OPTICAL MODE STUDY OF GALIUM NITRIDE BASED LASER DIODES

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Bachelor of Science

by

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Abstract

This paper focuses on the optical mode analysis of laser diodes to improve light emission. Under the mode analysis, we compare the optical confinement factor (OCF) percentage of the emitting light from the LDs. There are two structures which we analyze: a basic GaN waveguide structure and an InGaN waveguide structure. The second structure has additional InGaN waveguides and is analyzed under two additional design variations: the concentration of Indium and the thickness of the top waveguide layer. The results of this study indicate introducing InGaN waveguide layers correlates with lower order modes (zero and first order) and increase the OCF values. The top InGaN waveguide layer, which has a higher concentration of Indium, appears to increase the OCF. However, the increased thickness of the InGaN layer causes the lower modes' OFC to decrease. Over all, in the best case, InGaN LD has an OCF of 1.8896%, which is about a 312% improvement compared to that of GaN LD (OCF=0.4535%).

Chapter I. Introduction

Today Laser Diodes (LDs) are used for multiple applications. The use of solid state laser devices has been found in fiber optics, visual imaging, and in high quality media storage [1]-[3].

1.1 Understanding the Laser Diode

Laser diodes are classified under PN junction sense they have both donor (p-type) and acceptor (n-type) doped material. PN junctions form a bad gap created at the connecting section of the two materials. When a voltage is applied to the PN junction the potential energy, which is required for an electron to jump across the bad gap, is reduced allowing electrons to continually jump across for current to flow through the device. Consequently when the electron jumps across this band gap energy is released in the form of light (photons) or heat (phonons). This release of energy can be controlled depending on the type of martial being used, which lead to different types of electron devices such as diodes, light emitting diodes (LEDs), and LDs.

The distinction of LDs from other PN junctions is that LDs emit light under a controlled reaction. In order for LDs to emit light the device must be stimulated by obtaining a certain threshold of energy in the form of photons. Once this threshold is obtained light is emitted in a narrow polarized beam. In order to improve efficiency different methods have been used to reduce the energy threshold and improve the light extraction of LDs.

1.2 The Prospect of Gallium Nitride

Recently major development in wide-gap III-V nitride semiconductors by Shuji Nakamura have shown the practical application for LEDs and LDs [4][5]. GaN devices have been used for commercial blue and green LEDs due to direct band gap properties. The direct band gap properties allow electrons to jump across directly to holes creating photons, in comparison to indirect band gaps that do not produce photons due to an intermediate phase the electrons must jump through to reach the hole [6]. However there are disadvantages with GaN such as poor crystal quality, inability to receive p-type doping, high resistive p-type layer, and high refractive index [7]. S. Nakamura overcame these flaws by performing two techniques. The first technique was the Two Flow Metal

Organic Chemical Vapor Deposition (TFMOCVD), which improved the lateral growth of crystals by pumping in gas perpendicular and parallel to the substrate [4][5]. The second technique involved annealing the substrate in a hydrogen free environment at high temperatures [4][5]. This process released p-type impurities bound with hydrogen atoms such as Mg-H preventing the p-type semiconductor from becoming intrinsic and fixed the issues involving the p-type layer.

1.3 Current Issues and Progression with GaN

However the high refractive index of GaN was still an issue that reduces the efficiency of these structures due to total internal reflection [8]. The refractive index is a property of the material that defines how light waves will interact with the boundaries of the material, represented by Snell's law in equation (1).

$$n_1 \sin(\theta_1) = n_2 \sin(\theta_2) \quad (1)$$

The high refractive index causes multiple passive waveguide to form in the device leading to transverse mode coupling [9][10]. The total internal reflection along transverse mode coupling is the cause of ghost modes forming within the structure. This is due to the light being refracted back into the structure at the boundaries of the multiple passive waveguides [11][12]. Recently, InGaN waveguide layers have been used to enhance the intensity of GaN LDs in experiments [13]. This is due to the higher refractive index that Indium introduces in comparison to Gallium. The difference in refractive index helps control the photons in an active region to stimulate light emission [6]. Studies have found that lower active modes use less current and lower power to operate the LDs, which can also improve the lifetime of the LD [14]. The various modes can be compared by their optical confinement factor (OCF) percentage, which is a ratio comparing the amount of light emitted over the active region in relation to the entire structure [15]. In this paper, we use mode analysis to prove how the addition of InGaN waveguide layers improves the light emission of mode patterns in theory.

Chapter II. Simulations

2.1 Simulation Software

This paper focuses on understanding how each waveguide layer in a GaN based LD contributes to the traverse mode coupling and optical confinement factor of the entire device. For simplicity, we propose to use a 1D multi-layered structure model using RSOFT's LaserMOD software to run optical mode calculations [16]. The software defines each layer of the structure under a user defined material file. Once the structure is constructed the software uses the Ritz simultaneous iteration method perform the mode analysis. The Ritz simultaneous iteration uses Maxwell's waveguide theory by applying the Helmholtz equation, defined in equation 1, and iterating the propagation of the waves induced by the current. With the Ritz simultaneous iteration we can comparing the energy of a mode to the energy of the active region to calculate the strength and location of each mode of the optical confinement factor.

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

This equation (2) uses the following variables from the material file to perform the calculation of the optical confinement factor: the propagating field $E_m(x,y,z)$, refractive index $n_{eff,m}$, dielectric constant $\varepsilon(x,y)$, and the propagation factor k_o.

2.2 Laser Diode LaserMOD Design

In this study our objective is to improve the optical confinement factor and reduce ghost mode of GaN based LD devices by comparing two structures, a basic GaN waveguide structure and an InGaN waveguide structure. The injector and buffer layers are used for electric contacts to inject current. Additionally the n-GaN buffer layer is used as a base material to grow the laser diode. The cladding layers uses the small change in refractive indexes between the multiple layers to confined the photons from being released. The Electron Blocking Layer (EBL) controls the flow of electrons through the laser diode slowing the flow of electrons so they can be readily used for the active region. The spacer has a similar function to the cladding since it acts as a small buffer for the EBL and active region, while at the same time not letting a lot of photon emission due to the small changed in index of refraction from the EBL. The active region is the primary waveguide layer that emits photons out by using the large change in index of refraction from the space and using quantum wells. The first and second structure are identical expect for the two additional InGaN waveguides waveguide layers introduced in the second structure.

The first structure constructed was a basic GaN waveguide structure. The GaN waveguide structure can be seen in Figure 1 displaying the each layer. The properties and dimensions of each layer are defined in Table I. It includes the material, the thickness, the refractive index, and doping levels.

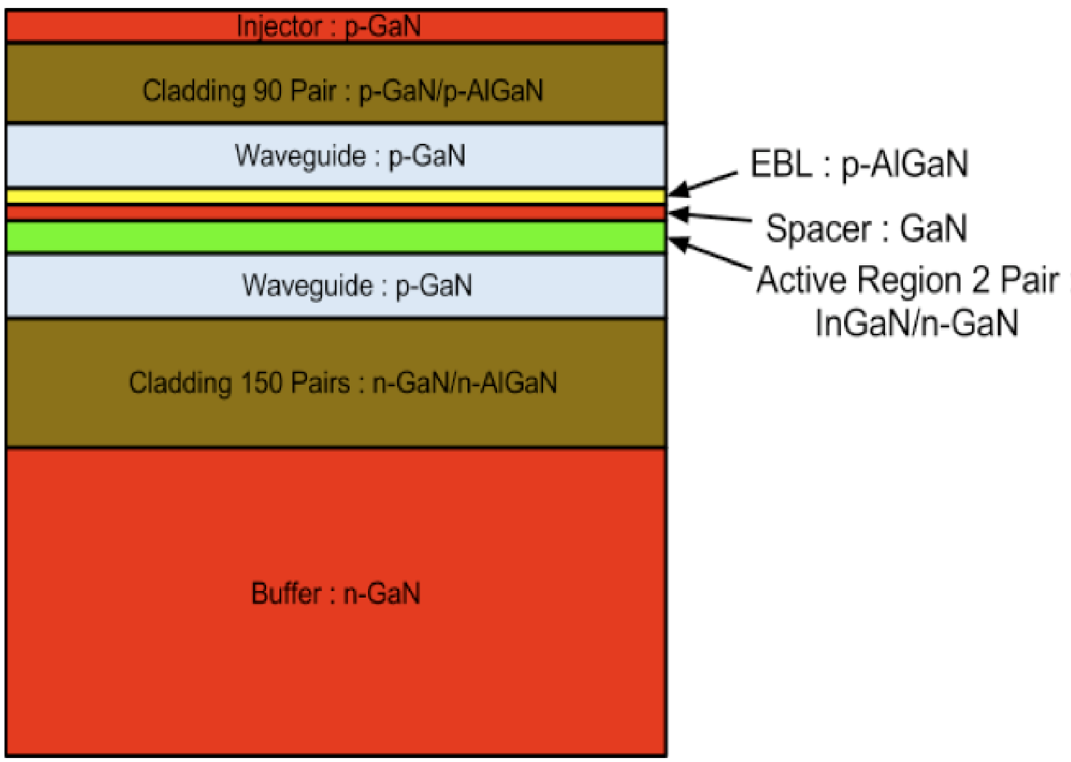


Figure 1 Basic GaN Waveguide Structure

Table I Properties of the Basic GaN Waveguide Structure

Layer	Material	Thickness [nm]	Refractive Index	Composition
Injection	p-GaN	30	2.5	-
Cladding 90 Pairs	p-GaN/ p-AlGaN	2.5/2.5	2.5/2.48	0.16
Waveguide	p-GaN	100	2.5	-
Electron Blocking Layer	p-AlGaN	20	2.48	0.18
Spacer	GaN	8.8	2.5	-
Active Region 2 Pairs	InGaN/ n-GaN	2.8/8.8	2.59/2.5	0.18/-
Waveguide	n-GaN	100	2.5	-
Cladding 150 pairs	n-GaN/ n-AlGaN	2.5/2.5	2.5/2.48	-/0.16
Buffer	n-GaN	3000	2.5	-

The second structure constructed was an InGaN waveguide structure. The InGaN waveguide structure can be seen in Figure 2 displaying the each layer. The properties and dimensions of each layer are defined in Table II. It includes the material, the thickness, the refractive index, and doping levels.

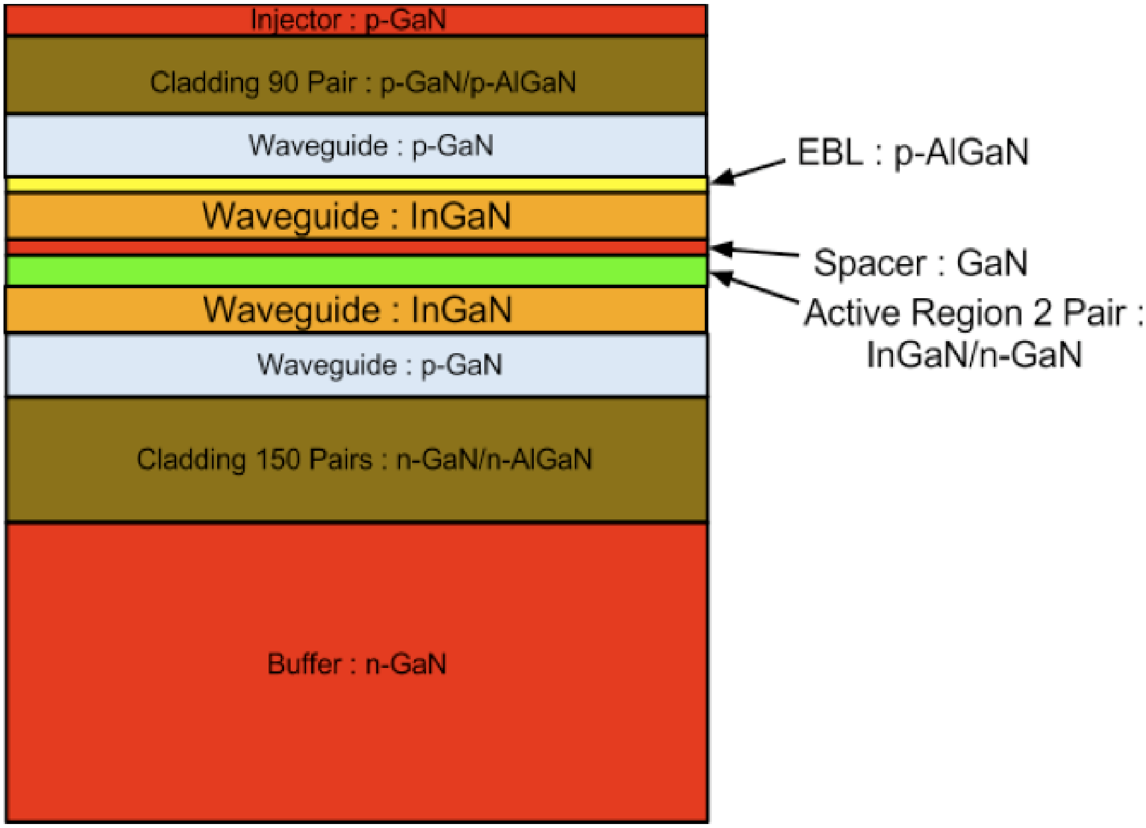


Figure 2 InGaN Waveguide Structure

Table II Properties of the InGaN Waveguide Structure

Layer	Material	Thickness (nm)	Refractive Index	Composition
Injection	p-GaN	30	2.5	-
Cladding 90 Pairs	p-GaN/ p-AlGaN	2.5/2.5	2.5/2.48	0.16
Waveguide	p-GaN	100	2.5	-
Electron Blocking Layer	p-AlGaN	20	2.49	0.18
Waveguide	InGaN	80	2.59	0.03
Spacer	GaN	8.8	2.5	-
Active Region 2 pairs	InGaN/ n-GaN	2.8/8.8	2.59/2.5	0.18/-
Waveguide	InGaN	80	2.59	0.03
Waveguide	n-GaN	100	2.5	-
Cladding 150 Pairs	n-GaN/ n-AlGaN	2.5/2.5	2.5/2.48	-/0.16
Buffer	n-GaN	3000	2.5	-

The first two simulations performed were modal analysis of the basic GaN waveguide structure and the InGaN waveguide structure. The analysis wave performed to measure the optical confinement factor for the first ten transverse electric modes at a wavelength of 450nm.

The third simulation performed was on the InGaN waveguide structure. This simulation focused improving the optical confinement factor of the fundamental modes and reducing ghost modes by altering the top InGaN waveguide. We altered the concentration of Indium in the top $In_xGa_{1-x}N$ waveguide from 3% to 15% in steps of 3% at 450nm wavelength. By altering the concentration of Indium in the $In_xGa_{1-x}N$ waveguide we change the refractive index of the waveguide. Below in Table III are the refractive indexes for each concentration of Indium.

Table III Refractive indices of $In_xGa_{1-x}N$ for each concentration of Indium

Material Composition	**Refractive index**
In(0.03)Ga(0.97)N	**2.59**
In(0.06)Ga(0.94)N	**2.63**
In(0.09)Ga90.91)N	**2.67**
In(0.12)Ga(0.88)N	**2.71**
In(0.15)Ga(0.85)N	**2.75**

The final simulation performed was on the InGaN waveguide structure. Similarly this simulation focused on altering the top InGaN waveguide to improve the optical confinement factor of the fundamental modes and reduce ghost modes. Using the mode analysis at 450nm wavelength, we observe how the OCF changes with each mode for the first ten modes. We altered the thickness of the top InGaN waveguide layer from 0.8µm to 1.08µm in steps of 0.1µm.

Chapter III. Simulation Results

3.1 Basic GaN Waveguide Structure and InGaN Waveguide Structure Results

For the first two simulations we performed modal analysis for the basic GaN waveguide structure and the InGaN waveguide structure as explained in the Simulation section Laser Diode LaserMOD Design. The basic GaN waveguide structure was used as a reference in comparison to the InGaN waveguide structure. The results of the basic GaN waveguide structure simulation can be seen below in Figure 3 displaying the OCF of each mode. The results show the maximum value of the OFC in our simulation is 0.4535% for modes 2 and 9, while the fundamental modes (modes 0 and 1) remain below 0.15%. The InGaN waveguide structure shows that the additional InGaN waveguides do in fact improve the performance in comparison to the basic GaN waveguide structure. The results of the InGaN waveguide can been seen below in Figure 4 displaying the OCF of each mode. Notice the structure clearly prefers fundamental modes (modes 0 and 1) with the OCF values of 1.5687%. The OCF here is increased by about 247% compared to the InGaN waveguide structure (OCF=0.4525%). Concurrently, the mode orders reduce from mode 2 and 9 to modes 0 and 1. This variation of mode order, to lower modes, shows the effects of the InGaN waveguide layers on the optical mode emission.

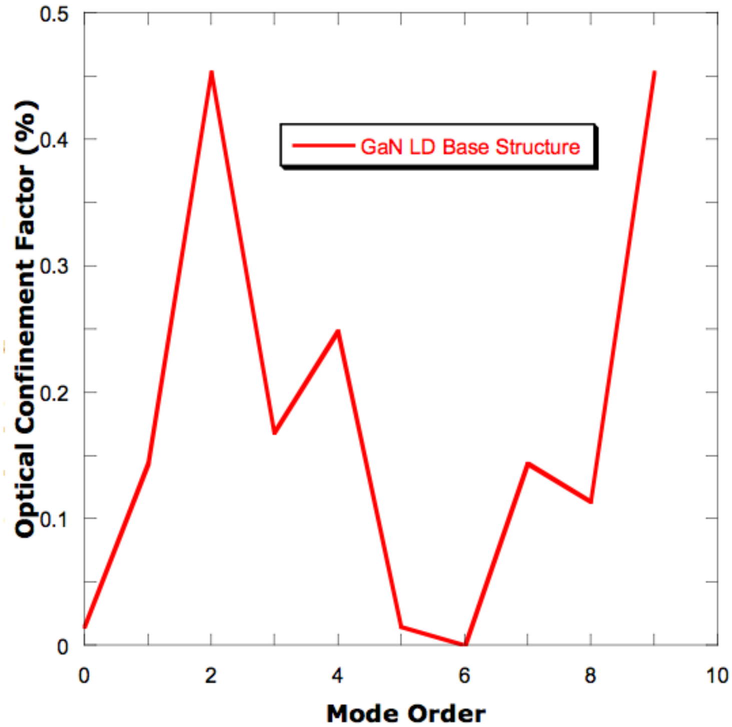


Figure 3 Modal analysis of the first structure displaying each mode's optical confinement factor

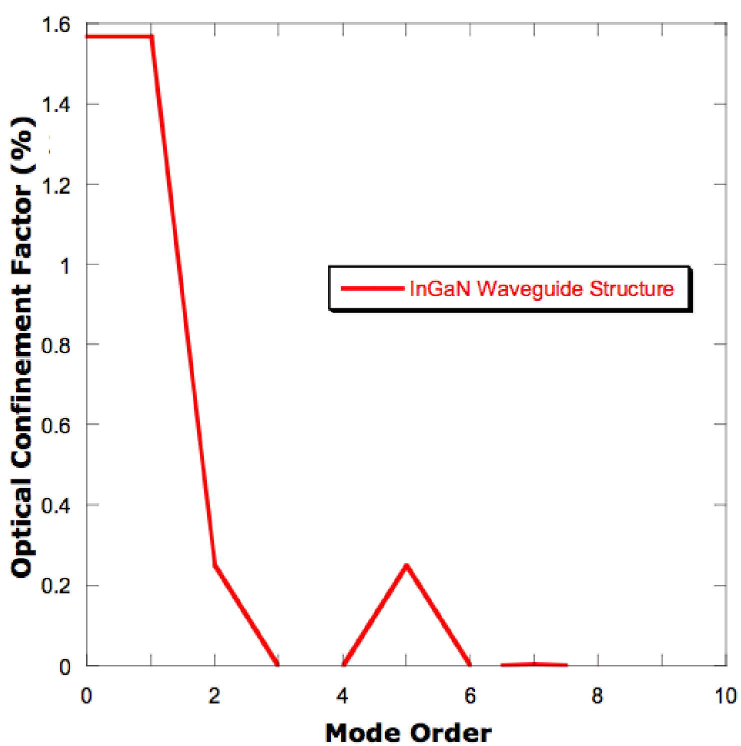


Figure 4 Modal analysis of the second structure displaying each mode's optical confinement factor

3.2 $In_xGa_{1-x}N$ Waveguide Concentration Alteration Results

We perform the additional modal analysis for the InGaN waveguide structure by varying the doping level of the InGaN waveguide located above the active region, on the y-axis. The simulation was performed using the same parameters as explained in the Simulation section Laser Diode LaserMOD Design. The results of the simulation can be seen below in Figure 5, which is the mode analysis under different doping levels of the top InGaN waveguide layer. The plot displays each modes' OCF and the legend displays the composition of the InGaN waveguide. The maximum values are always around the fundamental modes, with the highest values around 1.889%. As the concentration of Indium increased, we find an increase in the OCF from 1.5687% at In(0.03) to 1.889% at In(0.15). Furthermore, the OCFs decrease at the second order mode from 0.25% at In(0.03) to 0.08% at In(0.15). The improvement only seems significant in steps leading up to a 12% concentration of Indium at an OCF of 1.8696% since there is only a 0.02% increase in OCF from 12% Indium to 15% Indium concentration. From these results, the OCF has a 20% gain by using the $In_{0.12}Ga_{0.88}N$ waveguide layer over the basic $In_{0.03}Ga_{0.97}N$ structure.

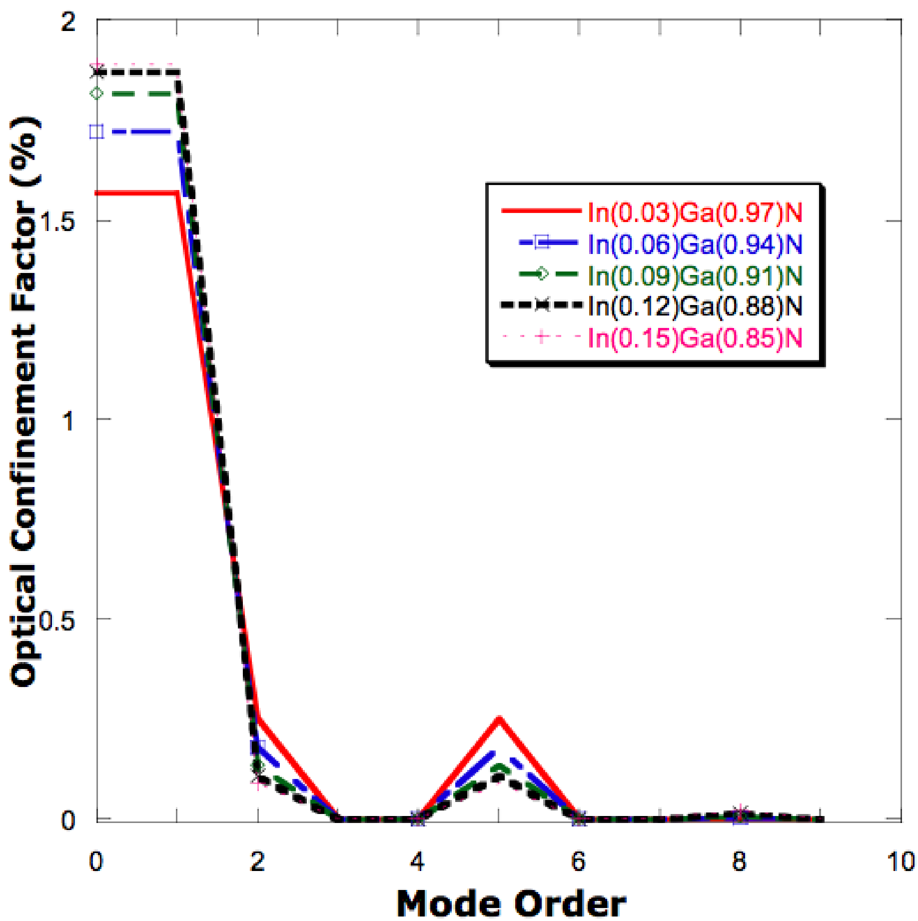
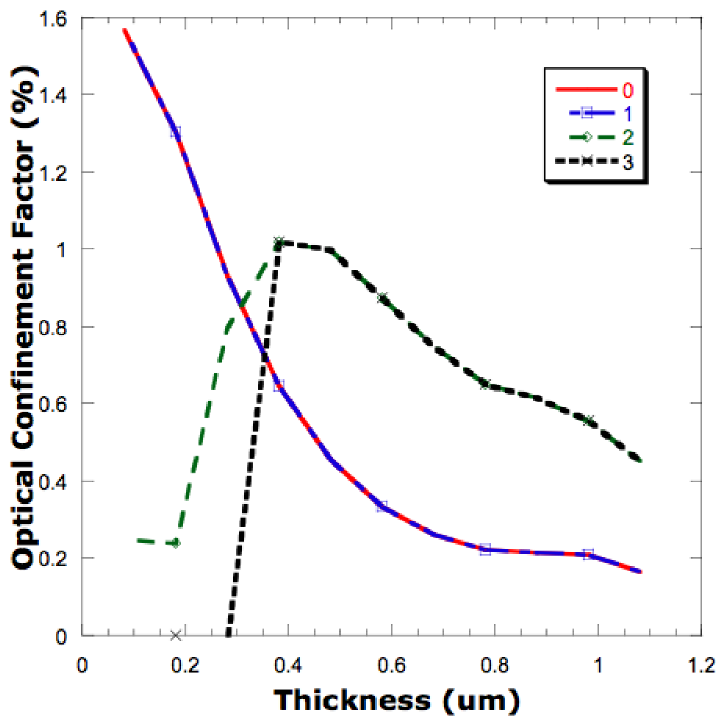


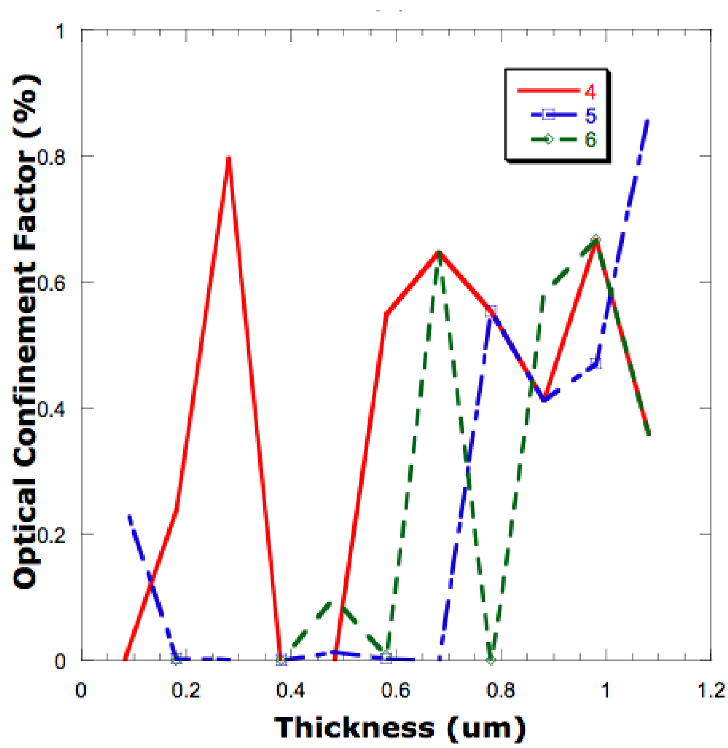
Figure 5 Modal analysis of the second structure with varying concentration of indium in the InGaN waveguide

3.3 InGaN Waveguide Thickness Results

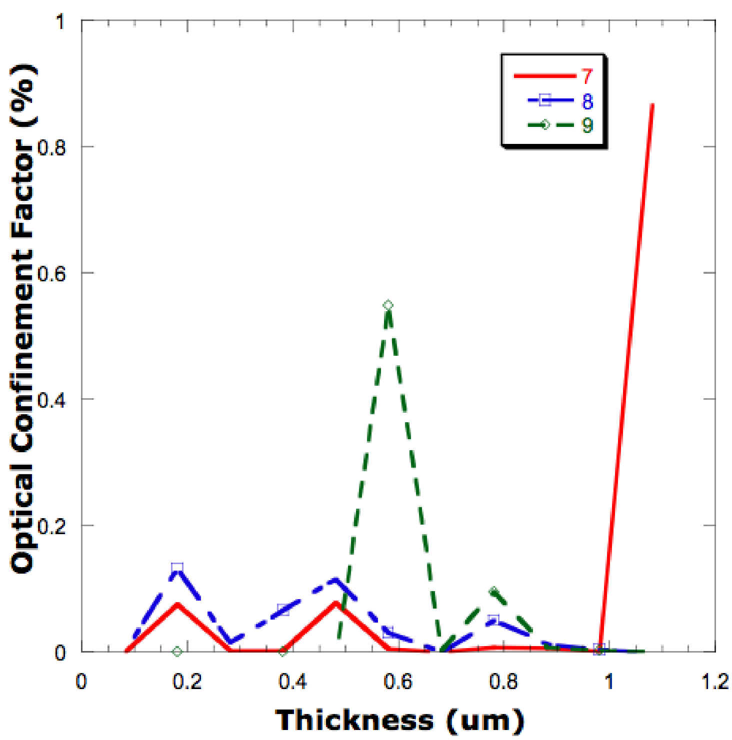
In the last simulation, we varied the thickness of the same $In_{0.03}Ga_{0.97}N$ waveguide layer. Again the simulation was performed using the same parameters as explained in the Simulation section Laser Diode LaserMOD Design. Figure 6 displays the OCF in relation to the changing thickness and the legend refers the mode order. From Figure 6(a), we notice fundamental modes share an inverse relationship between OCF and thickness since the increase in thickness relates to a decrease in OCF. However, for modes 2 and 3, we notice high values of an OCF about 1.02% at 0.38µm thickness and remains above 0.7% until a thickness of 0.68µm reached. From Figure 6(b), the high value of the OCF for mode 4 is 0.797% at 0.28µm, for mode 5 an OCF of 0.866% at 1.08µm. From Figure 6(c), the highest OCF value for mode 7 is 0.866% at 1.08µm, for mode 9 a high OCF value of 0.549% at 0.58µm. The results show the fundamental modes are most effective with thin layers, as well as in modes 2 and 3. The higher order modes display no clear trends, but have high OCF values with thicker waveguide layers. For the best results, the 0.08μm thickness has the highest OCF of 1.5687% for the lowest modes and the lower OCF for the high modes.



(a)



(b)



(c)

Figure 6 Top grating transmission efficiency for period A=200nm with grating height h= (a) 50nm, (b) 100nm, and (c) 150nm

3.4 *Conclusion*

Our simulations show that adding the InGaN waveguide layers can improve the OCF efficiency of the modal pattern. By using the first simulation model as a reference, the second simulation model shows that the InGaN waveguide shifts the active modes to modes 1 and 2 from 2 and 9, and increases the maximum OCF values to 1.5687% which is a 247% improvement. The increase concentration of Indium in the top InGaN waveguide results in a further increase in the OCF for lower order modes while decreasing the OCF for higher modes to 1.889% with a plateau at a 12% Indium concentration. This is about a 322% improvement compared to simulation model 1. Increasing the thickness of the top InGaN waveguide decreases the OCF of lower order modes and allows active high order modes to appear. In general, the 0.08µm is an ideal thickness of the InGaN layer in our simulations.

Chapter IV. Future Objectives

This paper focused on further understanding the effects of additional InGaN waveguide layer to the GaN LD. In the past InGaN waveguide layers have shown improvements in light extraction from the GaN LD. We have shown that the InGaN waveguide layers can reduce the mode order and improve the OCF of the device. Now it is important that we continue to understand how these additional InGaN waveguide layers affect GaN LDs by improving upon the top InGaN waveguide layer doped at 12% Indium with a 0.08μm thickness. This can be done understanding how the bottom layer could affect the mode pattern and OCF of the device. Further more, we can continue to understand how InGaN waveguide layers affect the current and voltage range of the device by performing Light-Current-Voltage (L-I-V) simulations. With a better understanding of the current and voltage range in relation to light extraction we could in-turn find methods to improve the efficiency of the device.

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