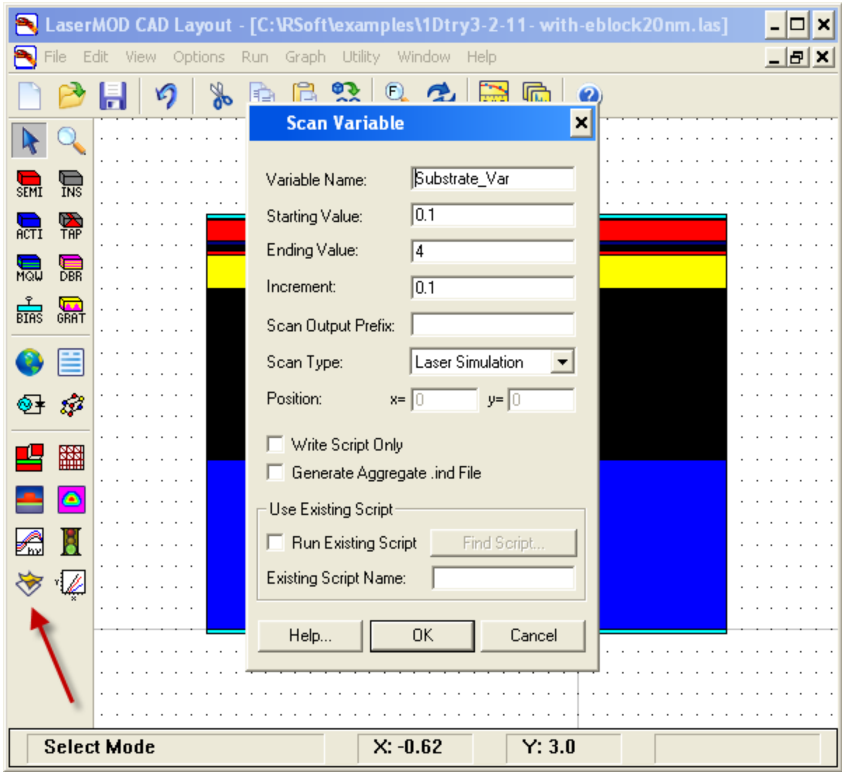



**Figure 4.5: Parameter Scan**

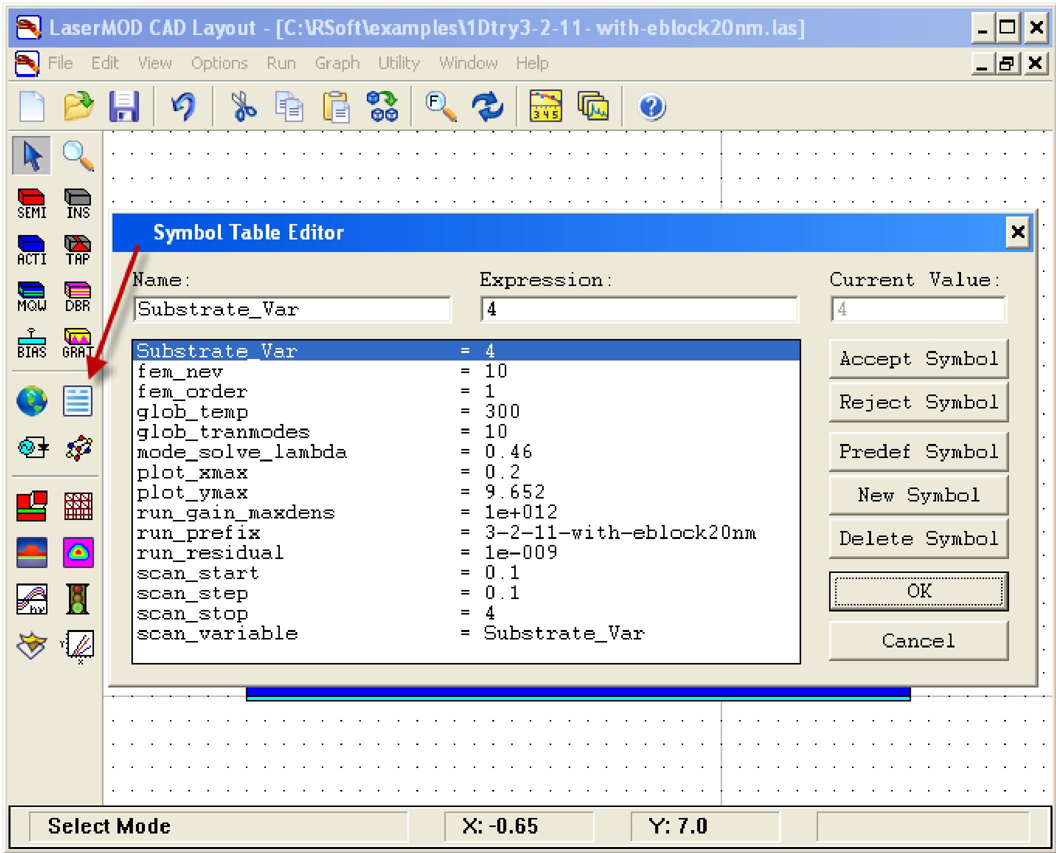



**Figure 4.6: Edit Symbols Tool**

## Chapter 5: Conclusion

The effects of lasing wavelength and electron block layer thickness upon the optical confinement factor are studied. Confinement factor of all modes dropped when the e-block was removed at 460nm wavelength, and the e-block can improve the OCF of LD by 14%. With a 35nm e-block, the lasing occurs with the 3$^{rd}$ mode and it had an optical confinement factor of 5.01%. The case with the 20nm e-block had the best optical confinement factor of 5.61%. But when the wavelength reduces, the e-block reduces the confinement factor. The case with no e-block at a 400nm wavelength produced the highest confinement factor at 7.61%, which is a 55% variation compared to the 460nm wavelength without e-block. The above simulation is all based on substrate thickness of 4µm. When the buffer layer is optimized with a 20nm e-block it is found that a thin buffer produced a better optical confinement at 5.7267%. This is a small improvement from 5.61% (4µm substrate) but is a step towards further optimization.

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