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| Title                | Towards a GaN-on-sapphire photonic integrated circuit via micro-transfer printing                                                            |
| Authors              | O'Brien, Megan                                                                                                                               |
| Publication date     | 2024                                                                                                                                         |
| Original Citation    | O'Brien, M. R. 2024. Towards a GaN-on-sapphire photonic integrated circuit via micro-transfer printing. PhD Thesis, University College Cork. |
| Type of publication  | Doctoral thesis                                                                                                                              |
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| Download date        | 2026-09-18 17:17:37                                                                                                                          |
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# Towards a GaN-on-sapphire photonic integrated circuit via micro-transfer printing

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**Thesis submitted for the degree of  
Doctor of Philosophy**

February 2024

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Research supported by Science Foundation Ireland

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## Abstract

Photonic integrated circuits (PICs) can alleviate the pressure on existing infrastructure for increasing bandwidth requirements by potentially offering faster data transmission with low energy consumption all on the same chip. The ability to integrate active lasing sources to waveguide platforms while also maintaining low-loss coupling is key for efficient PICs. This research focuses on the development of an AlGaIn/GaN-on-sapphire platform and the integration of 1.3  $\mu\text{m}$  edge-emitting InP-based multi-quantum well (MQW) and GaAs-based quantum dot (QD) lasing devices to the platform via micro-transfer printing ( $\mu\text{TP}$ ). Gallium nitride (GaN) can be used alternatively to traditional Si-based photonics due to its broad spectral transmission, birefringence, refractive index suitable for fiber coupling, and the possession of both the linear electro-optic effect and non-linear properties.

First, we design an AlGaIn/GaN structure that creates a single-mode, broad passive spot size for relaxed alignment tolerance of the transfer-printable laser-to-waveguide. Coupling losses as low as 0.6 dB were calculated for the optimal positioning of the laser. We also outline a double-tapered mode adapter that converts the dimensions to more suitable structures for light-routing. The integration of LiNbO<sub>3</sub> coupon to the AlGaIn/GaN platform is explored through simulations in order to enhance the electro-optic property, and a Mach-Zehnder modulator (MZM) design is proposed. Additionally, the simulations of (i) directional couplers, (ii) polarization converters and (iii) grating couplers on an AlGaIn/GaN platform are presented in this work.

Next, the fabrication of AlGaIn/GaN waveguides devices through BCl<sub>3</sub>-based etching recipes, along with the challenges of achieving smooth and vertical waveguide sidewalls, are discussed. A BCl<sub>3</sub> dry etch for forming a trench into sapphire is also developed for  $\mu\text{TP}$  alignment purposes. The AlGaIn/GaN waveguides were then characterized, and we distinguish the differences in propagation losses between the TE and TM polarizations. The average propagation losses ranged between 2.4-14.7 dB/cm for both polarizations. Following on from this, both the InP-based MQW and the GaAs-based QD laser coupons were characterized and transfer-printed and coupled to the fabricated GaN waveguides. A coupling output of 2.3 mW at 80 mA was achieved for the QD laser, giving a coupling efficiency of 10.3 %. The results show promise for GaN to be a suitable platform for integrated photonics.

## Acknowledgements

I would like to first thank my supervisor Brian Corbett for all the support and guidance over the last five years, and for giving me this opportunity. I would also like to extend thanks to my co-supervisor Frank Peters and my PhD monitor Fatima Gunning for their help and guidance. I was lucky enough that the group I carried out my research in, the III-V Materials & Devices group, is full of knowledgeable and helpful researchers. I can honestly say that I have learnt so much thanks to interacting with these people on a daily basis, and I am grateful to you all. Many thanks to Brendan Roycroft for the lab setup trainings, and to John Justice and James O'Callaghan for sharing their general fabrication knowledge. Special thanks also goes to Nicola Maraviglia for working closely with me on this research, and to Zhi Li and to Muhammet Genc for sharing their knowledge on GaN fabrication. Thanks to Vitaly Zubialeovich for growing the GaN epistructure for me, to Ann Foley for carrying out the sample dicing, to Alan Hydes for the guidance in developing a sapphire etch recipe and to Brendan McCarthy and Yeasir Arafat for the e-beam exposures.

I've been lucky enough to meet some wonderful people outside of my research group during my time in Tyndall, and it is safe to say that I have made friends for a lifetime. From the Tyndall Postgraduate Student Committee to going for a pint (or too many) after work, it has truly been a blast. I would also like to especially thank Shree Krishnamoorthy for all the PhD advice shared over many coffees and walks. A significant chunk of my PhD was spent in the Covid-era, and I am very grateful that I had my fellow residents of 19 Ros Barra during and after this time: Jack, John, Louise, Sorch, Kevin and Pablo. I would also like to thank my wider group of friends in "A Flip Just Switches" (don't ask) for all their support (generally via memes) throughout the years. To Anne-Marie for being there since we first met almost 10 years ago when we ended up in digs for student accommodation. I hope Ann has forgiven us since for our 1<sup>st</sup> year shenanigans. To my partner, Colum, to whom I am so thankful for all of his support for me. It only feels like yesterday when we first met in Tyndall, and every day since I have counted myself lucky that you're in my life. To my family, thank you for being my biggest supporters and for always encouraging me to go for what I wanted.

*Megan*



## List of Publications

### Publications

1. M. O'Brien, N. Maraviglia, A. Uzun, Y. Arafat, V. Zubialevich, M. Genc, Z. Li, B. Roycroft, J. O'Callaghan, P.J. Parbrook, and B. Corbett, "Integration of O-band quantum dot lasers with AlGaIn/GaN waveguides", *Optics Express* Vol.32 No. 13, 2024, doi = 10.1364/OE.527790

### Conference Proceedings

1. M. O'Brien, N. Maraviglia, V. Zubialevich, A. Uzun, M. Genc, Z. Li, P. Parbrook and B. Corbett, "Heterogeneous Integration on AlGaIn/GaN photonics for near-IR applications", *International Workshop on Nitride Semiconductors*, Berlin, Germany, 2022
2. M. O'Brien, N. Maraviglia, V. Zubialevich, and B. Corbett, "Designing a GaN photonic platform for near-IR applications", *European Conference on Integrated Optics*, Milan, Italy, 2022
3. M. O'Brien, R. Loi, M. Genc, Z. Li, V. Zubialevich, and B. Corbett, "Integration of III-V lasers on GaN photonics platform via micro-transfer printing", *Photonics Ireland*, Online, 2021

## Abbreviations

|          |                                            |
|----------|--------------------------------------------|
| 2DEG     | Two-Dimensional Electron Gas               |
| $\mu$ TP | Micro-Transfer Printing                    |
| AOC      | Active Optical Cables                      |
| BCB      | Benzocyclobutene                           |
| BOE      | Buffered oxide etch                        |
| CMOS     | Complementary Metal-Oxide Semiconductor    |
| CVCS     | Continuously Varying Cross-Section         |
| EAM      | Electro-absorption Modulator               |
| EME      | Eigenmode Expansion                        |
| FDE      | Finite Difference Eigenmode                |
| FDTD     | Finite Difference Time Domain              |
| FFT      | Fast Fourier Transform                     |
| HEMT     | High Electron Mobility Transistor          |
| ICP      | Inductively Coupled Plasma                 |
| LED      | Light-Emitting Diodes                      |
| MOVPE    | Metal-Organic Vapour Phase Epitaxy         |
| MQW      | Multi-Quantum Well                         |
| MZM      | Mach-Zehnder modulator                     |
| NA       | Numerical Aperture                         |
| OSA      | Optical Spectrum Analyser                  |
| PCB      | Printed Circuit Board                      |
| PECVD    | Plasma-Enhanced Chemical Vapour Deposition |
| PIC      | Photonic Integrated Circuit                |
| PML      | Perfectly Matched Layer                    |
| QD       | Quantum Dot                                |
| QW       | Quantum Well                               |
| TE       | Transverse Electric                        |
| TM       | Transverse Magnetic                        |
| VCSEL    | Vertical Cavity Surface Emitting Laser     |
| WDM      | Wavelength Division Multiplexing           |

*"Started making it. Had a breakdown. Bon appetit!" - James  
Acaster, Celebrity Great British Bake Off*

I, Megan O'Brien, certify that this thesis is my own work and I have not obtained a degree in this university or elsewhere on the basis of the work submitted in this thesis.

*Megan O'Brien*

# Chapter 1

## Introduction

### 1.1 Motivation

As the global population becomes ever more connected via technology, the need to transmit data at faster speeds increases. People now communicate through smartphones and video call services, consume media through streaming-based services, and even invest in cryptocurrency. 66% of the global population are internet users, over 70% have mobile connections, and there are 3.6 networked devices per capita [1, 2].

The start of the Covid-19 pandemic in 2020 saw a 40% rise in global internet traffic [3], as the majority of people had to work from home. While people have mostly returned to work in the physical office spaces, companies have started to incorporate remote working days each week for their employees, with others even advertising completely remote working jobs. In 2024, it is predicted that this year's global IP traffic will reach 33 exabytes per day on average, leading to an accumulation of 12.05 zetabytes for the year [4]. This prediction is a significant increase from the 122 exabytes per month in 2017. In other words, we are living in an increasingly online world, and there is no sign of the demands placed on these services slowing down any time soon.

This all suggests that there needs to be an infrastructure in place capable of providing and improving access to internet services and high-speed transmission from built-up areas to the remote parts of the world. Data centers are under pressure to facilitate communication links with high-enough bandwidths and low power consumption. Complementary metal-oxide semiconductor (CMOS)-compatible electronics is unsuitable for these demands

due to the limit of Moore's Law and unwanted signal attenuation and heat generation. However, photonic integrated circuits (PICs) that are compatible with CMOS technology can provide more efficient data transfer with lower energy consumption, and thus help data centers reach the demands imposed on them.

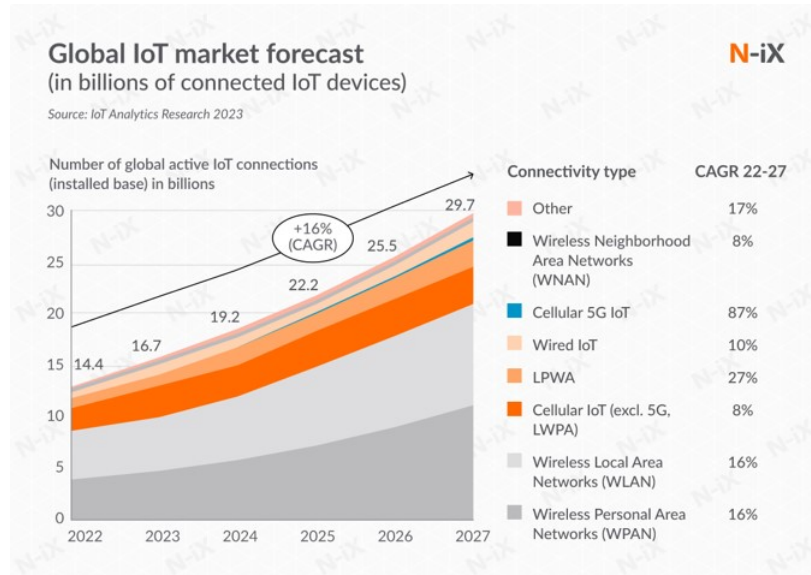


Figure 1.1: N-iX's estimation for the number of connected devices globally for 2024 [5]

## 1.2 Data center interconnects

Data centers are the physical storage units for our online, digital world. They are composed of networked computers, storage systems and computing infrastructure that allows for the processing and dissemination of data. In order for data to be passed within the center, interconnects are required; depending on the application, they can either be short-range, such as a connection between two chips on a printed circuit board (PCB), or long-haul, e.g. connections spanning thousands of kilometers. Figure 1.2 shows the typical data center infrastructure [6]: at the bottom the server racks are connected with a Tier 0 switch. As the Tier 0 connections are short range, copper cables are generally used for this, giving sufficient bandwidth at very low cost. These switches are then connected to Tier 1 switches, with active optical cables (AOC) being used for these connections. AOCs are optical fibers with optoelectronic modules in the connector head that convert electrical signals to light. The switches between Tier 1 and Tier 2, and Tier 2 and Tier 3, is when the connections start to go into the kilometer range. Fiber optics can

be used as interconnects at this point, as they have much higher data rates than copper wires, and the attenuation in fibres is quite low, with the attenuation values of the fibers depending on the wavelength propagating through them. The distance between connections and the cost are also factored in as well as attenuation for deciding the wavelength; the typical attenuation values at  $1.3\ \mu\text{m}$  (O-band) and  $1.55\ \mu\text{m}$  (C-band) wavelengths are  $\approx 0.35\ \text{dB/km}$  and  $0.22\ \text{dB/km}$  respectively [7] for a single-mode fiber, with these types of fibers being less costly than multi-mode fibers. For connections between Tier 1-Tier 2 and Tier 2-Tier 3, which are considered short-haul in comparison, the  $0.85\ \mu\text{m}$  wavelength is selected to be used with multi-mode fibers, despite having a higher attenuation rate of  $\approx 2\ \text{dB/km}$ . The three wavelengths mentioned are the most commonly used wavelengths in telecommunications due to having near-zero water vapour absorption in optical fibre.

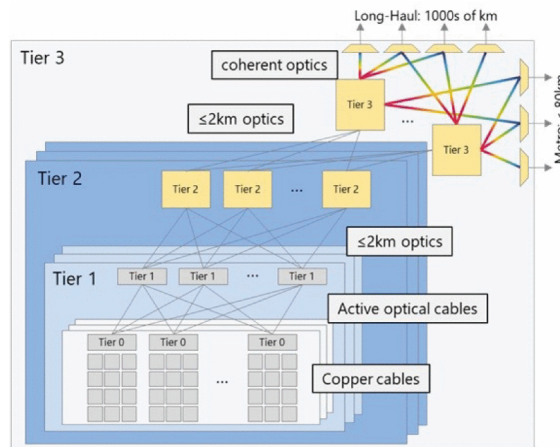


Figure 1.2: Schematic of a typical data center: Tier 0-Tier 1 are short range connections, while the connections between Tier 1-Tier 2 and Tier 2-Tier 3 is when the connections start going into the kilometre range [6]

One way of expanding the bandwidth would be to simply lay down more optical fibers, but this increases the costs of the infrastructure. Wavelength division multiplexing (WDM) is a solution to this, whereby multiple wavelengths are joined together at a multiplexer, propagate through a single fiber, and then split apart into separate signals again at a demultiplexer. A relatively large amount of power is still needed to be used to transmit the data, even with using a WDM system. In order to increase the power efficiency of the system, advanced light modulation formats need to be used. For this, careful control of the light source's phase is needed. While light-emitting

diodes (LEDs) could fulfil the power requirement, they are incompatible with phase modulation due to their incoherence. This is why lasers, being both high-powered and coherent light sources, are used in telecommunications instead.

For short-haul links, vertical-cavity surface-emitting lasers (VCSELs) at  $0.85\ \mu\text{m}$  are used due to offering very high modulation bandwidths at low currents and single-mode operation as a result of their short cavity length. VCSELs are also low cost in terms of processing, are thermally stable, offer scalability for arrays and have wavelength stability. However, the optical output power of single-mode VCSELs are low ( $\leq 10\ \text{mW}$  for a single device).  $1.31\ \mu\text{m}$  and  $1.55\ \mu\text{m}$  VCSELs are also possible to obtain, but offer much lower power. Therefore, for long-haul links, edge-emitting lasers are used. Tuning multiple laser sources independently however is not very cost and energy-effective. A frequency comb laser may be an alternative: a comb is made up of evenly spaced frequency domain lines that can be utilized as different optical carriers for WDM. The comb is produced from a single source and includes lines that are inherently spaced equally apart, eliminating the need for multiple laser sources.

It can be seen that there are many different components needed for data transmission over optical fibers, and thus there is pressure on the system to deliver the desired high bandwidths with low cost and power consumption. In order to accommodate this, the components can be packaged into an optical transceiver. These transceivers are photonic integrated circuits (PICs) that contain all the devices, with the fiber receiving the output and transmitting it to the next interconnect. The choice of materials for the different components, and the platform upon which they are all integrated, is outlined in the next section.

## 1.3 PICs

An efficient PIC allows for the manipulation of light all on the same platform. This involves the generation, routing, modulation, processing, and detection of light. Figure 1.3 shows a diagram of what a PIC could look like with all these functionalities incorporated onto the same platform. For all these processes to work, and for the PIC to be truly multi-functional, requires the combination of both active and passive devices all on one chip. Therefore, the choice of



material for the PIC is important based on the desired properties. Ideally, all components would be made out of the same material, and the material. This can be very challenging to achieve due to the different properties that materials have.

Such a PIC has been realized with Indium Phosphide (InP) as it fulfils all optical functionalities. However, the problems facing this approach is that InP substrates are expensive and small sized, and are not compatible with CMOS technology [8]. The technical expertise required to establish InP facilities capable of delivering commercial volumes of high performance PICs is also not at the same level as that of silicon (Si) photonics. In terms of passive device performance, waveguide propagation losses of 0.45 dB/cm at 1.55  $\mu\text{m}$  have been demonstrated on the InP platform [9]. For the monolithic integration of the active components with the passive components, the devices are selectively grown in order to optimize the performance. However, to keep the regrowth steps required to a minimum, the same doped structure is used for both the passive waveguides and the active phase modulators. This doping compromises the performance of the passive waveguides of the PIC, and generally increases the propagation losses to 2 dB/cm [10].

Si, the most widely used material for PICs, is CMOS-compatible due to its thermal and electrical properties and the existing established infrastructure for Si processing [11]. This allows for a high volume of PICs with low cost. The refractive index of Si at 1.55  $\mu\text{m}$  is 3.476, higher than InP's value of 3.165; this means that, by either being cladded with air or silicon dioxide ( $\text{SiO}_2$ ,  $n_{\text{SiO}_2} = 1.444$  at 1.55  $\mu\text{m}$ ), a high index contrast waveguide can be achieved which allows for more compact designs, e.g. waveguide bends with radii  $< 5 \mu\text{m}$ . This compactness allows for a higher density of devices on the PIC. The waveguide propagation losses are also  $\approx 0.1$  dB/cm, making it a suitable system for low-loss photonics. The high index contrast also allows for efficient coupling with an optical fiber either through tapering down the silicon waveguide dimensions to a few microns (inverse tapers) [12, 13], or by using an apodized grating coupler [14, 15].

However, unlike InP, there are a lot of important optical functionalities that Si cannot fulfil. Light generation is highly inefficient in Si due to its indirect bandgap, so a III-V device has to be integrated onto the Si platform. Phase and amplitude modulation in Si is also limited largely to the plasma dispersion effect and the thermo-optic effect by its indirect bandgap, effects that are both

slower in comparison to the electro-optic (Pockels) effect. While Si is good for detecting light in the near-ultraviolet (UV) and visible wavelength range, it cannot do so at wavelengths in the near-infrared (IR). Germanium-based devices are generally implemented for detection in this wavelength region for Si photonics [16–18].

Si is also limited to routing wavelengths  $> 1.1 \mu\text{m}$ , which can limit some of the commercial applications it can be used for, e.g. short-haul transmission operating at  $0.85 \mu\text{m}$ . There has been work in combining an InP membrane containing all the devices needed to a Si CMOS chip via adhesive wafer bonding and thereby exploiting the advantages of both materials[19], although there are challenges with both the (i) epitaxy needed to optimise the individual components of the membrane and (ii) thermal management of the active devices using this approach.

In recent years, silicon nitride ( $\text{Si}_3\text{N}_4$ ) has emerged as an alternative PIC platform to Si. Like Si, it is CMOS compatible for similar reasons [20], and propagation losses in passive components as low as 0.0005 dB/cm have been demonstrated on the  $\text{Si}_3\text{N}_4$  platform [21, 22]. The material is more thermally stable than Si ( $\frac{dn}{dT} \text{Si}_3\text{N}_4 \approx 2 \times 10^{-5} \text{K}^{-1}$  [23, 24],  $\frac{dn}{dT} \text{Si} = 1.86 \times 10^{-4} \text{K}^{-1}$  [25]) and has a wide transparency range from 0.4 -  $2.35 \mu\text{m}$ .  $\text{Si}_3\text{N}_4$  does not allow for as high an index contrast as Si ( $n_{\text{SiN}} = 1.996$  at 1550 nm), which results in a larger footprint, but can allow for high or low-index contrast waveguides depending on the desired waveguide properties. Components such as spot size converters, tunable waveguide filters and frequency comb generators have all been successfully demonstrated on the  $\text{Si}_3\text{N}_4$  platform [26].  $\text{Si}_3\text{N}_4$  is still an unsuitable material for active devices such as lasers and high-speed modulators on a PIC due to also possessing an indirect bandgap, and therefore other materials still have to be integrated on a platform to fulfil these roles.

For a PIC to fulfil high-speed modulation requirements using the Pockels effect, lithium niobate ( $\text{LiNbO}_3$ ) is the best material to work with as it possesses a large electro-optic coefficient ( $r_{33} = 31 \text{ pm/V}$  [27]). It is also transparent between  $0.2\text{-}5.3 \mu\text{m}$ , which opens it up for a wider range of applications. Previously,  $\text{LiNbO}_3$  waveguides were based either on titanium indiffusion or proton-exchange waveguides, due to the difficulty in etching the material for device fabrication. This process created small index contrast waveguides, leading to a weak optical mode confinement and thus large waveguide cross-sections and bend radii in the mm-cm range [28, 29]. However, the

technology for thin  $\text{LiNbO}_3$ -on-insulator (LNOI) photonics has progressed in the last decade, with optimized dry etching processes producing waveguide propagation losses as low as 0.03 dB/cm [29, 30], with comparable waveguide cross-sections to that of Si photonics and bend radii between 50-80  $\mu\text{m}$  [30, 31]. Dry-etching the  $\text{LiNbO}_3$  produces slanted sidewalls with sidewall angles between  $40\text{-}45^\circ$ , which needs to be taken into account when designing components. Heterogenous integration of  $\text{LiNbO}_3$  to Si and  $\text{Si}_3\text{N}_4$  has also been demonstrated, thus increasing the high index contrast and improving the efficiency for an integrated modulator [32, 33].

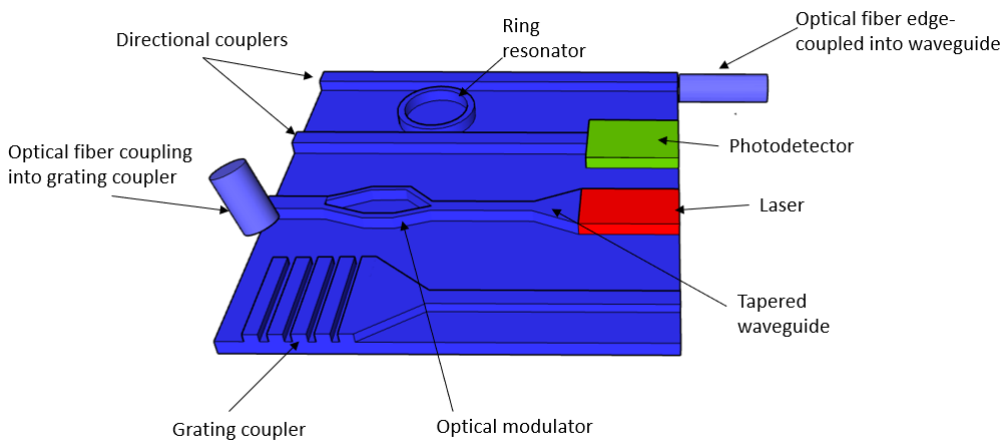


Figure 1.3: Schematic of a possible PIC: all the components in dark blue are waveguides with different functionalities, while the laser (red) and photodetector (green) are made from different materials and integrated onto the PIC. The optical fibers (light blue) can be used to couple light in or out of the PIC: in the schematic shown here we demonstrate it as either edge-coupling light in to a waveguide, or coupling light in to the PIC through a grating coupler. These coupling methods will be discussed later in this work.

## 1.4 Gallium nitride (GaN) in PICs

GaN is emerging as an alternative material for PICs due to spanning multiple applications in opto- and microelectronics as a result of the intrinsic properties that it possesses. Ever since the 1990s, the use of GaN in photonics is mostly associated with the fabrication of light-emitting diodes (LEDs) [34]. Due to its wide bandgap of 3.4 eV, and also when combined with alloys such as InGaN and/or AlGaN in the active region of the device, LEDs emitting in both the near-ultraviolet (UV) and visible range of wavelengths can be produced. White LEDs can also be fabricated by tinting the GaN-based device with phosphors.

GaN has shown promise to be a suitable single-photon, or quantum, emitter as a result of defects present in its lattice, emitting from the visible wavelength range to the near-IR wavelengths that are desired for quantum technology applications [35, 36]. There has also been research in developing GaN-based lasing devices in both the UV and visible wavelength range, although there are still issues in extending it to the visible green wavelengths due to both (i) the large difference in epitaxial growth temperature between the InGaN quantum well region and the p-AlGaN cladding layer, and (ii) the poor electrical properties of the p-AlGaN cladding layer. If telecommunication wavelengths for a lasing device are desired, then III-V material would still have to be integrated onto the platform.

GaN possess a refractive index value of  $\approx 2.3$  at  $1.31 \mu\text{m}$ , and thus offers better optical confinement than SiN or LNOI. Its intermediate refractive index value also offers flexibility with designing the waveguide structure: either the GaN is cladded by air to create a high-index contrast waveguide, or it is combined with AlGaN to create a low index contrast waveguide. The refractive index of AlGaN lies between  $\approx 2.1$ - $2.3$  at telecom wavelengths depending on the Al concentration chosen. By carefully selecting the Al concentration, the AlGaN/GaN waveguide allows for the possibility of minimizing mode mismatch with coupling between either an (i) optical fiber, or (ii) laser facet via edge coupling. GaN is also birefringent, which can be useful for designing polarization-controlling devices on the platform.

As with the aforementioned wide bandgap and thus large transparency window, a GaN-based PIC can be used for routing for both short-haul and long-haul transmission applications, as well as biophotonic applications where wavelengths as low as  $0.4 \mu\text{m}$  are desired. Waveguides [37, 38], ring resonators [39], photonic crystal cavities [40], arrayed waveguide gratings (AWGs) [41] and directional couplers [42, 43] have all been demonstrated on the platform. These structures have been designed for operating in the UV/visible wavelength range [38, 44, 45], and in the C-band range (1530-1565 nm) [37, 39–41, 43]. The O-band (1260-1360 nm) is of particular relevance for data-centre communications due to its low dispersion with recent interest in passive GaN-based PIC components [46]. Waveguide propagation losses in GaN waveguides have been demonstrated to be  $\approx 0.2 \text{ dB/cm}$  at 1550 nm [47] which is comparable to that of Si or  $\text{Si}_3\text{N}_4$ , although values as high as  $10 \text{ dB/cm}$  have also been reported due to sidewall roughness from dry etching [43]. Its low thermo-optic coefficient ( $\frac{dn}{dT}_{\text{GaN}} \approx 5 \times 10^{-5} \text{ K}^{-1}$  [48]), similar to

$\text{Si}_3\text{N}_4$  also makes it more temperature stable and therefore frequency stable.

Devices based on the GaN platform can also be used for light manipulation: due to its non-centrosymmetric crystalline structure, GaN has inherent second-order nonlinear properties, making it useful for applications such as comb generation, parametric conversion and frequency doubling [47]. It also displays the linear electro-optic effect, although it is limited in comparison to  $\text{LiNbO}_3$  as a high-speed electro-optic modulator due to possessing a smaller electro-optic coefficient of  $r_{33} = 1.91 \text{ pm/V}$  at  $0.63 \mu\text{m}$  [49]. The refractive index of AlGaIn/GaN being close to that of  $\text{LiNbO}_3$ , however, opens up the possibility of integrating the latter with the former in order to enhance the electro-optic effect of the platform. Its high electron mobility has also shown promise for AlGaIn/GaN high-electron mobility transistors (HEMTs) as optical modulators due to the generation of a tunable two-dimensional electron gas (2DEG) as a result of the free carrier plasma dispersion effect [50], although this has not yet been demonstrated experimentally. Electro-absorption modulators (EAMs) have been demonstrated using the Franz-Keldysh effect in the  $0.25 - 0.55 \mu\text{m}$  wavelength range [51].

The CMOS compatibility of GaN depends upon the substrate that it's grown on: it can be grown on a Si substrate, but the large lattice mismatch between the materials ( $\approx 17 \%$ ) and high thermal expansion coefficients makes it challenging to grow high-quality structures. Growing GaN on silicon carbide (SiC) allows for a much closer lattice match ( $3.4 \%$ ) and three times the thermal conductivity of GaN-on-Si, allowing the devices to run at much higher voltages and high power density in electronics, but such a substrate is very expensive to produce and is also limited in wafer size. Using a GaN substrate would eliminate lattice mismatch concerns; however this is also very expensive to do and requires careful optimization for a waveguide structure as the index contrast is lowered. While GaN-on-sapphire also has a large lattice mismatch ( $13 \%$ ), it offers low material and manufacturing costs and high processability in a wide range of temperatures.

All of these properties open up the possibility of building multi-functional photonic integrated circuits (PICs) on the GaN platform. However, despite its capabilities, demonstrations of GaN PICs have been limited overall compared to other PIC platforms. The fabrication of components on GaN-on-sapphire is difficult and not as advanced as Si or  $\text{Si}_3\text{N}_4$  for waveguiding. In addition, the heterogeneous integration via  $\mu\text{TP}$  of a lasing device at any operating

wavelength to a GaN-based PIC has not yet been demonstrated. In order to show GaN as a material that is more than just promising for PICs, a low-cost fabrication process of basic waveguide components needs to be demonstrated along with an on-chip coupled lasing source. Table 1.1 outlines the properties and applications of GaN, while Table 1.2 compares all the PIC material platforms and their properties outlined in this chapter.

| GaN                           |                                                                                  |
|-------------------------------|----------------------------------------------------------------------------------|
| Properties                    | Applications                                                                     |
| Wide Bandgap                  | UV and NIR waveguide system, UV LEDs, quantum emitters, biophotonic applications |
| Linear electro-optic effect   | Optical modulator                                                                |
| 2nd order nonlinearity        | Second harmonic generation, Optical parametric oscillator                        |
| 3rd order nonlinearity        | Frequency comb generation, Super-continuum source                                |
| Intermediate refractive index | Choice of high/low index contrast waveguides                                     |
| Low thermo-optic coefficient  | Frequency stabilization                                                          |
| Birefringence                 | Polarization control, phase modulation                                           |
| High electron mobility        | HEMTs                                                                            |
| Growth on sapphire substrate  | Low-cost                                                                         |

Table 1.1: The properties and applications of GaN that are beneficial for PICs

| Properties of different materials |                                  |                          |              |                                    |                                           |                       |
|-----------------------------------|----------------------------------|--------------------------|--------------|------------------------------------|-------------------------------------------|-----------------------|
| Material                          | n at 1.55 $\mu\text{m}$          | CMOS compatible          | Bandgap (eV) | Waveguide Propagation Loss (dB/cm) | $r_{ij}$ (pm/V)                           | $\frac{dn}{dT}$       |
| Si                                | 3.475                            | Yes                      | 1.12         | 0.1                                | -                                         | $1.86 \times 10^{-4}$ |
| Si <sub>3</sub> N <sub>4</sub>    | 1.996                            | Yes                      | $\approx 5$  | 0.0005 - 0.1 [21, 22]              | -                                         | $2 \times 10^{-5}$    |
| InP                               | 3.165                            | No                       | 1.34         | 0.45 [9], 2 [10]                   | -                                         | $2 \times 10^{-4}$    |
| LiNbO <sub>3</sub>                | 2.138 ( $n_e$ ), 2.211 ( $n_o$ ) | Only for LNOI            | 2.7-2.9      | 0.1-0.2, 0.03 [30]                 | 31 ( $r_{33}$ ) [27]                      | $3.2 \times 10^{-5}$  |
| AlN                               | 2.16 ( $n_e$ ), 2.12 ( $n_o$ )   | Only on Si/SiC/Ti        | 6            | 0.4 - 2                            | 0.67 ( $r_{33}$ ), 0.59 ( $r_{13}$ )      | $4.26 \times 10^{-5}$ |
| GaN                               | 2.317 ( $n_e$ ), 2.305 ( $n_o$ ) | Only on Si/SiC substrate | 3.4          | 0.17-0.24 [47], 0.9-2.5 [37],      | 1.91 ( $r_{33}$ ), 0.57 ( $r_{31}$ ) [49] | $5 \times 10^{-5}$    |

Table 1.2: The different materials mentioned throughout this chapter, and the properties associated with them

## 1.5 Thesis objectives

The purpose of this thesis is to contribute to the development of a GaN-on-sapphire PIC for 1.3  $\mu\text{m}$  operation. Due to the wavelength, heterogenous integration of the laser source to the GaN waveguide would have to be implemented. To date, no laser of any operating wavelength has ever been heterogeneously integrated to a GaN-based platform. In this work, the lasing structures to be integrated are known; therefore the GaN waveguide must be designed so that the laser mode is efficiently coupled to the passive waveguide mode. The factors that influence coupling between the laser and waveguide depend on the coupling method selected; for this work edge-coupling is chosen to take advantage of the low-index contrast between AlGaIn and GaN, and thus engineer the waveguide mode to best match the lasing mode. Selecting the correct geometry and epitaxial design for this waveguide, along with the coupling between the known laser and the waveguide, need to be assessed via simulations first to verify the idea. It is not enough, however, to just have coupling and guiding light as the only functionalities of the platform; to demonstrate the capability of GaN as a photonic platform, other functionalities need to be demonstrated to compete with other established platforms. Already it has been highlighted in Section 1.4 that GaN has many properties that could make it a multi-functional platform; this work also seeks to design structures that make use of these properties via simulations to further realize the potential for GaN as a photonic platform.

The simulated work will then inform the designs that need to be fabricated. A robust process for forming the AlGaIn/GaN waveguides must be developed, along with assessing how well the light is guided by the waveguides. The strength of the light guiding depends upon the waveguide quality after fabrication, i.e. the fabrication process can strongly impact the waveguide performance. Therefore these waveguides need to be characterized by obtaining the waveguide propagation loss  $\alpha$ , for both TE and TM-polarized light. To extract this characteristic, waveguide facets must be formed for edge-coupling fiber light in; therefore a method of forming sufficient quality facets for waveguide characterization must also be developed.

Another challenge is trying to integrate the laser to the target platform: for edge-coupling of a laser to the waveguide, alignment of the device is crucial, especially as the active region of the III-V device is at a different height to that



of the passive mode. Thus a method of forming a trench into the substrate in order to align the lasing active region to the waveguide mode must be developed. For this work, a technique known as micro-transfer printing is used to integrate the laser to the new platform; therefore there must be minimal roughness on the trench surface so as to aid the device bonding. There can also be a difference in performance of the device on its native substrate vs its new substrate; thus the laser needs to be characterized on these different substrates to assess whether micro-transfer printing can actually offer high performance of devices on new substrates. Finally, the laser coupled to the waveguide must also be characterized, in order to verify the edge-coupling designs.

By achieving these objectives, this thesis extends the possibility of using GaN for PICs in applications requiring near-IR wavelengths.

## 1.6 Thesis Outline

This thesis is divided into six chapters. After this introductory chapter, Chapter 2 discusses waveguide fundamentals and the key parameters for designing a waveguide for laser-to-waveguide edge-coupling. Different types of waveguide geometries and configurations on the GaN platform are explored for matching the passive waveguide mode to the active lasing mode, before recommending an AlGaIn/GaN waveguide design. This proposed structure is designed for two known  $1.3\ \mu\text{m}$ -emitting lasers, and the structures of these active devices are also presented. The alignment tolerances as a result of integrating the lasers via micro-transfer printing are outlined and taken into consideration for the waveguide design, and the laser-to-waveguide coupling loss is simulated as a function of misalignment.

Chapter 3 then explores different components on the AlGaIn/GaN platform based on the design for edge-coupling the known lasers. A mode adapter design is presented and simulated for converting the passive structure from the initial geometry for edge-coupling to a structure suitable for guiding the light around the PIC, along with the motivation as to why this design is necessary. When trying to develop the initial waveguide design for functionalities, limitations are discovered. These designs are then re-imagined with a different GaN epitaxial structure based on the initial challenges, and trying to combine the edge-coupling strategy from Chapter 2 with the new designs is discussed.

Chapter 4 gives an overview of the general fabrication steps that are

undertaken in a typical semiconductor process, along with the growth of the epistructure that was carried out by another research team in Tyndall. The individual steps are then discussed in terms of fabricating the AlGa<sub>N</sub>/Ga<sub>N</sub> waveguides, with both the challenges and solutions for processing the AlGa<sub>N</sub>/Ga<sub>N</sub> epistructure outlined. An overview of micro-transfer printing is then presented, along with the development of the micro-transfer printing trenches for aligning the laser to the waveguide.

Chapter 5 outlines the AlGa<sub>N</sub>/Ga<sub>N</sub> waveguide designs that were fabricated and the processing steps for the different iterations. A method for assessing the waveguide quality is defined, and the fabricated designs are characterized and analysed in this manner. The two active lasing devices presented in Chapter 2 are then characterised and integrated to the AlGa<sub>N</sub>/Ga<sub>N</sub> waveguide platform. The integrated laser-to-waveguide coupling is then assessed, and improvements are made to the coupling strategy.

Finally, Chapter 6 proposes possible next steps to further develop a PIC on the Ga<sub>N</sub> platform based on the results presented in this thesis and the challenges encountered during this work.

## Chapter 2

# Fundamentals for edge-coupled GaN waveguides

### 2.1 Chapter Overview

Waveguides form the channels that route light to other devices on a PIC to perform functionalities such as modulation and filtering. How the light is routed, or propagated around the PIC along with the coupling of light into the circuit is affected by how the waveguide is designed. This chapter gives an overview on the fundamentals of waveguides and the design parameters to take into consideration regardless of the PIC platform used such as the waveguide geometry and the refractive indices of the waveguide material. Both graphical and numerical methods are also demonstrated to show how waveguides are analysed. As the platform used in this work is GaN, intrinsic properties such as its birefringence are discussed, along with strategies on designing it for edge-coupling. From this, an AlGaIn/GaN waveguide design is presented for known 1.31  $\mu\text{m}$ -emitting lasers, along with simulations for coupling between laser and waveguide in all directions.

### 2.2 Fundamentals of Waveguides

#### 2.2.1 Planar Waveguide Structure

In order to explain the basics of light guiding in a waveguide, the planar waveguide structure is considered. A planar waveguide consists of a thin

dielectric layer with high index  $n_2$  (the core) that is transversely surrounded by two dielectric layers, both with low index  $n_1$  (the cladding) as seen in Figure 2.1. Light enters into the waveguide from a medium with refractive index  $n_0$ , and hits the core-cladding interface at an angle  $\phi = \frac{\pi}{2} - \theta_r$ , where we know from Snell's Law that

$$n_0 \sin(\theta_i) = n_2 \sin(\theta_r) \quad (2.1)$$

The condition for the light to be guided between the core and cladding regions, and thus the condition for total internal reflection to occur at the core-cladding interface, is given as

$$\phi > \phi_c = \arcsin \frac{n_1}{n_2} \quad (2.2)$$

Therefore, if this condition is reached, then light that is coupled into the waveguide is confined in the core and propagates along the longitudinal direction of the waveguide. The ability of the waveguide to allow light to enter from the surrounding medium  $n_0$  and be guided along the waveguide length depends upon the numerical aperture (NA) of the waveguide. The NA is related to the maximum angle of incidence by:

$$NA = n_0 \sin(\theta_i^{max}) = n_2 \sin\left(\frac{\pi}{2} - \phi_c\right) \quad (2.3)$$

The left hand side of the equation can be simplified down to

$$NA = n_0 \sin(\theta_i^{max}) = n_2 \sqrt{1 - \left(\frac{n_1}{n_2}\right)^2} = \sqrt{n_2^2 - n_1^2} \quad (2.4)$$

### 2.2.2 Geometrical Optics: Analysis of symmetric planar waveguides

We can also think of the light in the planar waveguide as propagating electromagnetic waves. These waves can be analysed by Maxwell's equations, with the solutions to these equations known as modes. A waveguide mode is a stable transverse field pattern that propagates along the longitudinal direction, which is defined to be the  $z$  axis in Figure 2.2. Its amplitude and polarization profiles remain constant along this propagation axis, and are dependent on the

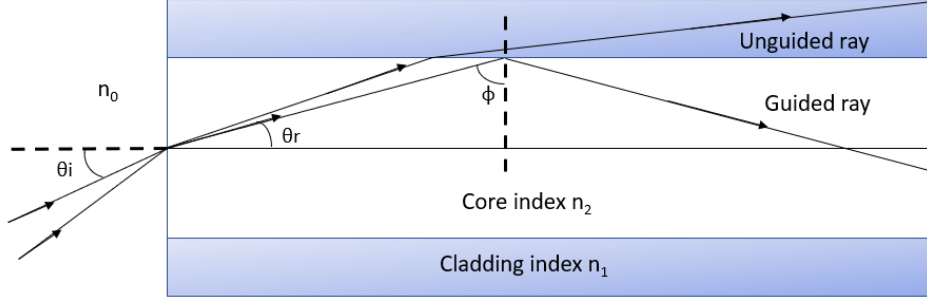


Figure 2.1: Schematic of the planar waveguide structure with core of high index  $n_2$  cladded by an upper and lower layer, both with a low index of  $n_1$ . Light enters from a surrounding medium of index  $n_0$  into the waveguide. If  $\phi > \phi_c$ , then light remains confined in the core region as it propagates along the longitudinal direction

operating wavelength, geometry and material composition of the waveguide. The polarization of a mode in a planar waveguide is either transverse electric (TE), or transverse magnetic (TM). Modes with a combination of both TE and TM polarization can also exist (known as hybrid modes), but for simplicity are left out of discussion in this section and will be explored later in Chapter 3. A TE mode has its electric field perpendicular to the plane of incidence (the x-z plane as defined in Figure 2.2), and thus possesses only the field components  $E_y$ ,  $H_x$  and  $H_z$ . A TM mode has its electric field parallel to the plane of incidence, and has the field components  $H_y$ ,  $E_x$  and  $E_z$ . We can write the electric and magnetic fields of the mode as:

$$E(x, y, z) = E(x, y)e^{i\beta z} \quad (2.5)$$

$$H(x, y, z) = H(x, y)e^{i\beta z} \quad (2.6)$$

where  $\beta$  is the z-component of the wavevector, and is known as the propagation constant. We can use the geometrical optics picture to analyse an asymmetric planar waveguide as shown in Figure 2.2 [52]. A waveguide is symmetrical if the same boundary conditions can be applied to both the upper and lower interfaces. The planar waveguide presented in Figure 2.1 is an example of a symmetrical waveguide as the refractive index values for both cladding layers are equal. The waveguide structure in Figure 2.2, however, is asymmetric as the upper and lower interfaces have different refractive indices and the boundary conditions are thus different.

In the asymmetric planar waveguide shown in Figure 2.2,  $n_2 > n_3 > n_1$ . The

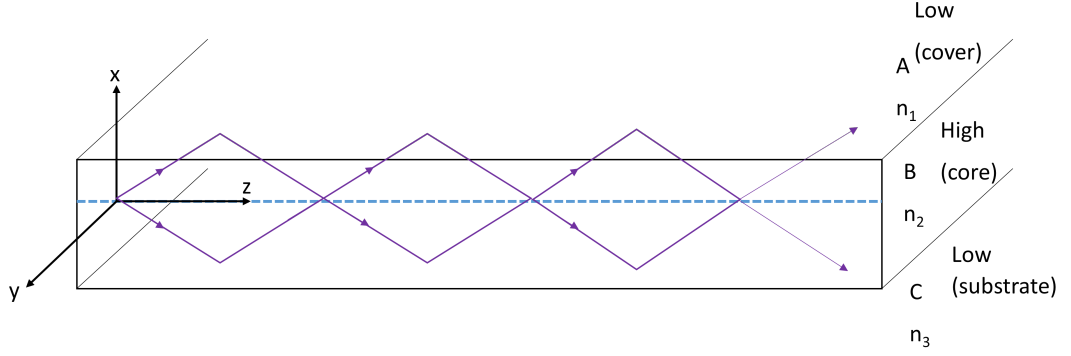


Figure 2.2: Geometrical optics picture for an asymmetric planar waveguide

propagation constants for the different regions can be defined for a wave with angular frequency  $\omega$  and free space wavelength  $\lambda$ :

$$k_1 = \frac{n_1\omega}{c}, k_2 = \frac{n_2\omega}{c}, k_3 = \frac{n_3\omega}{c} \quad (2.7)$$

where  $k_2 > k_3 > k_1$ . As a result of total internal reflection, we can see that the light ray is propagating in a zig-zag motion in Figure 2.2. In this case, there are two critical angles associated with the lower and upper interfaces, and using Eq 2.2 can be written as:

$$\theta_{c2} = \arcsin \frac{n_3}{n_2}, \theta_{c3} = \arcsin \frac{n_1}{n_2} \quad (2.8)$$

As  $n_3 > n_1$ , then  $\theta_{c2} > \theta_{c3}$ . The characteristics of the reflection and refraction of the ray at the interfaces depends on the angle of incidence  $\theta_i$  and the polarization of the wave. In this section,  $\theta_i$  is defined as the angle of incidence between the ray in the core and the normal to the upper interface with refractive index  $n_2$ . If  $\theta_i > \theta_{c2} > \theta_{c3}$ , then the wave inside the core is totally reflected at both interfaces and is trapped by the core, resulting in guided modes. As the wave is reflected back and forth between the interfaces, it interferes with itself. Thus, a guided mode can only exist in the waveguide if a transverse resonance condition is satisfied such that the repeatedly reflected wave can constructively interfere with itself. In the core region, the x component of the propagation constant is  $k_x = k_2 \cos \theta_i$  for a ray with angle of incidence  $\theta_i$ , while the z component of the propagation constant is  $\beta = k_2 \sin \theta_i$ . The phase shift in the optical field due to the round-trip transverse passage in the core of thickness  $d$  is given as  $2k_2 d \cos \theta_i$ . In addition to this, there are also phase shifts associated with the upper and lower interfaces, denoted as  $\phi_2$  and

$\phi_3$  respectively. As these are functions of  $\theta_i$ , then the transverse resonance condition for constructive interference in a round-trip transverse passage is given as

$$2k_2 d \cos \theta_i + \phi_2(\theta_i) + \phi_3(\theta_i) = 2m\pi \quad (2.9)$$

where  $m$  is an integer. As  $m$  can only have integral values, then only certain discrete values of  $\theta_i$  can satisfy Eq 2.9. This results in discrete values of the propagation constant  $\beta_m$  for guided modes identified by the mode number  $m$ . The guided mode with  $m = 0$  is called the fundamental mode and those with  $m \geq 1$  are high-order modes. While the critical angles in Eq 2.8 do not depend on the wave's polarization, the phase shifts as a result of reflections at the interface do. Therefore, TE and TM waves have different solutions for Eq 2.9, resulting in different  $\beta_m$  values and different mode characteristics for a given mode number  $m$ . For a given polarization, solution for Eq 2.9 yields a smaller value of  $\theta_i$  and a correspondingly smaller value of  $\beta$  for a larger value of  $m$ . Therefore,  $\beta_0$  for the fundamental mode has the largest value among the allowed values for  $\beta$ , and it decreases as  $m$  increases.

While geometrical optics gives an intuitive picture of the mode types that exist in a waveguide structure, it is very difficult to use this approach for waveguide structures with multilayers or inhomogeneous layers, and it doesn't give us any information about the field distribution or the mode orthogonality. For a complete description of the waveguide fields, rigorous analyses using Eqs 2.5 and 2.6 are required. We thus move to the wave optics treatment of the planar waveguide.

### 2.2.3 Wave Optics: Analysis of the symmetric planar waveguide

To solve for the waveguide modes, we have to solve for the wave equations using Maxwell's equations for a harmonic wave with angular frequency  $\omega$ :

$$\nabla \times \mathbf{E} = -\frac{\partial \mathbf{B}}{\partial t} = i\omega\mu_0\mathbf{H} \quad (2.10)$$

$$\nabla \times \mathbf{H} = \frac{\partial \mathbf{D}}{\partial t} \quad (2.11)$$

$$\nabla \cdot (\epsilon\mathbf{E}) = 0 \quad (2.12)$$

$$\nabla \cdot (\mathbf{H}) = 0 \quad (2.13)$$

where  $\mathbf{E}$  = electric field,  $\mathbf{B}$  = magnetic field,  $\mathbf{H}$  = magnetic field strength, and  $\mathbf{D}$  = electric displacement. These quantities are all in bold to denote that they are vectors. Using Eqs 2.10-2.13, along with the vector identity  $\nabla \times \nabla \times = \nabla \nabla \cdot - \nabla^2$ , the wave equations can be written as [52, 53],

$$\nabla^2 \mathbf{E} + k^2 \mathbf{E} = -\nabla \left( \frac{\nabla \epsilon}{\epsilon} \cdot \mathbf{E} \right) \quad (2.14)$$

$$\nabla^2 \mathbf{H} + k^2 \mathbf{H} = -\frac{\nabla \epsilon}{\epsilon} \times \nabla \times \mathbf{H} \quad (2.15)$$

Using Eqs 2.14 and 2.15, and taking the planar waveguide to be infinite in the y-direction and  $\nabla \epsilon = 0$ , we obtain the following wave equations for the TE and TM polarizations:

$$\begin{cases} \frac{\partial^2 E_y(x)}{\partial x^2} + (n(x)^2 k^2 - \beta^2) E_y(x) = 0 & \text{(TE)} \\ \frac{\partial^2 H_y(x)}{\partial x^2} + (n(x)^2 k^2 - \beta^2) H_y(x) = 0 & \text{(TM)} \end{cases} \quad (2.16)$$

where  $n(x)$  is the index profile of the planar waveguide. To simplify the analysis in this section, the planar waveguide is made symmetric, i.e.  $n_1 = n_3$ . Thus,  $n(x)$  is given as the following:

$$n(x) = \begin{cases} n_2 & |x| < a \\ n_1 & \text{(otherwise)} \end{cases} \quad (2.17)$$

where  $a$  is half the thickness of the core layer, the  $x$  origin is taken to be midway through the core,  $n_2$  is the refractive index of the core, and  $n_1$  is the refractive index of the cladding layers as shown in Figure 2.4. In order for the waveguide to support guided modes,  $n_2 > n_1$ . Therefore we must try and solve for these guided modes.

### 2.2.3.1 TE solution

We know from Eq 2.16 the wave equation for TE modes.  $\beta$ , the propagation constant of the mode, determines whether the field varies sinusoidally or exponentially in the waveguide structure. For guided modes, the field amplitude must decay exponentially outside the high index region, i.e.  $n(x)^2 k^2 - \beta < 0$  for  $|x| > a$ . However, the field continuity also requires that the field magnitude attains a maximum value, i.e.  $n(x)^2 k^2 - \beta > 0$ . Therefore, any confined modes in the waveguide must satisfy these conditions.



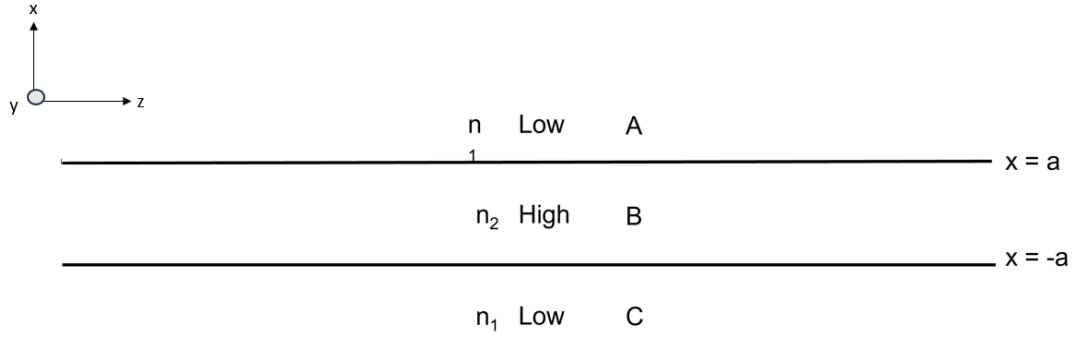


Figure 2.3: Schematic of the symmetric planar waveguide with the layers denoted as regions A, B and C. A and C both have low index value  $n_1$  while B has a high index value of  $n_2$ . The thickness of the core is given as  $2a$ , with the boundaries between the interfaces at  $|x| = a$ . Note that for the axes of this diagram,  $y$  is pointing out of the page (denoted by the enclosed circle).

If  $n(x)^2 k^2 - \beta > 0$ , then

$$E_y(x) = Ae^{ihx} + Be^{-ihx} \quad (2.18)$$

where  $h^2 = k^2 n_2^2 - \beta^2$ . If  $n(x)^2 k^2 - \beta < 0$ , then

$$E_y(x) = Ce^{\gamma x} + De^{-\gamma x} \quad (2.19)$$

where  $\gamma^2 = \beta^2 - k^2 n_1^2$ . Thus the solutions have the general form for the regions presented in Figure 2.3:

$$E_y(x) = \begin{cases} De^{-\gamma(x-a)} & x > a \\ A\cos(hx) & |x| < a \\ B\sin(hx) & |x| < a \\ Ce^{\gamma(x+a)} & x < -a \end{cases} \quad (2.20)$$

For Eqs 2.20 to be acceptable solutions, we need to match the solution in the cladding with the solution in the core. Therefore, boundary conditions must be specified at the core-cladding interfaces, i.e.  $E_y$  and  $H_z$  must be continuous at the interface. The full derivation is not presented in this section, but following on from these boundary conditions the following eigenvalue equations are obtained [52]:

$$v = u \tan(u) \quad (2.21)$$

$$v = -u \cot(u) \quad (2.22)$$

where  $u = ha$ , and  $v = \gamma a$ . As  $u$  and  $v$  are restricted to positive values, the propagation constants of the TE modes are obtained from the intersections of the curves generated by these equations, and a circle of known radius  $r = ka\sqrt{n_2^2 - n_1^2} = kaNA$ , which can be written in terms of  $u$  and  $v$  as:

$$u^2 + v^2 = r^2 \quad (2.23)$$

Eqs 2.21-2.23 are plotted below in Figure 2.4, for a planar waveguide with  $n_1 = 1.5$ ,  $n_2 = 1.6$ ,  $\lambda = 1.55 \mu\text{m}$ , and  $a = 2.5 \mu\text{m}$ . From the figure, we can see that four TE modes intersect with the circle  $r$ , i.e. the waveguide supports these four modes. The mode that does not intersect with  $r$  is not supported by the waveguide. The mode properties of a waveguide are commonly characterized in terms of dimensionless, normalized waveguide parameters. This normalized frequency, or V number, is defined as

$$V = ka\sqrt{n_2^2 - n_1^2} = kaNA \quad (2.24)$$

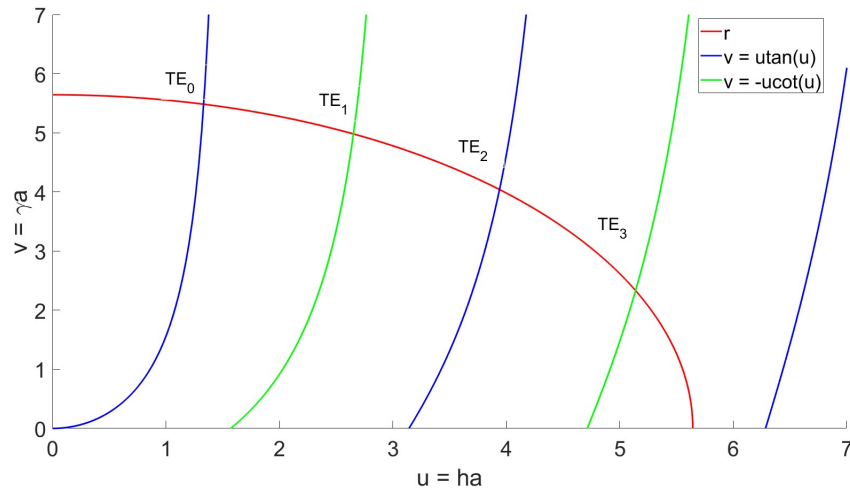


Figure 2.4: Graphic solution of Eqs 2.21-2.23 for a planar waveguide with  $n_1 = 1.5$ ,  $n_2 = 1.6$ ,  $\lambda = 1.55 \mu\text{m}$  and  $a = 2.5 \mu\text{m}$ . We can see that four of the five modes plotted intersect with  $r$ , which means that only these four modes are supported by the waveguide

From this, we can see clearly that  $r = V$ . Hence going back to Figure 2.4, four modes are supported by the waveguide for a particular normalized frequency ( $V = 5.64$ ). Varying the V number will show a different amount of modes being supported by the waveguide. We can also see that modes appear as V

increases, so we obtain the following equation:

$$\tan(ha - \frac{m\pi}{2}) = \frac{\gamma}{h} \quad (2.25)$$

where we use the fact that  $-\cot(x) = \tan(x - \frac{\pi}{2})$ . Therefore we get the following eigenvalue equation for TE modes:

$$ha - \frac{m\pi}{2} = \tan^{-1} \frac{\gamma}{h} \quad (2.26)$$

We can use this equation to rewrite the formula for V. We already know that  $h^2 = k^2 n_2^2 - \beta^2$  and  $\gamma^2 = \beta^2 - k^2 n_1^2$ , with both  $h^2$  and  $\gamma^2$  being positive.

Therefore, the value of  $\beta$  must lie between  $kn_1$  and  $kn_2$  such that  $kn_1 \leq \beta \leq kn_2$ . We can thus define  $\beta$  in terms of an effective index  $n_{eff}$ :

$$\beta = kn_{eff} \quad (2.27)$$

We then define a normalisation propagation constant b in terms of  $n_{eff}$ :

$$b = \frac{n_{eff}^2 - n_1^2}{n_2^2 - n_1^2} \quad (2.28)$$

which we can then rearrange for  $n_{eff}$ :

$$n_{eff}^2 = bn_2^2 + n_1^2(1 - b^2) \quad (2.29)$$

We can see from this equation that if  $b = 0$ ,  $n_{eff} = n_1$ , and if  $b = 1$ , then  $n_{eff} = n_2$ . Thus b is a useful parameter for determining whether the light is confined in the waveguide core, or if it leaks out to the cladding layers. This parameter will be mentioned later on when discussing the mode confinement factor. Using Eqs 2.23 and 2.24, we can now rewrite V in terms of b,  $\gamma$  and h as:

$$\gamma a = V\sqrt{b} \quad (2.30)$$

$$ha = V\sqrt{1 - b} \quad (2.31)$$

Substituting these into Eq 2.26, we get:

$$V = \frac{1}{\sqrt{1 - b}} \tan^{-1} \left( \sqrt{\frac{b}{1 - b}} \right) + m \frac{\pi}{2} \quad (2.32)$$

### 2.2.3.2 TM solution

Using the wave equation from Eq 2.18, we get the same solutions for  $H_y(x)$  as for  $E_y(x)$  in the TE solution:

$$H_y(x) = \begin{cases} De^{-\gamma(x-a)} & x > a \\ A\cos(hx) & |x| < a \\ B\sin(hx) & |x| < a \\ Ce^{\gamma(x+a)} & x < -a \end{cases} \quad (2.33)$$

A graphical solution is also used to obtain the propagation constants for the TM modes, so we obtain the following:

$$v = \frac{n_1^2}{n_2^2} u \tan(u) \quad (2.34)$$

$$v = -\frac{n_1^2}{n_2^2} u \cot(u) \quad (2.35)$$

The symmetric solutions for both the TE and the TM modes are shown in Figure 2.5, using a planar waveguide structure with  $n_1 = 3$ ,  $n_2 = 3.1$ ,  $\lambda = 1.55 \mu\text{m}$ , and  $a = 0.2 \mu\text{m}$ . The  $r$  parameter here is also equal to the  $V$  parameter as in the previous section. We can see that both the  $TE_0$  and  $TM_0$  are supported by the structure. However, the structure supports only these fundamental modes due to the thickness of the core layer and refractive indices of the core and cladding layers selected. Thus, we can clearly see that waveguide design plays an important part in how many guided modes propagate through the structure. The eigenvalue equation for the TM modes is given as

$$ha = \tan^{-1}\left(\frac{n_2^2 \gamma}{n_1^2 h}\right) + \frac{m\pi}{2} \quad (2.36)$$

and we can use this to rewrite the equation for  $V$  for the TM modes in the same way as for the TE modes:

$$V = \frac{1}{\sqrt{1-b}} \tan^{-1}\left(\frac{n_2^2}{n_1^2} \sqrt{\frac{b}{1-b}}\right) + m\frac{\pi}{2} \quad (2.37)$$

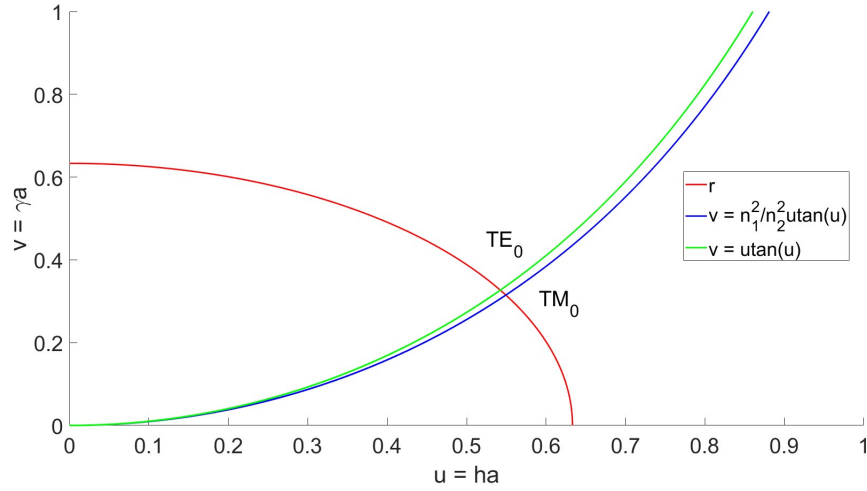


Figure 2.5: Graphic solution of Eqs 2.23, 2.34 and 2.35 for a planar waveguide with  $n_1 = 3$ ,  $n_2 = 3.1$ ,  $\lambda = 1.55 \mu\text{m}$  and  $a = 0.2 \mu\text{m}$ . We can clearly see from the graph that only the fundamental modes for both polarizations are supported by the waveguide.

### 2.2.3.3 Cutoff conditions

Cutoff occurs when the propagation angle for a given mode  $= \theta_c$ . At this angle a guided mode transits to an unguided mode. This corresponds to the condition that  $b = 0$  ( $n_{eff} = n_1$ ) and  $\gamma = 0$ . Thus the cutoff value  $V = V_c$  for a guided mode is the value of  $V$  at the point where  $b = 0$ . For  $\gamma = 0$  when  $b = 0$ , we get

$$V_c = ha \quad (2.38)$$

Substituting Eq 2.38 into Eq 2.25, we get the following for the cutoff condition:

$$V_c = \frac{m\pi}{2} \quad (2.39)$$

TE and TM modes have the same cutoff condition. We can also see clearly from Eq 2.38 that the cutoff for the fundamental modes occurs at zero waveguide thickness: therefore, any symmetric planar waveguide will always support the fundamental  $TE_0$  and  $TM_0$  modes as these modes do not have cutoff. We can also see from Eq 2.39 that the same number of modes is supported for both polarizations at the cutoff value in such a waveguide structure.

In order for only the fundamental modes to be supported by the waveguide, the condition for  $V$  is

$$V < \frac{\pi}{2} \quad (2.40)$$

This is known as the single mode condition.

### 2.2.4 Wave Optics: Analysis of the asymmetric planar waveguide

In reality, most planar waveguides are asymmetric: as the waveguiding layers are usually thin, a substrate is necessary for support of the structure. The index profile of the modes in an asymmetric slab waveguide is given as

$$n(x) = \begin{cases} n_1, & x < -a \\ n_2, & -a < x < a \\ n_3, & x > a \end{cases} \quad (2.41)$$

where  $n_1 < n_3 < n_2$ . For  $kn_3 < \beta < kn_2$ , the solution is sinusoidal in the core ( $-a < x < a$ ), but is exponential in the cladding layers. The modes that obey this condition are the guided modes of the waveguide. For  $kn_1 < \beta < kn_3$ , the solution corresponds to exponential behaviour in the  $x > a$  region, and sinusoidal behaviour in the  $x < -a$  region. These modes correspond to the substrate radiation modes. For the condition  $0 < \beta < kn_1$ , the solution becomes sinusoidal in all three regions. These modes are the radiation modes of the waveguide.

Defining the asymmetry parameter  $\delta_{asym}$  to be as follows:

$$\delta_{asym} = \frac{n_3^2 - n_1^2}{n_2^2 - n_3^2} \quad (2.42)$$

we get the following equation for the cut-off frequency  $V_c$  of the guided TE modes:

$$V_c = \frac{1}{2} \tan^{-1} \sqrt{\delta_{asym}} + \frac{m\pi}{2} \quad (2.43)$$

and the cutoff condition for the TM modes:

$$V_c = \frac{1}{2} \tan^{-1} \left( \frac{n_2^2}{n_1^2} \sqrt{\delta_{asym}} \right) + \frac{m\pi}{2} \quad (2.44)$$

### 2.2.5 Confinement Factor

A mode is guided in a waveguide structure if it is mainly confined in the core region. To determine how much of the mode power is actually guided along the core, i.e. the mode confinement, we can define a confinement factor  $\Gamma_i$

such that

$$\Gamma_i = \frac{\int_{-a}^a |E|^2 dx}{\int_{-\infty}^{\infty} |E|^2 dx} \quad (2.45)$$

Plugging in the solutions from Eq 2.20 into the integrals and writing it in terms of  $b$  and  $V$  from the previous formulas, we get the following equation for the mode confinement of a waveguide mode for a symmetric planar waveguide

$$\Gamma_x = \frac{V + b^{\frac{1}{2}}}{V + b^{-\frac{1}{2}}} \quad (2.46)$$

The equation also holds for a waveguide mode in the asymmetric planar waveguide. We can see from this equation that as  $n_{eff}$  goes to  $n_2$ ,  $b$  goes to 1 and hence  $\Gamma_x$  goes to 1, so there is total confinement in the core. As  $n_{eff}$  reduces with mode order, so too must  $b$ , and therefore  $\Gamma_x$  also reduces with mode order. Therefore the fundamental mode  $TE_0$  must have the strongest confinement out of all the possible modes.  $n_{eff}$  and  $b$  also increases with  $V$  for all modes. Therefore, increasing the index difference or contrast between the core and cladding increases the confinement of the mode.

## 2.3 Channel Waveguides

So far we have discussed the characteristics of planar waveguides. In reality, nonplanar waveguiding structures are used in PICs as the energy confinement in the planar waveguide is limited to one dimension. These waveguide structures are generally two-dimensional waveguides, where energy is confined in both transverse directions. As a result of this, the index profile  $n(x, y)$  is a function of both transverse coordinates  $x$  and  $y$ . The types of nonplanar waveguides in PICs are known as channel waveguides. Examples of this group are shown in Figure 2.6, and include the buried channel waveguide, the fully-etched ridge waveguides, and the partially etched ridge waveguides (also known as a rib waveguide).

A buried channel waveguide is formed with a high-index waveguiding core buried in a low-index surrounding medium. The waveguiding core can have any cross-sectional geometry, although it usually has a rectangular shape. A fully etched ridge waveguide has a structure where the ridge is the waveguiding core and is surrounded by air. Due to the high index contrast between the air and the core, such a structure has strong optical confinement.

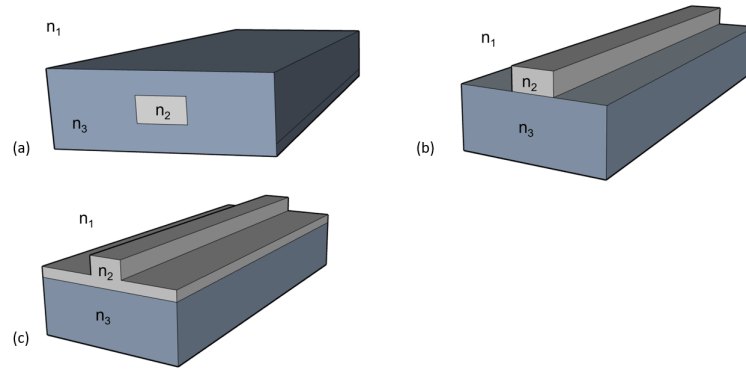


Figure 2.6: Examples of channel waveguides: (a) the buried channel waveguide, (b) the ridge waveguide (fully etched), and (c) the partially etched ridge waveguide, which is also known as a rib waveguide.

A partially etched ridge/rib waveguide has a structure similar to that of the fully etched ridge waveguide, but the ridge has the same index as the high-index planar layer beneath it and is part of the waveguiding core. While the partial etch reduces the optical confinement of the mode, a larger mode size is generated which may be beneficial for coupling purposes. The advantages and disadvantages of the fully etched ridge waveguide vs the partially etched ridge waveguides are discussed later on when designing a waveguide on the GaN platform. These three types of waveguides are usually classified as rectangular waveguides, though their shapes are normally not exactly rectangular as a result of fabrication processes.

Except for those few exhibiting special geometric structures, such as circular optical fibers, nonplanar dielectric waveguides generally do not have analytical solutions for their guided mode characteristics. However, numerical methods do exist for analyzing such waveguides. The finite difference eigenmode (FDE) method is used in this work and is discussed in the next section.

### 2.3.1 Finite Difference Eigenmode (FDE) Analysis

In a ridge waveguide with a high index contrast, the light is strongly confined in the core. Such a strong confinement can lead to the mode being scattered at the core-cladding interface and coupling into cladding layers. This leads to the formation of cladding, or leaky modes, which radiate energy away from the waveguide core. These leaky modes can either continue to propagate in the cladding layers, or else couple back into the waveguide core region. Such mode coupling leads to more complex mode profiles that have to be solved with numerical methods such as the finite difference eigenmode (FDE)



method. In this work, the FDE solver in ANSYS Lumerical MODE solutions is used to obtain and analyse the supported modes of the ridge waveguide structures [54]. These modes are found by solving Maxwell's equations on a cross-sectional mesh of the waveguide.

A more detailed explanation of how the commercial solver works is as follows: the waveguide structure is divided into a numerical grid of small cells. The grid spacing is chosen such that it is much smaller than  $\lambda$  of the mode (typically in the range of a few nanometres). We then use the finite difference method for discretizing the waveguide geometry. The finite difference equations approximate the derivatives of the wave equation using the values of the wave function at neighboring grid points. The discretization in Lumerical MODE is based on Yee's 2-D mesh [55, 56], shown in Figure 2.7 below. The mesh grids for electric fields lie on possible dielectric discontinuities. Since all the transverse field components are tangential to the unit cell boundaries, the continuity conditions are automatically satisfied.

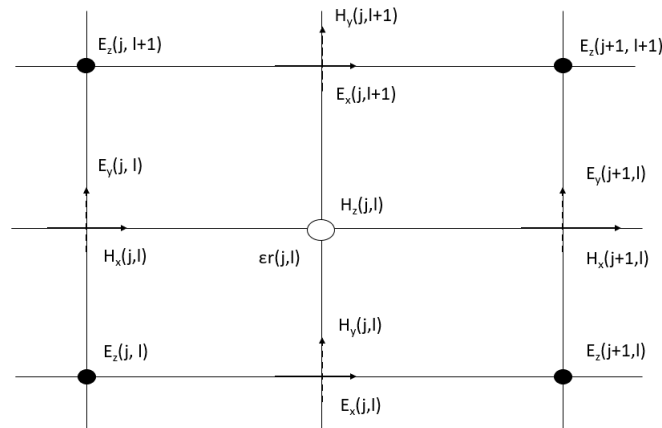


Figure 2.7: Yee's 2-D mesh used to discretize Maxwell's equations in space: the enclosed paths are out of plane

By discretizing the wave equation in this manner, we get the different field component. Thus, the discretized equations then form an eigenvalue problem given as:

$$\mathbf{P}\phi_E = \beta^2\phi_E \quad (2.47)$$

$$\mathbf{Q}\phi_M = \beta^2\phi_M \quad (2.48)$$

where  $\mathbf{P}, \mathbf{Q}$  = global matrices that represent the discretized form of the wave equation,  $\beta$  = eigenvalues which represent the propagation constants of the optical mode, and  $\phi_{E,M}$  = eigenvectors for the TE and TM polarizations

respectively. Therefore, the propagation constants and corresponding field distributions can be found by solving the eigenvalue matrix equation.

The boundary conditions are then applied to the matrix equations by setting the wave function to zero at the boundaries of the waveguide. The boundary conditions can be either perfectly matched layers (PML) or metal boundaries. If the electromagnetic fields extend beyond the edges of the simulation, then PML boundary conditions are used as they will absorb fields at the simulation boundary due to acting like an absorbing material that is also impedance matched to the surrounding materials. However, if the fields are very small or non-existent at the edge of simulations, then metal boundary conditions can be used. Metal boundary conditions are used later on in this chapter when trying to solve for the modes of an AlGaIn/GaN ridge waveguide. Later on in Chapter 3 though, PML boundary conditions will be used for analyzing waveguide bend structures.

## 2.4 Uniaxial Crystal

GaN is a uniaxial crystal; this is where the optical anisotropy of the material is governed by the optic axis of the crystal, as shown in Fig 2.8. All directions perpendicular to or at an angle to the optic axis are optically equivalent, thus rotating the crystal around the optic axis does not change its optical behaviour. As the refractive index depends upon the polarization when unpolarized light enters a uniaxial material, it is split into two beams propagating in different directions: one possessing the polarization of the ordinary wave and the other the polarization of the extraordinary wave. The propagation in a uniaxial material can be represented by an index ellipsoid [57]: given a wave with propagation direction  $\hat{u}$ , which forms an angle  $\theta$  with the optic axis, the index ellipse has half-lengths  $n_o$  and  $n(\theta)$ , where

$$\frac{1}{n^2(\theta)} = \frac{\cos^2\theta}{n_o^2} + \frac{\sin^2(\theta)}{n_e^2} \quad (2.49)$$

The ordinary wave has a refractive index  $n_o$  regardless of the value of  $\theta$ . The extraordinary wave, however, has a refractive index  $n(\theta)$  that varies from  $n_o$  to  $n_e$  for  $0 \leq \theta \leq 90$ . The vector  $\mathbf{H}$  of the ordinary wave is normal to the plane defined by the optic axis (z axis) and the wave propagation direction  $\mathbf{k}$ , and the vectors  $\mathbf{E}$  and  $\mathbf{D}$  are parallel. The extraordinary wave, on the other hand,

has a vector  $\mathbf{H}$  that is normal to  $\mathbf{k}$  and lies in the  $k$ - $z$  plane, while  $\mathbf{E}$  and  $\mathbf{D}$  are not parallel.

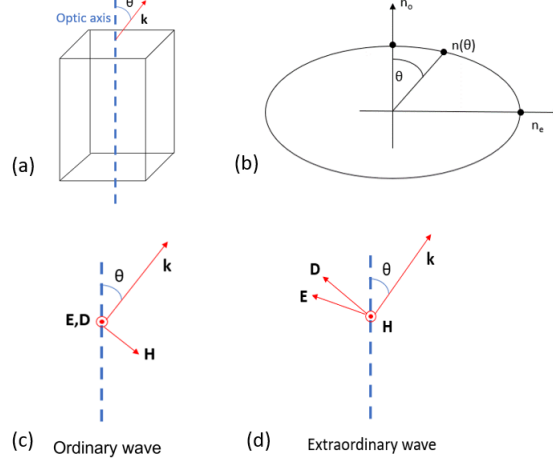


Figure 2.8: (a) Defining the optic axis in a uniaxial crystal, (b) schematic of how the refractive index  $n(\theta)$  varies with respect to the angle between the direction of propagation and the optic axis,  $\theta$ , and directions of the electromagnetic fields for (c) the ordinary wave, and (d) the extraordinary wave. The red dot at the origin is to signify that the direction of the vector is out of plane of the paper and towards the reader.[57]

As there is symmetry about the optic axis ( $z$ -axis), we can assume that the vector  $\mathbf{k}$  lies in the  $y$ - $z$  plane, with its direction given by the angle  $\theta$  it makes with the optic axis. Therefore, we can draw the  $k$ -surfaces only in the  $y$ - $z$  plane, as a circle and as an ellipse as shown in Fig 2.9. Given the direction  $\hat{\mathbf{u}}$  of the vector  $\mathbf{k}$ , the wavenumber  $k$  is obtained by finding the intersection with the  $k$  surfaces. The two solutions therefore define the two normal modes: the ordinary wave has wavenumber  $k = n_o k_o$ , while the extraordinary wave has wavenumber  $n(\theta) k_o$ . The magnitude of the difference between  $n_o$  and  $n_e$  is the birefringence of the material:

$$\Delta n = n_e - n_o \quad (2.50)$$

If  $n_e > n_o$ , the crystal is positive uniaxial, meaning that the extraordinary ray is refracted closer to the optic axis and the index ellipsoid takes on an oblate spheroid shape. The crystal is negative uniaxial if  $n_e < n_o$ , so the ordinary ray is refracted closer to the optic axis and the index ellipsoid takes on a prolate spheroid shape. GaN, the choice of platform for the PIC in this work, is a positive uniaxial material. At  $1.31 \mu\text{m}$ ,  $n_o = 2.28$  and  $n_e = 2.32$  for GaN. The advantages of GaN being birefringent include an enhancement of nonlinear

effects in the material, and being able to incorporate polarization-control devices such as splitters onto the platform. The incorporation of the latter on a GaN platform can be important for maintaining the efficiency of the overall PIC as polarization-dependent losses can be an issue.

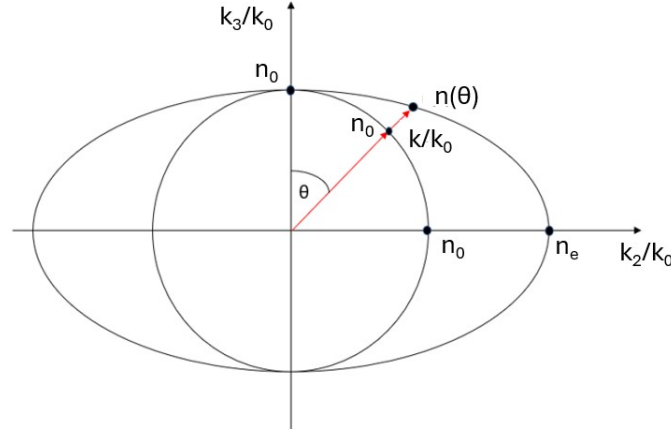


Figure 2.9: Intersection of the  $\mathbf{k}$  surfaces with the  $y$ - $z$  plane for positive uniaxial crystal

## 2.5 Coupling to the PIC

The coupling technique for a PIC depends on requirements such as low cost, high coupling efficiencies, mode selectivity and scalability to high volume production rates. Light coupling methods include end-fire coupling, edge (or butt) coupling, prism coupling, grating coupling and taper coupling. Each of these coupling methods have a set of advantages and disadvantages associated with them, so the technique to select depends on the requirements needed for the application. As the aim of this work is to integrate an edge-emitting laser to a GaN-on-sapphire, edge coupling and end-fire coupling (for waveguide characterization via optical fibers) are the most appropriate coupling methods and will be discussed in further detail in this section. However, tapered waveguide designs for the purpose of guiding light and grating coupler designs for coupling optical fibers into the PIC will be later discussed in Chapter 3.

### 2.5.1 Edge coupling

Edge-coupling (also known as butt-coupling) involves focusing light onto the end of the waveguide either via a lens or by “butting” two devices up to one another, as seen in Figure 2.10. The coupling relies on the modal overlap between the mode field of the light-emitting source and of the device receiving

the light. Grating couplers can be used in PICs instead of edge-coupling to couple light in via optical fiber, but the coupling depends on phase matching between the injected and coupled light leading to a wavelength and polarization-dependent device. As edge-coupling doesn't rely on phase matching, it allows a broad transmission spectrum and is less dependent on the specific material properties. However, this can lead to excitation of unwanted modes in waveguide structures supporting more light modes. Thus, the overlap integral of the modes determines the coupling efficiency which in turn depends on the experimental alignment and the size and shape differences of the coupled devices.

The alignment of devices in edge-coupling on a PIC depends on the device integration technique used. The lasing devices used in this work are released from their growth substrate (InP or GaAs based) and then bonded to the GaN-on-sapphire platform in a method known as micro-transfer printing. The details of this will be discussed in much greater detail in Chapter 4: while this technique allows for careful selection of where to place the device, it is impossible to achieve zero misalignment of the lasing mode (the active region of the laser) with respect to the passive waveguide mode. Lateral alignment accuracy  $\pm 0.5 \mu\text{m}$  ( $3\sigma$ ) has been achieved with state of the art tools [58], although for the tool used in this work the alignment tolerance is closer to  $\leq 1 \mu\text{m}$  for singular devices. Such tolerances need to be taken into consideration for both the integration design and the overall waveguide design for coupling.

For edge coupling, the amount of light that is actually coupled into the waveguide facet depends on reflection at the facet, which can be approximated as

$$R = \left| \frac{n_1 - n_2}{n_1 + n_2} \right|^2 \quad (2.51)$$

For an air/GaN interface, where  $n_1 = 1$  and  $n_2 = 2.3$ , the reflection is approximately 15 %. The light reflected also depends upon the refractive index of the lasing device: a higher contrast between the indices of the laser and the waveguide leads to an increase in reflections. Methods of reducing the reflections, and thus enhancing the coupling include using an anti-reflection (AR) coating on the lasing facet, or filling in the gap between the facets with a material such as benzocyclobutene (BCB,  $n \approx 1.5$ ).

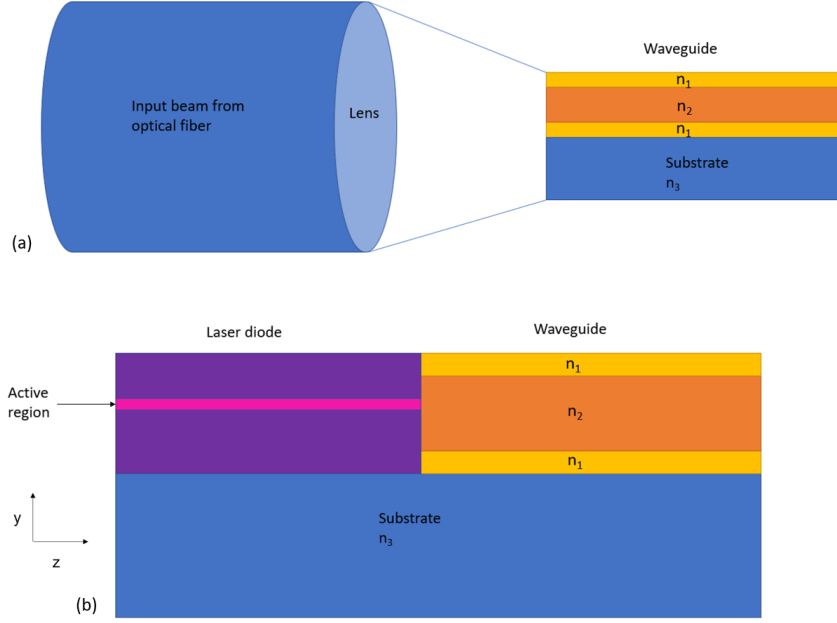


Figure 2.10: Schematic of (a) end-fire coupling from a lens-ended optical fiber to a waveguide and (b) edge coupling of an integrated laser source to the waveguide via micro-transfer printing. Note that the schematic shows zero gap between the devices in the longitudinal ( $z$ ) direction: this is not the case in reality due to the alignment restrictions of the transfer printing tool.

### 2.5.2 Coupling Efficiency

The coupling efficiency is given as the fraction of the total power in the light source which is coupled into the waveguide. We can represent this coupling efficiency  $\eta_c^m$  by taking into account both the overlap of the lasing mode and the waveguide mode, and the reflections at the waveguide interface by assuming the reflected mode has same profile as the incoming field [59]:

$$\eta_c^m = \frac{P_m}{P_{in}} = Re \left[ \frac{(\int \mathbf{E}_m \times \mathbf{H}_{in}^* \cdot d\mathbf{S})(\int \mathbf{E}_{in} \times \mathbf{H}_m^* \cdot d\mathbf{S})}{\int \mathbf{E}_{in} \times \mathbf{H}_{in}^* \cdot d\mathbf{S}} \right] \frac{1}{\int \mathbf{E}_{in} \times \mathbf{H}_{in}^* \cdot d\mathbf{S}} \quad (2.52)$$

where  $E_{in}$  and  $H_{in}$  are the electric and magnetic fields of the input beams, and  $E_m$  and  $H_m$  are the electric and magnetic fields of the  $m^{th}$  mode. We can also represent this in terms of dB as a coupling loss  $L_c^m$ :

$$L_c^m = 10 \log \frac{P_m}{P_{in}} (dB) \quad (2.53)$$

Thus, the coupling efficiencies between the laser and the GaN waveguide presented later in this chapter will be given as coupling losses according to

Eq 2.53.

## 2.6 GaN waveguides for edge coupling

The goal is now to design on the GaN platform for micro-transfer printed edge-emitting lasers at  $1.31\ \mu\text{m}$ . The GaN material in this work is grown on a sapphire substrate; due to the already mentioned large lattice mismatch between GaN and sapphire a thin AlN layer is usually grown first on the substrate to improve the GaN quality. The refractive index of sapphire is 1.75, so the index contrast between GaN and sapphire ensures the mode does not leak to the substrate, provided the correct waveguide dimensions are selected. We already know that the intermediate refractive index of GaN ( $n_{\text{GaN}} = 2.32$ ) allows for flexibility with the waveguide contrast: for example, a high contrast GaN waveguide can be demonstrated using a fully etched ridge waveguide, where the structure is cladded by air. Such a contrast ensures the mode is well confined to the GaN guided layer, but is not necessarily advantageous for edge coupling where both the size of the lasing modes and the alignment tolerances from transfer printing the devices have to be taken into account in the waveguide design.

The waveguide dimensions can be increased in order to match the lasing mode: in Figure 2.11 we can see the simulated waveguide mode profiles for a fully etched GaN ridge waveguide with width =  $2\ \mu\text{m}$  and height =  $2\ \mu\text{m}$ . Note that the color bars for these mode profile simulations, and for all simulated mode profiles in this work, are in units of normalized electric field intensity. These dimensions were chosen primarily to match the lasing ridge width of the available emitting 1300 nm lasers, and to see the effect of a thicker ridge waveguide in the transverse direction. We can see though from these dimensions that higher order modes are supported in both the transverse and lateral directions in Figure 2.11. Thus we want to be able to expand the waveguide mode while also keeping the waveguide single-mode. One possible suggestion would be to taper down the core region at the waveguide input and surround it completely with a material of lower refractive index in order to expand the waveguide mode size. It is not possible to encapsulate GaN in a buried channel waveguide structure with a lower refractive index material in a similar manner to the schematic provided earlier in Figure 2.6 (a), as GaN is limited by its choice of substrate due to lattice and thermal mismatch, although the waveguide could be partially encapsulated via an upper dielectric

cladding layer such as niobium oxide ( $n_{NbOx} = 2.24$  at  $1.31 \mu\text{m}$ ).

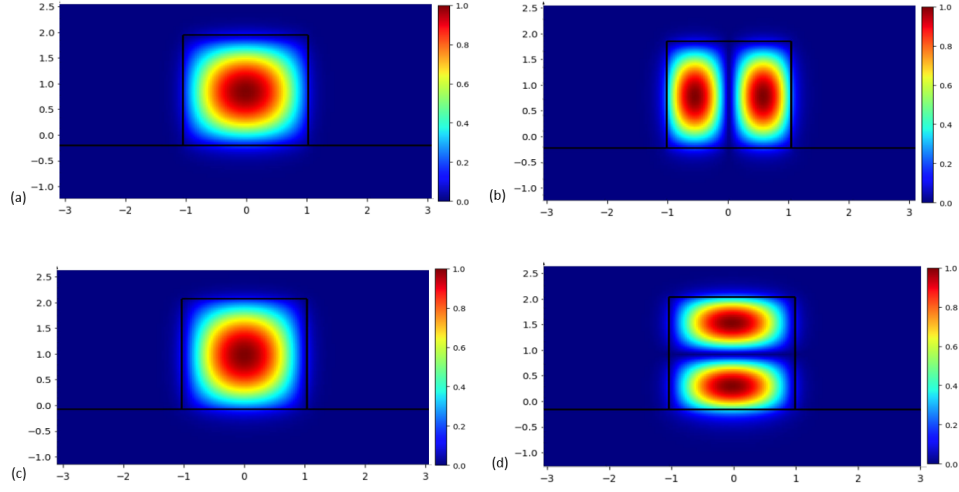


Figure 2.11: Simulations for the guided modes in a fully-etched GaN ridge on sapphire substrate with width =  $2 \mu\text{m}$  and total height =  $2 \mu\text{m}$ : the Ey components of the (a)  $TM_0$  mode and (b) the  $TM_1$  mode, and the Ex components of (c) the  $TE_0$  mode and the (d)  $TE_1$  mode.

A partially etched GaN ridge waveguide such as the one presented in Figure 2.6 (c) may be a solution to the problems mentioned: when we introduce a partially etched ridge, the optical confinement of the mode becomes broader laterally in comparison to the fully etched ridge waveguide due to a lower index contrast in Region I (it's now air/GaN/sapphire rather than just air/sapphire). If we divide up the partially-etched structure into different segments as shown in Figure 2.12, then the effective indices of the structure can be described as the following:

$$n_{eff}(y) = \begin{cases} n_I & y < -\frac{1}{2}b \\ n_{II} & -\frac{1}{2}b < y < \frac{1}{2}b \\ n_I & \frac{1}{2}b < y \end{cases} \quad (2.54)$$

For a mode to be guided by the ridge in Region II, the effective index  $n_{II}$  of the guided mode in Region II must be greater than the effective index  $n_I$  of the slab mode in Region I. Any modes that possess an effective index  $\leq n_I$  than this will leak out and couple with the slab modes. By carefully selecting the ridge etch depth, the ridge width and the overall thickness of the GaN structure, a GaN-on-sapphire waveguide can support only a single mode that's broader in size for both polarizations. This can be seen in Figure 2.13 for a GaN-on-sapphire waveguide with total height =  $2 \mu\text{m}$ , ridge etch depth =



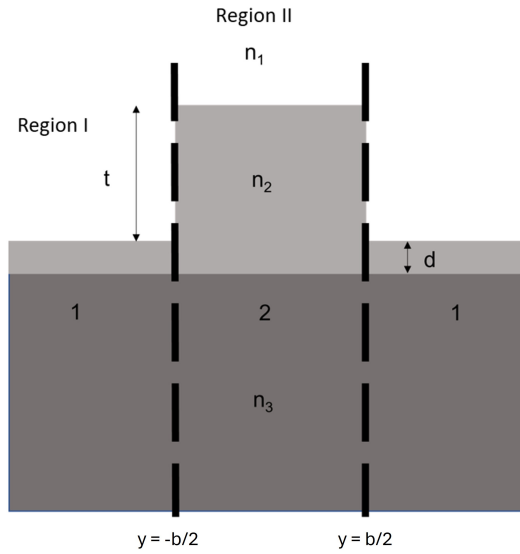


Figure 2.12: A schematic of a partially etched waveguide divided up into Region I and Region II; this is the design that we want to apply to the GaN waveguide in this work.

0.5  $\mu\text{m}$ , and width = 2  $\mu\text{m}$ . The effective indices of the guided modes in (a) and (c) were  $n_{effTM0} = 2.294$  and  $n_{effTE0} = 2.260$ , while the effective indices of the next were  $n_{effTM1} = 2.282$  and  $n_{effTE1} = 2.255$ . The slab effective indices were  $n_{effslabTM} = 2.286$  and  $n_{effslabTE} = 2.255$ , so both the  $TM_1$  and  $TE_1$  couple out into the slab regions. This can also be seen visually in Figure 2.13 (b) and (d), where the mode is very clearly leaking out laterally for both polarizations.

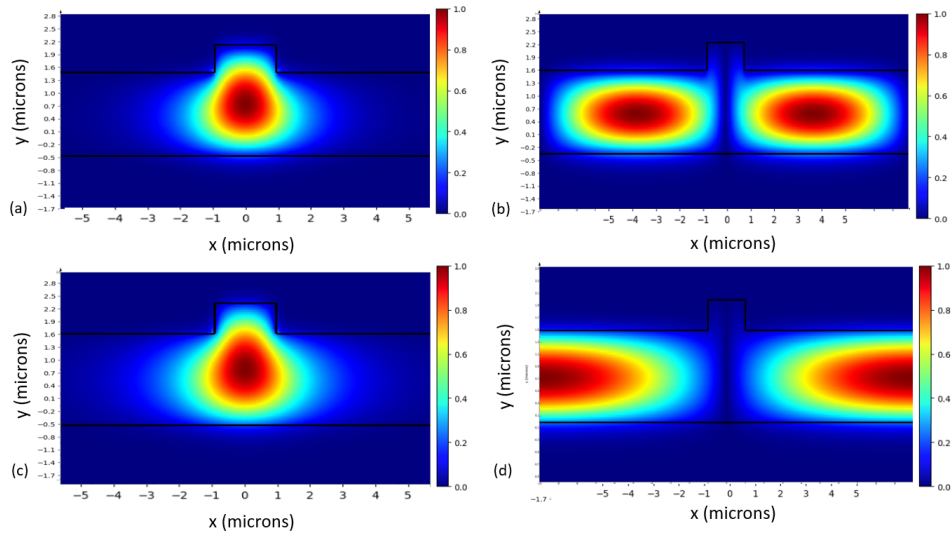


Figure 2.13: Simulated guided (a)  $TM_0$  and (c)  $TE_0$  modes in a partially-etched GaN ridge on sapphire substrate with width = 2  $\mu\text{m}$  and height = 2  $\mu\text{m}$ : we can clearly see for the (b)  $TM_1$  and the (d)  $TE_1$  modes that they are leaking out laterally due to the geometry being chosen such that they couple out to the slab modes. These simulations were carried out using ANSYS Lumerical Mode.

To best match the waveguide mode size to that of the lasing mode, we can make use of the AlGa<sub>N</sub> cladding layers to enhance the broadness of the waveguide mode in the partially-etched waveguide structure. This is done by carefully selecting the Al concentration such that the AlGa<sub>N</sub> refractive index is close to that of GaN. In order to estimate the refractive index values for Al<sub>x</sub>Ga<sub>1-x</sub>N, the dispersion can be parameterized as a function of the bandgap  $E_g$  [60, 61]:

$$E_g(\text{Al}_x\text{Ga}_{1-x}\text{N}) = 6.13x + 3.42(1 - x) - bx(1 - x) \quad (2.55)$$

where 6.13 eV and 3.42 eV are the room temperature bandgap values for AlN and GaN,  $b$  is the measured bandgap bowing parameter, and  $x$  is the Al concentration. Eq 2.55 can be used regardless of the growth technique used, but the bowing parameter value does vary with growth method. In this work  $b$  was chosen to be -0.39 eV [60]. Based on the measured refractive index data obtained in [60, 61], the Sellmeier dispersion formula was fitted as:

$$n(\lambda)^2 = 1 + (A_0\lambda^2)/(\lambda^2 - \lambda_0^2) \quad (2.56)$$

and then parameterized as a function of  $E_g$ :

$$A_0(E_g) = B_0 + B_1E_g + B_2E_g^2 \quad (2.57)$$

$$\lambda_0(E_g) = C_0 + C_1E_g + C_2E_g^2 \quad (2.58)$$

with the associated coefficients given in [60]. In Figure 2.14, both the theoretical ordinary and extraordinary refractive index with varying Al concentration up to 10 % is plotted for a wavelength of 1.31  $\mu\text{m}$ . Depending on the thickness of the layer desired, it can be difficult to grow AlGa<sub>N</sub> layers with Al concentration > 10 % because cracks can form due to lattice mismatch [62]. For an Al concentration of 3 %, the  $n_e$  of AlGa<sub>N</sub> = 2.31, while the  $n_o$  for 3 % Al concentration = 2.27. By choosing the Al concentration to be 3 %, we get a low index contrast waveguide that expands the mode size ( $\Delta n_{TE} = 0.0027$ ,  $\Delta n_{TM} = 0.0028$ ).

Thus, by using the partially etched waveguide geometry in conjunction with AlGa<sub>N</sub> cladding layers, we can design a large, single mode spot size for tolerant and efficient coupling between the  $\mu\text{TP}$  laser and the waveguide. The next section outlines the optimized AlGa<sub>N</sub>/GaN waveguide dimensions for two

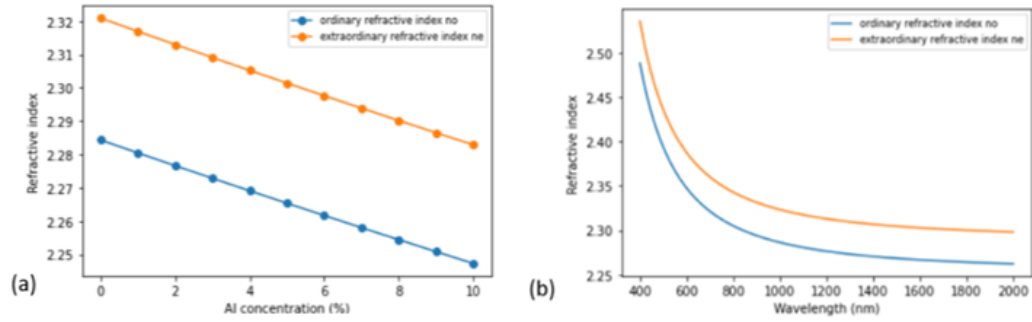


Figure 2.14: The  $n_o$  and  $n_e$  of  $\text{Al}_x\text{Ga}_{1-x}\text{N}$  (a) at  $\lambda = 1.31 \mu\text{m}$  for  $0 \leq x \leq 0.1$  ( $x$  = Al concentration), and (b) at  $x = 0.03$  for  $400 \text{ nm} \leq \lambda \leq 2000 \text{ nm}$  using Equations 2.61-2.63. The  $n_o$ ,  $n_e$  values modelled here are used to simulate the AlGaN/GaN waveguides in this chapter

available 1300 nm-emitting lasers, the structures of which will also be outlined later in this chapter.

### 2.6.1 AlGaN/GaN Waveguide Design

An AlGaN/GaN waveguide design is proposed based on the partially-etched ridge waveguide discussion, shown in Figure 2.15 (a): the GaN core is cladded by upper and lower AlGaN layers. A similar structure was designed for coupling to an optical fiber at  $1.55 \mu\text{m}$  [37]; to our knowledge this is the first to be designed for coupling between an integrated laser and waveguide at  $1.31 \mu\text{m}$ . A shallow ridge is introduced into the AlGaN upper cladding layer, which helps to confine the mode laterally. An advantage of etching the ridge into the AlGaN region rather than the GaN core is that as the mode is mostly concentrated in the core region it is going to interact less with the etched sidewalls as the light propagates along the waveguide, potentially reducing propagation losses as a result of sidewall roughness from dry etching the material. The fabrication techniques for forming the waveguides are discussed in Chapter 4.

The layer thicknesses shown in Figure 2.15 (a) were chosen to best match the lasing modes of the two available  $1.31 \mu\text{m}$ -emitting lasers. The AlGaN thicknesses with the 3 % Al concentration were also suitable for growing an epistructure free of cracks. To determine the cut-off points for single mode operation in the structure, a parameter sweep varying the ridge width between  $1\text{-}8 \mu\text{m}$ , and the ridge etch depth between  $0.05\text{-}0.5 \mu\text{m}$  was set up in Lumerical MODE solutions using the FDE solver with metal boundary conditions. The  $n_{eff}$  of the first two modes for both polarizations ( $\text{TE}_0$ ,  $\text{TE}_1$ ,

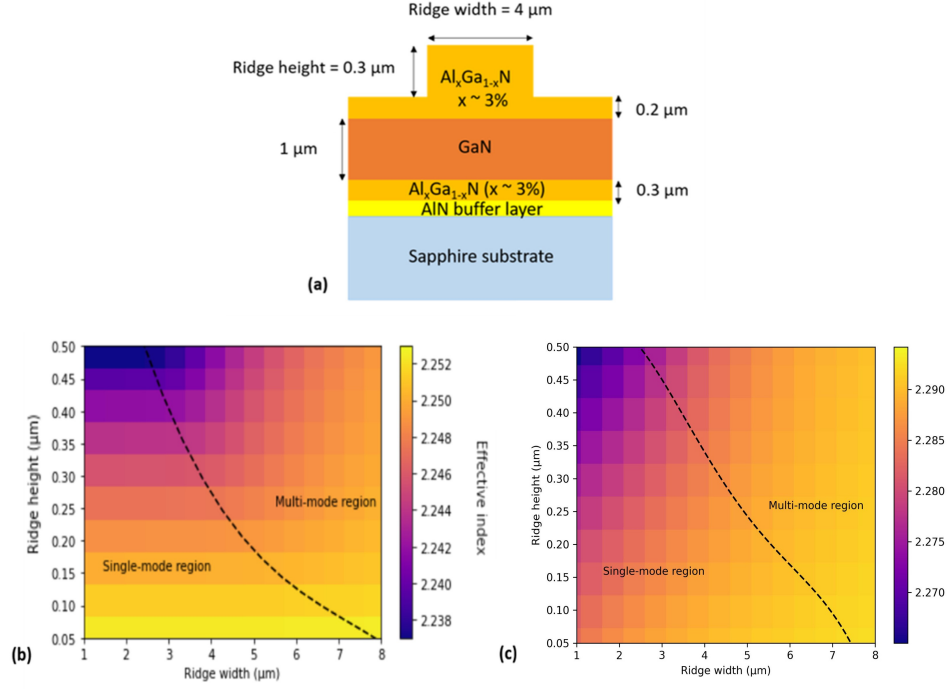


Figure 2.15: A schematic of (a) dimensions for a large single mode spot size, and the regions for single-mode and multi-mode operation for (b) TE polarization and (c) TM polarization for Al concentration = 3 %

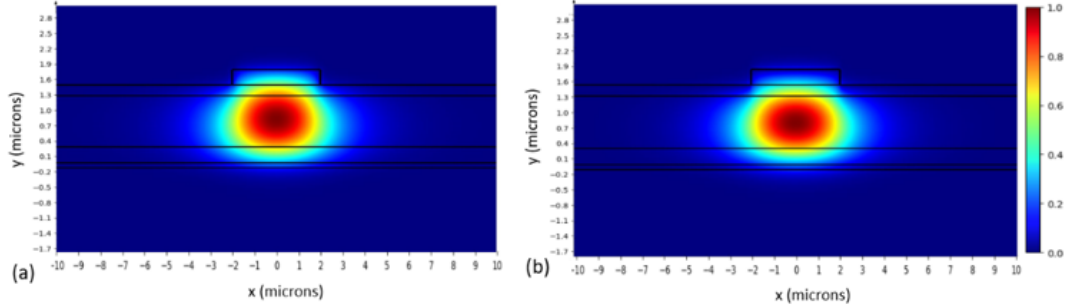


Figure 2.16: The mode profiles for the (a)  $E_x$  component of the  $TE_0$  mode, and (b)  $E_y$  component of the  $TM_0$  mode for the dimensions given in Figure 2.17 (a)

$TM_0$ ,  $TM_1$ ) were obtained from this sweep, and plotted as colour maps for ridge height vs ridge width. The boundary line between the single mode and multimode regions was determined by the  $n_{eff}$  of the slab modes: if  $n_{effTE1/TM1} < n_{effslabTE/TM}$  at a certain ridge height and width, then only  $TM_0/TE_0$  is supported. The waveguide dimensions at which this occurred were recorded and then modelled using a polynomial equation. This polynomial equation formed the boundary line and is plotted on the colour maps for both polarizations as seen in Figure 2.15 (b) and (c). We can see that, provided the ridge height is carefully selected, we can get single-mode operation for both

polarizations up to widths of  $7.5\ \mu\text{m}$ .

For the rest of this section, a waveguide of width  $4\ \mu\text{m}$  and ridge etch depth  $0.3\ \mu\text{m}$  is used in the simulations, with the waveguide mode profiles for both polarizations shown in Figure 2.16. This is because from initial simulations of the waveguide dimensions, these parameters provided waveguide modes that best matched the laser modes with a lasing ridge width of  $2\ \mu\text{m}$  (the ridge widths of the available laser structures).

### 2.6.2 Alignment Tolerance for $\mu\text{TP}$ laser - waveguide coupling

The purpose of designing a broad spot size waveguide is to relax the alignment for a  $\mu\text{TP}$  laser while also trying to match the passive waveguide mode size to the laser mode size. Therefore the coupling efficiency between the lasing mode and waveguide mode must be analysed as a function of positional misalignment. We examine the edge-coupling efficiency between the waveguide structure and (i) a TE-polarized quantum dot (QD) laser, and (ii) a TM-polarized quantum well (QW) laser in both the transverse and lateral directions, assuming no gap and no reflections between the laser facet and waveguide facet in the longitudinal direction. The calculated modes of both structures are shown below in Figure 2.17. It can be seen from these lasing mode profiles that there is also a defined ridge for optical confinement. For this simulation, the waveguide ridge width is kept fixed at  $4\ \mu\text{m}$ . The widths of the lasing ridges, however, are varied between  $2\text{--}5\ \mu\text{m}$ . The widths were capped at  $5\ \mu\text{m}$  as beyond this, the lasers ventured into multilateral mode lasing. The details of the epitaxial structures for both lasers can be found in Section A.0.1 of the Appendix.

To determine the coupling, the modal overlap between the two modes was calculated by using the power coupling function in Lumerical MODE [59]. The optimum power coupling between both modes were first calculated by finding the optimum position of the lasing mode coupling into the waveguide mode. This optimum position was then set to be (0,0). From this (0,0) position, the lasing mode was then shifted in both the transverse and the lateral directions, with the power coupling recorded at each point. These values were then converted to coupling losses using Eq 2.53. In Figure 2.18 we can see that for a ridge width of  $5\ \mu\text{m}$  for both lasing structures, an optimum coupling loss of 1 dB for the QW laser and 0.6 dB for the QD laser can be obtained. The

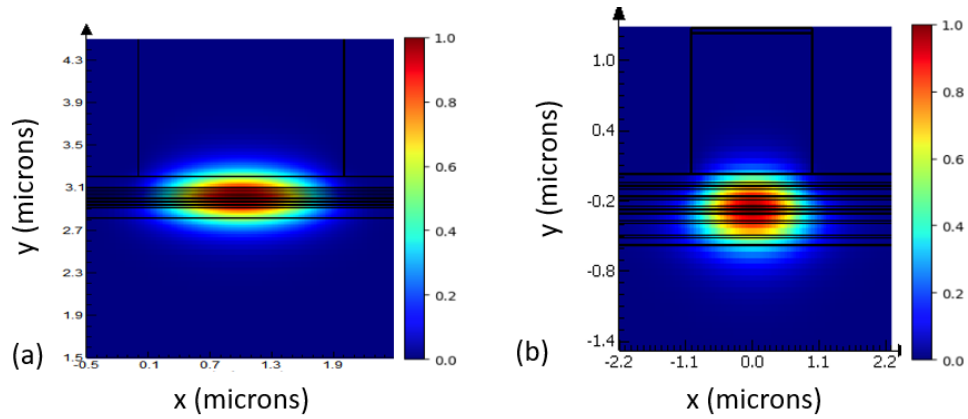


Figure 2.17: Fundamental mode profiles for (a) QW laser at ridge width =  $2\ \mu\text{m}$ , and (b) QD laser at ridge width =  $2.5\ \mu\text{m}$

alignment tolerance in the lateral direction is more relaxed than in the transverse direction for both structures: for  $\pm 1\ \mu\text{m}$  misalignment in the lateral direction we calculate between 2-4 dB loss for the QW laser, and between 1.5-2.2 dB for the QD laser. The tolerance is much tighter in the transverse direction, with the coupling loss surpassing 3 dB at  $\pm 0.25\ \mu\text{m}$  for both lasing structures. The difference between coupling losses can be attributed to larger mode size mismatch in the transverse direction, which is more significant for the QW laser as can be seen from the asymmetry in the graphs.

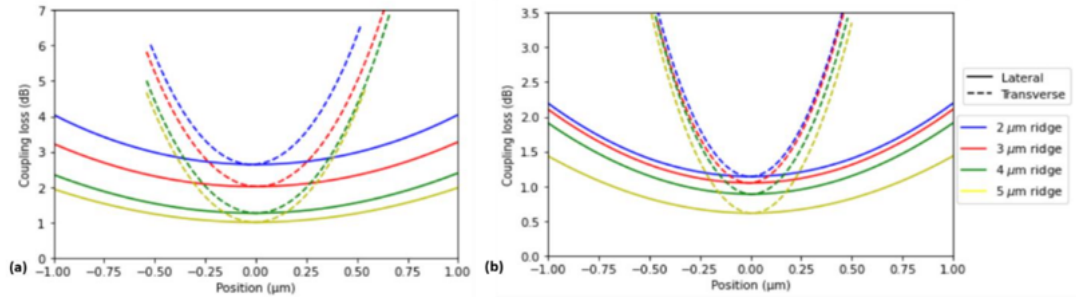


Figure 2.18: Coupling loss as a function of position misalignment for the (a) QW laser, and the (b) QD laser in both the lateral and the transverse directions

The calculations for the coupling efficiency is carried out with the waveguide modes, but does not take into account the physical dimensions of the laser with respect to the waveguide. While the epitaxial layer thicknesses of the waveguide were selected to match the lasing mode size, in reality the laser is thicker than the overall waveguide thickness, as the lasing devices require much thicker doped cladding layers for optimising the electrical performance of the device. From deducing the optimum position for coupling, it was found that for the lasing mode to properly align with the waveguide mode, the laser

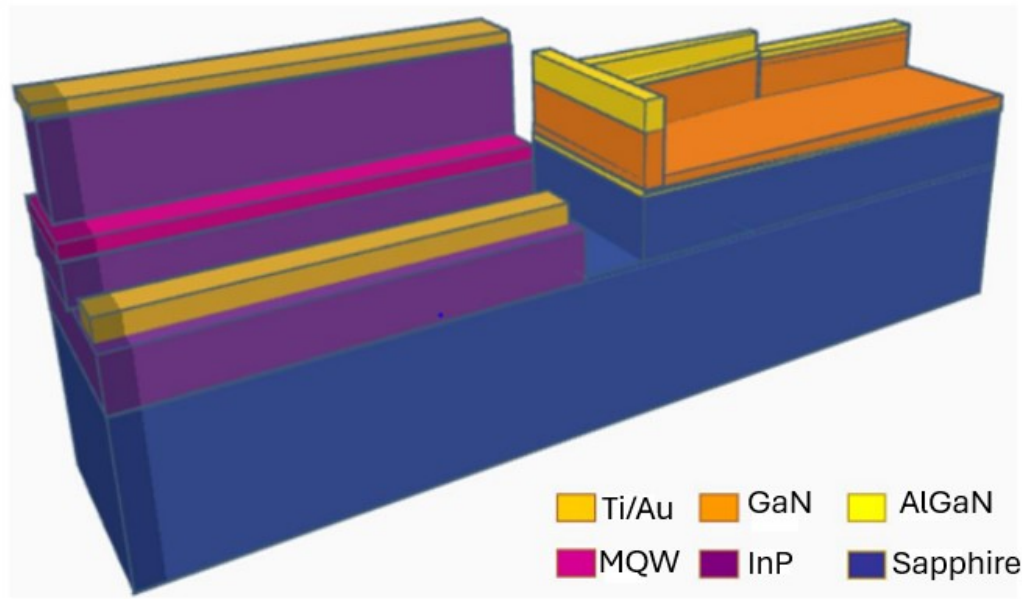


Figure 2.19: Schematic of the laser printed to the sapphire trench in order to properly align the lasing mode to the passive waveguide mode

would have to be shifted down by  $2.8 \mu\text{m}$  from the top of the waveguide. This means that a trench, or cavity would have to be formed in the sapphire substrate, as shown in Figure 2.19. Forming this trench is also discussed in Chapter 4.

In reality, it is very difficult to achieve zero gap between the facets, so misalignment in the longitudinal direction must be considered. This longitudinal misalignment is calculated using Lumerical FDTD simulations for varying laser ridge widths between  $2\text{-}5 \mu\text{m}$  and can be seen in Figure 2.20. For both the QW and QD lasing structures, regardless of the lasing ridge widths, the coupling decreases significantly by almost 3 dB when the air gap  $> 2 \mu\text{m}$ . Oscillations in the coupling loss are observed in the graphs, which is due to an unwanted Fabry-Perot cavity formed between the waveguide facet and lasing facet. By filling the gap with a polymer material ( $n = 1.55$ ), the coupling losses are reduced. This can be seen from Figure 2.20, where the coupling losses with the polymer infill are reduced by 2 dB at a gap of  $1 \mu\text{m}$  for both lasing structures. While the coupling losses also increase with a polymer infill as the separation between the facets increase, it is a steadier decline compared to the coupling with the air gap.



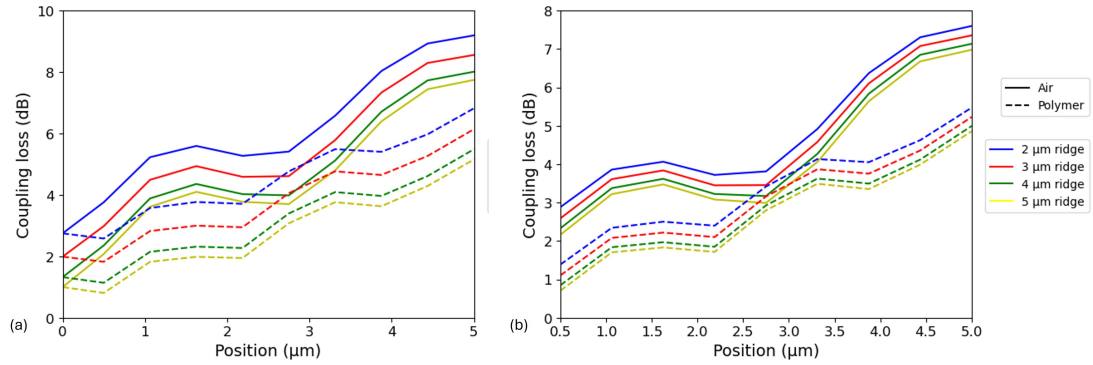


Figure 2.20: The coupling loss as a function of position misalignment for (a) QW laser and (b) QD laser in the longitudinal direction for varying laser ridge width between 2-5  $\mu\text{m}$ . The misalignment is calculated with both an air gap (denoted by the thicker lines) and a polymer with  $n = 1.55$  filled in the gap (denoted by dashed lines) between the laser facet and the waveguide facet.

## 2.7 Discussion and Conclusion

This chapter has outlined the key parameters in designing a waveguide for edge-coupled lasers. Geometrical parameters such as the waveguide width and height, and the index contrast of the waveguide epistructure influences how the passive waveguide mode matches the active lasing mode for efficient coupling. In order to take into account the alignment tolerances from micro-transfer printing the laser for edge-coupling to the waveguide, the GaN waveguide is designed to support laterally broad  $\text{TE}_0$  and  $\text{TM}_0$  modes with no higher order modes supported by the structure. Engineering the size of the mode for tolerant edge-coupling is achieved through (i) cladding the GaN core with AlGaIn layers to create a low-index contrast waveguide, and (ii) introducing a shallow waveguide ridge. The Al concentration is selected to be 3 % so that the refractive index of the cladding layers is close to that of the GaN core, and thus expanding the mode in the lateral direction. Both the Al concentration, and the cladding layer thicknesses allow for a crack-free epistructure. It is also shown that carefully selecting the width and etch depth of this ridge allows for single mode operation for both polarizations. The overall thickness of the waveguide structure is selected to best match the active mode in the transverse direction.

From simulating the coupling loss as a function of integrated laser misalignment in both the transverse and lateral directions, it is observed that the tolerance is much tighter in the transverse direction for both the QW and QD devices. However, alignment in this direction can be controlled by etching of the trench, which will be discussed in greater detail later on this work. It is



difficult to achieve a zero gap between the alignment of the trench to the waveguide facet, so misalignment in the longitudinal direction is also simulated to assess the impact of the air gap on the laser-waveguide coupling. It is also shown through simulation that filling the gap with a material with a refractive index = 1.55 (and thus higher than air) improves the efficiency of the coupling.

We now have a AlGaIn/GaN waveguide structure that is designed for single mode, tolerant edge-coupling via micro-transfer printing for known lasing structures emitting at 1.31  $\mu\text{m}$ . The next chapter deals with using this epistructure to design various key photonic components with more functionalities on the GaN platform.

## Chapter 3

# Photonic components on the AlGaN/GaN platform

### 3.1 Chapter Overview

This chapter goes through different PIC components simulated on a GaN-on-sapphire platform. First, a mode adapter design based on the structure proposed at the end of Chapter 2 is explored, thereby converting the optical confinement to a scale more suitable for bends. Waveguide bends and directional couplers are then simulated using these dimensions. To exploit the electro-optic effect in the circuit, integrating a  $\text{LiNbO}_3$  coupon with the platform is also investigated. For ease of waveguide testing, grating couplers are simulated on the platform as an alternative to edge coupling structures. As the platform is birefringent, polarization converter designs are also designed. For some of these functionalities, limitations with the proposed AlGaN/GaN epistructure are discovered and addressed.

### 3.2 Mode Adapting

The AlGaN/GaN waveguide design presented in Chapter 2 is advantageous for coupling as it creates a broad waveguide mode while also maintaining single mode operation provided the correct ridge width and etch depth are selected. The broadness of the waveguide mode helps relax the  $\mu\text{TP}$  alignment tolerances for edge-coupling the laser to the waveguide. However, there are issues with this design when it comes to propagation through more complex

geometries in a PIC. Waveguide bends are a basic component of a PIC for routing light: as a bend is introduced in the shallow AlGaIn ridge however, the previously guided mode shown in Figure 2.16 leaks out laterally and couples to the slab modes. This can be seen in Figure 3.1 when the ridge is given a bend radius of  $100\ \mu\text{m}$ , where the  $\text{TM}_0$  and  $\text{TE}_0$  modes are no longer guided by the ridge region and are coupling out laterally. Larger bend radii could be used to guide the modes around the bend, but this increases the footprint of the circuit and thus the overall integration density of the chip. We already know from Chapter 2 that in order to increase mode confinement the index contrast must be increased. However, the increase in index contrast reduces the waveguide mode size, making it less tolerant for misalignment of the laser source. Therefore there needs to be a way of introducing a deep etch into the core for a more suitable geometry for bends, without affecting the tolerant edge coupling. This section thus proposes an AlGaIn/GaN double taper design as an alternative design to adapt the mode for bends.

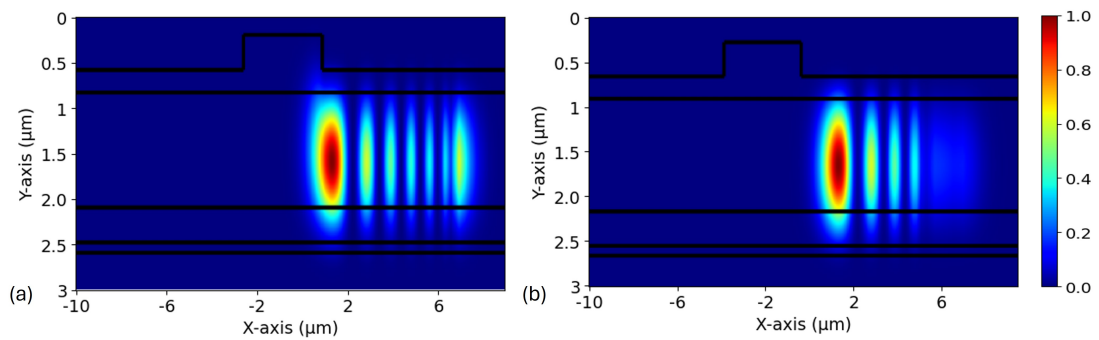


Figure 3.1: (a)  $\text{TM}_0$  and (b)  $\text{TE}_0$  of a  $4\ \mu\text{m}$ -wide shallow ridge waveguide with a  $100\ \mu\text{m}$  bend radius: as the waveguide transitions from a straight waveguide to the curved region, the mode leaks out and is no longer guided by the shallow ridge. Note that FDE simulations for bent waveguide analysis are taken at the centre of the simulation region, and the mode profiles are extracted from the bent section.

### 3.2.1 Adiabatic tapering

Usually a laterally tapered structure is used to change the size and shape of the guided mode in order to achieve high coupling efficiency between two waveguides with different cross sections. This is achieved adiabatically: the cross-section size of the taper is either increased or decreased very slowly, allowing the first-order mode to propagate through the taper without converting to higher order or radiation modes. The distance between the different cross-sections, or length of the taper, must be long enough in order to minimize the transmission loss of the mode through the taper. Depending on

the difference between the maximum and minimum cross section as well as the materials used in the structure and the desired transmission, tapered structures can range from being a couple of microns long to over a mm long to allow for efficient adiabatic propagation. Longer tapered structures can lead to higher propagation losses however, so a compact design is necessary.

For adiabatic operation, the tapered structure must obey the following design rule [63, 64]

$$\theta < \theta_m = \frac{\lambda_0}{2Wn_{eff}} \quad (3.1)$$

where  $\theta$  = half-angle of the taper at the point  $z$  (in radians),  $\theta_m$  = projection of ray angle of the 1st-order mode of the taper,  $\lambda_0$  = the wavelength in vacuum,  $W$  = width of the taper at point  $z$  and  $n_{eff}$  = effective index of the mode. A schematic of an adiabatic taper can be seen in Figure 3.2 below. The rule requires that the change in the waveguide width must be slower than the diffraction spreading of the lowest order mode, and that this mode will be confined without converting to higher order modes or radiation modes. If we go back to the ray picture to describe the mode propagation,  $\theta_m$  is defined as the projection of the ray angle of the first-order mode of the taper, and  $\theta$  is defined as the taper angle. If  $\theta > \theta_m$ , the ray doesn't reach the boundary of the taper, leading to the phase become distorted and the mode being converted to a higher order mode.

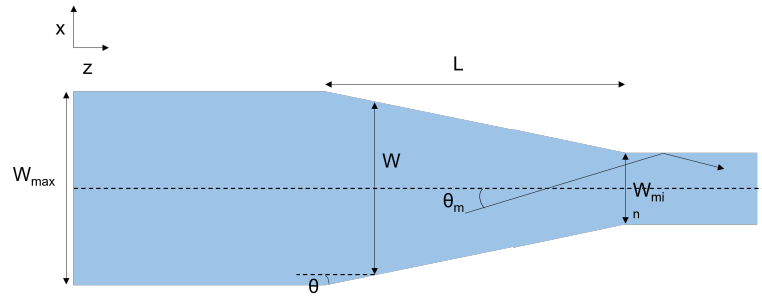


Figure 3.2: Top-view schematic of the linear taper design proposed in [63, 64].  $W_{max}$  is the maximum waveguide width of the taper,  $W_{min}$  the width of the single-mode waveguide,  $L$  is the length of the taper,  $\theta$  is the local half angle of the taper at point  $z$ , and  $\theta_m$  is the projection of the ray angle of the first-order mode of the taper.

### 3.2.2 Eigenmode Expansion (EME) solver

The EME solver is used to simulate tapered waveguides, with an example set-up in Lumerical MODE solutions shown in Figure 3.3. The geometry of the structure is divided up into multiple cells. Only a single cell is required for the

uniform cross-section of the input waveguide. For the multiple cells in the tapered region, the continuously varying cross-sectional (CVCS) method is used, which avoids a staircasing effect and thus improves the calculation accuracies at each cell. At the interface between adjacent cells, the modes are solved for using the FDE solver in the transverse direction (x-y). By matching the tangential E and H fields of the cell boundaries, then a scattering matrix  $S$  for each section is found. These matrices contain the transmission and reflection coefficients between the incident modes from one cell and the modes of the neighbouring cell.

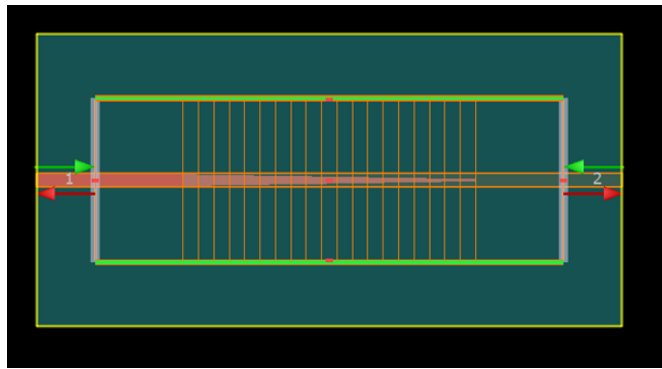


Figure 3.3: A top-down view of the EME solver set-up for the spot size converter example in Lumerical MODE solutions. The structure is spliced into the different sections by the cell, and Port 1 and 2 are defined at the first and last interface.

Once the  $S$ -matrices for the individual sections are obtained, we want to calculate the  $S$  matrix of the entire device by bidirectional propagation in each section: at the first and last cell interfaces, two ports are set up (denoted as 1 and 2 in Figure 3.3). The modes of the ports are selected, and it is only the  $S$  matrices of these source modes that are calculated for the entire device. From this, we can reconstruct the E and H field profile due to the source modes at any point along the propagation direction. We can then perform a taper length sweep without having to find the modes at each cell again. This is one advantage of using EME over the finite difference time domain (FDTD) solver, as for the latter the mode calculations would have to be performed again for any change in geometry. To deduce what taper length is needed to have efficient adiabatic propagation, we then plot the  $|S_{21}|^2$  against the varying taper length.

### 3.2.3 Mode adapter design

A double-etched taper structure is proposed for converting the broad spot size to a mode that can propagate around a bend with compact dimensions. The

requirements for this is that for the waveguide dimensions selected, there can only be one mode that is supported by the waveguide ridge as the waveguide transitions to a bend. The proposed design can be seen in Figure 3.4 (a) and (c), with a top down view provided in (b), and the varying cross sections of the device in (c), (d) and (e). For the edge-coupling, the shallow AlGaIn ridge remains with the same dimensions as outlined in Chapter 2 (shallow etch depth =  $0.3 \mu\text{m}$  into the AlGaIn, ridge width =  $4 \mu\text{m}$ ), but now with an additional deep etch of  $1.3 \mu\text{m}$  into the AlGaIn/GaN with width  $10 \mu\text{m}$ , as shown in Figure 3.4.

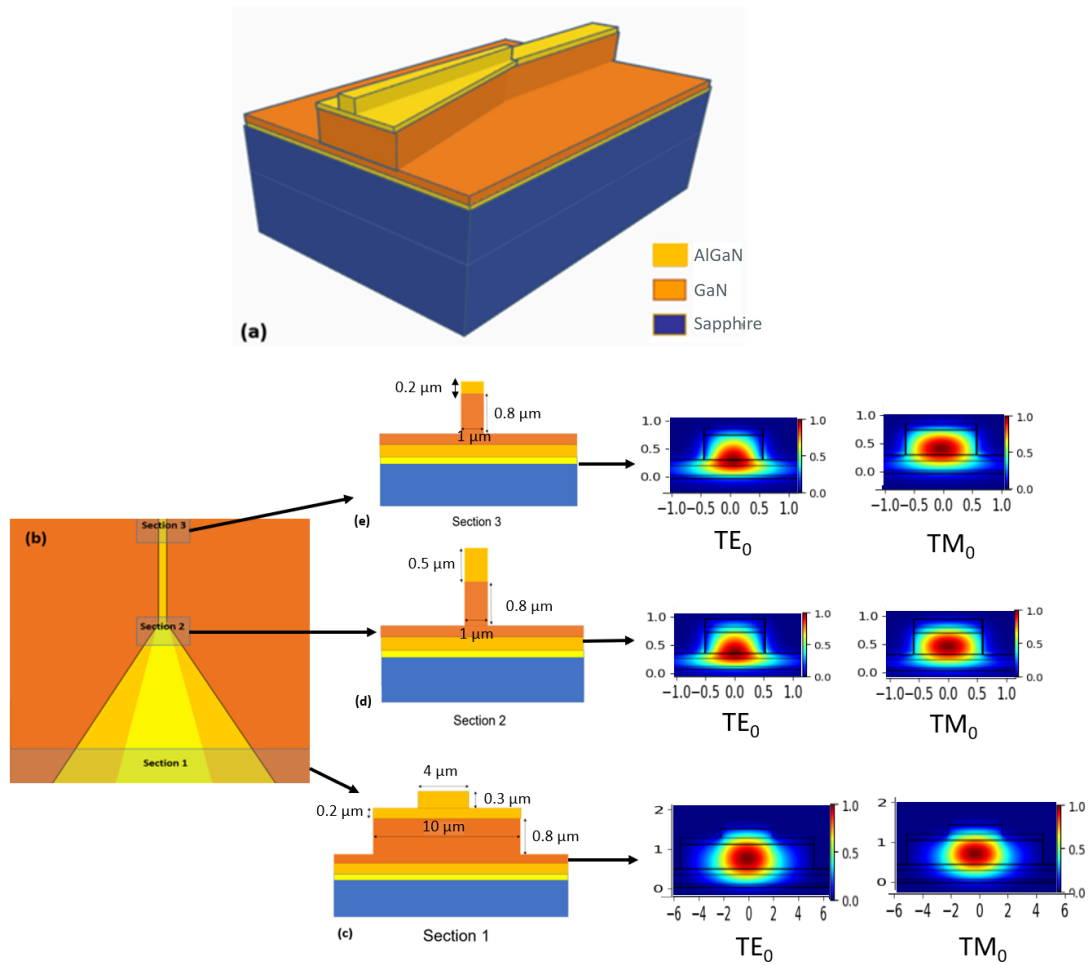


Figure 3.4: (a) Side view and (b) top-down view of the proposed double-etched taper design, with the changing cross section divided up into three sections: (c) the cross section at the input (Section 1), (d) the cross section at the end of the tapered section (Section 2), and (e) the cross section of the output waveguide (Section 3). Note that the shallow AlGaIn ridge terminates at Section 2.

Both the shallow AlGaIn ridge and the deep etched AlGaIn/GaN are then tapered down to the dimensions provided in Figure 3.4 (e). These dimensions

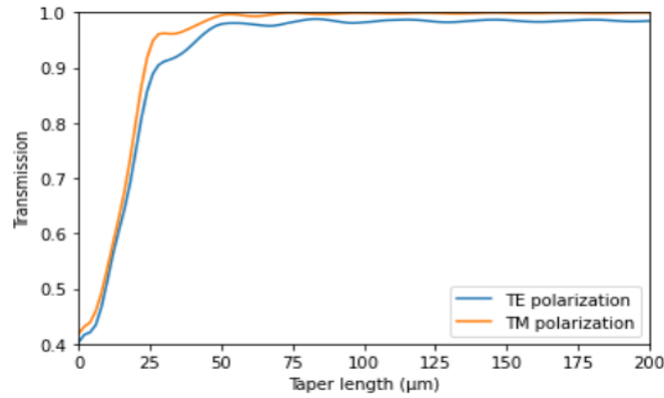


Figure 3.5: The transmission, or adiabatic propagation of both the  $TE_0$  and  $TM_0$  modes through the double taper structure design shown above

were chosen due to waveguide bend losses, which will be explained in further detail in the next section. For the taper length optimization, both the AlGaIn ridge taper and the deep etched AlGaIn/GaN taper were set to be the same length. This is because it is the deep-etched region that mainly guides the modes, and hence the tapering of this section impacts the mode rather than the shallow etch. Therefore it is the taper length of the deep-etched region that has the most impact on the adiabatic propagation, provided that the AlGaIn ridge region width matches that of the deep etch width by the taper's end. The AlGaIn ridge then terminates by Section 3 as shown in Figure 3.4 (e).

The taper length was then varied up to 200  $\mu\text{m}$ , with the transmission plotted against it in Figure 3.5 for both polarizations. Due to the low index contrast of the AlGaIn/GaN waveguide compared to state-of-the-art tapered structures on SOI platforms, it was expected that it would be more difficult to reach efficient adiabatic propagation with compact devices, although this simulation suggests that this is not the case as we can see that for taper lengths  $\geq 50 \mu\text{m}$ , transmission  $> 98 \%$  is achieved for both polarizations

A feature that can be noticed from the result in Figure 3.5 is that the taper length increase does not always give an increasing transmission and is thus oscillatory in some regions. This is possibly due to mode coupling as the waveguide tapers down [65]. The number of cells was increased in the simulation to ensure that the calculation was as accurate as possible, but the oscillations still appeared, which gives further credence that the oscillations are real. As the range of transmission values that the adiabatic taper oscillates between in the region  $\geq 50 \mu\text{m}$  is small, the mode coupling is considered negligible.

### 3.2.4 Calculating waveguide bend losses

Apart from propagation losses, there are two main sources of losses in a waveguide bend: (i) the radiation loss in the bent portion, and (ii) the insertion loss between the straight waveguide and bent waveguide. The radiation loss is when a fraction of the light is lost due to coupling with the slab modes as light propagates around a bend of uniform radius  $R$ . We can calculate this loss by using PML boundary conditions for the FDE solver in Lumerical MODE: as mentioned in Chapter 2, by setting these boundary conditions the solver acts as an artificial absorbing layer and can thus record the leakiness of the guided mode for a given  $R$ .

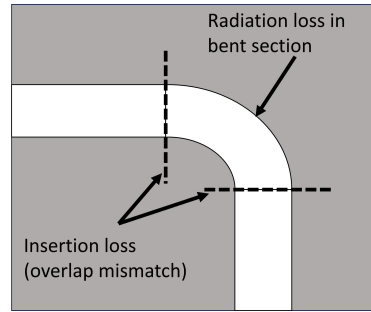


Figure 3.6: Schematic of a 90° bend highlighting the main sources of loss in the structure

The insertion loss is due to the mismatch between the mode of the straight waveguide portion, and the mode of the bent waveguide portion. This value can be obtained in the same manner as for the coupling efficiencies in Chapter 2: by using the power coupling function, we can determine how much the mismatch impacts the overall waveguide loss. We can thus calculate the total waveguide bend loss as follows:

$$\text{Total waveguide bend loss (dB)} = -20\log_{10}\left(\frac{P_m}{P_{in}}\right) + \left((R * \frac{\pi}{2}) * (\text{Radiation Loss})\right) \quad (3.2)$$

where  $P_m$  = power of the  $m$ th mode (the bent waveguide mode), and  $P_{in}$  = power of the input mode (the straight waveguide mode). The first term of the equation represents the insertion loss, while the second term of the equation is the radiation loss for a 90° waveguide bend. Note that the first term for the insertion loss is a variation of Eq 2.53: as there are two transitions between the straight and bent waveguides as seen in Figure 3.6, Eq 2.53 is thus multiplied by 2.



### 3.2.5 AlGaIn/GaN waveguide bend design

In Fig. 3.7 (c), it can be seen that bend losses  $< 0.02$  dB can be achieved for the TM polarization at a bend radius  $> 70$   $\mu\text{m}$ , while for the TE polarization bend losses  $< 0.04$  dB is obtained at a bend radius  $> 100$   $\mu\text{m}$ . At a bending radius of 200  $\mu\text{m}$ , the bending losses are  $< 0.01$  dB for both polarizations. In Fig 3.8, both contributions to the overall bend losses are separated out for the polarizations. It can be seen that the radiative losses for the TM polarization are negligible, with the transition loss contributing mainly to the overall losses. For the TE polarization, the radiative losses are significant up to a bend radius of 100  $\mu\text{m}$ , and after that they reach the order of  $10^{-3}$  dB/cm. The TE mode interacts more with the sidewalls than the TM mode, leading to the higher radiative losses. Even with tapering down the AlGaIn/GaN structure, the bend radii dimensions suitable for such a structure is still on the large scale when compared to achievable bend radii dimensions for the silicon platform due to the lower index contrast of AlGaIn/GaN and larger mode size. This compromises the potential for compact, high density integration on the AlGaIn/GaN platform. The  $\text{TE}_0$  and  $\text{TM}_0$  mode profiles of the deeply etched GaN waveguide structure are shown in Fig 3.7 (a) and (b). The etch depth into the GaN was selected to minimize the radiation losses as the mode propagates around the bend. It can be seen that before the bend commences, the  $\text{TE}_0$  mode is less confined than the  $\text{TM}_0$  mode. Increasing the ridge width improves the confinement, but higher order modes are supported as a result.

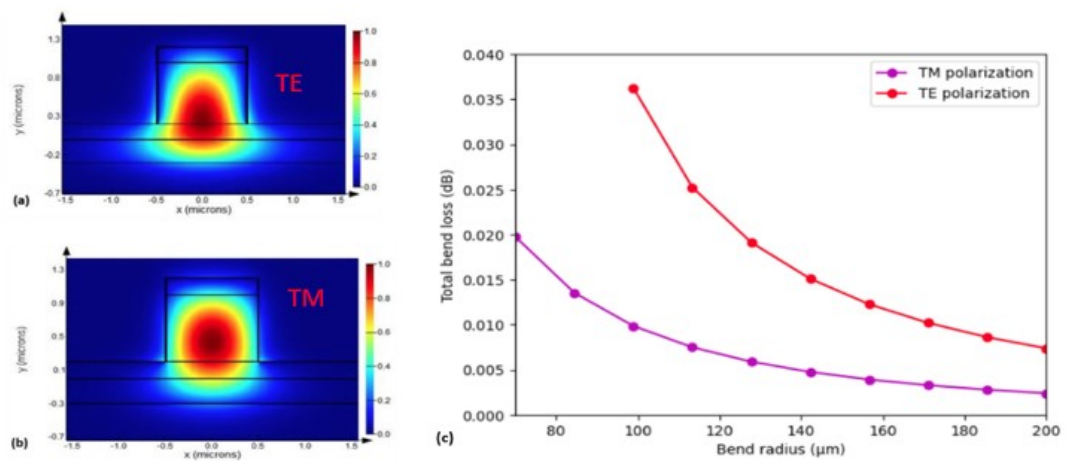


Figure 3.7: The (a)  $E_x$  component for the  $\text{TE}_0$  mode, the (b)  $E_y$  component for the  $\text{TM}_0$  mode, and the (c) total bend losses for both polarizations for a  $90^\circ$  bend with a  $0.8$   $\mu\text{m}$  etch height and  $1$   $\mu\text{m}$ -wide ridge

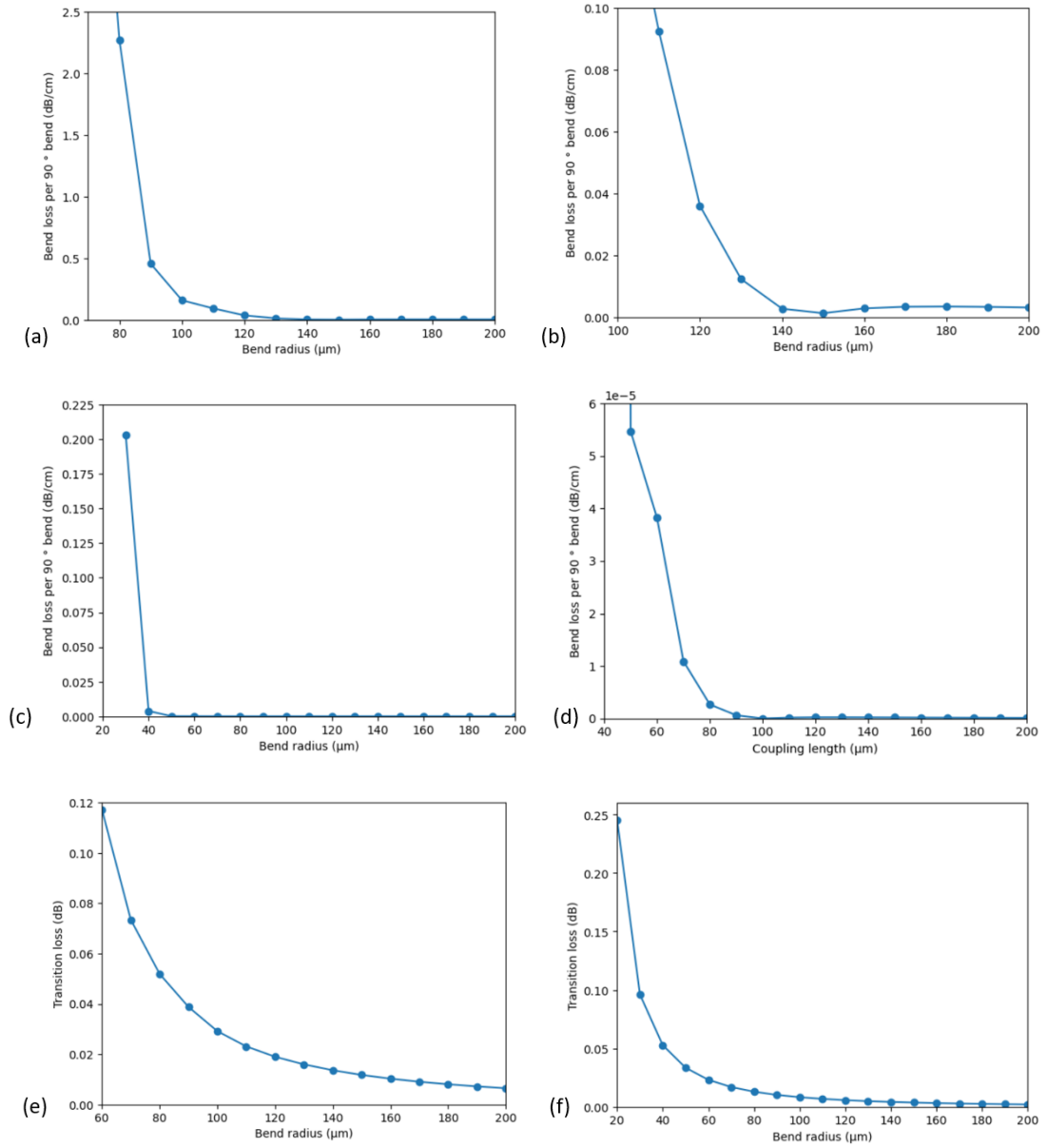


Figure 3.8: Bend loss for a 90° bend as a function of bend radius for (a) TE polarization, (b) zooming in on the TE polarization graph, (c) for TM polarization, and (d) zooming in on the TM polarization graph; and the transition loss for (e) TE polarization and (f) the TM polarization

### 3.3 Directional couplers

The directional coupler is an integral part of PICs as it is used for power splitting and as a combining component in devices such as ring resonators, Mach-Zehnder interferometers and other filtering systems. It evanescently couples light over from one waveguide to another: the fraction of the light that is coupled over depends upon the gap between the waveguides, which in turn determines the length of the waveguides required. This length is known as the coupling length  $L_c$  and will be denoted as such for the rest of the section. The  $L_c$  required depends upon the index difference between the two coupled modes: when the two waveguides are placed close enough to each other, the mode in the first waveguide is perturbed by the second waveguide and vice versa. Thus, rather than having two modes with the same effective indices (one localized in waveguide 1 and the other in waveguide 2), the modes split to form a symmetric mode in waveguide 1 with an effective index  $n_1$  (slightly larger than the effective index of the unperturbed waveguide mode), and an antisymmetric mode with effective index  $n_2$  (slightly smaller than the effective index of the unperturbed mode). The index difference between the symmetric mode and antisymmetric mode is given as

$$\Delta n = n_1 - n_2 \quad (3.3)$$

If we consider  $P_1$  to initially have 100 % of the power, then  $P_2$  can be written as

$$P_2(L_c) = P_1(0) \sin^2\left(\frac{\pi L_c \Delta n}{\lambda_0}\right) \quad (3.4)$$

#### 3.3.1 AlGaIn/GaN Directional Couplers

In order to design a directional coupler on the AlGaIn/GaN platform, the range of  $L_c$  values for both polarizations need to be determined for different waveguide gaps. This was done using the EME solver in Lumerical MODE, with the waveguide gaps set to (i) 0.5  $\mu\text{m}$ , and (ii) 1  $\mu\text{m}$ . Both the etch depth and waveguide width was set to be 1  $\mu\text{m}$ . These are the same dimensions that are presented in Figure 3.7 (a) and (b) in Section 3.2.5. Figure 3.9 shows both the cross section and the top-down view of the directional coupler design that was simulated in this section. The results for the coupling for different gaps are presented in Figure 3.10: at a gap of 0.5  $\mu\text{m}$ ,  $L_c = 250 \mu\text{m}$  for 100 % coupling for TE polarized light, and doubles for TM-polarized light. A 1  $\mu\text{m}$  gap

between the directional couplers leads to a drastic increase  $L_c$  for maximum coupling:  $1500 \mu\text{m}$  for TE-polarized light, and  $9000 \mu\text{m}$  for TM-polarized light. The polarization-dependent coupling lengths for larger gaps is due to the optical confinement of the modes at the given waveguide geometries: it is already shown in the previous section that the  $\text{TM}_0$  mode is more optically confined to the waveguide ridge, making it more difficult to evanescently couple over. Decreasing the etch depth at these given gaps and also widening the waveguide widths helps to lessen the polarization dependence of the  $L_c$ . However, the latter will increase the overall  $L_c$  for both polarizations. A longer  $L_c$  increases the overall losses of the circuit, so it can be more advantageous to go for a smaller waveguide gap depending on the coupling strength that is desired. In a device such as a ring resonator, a small fraction of light may only be needed to keep it in the critical coupling regime: for example, if  $< 10 \%$  of light is needed to couple over into the ring from the bus waveguide, then from the results shown in this section we can see that the gap requirement can be possibly extended to  $1 \mu\text{m}$  depending on the fraction of light required while also keeping the  $L_c$  and the device footprint more compact.

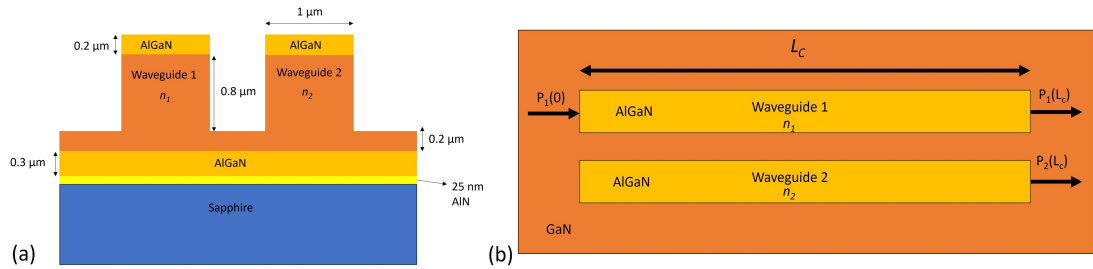


Figure 3.9: (a) Cross section and (b) top-down view of the directional coupler simulated in this work. The dimensions presented in (a) are the same as that of the structure presented in Figure 3.7 for the waveguide bends. Note that the gap is not denoted in this schematic as this was the variable during simulations. The light enters waveguide 1 (with the light power denoted as  $P_1(0)$ ) and, depending upon the gap and the coupling length  $L_c$ , a fraction of it couples over to waveguide 2 ( $P_2(L_c)$ ) while the rest of the light exits waveguide 1 ( $P_1(L_c)$ ).

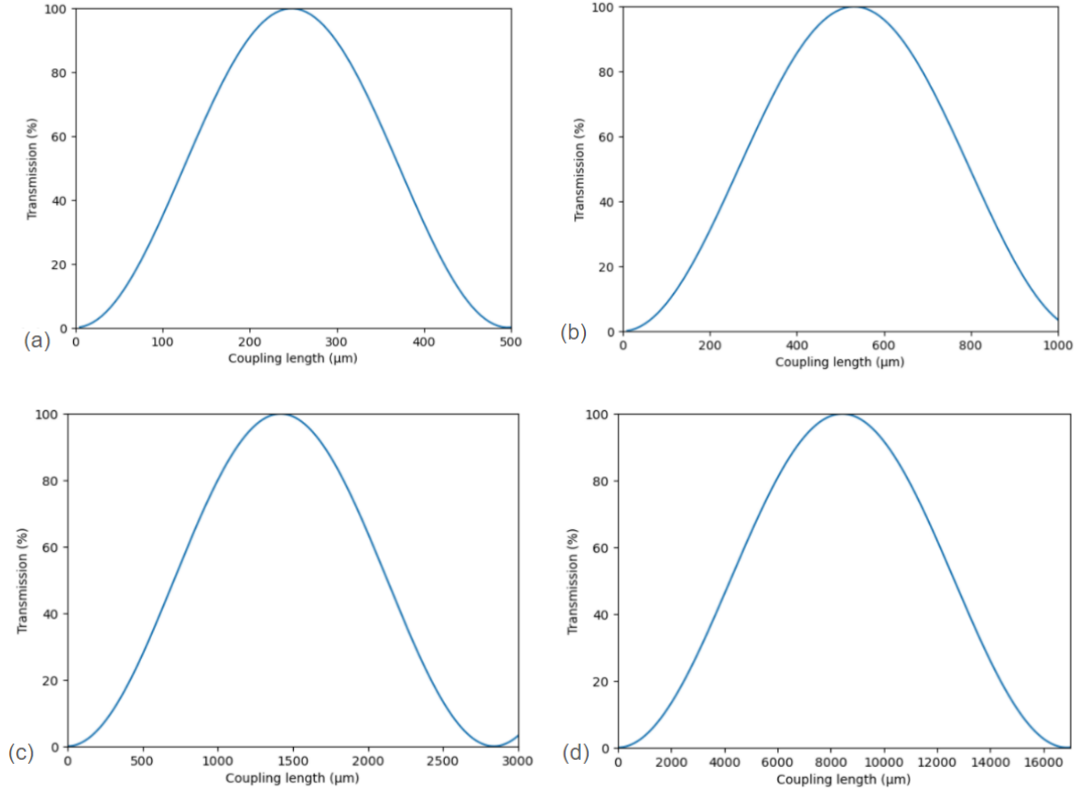


Figure 3.10: Coupling between the waveguides as a function of directional coupler length (a) at a gap of 0.5  $\mu\text{m}$  for TE polarization, (b) for TM polarization, and (c) at a gap of 1  $\mu\text{m}$  for TE polarization and for (d) TM polarization. The increase in  $L_c$  for increasing waveguide gap is more significant for the TM-polarized light due to the mode being more optically confined with the waveguide geometry used in the simulations.

### 3.4 LiNbO<sub>3</sub> on GaN

While GaN can in theory be used for electro-optic applications, it possesses a small electro-optic coefficient ( $r_{33} = 1 \text{ pm/V}$ ) in comparison to LiNbO<sub>3</sub>, the leading material for such applications ( $r_{33} = 30 \text{ pm/V}$ ). LiNbO<sub>3</sub> has already been integrated with SiN through bonding in order to enhance the electro-optic effect [66], as it has a refractive index higher than SiN ( $n_{e\text{LiNbO}_3} = 2.14$ ,  $n_{o\text{LiNbO}_3} = 2.21$ ,  $n_{\text{SiN}} = 1.98$  at 1.31  $\mu\text{m}$ ), leading to the mode being mostly confined in LiNbO<sub>3</sub>. This section thus proposes integrating LiNbO<sub>3</sub> with GaN via  $\mu\text{TP}$ . For simulations, the dimensions of  $\mu\text{TP}$  coupons were set to be the same as available coupons. The coupon is x-cut and 300 nm thick: due to this orientation cut, the TE<sub>0</sub> mode interaction between the LiNbO<sub>3</sub> coupon and GaN waveguide is key for accessing the largest electro-optic coefficient of LiNbO<sub>3</sub>. To determine the TE<sub>0</sub> mode confinement in the LiNbO<sub>3</sub> coupon, the GaN waveguide width and height are varied. The

epitaxial structure that is first designed in this chapter is too thick to confine the mode in the LiNbO<sub>3</sub>; thus for the simulations in this section the epitaxial structure is converted to fully etched GaN-on-sapphire, with both the width and height of the GaN varied. As it is the  $r_{33}$  coefficient we want to access, then it is the extraordinary refractive index  $n_e$  that matters: the change in this for an applied electric field  $E_{ext}$  is given as

$$\Delta n_e = -\frac{n_e^3}{2} r_{33} E_{ext} \Gamma \quad (3.5)$$

where  $E_{ext} = \frac{V}{d}$  (applied voltage/electrode gap), and  $\Gamma$  = the mode confinement in the LiNbO<sub>3</sub> region. This change in the index as a result of the external electric field changes the optical path length and thus modulates the phase of the incoming light,  $\Gamma$  can be optimised through the GaN waveguide geometry: Figure 3.11 shows the  $\Gamma$  for varying GaN waveguide widths with a height of 0.3  $\mu\text{m}$ . At a waveguide width of 0.2  $\mu\text{m}$ ,  $\Gamma = 72\%$ . The modal overlap for this waveguide width can be observed in Figure 3.11 (b). The  $E_{ext}$  can also be varied to maximise  $\Delta n_e$  through changing the applied voltage and the separation between the electrodes. A buried ridge structure is used to support the suspension of both the LiNbO<sub>3</sub> coupon and the electrodes on the GaN waveguide. The optimum distance between the GaN waveguide and the buried GaN ridges would have to be verified experimentally from  $\mu\text{TP}$  tests; therefore there is no number given for what the gap should be. The electrodes are located on the LiNbO<sub>3</sub> coupon. Figure 3.11 (d) plots  $\Delta n_e$  for varying applied voltage for different electrode gaps (GaN height = 0.3  $\mu\text{m}$ , width = 0.2  $\mu\text{m}$ ); it can be seen that a smaller electrode gap increases  $\Delta n_e$ . A Mach-Zehnder modulator (MZM) is a common configuration for electro-optic modulation using integrated LiNbO<sub>3</sub> [67–69] as it offers low power consumption and can work at high speeds. The MZM splits light into two paths; the paths are then biased in opposing directions that produce phase shifts in each arm, before recombining the light into a single output. The phase shift from applying a voltage between the electrodes is given as:

$$\Delta\phi = \Delta\beta L = \frac{2\pi\Delta n_e L}{\lambda} \quad (3.6)$$

where  $L$  = length of the modulator. A common figure of merit for an electro-optic modulator is the half-wave voltage,  $V_\pi$ , the voltage that needs to be applied in order to induce a  $\pi$  phase shift. Thus we can rearrange Eq 3.6

and substitute in Eq. 3.5 to get an equation for the modulation efficiency  $V_\pi L$ :

$$V_\pi L = \frac{d\lambda}{2r_{33}n_e^3\Gamma} \quad (3.7)$$

Figure 3.11 (e) plots the modulator length vs  $V_\pi$  for  $\Gamma = 72\%$  at different electrode gaps. For a  $5\ \mu\text{m}$  electrode gap,  $V_\pi L = 1.36\ \text{Vcm}$ . The optical mode can leak into the electrodes if the gap is too small: the absorption losses were calculated using Lumerical MODE, with the gap varied between 300 nm-thick, 9.5  $\mu\text{m}$ -wide Au contacts. From Figure 3.11 (f) it can be seen that for an electrode gap of  $5\ \mu\text{m}$ , the absorption loss is 37.2 dB/cm. Increasing the electrode gap to  $9\ \mu\text{m}$  reduces the loss to a more acceptable value,  $< 1\ \text{dB}$ , but this reduces the overall  $\Delta\phi$  and increases the  $V_\pi L$  thereby reducing the modulation efficiency. Thus, finding the balance between the optimal  $\Gamma$  and electrode separation is challenging when designing an electro-optic modulator.

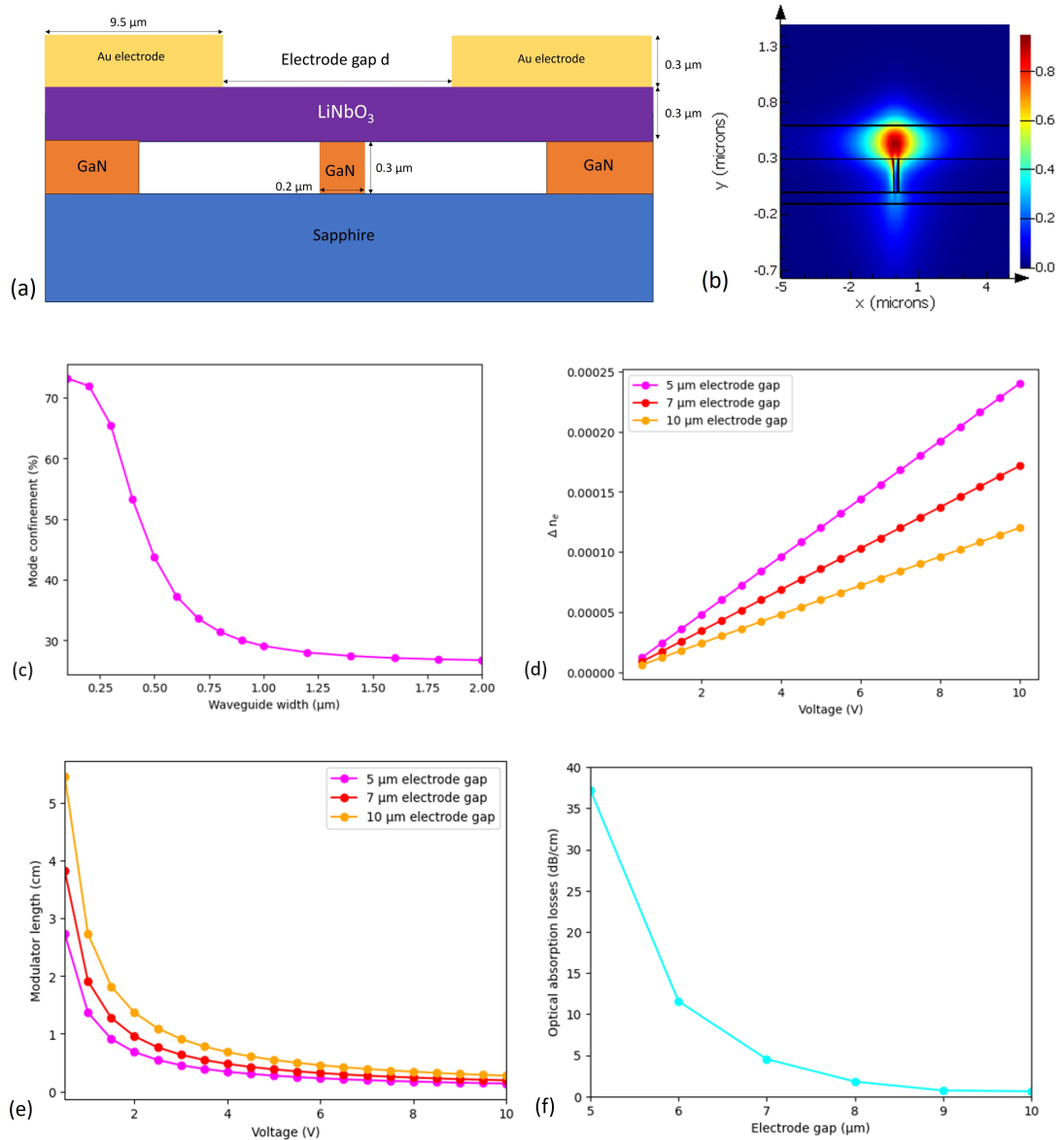


Figure 3.11: (a) Schematic of the LiNbO<sub>3</sub> integrated onto the GaN platform; (b)  $E_x$  component of the TE<sub>0</sub> mode for GaN ridge width = 0.2 μm; (c) the modal confinement in the LiNbO<sub>3</sub> as a function of waveguide ridge width, which corresponds to 72 % at a waveguide ridge width of 0.2 μm; (d) the change in the extraordinary refractive index  $\Delta n_e$  for different electrode gaps and varying applied voltage; (e) the length of the modulator for different  $V_\pi$  at different electrode gaps with  $\Gamma = 72\%$ ; and (f) the optical absorption losses for varying electrode gap when  $\Gamma = 72\%$ .

Etching a shallow ridge into the LiNbO<sub>3</sub> coupon can help confine the mode and reduce the absorption without compromising the key parameters: Figure 3.12 (b) shows the mode confined in the LiNbO<sub>3</sub> with a 2 μm-wide ridge and an etch depth of 0.1 μm. The dimensions of the GaN waveguide remain as width = 0.2 μm, height 0.3 μm. From the mode confinement of the structure



presented in Figure 3.12 (c), it can be seen that the  $\Gamma$  values are comparable to that of the unetched LiNbO<sub>3</sub> coupon. For a GaN waveguide width = 0.2  $\mu\text{m}$ ,  $\Gamma = 70\%$ . The optical absorption loss for this structure with a 5  $\mu\text{m}$  electrode gap was calculated to be 0.048 dB/cm. Therefore it is more advantageous for optimising the design to have a confining ridge introduced into the LiNbO<sub>3</sub>.

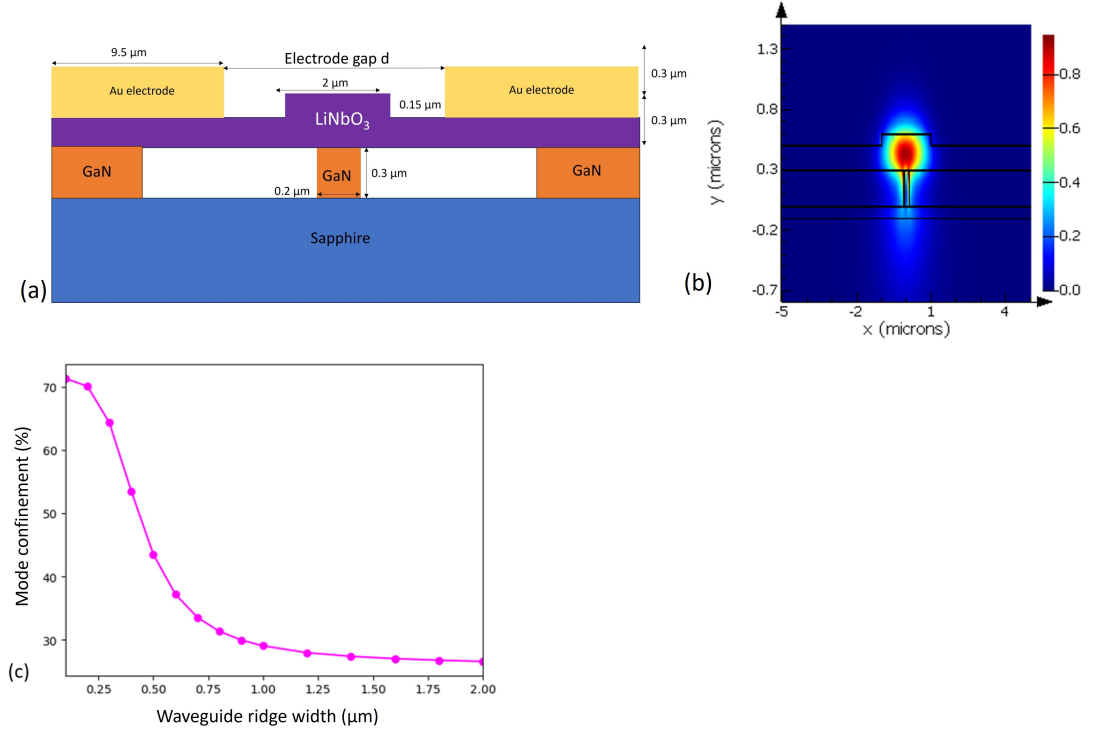


Figure 3.12: (a) Schematic of the etched ridge in the LiNbO<sub>3</sub> integrated onto the GaN waveguide; (b)  $E_x$  component of the TE<sub>0</sub> mode for GaN ridge width = 0.2  $\mu\text{m}$  with an etch depth of 0.1  $\mu\text{m}$  into the LiNbO<sub>3</sub>; (c) the modal confinement in the LiNbO<sub>3</sub> as a function of waveguide ridge width, which corresponds to 70 % at a waveguide ridge width of 0.2  $\mu\text{m}$ . At an electrode gap of 5  $\mu\text{m}$ , the absorption loss is 0.048 dB/cm

The schematic of the proposed MZM on the GaN platform can be seen in Figure 3.13. In order to realize the MZM configuration, a multimode interference (MMI) coupler is used to split the light. The advantages of using an MMI coupler is that it is more fabrication-tolerant than y-branches, can be designed to be compact and can also offer large bandwidth. The MMI coupler was simulated using the EME solver in Lumerical MODE. The taper lengths and the input/output widths of the taper (denoted as  $W_1$  and  $W_2$  in Figure 3.14 (a)) were fixed to be 20  $\mu\text{m}$ , 1.3  $\mu\text{m}$  and 0.8  $\mu\text{m}$  respectively. The MMI length, the separation between the output ports and the MMI core width were found by performing parameter sweeps. It was found that for  $L_{MMI} = 28\ \mu\text{m}$ ,  $W_{MMI} = 6\ \mu\text{m}$  and separation = 1.8  $\mu\text{m}$ , the MMI split light 50:50 with

transmission  $\approx 48.2\%$  from each output. The output arms of the MMI then turn into S-bends with width  $0.8\ \mu\text{m}$ ; the total bend loss is calculated for varying bend radius for the  $0.3\ \mu\text{m}$  thick,  $0.8\ \mu\text{m}$  wide GaN waveguide. It can be seen in Figure 3.14 (d) that losses  $\leq 0.01\ \text{dB}$  are achieved for bend radii  $\geq 60\ \mu\text{m}$ . After the S-bend, a tapered GaN waveguide structure with LiNbO<sub>3</sub> on top is introduced in order to couple the mode into the LiNbO<sub>3</sub>. The structure was simulated in the EME solver, using both (i) unetched LiNbO<sub>3</sub> and (i) etched LiNbO<sub>3</sub> with a  $2\ \mu\text{m}$  ridge. Figure 3.15 shows the taper transmission for (a) the unetched LiNbO<sub>3</sub> coupon on GaN, and (b) the LiNbO<sub>3</sub> coupon with etch depth =  $0.1\ \mu\text{m}$ . It can be seen that for the unetched LiNbO<sub>3</sub> the taper length has to be  $> 200\ \mu\text{m}$  for taper transmission  $\geq 99\%$  to be achieved, while for the etched LiNbO<sub>3</sub> the same transmission is achieved for taper lengths  $\geq 20\ \mu\text{m}$ . Table 3.1 lists all the dimensions required in order to design an MZM using the LiNbO<sub>3</sub> integrated with GaN.

| MZM Design                             |                    |
|----------------------------------------|--------------------|
| Properties                             | Dimensions         |
| GaN thickness                          | $0.3\ \mu\text{m}$ |
| LiNbO <sub>3</sub> thickness           | $0.3\ \mu\text{m}$ |
| LiNbO <sub>3</sub> ridge width         | $2\ \mu\text{m}$   |
| LiNbO <sub>3</sub> ridge height        | $0.1\ \mu\text{m}$ |
| LiNbO <sub>3</sub> length              | $1.4\ \text{cm}$   |
| Electrode spacing                      | $5\ \mu\text{m}$   |
| MMI taper output width                 | $1.3\ \mu\text{m}$ |
| MMI taper output width                 | $0.8\ \mu\text{m}$ |
| MMI taper length                       | $20\ \mu\text{m}$  |
| MMI width                              | $6\ \mu\text{m}$   |
| MMI length                             | $28\ \mu\text{m}$  |
| Bend radius                            | $50\ \mu\text{m}$  |
| LiNbO <sub>3</sub> on GaN taper length | $20\ \mu\text{m}$  |
| LiNbO <sub>3</sub> on GaN taper tip    | $0.2\ \mu\text{m}$ |

Table 3.1: The optimized dimensions for designing an MZM via integrated LiNbO<sub>3</sub> onto the GaN platform

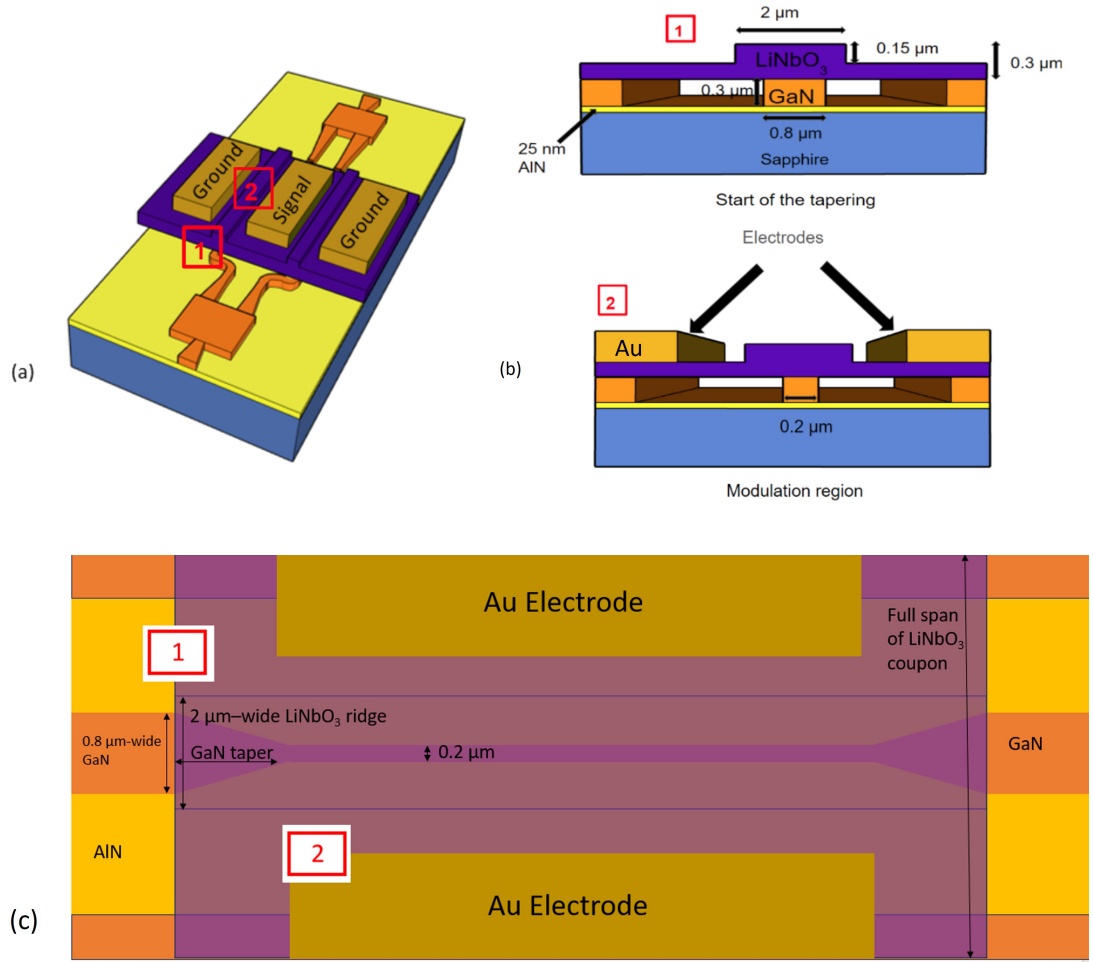


Figure 3.13: (a) The MZM layout: the MMI splits the input light 50:50 into the MZM arms where the etched LiNbO<sub>3</sub> is transfer printed to. The arms consist of two sections: a GaN waveguide that tapers down from 0.8 μm to 0.2 μm in order to achieve the optimal mode overlap in the LiNbO<sub>3</sub> region (denoted as [1]), and the part of the arm where the voltage is actually applied (denoted as [2]). A ground-signal-ground configuration is used for push-pull operation of the MZM. The cross sections of [1] and [2] are shown in (b). Both arms then taper back up to a 0.8 μm wide GaN waveguide and then coupled back into an MMI for a single output. A top-down view of the region where the LiNbO<sub>3</sub> is integrated to is shown in (c).

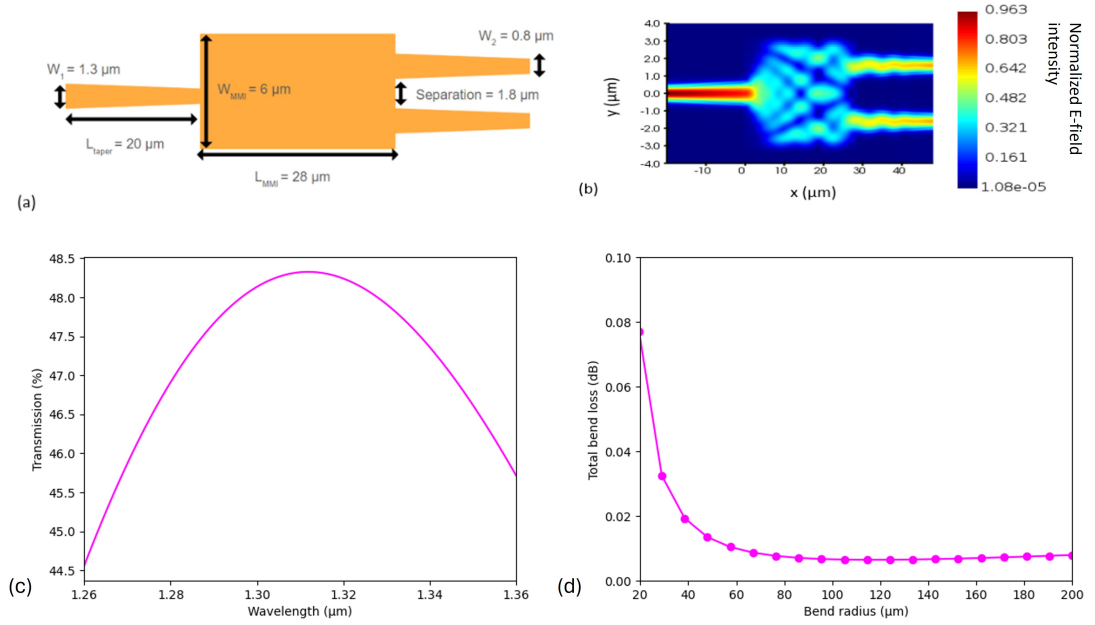


Figure 3.14: (a) Schematic of the MMI with the optimised dimensions; (b) Electric field profile of the MMI with the dimensions outlined in (a); and (c) the transmission from port 1 over the 1.26-1.36  $\mu\text{m}$  wavelength range. The MMI split the light 50:50, so port 2 also had the same results as (c). In (d), the total bend loss for the 0.8  $\mu\text{m}$  wide, 0.3  $\mu\text{m}$  thick GaN on sapphire waveguide is presented.

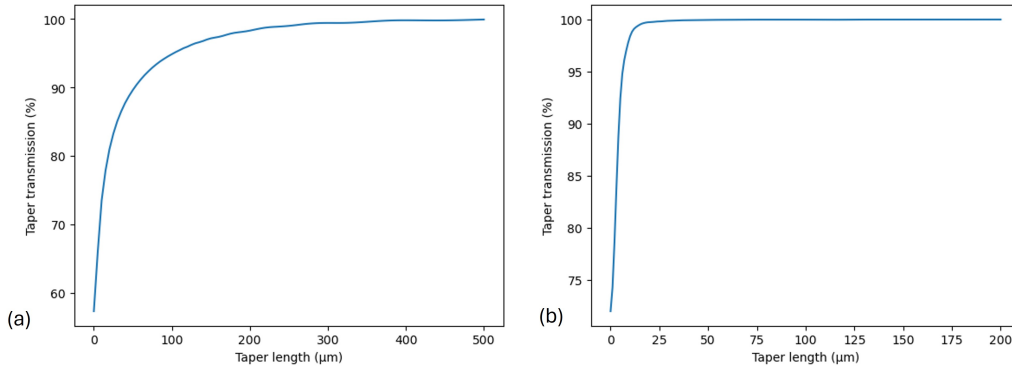


Figure 3.15: Transmission of the GaN-on-sapphire taper with (a) unetched LiNbO<sub>3</sub> transfer-printed on top, and (b) LiNbO<sub>3</sub> coupon with an etch depth of 0.2  $\mu\text{m}$

### 3.5 Grating couplers

For characterizing the waveguide components on a PIC, an optical fiber couples into the system either through (i) edge-coupling as outlined in Chapter 2, or through (ii) a grating coupler. Edge coupling can achieve high coupling efficiency, as well as a large bandwidth and low polarization-dependent losses, but relies on good quality facets. Forming suitable facets can be easily done by cleaving for III-V materials such as InP, but is very difficult to achieve for a GaN-on-sapphire platform due to the

hardness of sapphire. Dicing and polishing the facets to ensure high quality facets can drive up the fabrication costs. In addition, there is less flexibility with the footprint of the PIC as the facets must be placed at the edge of the chip, and the tolerance for fiber-chip alignment is also low.

Grating couplers in contrast can be placed anywhere on the chip allowing for wafer-scale testing of PICs. However, the coupling efficiency can be affected by the grating directionality (light coupling into substrate rather than out into the output fiber) and mode mismatch. The mode mismatch is due to the optical intensity profile output of a uniform grating: along the propagation direction of the grating, the intensity output from the grating decays exponentially, thus when the light is being coupled out of the grating to the fiber there is a reduction in the overall mode overlap between the grating and the Gaussian beam of the fiber [70, 71]. To improve the coupling efficiency of the grating, parameters such as the grating period and fill factor can be apodized [70]. Grating couplers are also sensitive to wavelength and polarization, in contrast to edge-coupling. This section explores designing a uniform grating coupler on the AlGaIn/GaN platform.

### 3.5.1 AlGaIn/GaN grating couplers

In a uniform grating coupler, trenches have a length  $L_e$  and an etch depth with periodicity  $\Lambda$ . The fill factor  $F$  is defined as the ratio of the unetched length  $L_0$  to the total length of the structure. Therefore the effective index  $n_{eff}$  of the grating coupler is given as

$$n_{eff} = F n_{unetch} + (1 - F) n_{etch} \quad (3.8)$$

where  $n_{unetch}$  = effective index of the unetched regions, and  $n_{etch}$  = effective index of the etched regions. As a result of the periodic refractive index change between the etched and unetched regions, the propagating mode is diffracted to free space. According to the Bragg condition, the grating periodicity  $\Lambda$  for a grating coupler with air as the surrounding medium is given as

$$\Lambda = \frac{\lambda_c}{n_{eff} - \sin \theta_{air}} \quad (3.9)$$

where  $\lambda_c$  = coupling wavelength, and  $\theta_{air}$  = incident angle. For simulations in this section,  $\theta_{air}$  is fixed at  $10^\circ$  with respect to the grating coupler.  $\theta_{air}$  angles

between  $8\text{-}13^\circ$  have been used to get efficient coupling in the literature [72, 73]. To minimize the number of variables in the simulation, the angle was kept fixed. A Gaussian source with a beam waist  $\approx 4\text{ }\mu\text{m}$  is used as the injection light. The AlGaIn/GaN epitaxial thickness proposed for edge coupling to the  $\mu\text{TP}$  laser is used. The  $n_{\text{unetch}}$  and  $n_{\text{etch}}$  is first calculated in Lumerical Mode, with the latter calculated for an etched depth of  $0.5\text{ }\mu\text{m}$ . Using these values along with an initial duty cycle of 0.5 gave  $n_{\text{effTM}} = 2.27$ ,  $n_{\text{effTE}} = 2.24$  via Eq 3.8. An initial  $\Lambda$  is then obtained for the grating structure via Eq 3.9. The simulation of the light source coupling into the grating coupler structures in this section is carried out using Lumerical FDTD. After the initial transmission into the output waveguide is obtained, the structure is then optimized for the parameters  $\Lambda$ ,  $F$  and etch depth. The general schematic of

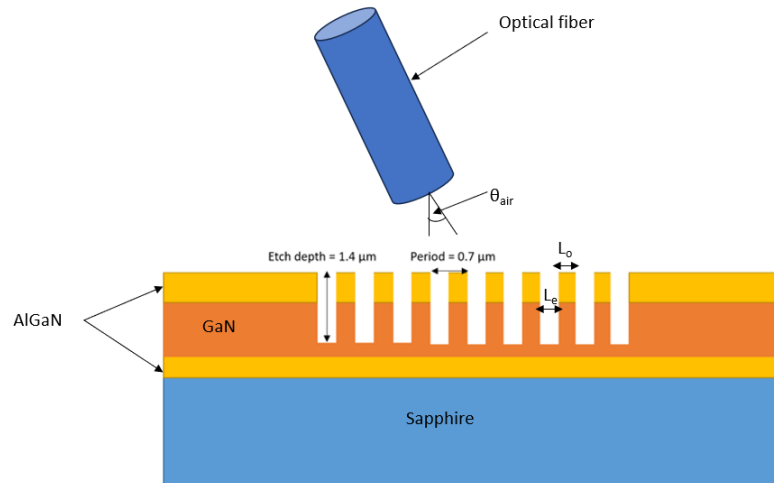


Figure 3.16: Schematic of the optimized grating coupler structure designed with the AlGaIn/GaN epitaxial structure

the grating coupler is presented in Figure 3.16, while the coupling efficiency for the TE- and TM-polarized light is presented in Figure 3.17. With a fixed duty cycle of 0.5, the coupling efficiency was found to be optimal for an etch depth of  $1.4\text{ }\mu\text{m}$  and  $\Lambda = 0.7\text{ }\mu\text{m}$ . With these parameters, coupling efficiencies  $> 40\%$  are achieved for both polarizations. Taking a closer look at the coupling efficiency, it was realised that it was a combination of the first three mode orders that contributed to the overall transmission. The individual transmission of these modes are presented in Figure 3.17 (c) for the TM-polarized light. It can be seen that a maximum  $12\%$  light is coupled into the  $\text{TM}_0$  mode; this low amount is due to the low index contrast of the grating structure. Thus, suppressing higher order modes and improving the coupling

efficiency are the two main objectives when modifying the design on the GaN platform. To suppress the higher-order modes, the epistructure is redesigned

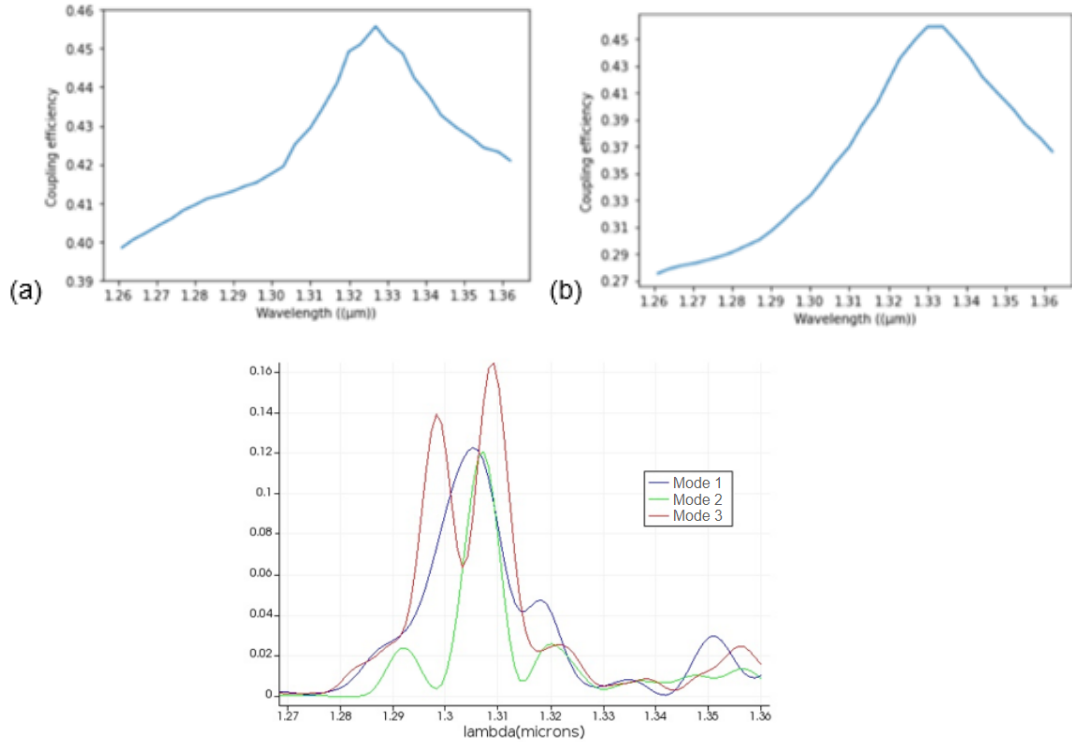


Figure 3.17: Coupling efficiency for (a) TE-polarized light and (b) TM-polarized light as a function of wavelength for the structure presented in Figure 3.16; (c) the individual transmission of the first three modes in the grating coupler shown above for TM-polarization. It was discovered that the sum of the transmission made up the overall coupling efficiencies achieved for the grating coupler for both polarizations

to be  $0.5 \mu\text{m}$  GaN. To improve the coupling, a  $0.2 \mu\text{m}$ -thick layer of amorphous Si ( $n = 3.5$ ) is also included as an upper layer, thereby increasing the index contrast of the structure. A schematic of this design is presented in Figure 3.18. The coupling efficiencies for both TE and TM polarization are found below in Figure 3.19. From trying to optimise the coupling efficiency it was found that the grating coupler was strongly polarization dependent; for example,  $\leq 1\%$  of light is coupled for TM-polarized light with the same parameters that couple  $30\%$  of light for the TE polarization. This was the same for the TE-polarization for the parameters that coupled in  $27\%$  of TM-polarized light. The etch depth and the period were the key parameters that differed: the period was  $0.6 \mu\text{m}$  for the TE-polarized light, and  $0.5 \mu\text{m}$  for the TM-polarized. The TE-polarized grating coupler required the GaN to be all the way etched down, while the TM-polarized grating required a shallow  $0.1 \mu\text{m}$  etch depth for optimum coupling. Both polarizations required a duty cycle of  $0.9$  for optimum coupling. Thus, from the different criteria needed to optimize

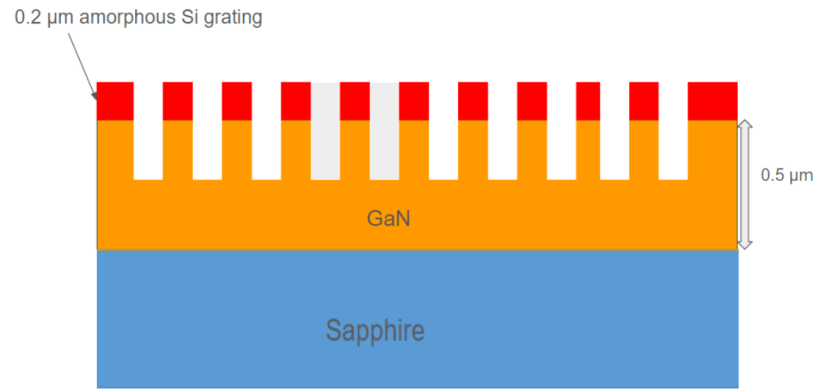


Figure 3.18: Schematic of the Si-GaN grating coupler

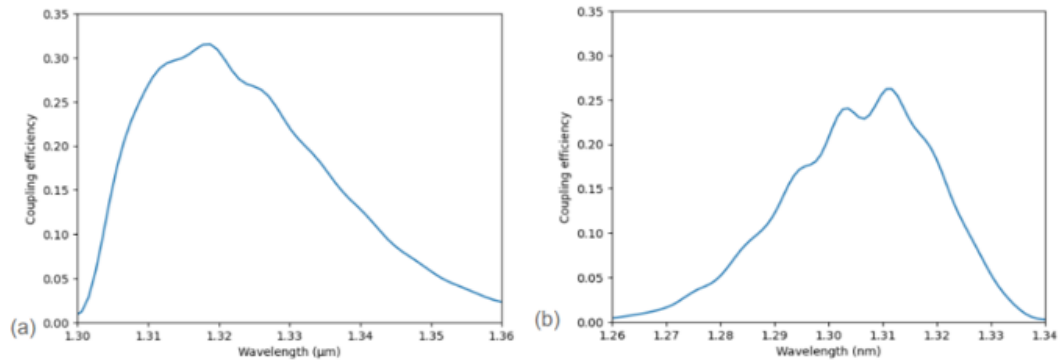


Figure 3.19: The coupling efficiency for the Si-GaN grating for (a) TE-polarized light and (b) TM-polarized light

the coupling for the different polarizations, it is difficult to design a grating coupler that is polarization-independent. In addition, while the coupling efficiency is improved, the coupling is still below that of SOI grating couplers [70] due to the refractive indices of GaN and sapphire. A bottom reflector could be employed in the design in order to improve the grating directionality: indeed, coupling losses of 0.55 dB were demonstrated experimentally on a  $\text{Si}_3\text{N}_4$ -on- $\text{SiO}_2$  platform with an Al back reflector [74], suggesting that low-index contrast structures can be comparable to the state-of-the-art. However, fabricating the structure to include the reflector is a complex process as it requires the removal of the substrate the GaN coupler is on. As will be discussed in more detail in Chapter 4, sapphire is a difficult material to remove due to its hardness. Therefore, a GaN grating coupler with a back reflector would have to be processed with a more suitable substrate such as Si.



## 3.6 Polarization converters

The propagation losses in a PIC can be higher for one light polarization over the other. In the case of GaN, similar waveguide structures have reported higher propagation losses for the TM-polarized light over the TE polarization [37]. A polarization converter can be used to switch the polarization from TM to TE without having to change the light source. Polarization converters are also desired in PICs for applications such as light intensity modulation or polarization bit interleaving. For all these applications, an efficient broadband polarization converter is the key component.

### 3.6.1 Mode Hybridization

So far, we have denoted the mode polarizations in the waveguide structures in this chapter to be either TE or TM. However, guided modes in channel waveguides are not purely TE/TM modes: instead, they have all six field components to be non-zero. We can distinguish between modes though by their dominant E and H components and denote them as quasi-TE (qTE) and quasi-TM (qTM) modes. Some waveguide structures however guide modes where the dominant and non-dominant field components are almost equal: these modes are classified instead as hybrid modes. These hybrid modes occur when two modes of different polarizations with similar effective indices couple to each other. Such modes are created due to either asymmetry in the waveguide geometry, or a dielectric perturbation with the upper and lower cladding layers having different refractive indices. The two hybrid modes couple with each other at anti-crossing points, i.e. the waveguide modes do not cross in the dispersion graphs. The modes couple with a coupling factor  $\kappa$  given by

$$\kappa = \frac{\beta_{s1} - \beta_{s2}}{2} = \frac{\Delta\beta}{2} \quad (3.10)$$

where  $\beta_{s1}, \beta_{s2}$  are the propagation constants of hybrid modes at the anti-crossing points. As GaN is birefringent, the qTE modes experience a refractive index  $n_o$ , while the qTM modes experience  $n_e$ . The birefringence results in the modes experiencing a difference in velocity. The hybridness is quantized by a parameter called the TE polarization fraction ( $\gamma_{TE}$ ), which indicates the fraction of power in the horizontal component of a mode, given as

$$\gamma_{TE} = \frac{\int |E_x|^2 dx dy}{\int (|E_x|^2 + |E_y|^2) dx dy} \quad (3.11)$$

When  $\gamma_{TE}$  is close to 1, then the mode is qTE, while a mode close to 0 represents a qTM mode. If  $\gamma_{TE} = 0.5$ , then the mode is strongly hybrid. In this section, a mode is considered hybrid if  $0.4 < \gamma_{TE} < 0.6$ . In order to excite hybrid modes in the structure, the minor field components of the mode needs to be enhanced. Previous methods of enhancing the minor field component on other platforms include introducing bends in the waveguide [75], using index asymmetry in the vertical direction [76], and using structural asymmetry in the waveguide design [77, 78]. Here we use structural asymmetry to design a polarization converter on the AlGaIn/GaN platform: to our knowledge, this is the first time that such a converter has been designed in GaN.

### 3.6.2 Converting between polarization states

Light of an either TE or TM polarized state is coupled into the waveguide. This light input is then projected onto the hybrid modes that the waveguide supports. As the hybrid modes have different propagation constants, a phase shift is created as they propagate along the length  $L$  of the device:

$$\Delta\phi = \Delta\beta L \quad (3.12)$$

Therefore, by carefully selecting the length of the polarization converter, different polarization states can be achieved. The phase shift causes the polarization of the modes to vary periodically along the propagation distance and hence creates a beating pattern between the modes. This beating pattern is equal to a phase shift of  $2\pi$ . Thus the length of the device in order to achieve this beating pattern is given as:

$$L_{2\pi} = \frac{2\pi}{\Delta\beta} \quad (3.13)$$

$L_{2\pi}$  means that light undergoes TE/TM - TM/TE - TE/TM conversion for this length. Following on from this, in order to get a TE/TM - TM/TE output, the phase shift is  $\pi$ : this converter length is known as the half-beat length  $L_\pi$ :

$$L_\pi = \frac{\pi}{\Delta\beta} \quad (3.14)$$

The polarization conversion efficiency  $P_c$  is defined to be

$$P_c = \frac{P_{TM/TE}}{P_{TE/TM} + P_{TM/TE}} \quad (3.15)$$

where  $P_{TE}$  and  $P_{TM}$  are the polarized output powers. Generally, the light couples from the input waveguide to the polarization converter in one polarization state, and then couples back out to the output waveguide in the other polarization. To reduce propagation losses, it is ideal to design the polarization converter to be as short as possible. We can thus see from Eq 3.14 that for a compact polarization converter  $\Delta\beta$  has to be maximised (i.e. the difference in effective indices between the hybrid modes). However, the asymmetry in the waveguide geometry needed in order to get the desired  $\Delta\beta$  value and thus desired  $L_\pi$  does not necessarily match with the input and output waveguide cross-sections, i.e. there may be a significant insertion loss for the overall device. Therefore, minimal insertion loss along with an efficient polarization conversion and short converter length are necessary qualities to focus on when designing a polarization converter. It can be difficult to achieve the optimum for all three for the same device, so compromises may have to be made depending on what is deemed the most important parameter for the application.

### 3.6.3 Designing a polarization converter on the AlGaIn/GaN platform

Two converter designs using structural asymmetry are explored for the AlGaIn/GaN platform: (i) a waveguide with a triangular symmetry, and (ii) an L-shaped waveguide. The former has been demonstrated on the InP platform [77], with a converter length of 4  $\mu\text{m}$  achieving a polarization conversion loss of 0.1 dB. The latter has been demonstrated on the silicon-on-insulator (SOI) platform [78], with converter lengths  $\approx 10 \mu\text{m}$  being achieved for a polarization conversion loss of 0.51 dB.

#### 3.6.3.1 Triangle

The slope of the triangle is fixed at  $45^\circ$ , in order to compare with the results on the InP platform [77]. Originally, the total thickness of the structure was set to be 1.2  $\mu\text{m}$ , which matches the dimensions of the tapered waveguide presented in Section 3.2.3. However, there was no evidence of hybrid modes found at

this thickness. Therefore, to find the hybrid mode region, the thickness of the GaN core layer is varied. From Figure 3.20 (c), it can be seen that the hybrid modes are formed at a GaN core thickness of  $0.5 \mu\text{m}$ . Another key factor for an efficient polarization converter is the insertion loss of the input waveguide coupling into the triangular section. For a triangular converter with GaN thickness =  $0.5 \mu\text{m}$ , an input waveguide with a height of  $0.4 \mu\text{m}$  and a width of  $0.5 \mu\text{m}$  as presented in Figure 3.20 (a) gives the lowest insertion losses of 0.081 dB for TE-TM conversion, and 0.082 dB for TM-TE conversion. The corresponding electric field components of the modes can be seen in Figure 3.21. Figure 3.22 shows the polarization conversion for both (a) TE-TM, and

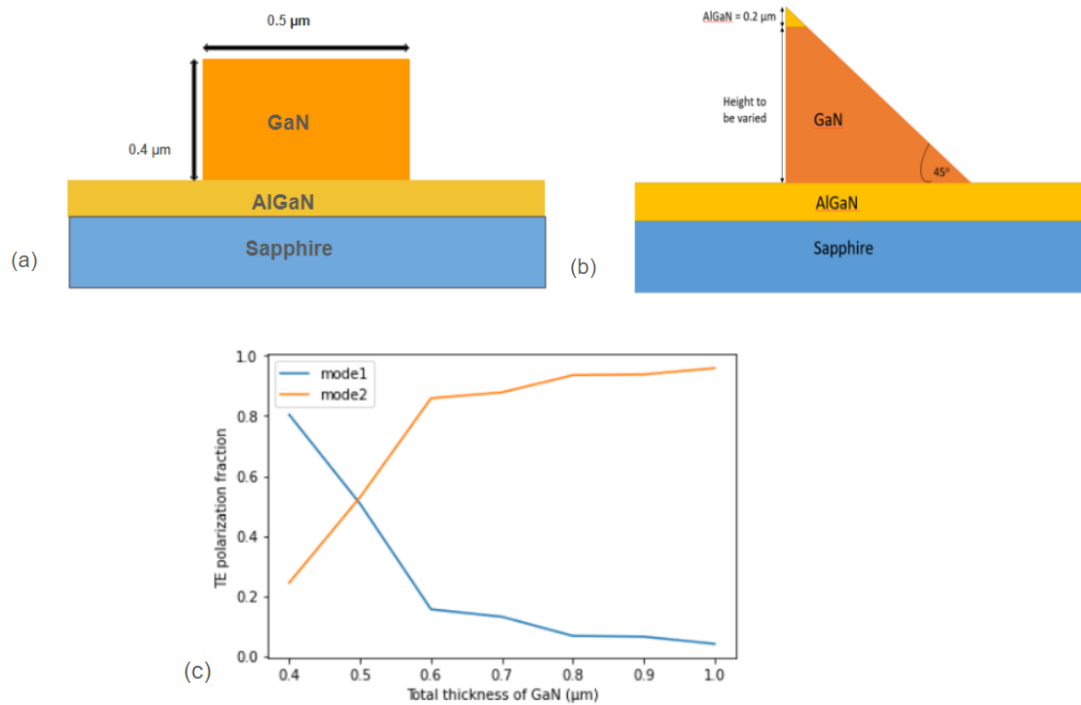


Figure 3.20: Dimensions of the input waveguide for the polarization converter, (b) Schematic of the AlGaIn/GaN triangular-shaped polarization converter, and (c) polarization fraction of the two supported modes for varying GaN thickness. It can be seen from (c) that the hybrid modes appear at a GaN core height of  $0.5 \mu\text{m}$

(b) TM-TE. It can be seen that at a rotation length of  $27 \mu\text{m}$ , a polarization conversion efficiency  $\approx 92.35 \%$  is achieved for both TE-TM and TM-TE.

### 3.6.3.2 L-shaped

As mentioned before, the dimensions of the triangular polarization converter does not match with the thicknesses given for the edge-coupling structure in Section 3.2.3. Therefore, an L-shaped polarization converter may be an easier

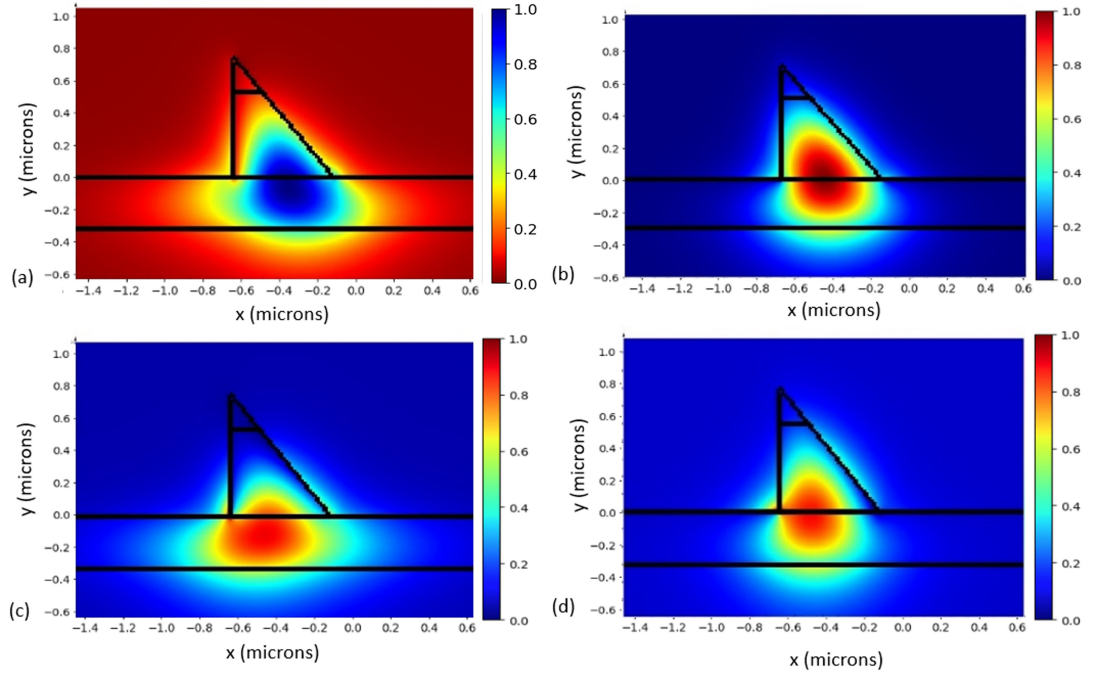


Figure 3.21: (a)  $E_x$  component, and (b)  $E_y$  component of the  $TE_0$  mode, and (c)  $E_x$  component and (d)  $E_y$  component of the  $TM_0$  mode for a GaN thickness of  $0.5 \mu\text{m}$

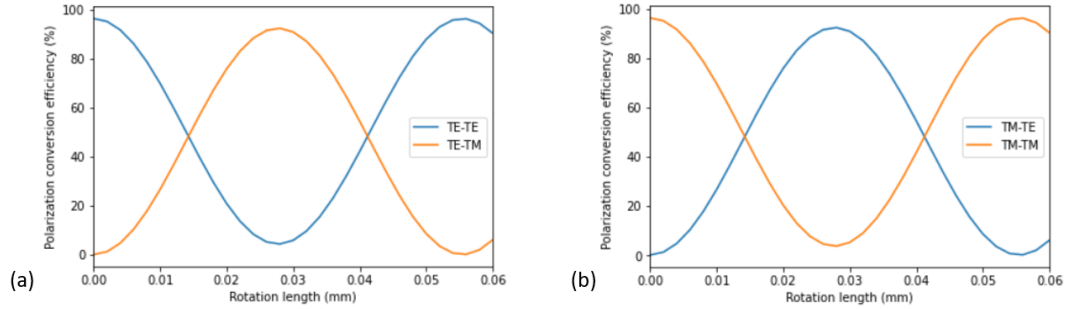


Figure 3.22: The polarization conversion efficiency for (i) TE incident light, and (ii) TM incident light at an input waveguide width of  $0.5 \mu\text{m}$  and input waveguide height of  $0.4 \mu\text{m}$ . The insertion losses are 0.081 dB for the incident TE light, and 0.082 dB for the incident TM light. The dimensions for the polarization converter were the same as given in Fig 3.20

design to integrate into the circuit with the dimensions needed for laser-waveguide coupling. The total height of the L-shaped structure is set to  $1.2 \mu\text{m}$ , while the total width of the structure is set to  $1 \mu\text{m}$  as shown in Figure 3.23 (a). The etched height and the unetched width of the structure is varied to find the mode hybridization region. It can be seen that at an etched depth of  $0.8 \mu\text{m}$ , the hybrid modes appear between widths  $0.35\text{--}0.4 \mu\text{m}$ . Upon closer examination, it can be seen that the components of the modes are almost equal at  $0.37 \mu\text{m}$  in Figure 3.23 (c). The corresponding electric field components of the modes can be seen in Figure 3.24. Setting these to be the

dimensions of the device, the polarization conversion efficiency is shown in Fig 3.25 (a) for incident TE-polarized light, and in (b) for incident TM-polarized light. It was found that when the input waveguide width was set to  $0.5\ \mu\text{m}$ , an insertion loss of 1.42 dB was achieved for both polarizations. It can also be seen that the maximum polarization conversion efficiency is already 30% less than that of the triangular waveguide, and occurs at a rotation length almost three times as long. Checking the alignment of the input waveguide to the converter may improve the insertion losses and thus the overall polarization conversion efficiency; however, it is more than likely based on what was found with the triangular waveguide that the waveguide dimensions are too thick to be an efficient converter.

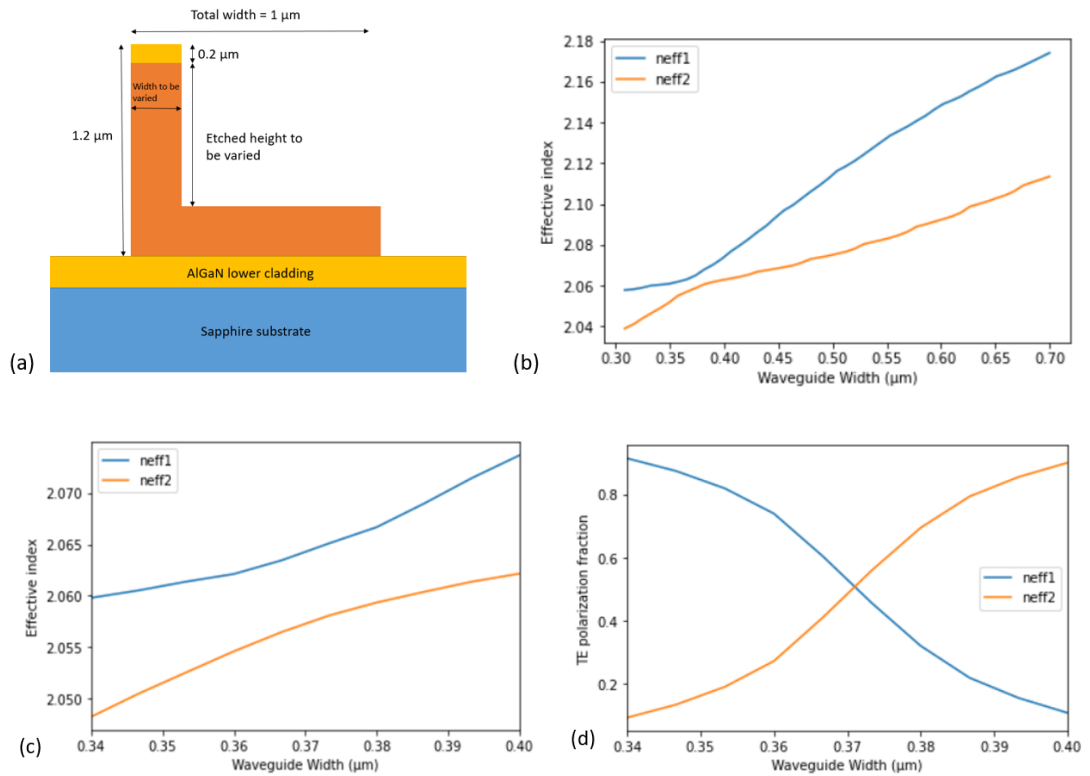


Figure 3.23: (a) Schematic of the L-shaped AlGaN/GaN polarization converter, (b) the effective indices of the two supported modes for varying waveguide width, (c) zoom-in of the hybrid mode region, (d) polarization of the two modes for varying waveguide width

### 3.7 Alternative epitaxial structure

Trying to link the proposed edge-coupling design with the designs remain challenging: further designs that try to introduce some functionalities suggest

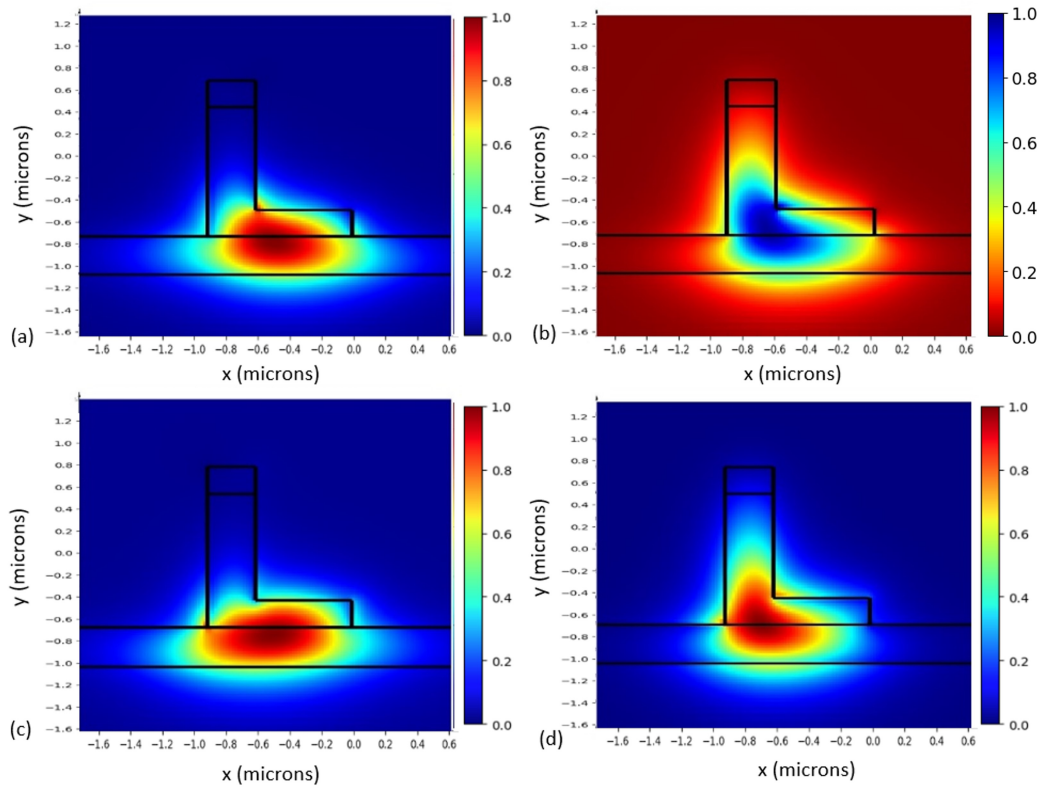


Figure 3.24: (a)  $E_x$  component, and (b)  $E_y$  component of the  $TE_0$  mode, and (c)  $E_x$  component and (d)  $E_y$  component of the  $TM_0$  mode for a polarization converter width of  $0.37 \mu\text{m}$

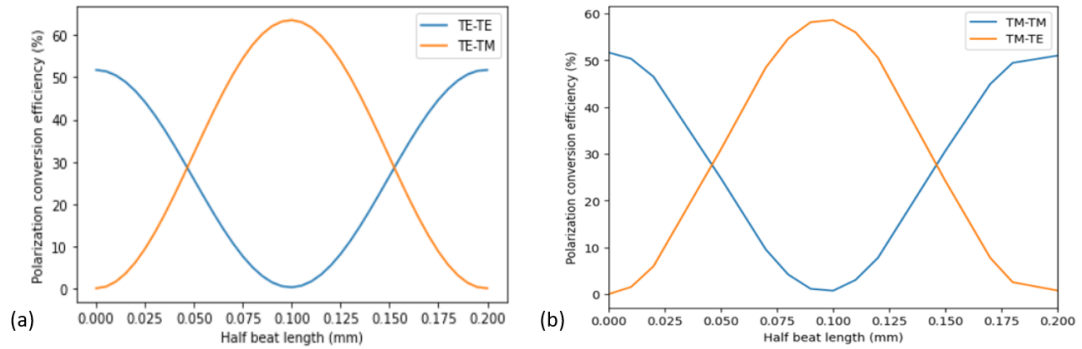


Figure 3.25: Polarization conversion efficiency for (a) TE-polarized incident light, and for (b) TM-polarized incident light for a width of  $0.37 \mu\text{m}$

that a thin layer of GaN works best. One possible solution without compromising on the edge-coupling strategy would be to redesign the epitaxial thicknesses: Figure 3.26 shows a proposed new structure. The AlGaIn cladding layers expand the spot size, while the fully etched AlGaIn ridge allows for higher order modes to be coupled out. The coupling in the transverse and lateral directions for both lasing structures of various ridge widths to the new structure can also be seen in Figure 3.26. The optimum coupling losses for

both structures is below 1 dB for all lasing ridge widths, but the alignment tolerance in the transverse direction is much tighter than the previous epistructure design. A misalignment by  $0.25 \mu\text{m}$  gives a 4 dB loss for both lasing structures. Therefore, there is a trade-off with the edge-coupling design: adapt the epistructure for tolerant coupling, but limit the performance of more complex structures on the platform, or redesign the structure for optimum performance of these functionalities, but reduce the coupling tolerance.

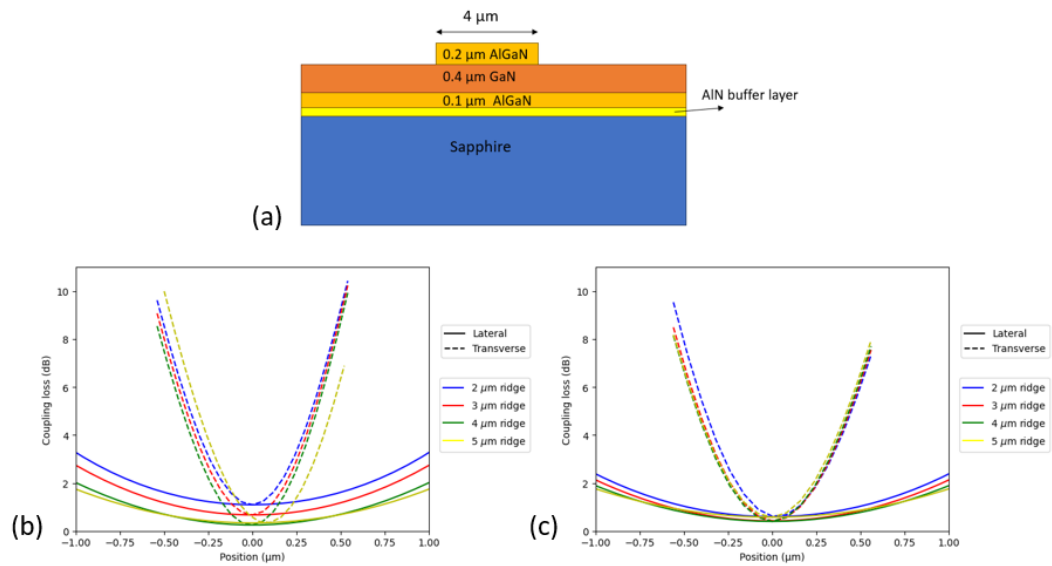


Figure 3.26: (a) The proposed new structure for edge-coupling to aid the design of further functionalities, and the edge coupling in the transverse and lateral directions for (b) the QW laser and (c) QD laser

### 3.8 Conclusions and Discussion

While the epitaxial design proposed in Chapter 2 is suitable for edge-coupling, it can be difficult to add functionalities to the platform as a result of the thickness. The mode converter allows for waveguide dimensions more compatible with bends, but it can be seen that the waveguide bend radius needs to be large ( $> 80 \mu\text{m}$ ) in order to minimize losses for both polarizations. The difference in indices between  $\text{LiNbO}_3$  and GaN also make it difficult to design a structure that allows for sufficient modal overlap in the  $\text{LiNbO}_3$  region using the proposed edge-coupling thickness for GaN, and thus thin film GaN on sapphire is required to make this a reality. A grating coupler structure based on the initial epitaxial structure is found to be multi-modal with 12 % coupling into the fundamental mode: a thinner structure in conjunction with



an amorphous Si grating gives coupling efficiencies of 30 % and 27 % for TE and TM polarization at 1.31  $\mu\text{m}$ . For a possible polarization converter design, the thickness required depends on the selected design: a triangular converter requires half the thickness of the proposed structure and provides the shorter converter length, better conversion efficiency and reduced insertion loss. An L-shaped converter can be used in theory with the 1.2  $\mu\text{m}$  thick AlGaIn/GaN, but is reduced in performance in the three criteria mentioned. In addition, the width that is required for mode hybridization to occur has a small tolerance, and is very difficult to achieve with fabrication processes. For future work, a thinner epitaxial structure is advised for the more complex designs outlined in this chapter, with the trade-off being reduced  $\mu\text{TP}$  tolerances.

## Chapter 4

# Fabrication and Device Integration Techniques

### 4.1 Chapter Overview

In order for GaN to compete as an alternative PIC material, a robust fabrication process needs to be developed in order to produce components on the PIC. Fabricating devices on AlGaIn/GaN-on-sapphire for edge-coupling can be difficult however due to the (i) crystallographic structure of GaN and the (ii) hardness of the sapphire substrate. In this chapter, the steps involved in fabricating the AlGaIn/GaN waveguides and the integration of InP lasing devices to the platform are presented. First, the growth of the AlGaIn/GaN on a sapphire epitaxial structure for this thesis is outlined. Then, the issues encountered during patterning and etching GaN in this work are discussed, along with the solutions to these challenges. An optimized sapphire dry etching recipe developed during this work for forming the  $\mu$ TP is presented, along with a method of forming waveguide facets for optical coupling. Finally, micro-transfer printing, the technique for integrating the laser to the AlGaIn/GaN platform in this thesis, is discussed.

## 4.2 Fabrication Steps

### 4.2.1 Growth of the epitaxial structure

The designed structure (outlined in Chapter 2) was grown epitaxially on a 50-nm diameter c-plane AlN/sapphire (Kyma Technologies, Inc.) wafer using metal-organic vapour-phase epitaxy (MOVPE) by another research group in Tyndall. The overall structure was composed of a 0.3  $\mu\text{m}$ -thick  $\text{Al}_{0.03}\text{Ga}_{0.97}\text{N}$  bottom cladding followed by 1  $\mu\text{m}$ -thick GaN waveguide, and 0.5  $\mu\text{m}$ -thick  $\text{Al}_{0.03}\text{Ga}_{0.97}\text{N}$  top cladding. The AlGaIn/GaN layers grow with a 90° rotation to that of sapphire to ease the lattice mismatch: as a result of this rotation the m-planes of the AlGaIn/GaN layers are parallel to the a-planes of sapphire, and the a-planes of GaN are parallel to the m-planes of sapphire. The layout of the planes is outlined in Figure 4.1. Standard GaN growth conditions were used for both GaN and AlGaIn layers: 1060°C, 150 mbar, high V/III ratio (1000). Trimethyl-gallium, trimethyl-aluminium and ammonia were used as group III (Ga, Al) and group V (N) precursors, respectively, with hydrogen as the carrier gas.

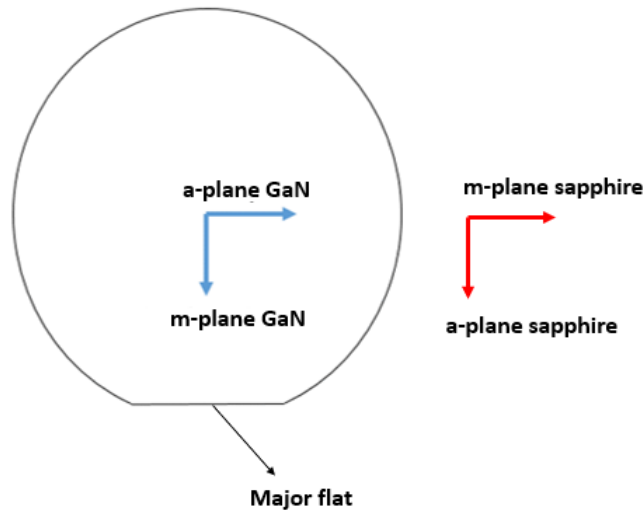


Figure 4.1: The a-planes and m-planes of both GaN and sapphire with respect to the wafer: the a-plane of GaN and the m-plane of sapphire lie parallel to the wafer's major flat, while the m-plane of GaN and the a-plane of sapphire are perpendicular to the major flat.

Due to the lattice and thermal mismatch between the epitaxial layers and the substrate, the resulting wafer may have a bow. Not having a flat wafer can lead to processing non-uniformity and pattern misalignment during lithography. The bow was measured for a 2-inch wafer using the KLA Tencor P-17

profilometer, with the resulting profile shown in Figure 4.2. The wafer was found to have a measured bow of  $6.9 \mu\text{m}$ . From this measured bow, the radius of curvature for the wafer  $R$  can also be obtained using the following equation:

$$R = \frac{W^2}{8Bow} + \frac{Bow}{2} \quad (4.1)$$

where  $W$  = the scanning distance. The radius of curvature was calculated to be  $11.5 \text{ m}$ . The bowing and radius of curvature of the AlGaIn/GaN epistructure is not considered to impact the semiconductor processing that will be outlined in this chapter [79].

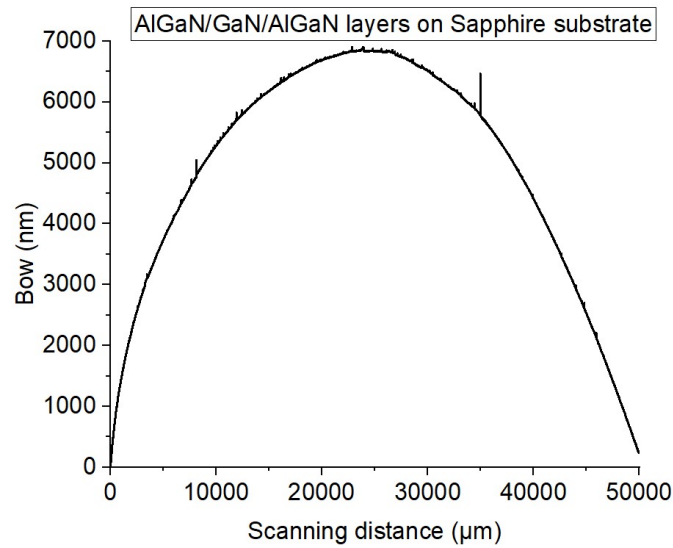


Figure 4.2: Measured bowing of the epitaxial structure grown for this work

### 4.2.2 Lithography

Lithography involves the transferring of a predefined pattern to a substrate for device formation. This can either be done via optical lithography (UV light) or through electron-beam (e-beam) lithography. The type of lithography selected depends on the desired resolution, which in turn depends on the wavelength of light used. Resolution down to 10s of nm has been achieved with optical lithography using wavelengths in the deep ultraviolet (DUV) and extreme ultraviolet (EUV) range. The optical lithography tool used in this work operates in the ultraviolet range at 405 nm thereby limiting the resolution to  $\approx 1 \mu\text{m}$ . E-beam can pattern features down to  $\approx 10 \text{ nm}$ : however it is costly and takes much longer due to the write time needed to pattern the substrate.

Before lithography commences, the substrate is covered with either a positive or negative photoresist. The parts of the substrate that are exposed via the mask will be hit by the UV light or the e-beam. If a positive resist is used, the chemical structure of the exposed areas changes. These exposed areas are then washed away with the photoresist developer solvent, leaving the underlying material. The areas of the photoresist that aren't exposed to the UV light or the e-beam are left insoluble to the photoresist developer. If a negative resist is used, the chemical structure of the exposed areas polymerize; exposed negative resist remains on the surface while the photoresist developer solution works to remove the areas that are unexposed.

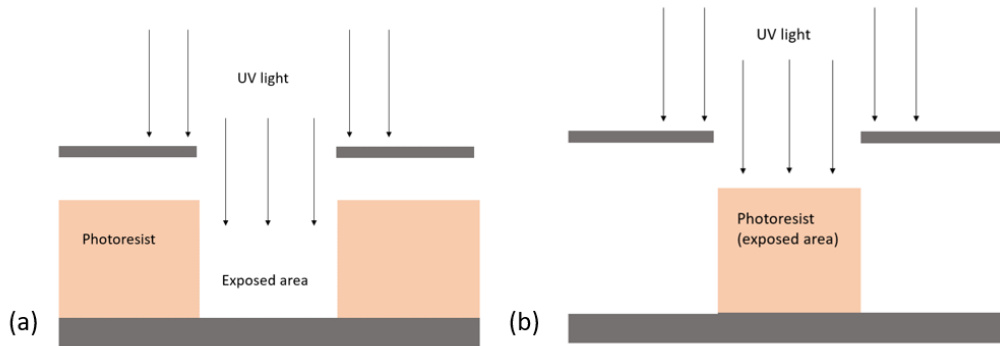


Figure 4.3: The mechanics of (a) positive and (b) negative photoresist for UV lithography. When positive photoresist is exposed to the light, the chemical structure changes and becomes more soluble in the photoresist developer. These exposed areas are then washed away with the photoresist developer solvent, leaving the underlying material. The areas of the photoresist that aren't exposed to the UV light are left insoluble to the photoresist developer. It is the inverse then for negative photoresist, where UV light exposure causes the chemical structure of the photoresist to polymerize

To determine if the resolution is good enough to continue with the fabrication process, there are verification patterns on the mask of varying sizes. For fabrication processes that require multiple etch depths of the substrate, then more than one lithography step, or mask level is needed. To accommodate this, there are also alignment marks on the mask. The alignment tolerance needed between the levels is also another factor in determining which lithography technique to select for a process.

Both optical and e-beam lithography were used in this work when fabricating the waveguides. With e-beam, a Cr layer was deposited onto the sample which acted as a hard mask for the dry etching. In order to pattern the sample with Cr, a lift-off process was required. A trial run of fabricating the mode adapter designs was carried out using optical lithography for both levels, but the

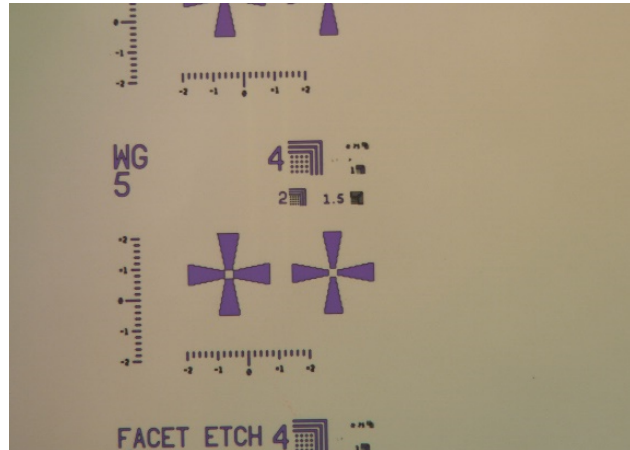


Figure 4.4: Example of an alignment mark patterned on a substrate

misalignment of the tapers was  $> 1 \mu\text{m}$ . Hence e-beam was used for fabricating such structures. The initial trial run, along with the outcomes of using the e-beam process, is discussed later in Chapter 5.

### 4.2.3 Etching

Once the patterns are developed after exposure, they need to be defined into the substrate. This is done by etching: the areas where the semiconductor material is not covered by photoresist is removed, giving the structures either a defined height or depth. In this work inductively-coupled plasma (ICP) dry etching is used to etch (i) the AlGaIn/GaN waveguides and (ii) the trench into the sapphire substrate.

#### 4.2.3.1 GaN etching

Dry etching using  $\text{Cl}_2/\text{BCl}_3$  plasmas is the most common way to etch GaN: Cl radicals chemically etch the material, while the  $\text{BCl}_3$  controls the physical etching effect. The addition of  $\text{BCl}_3$  in the plasma also results in smoother-etched surfaces with minimum damage [80], although increasing the  $\text{BCl}_3$  concentration in the plasma also leads to a reduced mask selectivity, i.e. the mask etches faster than the GaN. This is due to the generation of heavy ions such as  $\text{BCl}^{+2}$  or  $\text{BCl}^{+3}$  [81].

Etching rates up to 600 nm/min have been achieved with  $\text{Cl}_2/\text{BCl}_3$  recipes, with selectivities between 10-16 using a  $\text{SiO}_2$  etching mask. However, pillars have also been observed during  $\text{Cl}_2/\text{BCl}_3$  dry etches in the literature, possibly due to spontaneous oxidization as a result of contamination from the hard

mask or chamber itself [82, 83]. Running a pre-etch clean, optimizing the  $\text{BCl}_3$  concentration, and switching the hard mask from  $\text{SiO}_2$  to  $\text{SiN}_x$  have all been solutions to reducing the density of the pillars on the surface during etching. An example of high density of pillars as a result of  $\text{Cl}_2/\text{BCl}_3$  dry etching can be seen in Fig 4.5 below, where the concentration of  $\text{BCl}_3$  was 2 % of the overall gas flow. The dry etching of GaN in this thesis was carried out using the PlasmaPro 100 Cobra ICP etching system from Oxford Instruments. From various tests with the  $\text{Cl}_2/\text{BCl}_3$  recipe, using a variety of hard masks such as  $\text{SiO}_2$ ,  $\text{SiN}$  and  $\text{Cr}$ , it was found that increasing the etch depth increased the likelihood of pillars forming during the etch. While running an additional  $\text{O}_2$  plasma clean in the etching chamber has helped reduce the problem in some cases, the pillars can still appear regardless of the hard mask selected. It is likely that there is an issue with the striking of the plasma onto the substrate, but more investigation needs to be carried out to determine this.

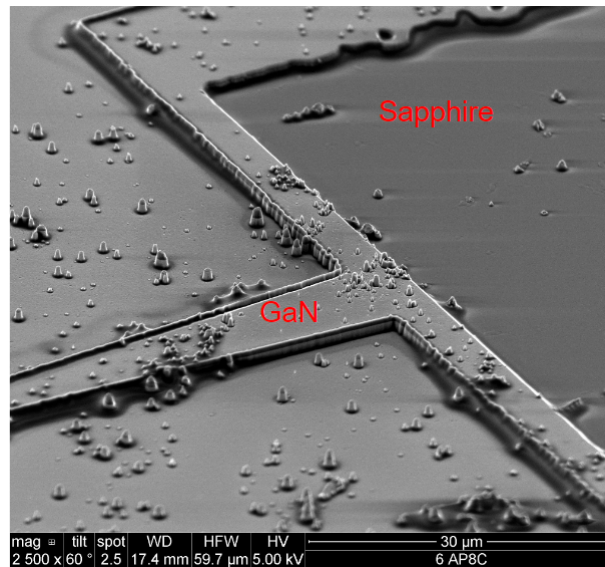


Figure 4.5: Formation of pillars on a GaN sample during a  $\text{Cl}_2/\text{BCl}_3$  etch

To remove the etching damage as a result of dry etching with  $\text{Cl}_2/\text{BCl}_3$ , a wet etching treatment can be carried out on the substrate using a TMAH-based solution [84]. The TMAH wet etch treatment only produces vertical sidewalls in the m-plane of GaN however, where the facets are positioned: in the a-plane where the sidewalls are oriented, the sidewalls would become triangular with TMAH treatment due to the crystallography of GaN. To minimize both the roughness of the dry etch, and the formation of pillars, a pure  $\text{BCl}_3$  dry etch was used in this thesis. It was found from trial etches that the  $\text{BCl}_3$  undercut the pillars during etching. While this leads to a poorer selectivity compared to

the  $\text{Cl}_2/\text{BCl}_3$  plasma for reasons already mentioned in this section, the selectivity with this recipe is still between 1-2 (depending on whether  $\text{SiN}$  or  $\text{SiO}_2$  is used as the etching mask) with a reasonable GaN etching rate of 60 nm/min. The etch results in slanted sidewalls, with the sidewall angle depending on the etch parameters and the plasma gas used; while vertical sidewalls are generally desired for waveguides, simulations show that this does not cause a problem provided the right waveguide geometry is selected. These simulations are outlined later in Chapter 5.

#### 4.2.3.2 Defining the trench via sapphire etching

From the simulations of the AlGaIn/GaN waveguide coupling to the laser in Chapter 2, it is already known that in order for the passive waveguide mode to align correctly with the active lasing mode, a trench with a depth of  $2.8\text{ }\mu\text{m}$  needs to be created at the front facet of the waveguide. This means that the sapphire needs to be etched by  $1\text{ }\mu\text{m}$  for successful laser integration. There has been work in developing both wet and dry etches for sapphire, mostly for the purpose of patterned sapphire substrates; such substrates are desired for GaN LEDs as they help to reduce the dislocation density and thus improve the output powers from the device [85]. As sapphire is chemically inert and highly resistive to acids at room temperature, wet etching sapphire requires mixtures of  $\text{H}_2\text{SO}_4$  and  $\text{H}_3\text{PO}_4$  at very high temperatures ( $> 200\text{ }^\circ\text{C}$ ) [86]. Even then, the sapphire etch rate is very slow ( $\leq 1\text{ }\mu\text{m hr}^{-1}$ ) and the resulting profiles are groove-like. For integration of the  $\mu\text{TP}$  laser to the waveguide, a trench formed with this profile could affect coupling between the devices. In comparison, dry etching sapphire can provide an anisotropic profile with much faster etching rates. Generally a  $\text{BCl}_3$  plasma gas is advantageous for dry etching sapphire as the  $\text{BCl}$  radicals scavenge the oxygen from the Al-O bonds[80].

Dry etching sapphire with the aforementioned plasma has been carried out with a variety of hard masks such as photoresist with an etching selectivity between 0.5 to 1.2 [87, 88],  $\text{SiO}_2$  with an etching selectivity of 0.52 to 6 [89–91], and nickel (Ni) and chromium (Cr) with etching selectivities of 4-7.6 [92, 93] and 5.1-6.1 [89, 94], respectively. Using a photoresist mask, an etching rate of  $363\text{ nm min}^{-1}$  with a selectivity of 1.2 was reported using  $\text{BCl}_3/\text{Cl}_2$ , while the addition of argon (Ar) to the plasma increased the etching rate to  $377\text{ nm min}^{-1}$  with a selectivity of 1 [88]. For a Cr mask, an etch rate of  $355\text{ nm min}^{-1}$  with a selectivity of 6.1 was obtained using a  $\text{BCl}_3/\text{Cl}_2/\text{Ar}$



recipe, while a  $\text{BCl}_3/\text{Cl}_2/\text{Xe}$  plasma slightly decreases the etch rate to  $350 \text{ nm min}^{-1}$  with a selectivity of 5.1 [89]. With a Ni hard mask, an etch rate of  $261.1 \text{ nm min}^{-1}$  with a selectivity of 7.6 was achieved using a  $\text{BCl}_3/\text{Cl}_2/\text{Ar}$  plasma [93]. Meanwhile, the highest etch rate with a  $\text{SiO}_2$  mask was  $338 \text{ nm min}^{-1}$  with a selectivity of  $\approx 0.5$  [89], also with a  $\text{BCl}_3/\text{Cl}_2$ . The addition of  $\text{CHF}_3$  [95] and  $\text{HBr}$  [96] to the  $\text{BCl}_3$  plasma has also lead to high etch rates and sufficient selectivities. Table 4.1 is a summary of the reported dry etches for sapphire along with the etch parameters.

Tests were carried out in order to develop a sapphire etch recipe for defining the  $\mu\text{TP}$  trench based on Table 4.1. The dry etches in this section were all carried out using the PlasmaPro 100 Cobra ICP etching system. The literature suggested that a  $\text{BCl}_3/\text{Cl}_2$  plasma etch would provide a high etch rate with a sufficient selectivity with resist, with the addition of gases such as Ar also possibly beneficial. Table 4.2 displays the optimized recipes with the different plasma gas mixtures, masking materials and etching parameters used. It was difficult to replicate the existing work, as evidenced by the selectivities and etching rates shown. The highest temperatures shown in the table was at  $20^\circ\text{C}$ : previous reports showed high etch rates and suitable selectivities with higher substrate temperatures as seen in Table 4.1, [88]. Etches where no vacuum oil was used to hold the sample in place (and thus increasing the temperature to  $> 100^\circ\text{C}$ ) led to the resist reflowing, making it difficult to determine the selectivity of the photoresist to sapphire. When the depth of the sapphire was measured after these etches, it was also found that there was no significant improvement in the sapphire etch rate with the much higher temperature. While hard-baking the photoresist before the dry etch prevented re-flow from occurring, it did not improve the selectivity of the etch.

Eventually, it was found that by using a  $\text{BCl}_3/\text{H}_2$  etch chemistry, setting the temperature to  $10^\circ\text{C}$  and reducing the pressure to 2 mTorr (giving a DC bias of 638 V), a sapphire etch rate of  $82 \text{ nm/min}$ , with a selectivity of 0.73 using a photoresist mask was obtained. The reduction in pressure may have improved the striking of the plasma on the sample, while keeping the temperature below  $20^\circ\text{C}$  minimized the risk of the photoresist reflowing during the etch. Additional etch tests would need to be carried out in order to verify that the pressure was a key parameter in the increase of the sapphire etch rate. A similar etch rate using a pure  $\text{BCl}_3$  plasma was also demonstrated, with a higher selectivity of 3 using a Ni mask. However, the maximum thickness of Ni that can be evaporated due to stresses is  $\approx 100 \text{ nm}$ ; as the desired etch depth

| Sapphire dry etches from the literature   |                   |               |                           |                  |                |                |             |                     |  |
|-------------------------------------------|-------------------|---------------|---------------------------|------------------|----------------|----------------|-------------|---------------------|--|
| Plasma gas                                | Flow rates (sccm) | ICP power (W) | RF power (W)/d.c bias (V) | Pressure (mTorr) | Temp (°C)      | Hard Mask      | Selectivity | Etch rate. (nm/min) |  |
| $\text{BCl}_3/\text{Cl}_2$ [88]           | 50:50             | 800           | -300 V                    | 30               | 70             | PR             | 1.2         | 362.7               |  |
| $\text{BCl}_3/\text{Cl}_2/\text{Ar}$ [88] | 50:50:20          | 800           | -300 V                    | 30               | 70             | PR             | 1           | 377                 |  |
| $\text{BCl}_3/\text{Cl}_2/\text{Ar}$ [89] | 80:20:10          | 1600          | -250 V                    | 15               | 70             | Cr             | 6.1         | 355                 |  |
| $\text{BCl}_3/\text{Cl}_2/\text{Xe}$ [89] | 80:20:10          | 1600          | -250                      | 15               | 70             | Cr             | 5.1         | 350                 |  |
| $\text{BCl}_3/\text{Cl}_2/\text{Ar}$ [93] | 68:10:20          | 650           | 80 W                      | 7.5              | Not mentioned. | Ni             | 7.6         | 261.1               |  |
| $\text{BCl}_3/\text{HBr}/\text{Ar}$ [96]  | 81:9:10           | 1400          | -800                      | 10               | 3              | PR             | 0.87        | 550                 |  |
| $\text{BCl}_3/\text{Cl}_2$ [89]           | 80:20             | 1600          | -250 V                    | 15               | 70             | $\text{SiO}_2$ | 0.5         | 338                 |  |
| $\text{BCl}_3:\text{CHF}_3$ [95]          | 80:20             | 2000          | 1000 W                    | 52.5             | Not mentioned  | PR             | 1.3         | > 100               |  |

Table 4.1: A list of sapphire dry etching recipes from the literature referred to in this section.

| Sapphire dry etches from etch experiments         |                   |               |              |                  |           |                |             |                    |  |
|---------------------------------------------------|-------------------|---------------|--------------|------------------|-----------|----------------|-------------|--------------------|--|
| Plasma gas                                        | Flow rates (sccm) | ICP power (W) | RF power (W) | Pressure (mTorr) | Temp (°C) | Hard Mask      | Selectivity | Etch rate (nm/min) |  |
| $\text{BCl}_3/\text{Cl}_2$                        | 40:10             | 1200          | 225          | 24               | 20        | PR             | 0.14        | 22.5               |  |
| $\text{BCl}_3/\text{Cl}_2$                        | 49:1              | 800           | 226          | 15               | 20        | $\text{SiO}_2$ | 0.57        | 21                 |  |
| $\text{BCl}_3/\text{Cl}_2/\text{CF}_4/\text{H}_2$ | 40:10:4:11        | 800           | 100          | 6                | 20        | PR             | 0.33        | 18                 |  |
| $\text{BCl}_3/\text{Cl}_2/\text{Ar}$              | 68:10:20          | 650           | 500          | 7.5              | 20        | PR             | 0.25        | 32.5               |  |
| $\text{BCl}_3/\text{Cl}_2/\text{Ar}$              | 80:10:20          | 650           | 200          | 15               | 20        | Ni             | 6           | 20                 |  |
| $\text{BCl}_3/\text{HBr}/\text{Ar}$               | 81:9:10           | 1000          | 260          | 10               | 3         | PR             | 0.46        | 40                 |  |
| $\text{BCl}_3/\text{H}_2$                         | 30:5              | 1000          | 400          | 2                | 10        | PR             | 0.73        | 82                 |  |
| $\text{BCl}_3$                                    | 70                | 1000          | 150          | 2                | 10        | Ni             | 3.8         | 78.6               |  |

Table 4.2: A list of the best sapphire dry etching results from all the recipes used

of sapphire is  $1\ \mu\text{m}$  then a Ni layer with thickness  $> 300\ \text{nm}$  would have to be electroplated. To simplify the process, the  $\text{BCl}_3/\text{H}_2$  recipe with the photoresist mask was selected moving forward.

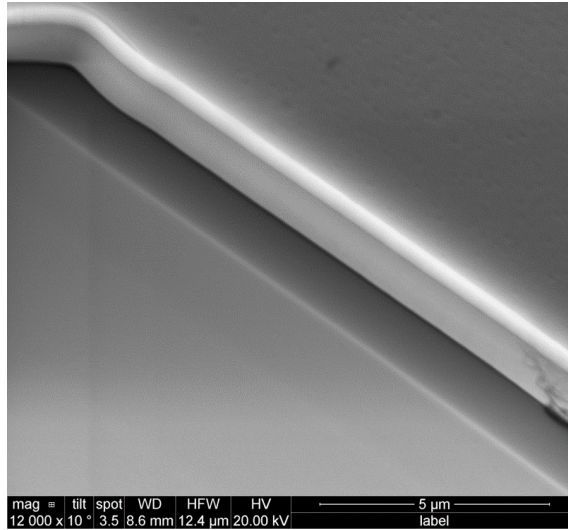


Figure 4.6: Profile of the  $\mu\text{TP}$  trench using the  $\text{BCl}_3/\text{H}_2$  etch with a photoresist mask. The surface where the device to be transfer printed is smooth, and devices have successfully bonded to it as demonstrated in Chapter 5.

#### 4.2.4 Facet preparation

Smooth waveguide facets are essential for efficient light coupling. Dry etching, polishing, and cleaving have been some of the methods used to develop high-quality facets in sapphire. For III-V materials such as GaAs and InP, where the crystal structure is zinc blende, a smooth facet can be achieved by cleaving, as it allows the crystal to break along its natural cleavage plane. For GaN-on-GaN epitaxial structures (where the substrate is also GaN), facets can also be formed by cleaving along the *m*-planes of GaN. However, this is not possible for GaN-on-sapphire due to the hardness of the sapphire substrate. Therefore, GaN-on-sapphire devices are usually laser diced, and the facet polished back due to the roughness and debris produced after dicing. For a PIC that may have a high density of input and output facets, this can be very time consuming. Using gratings instead for coupling can remove the problem of facets, but this also has its own problems as outlined previously in Chapter 3. Dry etching the facets is possible, but the required depth to etch down into the sapphire for fiber-coupling means that both the etch rate of sapphire and the selectivity would need to be improved from the developed etch recipes. Wet-etching the facets after dicing or cleaving can give smooth facets, but this

is only possible along the GaN's m-plane: the waveguide sidewalls, which are orientated along the GaN's a-plane, form a triangular profile with this etch, making it unsuitable for guiding purposes. To avoid this while still producing good quality waveguide facets, a method of partially dicing the sapphire and then cleaving afterwards was developed.

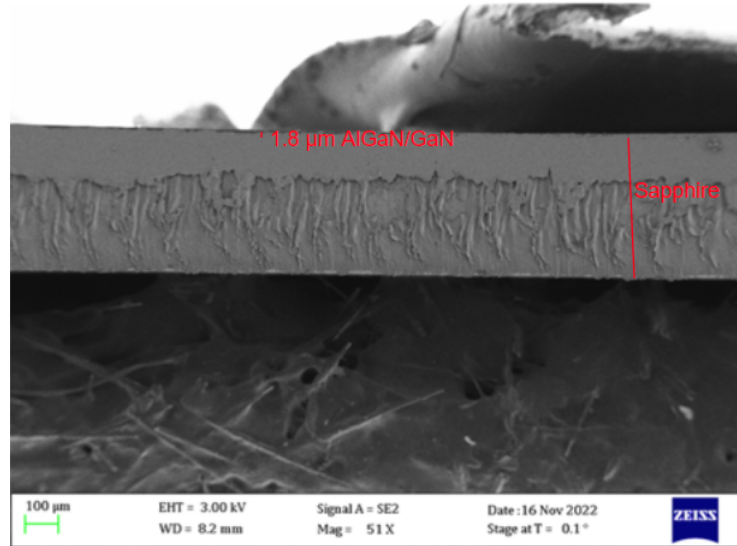


Figure 4.7: The facet at a distance along the test piece for 30 passes of the laser dicing: it can be seen that the debris, which is generated as a result of the laser dicing, was  $\geq 100 \mu\text{m}$  away from the facet zone of the chip. In this work the facet of the waveguides is in the GaN's m-plane (perpendicular to the major flat and to the sapphire's m-plane), while the sidewalls are orientated in the GaN's a-plane (parallel to the major flat and to the sapphire's m-plane) for cleaving purposes

The dicing of the sample was carried out on the sapphire backside of the sample using a LASEROD laser dicer. This tool is made up of a 1064 nm Nd:YAG rod laser optically pumped with a solid state laser diode. The laser operates in pulsed mode with a pulse width of  $8 \mu\text{s}$ . At 72 % of the lasing current, a lasing spot size between  $40\text{-}50 \mu\text{m}$  is produced at a 6 kHz setting. The number of passes for the laser was set to be 30: in order to fully dice the sapphire, the number of passes required is 40. A test was carried out in order to determine the quality of facets for the number of passes selected between 20-30, but it was found that the debris was largely  $\geq 100 \mu\text{m}$  away from the facets as seen in Figure 4.7, regardless of the number of passes selected. As the sample was being diced from the backside to prevent facet roughness, a  $3 \mu\text{m}$  thick  $\text{SiO}_2$  layer was deposited via PECVD onto the front size in order to protect the waveguides.

The partial dicing and cleaving was carried out as follows, with a schematic

shown in Figure 4.8: for this example, a 2 cm-long chip was used. The sample was diced with 30 passes mostly along the chip (on both the right hand side and left hand side), leaving a 1mm-long section untouched, as shown in Figure 4.8 (a). The sample was then turned over to the front side, with the AlGaIn/GaN epilayers protected by 3  $\mu\text{m}$  thick  $\text{SiO}_2$  layer. A diamond scribe was then used to make a notch on the untouched 1 mm sections on the front sides of both pieces. Pressure was then applied to the scribed section to cleave and form the facets on either side of the waveguides. From imaging the sample as shown in Figure 4.9, we can see that we can get waveguide facets with minimal roughness. Again, the debris generated from the dicing was mostly kept away from the facet region at distances  $\geq 100 \mu\text{m}$ , although there were some areas located where the minimum distance was  $10 \mu\text{m}$ .

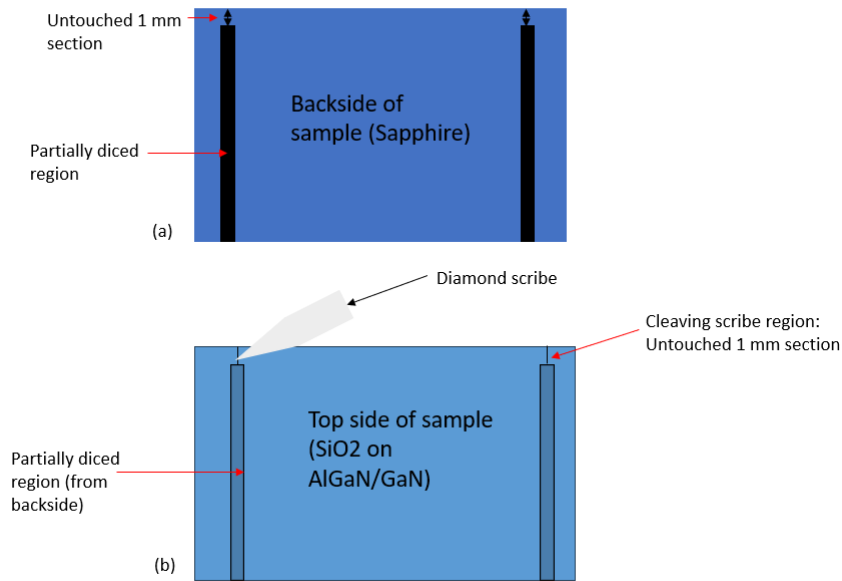


Figure 4.8: Schematic of the partially dicing and cleaving method in order to form the waveguide facets for edge coupling: (a) the sample is diced partially from the sapphire backside (with 30 passes) along most of the chip, leaving a 1 mm-long section untouched. The sample is then turned to its front side as shown in (b), where the AlGaIn/GaN epistructure is covered with PECVD-deposited  $\text{SiO}_2$  for protection. As the epistructure is transparent, the dicing marks from the backside can also be seen through the front side. A scribe mark is made on the untouched 1 mm-long section on the front side (in line with the dicing mark), and pressure is then applied to this region to cleave this region.

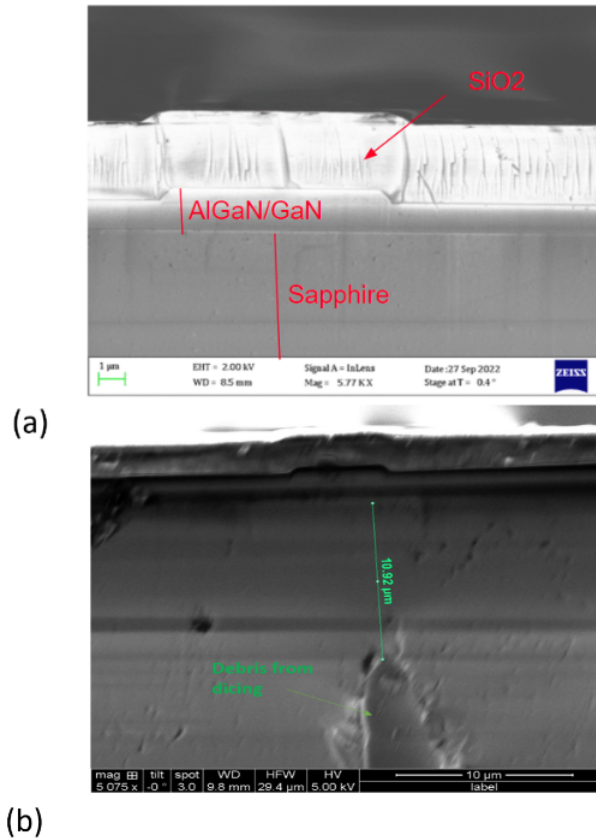


Figure 4.9: SEM of the (a) waveguide facet after the laser dicing and partial cleaving, and (b) section of the same chip where the minimum distance between the debris and the facet region is 10  $\mu\text{m}$

## 4.3 Device Integration Techniques

### 4.3.1 Monolithic, Hybrid and Heterogeneous Integration

The challenge in realising photonic circuits is the integration of the various opto-electronic components needed onto the same platform. It would be most ideal to do this through monolithic integration, i.e. all the devices made out of the same material. This has been demonstrated with InP, but is limited by packaging and CMOS compatibility. Therefore there needs to be some way of integrating different materials on the PIC in order to provide for the multiple functionalities needed.

One way of overcoming this is to use hybrid integration, where two or more PIC chips of different materials are combined into the same package. For example, a laser chip can be mounted on top of, or directly next to, a passive PIC via flip-chip bonding. The chips are integrated after being fully processed, at the packaging stage. This technique allows for device testing before the

chips are integrated, thus increasing the yield and improving the overall performance. However, the device alignment and integration process is time-consuming and can have limited throughput, making it an unsuitable process for PICs with high device density.

A more suitable option would be to use heterogenous integration, where two or more materials are combined into a single PIC. This process is performed during the fabrication of the PIC, where the III-V thin film is bonded onto the pre-processed wafer in a process known as die-to-wafer bonding. The III-V material is then patterned into the desired lasing structure. This produces a high throughput of device integration and also provides high alignment accuracy between the active and the passive waveguides. However, the process is limited to integrating a single III-V material to the circuit, and can also waste a lot of material. It is also a technique that does not allow for device testing before integration, as the device is only fully processed after being bonded. This can especially be an issue if there are defects arising as a result of the bonding of two materials, thus limiting the performance of the device. The solution to all this would be to have a technique that allows for device testing pre-integration while also achieving high alignment accuracy and throughput.

### 4.3.2 Micro-transfer Printing

Micro-transfer printing ( $\mu$ TP) allows the heterogenous integration of pre-fabricated and tested III-V devices onto the same platform while maintaining a high throughput. The process starts with the preparation of the III-V material on the source wafer, where the active layers of the device is grown on top of a release layer. The material of the release layer depends upon the lasing material, e.g. for InP-based active devices it is generally InAlAs or InGaAs, while for GaAs-based active devices it is AlGaAs. The device and release layer is patterned, and then encapsulated with a polymer layer. By wet-etching with a  $\text{FeCl}_3$ -based solution, the release layer is removed from the devices. The device is thus suspended, and tethered only to the source wafer by the polymer.

Figure 4.10 outlines the process of  $\mu$ TP: a polydimethylsiloxane (PDMS) stamp is used to pick up devices that are tethered to their native substrate. The device is then broken away from the polymer tethers by acceleration of the PDMS stamp, and then transferred to the target substrate, or PIC platform. The device is bonded via Van Der Waals forces to the new substrate by slowly



pulling the PDMS stamp away. If there are issues with the device bonding to the new substrate, then a thin adhesive layer can be used between the interfaces such as BCB or intervia. The polymer encapsulation surrounding the device is dry etched away, and the device is then electrically contacted to the new substrate.

$\mu$ TP can be carried out one device at a time, or the stamp can be arranged to print arrays of devices. It has been successfully demonstrated for devices such as III-V lasers and semiconductor optical amplifiers (SOA) [97, 98],  $\mu$ LEDs [99, 100], and photovoltaic cells [101] onto the Si platform. It has not yet been demonstrated for III-nitride platforms. As mentioned earlier in this work, the lasing device mode must be aligned carefully to the passive waveguide mode for efficient edge coupling. While it has been shown that the mode size can be engineered to be wide enough for tolerant coupling, the laser device thickness with respect to the waveguide thickness is larger. Thus, for the active region of the lasing device to be aligned to the waveguide mode, a trench into the platform has to be introduced. In this work, the trench needs to be etched down into 1  $\mu$ m of sapphire. As well as the trench needing to be a specific depth, the surface must be smooth enough for the device to bond well to. As mentioned above, a small layer of intervia or BCB can be used if the roughness is on a small scale, but thicker layers would have to be used if the roughness is significant. A thick adhesion layer can affect the thermal properties of the laser and the overall performance. Therefore, a sapphire etch that can provide minimal roughness needs to be developed. The  $\mu$ TP of the QW and QD lasers to the sapphire trenches are outlined in the next chapter.

## 4.4 Discussion and Conclusion

The quality of the AlGaIn/GaN waveguides and the efficiency of the coupling between (i) the external laser source and waveguide for waveguide characterization and (ii) the integrated  $\mu$ TP laser and waveguide, is dependent on the processing steps outlined in this chapter. From outlining the processing steps involved in fabricating the AlGaIn/GaN waveguides, it can be seen that there were challenges faced, particularly when (i) patterning and etching the waveguide patterns, (ii) etching the sapphire trench for  $\mu$ TP, and (iii) forming the waveguide facets for edge-coupling the optical fiber for waveguide characterization. For patterning waveguide structures, the choice of lithography depends upon the feature sizes that are needed: as the waveguide

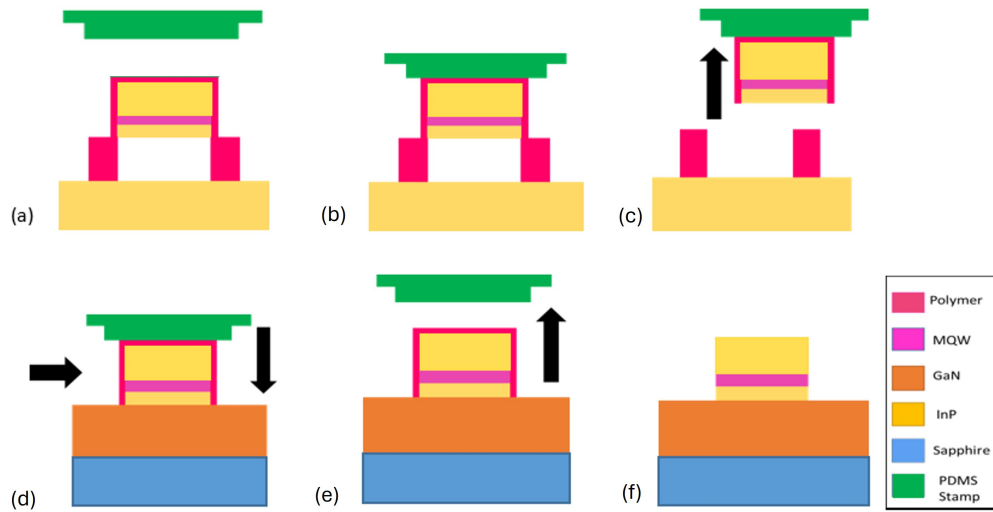


Figure 4.10: Schematic of how  $\mu$ TP works: at the end of the laser fabrication process, (a) the lasing device is suspended on its native substrate by the tethers, (b) the PDMS stamp comes down, (c) breaks the device away from the tethers, and (d) places the device down on the target substrate; (e) the PDMS stamp slowly peels away from the device, with the device now bonded to its new location; and then the (f) encapsulation layer is removed from the device via  $O_2$  plasma ashing.

designs based on AlGaN/GaN go down to  $1\ \mu\text{m}$ , it can be challenging to use optical lithography as this is the resolution limit for the tool. In addition, aligning two waveguide levels for a design such as the mode adapter presented in Chapter 2 is also difficult with optical lithography. Patterning using both optical and e-beam lithography is discussed in the next chapter in more detail in relation to fabricating the AlGaN/GaN waveguides.

Etching the waveguides also posed some issues as pillars formed whenever a  $\text{Cl}_2$ -based plasma etch was used. It was found that using  $\text{BCl}_3$  for etching the AlGaN/GaN waveguides reduced the number of pillars found on the surface post-etch, but resulted in slanted sidewalls with roughness observed. Further optimization of the etch is needed in order to improve the verticality and the smoothness for future designs on the AlGaN/GaN platform. A  $\text{BCl}_3$  etch was also found to be advantageous for etching the sapphire at a suitable rate and with an acceptable selectivity. The  $\mu$ TP of the active devices to these trenches will be discussed in detail in the next chapter.

Due to the hardness of sapphire it was difficult to establish a method of forming the waveguide facets with satisfactory quality for coupling the optical fiber. Partially dicing the chip from the sapphire side, and then cleaving from the AlGaN/GaN side seems to provide satisfactory facets, with the debris generated from the dicing lying largely away from the facet region. However,

it is unclear what yield of good-quality facets can be obtained from this method, and how the waveguide length to be cleaved can impact this. This will be explored also in the next chapter.

The difficulties faced at the relevant process steps and the solutions that were found have been highlighted in this chapter. It is these solutions that are used to fabricate the waveguides for characterization in the next chapter. The process flows for the structures are discussed in greater detail in the next chapter.

## Chapter 5

# Waveguide Fabrication and Characterization

### 5.1 Chapter Overview

This chapter outlines the fabrication process and the characterization of two iterations of AlGaIn/GaN waveguides: the first iteration is mainly used to verify process steps and to understand the magnitude of the waveguide propagation losses through single etched straight waveguides and tapered waveguides with varying ridge widths and taper lengths/tip dimensions. The second iteration is to realize the double-tapered mode adapter outlined in Chapter 3 that is designed to improve both light coupling and mode confinement for better light routing. The InP QW and GaAs QD lasers from the previous chapter are then transfer printed to the trenches etched through the AlGaIn/GaN down to the sapphire substrate. This is the first time that a laser has been coupled heterogeneously to a GaN waveguide. A light-current (L-I) characterisation has been performed by measuring the light coupled from the laser to the waveguides. The results, and the challenges encountered during the fabrication and characterization are then discussed.

### 5.2 Methods to investigate the waveguide propagation loss

Waveguide propagation loss is generally measured by either (i) the cutback method or (ii) the Fabry-Perot cavity method. For the cutback method, the

power collected at the output of the waveguide in dB at a fixed input power is measured for waveguides of different lengths, and the transmission expressed in dB is then plotted against the lengths. The slope of the fitted line for this plot is equal to the propagation loss. For the estimate to be reliable, the variation of the input/output coupling efficiency should be negligible with respect to the transmission loss of the longer waveguides. The Fabry-Perot cavity method, on the other hand, is independent of this coupling as it relies on the facet reflections within the waveguide cavity. With this method, the interference pattern in the transmission spectrum generated from interference of these reflections is used to determine the upper limit of the propagation loss. The normalized transmitted intensity,  $I_T$ , of a Fabry-Perot waveguide is given as [102]

$$I_T = \frac{1}{(1 - \tilde{R})^2 + 4\tilde{R}\sin^2(\frac{\phi}{2} + \phi_0)} \quad (5.1)$$

where  $\phi = \frac{\phi}{2} + \phi_0$  is the phase accumulated in one round trip.  $\phi = \frac{4\pi n_g L}{\lambda}$ , where  $n_g$  = group index and  $L$  = length of the waveguide, while  $\phi_0$  is dependent on the reflection condition but not on the light propagation.  $\tilde{R}$  is defined as  $RA_f e^{-\alpha L}$ , where  $R$  is the facet reflectivity,  $A_f$  is a correction due to the facet loss, and  $\alpha$  is the propagation loss coefficient of the waveguide. As  $\lambda$  varies,  $I_T$  oscillates between  $I_{max}$  and  $I_{min}$ . The contrast of these oscillations,  $K$ , is defined as

$$K = \frac{(I_{max} - I_{min})}{(I_{max} + I_{min})} \quad (5.2)$$

We can also express  $\tilde{R}$  in terms of  $K$  as

$$\tilde{R} = \frac{1}{K}(1 - \sqrt{1 - K^2}) \quad (5.3)$$

Using both expressions for  $\tilde{R}$ ,  $\alpha$  can be determined experimentally, while  $R$  is determined by FDTD calculations. If we assume ideal facet mirrors ( $A_f = 1$ ), then  $\alpha$  can be calculated from the following equation;

$$\alpha = \frac{4.34}{L} \ln \frac{R}{\tilde{R}} \quad (5.4)$$

If the facets are non-ideal due to surface roughness for example ( $A_f \leq 1$ ), then the  $\alpha$  calculated is an upper limit for the actual propagation loss. Figure 5.1 shows a simulated Fabry-Perot resonance profile for a 2 mm-long waveguide

using Eq 5.1 with  $R = 0.15$  and  $\alpha = 3.6$  dB/cm.  $K$  is obtained by the fitting of the peaks (red dots) and minima (green dots) to the fringes, which is then used to calculate  $\tilde{R}$  and thus  $\alpha$ . Therefore,  $K$  and  $\tilde{R}$  are calculated for each fringe, and then the average  $\alpha$  is taken as the overall propagation loss for the waveguide.

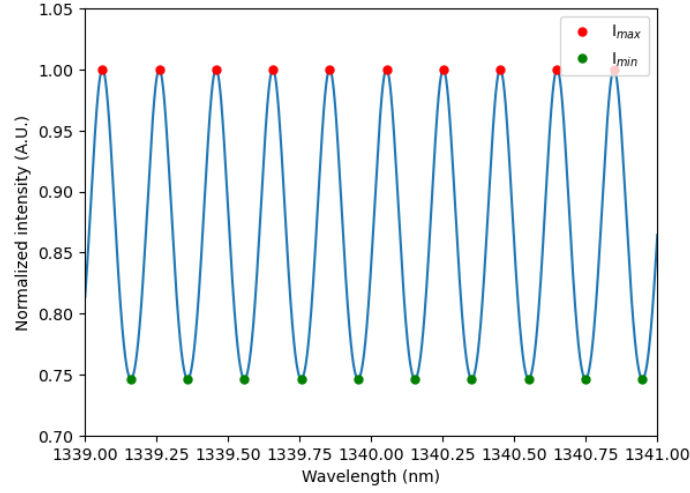


Figure 5.1: Simulated Fabry Perot fringes using Equation 5.1 for a 2 mm-long waveguide with effective index  $n_{eff} = 2.26$ , reflectivity  $R = 0.15$  and  $\alpha = 3.6$  dB/cm.  $K$  is calculated by extracting the maximum peaks (denoted as  $I_{max}$  in the graph) and the minimum peaks ( $I_{min}$ ) of the fringes. We can see from this simulation that  $K = 0.25$ .

Distinguishing between the TE propagation loss  $\alpha_{TE}$  and the TM propagation loss  $\alpha_{TM}$  in the waveguide is done by obtaining the fast Fourier transform (FFT) of the Fabry-Perot fringes [103]. When the fringes are Fourier-transformed, the phase shifts that the propagating mode in the waveguide experience are represented as peaks spaced at integer multiples of the optical path length  $L_{opt}$ . This  $L_{opt}$  is equal to the physical cavity length multiplied by the  $n_g$  of the propagating mode. This can be seen in Figure 5.2 for the same waveguide as in Figure 5.1 (this time over a 10 nm span): the resulting three peaks at integer multiples of  $2.26 \times 2$  mm ( $2.26 = n_g$ ,  $2$  mm = waveguide cavity length). Thus, if we have two sets of fringes where one should correspond to the TE polarization and the other to the TM polarization, the peaks in the FFT should appear at different points due to their different  $n_g$  values.

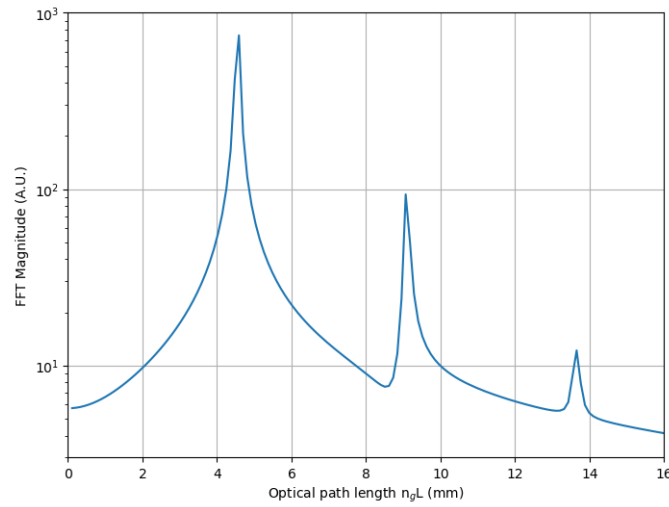


Figure 5.2: Simulated FFT for a 2 mm-long waveguide with group index  $n_g = 2.26$ , reflectivity  $R = 0.15$  and  $\alpha = 3.6$  dB/cm over a  $1.335$ - $1.345$   $\mu\text{m}$  wavelength range. The spacing between the peaks is equal to the waveguide's optical path length.

## 5.3 First iteration of designs

### 5.3.1 Waveguide Fabrication

The first set of waveguide devices are to verify that straight and tapered waveguides can be fabricated on the AlGaIn/GaN platform using the recipes and methods outlined in Chapter 4. The GDS mask and patterns can be found in Appendix B and were designed for a quarter piece of a 2-inch wafer, with two levels being used in the fabrication: (i) the waveguide etch, and (ii) the trench etch for  $\mu\text{TP}$ .

The straight waveguides are varied in width from  $1$   $\mu\text{m}$  to  $10$   $\mu\text{m}$ , while the tapered waveguide designs had variations of the input width between  $2$ - $10$   $\mu\text{m}$ , with the taper tip set to be either  $1$  or  $2$   $\mu\text{m}$ . There are two sets of taper designs on the mask: (i) two tapers at either end of the chip connected by a straight waveguide with width = taper tip width, and (ii) tapered waveguide chain, as seen in Figure 5.3. The chain is designed so as to try to evaluate the taper transition loss, i.e. total signal loss through the chain/no. of tapers = loss per taper. It can be seen in Figure 5.3 that there are  $400$   $\mu\text{m}$ -long rectangular sections between the tapers with widths corresponding to the input width. These are added to account for the (i) accuracy of the partial dicing to form the facets (for cleaving different waveguide lengths, and in the case of evaluating the loss (ii) to be representative of the edge tapers. From the trial runs outlined earlier in Chapter 4, it was found that the accuracy was

$\pm 100 \mu\text{m}$ . The taper lengths are selected to be  $50 \mu\text{m}$ ,  $200 \mu\text{m}$  and  $500 \mu\text{m}$ : based on the simulations presented in Chapter 3, all of these lengths should have a conversion efficiency  $\geq 98 \%$ .

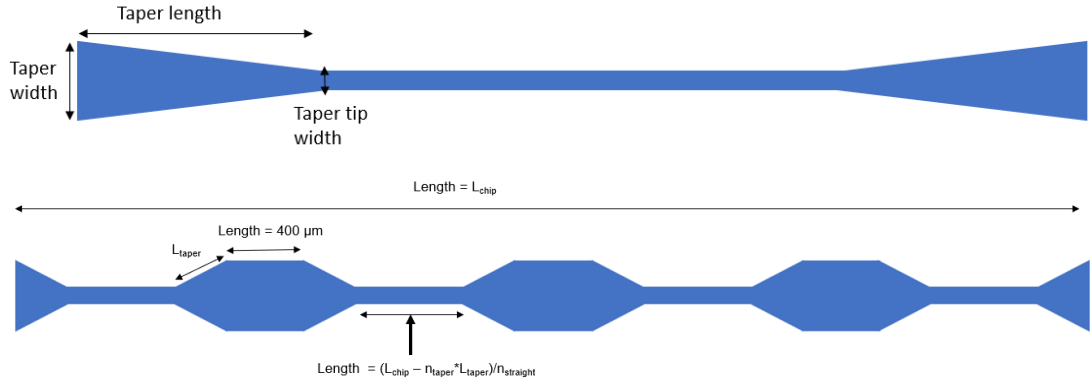


Figure 5.3: The schematic of two types of tapered structure designs used in this work: the (a) tapered structure connected by a straight waveguide with width = taper tip width, and (b) the taper chain design proposed to try to examine the taper transition loss

The fabrication sequence for the first iteration of designs is shown in Figure 5.4 and went through the following steps:

- $1.3 \mu\text{m}$ -thick SiN layer was deposited on the sample using PECVD
- The waveguide patterns were defined using optical lithography
- The pattern is transferred into the SiN via dry etching
- Using the SiN as a hard mask, the waveguide patterns were etched into the AlGaIn/GaN at a depth of  $1 \mu\text{m}$  using a  $\text{BCl}_3$  plasma.
- The remaining SiN was removed using a  $\text{CF}_4$  dry etch that doesn't affect the AlGaIn/GaN.
- The trenches for  $\mu\text{TP}$  were then patterned via optical lithography, and then etched using the  $\text{BCl}_3/\text{H}_2$  dry etching recipe. The photoresist acted as the mask for the etching, and was then removed afterwards via  $\text{O}_2$  plasma ash.
- A thick  $3 \mu\text{m}$  layer of  $\text{SiO}_2$  was deposited onto the waveguides to protect the waveguides during the partial dicing and cleaving to form the facets.
- The sample was diced and cleaved up in the manner already presented in Figure 4.8 in Chapter 4 into different waveguide lengths:  $1 \text{ mm}$ ,  $2 \text{ mm}$ ,  $3 \text{ mm}$ ,  $7 \text{ mm}$  and  $18 \text{ mm}$



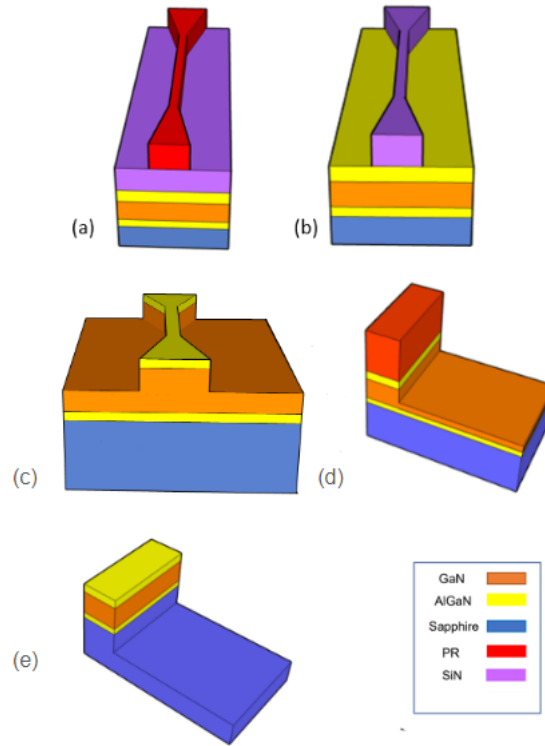


Figure 5.4: The process flow for the first fabrication run of the AlGaIn/GaN waveguides: (a) SiN is deposited via PECVD, photoresist is spun on and the pattern to be fabricated is defined via optical lithography; (b) the pattern is transferred from the photoresist to the SiN through a dry etch, and the remaining photoresist is removed; (c) the pattern is transferred from SiN to AlGaIn/GaN for a  $1\ \mu\text{m}$  depth via  $\text{BCl}_3/\text{Cl}_2$  etch, and the remaining SiN is then removed via a  $\text{CF}_4$  etch; (d) the trench for  $\mu\text{TP}$  is defined via optical lithography beside the T-bar region (area covered in resist); (e) the pattern is dry etched via the AlGaIn/GaN and into the sapphire using a  $\text{BCl}_3/\text{H}_2$  with the photoresist acting as a hard mask, and this photoresist is then removed via  $\text{O}_2$  plasma ash once the etch is completed

As mentioned earlier in Chapter 4, the  $\text{BCl}_3$  etch used to form the AlGaIn/GaN waveguides results in slanted waveguide sidewalls. The simulations from Chapter 2 and 3 were redone taking this into account using Lumerical MODE for the mode profiles and related  $n_g$  values, and FDTD in order to calculate  $R$ . The  $n_g$  and  $R$  values for the  $\text{TE}_0$  and  $\text{TM}_0$  modes can be found in Table 5.1 for varying waveguide width for the fully etched straight waveguide. The sidewall angle was set to be  $63^\circ$ , based on measurements of the sidewall angle from initial trial runs. The fundamental mode profiles for both polarizations can be seen in Figure 5.5 for ridge width =  $4\ \mu\text{m}$  for (i) the fully-etched straight waveguide, and (ii) the double-etched tapered waveguide. Despite the angled sidewalls, the mode profiles for the double-tapered waveguide structures do not deviate from what has been presented earlier in this report for the waveguides with vertical sidewalls, i.e. the interaction of the mode with the

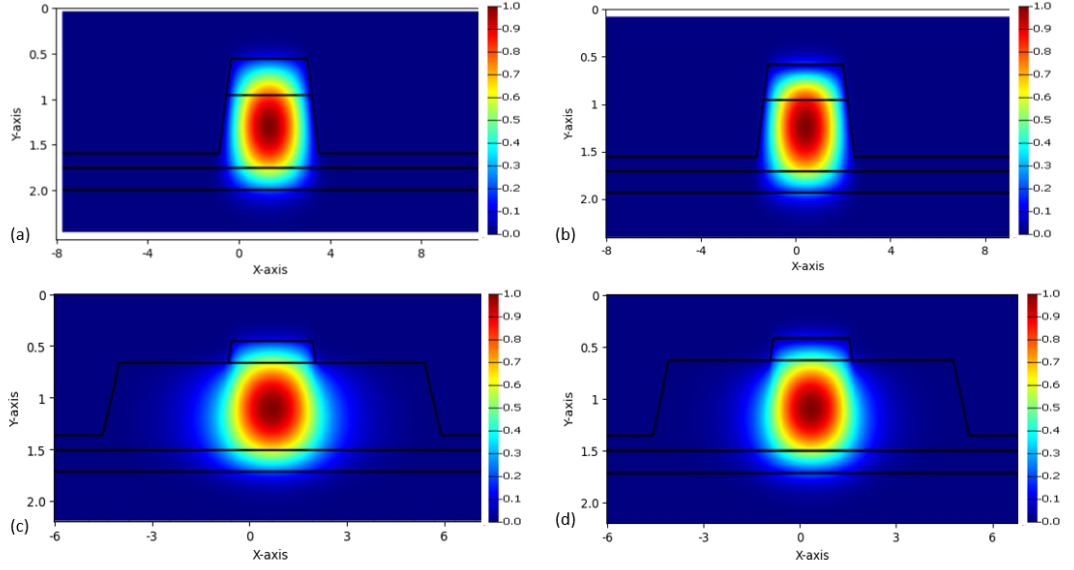


Figure 5.5: The (a)  $E_x$  profile for the  $TE_0$  mode and (b)  $E_y$  profile for the  $TM_0$  mode for the single-etched  $4\ \mu\text{m}$ -wide waveguide, and the (c)  $E_x$  profile for the  $TE_0$  mode and (d)  $E_y$  profile for the  $TM_0$  mode for the double etched waveguides with a  $4\ \mu\text{m}$ -wide shallow ridge.

sidewall is low as the mode is still guided by the shallow-etched ridge. The coupling efficiency between the active lasing mode and the passive waveguide mode with the sidewalls taken into account is discussed later on in this chapter when analysing the  $\mu\text{TP}$  of the lasers to the GaN platform.

| Waveguide width ( $\mu\text{m}$ ) | $R_{TE}$ | $n_{gTE}$ | $R_{TM}$ | $n_{gTM}$ |
|-----------------------------------|----------|-----------|----------|-----------|
| 1                                 | 0.147    | 2.361     | 0.152    | 2.396     |
| 2                                 | 0.148    | 2.345     | 0.153    | 2.389     |
| 4                                 | 0.149    | 2.340     | 0.153    | 2.386     |
| 6                                 | 0.149    | 2.338     | 0.153    | 2.384     |
| 8                                 | 0.149    | 2.338     | 0.154    | 2.383     |
| 10                                | 0.149    | 2.337     | 0.154    | 2.383     |

Table 5.1: The  $R$  and  $n_g$  values for the fundamental  $TE_0$  and  $TM_0$  modes for the AlGaN/GaN waveguide structure with varying ridge width.

## 5.3.2 Waveguide Characterisation

### 5.3.2.1 Characterisation Set-Up

A schematic of the characterization setup that was used is shown in Figure 5.6. The sample was placed on a stage, with single-mode polarization-maintaining

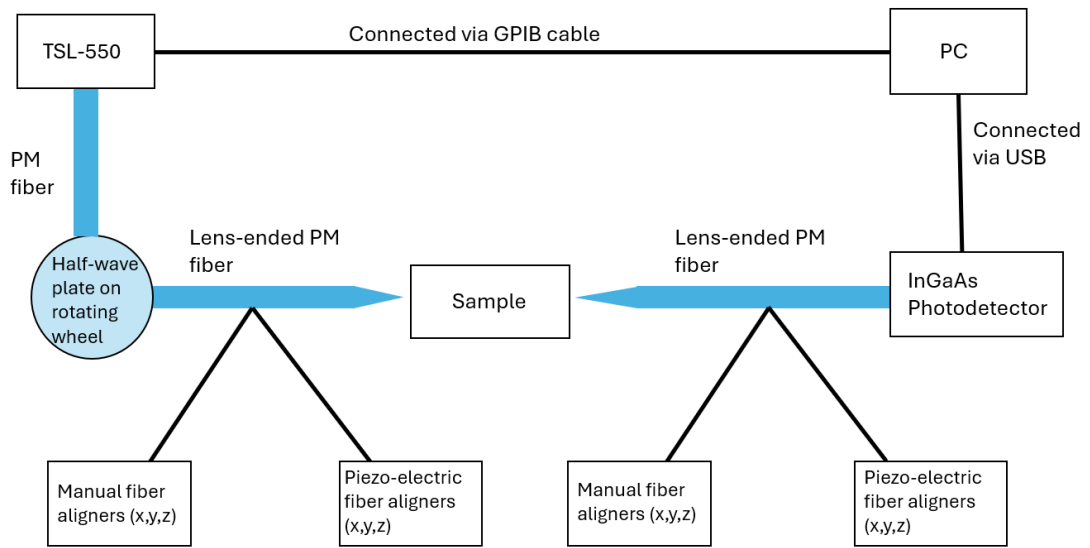


Figure 5.6: Schematic of the experimental setup used to characterize the waveguides

lens-ended fibers with  $2.5\ \mu\text{m}$  spot sizes placed on either side of the sample: one to couple the Santec TSL-550 laser source into the waveguide, and the other fiber to couple the light out to the photodetector. The fibers are placed in translation stages on either side of the sample with two sets of arms corresponding to x,y, and z. One set allows for manual alignment of the fibers to the waveguide facets, while the other set are controlled piezoelectrically: these piezoelectric arms are connected to a DALI E-2100 piezo autoalign controller.

The waveguide chips were mounted onto the stage and characterised. As the waveguides can be difficult to distinguish even through the microscope, 670 nm-laser light was first coupled into the waveguide to ensure that the fibers were properly aligned to the waveguide. The experiment was then carried out using the Santec TSL-550 tunable laser. A half-wave plate on a rotating wheel was used to find the maximum and the minimum signal at 1340 nm. The fiber used between the TSL and the half-wave plate was also polarization maintaining. To ensure that the fringes were properly resolved while also minimizing the scan time, the maximum range at each time of characterizing was 4 nm with a step size of 0.005 nm. The span was centred at 1340 nm; this is due to the actual lasing wavelength of the InP QW devices that will be transfer-printed later in this chapter. The tunable laser was then set to run at the rotations that produced the maximum and minimum signal.

### 5.3.2.2 Modelling the group and refractive index

In Chapter 2, the Sellmeier equations were outlined in order to calculate the  $n_o$  and  $n_e$  of AlGaIn for varying Al concentration. Using a 2 mm-long waveguide with width = 4  $\mu\text{m}$ , the waveguide Fabry-Perot fringes were obtained over a wavelength range 1.26  $\mu\text{m}$  - 1.36  $\mu\text{m}$ , with a step size of 0.005 nm. These fringes can be seen in Figure 5.7. Despite the issues mentioned previously with the shorter cavities, the 2 mm-long chip was chosen as the fringes need to be resolvable for modelling the refractive index without the wavelength scan taking too long before the fiber probes start to drift. There is no measure on the distance the probes drift by in a certain amount of time; however from experience the alignment of the fiber probes needs to be checked every 2 hours to ensure maximum coupling into the waveguides. The  $n_g$  of the waveguide can also be modelled if  $n_{o,e}$  are known:

$$n_g = n_{o,e} - \lambda_0 * \frac{dn_{o,e}}{d\lambda_0} \quad (5.5)$$

The results of the modelling based on the experimental data can also be seen in Figure 5.7 below. The coefficients that were used in the Sellmeier equation came from [61]. It can be seen that the experimental data mostly aligns with the theoretical  $n_o$  and  $n_e$  values, with fluctuations observed in parts of the wavelength range. At 1.34  $\mu\text{m}$ , the  $n_o^g$  and  $n_e^g$  from the experimental data were 2.335 and 2.393. From comparing to the simulated values, there is a deviation of 0.005 for the  $n_o^g$  value and 0.007 for the  $n_e^g$  value.

### 5.3.2.3 Results

The Fabry-Perot method was first used to extract the  $\alpha_{TE}$  and  $\alpha_{TM}$  for waveguide lengths of 0.22 cm, 0.33 cm, 0.70 cm and 1.8 cm. For the straight waveguides, the waveguide widths examined were 4  $\mu\text{m}$  and 10  $\mu\text{m}$ . The resulting  $\alpha_{TE}$  and  $\alpha_{TM}$  values are shown in the scatter plot below in Figure 5.8 - we can see that there is a wide spread in the values obtained. In general,  $\alpha_{TE}$  were lower than  $\alpha_{TM}$  for the same waveguide length and width. In order to measure the loss as a function of the waveguide length, the cutback method was tried. However, there was too much variation in the output power to get a fit for extracting  $\alpha$ . In order to get rid of this dependence on the power coupling into the waveguide,  $\alpha L$  as obtained by the Fabry Perot method was plotted against the length of the measured waveguide. The  $\alpha * L$  for both the

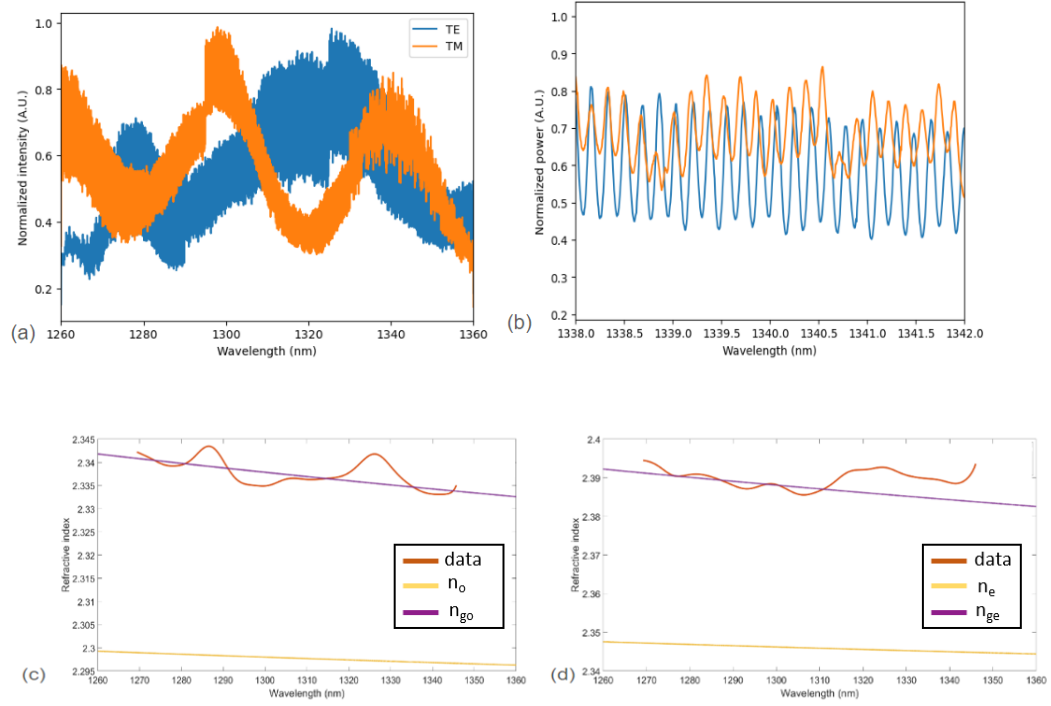


Figure 5.7: (a) The normalized transmission profile for the TE and TM polarizations for waveguide width =  $2\ \mu\text{m}$ ; (b) zoomed-in part of this transmission profile, (c) the fitting of the experimental data to obtain the  $n_o^g$  and  $n_o$  for varying wavelength for the TE polarization and (d) the  $n_e^g$  and  $n_e$  for the TM polarization.

$4\ \mu\text{m}$  waveguide and the  $10\ \mu\text{m}$  waveguide are plotted in 5.9. The data is

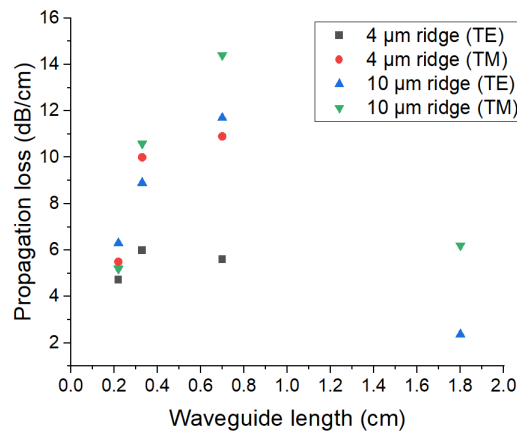


Figure 5.8: The  $\alpha_{TE}$  and  $\alpha_{TM}$  values obtained for the different waveguide lengths for waveguide widths =  $4\ \mu\text{m}$  and  $10\ \mu\text{m}$  using the Fabry Perot method.

presented as a scatter plot without a fit: for the  $10\ \mu\text{m}$  waveguide it is obvious visually that there is no linear regression present, while the data for  $4\ \mu\text{m}$  waveguide can be fitted, but it can only use three data points which can't be

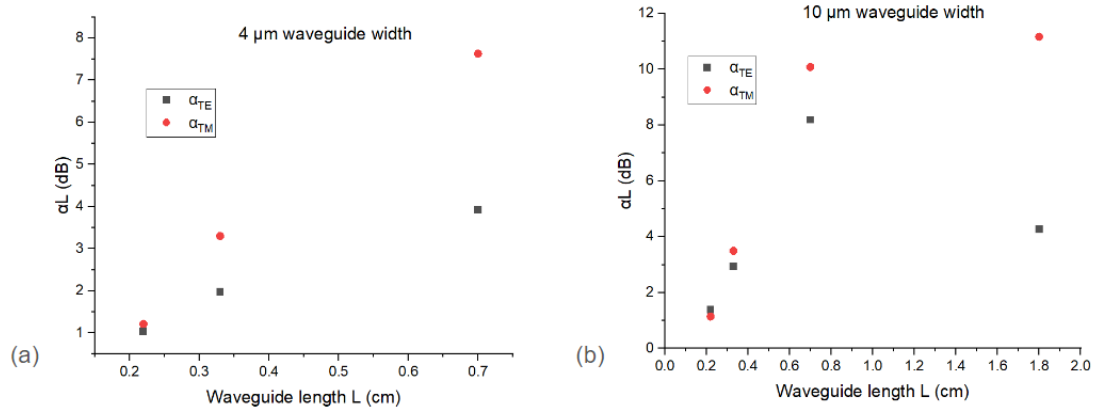


Figure 5.9:  $\alpha \cdot L$  vs  $L$  for the 4  $\mu\text{m}$  and 10  $\mu\text{m}$ -wide waveguide widths at both polarizations. Trying to fit for the 4  $\mu\text{m}$  waveguide is limited by only possessing three data points, while there is no observable linear regression for the 10  $\mu\text{m}$ -wide waveguide.

relied upon. These issues with using variation in waveguide length are attributed to the following:

- Low yield for certain waveguide dimensions: Some of the waveguides suffered interruptions along the chip. In particular, this impacted a lot of the waveguides on the 1.8 cm chip thus leaving out some points. For the variation in waveguide width for the straight waveguides, the 2  $\mu\text{m}$ , 4  $\mu\text{m}$  and 10  $\mu\text{m}$  widths were selected to be examined. However, the 2  $\mu\text{m}$  widths had to be largely discarded as there wasn't enough available to extract meaningful information. There was an interruption also observed for the 4  $\mu\text{m}$  waveguide on the 1.8 cm chip, limiting the attempted fit to three data points.
- Facet quality: Despite the trial runs carried out in the previous chapter, the facets were of variable quality along the chip. This could be visually seen for the shorter waveguide lengths (i.e. the 0.22 cm and 0.33 cm-long chips), where there is a jaggedness to the edge of the chip after cleaving as seen in Figure 5.10 (interruptions in some of the waveguides can also be observed.) This variation in facet quality was not nearly as strong for the longer 0.7 cm and 1.8 cm chips when visually inspected. Thus, the variation in facet quality is causing fluctuations in reflections at the facet, thereby affecting the accuracy of the measurements for shorter cavity lengths.

The Fabry-Perot fringes, along with the FFT, are presented in Figure 5.11 for the 10  $\mu\text{m}$  wide waveguide on the 1.8 cm-long chip. From extracting the

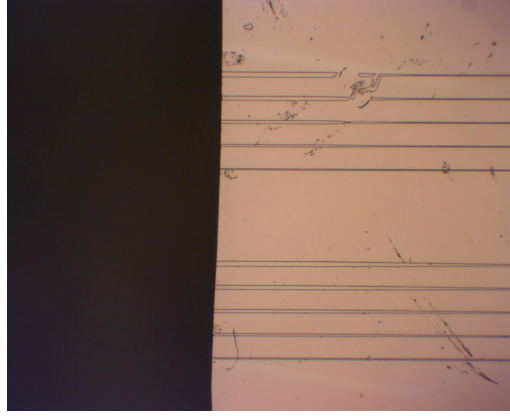


Figure 5.10: An example of a chip diced and cleaved where both a jagged edge and some interrupted waveguides can be observed. This was a 0.33 cm-long chip.

maxima and minima of the fringes in Figure 5.12, the  $\alpha_{TE}$  and  $\alpha_{TM}$  were calculated to be 2.4 dB/cm and 6.2 dB/cm respectively. The difference in  $\alpha$  based on the polarization is due to either (i) edge dislocations in the epitaxial structure due to growth conditions, or (ii) the directionality of the sidewall roughness. The waveguide is multi-modal at 10  $\mu\text{m}$ , and it is also possible that higher modes were excited for the TM polarization. However, there is no clear evidence of a double peak in the FFT to confirm this.

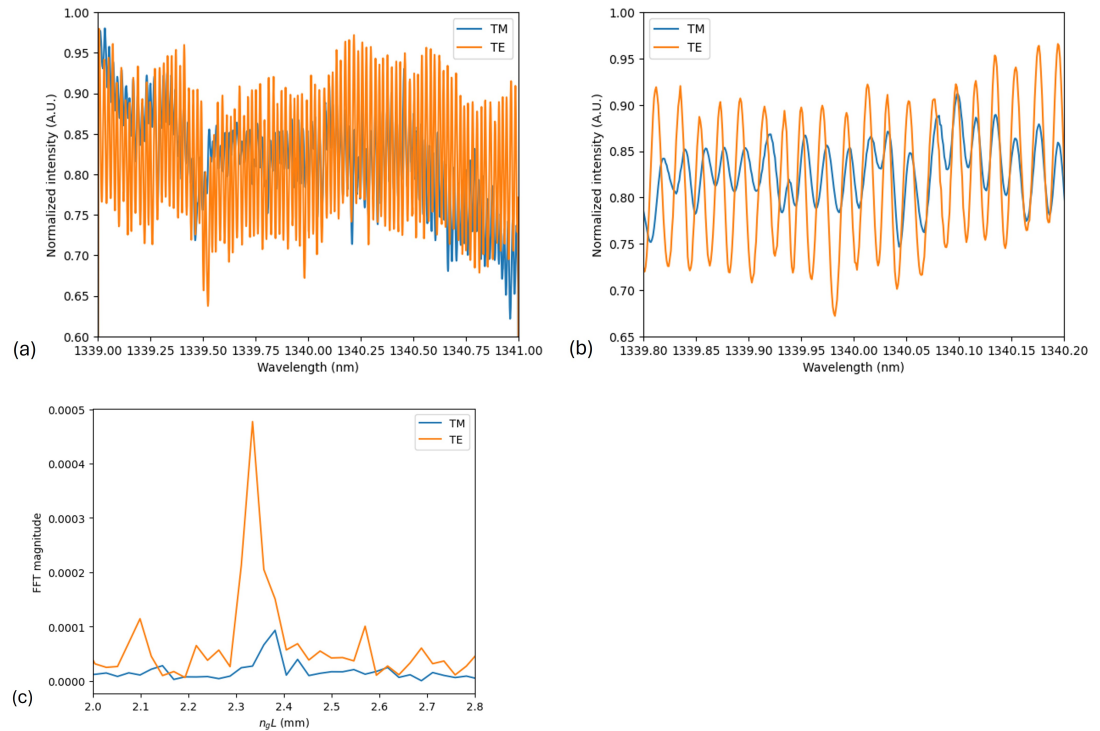


Figure 5.11: The (a) normalized transmission for the 10  $\mu\text{m}$ -wide, 1.8 cm-long waveguide, (b) zoom in on a portion of the spectra, and (c) the FFT of the spectra in order to distinguish between the TE and TM polarizations.

The tapered waveguide structures were difficult to analyze in the same manner as there were a lot of interruptions encountered in the physical chips. This was especially problematic for the 0.7 cm and the 1.8 cm-long chips. Thus, the results presented here come from the 0.22 cm and 0.33 cm-long waveguides, which have already been highlighted as problematic due to the facet quality. As a result, the fringes can be very hard to determine  $K$  from, as shown in Figure 5.12. This low  $K$  however may also be due to the impact of the long waveguide between the input/output tapers being of widths = 1, 2  $\mu\text{m}$  and thus light interacting heavily with the sidewalls and being scattered. The mode profiles at this width can be observed in Figure 5.13.

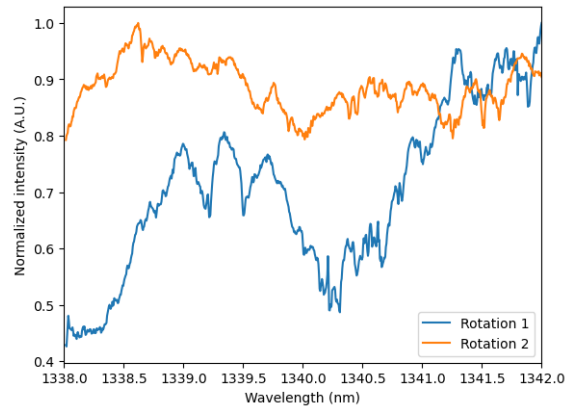


Figure 5.12: An example of a tapered structure where although light is coupled in, a  $K$  value cannot be determined accurately to give meaningful  $\alpha$  values. The tapered structure used here had taper lengths = 50  $\mu\text{m}$ , taper width = 1  $\mu\text{m}$  and was 0.33 cm long in total.

The results from the measurable tapered waveguides are presented in Table 5.2: the average power was obtained from the resulting transmission and compared to the input power to get a loss in dB. In order to estimate the tapered waveguide loss, the fiber-fiber coupling is subtracted from the average power. This fiber-fiber coupling was measured to be -13.72 dB for an input power of 2 mW.



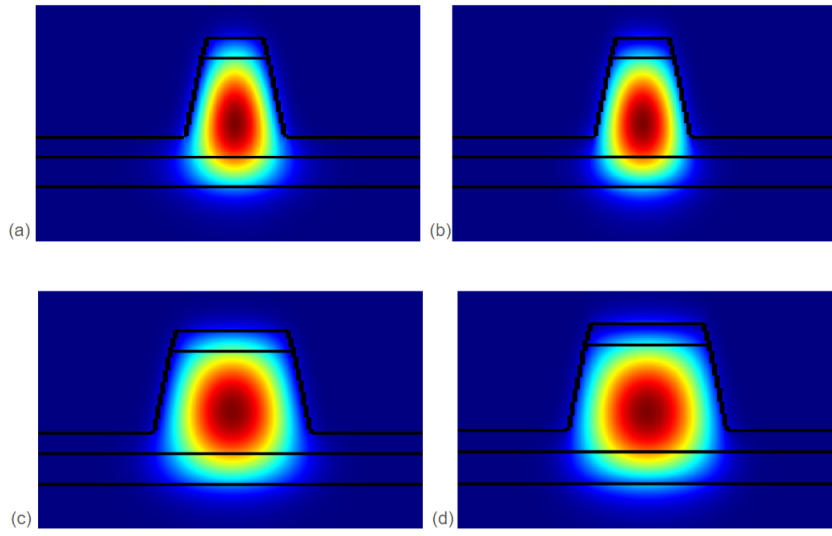


Figure 5.13: The (a)  $E_x$  for the  $TE_0$  mode and (b)  $E_y$  for the  $TM_0$  mode for 1  $\mu\text{m}$ -wide tapered region, and (c)  $E_x$  for the  $TE_0$  mode and (d)  $E_y$  for the  $TM_0$  mode for the 2  $\mu\text{m}$ -wide tapered region

| Total loss for tapered structures for single etch |                                |                               |                             |                    |                    |
|---------------------------------------------------|--------------------------------|-------------------------------|-----------------------------|--------------------|--------------------|
| Total device length (mm)                          | Taper length ( $\mu\text{m}$ ) | Input width ( $\mu\text{m}$ ) | Taper tip ( $\mu\text{m}$ ) | Total TE loss (dB) | Total TM loss (dB) |
| 2.2                                               | 50                             | 4                             | 2                           | -15.48             | -19.72             |
|                                                   | 200                            |                               | 1                           | -17.51             | -15.34             |
|                                                   |                                |                               | 2                           | -14.67             | -15.64             |
|                                                   | 500                            |                               | 1                           | -16.25             | -13.02             |
|                                                   |                                |                               | 2                           | -12.4              | -14.26             |
|                                                   |                                | 10                            | 1                           | -15.84             | -16.89             |
| 3.3                                               |                                |                               | 2                           | -21.55             | -19.53             |
|                                                   | 50                             | 4                             | 1                           | -15.32             | -14.84             |
|                                                   | 500                            |                               | 2                           | -23.07             | -24.31             |
|                                                   |                                | 10                            | 2                           | -21.24             | -22.66             |

Table 5.2: The loss values recorded for the measurable tapered structures in dB

## 5.4 Second iteration of designs

### 5.4.1 Waveguide Fabrication

The purpose of the second generation of devices was to fabricate the mode adapter design outlined in Chapter 3 based on the processing for the first generation. The GDS layout for this generation can be found in Appendix B. The processing for this mode adapter was designed as a self-aligned process: an existing pattern in the first waveguide level is used for etching features in the second waveguide level. A trial run for fabricating these devices was carried out using optical lithography for both waveguide levels. However, the misalignment of the tapered waveguides when using optical lithography levels was  $\geq 1 \mu\text{m}$ , as seen in Figure 5.14. The process flow was thus modified to use e-beam lithography instead. The process flow is outlined in Figure 5.15 and is

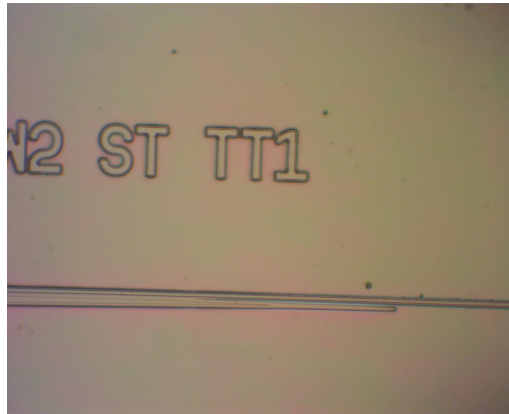


Figure 5.14: An example of the taper misalignment for the trial run with 2 optical lithography levels

as follows:

- A  $1.3 \mu\text{m}$  thick SiN layer was deposited onto the sample using PECVD
- The shallow ridge pattern was then defined using e-beam lithography.
- A 50 nm thick chrome (Cr) layer was then evaporated onto the sample, and a liftoff process was performed, with only the waveguide patterns covered in Cr.
- The pattern is then transferred into the SiN from Cr via dry etching, and the remaining Cr is removed using a chromium etchant. The purpose of using the dielectric mask in between the Cr and the AlGaIn/GaN rather than directly use the Cr as a hard mask for the AlGaIn/GaN is to try and avoid the transferring of the edge roughness from the Cr.

- A 1  $\mu\text{m}$ -thick layer of  $\text{SiO}_2$  was then deposited using PECVD, and the deep etch ridge was defined again through e-beam. The misalignment between the first and second lithography levels was measured to be 0.13  $\mu\text{m}$ : optical images of the second level after the e-beam exposure can be seen in Figure 5.16.
- 50 nm Cr was again evaporated, and the liftoff also carried out
- The deep etch pattern was transferred from the Cr to the  $\text{SiO}_2$  via dry etching, and the residual Cr was removed with the chromium etchant again.
- The self-aligned process occurred in the next step: the deep etch pattern was etched at a depth of 1  $\mu\text{m}$  using  $\text{BCl}_3$  dry etching into the AlGaIn/GaN, with the  $\text{SiO}_2$  acting as a hard mask in the tapered regions, and the SiN acting as hard mask in the 1  $\mu\text{m}$  regions. The remaining  $\text{SiO}_2$  was removed using BOE.
- The remaining SiN was then used as a hard mask to etch 0.3  $\mu\text{m}$  into the AlGaIn/GaN to form the shallow ridge region. After this etch, the residual SiN was removed using the  $\text{CF}_4$  dry etch. The sidewalls after the dry etching can be seen in Figure 5.17, giving a sidewall angle of  $63^\circ$ .
- The trenches for  $\mu\text{TP}$  were then patterned via optical lithography, and then etched using the  $\text{BCl}_3/\text{H}_2$  dry etching recipe. The photoresist acted as the mask for the etching, and was then removed afterwards via  $\text{O}_2$  plasma ash.
- In the same manner as in the previous iteration, a thick 3  $\mu\text{m}$  layer of  $\text{SiO}_2$  was deposited onto the waveguides to protect the waveguides during the partial dicing and cleaving to form the facets. The  $\text{SiO}_2$  was then removed afterwards using BOE.

After the dicing and cleaving, some of the facets from the 0.7 mm chip were investigated under the SEM, as shown in Figure 5.18. Already there is a wide range of facet quality, with some of them appearing to have been broken off during the cleaving/dicing process.

#### 5.4.1.1 Results

The  $\alpha_{TE}$  and  $\alpha_{TM}$  for the straight waveguides are presented in Figure 5.19, along with the  $\alpha L$  vs  $L$  in Figure 5.20. Both waveguide widths are limited by

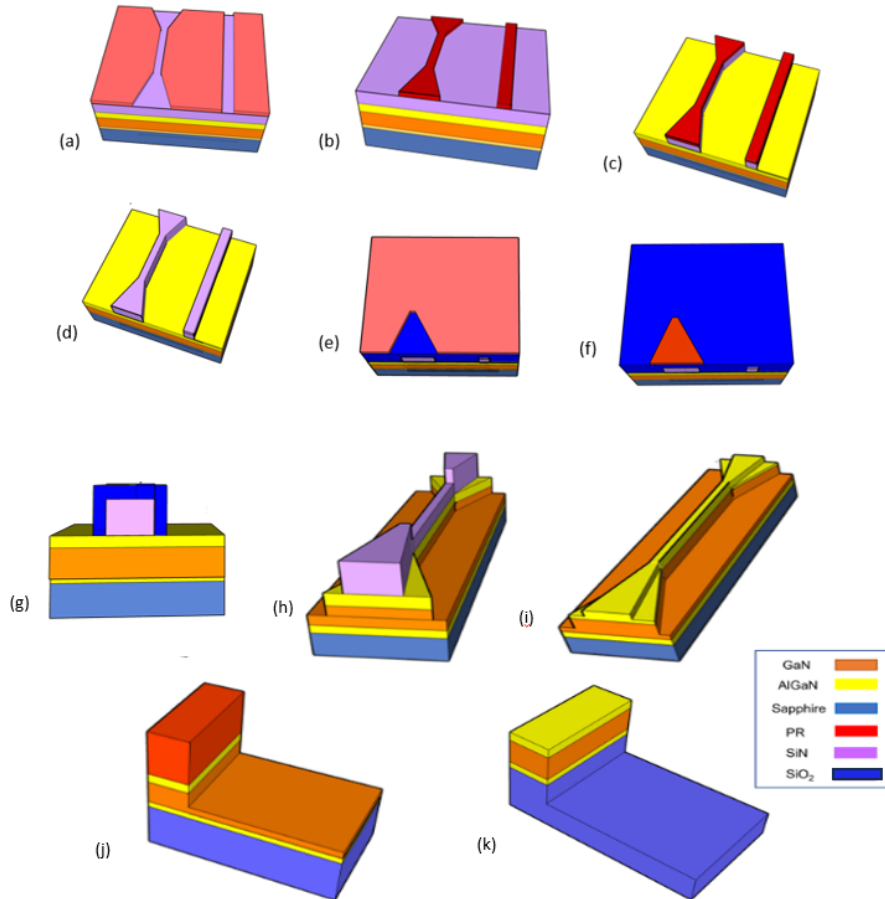


Figure 5.15: The fabrication process for the second generation of waveguide devices: (a) SiN is deposited onto the sample, and the shallow ridge pattern is defined via e-beam lithography; (b) Cr is evaporated onto the sample and liftoff is performed; (c) the dry etching then transfers the pattern from Cr into the SiN; (d) the Cr is removed; (e) SiO<sub>2</sub> is deposited onto the sample and the deep etch pattern is defined via e-beam lithography; (f) Cr is evaporated and the liftoff is performed; (g) the deep etch pattern is then transferred from the Cr into the SiO<sub>2</sub>, and the remaining Cr is removed using a chromium etchant; (h) the pattern is transferred from the SiO<sub>2</sub> to the AlGaIn/GaN using a BCl<sub>3</sub> dry etch and the remaining SiO<sub>2</sub> is removed via BOE; (i) the shallow ridge pattern is then transferred to the AlGaIn/GaN from the SiN using the same dry etching recipe, and the remaining SiN is removed using CHF<sub>3</sub>; (j) the trench for  $\mu$ TP is defined via optical lithography; (k) the pattern is dry etched via the AlGaIn/GaN and into the sapphire using a BCl<sub>3</sub>/H<sub>2</sub> with the photoresist acting as a mask, and this photoresist is then removed via O<sub>2</sub> plasma ash once the etch is completed

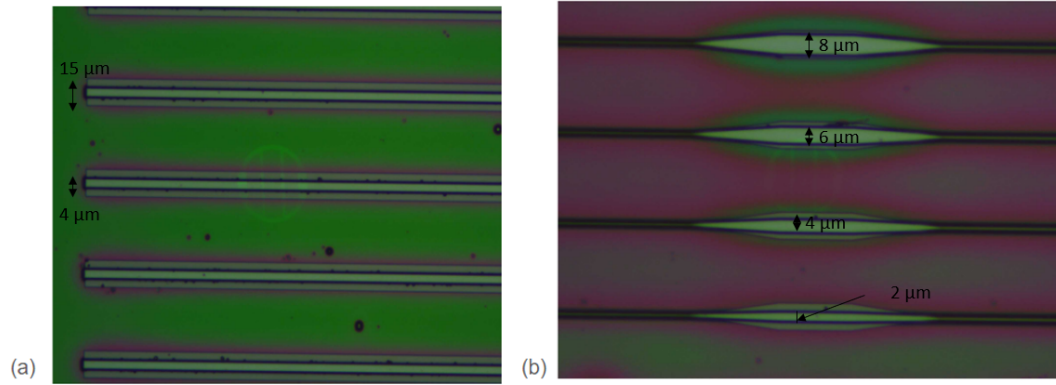


Figure 5.16: E-beam lithography for the 2nd level: we can see it aligned to the 1st level waveguide for (a) the straight waveguides, and (b) the tapered waveguides. The misalignment between the levels was  $\approx 130$  nm

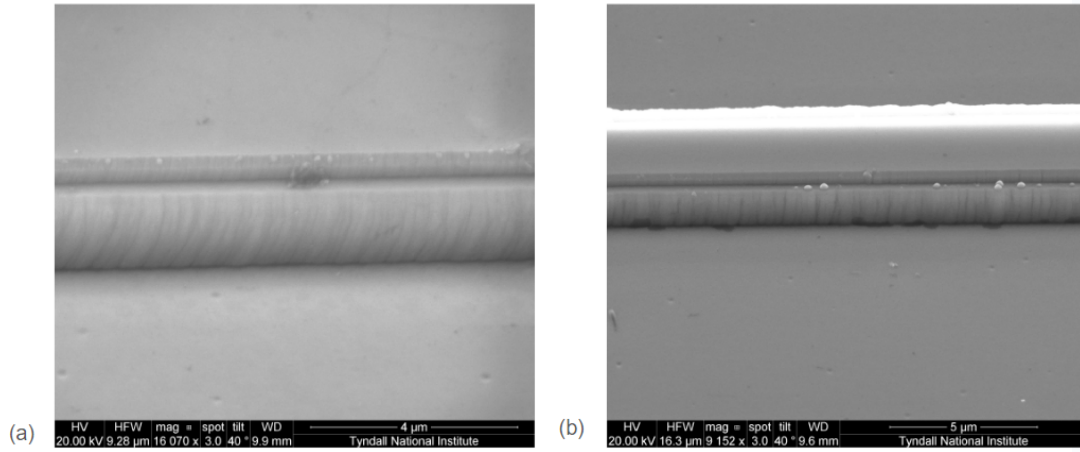


Figure 5.17: (a) A close-up and (b) zoomed-out SEM of the double-etched waveguide sidewall to assess the roughness after dry etching.

the number of data points available to be able to do a fit. However, it can be seen for the 10 μm waveguide width that the data for the 1.8 cm is more in line with the 0.22 cm and 0.33 cm chips, suggesting that there is less of a variation in facet reflections than for the single etched chip. The Fabry-Perot fringes are presented for the 10 μm-wide, 0.22 cm long waveguide in Figure 5.21. The  $\alpha_{TE}$  and  $\alpha_{TM}$  extracted from the fringes were 4.52 dB/cm and 9.68 dB/cm. Overall, the range of the  $\alpha$  obtained for the straights is similar to the first iteration, despite the change in lithography used.

The point of this iteration was to be able to demonstrate the mode adapter design to work. However, the taper data was of similar poor quality to the previous iterations due to poor facet quality and low yield of structures, and are presented in Table 5.3. Two similar tapered chains, one from this iteration

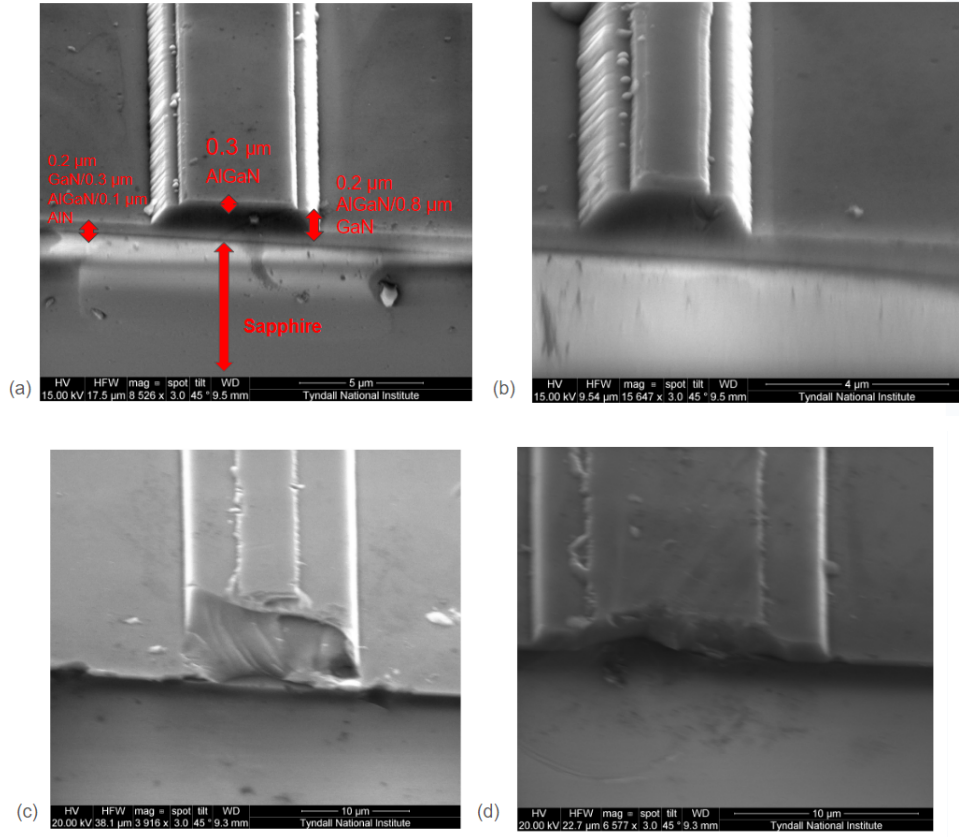


Figure 5.18: The facet quality along one of the chips: we can see that in (a) and (b) the facets are of sufficient quality after the partial dicing and cleaving outlined earlier. From a ridge formation point of view, the process of forming the facets look to be successful and in line with the trial runs carried out in Chapter 4. However, going along the same chip, we can observe damaged facets in (c) and (d).

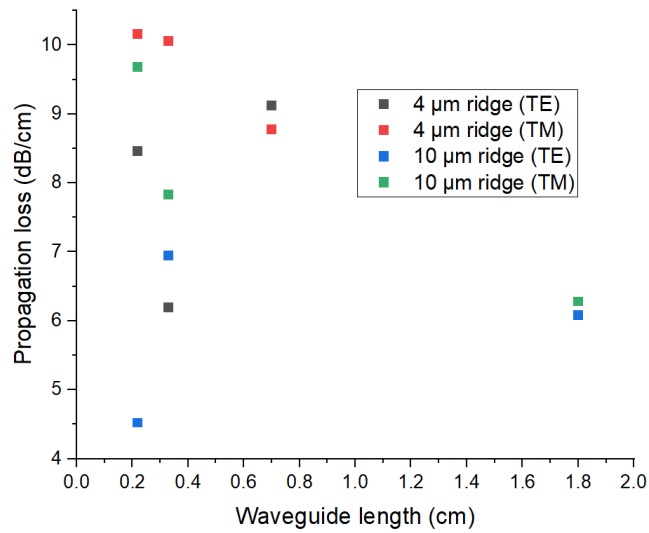


Figure 5.19: The  $\alpha_{TE}$  and  $\alpha_{TM}$  values obtained for the different waveguide lengths for waveguide widths = 4  $\mu\text{m}$  and 10  $\mu\text{m}$  using the Fabry Perot method

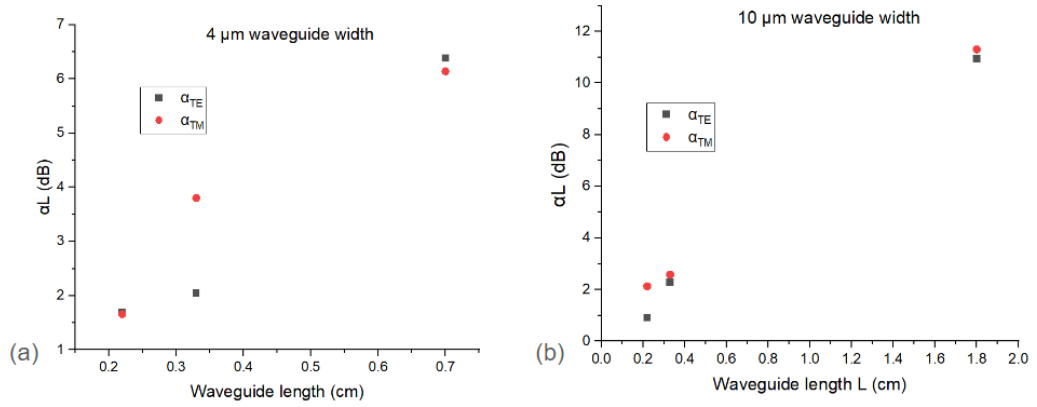


Figure 5.20: The  $\alpha_{TE}L$  and  $\alpha_{TM}L$  values obtained for the different waveguide lengths for waveguide widths (a) 4  $\mu\text{m}$  and (b) 10  $\mu\text{m}$  using the Fabry Perot method

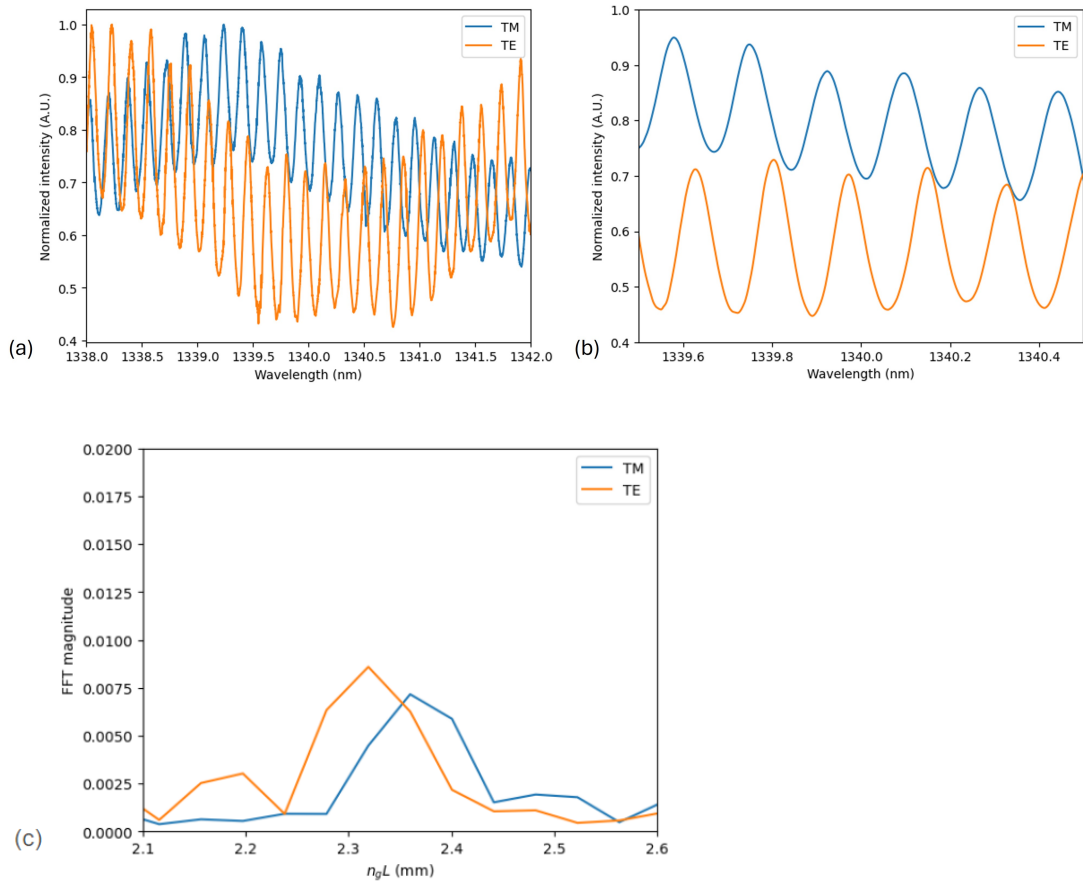


Figure 5.21: The (a) normalized transmission for the 10  $\mu\text{m}$ -wide, 0.22 cm-long waveguide, (b) zoom in on a portion of the spectra, and (c) the FFT of the spectra in order to distinguish between the TE and TM polarizations

and the other from the first iteration, were compared to see if the double taper was more effective than the single taper. These figures are presented in Table 5.4: we can see from the calculations that the double taper structure is less lossy compared to the single taper. Low yield of the tapered chains after



processing affected the study, but this shows promise for the double tapered design.

### 5.4.2 $\mu$ TP Laser-Waveguide Coupling

The next step was to couple laser light to the waveguides via  $\mu$ TP. Both lasing structures required a thin layer of intervia to aid bonding to the sapphire. For the InP QW lasers, this was due to roughness  $\approx 20$  nm from etching the AlInAs release layer. These coupons can be observed in Figure 5.22. The intervia was spin coated onto the sample to give a thickness  $< 50$  nm.

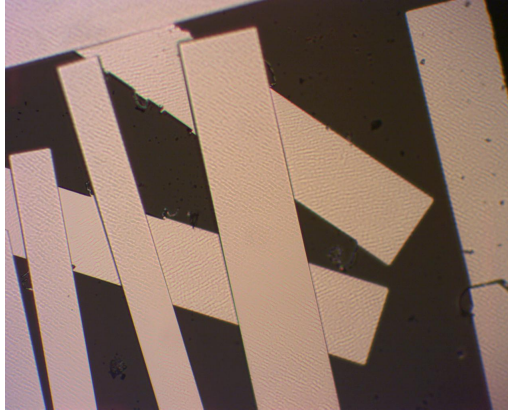


Figure 5.22: The backside of test coupons during release: it can be seen that there is minimal to no roughness on the backside, which is advantageous for bonding to the target substrate

#### 5.4.2.1 QW laser on flat Si and sapphire

The QW lasers were first transfer printed to the edge of a (i) flat Si piece and (ii) flat sapphire piece (with a thin adhesive layer  $< 50$  nm on both substrates) in order to characterise the maximum output power and threshold current. The laser ridge width and cavity length were  $2\ \mu\text{m}$  and  $0.55\ \mu\text{m}$  respectively. The optical power was measured using a Newport 918D-IG-OD3 InGaAs detector connected to a Newport 844-PE-USB power meter. The lasers were characterized under continuous-wave (CW) operation, using a Keithley 2602A source. The temperature of the chip was controlled via a TEC that was connected to the testing mount that the  $\mu$ TP laser-on-Si/sapphire was placed on. The threshold current  $I_{TH}$  for the QW laser printed on Si is 24 mA, while for the laser printed on sapphire it is higher at 34 mA. This higher threshold current is attributed to sapphire possessing a poorer thermal conductivity



| Total loss for tapered structures for double etch |                                |                               |                             |                    |                    |  |
|---------------------------------------------------|--------------------------------|-------------------------------|-----------------------------|--------------------|--------------------|--|
| Total device length (mm)                          | Taper length ( $\mu\text{m}$ ) | Input width ( $\mu\text{m}$ ) | Taper tip ( $\mu\text{m}$ ) | Total TE loss (dB) | Total TM loss (dB) |  |
| 2.2                                               | 200                            | 4                             | 1                           | -16.49             | -15.76             |  |
|                                                   |                                |                               | 2                           | -6.6               | -6.53              |  |
|                                                   |                                | 10                            |                             | -10.17             | -13.08             |  |
|                                                   | 500                            | 4                             |                             | -19.93             | -28.98             |  |
|                                                   |                                | 10                            | 1                           | -17.01             | -16.62             |  |
|                                                   |                                |                               | 2                           | -13.61             | -10.02             |  |
| 3.3                                               | 50                             | 4                             | 2                           | -13.32             | -13.28             |  |
|                                                   |                                | 10                            | 1                           | -18.3              | -15.22             |  |
|                                                   |                                |                               | 2                           | -13.37             | -14.34             |  |
| 7                                                 | 200                            | 10                            | 2                           | -9.32              | -9.88              |  |
|                                                   | 50                             | 4                             | 2                           | -14.02             | -13.19             |  |
|                                                   |                                | 10                            |                             | -12.11             | -13.46             |  |
|                                                   | 200                            |                               | 1                           | -20.85             | -15.5              |  |

Table 5.3: Data obtained for the double tapered structures

| Comparison between single vs double etched tapered waveguide |                   |                  |                |               |                    |                 |                    |                 |
|--------------------------------------------------------------|-------------------|------------------|----------------|---------------|--------------------|-----------------|--------------------|-----------------|
| Structure                                                    | Taper length (μm) | Input width (μm) | Taper tip (μm) | No. of tapers | Total TE loss (dB) | Loss/taper (dB) | Total TM loss (dB) | Loss/taper (dB) |
| Single etch                                                  | 500               | 10               | 2              | 30            | -29.12             | -0.97           | -35.51             | -1.18           |
| Double etch                                                  |                   |                  | 1              |               | -19.06             | -0.64           | -21.29             | -0.71           |

Table 5.4: Comparing the effectiveness of the double-tapered structure to the single-etched taper structure; it can be seen that the single-etched structure is slightly lossy, but the study is limited in terms of available structures.

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( $\sigma_{\text{sapphire}} = 40 \text{ Wm}^{-1}\text{K}^{-1}$ ) than Si ( $\sigma_{\text{Si}} = 148 \text{ Wm}^{-1}\text{K}^{-1}$ ). A maximum output optical power of (i) 2.5 mW for the device printed on Si and (ii) 2.7 mW for the device printed on sapphire is recorded at a current of 80 mA. Evidence of the thermal conductivity having an impact on measurements can also be seen when comparing the L-I curves: the L-I for the device printed on sapphire suffers a more drastic thermal rollover than the device printed on Si. The characteristic temperature  $T_0$  is an additional measure of the thermal stability of a lasing device:  $I_{TH}$  varies with temperature  $T$  as

$$I_{TH}(T) = I_{TH}(T_1) \exp\left(\frac{T - T_1}{T_0}\right) \quad (5.6)$$

where  $I_{TH}(T_1)$  is the threshold current density at  $T_1 = 293.15 \text{ K}$ . The higher the  $T_0$  value, the more stable the lasing device is. The L-Is for varying temperature were recorded for both devices, and the extracted  $I_{TH}$  values plotted as shown in Figure 5.23. The device printed on sapphire did not lase above  $40^\circ$ , and thus only three data points were obtained. From the fit, the  $T_0$  of the devices were calculated to be 46.3 K on Si, and 32.89 K on sapphire. The similar  $T_0$  values, despite the difference in thermal conductivity of the substrates, is due to the poor thermal characteristics of the InP laser [104]. Spectral characterization of the device printed on Si and on sapphire was conducted using an ANDO AQ36317B optical spectrum analyzer (OSA), with a resolution of 0.02 nm. It can be seen from Figure 5.23 that the spectrum is multi-modal and lases at  $\approx 1347 \text{ nm}$  for the device on Si and at  $\approx 1350 \text{ nm}$  for the device on sapphire at a bias current of 50 mA.

#### 5.4.2.2 QD laser on flat Si and sapphire

The GaAs-based QD lasers were then printed on (i) flat Si and (ii) flat sapphire with a thin adhesive layer  $< 50 \text{ nm}$  on both substrates. The devices were characterised in the same manner as for the InP QW structures. At  $20^\circ\text{C}$ , the  $I_{TH}$  is (i) 16 mA for the device printed on Si, and (ii) 17 mA for the device printed on sapphire. It can be seen from Figure 5.24 that the device printed on sapphire experiences a thermal rollover for bias current  $> 130 \text{ mA}$ , along with a lower output power of 17.5 mW at 80 mA compared to 25 mW for the device printed on Si. The lower output powers and rollover is again attributed to the difference in thermal conductivity of the substrates. The  $T_0$  for  $\mu\text{TP}$  QD lasers were much higher overall than the QW lasers: (i) 157.2 K on Si, and (ii) 82.2 K on sapphire. The AlGaAs layers in the epistructure have higher

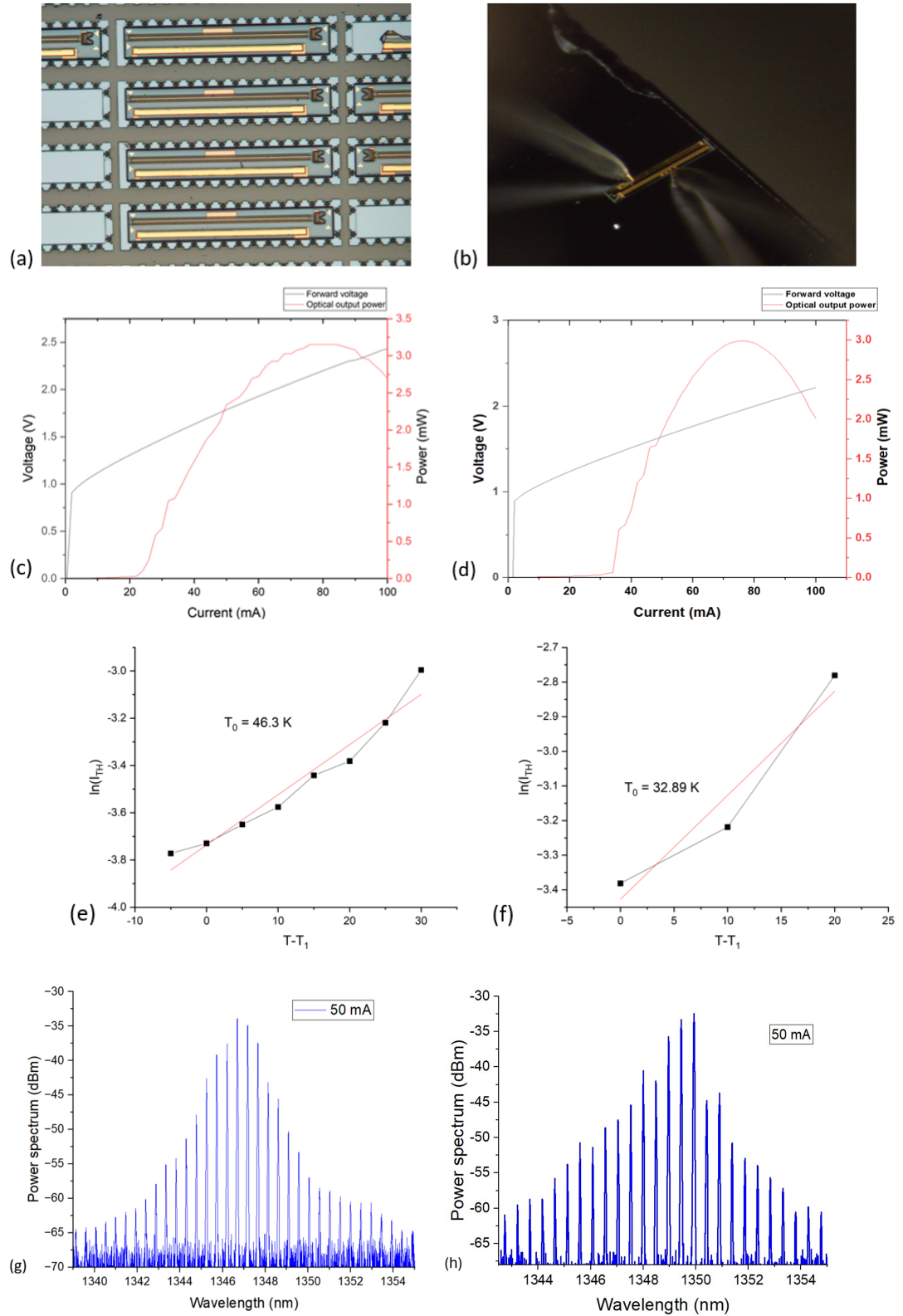


Figure 5.23: The (a) InP-based QW lasers before release for  $\mu$ TP; (b) the devices printed to and probed on a Si test piece; the L-I-V characteristics for the device printed on (c) Si and (d) sapphire at 20°C; the  $T_0$  for (e) device on Si and (f) device on sapphire obtained from temperature dependent L-Is, and (g) the lasing spectra of the device on Si and (h) on sapphire at a bias current of 50 mA.

bandgaps than the InGaAsP layers used in the InP-based devices, thus leading to reduced carrier leakage which improves the performance of the device at increased temperatures. The spectra is also presented in Figure 5.24 for the devices on both substrates at a lasing current of 150 mA. For the device printed on Si, the lasing spectra is centred around 1295 nm and is multimodal. For the device printed on sapphire, the spectra is centred at 1281 nm. It is surprising that the spectra from the device on sapphire lases at a shorter wavelength than the device on Si at the same bias current: as the device operates at a higher temperature on sapphire due to the poor thermal conductivity of the substrate, it is expected that the device would lase at a longer wavelength than the device on Si.

#### 5.4.2.3 Formation of the $\mu$ TP region

As mentioned already in this thesis, a trench has to be etched into the sapphire in order to align the lasing mode to the passive waveguide mode. The GDS design for the transfer printing regions aligned to the waveguide facet can be seen in Figure 5.25. The trenches were designed to be 160  $\mu\text{m}$  wide x 6 mm long, to account for both the dimensions of the lasing devices (QW laser = 80  $\mu\text{m}$  x 550  $\mu\text{m}$ , QD laser = 60  $\mu\text{m}$  x 2 mm), and to also allow for double printing of the coupons. It is difficult to align the  $\mu$ TP trench exactly to the waveguide facet, i.e. achieve a zero gap between the waveguide facet and the start of the trench. Thus a T-bar is designed to connect to the waveguides with a width of 5  $\mu\text{m}$ .

During processing however, it was difficult to achieve an alignment between the trench and the T-bar better than 1  $\mu\text{m}$ . As a result of the misalignment, in some areas the trench overlapped completely with the T-bar region, while in other areas on the chip a ledge was formed between the waveguide facet and the start of the trench, as seen in Figure 5.26. The minimum ledge size measured was 2.3  $\mu\text{m}$ ; thus depending on where the devices are printed, the lasing devices will always be at least 2.3-5  $\mu\text{m}$  away from the waveguide facet in the longitudinal direction.

#### 5.4.2.4 Lasers $\mu$ TP and coupled to AlGaIn/GaN waveguide

The QW and QD lasers were then transfer printed to the sapphire trenches, and characterized in the manner shown in Figure 5.27. To determine the coupling efficiency of the laser to the waveguide, the coupled L-I was

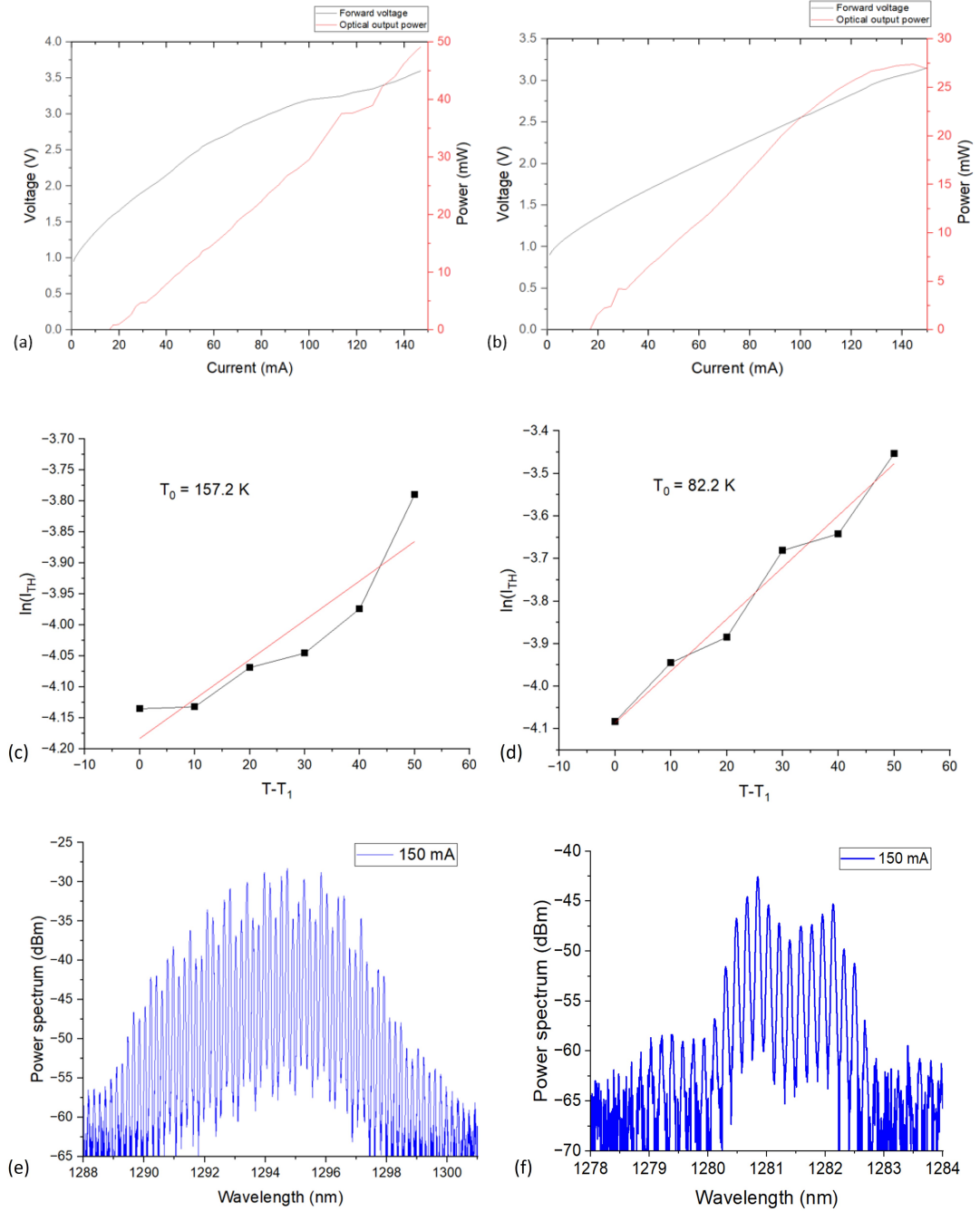


Figure 5.24: The L-I-V characteristics for the GaAs-based QD devices printed on (a) Si and on (b) sapphire at 20°C; the  $T_0$  for the device (c) on Si, and (d) on sapphire; and the spectra at 150 mA for the device on (e) Si and (f) on sapphire.

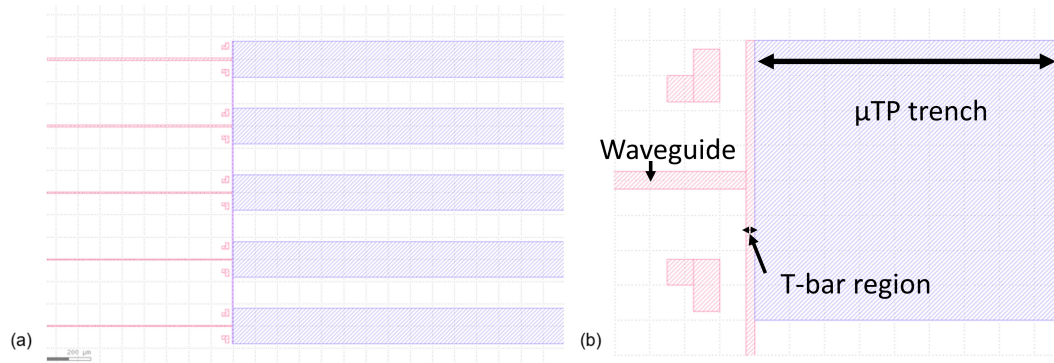


Figure 5.25: (a)  $\mu$ TP trenches in the GDS, along with a (b) zoom-in of the area: as zero misalignment is hard to achieve, a T-bar is included in the design (in pink, connected to the waveguides). The pink L-shaped patterns are the alignment marks for printing the laser to the waveguide

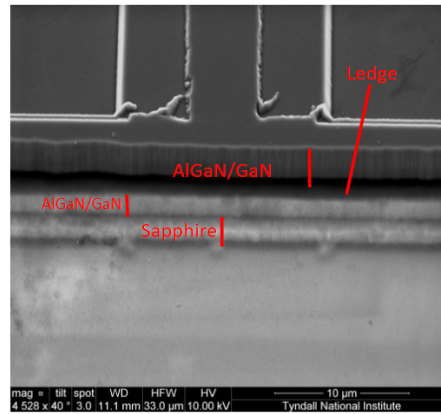


Figure 5.26: An example of the ledge formed between the waveguide facet and the trench as a result of misalignment during processing.

obtained. To estimate the coupling efficiency from the L-Is, the power obtained at a defined current is compared to the power obtained at that current for the reference lasers. It can be seen from the L-Is presented in Figure 5.28 for both the devices that the best coupling between laser and waveguide was with a  $4\ \mu\text{m}$ -wide,  $0.64\ \text{cm}$ -long straight waveguide; an optical output power of  $32\ \mu\text{W}$  was obtained for the coupled QW device at  $80\ \text{mA}$ , while for the QD laser an output power of  $200\ \mu\text{W}$  was obtained. The coupling efficiencies was estimated to be (i)  $1.6\ \%$  for the QW device, and (ii)  $1.1\ \%$  for the QD device. Both the longitudinal distance and the air gap are contributing factors to the low coupling efficiency. The separation between the QD laser and the waveguide facet was measured to be  $7.3\ \mu\text{m}$ , which corresponds to a coupling loss of  $8\ \text{dB}$  as shown in Figure 5.29. The simulations are carried out assuming perfect alignment in the transverse and lateral directions. The air gap also creates undesired scattering losses, which appears as oscillations in the plot; to

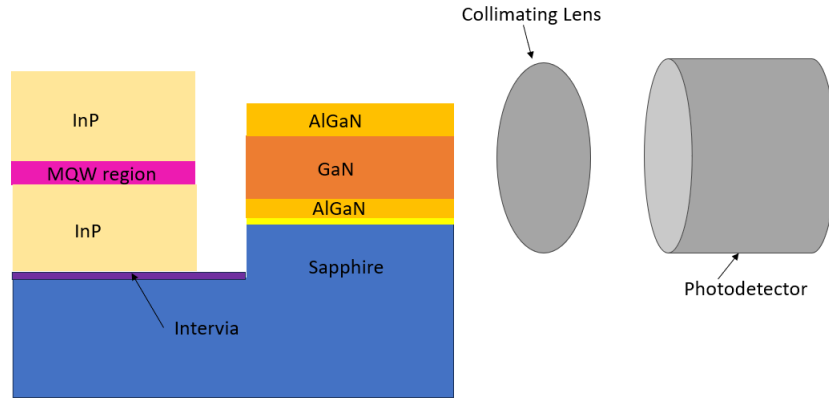


Figure 5.27: Schematic of edge-coupling from the integrated laser to the AlGaIn/GaN waveguide and the coupling from the waveguide facet to a broad area detector.

reduce this effect a epoxy material can be used to fill the gap, also shown in the simulations in Figure 5.28. At the same longitudinal distance, the coupling loss is reduced down to  $<6$  dB. Such a material reduces the reflectivity of the waveguide facet from  $\approx 15\%$  to  $\approx 3\%$ , thereby decreasing the coupling loss.

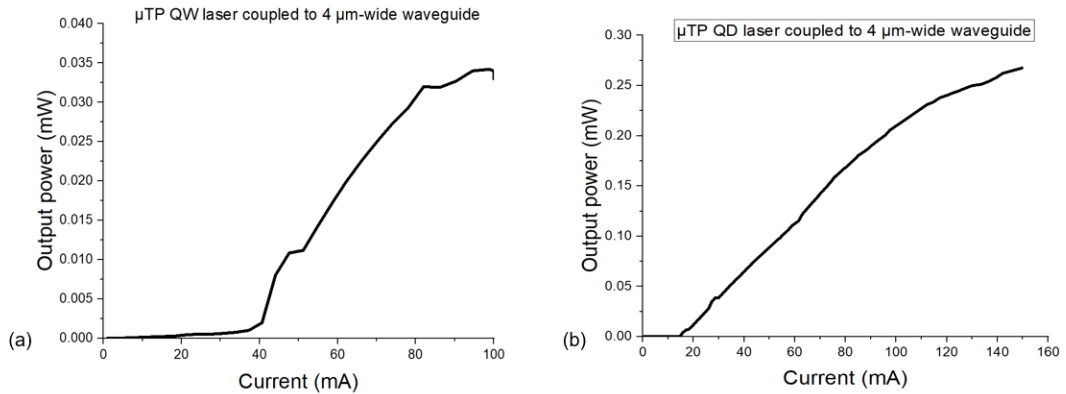


Figure 5.28: The coupled L-I at 20°C for (a) the QW laser and (b) the QD laser, both coupled to a 4  $\mu$ m-wide waveguide.

#### 5.4.2.5 QD laser coupled to AlGaIn/GaN waveguide: polymer infill

The L-I characterisation is conducted again for the QD laser coupled to the waveguides after infilling the longitudinal spacing between the waveguide facet and laser facet with an epoxy material (Norland 61 UV sensitive fiber glue, refractive index = 1.56). This glue was cured for 2 minutes using UV light. The device coupled to the waveguide after filling the gap can be seen in Figure 5.30. The temperature-dependent L-Is for coupling to the 4  $\mu$ m-wide waveguide after the curing can be seen below in Figure 5.31. The inset of this



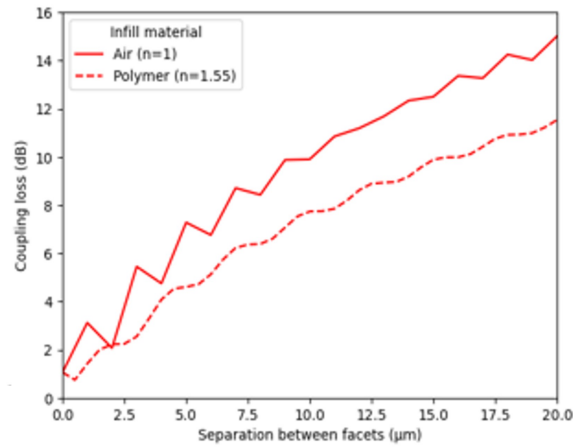


Figure 5.29: The simulated coupling loss as a function of longitudinal misalignment for the fully-etched, 4  $\mu\text{m}$ -wide waveguide

figure also shows the near-field image of the waveguide while the laser is biased at 80 mA and 20°C. The 2D scan is recorded by scanning the single mode lensed fiber across the waveguide in lateral and vertical direction using the Elliot Scientific DALI E-2100 piezo autoalign controller. At 80 mA, an output power of 2.3 mW is measured from the waveguide end. The measured threshold increase of 2 mA is taken to be small allowing an estimate of the coupling efficiency by comparing the power obtained at a defined current and temperature with that for the reference laser in Section 5.4.2.2. This leads to a coupling efficiency of 10.3%. The excess loss of the 0.64 cm-long, 4  $\mu\text{m}$ -wide waveguide is  $-2.88$  dB. In addition, the exit AlGaIn/GaN waveguide facet has a reflectivity  $\approx 15.5\%$ , leading to an estimated initial internal waveguide power of 5.3 mW at 80 mA and a realistic coupling efficiency of  $> 20\%$ . The  $T_0$  obtained from the temperature-dependent L-Is is 82 K, which is higher than that of the reference device on sapphire. At 70°C, an output power of 1.5 mW is measured at 100 mA. For all of the temperature-dependent L-I measurements, kinks were observed in the output power at bias currents above 70 mA. The detail of the lasing spectrum at 80 mA is shown in Figure 5.31(b); from this it can be seen that additional modes to the Fabry-Perot longitudinal modes are evident at this current. The behaviour of the coupled spectra may be due to feedback from the QD device and needs to be investigated further to understand the dynamics at play [105].

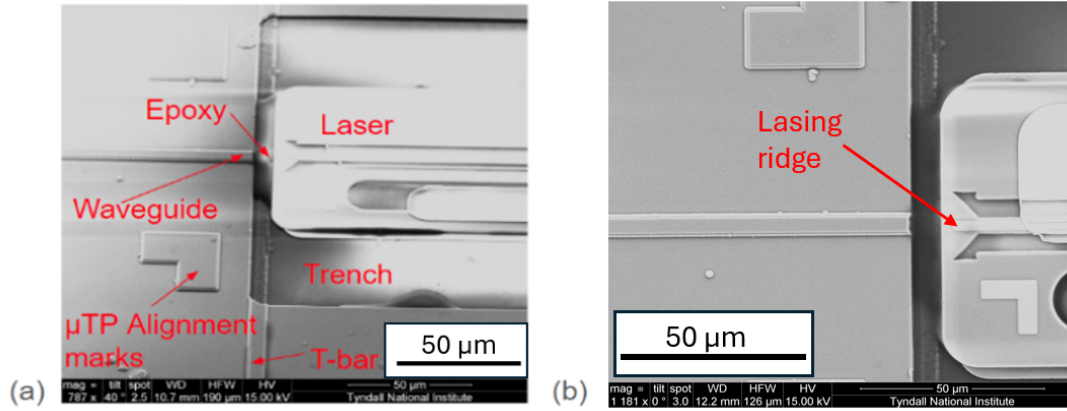


Figure 5.30: (a) SEM of the QD laser coupled to the 4 μm-wide waveguide after the gap between facets is filled with epoxy; (b) zooming in of the same region [105]

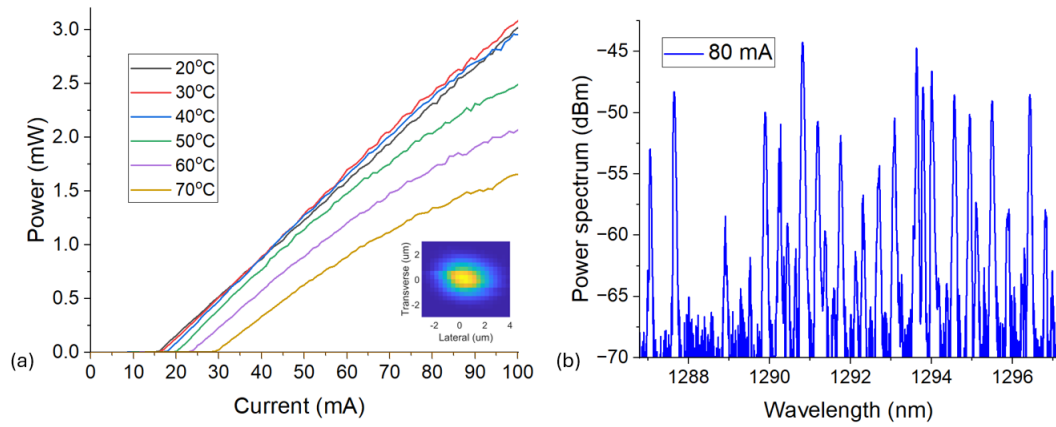


Figure 5.31: (a) The temperature-dependent L-Is for the QD laser coupled to the AlGaIn/GaN waveguide after filling the gap with index-matching glue, (b) the spectra obtained at 80 mA at 20°C [105]

## 5.5 Conclusion and Discussion

In this chapter, AlGaIn/GaN waveguides were successfully fabricated and characterized, with the facets formed from the cleaving and dicing as outlined in Chapter 4. The facet reflections as a result of the varying facet quality from cleaving is causing issues in being able to determine trends in the results. Etched facets would be one way of making sure that there is less variability in the facets, but would require a much deeper etch into the sapphire for fiber-coupling. As already outlined in Chapter 4, it is difficult to etch the required depth due to the sapphire etch rate and selectivity to the mask material used. Alternatively, the dicing line would have to be located around 20-30 μm away from the etched facet in order to be able to bring the fiber at its working distance from the waveguide facet. Polishing the facets after dicing is another solution, but this is a time-consuming process to do for multiple

waveguide facets.

A more feasible solution would be to have multiples of the same designs on the one chip, i.e. one chip consists of straight waveguides only, another could have tapered structures. While keeping the same methods of cleaving and dicing would still cause the facet variation, there would be enough devices to be able to determine the intrinsic value of  $\alpha$  without the effect of the facet. Keeping the waveguide lengths long, i.e. test lengths between 0.7 - 2 cm could reduce cleaving issues. Going for lengths longer than 2 cm would require moving away from quarter wafer pieces for processing, but the estimated high propagation losses for the structures may make it difficult to couple out a sufficiently powerful signal. Using a grating coupler for testing structures would generally be a solution, but it has already been shown in Chapter 3 that the optimal design for this epitaxial structure results in multi-mode behaviour. To suppress the higher order modes for the grating coupler, a thinner epitaxial structure is required.

The propagation losses presented in this chapter are between 2.4-14 dB/cm for the straight waveguides depending on the polarization, which would suggest that optimization of the dry etching process is needed to improve the sidewall roughness. The best propagation loss achieved in this work was 2.4 dB/cm for a 10  $\mu\text{m}$  wide, 1.8 cm long waveguide for TE-polarized light. There is some indication that the double-tapered structure may be more effective than the single taper for mode adapting, but this study suffered from low yield of devices and would require further experiments to verify.

Both the InP QW and GaAs QD lasers were successfully transfer printed and coupled to the AlGaIn/GaN waveguide. To the best of our knowledge this is the first time that such structures have been heterogenously integrated to the GaN platform at operating wavelengths near 1.31  $\mu\text{m}$ . The presence of an air gap between the waveguide and laser facets due to separation arising from a ledge formed during processing limited the coupling efficiencies to 1.1-1.6 %. Filling the gap with an optical glue improved the efficiency to 12.5 %. This coupling efficiency is comparable to that of similar devices integrated on SOI/SiN platforms [106]. As well as the issue of the gap arising from the ledge, improving the performance of the AlGaIn/GaN waveguides and thus reducing waveguide propagation losses is key to improving the laser-waveguide coupling efficiency.

# Chapter 6

## Conclusion and future work

### 6.1 Overview of contributions to the state of the art

Over the duration of this work, the edge-coupling of both InP-based and GaAs-based lasers to AlGaIn/GaN waveguides via  $\mu$ TP were demonstrated. This is the first time that a laser of any operating wavelength has been heterogeneously integrated to a GaN-based waveguide platform, extending the possibility of using nitride-based PICs for data-communications and other applications. With the aid of an index-matching epoxy, the coupling efficiency of the GaAs QD laser to the AlGaIn/GaN waveguide was  $> 20\%$ , with 2.3 mW of light power recorded at 80 mA bias current [105]. The high power, performance at higher temperatures and low threshold current of QD lasers on the GaN/sapphire substrate demonstrates that micro-transfer printing can offer high performance in integrated photonics.

The coupling efficiency was also dependent on the GaN waveguide design: an AlGaIn/GaN epitaxial structure with low index contrast was designed to best match the lasing modes of the available 1.3  $\mu$ m-emitting lasers, as well as relaxing the  $\mu$ TP tolerances. While this epitaxial structure was ideal for tolerant edge-coupling, and could also be converted into a structure more suitable for components such as waveguide bends, it was found from simulations that the epitaxial thickness limited the potential of introducing components such as grating couplers and MZMs via LiNbO<sub>3</sub> integration. Thus, a thinner epitaxial structure is proposed for these functionalities. The proposed and simulated designs for the (i) polarization converters based on

structural asymmetry and (ii) the MZM configuration based on evanescent coupling to a LiNbO<sub>3</sub> coupon are the first demonstrations of these types of structures on the GaN platform.

For etching the AlGaIn/GaN waveguides, a pure BCl<sub>3</sub> etch was developed to prevent the formation of pillars. However, this etch resulted in sloped waveguide sidewalls: while this slope was not an issue for the structures fabricated in this work, this might pose a challenge for more complex structures. In order to match the active lasing mode with that of the passive waveguide mode, a trench needed to be etched into the AlGaIn/GaN epilayers and sapphire substrate. While the hardness of sapphire proved challenging for developing an etch with suitable etch rate and selectivity, a BCl<sub>3</sub>/H<sub>2</sub> dry etch was developed and was sufficient for producing the required etch depth of 1  $\mu$ m into the sapphire. Despite the smooth surface of the sapphire trench after dry etching, a thin adhesion layer was needed to aid the printing of both the InP QW laser and the GaAs QD laser. In the case of the InP QW laser, this was due to roughness on the coupon backside. A method of creating waveguide facets for fiber coupling using partial dicing and cleaving was also developed during this work. While facets with minimal roughness can be produced using this method, it was found that there was facet variability for shorter cleaved waveguide lengths.

The AlGaIn/GaN waveguides were characterized using the Fabry-Perot method, with the propagation losses for the straight waveguides ranging from 2.4-14 dB/cm depending on the light polarization. This spread of results was due to the facet variation for the shorter waveguide lengths characterized. A low yield of the tapered structures also prevented the extraction of a conversion efficiency for varying taper length, and for assessing whether the double-etched tapered structure was better for mode adapting. This efficiency was aided by filling the gap between the lasing facet and waveguide facet with an epoxy, thus reducing the scattering that arises from (i) the air gap and (ii) the ledge that forms from aligning the trench region to the waveguide facet region during processing.

This chapter outlines improvements that could be made to the work carried out so far, and also outlines potential steps for the future of GaN as a PIC.

## 6.2 Improvements in the waveguide fabrication process

The  $\text{BCl}_3$  etch used to form the AlGaIn/GaN waveguides provided angled sidewalls which were not initially taken into account when first designing the structures. While this did not pose issues for the designs that were fabricated, there could potentially be issues for (i) designs featuring directional couplers, where a certain amount of light couples over based upon the gap in between the waveguides, and (ii) the grating coupler design. Experiments would have to be carried out to see the effect of the dry etch parameters on the sidewall angles. Changing the gas flow by adding  $\text{Cl}_2$  may also help the verticality, although we know from experience that a  $\text{Cl}_2/\text{BCl}_3$  (with  $\text{Cl}_2$  as the majority) produces a high density of micropillars. Work also needs to be done to improve the roughness of the sidewall etch: from investigation for both waveguide generations, it appears that the roughness is transferred from the etching dielectric mask. Thus, also optimizing the dry etch for both the  $\text{SiO}_2$  and the SiN will improve the outcome of the fabrication process.

Low yield of the tapered waveguide designs during processing also was an issue in trying to verify the performance of such a structure: as already suggested in Chapter 5, having multiple instances of the designs with the same dimensions on one chip would help. Multiple iterations of designs, along with sticking to longer length waveguides would also reduce the impact of facet variability. While the coupling efficiency from the simulation results presented in Chapter 3 were low, fabricating grating couplers instead for waveguide testing is a solution. However, experience in fabricating the grating couplers and characterizing the expected loss beforehand is necessary before they can be used for characterizing waveguide performance.

## 6.3 Functionalities for the platform

As highlighted earlier in Chapter 3, trying to add functionalities to the initial epistructure is difficult due to the thickness required for matching the passive waveguide mode to the active lasing mode in the transverse direction. A new structure is also outlined that utilizes the mode adapter design for converting to dimensions suitable for some of the structures outlined in Chapter 3. However, the trade-off is that the alignment tolerance in the transverse

direction is reduced due to the reduction in epitaxial layer thicknesses. The proposed new epitaxial structure can be seen below in Figure 6.1.



Figure 6.1: Proposed new epitaxial design based on the designs outlined earlier in Chapter 3

It was also suggested earlier in Chapter 3 that  $\text{LiNbO}_3$  could be integrated onto the platform to enhance the electro-optic effect via  $\mu\text{TP}$ . To realize this, the GDS mask would have to be redesigned to include buried ridge designs, and printing tests on the waveguide structures would also have to be carried out. An additional level would also have to be included in the processing for forming metal contacts for biasing. The coupling efficiency of the grating coupler from simulations would also have to be verified via fabricating and characterizing. The results presented in Chapter 3 are for the optimum parameters for a given epistructure and fixed fiber tilt, but do not take into account the variation in some parameters as a result of fabrication tolerances. Therefore this would have to be verified before including it. Again, the impact of such variation would have to be assessed by going through a fabrication process and then testing the structures.

A common structure for PICs that was not discussed in this work was ring resonators. While initial simulations were carried out, the only fabrication work was initial tests with optical lithography, where the patterns lifted. Waveguide bends in general were also difficult to fabricate as a result of this, and therefore the simulation results in Chapter 3 for the varying bend radii was not verified experimentally. In this work we have demonstrated working waveguides using e-beam lithography, although currently fabricating ring resonators may still be challenging due to the sloped sidewalls produced by the dry etch. Being able to demonstrate working ring resonators could open up possibilities for filtering applications, or even exploiting their nonlinear properties for frequency comb generation [47].

## 6.4 Heat sinking for improved lasing performance

For the InP-based MQW laser, the low  $T_0$  of the laser device on both Si and sapphire show that a bonding interface with better heat sinking is needed. While the GaAs-based QD laser demonstrated a much-improved  $T_0$  on both platforms, the low thermal conductivity of sapphire had an impact on the overall performance of the printed device compared to the performance of the same device on Si. An alternative substrate to sapphire may thus be needed. Growing GaN on SiC, or rather its polytypes 4H-SiC and 6H-SiC could be a solution as there is a relatively low lattice mismatch ( $\approx 3.1\%$ ) as well as its higher thermal conductivity  $\sigma = 380 \text{ Wm}^{-1}\text{K}^{-1}$  [107]. However, both 4H-SiC and 6H-SiC possess a higher refractive index than GaN of around 2.57-2.6 (depending on the polytype) at  $1.31 \mu\text{m}$ , so the light leaks into the substrate. Rather than using a completely new substrate, micro transfer printing a suitable material to the trench area could be suitable. Diamond has one of the best thermal conductivities ( $\sigma_{\text{diamond}} = 2000 \text{ Wm}^{-1}\text{K}^{-1}$ ), and transfer printing of devices made from diamond to the GaN-on-sapphire platform has already been demonstrated [108]. It also has a suitable refractive index of 2.38 at  $1.31 \mu\text{m}$ , ensuring the light does not leak into the substrate. Metal could also be evaporated onto the PIC in a configuration as shown in Figure 5.11. Au has been proposed previously for heat sinking  $\mu\text{TP}$  InP devices [97, 109] on Si, and has been demonstrated experimentally to have a low thermal impedance [109]. Depending on the thickness needed for adequate heat-sinking, it can be difficult to obtain smooth morphology for the metal for transfer printing. While an adhesion layer can aid with  $\mu\text{TP}$  in this case, the thickness of the adhesion layer required depends upon the height of the roughness. Too thick an adhesion layer could potentially compromise the heat sinking abilities of the metal.

## 6.5 Integration of different gain materials to the platform

The wide transparency range of GaN means that gain materials of different wavelengths could be integrated onto the AlGaIn/GaN platform. We have already demonstrated the integration of InP and GaAs-based gain blocks emitting near  $1.31 \mu\text{m}$  to the platform with the aid of a very thin adhesive layer, so moving to other near-IR wavelengths such as  $1.55 \mu\text{m}$  is possible



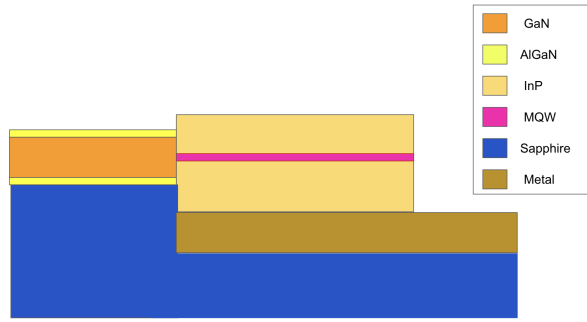


Figure 6.2: A schematic of what a metal heat sink could look like, evaporated onto the trench with the InP laser micro-transfer printed to it. A thin layer of intervia or BCB (around 50-100 nm thick) could be applied to help with adhesion of the laser to the surface without compromising the metal's heat sinking ability. The adhesion layer thickness depends upon the metal's surface morphology

provided the lasing epistructure is prepared for  $\mu$ TP. There is a desire to be able to integrate GaN lasers onto a GaN-based PIC for applications requiring visible blue and near-UV wavelengths [110, 111]. Figure 6.3 below shows the  $TE_0$  and  $TM_0$  mode profiles at a wavelength of  $0.45 \mu\text{m}$  being supported by the same design presented for  $1.31 \mu\text{m}$  operation in this report. At the time of this work, no GaN-based laser was available for  $\mu$ TP and thus we do not present a potential waveguide design for edge-coupling at this wavelength. However, provided the right layer thicknesses and waveguide geometries are chosen, we can potentially use the AlGaIn/GaN system outlined in this work for wavelengths outside of the near-IR regime.

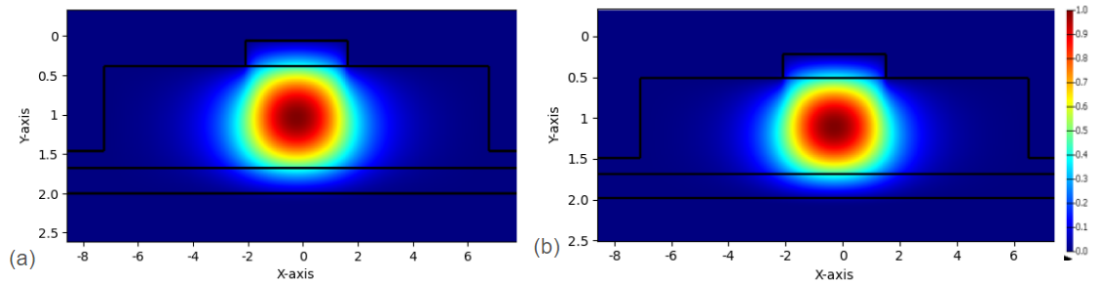


Figure 6.3: The (a)  $E_x$  for the  $TE_0$  mode and the (b)  $E_y$  profile for the  $TM_0$  for the double tapered structure with a shallow ridge width =  $4 \mu\text{m}$  at a wavelength =  $0.45 \mu\text{m}$ .

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# Appendix A

## Laser Epitaxial Structures

### A.0.1 InP-based quantum well laser

| Layer                                                                 | Thickness (nm) | Refractive index |
|-----------------------------------------------------------------------|----------------|------------------|
| InGaAs cap                                                            | 120            | 3.51             |
| InGaAsP Eg step                                                       | 20             | 3.29             |
| InP clad                                                              | 1150           | 3.2              |
| InP clad                                                              | 400            | 3.2              |
| InP clad                                                              | 100            | 3.2              |
| InGaAs CIL                                                            | 2              | 3.51             |
| $\text{Al}_{0.352}\text{Ga}_{0.118}\text{In}_{0.53}\text{As}$ LM WG   | 100            | 3.4044           |
| $\text{Al}_{0.3}\text{Ga}_{0.08}\text{In}_{0.62}\text{As}$ barrier x6 | 20             | 3.4212           |
| $\text{Al}_{0.0325}\text{Ga}_{0.6175}\text{In}_{0.35}\text{As}$ QW x6 | 10             | 3.53365          |
| $\text{Al}_{0.3}\text{Ga}_{0.08}\text{In}_{0.62}\text{As}$ barrier    | 20             | 3.4212           |
| $\text{Al}_{0.352}\text{Ga}_{0.118}\text{In}_{0.53}\text{As}$ LM WG   | 100            | 3.4044           |
| InP clad                                                              | 500            | 3.2              |
| InP clad                                                              | 1150           | 3.2              |
| InGaAs CIL                                                            | 100            | 3.51             |
| AlInAs ERL                                                            | 500            | 3.24             |
| InP buffer                                                            | 300            | 3.2              |
|                                                                       |                |                  |

Figure A.1: Epitaxial structure for the InP-based MQW lasing device used in this work

## A.0.2 GaAs-based quantum dot laser

| Layer           | Thickness (nm) | Refractive index |
|-----------------|----------------|------------------|
| GaAs Cap        | 50             | 3.4094           |
| AlGaAs          | 1200           | 3.2483           |
| AlGaAs          | 1              | 3.2483           |
| GaAs spacer x15 | 35             | 3.4094           |
| InGaAs x 14     | 5              | 3.5              |
| InAs x 14       | 1              | 3.6              |
| AlGaAs          | 1200           | 3.3002           |
| GaAs            | 400            |                  |
| Substrate       |                |                  |
|                 |                |                  |

Figure A.2: Epitaxial structure for the GaAs-based QD lasing device used in this work

# Appendix B

## GDS masks

### B.0.1 First iteration

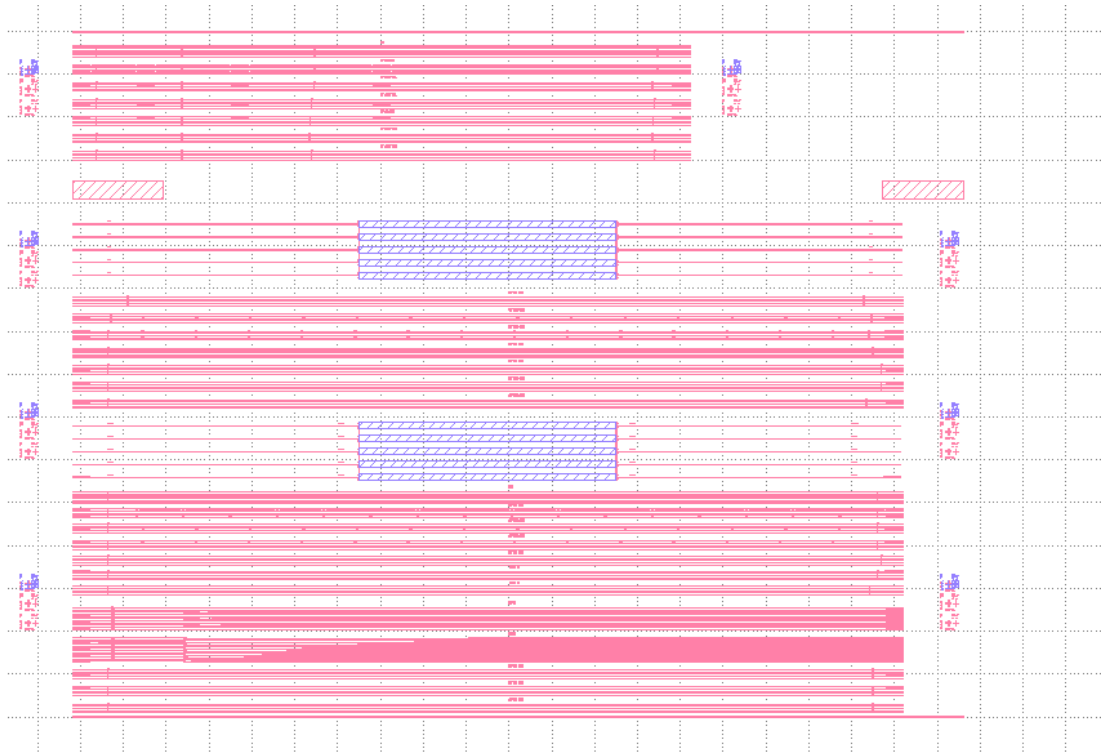


Figure B.1: The GDS mask used for the first iteration of AlGaIn/GaN waveguides: the pink designs correspond to the waveguide patterns, while the blue designs is for the  $\mu$ TP trenches

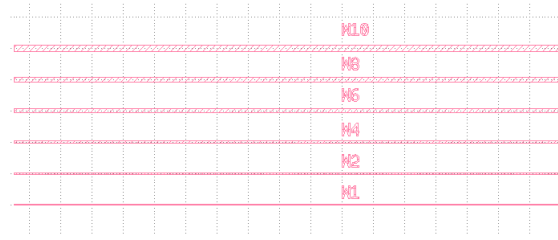


Figure B.2: The straight waveguides to be fabricated: the variation is in the width of the waveguide, going from 1-10  $\mu\text{m}$

## B.0.2 Second iteration

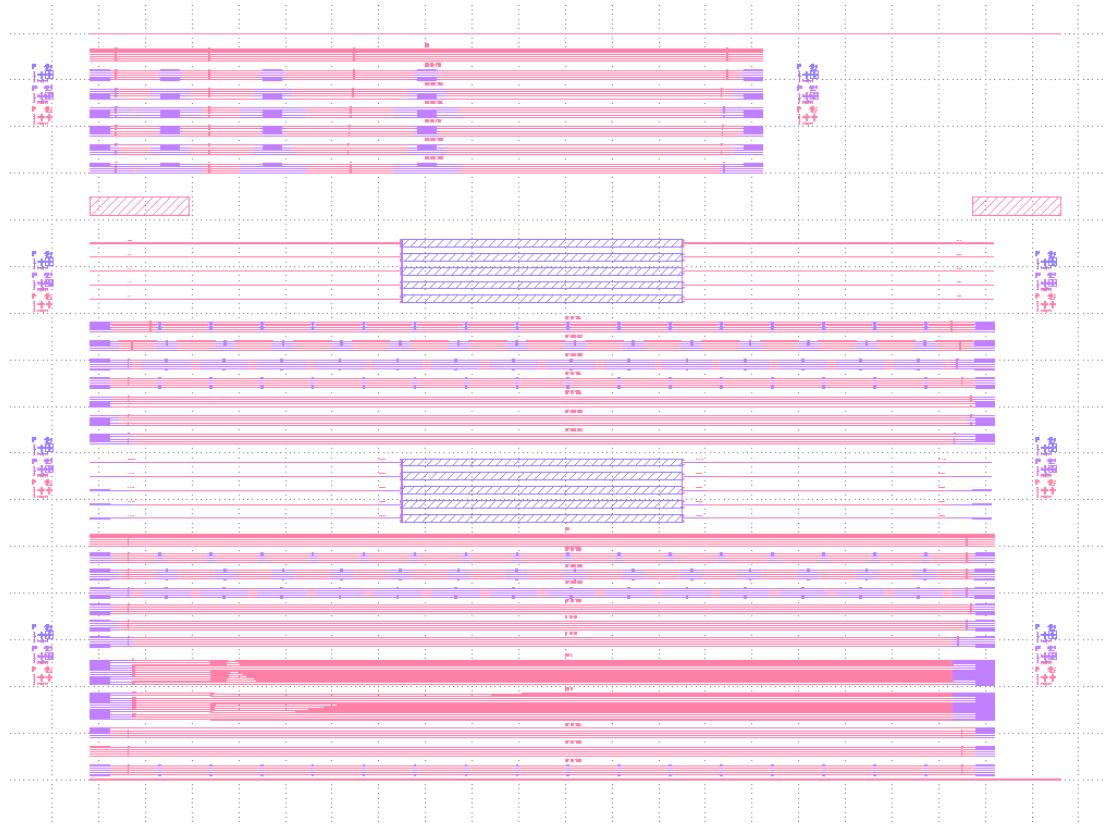


Figure B.3: An overview of the GDS mask for the second iteration of the mask: while the configuration of designs is the same as the GDS for the first iteration, the key difference is that there is a second waveguide level (in purple) in order to fabricate the mode adapter design outlined in Chapter 3.



# Appendix C

## List of Tools used

### C.0.1 Simulation tools

- Lumerical FDE Solver  
(<https://optics.ansys.com/hc/en-us/articles/360034917233-MODE-Finite-Difference-Eigenmode-FDE-solver-introduction>)
- Lumerical EME Solver  
(<https://optics.ansys.com/hc/en-us/articles/360034396614-MODE-EigenMode-Expansion-EME-solver-introduction>)
- Lumerical FDTD Solver  
(<https://optics.ansys.com/hc/en-us/articles/360034914633-Finite-Difference-Time-Domain-FDTD-solver-introduction>)

### C.0.2 Fabrication tools

- Mask aligner MA6 ([https://www.nist.gov/system/files/documents/2017/05/09/Manual\\_MA6.pdf](https://www.nist.gov/system/files/documents/2017/05/09/Manual_MA6.pdf))
- Elionix E-beam lithography system (<https://sts-elionix.com/>)
- PlasmaPro 100 Oxford Cobra ICP etcher  
([https://cns1.rc.fas.harvard.edu/facilities/docs/Oxford\\_Operation\\_Manual\\_220275\\_Part1.pdf](https://cns1.rc.fas.harvard.edu/facilities/docs/Oxford_Operation_Manual_220275_Part1.pdf))
- SPTS Synapse etcher  
(<https://norfab.no/technology/dielectric-etch-spts-synapse/>)
- Micro Transfer Printer (<https://x-celeprint.com/technology>)

- PECVD (<https://www.sentech.com/products/plasma-process-technology/icpecvd/>)

### **C.0.3 Characterization Tools**

- Santec TSL-550 laser  
(<https://www.manualslib.com/manual/3097555/Santec-Tsl-550.html?page=2#manual>)
- Elliot Scientific DALI E-2100 piezo autoalign controller  
(<https://www.equipx.net/elliott-scientific-dali-2100-piezo-autoalign.html>)
- ANDO AQ36317B optical spectrum analyzer  
(<https://www.testwall.com/wp-content/uploads//2015/09/ANDOAQ6317B.pdf>)
- Newport 918D-IG-OD3 InGaAs detector  
(<https://www.newport.com/p/918D-IG-OD3R>)
- Newport 844-PE-USB power meter  
(<https://www.newport.com/p/844-PE-USB>)