Simulation of Single-Mode Waveguides of Gallium Nitride/ Aluminum Nitride (GaN/AlN) on Sapphire by using Finite Difference Mode (FDM) solver

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ABSTRACT

This paper presents a model of the optical waveguide of GaN/ AlN on a sapphire based on the different refractive index (n) between the wave's guideline regions and the surrounding medium (cladding). The model analysis is done by using finite-difference mode (FDM) solver simulation is performed by FDTD (finite-difference-time-domain). In the infrared area, this study reveals a fully unique and rigorous modal analysis waveguide. The investigation includes both primary and single-mode polarization; the waveguide is reliant on the refractive index of the layers, thickness, and substrate type. The primary novelty here for the micro-waveguide single-mode is to realize optical characteristics such as attenuation, amplitude, and full width half maximum (FWHM), which has not been done previously for specific thickness (given thickness) and for that geometrical design. Despite, we investigated how Optical waveguides are structures that confine and direct optical signals in a region of a higher effective index than its surrounding media. Our experiment (simulation) aims to investigate the single-mode waveguide of Gallium Nitride/ Aluminum Nitride GaN/ AlN on sapphire of a specified thickness in order to obtain infrared waveguide mode with minimum attenuation. Attenuation refers to any decrease in the propagated signal power that does not affect its waveform while the input wavelength is $1.55\mu m$. Additionally, describe the characterization of the mode, in keeping with our modal analysis. The waveguides have many applications in various fields such as Optical fiber communication and Photonic integrated circuits.

1. Introduction

The waveguide could be a type of transmission line that directs waves across the size of a slab. In this case, the slab GaN/AlN provides a medium for transporting power (energy). To improve coupling efficiency between segments with varying cross-sections, the optical waveguide is frequently required to change the size of the bright spot[1]. In order to avoid losing energy, waveguide replaced the transmission lines due to extra attenuation and path losses, were related to transmission lines. Like the assistance of a waveguide, small-signal attenuation and huge bandwidth will be earned. Creating a micro-scale waveguide is key in several physics areas like optical data storage and acoustic engineering etc[2-7].

One method for establishing a micro-scale spot within field distribution (waveguide distribution) is to use exciting plasmonic modes in tight metallic waveguides, which have been used in a variety of applications. We introduce the primary actualization of $10\mu m$ GaN width and $2.5\mu m$ AlN width on sapphire, which is suitable for optical modes. The principle of our work is that the waveguides generated between interfaces are caused by different indexes of refractive and that we use the input planner source which has $1.55\mu m$ wavelength, power is $0.01\,W$ and amplitude $1V/m$, and also the other hand we calculate modes and TE and TM mode with relation to the thickness of GaN layers. GaN/AlN may very well be the most capable region, which may prolong radiation due to the visibility of the future past of this region. In this paper, we present a comprehensive, unique, modal analysis of the GAN/ AlN IR-waveguide. In the course of this study, the cut-off conditions are given for both the transverse electric mode, the transverse magnetic mode That's why we give the sizes of the waveguide (height and width), that offers maintenance for the optical modes in the infrared range, and to study the influence of these values on the effective index of refractive of single-mode[8-10].

To describe the loss (attenuation) mechanism due to the absorption in layers, attenuation is the loss of optical power as a result of absorption, scattering, and other loss mechanisms as the

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light travel through the structure. The total attenuation is a function of the wavelength λ of the light, in this case the λ = 1.55μm. Attenuation refers to any decrease in the propagated signal power that does not affect its waveform. An attenuation constant (a) measured at L is used as a mathematical description of the power loss due to attenuation in the waveguides. It is expressed in *dB* according to the following formula[11]:

$$a = 10\log\left(\frac{p_i}{p_o}\right) \qquad 1$$

p_i &p_o Optical power measured in the waveguide in points b_1 and b_2 at a distance of L

Knowing these effective indices, we can estimate the propagation losses. The losses are characterized either by the absorption coefficient σ:

$$\sigma = \frac{4\pi}{\lambda}\ im(n) \qquad 2$$

$im(n)$: Imaginary part of refractive index

2. GaN/AlN Simulation Experiment and Structure Design

Waveguides have some of the optical field spreading that is constant on the propagation of the time and correspond it is in line with the so-called waveguide modes, which rely on the refractive index profile. The FDM solver can receive the modes (mode profile and effective index) aided by this waveguide at a specific signal frequency for certain refractive indices and waveguide dimensions. At special lengths, the FDM solver would be ready to analyze the first waveguide mode TE_0 or TM_0 these are primarily used by the propagation of electromagnetic [E&M] energy over a micron-sized area. For the duration of this paper; we focus on single-mode micro waveguide of the GaN/AlN on sapphire. The slab material used in this work for building waveguide consists of $10\mu m$ width GaN core layer placed under $2.5\mu m$ width AlN layer which is inserted on the sapphire substrate and also there's air cladding at the top of the AlN as shown in figure 1a. The index of refraction of GaN, AlN, and sapphire is $2.31, 2.02\ and\ 1.75$ correspondingly. The axial cladding is made of air, and it has a refractive index of one. The input planer wavelength is$1.55\mu m$. On the other side, radiation is transmitted over a waveguide section. Here are two field elements that are used are mutually perpendicular to each other that is an electric field and a magnetic field, the mode with electric-field polarization adjacent to the wafer direction, and thus the mode with magnetic-field polarization side by side to the wafer direction.

As a result, the GaN/AlN on sapphire waveguide design must initially sustain both foundational TE_0 and TM_0 modes, so by having to change the waveguide lengths. The optical modes in Figure 1b's waveguide topology are restricted mainly inside the higher-index GaN layer, decaying evanescently into the slight index AlN cladding. Figure 1b also shows a color map of the basic mode that expresses how the waveguide modes distribution over medium with different refractive indexes, as a result, the amplitude of such modes at sapphire is negligible [12,15]. Full width
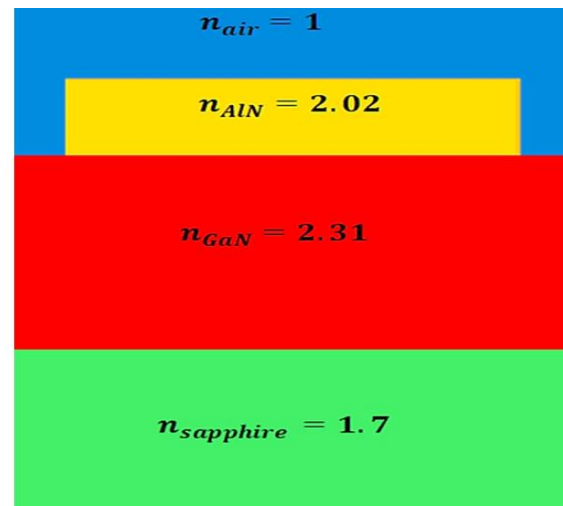

Figure 1.a: 2D constructs multi layers of the GaN/AlN waveguide cross-section with different refractive index.
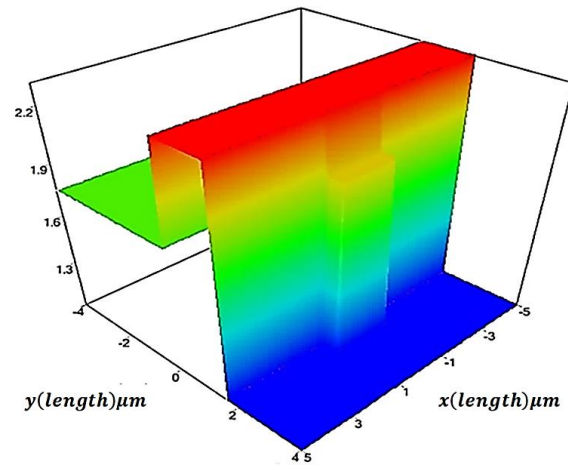

Figure 1.b: 3D waveguide geometry of GaN/AlN in different medium

half maximum FWHM is another term that is significant to elucidate waveguide, it is being explained thoroughly within the following section there are other parameters that are vital in this work as shown in table 1. The optical micro waveguide and (TE&TM) are analyzed by an FD mode solver.

Table 1: Each medium's crucial parameters which were put to use in the simulation.

Parameter name	Value
GaN thickness	10μm
AlN thickness	0.4μm
GaN refractive index	2.31
AlN refractive index	2.02
Sapphire refractive index	1.75
Air refractive index	1
power	0.01W
Amplitude	1V/m
Input wavelength	1.55μm

3. Simulation result, Characterization and Discussion

A study is reported in this work of the single-mode micro waveguide of (gallium nitride) GaN microstructure core and AlN, Sapphire layers are clad to optimize waveguide features and optical refractive indices [TE_0, TM_0 polarization]. An attempt was made to link the perceived microstructure characteristic with optical properties such as the index of refraction obtained from this practice[16]. Thru this study, it seems the refractive index contains a massive role to provide waveguide along with the slab, according to the analyzed guide mode, the energy is confined within the higher index of refractive of the GaN middle layer. Each mode is created by the evanescent wave, which eventually ends up in the cladding, we discussed in the previous section. The width of GaN and AlN is $10\mu m$, they're a perfect region to build an infrared waveguide [17]. The GaN mode is tightly confined between the top and lower cladding, as depicted in the figure (2.a), from the same figure each zone matched for a certain refractive index, [n_1=1.75] equivalent to the sapphire index of refraction, n_2=2.31 is that the index of refraction of GaN zone, the refractive index of AlN is n_3=2.02]. Figure (2.b) indicates how the mode distributes over block sample (GaN/AlN on sapphire) in 3-dimension with varied refractive indices.
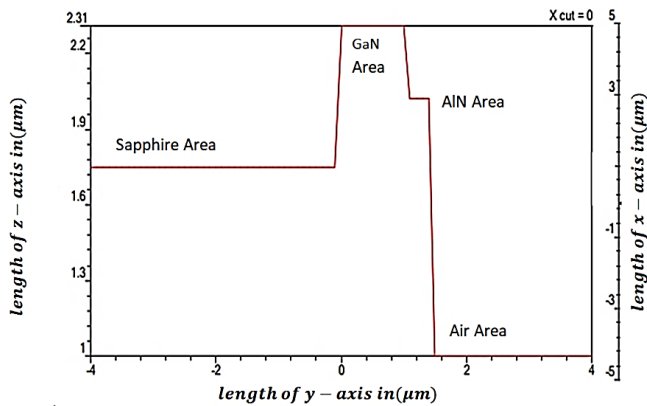

Figure 2.a: 2D waveguide distributes over slab materials with different medium in refractive index while x-cut=0.
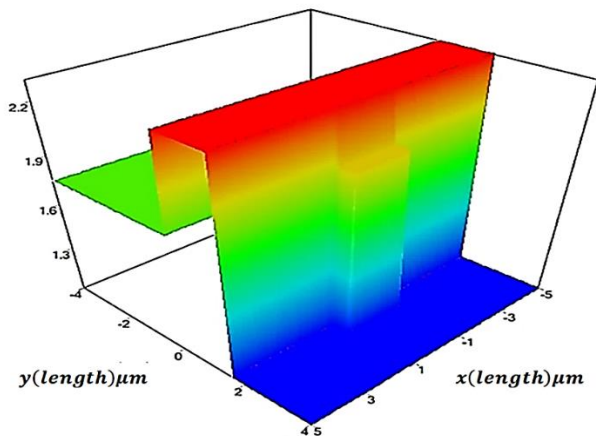

Figure 2.b: 3D waveguide distributes over slab materials (GaN-AlN-sapphire) with different refractive index.

Figure (3.a) displays how the density of waveguide accumulated (energy confined) at the center of the mode (red peak) in a single-mode waveguide that reaches a high value in (a.u). As seen in figure (3.b) the amplitude (red line) is the highest value 1 (a.u) at the center of the mode because that region has a high refractive index, which matches the GaN zone. In the lack of minimum loss, the geographical field distribution of a waveguide mode does not really vary with spreading, making it a stable propagation mode. The cross-sectional refractive index distribution of the micro waveguide affects the waveguide's modes.
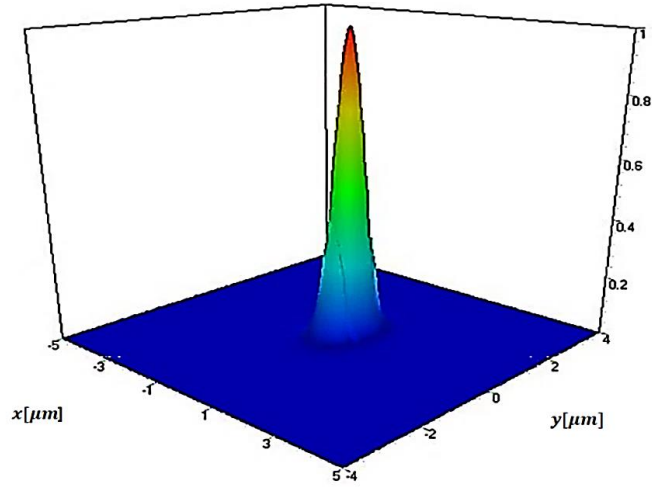

Figure 3.a: The output of a basic waveguide simulation,3D full mode at the interface between GaN-AlN on sapphire layer in x-y profile, Due to the difference medium in refractive index
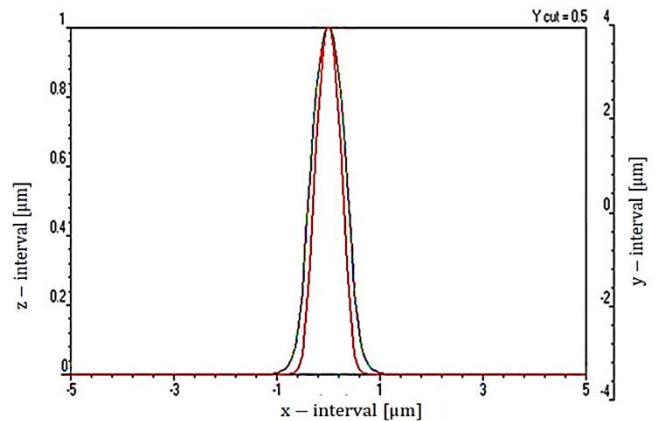

Figure 3.b: intensity black line (a.u) and amplitude (a.u) red line of the waveguide mode while at Y-cut (Y=0.5)

The X-cut and Y-cut are two more terminologies used to define the mode's amplitude and intensity; the red and black lines represent amplitude and intensity, respectively, and both of them reach 1 $in\ (a.u)$ from interval ($-1.4\ to\ 1.4)\mu m$, ($-1.2 to\ 1.2)\mu m$ respectively in x-direction that appeared in Figures 4a. Based on figure (4b), the peak of the amplitude corresponding to the waveguide mode GaN, the same peak is decreasing gradually as a Gaussian form at the cladding region. It means there is no waveguide mode this situation clearly perceived because of decreasing refractive index of the cladding region. The same description is true for intensity. The maximum amplitude and intensity could be achieved at positions 0.03 and

0.5 in x-cut and y-cut respectively, at that point the mode is pure. In this modulation, we realized that the modes are possible for micro-operating wavelength and micro variation multi-layer construction.
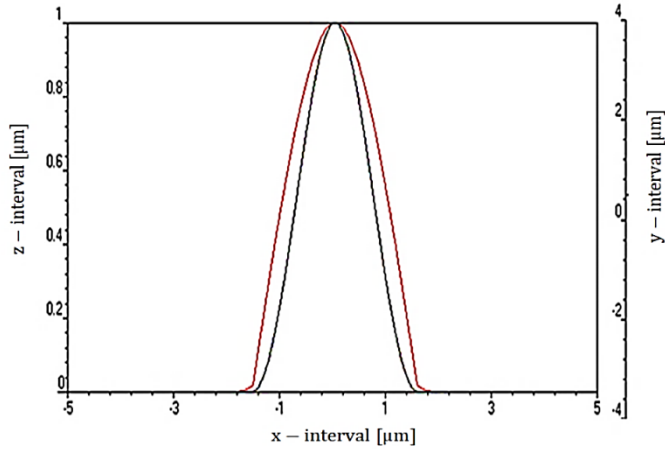

Figure 4.a: amplitude [red solid line (a.u)] and intensity [black solid line (a.u)] of fully waveguide single mode in(x-y) profile.
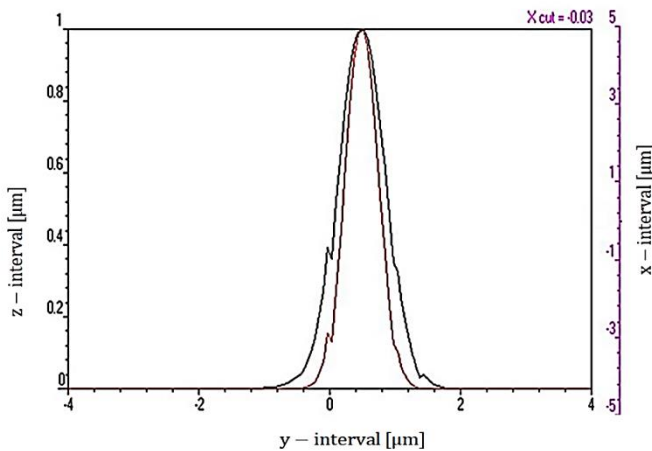

Figure 4.b: intensity with (a.u) and amplitude with (a.u) of the single mode waveguide at X-cut (X=0.03)

In terms of transverse, the electrical field component is completely transverse to the direction of wave propagation through this whole mode of wave propagation, whilst the magnetic field component is not entirely transverse to the propagation track. The elementary TE0 mode could also pass with the smallest losses through the TE-pass polarizer, while TM0 must be banned [18,19].

$$E_z=0; H_z\neq0$$

Concerning TM0 wave the magnetic field portion is entirely transverse to the direction of the wave for this mode of wave propagation, whilst the TE0 is not fully transverse to the direction of the wave.

$$E_z \neq 0 \; ; H_z = 0$$

The TM0 mode should become blocked and enter the cut-off range, even as TE0 can pass with minimal loss. In both TE&TM modes full width half maximum (FWHM) is $0.965 \; and \; 2.07$ within their value is $0.5 \; and \; 0.17$ in x-cut and Y-cut respectively shown in figure (5). Additionally, the maximum amplitude of the single mode is about $1 \; and \; 0.225$ in (a.u) at X-cut & Y-cut as shown in figure 5. In both locations [x-cut, y-cut], they are perfect position to create waveguides with high energy and low waste.
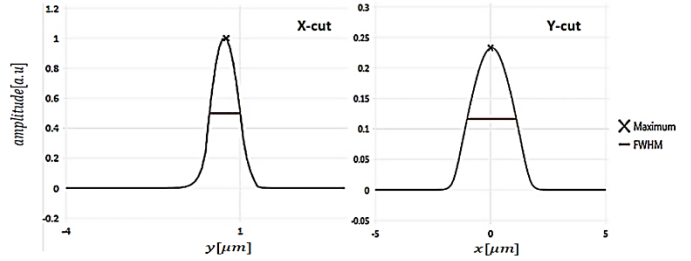

Figure 5: In both the X-CUT and the Y-CUT, the FWHM and amplitude of the polarization mode [TE0&TM0].

As light passes through a material, attenuation is the loss of optical power due to absorption, scattering, and other loss causes. Any decrease in the transmitted signal's power that does not modify its waveform is referred to as attenuation. A transfer of signal wave energy to the medium in which the wave propagates is defined as absorption loss. The energy is lost due to particle vibrations. Also, the absorption loss is dependent on the refractive index of material, which is expressed in equation (2). According to equation (2), more refractive index makes the energy of the waveguide is confined compared to other zones that have a less refractive index. Generally, Attenuation can be caused by the materials employed, such as the physical features of the core, or by waveguide construction. Moreover, the length L is a parameter that has a massive role in attenuation rate (attenuation coefficient), which is expressed in this formula

$$a_l = \frac{10}{L} \log \left(\frac{p_i}{p_o}\right) \qquad 3$$

a_l: Attenuation coefficient. It could calculate the attenuation rate from equation (3) by knowing the parameters in the equation. Figure 6 show that the power of waveguide was $0.1 \; mw$ at a high refractive index known as p_o matched to the GaN, $p_i = 0.01w$ given.

The operation wavelength of the waveguide is 1.55 micron, this wavelength has been chosen because the loss of any optical structure is minimum, I can say that due to the absorption characteristics of the material used in a waveguide structure. Also, at the same range of wavelength, the transmission is well. We could measure attenuation. We took[$p_o = 0.1 \; mw$]for GaN. Put the all known parameter ($p_o, and p_i$) in equation (1) then we calculated the value of attenuation (a), which was($20dB$). By knowing that parameters, its attenuation coefficient can be determined by calculating equation (3) for single mode:

For GaN $L = 10cm$, the attenuation coefficient value was ($2dB/cm$) at 1.55 μm which is a minimum fairly. We were able to compare our results using another finding that computed $a_l =$

$(0.61) dB/cm$ [20]. The same mathematical technique can be applied for AlN layer, the result is about $2.3 dB/cm$ for a given p_o in figure 6. This structure has various applications in optical fiber and communication because of its low attenuation[20,21].
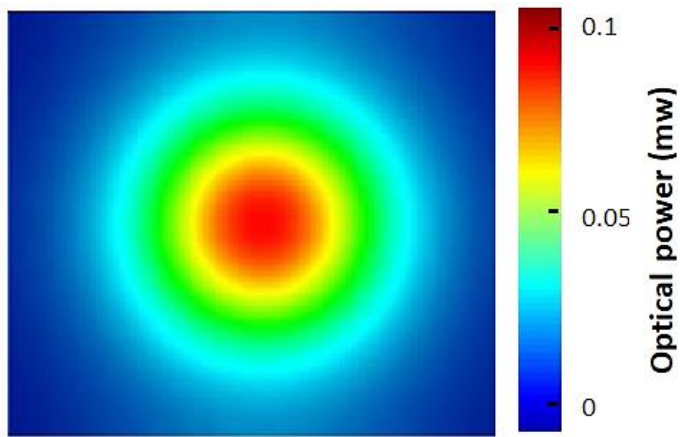

Figure 6: Optical output power of GaN/AlN waveguide at 1.55μm wavelength

4. Conclusion

The simulation (modeling) and design structure of GaN/AlN waveguides on sapphire were discussed in this study. At the range of infrared frequency, we executed extensive research on optical waveguides in GaN. In an optical waveguide, we've explored single-mode waveguides including both transverse electric and transverse magnetic modes. They may arise as a result of the mode electric and magnetic in specific micro waveguide size limits, which was seen in the analysis. The existence of a mode in GaN inside the infrared spectrum region was validated by our stimulated results. On the other hand, the simulation results were also exposed to single-mode intensity and amplitude that might be achieved in micro range, both of them reached $1\ in\ (a.u)$ from interval $(-1.4\ to\ 1.4)\mu m$, $(-1.2 to\ 1.2)\mu m$ respectively. Furthermore, the research indicates the characterization (x-cut and y-cut) frequency, which is the greatest location that the mode is available at which a mode will pass in an electromagnetic waveguide with minimum loss. Furthermore, on the GaN/AlN on the sapphire platform, we demonstrated a basic micro-thick waveguide of GaN in the infrared range. The micro-thin GaN waveguide has an attenuation coefficient loss of $2 dB/cm$ $at\ 1.55\ \mu m$. The outcomes and fabrication techniques established throughout this study pave the way for the development of III-nitride integrated photonics for nonlinear optics and quantum photonics applications in micro region.

Conflict of interests
None.

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