MONOLITHIC INTEGRATION OF ACTIVE AND SECOND-ORDER NONLINEAR FUNCTIONALITY IN BRAGG REFLECTION WAVEGUIDES

by

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A thesis submitted in conformity with the requirements for the degree of Doctor of Philosophy
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Abstract

Monolithic integration of active and second-order nonlinear functionality in Bragg reflection waveguides

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Doctor of Philosophy
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University of Toronto
2011

This thesis explored the theory, design, fabrication and characterization of AlGaAs Bragg reflection waveguides towards the goal of a platform for monolithic integration of active and optically nonlinear devices. Through integration of a diode laser and nonlinear phase-matched cavity, the possibility of on-chip nonlinear frequency generation was explored. Such integrated devices would be highly useful as a robust, alignment free, small footprint and electrically injected alternative to bulk optic systems.

A theoretical framework for modal analysis of arbitrary 1-D photonic crystal defect waveguides is developed. This method relies on the transverse resonance condition. It is then demonstrated in the context of several types of Bragg reflection waveguides (BRW). The framework is then extended to phase-match second-order nonlinearities and incorporating quantum-wells for diode lasers.

Experiments within a slab and ridge waveguide demonstrated phase-matched Type-I second harmonic generation at fundamental wavelength of 1587 and 1600 nm, respectively; a first for this type of waveguide. For the slab waveguide, conversion efficiency was 0.1 %/W. In the more strongly confined ridge waveguides, efficiency increased to 8.6 %/W owing to the increased intensity. The normalized conversion efficiency was estimated to be at 600 %/Wcm².
Diode lasers emitting at 980 nm in the BRW mode were also fabricated. Verification of the Bragg mode was performed through imaging the near-field of the mode. Propagation loss of this type of mode was measured directly for the first time at ≈14 cm$^{-1}$. The lasers were found to be very insensitive with characteristic temperature at 215 K.

Two designs incorporating both laser and phase-matched nonlinearity within the same cavity were fabricated, for degenerate and non-degenerate down-conversion. Though the lasers were sub-optimal, a parametric fluorescence signal was readily detected. Fluorescence power as high as 4 nW for the degenerate design and 5 nW for the non-degenerate design were detected. The conversion efficiency was 4176 %/Wcm$^2$ and 874 %/Wcm$^2$, respectively. Neither design was found to emit near the design wavelength. In general, the signal is between 1600-1800 nm and the idler is between 2200-2400 nm. Improvements in laser performance are expected to drastically increase the conversion efficiency.
Acknowledgements

First, I would like to thank my supervisor, Prof. Amr S. Helmy, for his support through this endeavour and believing in me when I applied to the University of Toronto for graduate studies. His guidance and advice have been instrumental in my growth as a researcher and in completing this thesis.

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To my family I owe the most, as your love and kindness provided a gentle and continuous support. It was very much appreciated and you have my gratitude forever.
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<tr>
<td>BRW</td>
<td>Bragg reflection waveguide</td>
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<tr>
<td>CMC</td>
<td>Canadian Microelectronics Corporation Microsystems</td>
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<td>DFG</td>
<td>Difference frequency generation</td>
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<td>DML-BRW</td>
<td>Dual matching-layer Bragg reflection waveguide</td>
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<tr>
<td>DRO</td>
<td>Doubly-resonant oscillator</td>
</tr>
<tr>
<td>FF</td>
<td>Fundamental frequency</td>
</tr>
<tr>
<td>FWHM</td>
<td>Full width at half maximum</td>
</tr>
<tr>
<td>ICP</td>
<td>Inductively coupled plasma</td>
</tr>
<tr>
<td>ML-BRW</td>
<td>Matching-layer Bragg reflection waveguide</td>
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<tr>
<td>MOCVD</td>
<td>Metal-organic chemical vapour deposition</td>
</tr>
<tr>
<td>OPO</td>
<td>Optical parametric oscillator</td>
</tr>
<tr>
<td>OSA</td>
<td>Optical spectrum analyzer</td>
</tr>
<tr>
<td>PBG</td>
<td>Photonic bandgap</td>
</tr>
<tr>
<td>PECVD</td>
<td>Plasma-enhanced chemical vapour deposition</td>
</tr>
<tr>
<td>PF</td>
<td>Parametric fluorescence</td>
</tr>
<tr>
<td>PIC</td>
<td>Photonic integrated circuit</td>
</tr>
<tr>
<td>PM</td>
<td>Phase-matching</td>
</tr>
<tr>
<td>PPLN</td>
<td>periodically poled Lithium Niobate</td>
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<td>Qt-BRW</td>
<td>Quarter-wave Bragg reflection waveguide</td>
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<td>Acronym</td>
<td>Abbreviation</td>
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<td>QW</td>
<td>Quantum-well</td>
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<td>RF</td>
<td>Radio frequency</td>
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<td>RIE</td>
<td>Reactive ion etch</td>
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<td>SEM</td>
<td>Scanning electron microscope</td>
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<td>SFG</td>
<td>Sum frequency generation</td>
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<td>Second harmonic</td>
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<tr>
<td>SHG</td>
<td>Second-harmonic generation</td>
</tr>
<tr>
<td>SRO</td>
<td>Singly-resonant oscillator</td>
</tr>
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<td>TBR</td>
<td>Transverse Bragg reflector</td>
</tr>
<tr>
<td>TE</td>
<td>Transverse electric</td>
</tr>
<tr>
<td>TEC</td>
<td>Thermo-electric cooler</td>
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<tr>
<td>TIR</td>
<td>Total internal reflection</td>
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<td>TM</td>
<td>Transverse magnetic</td>
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<td>TRC</td>
<td>Transverse resonance condition</td>
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Chapter 1

Introduction

1.1 Background

Just fifty years ago at the advent of the first laser, no one could have predicted the applications and benefits the invention would have on society. From medical treatments, to telecommunications, sensing, entertainment and even weapons, the laser’s coherent beam and spectral qualities have made an impact on almost everyone on the planet. With recent applications in new fields such as dentistry, they will continue to enhance our lives.

In particular, it is the coherence, power and wide range of wavelengths that have made lasers so useful. For example, lasers emitting soft x-rays with 15 nm wavelength have been demonstrated. On the other side of the spectrum, lasers such as the Carbon dioxide (CO$_2$) laser can emit 10 $\mu$m radiation, very low-energy photons. Nonetheless, these rely on the gain properties of materials which can have limited bandwidth in wavelength, particularly where tunability may be required. For example, many chemicals have near to mid-infrared absorption bands and hence require tunable IR sources for absorptive detection.

Currently, optical parametric oscillators (OPOs) provide the widest wavelength tuning
range by using nonlinear crystals such as periodically poled Lithium Niobate (PPLN). Powerful lasers pump these nonlinear crystals to induce nonlinear interactions, which generate coherent optical radiation through a combination of parametric gain and optical feedback. However, such OPOs typically have a large footprint consisting of large external cavities and long interaction lengths. They are mostly restricted to laboratories and can be quite sensitive to mechanical alignment and vibrations. Such a disadvantage limits their use in the field or in situations where there are space constraints.

It is expected that these disadvantages can be circumvented through an all-semiconductor platform to realize monolithically integrated, electrically pumped OPOs [1]. Specifically, III-V semiconductors such as the AlGaAs or InGaAsP systems can offer many advantages. For example, AlGaAs has transparency well into the mid-IR (≈17 μm), relatively large second-order nonlinearity, established epitaxial growth technology and microfabrication technology. Recently there has been a tremendous drive in many fields to miniaturize devices by use of micro fabrication, most notably in MEMS and microfluidics. In a similar fashion, much research and effort is put into integrated optics to find the means of providing high functionality with small footprint. The result is a significant advantage over conventional tabletop configurations in coherent optical generation, which enables new applications.

This thesis will examine the use of Bragg reflection waveguides (BRW) as a waveguide platform from which to achieve these goals. Essentially a one-dimensional photonic crystal defect waveguide [2], BRWs guide light via the photonic bandgap (PBG) effect rather than total internal reflection. This allows Bragg modes to propagate with unique modal properties [3]; most of which can be widely tuned through waveguide structure and design. Most notably is the tuning of modal dispersion which can be modified greatly, from very large to zero and even negative (anomalous dispersion) [4]. Via appropriate design, it has been shown that Bragg modes can utilize the strong dispersion of semiconductors near the bandgap towards phase-matching second-order nonlinear processes [5]. Further,
because the BRW layer structure is identical to that of vertical cavity surface emitting lasers (VCSEL), active devices can be fabricated within BRWs. This combination of active and nonlinear capability within the same structure is unique. The forthcoming chapters will explore the various design, fabrication and characterization of either device type. Further, integrating both functionalities within a single cavity will also be explored.

### 1.2 Second-order nonlinear optics

Nonlinear optics is the field whereby a nonlinear optical material is suitably utilized for the interaction of many frequencies of light. Depending on the process, this can involve optical generation, conversion, spectroscopic scattering and more. Efficient frequency conversion must satisfy energy and momentum conservation conditions. In the case of compound semiconductors, the second-order nonlinear susceptibility $\chi^2$ is most utilized for frequency conversion; the primary process is three-wave mixing (3WM). Equations 1.1a and 1.1b are the energy and momentum conservation conditions as related to 3WM, respectively.

$$\omega_1 + \omega_2 + \omega_3 = 0 \quad (1.1a)$$

$$\vec{k}_1 + \vec{k}_2 + \vec{k}_3 = 0 \quad (1.1b)$$

Here, three waves labeled numerically as 1, 2 and 3, interact via a suitable nonlinear material. In general, there are three conversion processes in 3WM: sum-frequency generation (SFG), second-harmonic generation (SHG) and difference-frequency generation (DFG). The processes can be described visually as an interaction of three photons as shown in Figures 1.1. SFG is the combination of one photon at $\omega_1$ and another at $\omega_2$ to generate a third photon at $\omega_3$. SHG is a degenerate case of SFG where $\omega_1 = \omega_2$ creating a photon at the second harmonic, $2\omega_1$. Lastly, DFG is the process where-by a high energy photon, $\omega_1$, splits into two lower energy photons, $\omega_2$ and $\omega_3$. 
Chapter 1. Introduction

(a) Sum-frequency generation.
(b) Second-harmonic generation.
(c) Difference-frequency generation.

Figure 1.1: Three-wave mixing photon interaction diagrams

In the case of guided waves such as our Bragg modes, the momentum vectors, \( \vec{k}_i \), in Equation 1.1b can be replaced by the modal wavenumber \( \beta_i \) to a reasonable approximation. This simplifies the momentum conservation condition to Equation 1.2. The derivation of this from the wave equation is beyond the scope of this document.

\[
\beta_1 + \beta_2 + \beta_3 = 0 \quad (1.2)
\]

Looking at Equation 1.2, it becomes evident that a good knowledge of the modal effective indices is crucial to achieving phase-matching. Nonlinear conversion involving BRWs has been described as an interaction between Bragg modes and total internal reflection modes (TIR), sometimes called bound modes \([5]\). Due to typical normal material dispersion (decreasing refractive index with wavelength), the Bragg mode at a smaller wavelength must be phase-matched with a TIR mode at a higher wavelength. This is because the Bragg mode effective index is always lower than any material index. For example, in the case of Type-II difference frequency generation, the phase-matching condition in Equation 1.3 applies, and can be used when designing nonlinear conversion devices.

\[
\beta_{TE}^{BRW} (\omega_1) + \beta_{TE}^{TIR} (\omega_2) + \beta_{TIR}^{TM} (\omega_2 - \omega_1) = 0 \quad (1.3)
\]
1.3 Diode lasers

Semiconductor diode lasers were discovered within just a few years after the invention of the first laser [7]. Since then, they have been a vital part of everyday life with applications as laser pump sources, presentation pointers and telecommunications. The prime benefits of semiconductor diode lasers is that they operate through low-voltage electric current and have a very small footprint. This has allowed these lasers to be used in applications where portability is an asset. This has allowed the semiconductor diode laser to have wide penetration in household products (e.g. DVD players).

Semiconductor gain is typically achieved by carrier confinement; meaning holes and electrons within the same physical space. Originally, this was obtained at the interface of PN junctions, or within the intrinsic region of PIN junctions. Later, quantum confined structures such as quantum wells or quantum dots were added to the intrinsic region. This allowed for more precise control of the emission wavelength through structural control of the interacting quantum states. Today, quantum-well diode lasers have become the most prevalent semiconductor laser in mass production.
Figure 1.3: Example of BRW based photonic integrated circuit. Here, the circuit is comprised of a diode laser, multi-mode combiner, ring resonator filter and nonlinear converter.

In this thesis, a laser emitting in the Bragg mode was designed and characterized. A sketch of such a device emitting a Bragg mode is shown in Figure 1.2. Designing such a laser is not a trivial task, particularly due to the ‘leaky’ nature of PBG modes. The difficulties are compounded by the TIR modes also present in the structure that may achieve lasing before the PBG mode. Hence, it becomes vital to design the BRW structure to tailor the gain to benefit the Bragg mode over all other in the structure. These challenges are not insurmountable. Similar modal gain engineering was used by Rossi et al. in fabricating a third-order mode laser [8], or Erbert et al. in reducing higher-mode gain [9]. The coming chapters will highlight the design strategy behind the BRW lasers tested, the characterization performed and verification of Bragg mode lasing.

1.4 Monolithic Integration

Photonic integrated circuits (PIC) have offered the promise of reduced footprint and cost for over 40 years [10]. The benefits of monolithic integration has many benefits including simplicity, physical robustness, reduced integration losses between elements and alignment free fabrication. An integrated circuit could involve the combination of
Figure 1.4: Intracavity frequency conversion within a BRW diode laser. The Bragg mode interacts with phase-matched TIR modes through the 3WM process.

several on-chip lasers, heater wavelength tuning elements, ring filters and even modulators. PIC devices have been typically developed for the telecommunications industry, focusing mainly on the combination of active and passive devices [11, 12]. The lack of nonlinear functionality within semiconductors due to phase-mismatch has been the main restricting factor to integrated nonlinear conversion devices. Recently, there have been many demonstrations of Silicon-on-insulator as a medium for third-order ($\chi^{(3)}$) nonlinear optics due to its low propagation losses [13]. However, this comes at the cost of on-chip gain and lasing. Other integration schemes have sought to bring nonlinear functionality to III-V semiconductors via different phase-matching schemes. Some examples are the use of quantum-well intermixing coupled with quasi-phase-matching [14] and modal phase-matching [15].

This thesis will show that Bragg reflection waveguides are an ideal vehicle for monolithic integration of nonlinear and active functionalities. An example of a BRW based PIC composed of on-chip laser, ring resonator filter and nonlinear converter is shown in
Figure 1.3. The use of a single PBG-based waveguide for such broad application has not been explored before.

An intracavity conversion scheme is explored both theoretically and experimentally in this thesis. The technique is elegant in that it integrates the two functions by proposing a laser diode device which is designed to be phase-matched for frequency conversion. A sketch of such an intracavity conversion laser is shown in Figure 1.4. Several groups have attempted to design and fabricate such a device based on other phase-matching schemes. Lammert et al. [16] have utilized the M-waveguide technique to achieve phase-matching within a diode laser, though no direct evidence of conversion was found. Khurgin, Rosencher and Ding [1] have also explored utilizing an all-semiconductor platform for intracavity frequency conversion. However, the high nonlinear conversion of BRWs [17] make them a unique candidate for efficient on-chip converters and place them in a unique position to exceed past demonstrations.
Chapter 2

Bragg reflection waveguides: Modal analysis

This section will detail the method utilized to analyze the modal properties of Bragg reflection waveguides (BRW). Many methods have been described in literature such as Bloch waves formalism [4], coupled-mode theory [18] and transfer matrix dispersion [19]. However, in this work we use the transverse resonance condition for several reasons. The technique has been explored for fibers [20] and dielectric waveguides [21] as a simple, robust means to waveguide analysis. Further, it is general enough to be extended to other types of photonic band gap (PBG) designs such as ones with chirped or asymmetric mirrors [22] as well as structures with additional core layers such as quantum-wells. It is also an exact technique for finite structures, a fact which the Bloch wave formalism ignores.

This work has focused on practical device designs, within the scope of current technologies. Our choice of semiconductor is Aluminum Gallium Arsenide (AlGaAs), which is a proven optoelectronic material. Epitaxial growth of AlGaAs has reached a stage whereby accurate deposition within monolayers can be placed on top of other AlGaAs layers. Further, microfabrication has reached a mature level whereby active and passive
Figure 2.1: Simple planar Bragg reflection waveguide structure. A core region is surrounded on both sides by transverse Bragg reflectors. The direction of propagation is $z$.

Photonic devices can be readily manufactured. Analysis of AlGaAs waveguides requires a precise knowledge of the material refractive indices. Thus, we utilize the refractive index model developed by Gehrsitz et al. [23].

After a short description of BRWs and the transverse resonance condition, the remaining sections of this chapter will focus on applying the condition to several BRW cases. These are the quarter-wave BRW (Qt-BRW), the matching-layer BRW (ML-BRW), the dual matching-layer BRW (DML-BRW). It will be shown that the technique is broad and useful to modal analysis of these and many other types of one-dimensional PBGs.

## 2.1 Bragg reflection waveguides

Originally described by Ash [24], then detailed by Yeh and Yariv [25], BRWs are essentially one-dimensional photonic crystal waveguides. A core region is sandwiched between two transverse Bragg reflectors (TBR) as shown in Figure 2.1. Through appropriate design of the structure, low-loss guiding based on Bragg reflection is possible. It can be shown that such modes lie within the photonic bandgap of the structure [19] owing to its photonic crystal nature.
Chapter 2. Bragg reflection waveguides: Modal analysis

2.2 Transverse resonance condition

The transverse resonance condition is sometimes also called the zigzag ray optics model [2] or the self-consistency condition [20]. Shown schematically in Figure 2.2, it can be seen why the TRC is called the zigzag model. It states that the mode must form a standing wave in the $x$-direction, meaning it won’t change shape during propagation; this is essentially the definition of a mode. The condition is stated in Equation 2.1.

$$2 \cdot k_{c,x} d_c + \phi_{left} + \phi_{right} = 2m\pi$$

(2.1)

Here, $k_{c,x}$ is the transverse wavevector component of the full wavevector $k_c$, as shown in Figure 2.2. The terms $\phi_{left}$ and $\phi_{right}$ are phase shifts due to reflection from the left and right mirror stacks, respectively. These phase shifts can be found from the complex reflectivity through the relation $r = |r|e^{-i\phi}$. The mode order is $m$.

$$k_{c,x} = k_0 \cdot n_c \cos(\theta)$$

(2.2a)
Equation 2.1 can be clarified by making the substitutions shown in Equations 2.2, resulting in Equation 2.3.

\[
\frac{4\pi d_c n_c(\lambda) \cos(\theta)}{\lambda} + \phi_{left}(\theta, \lambda) + \phi_{right}(\theta, \lambda) = 2m\pi \tag{2.3}
\]

To find the modal effective index, \( n_{eff} \), we must first find the angle \( \theta \) that satisfies Equation 2.3. From there, the mode effective index can be computed through \( n_{eff} = n_c \cdot \sin(\theta) \). Note that in general, Equation 2.3 is transcendental in \( \theta \) and best solved via computation. Nonetheless, this technique is powerful and general enough for a wide array of 1-D PBG type waveguides because the mirror reflectivity can be calculated for arbitrary layered structures. In the coming sections, this equation will be utilized to solve the mode effective indices of several types of different BRW structures along with the benefits of each kind.

### 2.2.1 Simple quarter-wave

The quarter-wave dielectric stack has been used in the past for many applications such as high-power mirrors and vertical-cavity surface emitting lasers. These mirrors have repeating units containing high and low refractive index materials that provide very high reflectivity at a given wavelength through Bragg reflection. The special case of quarter-wave TBR reflectors in a BRW structure, termed quarter-wave BRWs (Qt-BRW), lead to useful analytic expressions \[3\]. It is known that quarter-wave mirrors provide the highest reflectivity from a finite stack at the center of the bandgap. For Bragg modes, this relates to largest modal confinement and minimized losses.

In this section, the expression for Qt-BRW modal effective index will be derived beginning with the TRC. The thickness of the layers follow the quarter-wave relation
shown in Equation 2.4.

$$d_x n_x \cos (\theta) = \frac{\lambda_0}{4}$$ (2.4)

Here \(\{x\}\) is \{1,2\} indicating the high and low index material, respectively. This generalized form can be simplified to the well-known case of normal incident radiation when \(\theta=0^\circ\). Here, \(\theta\) is the mode angle referred to in Equation 2.3 and shown in Figure 2.2.

The phase of reflection from a quarter-wave stack at the center of the bandgap is exactly \(\pi\) [26]. Knowing this, Equation 2.1 simplifies to Equation 2.5.

$$2 \cdot k_{c,x}d_c + 2\pi = 2m\pi$$ (2.5)

In terms of phase, \(2\pi = -2\pi\) as it implies one full revolution in either direction. This leads to the condition, \(k_{c,x}d_c=(m+1)\pi\) where \(m=0,1,2,3...\) which applies for both TE and TM polarizations. Simplifying this condition further leads to the expression for modal effective index shown as Equation 2.6d, and derived below in Equations 2.6.

$$k_{c,x} = k_0 \cdot \sqrt{n_c^2 - n_{eff}^2} = \frac{(m + 1) \pi}{d_c}$$ (2.6a)

$$\frac{2\pi}{\lambda} \cdot \sqrt{n_c^2 - n_{eff}^2} = \frac{(m + 1) \pi}{d_c}$$ (2.6b)

$$n_c^2 - n_{eff}^2 = \frac{\lambda^2 (m + 1)^2}{4d_c^2}$$ (2.6c)

_for the fundamental mode, \(m = 0\)

$$n_{eff} = \sqrt{n_c^2 - \frac{\lambda^2}{4d_c^2}}$$ (2.6d)

This equation is valid for both TE and TM polarizations, with the same effective index for both. This means there is a lack of birefringence at the quarter-wave frequency, a unique property of Qt-BRWs. This analytical expression for the modal effective index
Figure 2.3: Examples of field and refractive index profile for a quarter-wave Bragg reflection waveguide. The modal effective index is below any material refractive index. Note, the field is either a node or anti-node at interfaces, a property of quarter-wave mirrors.

makes design of Qt-BRW structures a simple task. An example of the Bragg mode in a Qt-BRW is shown in Figure 2.3(a). The corresponding layer indices are shown in Figure 2.3(b). As is typical of Bragg mirrors, the field profile at interfaces are either nodes or anti-nodes. Further, typical of PBG waveguides, there is significant contribution from the stacks but there is clear confinement in the central core region.
2.2.2 Defects in transverse Bragg reflector

A quarter-wave Bragg reflector design is the simplest mirror design one can make because of its analyticity. However, in many cases the aim may not be to just create an efficient reflector at one wavelength. In fact, many have found that modifying a quarter-wave mirror can be advantageous for certain applications. For example, chirping a mirror is used in many ultra-fast lasers due to improved reflection bandwidths and dispersion compensation [27]. Another example is the use of sampled grating reflectors in DBR diode lasers for greater tuning range [28]. However, these mirrors are utilized for normal-incidence applications and their use is generally not phase-dependent; phase upon reflection is important towards the modal qualities of Bragg modes.

Some very simple modifications have been made to the quarter-wave design, namely, the addition of defects into the mirror design. These are substitution defects whereby the first few layers adjacent to the core are replaced by layers of different composition or thickness. This in turn modifies the phase upon reflection, $\phi_i$, and the modal index. Consequently, the partials $\frac{\partial \phi_i}{\partial x}$ and $\frac{\partial \phi_i}{\partial \theta}$ also change which impact the modal dispersion. The modified layers also effect the field profile, allowing for additional control in devices, such as second harmonic generators, where field overlap is important. The coming sections will detail how the TRC can be utilized to analyze the modes of such BRWs.

**Single matching layer**

The simplest modification studied is the case of replacing the first layer adjacent to the core as shown in Figure 2.4(a). The first high-index layer of the mirror is replaced with a layer of different composition and thickness. Such a layer adjusts the phase response of the reflector and thus the effective index. This structure is called the matching-layer Bragg reflection waveguide (ML-BRW), first proposed by Mizrahi [29].

Modal analysis of ML-BRWs can also be accomplished through the TRC by first noting the Fabry-Pérot (FP) nature of the matching layer itself, shown in Figure 2.4(b).
Light incident from the core at the angle $\theta_c$ is refracted at the interface to the angle $\theta_L$, determined by Snell’s Law. Here, we are interested in the phase of reflection (the complex reflectivity). To calculate this, we consider each side of the BRW as a separate FP entity. The core being the incident medium, the matching layer as the inner layer and the quarter-wave mirror as an effective outgoing material. The FP reflection, $r_{ML}$, can be found through the formula in Equation 2.8. Here, $r_{ij}$ is the Fresnel reflection going from material $i$ to $j$. The core is material 1, matching layer is 2 and effective mirror is 3.
\[ r_{ML} = \frac{r_{12} + r_{23} e^{-2i\phi_L}}{1 + r_{12} r_{23} e^{-2i\phi_L}} \]  
\[ \phi_L = k_{L,x} d_L = k_0 n_L \cos(\theta_L) d_L \]  

The Fresnel reflection from the core to the matching-layer, \( r_{12} \), can be easily calculated using the well known Fresnel formulas \([30]\). However, the Fresnel reflection from the matching-layer to the mirror, \( r_{23} \), is more complicated. Here, we must utilize the field-transfer matrix method to calculate the reflection at the new angle, \( \theta_L \), as shown in Equations 2.8. Here, the subscript \( j \in \{1, 2, 3, ..., N\} \) represents the layer number in the mirror; \( j=1 \) is the incident material and \( j=N \) is the outer material (cover or substrate).

\[ T = M_1 M_2 \ldots M_{N-2} M_{N-1} \]  
\[ \text{where } M_j = \begin{pmatrix} A_j & B_j \\ C_j & D_j \end{pmatrix} \]
\[ A_j = 0.5 \left( 1 + F_j \right) \cdot e^{-i d_{j+1} k_{j+1,x}} \]  
\[ B_j = 0.5 \left( 1 - F_j \right) \cdot e^{+i d_{j+1} k_{j+1,x}} \]
\[ C_j = 0.5 \left( 1 - F_j \right) \cdot e^{-i d_{j+1} k_{j+1,x}} \]
\[ D_j = 0.5 \left( 1 + F_j \right) \cdot e^{+i d_{j+1} k_{j+1,x}} \]
\[ F_j = \begin{cases} \frac{k_{j,x}}{k_{j+1,x}} & TE \\ \frac{n_j^2}{n_{j+1}^2} \frac{k_{j+1,x}}{k_{j,x}} & TM \end{cases} \]

The reflectivity of the mirror can then be computed using elements of the \( T \) matrix through Equation 2.13.

\[ r = \frac{T_{2,1}}{T_{1,1}} \]  

The procedure for finding the modal effective index, \( n_{\text{eff}} \) is to scan all possible values of \( \theta_c \) till one satisfies the TRC. This angle is related to \( n_{\text{eff}} \) of the Bragg mode. The
possible values for the $n_{eff}$ range from 1 to $\min\{n_j\}$, where $n_j$ is the refractive index for layer $j$. Note that every possible value of the effective index tested will constitute a physically separate structure due to the quarter-wave condition of the mirrors. The solver procedure flowchart is shown in Figure 2.6. An example of a matching-layer Bragg mode field profile is shown in Figure 2.5(a), along with corresponding refractive index profile in Figure 2.5(b). Note again how the field has nodes and anti-nodes at the mirror interfaces due to the quarter-wave condition. The matching-layer acts as an intermediary to ‘match’ the phases between the core and mirror.

Figure 2.5: Examples of field and refractive index profile for a matching-layer Bragg reflection waveguides. Again, the modal effective index is below any material refractive index. The field is either a node or anti-node at interfaces within the mirrors.
Chapter 2. Bragg reflection waveguides: Modal analysis

Given
- Core material, \( x_c \)
- High and low mirror material, \( x_1 \) and \( x_2 \)
- Matching layer material, \( x_L \)
- Core thickness, \( d_c \)
- Matching layer thickness, \( d_L \)

1. Determine \( \{n_i\} \) for each layer
2. Determine \( \{n_{\text{eff},i}\} \), set of possible effective indices (and \( \{\Theta_{c,i}\} \))
3. Choose \( \Theta_c \), determine \( \Theta_L \) for right mirror
4. For given \( n_{\text{eff},i} \), determine quarter-wave mirror thickness'
5. Compute \( r_{23} \) from transfer-matrices at \( \Theta_L \)
6. Compute \( r_{\text{right}} \) and \( \phi_{\text{right}} \) from Fabry-Pérot equation at \( \Theta_c \)
7. Repeat for left mirror
8. Satisfy transverse resonance condition?
   - Yes
   - No
     - Choose next \( i \)

9. Refine value
10. Compute modal properties and fields

End

Figure 2.6: Flowchart to solve the modal effective index of matching-layer Bragg reflection waveguides.
Additional defect layers

Similar to the single defect / matching-layer BRW concept, further defects in the mirror can be added for additional control of the field profile and modal properties. Again, these parameters would be useful in devices where dispersion of field overlap is important. The modal analysis of such structures becomes slightly more complicated than with the single defect case in Section 2.2.2 above. The Fabry-Pérot like behaviour of the matching-layer simplified computation due to its analyticity. In this section, a more generic analysis procedure will be detailed and applied to the specific case of two matching-layers. For this structure, two substitution defect layers, in both composition and thickness, will replace the first reflector period completely.

For more generic modal analysis, it is beneficial to return to the three material TRC in Equation 2.1. We will treat the two mirrors as ‘effective’ materials with their own reflectivity \( r_{\text{left}}, r_{\text{right}} \) and phase \( \phi_{\text{left}}, \phi_{\text{right}} \). Note both \( r \) and \( \phi \) are functions of wavelength \( \lambda \) and incident angle \( \theta_c \).

A dual matching-layer Bragg reflection waveguide (DML-BRW), requires two layers directly beside the core with composition \( x_{L,1}, x_{L,2} \) and thicknesses \( d_{L,1}, d_{L,2} \). This can be considered as consecutive Fabry-Pérot resonators one after the other. However, the simplest way to analyze such a structure is to treat the quarter-wave layers with matching-layers as one effective reflector. Here, the complex reflection can be computed by again utilizing the field transfer matrix method, described in Equation 2.8. By scanning over the range of allowed effective indices and evaluating the TRC at each point, the Bragg mode effective index can be determined. The flowchart of the computation procedure is shown in Figure 2.8(a). Note this method is generic and can be utilized to solve any transverse Bragg reflector type structure; assuming the complex reflection can be computed via the field transfer-matrix method. An example of a DML-BRW Bragg mode is shown in Figure 2.8(a) with the corresponding refractive index profile in Figure 2.8(b)
Given
Core material, $x_c$
High and low mirror material, $x_1$ and $x_2$
Matching layer material, $x_{L,1}$ and $x_{L,2}$
Core thickness, $d_c$
Matching layer thickness, $d_{L,1}$, $d_{L,2}$

Determine $\{n_i\}$ for each layer
Determine $\{n_{\text{eff},i}\}$, set of possible effective indices (and $\{\Theta_{c,i}\}$)

Loop cycling $n_{\text{eff},i}$
For given $n_{\text{eff},i}$, determine quarter-wave mirror thickness
Compute $r_{\text{right}}$ and $\phi_{\text{right}}$ from transfer matrix at $\Theta_c$
Repeat for left mirror
Satisfy transverse resonance condition?

Yes
Refine value
Compute modal properties and fields

End

No
Choose next $i$

Figure 2.7: Flowchart to solve the modal effective index of dual matching-layer Bragg reflection waveguides. This method is generic and can be utilized to solve any 1D photonic bandgap waveguide structure.
Figure 2.8: Examples of field and refractive index profile for a dual matching-layer Bragg reflection waveguides found through the generic solving procedure in Figure 2.7.

The example above was specific to a DML-BRW design, however, the method is generic for many other types of designs. For example, a triple matching-layer design may improve field overlap further for nonlinear optics. It can also be employed for non-quarter-wave mirror designs for additional controls. Among other designs left unexplored are ones involving chirped, asymmetric or even completely aperiodic mirrors.
2.3 Phase-matching for nonlinear optics

The previous sections of this chapter went into detail on the procedure for determining Bragg mode effective indices. The following sections will detail how to determine TIR mode indices through similar transfer matrix methods, and then the procedure to attaining phase-matched BRW structures. Finally, methods for estimating Bragg mode loss are explored.

2.3.1 Bound-modes

TIR modes, sometimes called Bound modes, are guided via total internal reflection and not Bragg reflection as in Bragg modes. Though the transverse resonance condition is applicable in finding such modes, it is not universal. For example, for some multi-layer structures, the TIR modal effective index is larger than the core refractive index and $k_{c,x}$ in Equation 2.1 becomes imaginary. In such situations, the equation has no solutions. For such situations, a more generic transfer-matrix method has been developed by Chilwell and Hodgkinson [31]. Here, the full cover-to-substrate field transfer-matrix is computed. From there, the condition shown in Equation 2.14 must be satisfied for a mode to exist. The subscripts $c$ and $s$ signify the cover and substrate materials, respectively. The allowable range of effective indices for TIR modes is between $\min([n_i])$ and $\max([n_i])$, where the set $[n_i]$ is the list of material refractive indices.

$$
\gamma_c T_{1,1} + \gamma_c \gamma_s T_{1,2} + T_{2,1} + \gamma_s T_{2,2} = 0 \quad (2.14a)
$$

$$
\gamma_i = \begin{cases} 
\frac{n_i \sqrt{\mu_0}}{\mu_0} \cos \theta_i & TE \\
\frac{\mu_0}{n_i \sqrt{\varepsilon_0}} \cos \theta_i & TM 
\end{cases} \quad (2.14b)
$$
2.3.2 Second harmonic generation

This section will describe the procedure for designing a phase-matched BRW structure for second harmonic generation (SHG). SHG is the process whereby incoming light at $\omega$ (fundamental) is converted to $2\omega$ (second harmonic) through the $\chi^{(2)}(-2\omega; \omega, \omega)$ nonlinear tensor. There are two modes of SHG termed Type-I and Type-II depending on the fundamental polarization. The phase-matching restriction for either case then simplifies to Equation 2.15.

**Type-I:**
\[ n_{\text{eff}, \text{TIR}}^{\text{TE}}(\omega) = n_{\text{eff}, \text{BRW}}^{\text{TM}}(2\omega) \]  
(2.15a)

**Type-II:**
\[ n_{\text{eff}, \text{TIR}}^{\text{TE}}(\omega) + n_{\text{eff}, \text{TIR}}^{\text{TM}}(\omega) = n_{\text{eff}, \text{BRW}}^{\text{TE}}(2\omega) \]  
(2.15b)

To design phase-matched BRW structures, we have opted to simply reduce one degree of freedom from the list of required structure parameters, due to the added restriction of phase-matching. For example, the required parameters in a Qt-BRW are $[d, x_c, x_1, x_2]$. To phase-match, we remove $d$ from this list and leave it to be determined by the algorithm. By scanning a range of possible core thicknesses, it is possible to determine if phase-matching is attained at some value. An example of this calculation is shown in Figure 2.9. Here, the phase-mismatch varies over a large range as the core thickness is varied. There is however a phase-matched value at 249 nm. This algorithm is shown as a flowchart in Figure 2.10.

For the parameters used in Figure 2.9, the resulting modal profiles are shown in Figure 2.11; the fundamental TIR mode is the dashed line and the second harmonic BRW mode is a solid curve. Note this is a Type-I configuration. The field profiles show regions where a positive TIR field interacts with a negative BRW field. Such regions degrade nonlinear performance due to the negative overlap. As mentioned in previous sections, the purpose of defect mirrors in BRW structures, such as the ML-BRW, can
Figure 2.9: Example of phase-mismatch with respect to core thickness, \( d_c \) for a Qt-BRW structure. Here, \( x_1 = 0 \), \( x_2 = 0.4 \), \( x_c = 0.15 \). The fundamental wavelength is 1550 nm. The algorithm determined value for phase-matched core thickness is 249 nm.

greatly improve the overlap of these modes.

### 2.3.3 3-wave mixing

This section will briefly expand on the theoretical description of second-harmonic generation to the more generalized three-wave mixing processes, first described in Equation 1.1a. Second harmonic generation is the degenerate case of sum-frequency generation (SFG). SFG is the process whereby two incident photons of different frequency, labeled \( \omega_{p,1} \) and \( \omega_{p,2} \), are combined to form a photon at the sum-frequency, \( \omega_{SFG} \), by utilizing the \( \chi^{(2)}(-\omega_{SFG}; \omega_1, \omega_2) \) tensor. This energy conservation is described mathematically in Equation 2.16

\[
\omega_{SFG} = \omega_{p,1} + \omega_{p,2}
\]  

(2.16)

Similarly, the opposite process is also possible and is termed difference-frequency
Given
Core material, \(x_c\)
High and low mirror material, \(x_1\) and \(x_2\)

Determine \(\{n_i\}\) for each layer

Determine \(\{n_{eff,i}\}\), set of possible effective indices (and \(\{\Theta_{c,i}\}\))

Loop cycling \(d_{c,j}\)

Loop cycling \(n_{eff,i}\)

For given \(n_{eff,i}\), determine quarter-wave mirror thickness'

Compute \(r_{right}\) and \(\phi_{right}\) from transfer-matrix at \(\Theta_c\)

Repeat for left mirror

Satisfy transverse resonance condition?

Yes

Satisfy phase-matching condition?

Yes

Refine value
Compute modal properties and fields

End

Figure 2.10: Algorithm for determining phase-matched BRW structures.
Figure 2.11: Modal field profiles of a phase-matched Qt-BRW structure. The dashed curve is the TIR bound mode and solid is the Bragg PBG mode.

Generation (DFG). Here, an incident photon of high frequency, $\omega_1$, interacts with a second photon of lower frequency, $\omega_2$, to produce a third photon at the difference of the two frequencies, $\omega_{DFG}$, by utilizing the $\chi^{(2)}(-\omega_{DFG}; \omega_1, -\omega_2)$ tensor. The mathematical description is shown below in Equation 2.17.

$$\omega_{DFG} = \omega_1 - \omega_2$$  \hspace{1cm} (2.17)

Both processes must also phase-match for efficient conversion. Following the same simplification used to arrive at Equation 2.15 for SHG, we arrive at the similar conditions for SFG and DFG in Equations 2.18a and 2.18b, respectively. Here, $\lambda_j$ is the wavelength of frequency $j$. The procedure for determining SFG or DFG specific phase-matched structures follows the same algorithm shown in Figure 2.10.

$$\frac{n_{eff}(\omega_3)}{\lambda_3} = \frac{n_{eff}(\omega_1)}{\lambda_1} + \frac{n_{eff}(\omega_2)}{\lambda_2}$$  \hspace{1cm} (2.18a)

$$\frac{n_{eff}(\omega_3)}{\lambda_3} = \frac{n_{eff}(\omega_1)}{\lambda_1} - \frac{n_{eff}(\omega_2)}{\lambda_2}$$  \hspace{1cm} (2.18b)
2.3.4 Leakage loss

Estimating the leakage loss of the Bragg mode is important for the nonlinear and laser applications utilized in this work. Nonlinear conversion efficiency can be significantly hampered and laser threshold can also become unacceptably high because of losses. Such leakage losses can then be minimized through appropriate design of the structure. This section will detail the technique used in this work.

There have been many methods detailed in literature on estimating Bragg mode propagation loss. These have stemmed from the finite nature of practical BRW claddings. An infinite Bragg reflector would have zero loss due to complete reflection, finite reflectors as those analyzed would have very high reflection, though still <1. West and Helmy derived a technique to estimate loss based on the loss per reflection [3]. Similarly, Li and Chi-ang derived an expression for the loss, calculated specifically for periodic claddings [32]. Here, we utilize the more general transfer-matrix method developed by Ghatak, Thyagarajan and Shenoy [33] and elaborated towards PBG waveguides by Dasgupta, Ghatak and Pal [34].

This technique requires first computing the cover to substrate field transfer matrix for a range of effective indices that encompasses the Bragg mode effective index. The method then requires plotting the ratio $\frac{|E_c|}{|E_s|}$. Here, $E_c$ is the outgoing field in the core and $E_s$ the substrate. This ratio represents the confinement of the optical power in the core over leakage into the substrate. Therefore, the peak represents the modal effective index. An example plot of the Bragg mode of Figure 2.11 is shown in Figure 2.12.

The authors had shown these points can be fit to a Lorentzian curve and the full-width at half maximum (FWHM), $\Delta n$ is related to the leakage propagation loss by $\alpha = \Delta n k_0$ [33]. We have utilized this technique due to its simplicity and generality. The method can be utilized for any generic PBG layered structure because it relies on field-transfer matrix analysis. Thus, it can be utilized for all types of BRW’s used in this work. Through appropriate design and optimization of PBG structures, the calculated leakage
Figure 2.12: Field confinement in the core versus substrate for loss calculation. The peak of this curve represents the modal effective index and the FWHM is the leakage propagation loss.

loss can be reduced significantly, to less than 0.01 cm$^{-1}$ in some cases. Nonetheless, such optimization does not address the many other forms of loss which affect the practical operation of devices. This includes the ridge scattering losses, free electron scattering and contact metal absorption. As such, the minimization of leakage loss should be considered in the context of reducing overall loss as well.
Chapter 3

Fabrication of ridge waveguides and diode lasers

Microfrabrication is an essential component of semiconductor photonics, especially for integrated optics and optoelectronics. Many of these tools and processes have been available for the microelectronics industry for quite some time, making analogous photonics fabrication simpler. However, robust processes for ridge waveguides and diode lasers did not exist within the University of Toronto in 2005 when I began my graduate studies. Process development was thus one of my first tasks. This section details the developed process on fabricating ridge waveguides and diode lasers. A separate chapter, Appendix A, is dedicated to the fine-details of the process in a step-by-step format.

3.1 Summary of process

There are many steps to fabricating diode lasers, typically taking a minimum of three days. This is due to the many deposition, lithography and etching phases. Since the first step to making the diode lasers involves ridge waveguide fabrication, a separate section for the fabrication of passive devices will not be needed.

The process can be broken into three categories / stages, detailed in the flowchart
shown in Figure 3.1. Each stage is composed of many steps, any of which can cause device performance to diminish if performed improperly. Thus it is important to be patient in the cleanroom and inspect your samples frequently to know if any errors have occurred. Below in Figures 3.2, 3.3, 3.4 are the detailed flowchart descriptions of each stage.

In stage 1, ridge waveguide patterns are defined into the substrate by dry etching. This first requires transferring the pattern into a suitable hard mask, in this case silica (SiO$_2$). In stage 2, the surface is electrically isolated using freshly deposited silica. Then, an opening is patterned just above the ridge to allow current to flow into the active region from this gap and nowhere else. In stage 3, suitable p-type and n-type contacts are deposited and the sample is thinned to allow ease of cleaving. The result is well-formed facet mirrors for the lasers.

### 3.2 Sample handling

Keeping samples clean and defect free is the extremely important in microfabrication, especially when the critical pattern dimensions are on the order of a few micrometers. There are some key, common sense techniques to assuring this which are listed below.
Figure 3.2: Breakdown of stage 1: Fabricating ridge waveguides into the semiconductor substrate. This requires first patterning a hard silica mask for the etch process.
Figure 3.3: Breakdown of stage 2: Electrically isolating the ridges by depositing silica and then opening a hole just above the ridge.
Figure 3.4: Breakdown of stage 3: depositing the top and bottom contacts. This stage also consists of thinning the sample to a suitable thickness for cleaving flat facets.
Chapter 3. Fabrication of ridge waveguides and diode lasers

- When cutting your sample, dust and tiny shards of semiconductor are released and can land on your sample. Use the nitrogen spray gun or iso-propanol liberally to remove this dust.

- Though the cleanroom is considered extremely clean, there are still some particles in the air. These can land on your sample. Keep your samples in a container or covered as much as possible (even during processing).

- The cleanroom user is a big source of particles such as from your breath or dandruff.

- Plastic or carbon fiber tipped tweezers will ensure you leave no permanent marks on the semiconductor surface in case your fingers slip. Use your hand to cup the sample when moving long distances with it to prevent it falling and shattering on the ground.

- Utilize the acetone and iso-propanol solvents liberally to maintain a clean surface.

This is by no means a complete list, however many users in the cleanroom do not take such precautions and their devices echo this. It is important to be patient in the cleanroom as rushing has lead to many errors on my part. Allot your time appropriately and you will find your yield and results improve.

3.3 Photolithography

Photolithography is the process by which light is used to transfer a pattern into a photosensitive material, typically a photoresist. In our process, photolithography is used entirely to define patterns using spin-on positive photoresists made by Shipley, namely S1818 and S1811. We utilize spinners with control of rotation speed and acceleration to spin thin-film layers of the photoresist onto the substrate. Rotation speed, in rotations per minute (RPM) control the final thickness of the film; the faster the RPM, the thinner the film.
After spinning, soft-baking at 103°C is used to evaporate many of the solvents contained within the photoresist. Now the sample can be placed under a mask and exposed to ultra-violet light for a dosage suitable to the photoresist. After much development, a choice of 6.5 to 8 seconds was found to be suitable for S1818 and 5 to 6 seconds for S1811. These times are highly dependent on the baking temperature. The sample is then dipped in a developer such as MF-321 where exposed regions are dissolved while unexposed areas remain. Figure 3.5 shows an optical microscope image of photoresist patterns of ridge waveguides.

Some lithography steps require precise alignment of the pattern with the substrate. In the case of the ridge waveguides, mirror facets perpendicular to the waveguide requires alignment of the crystal axes to the pattern. For this, it is best to align the ridge pattern to the sample edge. However, this requires good cleaving to make the sample and is not necessarily easy. Do not apply too much pressure on the sample when cleaving as this can cause damaged or curved edges.

For the oxide opening stage, the gap in the pattern must be aligned with the top of the ridge. This step is extremely important and the user should take his/her time. Use the highest magnification available and rotate the sample carefully. It is best to use opposite ends of the sample as this allows the greatest distance for any misalignment to become
Figure 3.6: Scanning electron micrographs of oxide opening alignment. When alignment is done well, the oxide opening occurs just above the ridge allowing current to flow from the highly doped contact layer. Poor alignment would remove isolating oxide from the sides of the ridge.

3.4 Plasma-enhanced chemical vapour deposition

The process utilizes SiO$_2$ as both a hard dielectric mask for etching and for electric isolation. This requires a deposition method which can create high quality dielectric films of low defect inclusion. The instrument we used is an Oxford Plasmalab 100 plasma-enhanced chemical vapour deposition (PECVD) system, shown in Figure 3.7(a). The Plasmalab creates a high-density, high-pressure plasma above a heated substrate that allows the chemicals to crack and deposit onto the sample surface as shown in Figure 3.7(b). Due to the high-temperatures used, volatile by-products and gases tend to leave the surface resulting in high-quality dielectric films.

The Plasmalab was configured to deposit SiO$_2$ using a combination of Silane (source
Chapter 3. Fabrication of ridge waveguides and diode lasers

(a) Oxford Plasmalab 100 instrument

(b) Schematic of PEVCD operation

Figure 3.7: Plasma-enhanced chemical vapour deposition instrument and operation. Inert gas is mixed with process gas and sent into the chamber where an RF supply ignites the plasma. The ions and radicals in the plasma diffuse and drift to the heated surface where they crack and bond to form the dielectric film.

of silicon) and Nitrous Oxide gases (source of oxygen) with Nitrogen as the inert background gas. Though Nitrogen gas is volatile enough to exhaust from the surface, the produced Hydrogen gas remains in small quantities. The impurity level decreases with increased temperature; our process temperature was 400°C to reduce hydrogen inclusion and increase electrical resistivity. The process recipe details are listed in Table 3.1.

3.5 Reactive ion etching

Reactive ion etching is a form of dry etching which utilizes energetic particles within a plasma to mill exposed regions of a sample. In this way, pattern transfer of the mask to the substrate is accomplished. Plasma etching is also useful when anisotropy and selectivity in etching are needed. The etchers used in this research are Trions inductively coupled plasma (ICP) etchers, the Phantom II and Minilock II shown in Figure 3.8(a).

The chamber configuration is very similar to the PECVD chamber in Figure 3.7(a) with some notable differences. First, the pressure and flowrate are far lower allowing
for highly energetic particles with long mean free paths. This allows the ions to attain faster velocities before collisions. Secondly, the substrate is not heated as there is no need for cracking of molecules for film deposition. Rather, collision of energetic ions with a cold surface allows for faster etch rates. A diagram of this etch process is shown in Figure 3.8(b).

The two instruments in Figure 3.8(a) are the Phantom and Minilock etchers used for Fluorine and Chlorine etching, respectively. The Phantom is useful for etching group IV semiconductors such as Silicon (Si), and certain dielectrics such as Silica (SiO$_2$) and Silicon Nitride (Si$_3$N$_4$). The Minilock’s Chlorine chemistry is useful for etching III-V semiconductors such as Gallium Arsenide (GaAs) and Indium Phosphide (InP) as well as some metals such as Chromium (Cr). In the coming sections, our developed recipes for dry etching will be detailed.

Table 3.1: Process recipe for the deposition of SiO$_2$ @ 400° in the Oxford Plasmalab 100. The rate of deposition is between 60 to 70 nm/min.

<table>
<thead>
<tr>
<th>Step #</th>
<th>Name</th>
<th>Process</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Pump down</td>
<td>1 minute wait for full pumpdown to vacuum</td>
</tr>
<tr>
<td>2</td>
<td>Pre-heat</td>
<td>10 minute pre-heat with 1000 sccm N$_2$ at 1500 mTorr to compensate for heat loss due to gas flow</td>
</tr>
<tr>
<td>3</td>
<td>Nitrogen clean</td>
<td>30 second clean of substrate surface with N$_2$ plasma</td>
</tr>
<tr>
<td>4</td>
<td>SiO$_2$</td>
<td>Deposition of SiO$_2$ onto substrate using following conditions: 170 sccm 5% SiH$_4$/N$_2$, 710 sccm N$_2$O, 1000 mTorr pressure, 30 W RF power</td>
</tr>
<tr>
<td>5</td>
<td>Pump down</td>
<td>1 minute wait for full pumpdown to vacuum to ensure dangerous gases leave chamber</td>
</tr>
</tbody>
</table>
3.5.1 Silica

Several steps of the fabrication process flowchart shown in the Summary of process (3.1) require etching a patterned into PECVD silica. A process was developed on the Phantom etcher utilizing CHF$_3$ gas. It is well known that plasmas utilizing CHF$_3$ gases form a fluorocarbon film (CF$_x$) on the surface [35]. This film is the reactive component to the etching of silica. Our recipe is found to be relatively anisotropic and leaves no micro-masking or damage on the etched surface. Nonetheless, it is believed that any unseen silica remaining on the surface is responsible for micro-masking effects in the AlGaAs etch stage. By dipping the etched sample in 10:1 buffered oxide etchant (BOE) for 10 to 15 seconds, micro-masking was drastically reduced. BOE is a mixture of ammonium fluoride (NH$_4$F) and hydrofluoric acid (HF) and should be used carefully and within the guidelines of the cleanroom and common sense. Table 3.2 contains the specific settings for this recipe.
Table 3.2: Process recipe for the etching of SiO$_2$ in the Trion Phantom II using CHF$_3$ inductively coupled plasma. The etch rate is between 4.2 to 4.5 nm/sec.

<table>
<thead>
<tr>
<th>ICP RF power (W)</th>
<th>RIE RF power (W)</th>
<th>Pressure (mTorr)</th>
<th>CHF$_3$ flowrate (sccm)</th>
<th>He cooling flowrate (sccm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>400</td>
<td>70</td>
<td>15</td>
<td>50</td>
<td>8</td>
</tr>
</tbody>
</table>

3.5.2 Aluminum Gallium Arsenide

Defining the ridge waveguide is one of the most important steps to device performance, whether it be nonlinear optics or a laser. The quality of etching can have a significant impact on optical losses and modal confinement. The AlGaAs etching recipe was the most time consuming to develop going through many iterations, many due to equipment failures or changes upstream in the process. Nonetheless, two recipes were developed for AlGaAs etching; one is fast with low selectivity, the other is slow with higher selectivity.

Trion’s Minilock II etcher has a load lock to prevent contamination of the process chamber itself. The added benefit is a much lower base pressure, typically 10$^{-6}$ Torr compared to 10$^{-5}$ Torr for the Phantom. The process gases used for etching are Ar, Cl$_2$ and BCl$_3$. The choice of ratio between these can affect the etch drastically. For example, increasing Cl$_2$ would improve the chemical etch rate and selectivity between the mask and AlGaAs, but at the expense of decreased anisotropy. Increasing Ar would improve physical etching and anisotropy at the expense of selectivity. Lastly increasing BCl$_3$ provides a mix of chemical and physical etching as it produces heavy, but reactive BCl$_x$ ions [36]. The appropriate mix, along with choices of power and pressure, was one of the most time consuming steps to development.

During development, it was found that chamber conditions were extremely vital to the etching process. Variability from day to day was significant in regards to etch quality and etch rate. It was later found that certain radicals and contaminants degrade or modify plasma characteristics over time if not treated. Murad et al. found that Chlorine
radicals attached to the chamber walls from previous etches can reduce reactive chlorine concentrations from the plasma [37]. Similarly, Ullal et al found that silica films on the chamber wall from quartz windows and carrier plates can also reduce etch rates [38]. Both articles stressed the importance of cleaning the chamber using appropriate plasma discharges, in this case, H$_2$ plasma for Chlorine radicals and O$_2$ plasma for silica removal. The developed process relies on the clean recipe in Table 3.3 after each run for reproducibility.

Table 3.3: Process recipe for cleaning the Trion Minilock II chamber using H$_2$ and O$_2$ inductively coupled plasmas for reproducibility.

<table>
<thead>
<tr>
<th>Step</th>
<th>ICP RF power (W)</th>
<th>RIE RF power (W)</th>
<th>Pressure (mTorr)</th>
<th>H$_2$ flowrate (sccm)</th>
<th>O$_2$ flowrate (sccm)</th>
<th>Time (mins)</th>
</tr>
</thead>
<tbody>
<tr>
<td>H$_2$ clean</td>
<td>400</td>
<td>100</td>
<td>45</td>
<td>50</td>
<td>0</td>
<td>15</td>
</tr>
<tr>
<td>O$_2$ clean</td>
<td>300</td>
<td>100</td>
<td>110</td>
<td>0</td>
<td>50</td>
<td>10</td>
</tr>
<tr>
<td>cool down</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>10</td>
</tr>
</tbody>
</table>

**Fast process**

This recipe was developed for situations where throughput and speed are important. Etch quality is very good, as shown in Figure 3.9(a) with excellent side-wall smoothness, shown in Figure 3.9(b). The etch rate is between 1900-2050 nm/min. Unfortunately, selectivity against the silica hard mask was not sufficient to etch past 3200 nm before damage to the ridge occurs, seen in Figure 3.9(c). Thus, the fast etch process is limited to shallow etches, preferably below 2500 nm. The recipe settings are contained in Table 3.4

**Slow process**

This recipe was developed to allow for deep, highly anisotropic features such as the ones used for our ridge Bragg reflection waveguides. The fast recipe described in Section 3.5.2
is not suitable to reach the depths required. As such, this recipe was developed with selectivity of the mask in mind at the expense of speed; the etch rate is between 700-775 nm/min. Counter to intuition, the carrier and sample get much hotter in the slow recipe compared to the fast one. To compensate for the degrading effects of heat, we employ step based etching. The RF power is turned on for 90 seconds, then the RF is turned off
for cooling for 180 seconds. This is repeated till the desired etch depth is attained. The settings for the slow recipe are contained in Table 3.5.

The SEM cross-section profile in Figure 3.10(a) shows anisotropy has not degraded when compared to Figure 3.9(a) of the fast process. Neither has the wall roughness, as seen in Figure 3.10(b). In Figure 3.10(a), the silica mask is almost completely intact, attesting to the high selectivity of the semiconductor in this process. If the on-off method to control heating is not employed, isotropic etching can become dominant and degrade the etch quality, shown in Figure 3.10(c).

![SEM cross-section profile](image1)

![SEM of wall roughness](image2)

![Isotropic chemical etching due to heat](image3)

Figure 3.10: Scanning electron micrographs of slow recipe for AlGaAs etching. Note the silica mask is almost fully intact indicating a very high selectivity.
Table 3.5: Recipe for etching AlGaAs at a slow rate in the Trion Minilock II. The etch rate is between 700-775 nm/min.

<table>
<thead>
<tr>
<th>ICP RF power (W)</th>
<th>RIE RF power (W)</th>
<th>Pressure (mTorr)</th>
<th>( \text{Cl}_2 ) flowrate (sccm)</th>
<th>( \text{BCl}_3 ) flowrate (sccm)</th>
<th>Ar flowrate (sccm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>200</td>
<td>50</td>
<td>5</td>
<td>8</td>
<td>4.5</td>
<td>5</td>
</tr>
</tbody>
</table>

3.6 Contact deposition

Deposition of good, ohmic metal contacts onto the semiconductor is important for interfacing and activating the diode laser. For AlGaAs, ohmic contacts are multi-layers of two or more metals to properly interface with the bandgap of the material. A typical n-type contact is a stack of Au-Ge-Ni-Au metals and a typical p-type contact is Ti-Au. Currently, we do not have a process to deposit these metals as the control mechanism for thickness is inadequate. As such, we have utilized the deposition services of University of Sherbrooke in Quebec for these contacts.

The top p-type contact needs patterning to isolate individual lasers, achieved by removing a 50 \( \mu \text{m} \) strip between each ridge waveguide through a liftoff technique. Before contact deposition, photoresist is patterned such that strips remain between ridges. The photoresist is treated with toluene before development to harden the surface. During development, the region near the surface of the resist dissolves slower than the lower parts creating an undercut. After deposition of the metals, acetone and ultra-sonic agitation can remove the patterned photoresist leaving regions of no metal. The bottom n-type contact does not require patterning as charges flow only through the laser being selected from the top contacts.
3.7 Sample thinning and cleaving

Splitting a larger semiconductor sample into tiny bars with mirror facets requires cleaving along crystal slip planes. Assuming the ridge waveguides were placed orthogonal to these planes, as mentioned in Section 3.3, this should not be an issue. However, the minimum length of cleaving is typically related to the wafer thickness. Based on experience, the minimum cleavable length by hand is about $3 \times$ the thickness of the sample. Since most wafers are between 400 to 600 $\mu$m thick, the smallest length we could achieve is over 1.5 mm. This is an unacceptable minimum length for a diode laser cavity, especially since internal differential efficiency is inversely proportional to length.

To achieve smaller lengths, the wafer was thinned (sometimes called lapping) to between 100 to 150 $\mu$m. This allows for a minimum sample length of about 300 $\mu$m, an achieved value. For thinning, an Ecomet III lapping instrument is used, shown in Figure 3.11(a). This machine has a rotating wheel onto which abrasive powder and water is placed. The samples are affixed to a special fixture, seen in Figure 3.11(b) using a wax meant for lapping. This wax is easily dissolved with acetone. The fixture allows the user
Chapter 3. Fabrication of ridge waveguides and diode lasers

Figure 3.12: Utilizing dicing tape to cleave devices from fragile thinned samples. The tape provides mechanical support while scribe marks are placed and used to cleave desired device lengths.

to select a final thickness via thin shims. These shims increase or decrease the fixture size relative to the sample allowing precision within 25 $\mu$m.

As the wheel rotates, the abrasive particles slowly eat away at the bottom of the sample and reduce its thickness. For our GaAs substrates, Alumina ($\text{Al}_2\text{O}_3$) abrasive was used. Initially, 30 $\mu$m Alumina laps the sample quickly till a thickness of about 150 to 200 $\mu$m. A second polishing step with 5 $\mu$m Alumina reduces the thickness a further 50 $\mu$m while providing a flatter finish. Note this process must be done before the bottom n-contact is deposited.

Handling a thinned sample is quite difficult. Don’t be alarmed to find you have applied too much force on tweezers and the sample has cracked; this is an acquired skill. The sample is cleaved by first placing it on an adhesive dicing tape shown in Figure 3.12(a), made for holding wafers. Then, scribe marks are placed along one edge of the sample by a diamond scribing tool. It is extremely useful to perform this under a microscope to gauge the location of the scribe marks as well as the force applied to make them. The second layer is then reapplied onto the scribed sample, sandwiching it between them.
This protects it from the next stage which uses one’s fingers to gently force the sample over the edge of a glass slide. Assuming the sample thickness is adequate, very little pressure will be needed to initiate the cleave. The process is repeated for all scribe resulting in many devices as seen in Figure 3.12(b).

Once the individual cleaved devices are carefully removed from the tape to an appropriate adhesive lined container, their facets can be individually inspected. Again, this must be performed under a high-magnification microscope. Sometimes the cleave will fail and would damage a facet. Such devices should be clearly marked or discarded. The microscope can also be utilized to measure the actual device lengths as this information is very important for characterization.
Chapter 4

Second harmonic generation in BRWs

With the framework for phase-matched BRW’s for frequency conversion by Helmy and West [5, 39], the next logical step was to experimentally verify the theory. For this, the simplest $\chi^{(2)}$ process, second harmonic generation (SHG), was chosen to reduce complexity of the experiment. This process is the up-conversion of a fundamental frequency (FF), $\omega_{FF}$, to its second harmonic (SH), $\omega_{SH} = 2 \cdot \omega_{FF}$. Here, only the fundamental is required to be input to the waveguide making it a simple experiment for the proof-of-principle. This section will detail my contribution in the experiments performed in SHG.

4.1 Waveguide design

The first BRW design for SHG, called SH1, was a Qt-BRW due to the simplicity of the design equations [39]. SH1 was designed to convert 1550 nm fundamental light to 775 nm. This fundamental wavelength was chosen due to its positioning within the telecommunications C-band where many sources exist for the experiment. Some examples of such sources are tunable InP diode lasers, Erbium-doped fiber amplifiers or tunable pulsed optical parametric oscillators. This allows for the ease of sweeping fundamental
input frequencies into SH1 to locate the phase-matched wavelength.

The SH process of SH1 can be simply described by the phase-matching condition shown in Equation 4.1. Here, \( n_{\text{eff,BRW}}^{TM}(755 \text{ nm}) \) and \( n_{\text{eff,TIR}}^{TE}(1550 \text{ nm}) \) are the modal effective indices of the Bragg TM mode at 775 nm and TIR TE mode at 1550 nm, respectively. This arrangement is consistent with the polarization conditions for type-I phase matching of the bulk \( \chi^{(2)}_{xyz} (d_{14}) \) coefficient.

\[
\Delta n = n_{\text{eff,BRW}}^{TM}(755 \text{ nm}) - n_{\text{eff,TIR}}^{TE}(1550 \text{ nm}) = 0
\]  

(4.1)

The structure was designed with quarter-wave mirrors of Al\(_{0.6}\)Ga\(_{0.4}\)As and Al\(_{0.2}\)Ga\(_{0.8}\)As bilayers with thicknesses of 278 nm and 118 nm, respectively. The top stack consisted of 8 periods while the lower stack had 10 periods. More periods on the lower stack reduces leakage loss to the high-index substrate and also reduces the distance needed for etching the top stack for ridge waveguides. The core material was chosen as Al\(_{0.4}\)Ga\(_{0.6}\)As, exactly in between the mirror stack materials. For this design, the refractive index model by Adachi [40] was used. From all these parameters, the algorithm shown in 2.10 can
Figure 4.2: (a) Normalized Fields and refractive index profiles for the (b) SH and (c) FF for SH1. The dashed lines represents the modal effective index.

provide a phase-matched core thickness, $d_c$. The effective indices of the Bragg mode and TIR mode with respect to $d_c$ are shown in Figure 4.1. The core thickness for which phase-matching occurs is 328 nm. The structure was nominally undoped and grown using metal-organic chemical vapor deposition (MOCVD). It had a 500 nm GaAs buffer grown on the GaAs substrate first. The wafer was capped with a 50 nm layer of GaAs. A complete epitaxial growth list is provided in Appendix C.1.

The simulated fields for the Bragg and TIR modes are shown in Figure 4.2(a). The solid curve is the Bragg mode while the dashed curve is the TIR mode. Figures 4.2(b)
Figure 4.3: Setup for the testing of SH1. A Ti:Sapphire pumped OPO is input into the sample after beam shaping and polarization control. The output is measured for power and spectrum.

and 4.2(c) are the refractive index profiles for the SH and FF wavelengths, respectively. The dashed line in either profile represents the modal effective index.

4.2 Experimental setup

Initially, a slab waveguide configuration instead of a ridge waveguide arrangement was chosen to test these structures. This simplifies this first experiment for the proof-of-principle while eliminating any bias induced by the two-dimensional ridge fabrication. In ridge waveguide configuration, this variation would be convoluted with those introduced during epitaxial growth. This interferes with our ability to analyze the properties of the phase-matching technique. Nonetheless, ridge waveguide SHG and its experimental results will be explored later on in the chapter.

The characterization was carried out using a singly-resonant KTP OPO synchronously pumped by a mode-locked Ti:sapphire laser. Output pulses with full width at half-
Figure 4.4: Gaussian beam simulation of beam shaped through a cylindrical lens for the (a) Horizontal axis and (b) Vertical axis. The shaded region represents the sample.

Pulses with a center wavelength around 1550 nm were end-fire coupled into a 2.38 mm long sample using an anti-reflection coated 40× objective lens. A cylindrical lens with a focal length of 150 mm was used at the input to render the beam elliptical. This enhances the coupling efficiency into the slab and maintains a minimum beam waist inside the sample. A schematic of the setup is shown in Figure 4.3.

Through modeling the incident beam, it was predicted that the optimum configuration obtained using this setup provides a beam with a spot size of 37.5 μm at the sample.
facet. The beam focuses in the horizontal direction ($x$-axis) 1 mm inside the sample with a minimum beam waist of 27.8 $\mu$m. At the output of the sample the beam spot size is 50 $\mu$m. The beam waist remains constant in the vertical direction ($y$-axis) due to the vertical guiding structure. The Gaussian beam simulation results are shown in Figures 4.4(a) and 4.4(b) for the vertical and horizontal directions, respectively. The beam is focused at the facet of the $y$-axis to excite the TIR mode. In the $x$-axis, the beam is focused within the sample to enhance nonlinear conversion by maximizing the region of high-intensity.

After the light was coupled into the slab with the aid of an infrared camera, the output of the slab was focused onto a power meter to measure the amount of transmission through the samples. The light was then coupled into an optical spectrum analyzer to track changes in the output spectrum.

4.2.1 Slab waveguide SHG

This section will describe the results of this experiment [41]. Initially, the linear properties of the slab waveguide were examined using the cut-back method. The coupling efficiency into the slab was measured to be $\approx 20\% \pm 5\%$ and the propagation loss was found to be $\approx 2.5$ cm$^{-1} \pm 1.5$ cm$^{-1}$. The power-in/power-out relation was then inspected to ensure that no dominant two-photon absorption effects take place. Such effects were not expected to be significant since the operating wavelengths are more than 173 meV below the half-bandgap of the lowest Al-containing layers in the structure (Al$_{0.2}$Ga$_{0.8}$As); this was by design.

Based on Equation 4.1, SH output should be expected in the TM polarization for the TE FF input. By monitoring the TM-polarized SH output power at different TE-polarized pump wavelengths, the tuning curve can be generated as shown in Figure 4.5. As expected, no SH power could be detected when the input is switched to TM polarization. However, unphase-matched SH power could be detected throughout the range
of wavelengths studied. At the regime where the BRW phase matching takes place (at $\lambda_{FF} = 1587.8$ nm) the SH output power increases by one order of magnitude. This is the phase-matching wavelength and the feature exhibited a width (FWHM) of 2.22 nm.

Though the structure was designed for phase-matching at 1550 nm, experiment shows the actual wavelength this occurs at is 1587.8 nm. MOCVD growth variations are likely to be present in the cladding and core layers. Due to the dispersive nature of BRW modes, slight changes in layer thickness or composition could cause this shift. Further, the Adachi model used for AlGaAs refractive indices is outdated. Future BRWs utilized the more recent Gehrsitz model [23] and demonstrated improvement.

SH power is governed by a quadratic relation of the form $P_{SH} \propto P_{FF}^2$. This quadratic dependence of the SH power on the pump power was checked on- and off phase-matching as shown in Figure 4.6. The slope of both curves is approximately equal to 2 on a log-log scale, confirming the parabolic power dependence. No sign of saturation could be detected.

Further insight can be acquired when the spectra of the SH are inspected. Spectra for two TE-polarized pump signals with wavelengths of 1578.8 and 1587.8 nm are shown...
Figure 4.6: Fundamental power in versus converted power out for slab waveguide SH1 [41] on a log–log plot, shown for both phase-matched (squares) and unphase-matched (circles). Linear fits show slope of 2 verifying quadratic relationship.

in Figure 4.7. They are denoted FF$_a$ and FF$_b$, respectively. Also plotted are the spectra of their corresponding TM-polarized SH signals at 789.5 and 794 nm, which are denoted SH$_a$ and SH$_b$, respectively. The spectral width of the non phase-matched signal SH$_a$ (FWHM, 1.21 nm) is about half that of the pump wavelength (FWHM, 2.88 nm). This is not the case for SH$_b$ where phase-matching takes place. In this case, the SH spectral width (FWHM, 0.43 nm) is nearly one order of magnitude smaller than the width of its associated pump (FWHM, 3.54 nm). This is strong evidence of the change in the nature of SH and its transition from unphase-matched into phase-matched at the wavelength of 1587.8 nm. The narrower spectral width suggests that the limitation of the phase-matching bandwidth is determined by the BRW structure. From previous work [39], we were able to predict the bandwidth of these structures.
Figure 4.7: Comparison of fundamental input spectra (FF\textsubscript{a} and FF\textsubscript{b}) and second harmonic output spectra (SH\textsubscript{a} and SH\textsubscript{b}) for both unphase-matched and phase-matched cases, respectively [41]. Note the FWHM for SH\textsubscript{b} is much smaller than for SH\textsubscript{a}. This is a consequence of the limited phase-matching bandwidth in the conversion process.

4.2.2 Ridge waveguide SHG

The slab results above demonstrated the proof-of-principle of the BRW phase-matching scheme. However, the 0.1%/W internal conversion efficiency is far too low for practical use. The enhanced intensity within the ridge waveguide in comparison to modes in slab waveguides serves to substantially enhance the conversion efficiency. For example, a 3 \( \mu \)m ridge will have an order of magnitude smaller mode size in the \( x \)-direction. If we assume this results in an order of magnitude increase of intensity, then the converted power would increase by two orders of magnitude due to the quadratic power relation. Hence, ridge waveguides were fabricated from the SH1 wafer and the SHG experiment was repeated. The results will be summarized in this section [42].

Utilizing a similar fabrication process to that detailed in Chapter 3, ridges \( \approx 3\mu\text{m} \)
Chapter 4. Second harmonic generation in BRWs

Figure 4.8: Scanning electron microscope images of SH1 ridge waveguide showing (a) the profile and (b) side-wall roughness. Note the imperfect etch caused by mask-failure. The etch quality is otherwise good.

width and $\approx 4\mu m$ depth were fabricated on a $5 \times 5$ mm sample of the SH1 wafer. Since this sample was prepared before the process was perfected, the etch results were not ideal. Nonetheless, the ridges were sufficient to perform the experiment. This brought the etch to just past the core. Figure 4.8(a) shows an SEM profile cross-section of the SH1 waveguides showing an almost vertical sidewall ridge. Note the defect due to etch-mask failure at the top of the ridge. Also, the wall quality is reasonable as shown in Figure 4.8(b). Using these parameters, the 2D intensity profiles of both the Bragg and TIR modes can be found for the ridge structure as shown in Figure 4.9. These profiles were simulated using the COMSOL Multiphysics 2D eigenmode solver [43].

Using an end-fire coupling setup, the samples were initially characterized for linear loss using a C-band tunable distributed feedback laser-diode source (JDS Uniphase SWS15101). The propagation loss at 1555 nm was measured to be $5.9 \pm 0.2 \text{ cm}^{-1}$ using the Fabry-Pérot method [44]. This value is higher than the slab value mentioned in the previous section and is likely due to roughness from the deep etch.

The nonlinear testing setup is similar to the one used in the slab case with the noted distinction that the cylindrical lens has been removed. This is because we are no longer
coupling into a slab mode and a circular input is preferred to increase coupling efficiency. A second modification was the sample stage was modified for temperature control. A temperature controller (Keithley 2510-AT) monitored the stage temperature through a thermistor and controlled it via a thermo-electric cooler (TEC). This was added to test the phase-matching tunability through temperature control.

Prior to conducting the SHG experiments, confirmation of the significant contribution of two-photon absorption was observed at high intensities (average input powers above 25 mW at the facet). Using lower input fundamental power (21 mW at the facet) where this absorption is minimal, 61.8 µW output of the fundamental was measured. Utilizing the values of the linear losses obtained from measurements, while assuming an approximate facet reflectivity of 30% and 35% transmissivity of the output objective lens, the coupling efficiency is estimated to amount to 1.8±0.3%. This low value is expected and is attributed to the thin core thickness of SH1 which reduces the numerical aperture.
First, the wavelength tuning curve for type-I SHG was found by observing the SH output power as the fundamental wavelength was tuned. The resulting plot is shown in Figure 4.10. A clear peak can be seen at 1600 nm indicating the location of phase-matched conversion. In this case, the available average input power allowed 3.2 mW of the pump to be coupled into the waveguide, just inside the front facet. Modulation of the tuning curve by the Fabry-Pérot fringes of the pump is noticeable but is not pronounced due to the wide bandwidth of the pulsed source.

The peak at which the PM takes place is shifted by 12 nm from the slab case. The shift is attributed to the influence of the two-dimensional (2D) guiding on the propagation constant of both the pump and the SH signals. This effect was confirmed through numerical simulation of the dependence of the ridge width on phase-matching wavelength. The results are illustrated in Figure 4.11 where a redshift of the PM wavelength due to ridge confinement is evident. Thus, this phase-matched wavelength is within our expected range.

The spectra of both the phase-matched ($\text{SH}_a$) and unphased-matched SH ($\text{SH}_b$) sig-
Figure 4.11: Sensitivity of the phase-match wavelength on ridge width for SH1 [42]. A shift of 12 nm is expected between the slab and ridge case. Further, this can explain the second-harmonic spectral width as due to slight variations in ridge width from side-wall roughness.

Signals, along with a typical fundamental spectrum (FF) are shown in Figure 4.12. Contrary to the slab case in Figure 4.7, there was no noticeable change in the SH spectral FWHM between the phase-matched and unphase-matched cases. This can be ascribed to the finite side wall roughness of the etched waveguide to which both the photolithography and plasma etching processes contribute. In the case of slab BRW, the FWHM of the SH spectra was 0.45 nm, as predicted from theory [39] while it is 0.96 nm for the ridge case. From the simulations of the phase-match dependence on ridge width in Figure 4.11, it was established that this broadening can be caused by a variation in waveguide width of \( \approx 40 \) nm. Roughness on this scale would in turn broaden the SH spectrum as well as the tuning curve. Note the FWHM of the tuning curve is 4.5 nm, also approximately twice that of the slab case.

It has been previously reported that propagation losses can also contribute to this broadening [45]. However, based on our simulations, the SH losses required to explain
**Figure 4.12:** Fundamental (FF) and second harmonic spectra for ridge waveguide SH1 at the phase-matched (SH$_a$) and un-phase-matched (SH$_b$) wavelengths [42].

Note that the FWHM of SH$_a$ doesn’t reduce compared to SH$_b$ as in the slab waveguide. This could be due to variations in the side-wall roughness.

This FWHM need to be $>80$ cm$^{-1}$. This level of propagation loss value is not conducive to this type of waveguide. Further, it cannot be explained solely through band-tail absorption [46] for this detuning from the bandgap or through substrate leakage [39]. Further investigation through simulation of the nonlinear Schrödinger equation is required to provide a more complete picture of all the contributing effects (e.g. group velocity mismatch, group velocity dispersion, spectral overlap with nonlinear conversion bandwidth).

We further investigated control and tuning of the phase-match wavelength of the structure by varying the temperature. As mentioned earlier, the sample was mounted on a temperature controlled sample holder. Each temperature point was held constant for about 5 minutes before the end-fire rig was re-aligned to maximize input and output. This is because the new temperature has slightly shrunk or expanded the metallic stage out of alignment. The wavelength tuning curve discussed above was repeated for temperatures between 15 and 40 °C. For this temperature range, the tuning slope was found to be
Figure 4.13: Temperature tuning of the phase-matching wavelength for ridge waveguide SH1 [42]. Experimental values are shown as squares and the theoretical calculation follows the solid line.

0.25 nm/°C, as illustrated by the open squares in Figure 4.13. The dashed line is the theoretical calculation. This wavelength shift is in rough agreement with rate on the order of magnitude expected from the simulation.

### 4.3 Conversion efficiency

The conversion observed in this work is more efficient than the slab case as predicted. We define the conversion efficiency as $P_{\text{out}}(2\omega)/P_{\text{in}}^2(\omega)$, where $P_{\text{out}}(2\omega)$ is the SH power just before the output facet and $P_{\text{in}}(\omega)$ is the pump power just after the input facet.

At low input powers for which the nonlinear absorption was minimal, the average conversion efficiency was calculated to be $8.6\pm1\%$/W compared to $0.1\%$/W for the slab. The enhancement can be attributed to the increased modal intensity provided by the 2D confinement of the ridge.

The normalized internal conversion efficiency $\eta_0$ is challenging to estimate because of
the difficulty in directly measuring the SH mode loss. However, a lower bound can be estimated by assuming no loss at the SH from [45], shown as Equation 4.2.

\[
\eta = e^{-2\alpha_\omega L} \left( 1 - e^{-(0.5 - \alpha_2\omega - \alpha_\omega) L} \right)^2
\]

(4.2)

Here, \(\alpha_\omega\) and \(\alpha_2\omega\) are the losses at the FF and SH, respectively. The length of the sample is \(L\) and \(\eta\) is a measured internal conversion efficiency, uncompensated for losses. It can be calculated through measured values from the experiment using Equation 4.3.

\[
\eta = \frac{P_{out,2\omega}}{P_{in,\omega}^2 \cdot L^2}
\]

(4.3)

As such, \(\eta_0\) is a more representative figure-of-merit of the actual nonlinear conversion process. For this sample, \(\eta\) was found to be \(205 \pm 10\% / \text{Wcm}^2\) at \(1600\) nm. Assuming no loss for the SH mode and using Equation 4.2, \(\eta_0\) is found to be at least \(600\% / \text{Wcm}^2\). This is on par or greater than numbers obtained for periodically poled lithium niobate (PPLN) [45][47]. This calculated value is just a lower bound. The actual value of \(\eta_0\) is expected to be much larger after SH loss \((\alpha_2\omega)\) is included. This is because the SH wavelength is in the proximity of the bandgap of the materials and some band-tail absorption is likely to occur.

Lastly, note we have assumed 100% collection efficiency of the output objective in these calculations. Due to the large divergence angle of Bragg modes, the collection from a typical objective lens is expected to be very poor. This is typical of leaky modes or higher-order modes. For example, Moutzouris et al. [15] estimated <30% collection efficiency of a third-order mode in their SHG experiments. We expect similar inefficiency within our setup.
4.4 Summary / Discussion

This chapter has detailed the first few experiments into nonlinear conversion within this BRW modal phase-matching scheme. Despite being the initial demonstration, the conversion value is well within an order of magnitude of other reported values in AlGaAs waveguides such as birefringent phase matching [47], modal phase matching [15], and quasi-phase matching [48]. This demonstrates the efficiency of the internal conversion process through utilizing the nonlinear coefficient of AlGaAs, which is higher than popular nonlinear crystals such as PPLN.

Here, Type-I SHG is demonstrated for the first time in both slab and ridge BRWs. In slab configuration, the conversion efficiency is found to be 0.1 %/W at a phase-matched wavelength of 1587 nm. Quadratic power dependence confirmed that the detected signal was SHG. The ridge configuration had conversion efficiency of 8.6 %/W, due in part to the higher intensity from lateral confinement. Here, the phase-matched wavelength was at 1600 nm, a shift of 13 nm towards longer wavelengths. This was expected from simulation of the true effective index of a 2D transverse structure. The phase-matched wavelength was also found to shift with temperature at a rate of 0.25 nm/°C. The lossless normalized conversion efficiency was estimated to be at least 600 %/Wcm².

More recent work into this form of phase-matching has yielded much improved performance with $\eta_0$ approaching well over 5000 %/Wcm² for Type-I SHG and over 10000 %/Wcm² for Type-II SHG [49]. This was accomplished through the use of other types of BRWs such as ML-BRW and DML-BRW (Section 2.2.2). Such structures allow for better overlap of the interacting modes and lower propagation losses [50]. Further, the technology has been demonstrated for SHG with CW sources [17], for SFG [51] and DFG [52].
Chapter 5

BRW cavity design for intracavity devices

BRW cavities are advantageous towards monolithic integration due in part to the layered, all-semiconductor structure. Not only can the design be grown via current epitaxial growth technology down to the nanometer and percentage composition, but fabrication of complex waveguides and devices can take advantage of mature micro-fabrication technologies. Since our choice of material is AlGaAs, there is the added benefit of doping such structures and creating active components such as diode-lasers and amplifiers. Other platforms for nonlinear optical devices, such as AlO$_x$ form-birefringent waveguides [47], cannot boast this advantage. As such, BRW’s offer an attractive platform for passive, active and nonlinear devices from a single wafer.

This chapter will detail the theory and design of laser and nonlinear devices for efficient operation. The important parameters will be defined and some examples of optimized designs will be described. Further, the trade-offs and practical concerns for design will also be detailed. Lastly, combined devices will be analyzed whereby phase-matched laser cavities will be designed. Such intracavity frequency converters will be explored in terms of laser performance, nonlinear efficiency and towards parametric oscillation on
5.1 Diode lasers in BRWs

Recently, PBG mode lasers have been explored heavily, particularly 2D air-hole designs. The predicted benefits of such lasers are many, owing to bandgap guiding and structural tunability. Pasenow et al. show an increase in light-matter interaction through simulations [53]. Such improvement would reduce spontaneous emission into other modes and reduce threshold. Liang et al. [54] and Her [55] have shown that such waveguides can have very large modal volumes due to the large contribution of the claddings. They speculate this property can be exploited for high-power lasers or amplifiers. Others have also speculated that PBG lasers could operate in single mode at higher temperatures or pump intensity / current density [56][57]. This is because the difference in effective index between the fundamental and higher order modes is much larger for PBG guiding compared to TIR guiding. Thus, high order PBG modes tend to have much higher losses. These advantages all stem from the versatility of the PBG structure to open a wide range of modal properties for device design.

Though the majority of literature is currently based on 2D air-hole photonic crystal waveguides (PCW), there are several key drawbacks. First, the fabrication is challenging due to the air-hole radius dimensions, typically between 100-500 nm. Such tight restrictions on size, shape and quality make reproducibility a difficult task. Secondly, the defects at air-semiconductor interfaces impede the flow of electric current through the device. Hence, electrically-injected 2D air-hole lasers are extremely difficult, though some examples exist in literature [58][59]. Layered BRW designs do not suffer from these disadvantages. First, layered media can be grown to nanometer accuracy through epitaxial technology. Second, vertical-cavity surface emitting lasers (VCSEL) have the same layer structure as BRWs, thus offering insights and precedent to efficient current inje-
tion. Therefore, BRWs are an elegant and simple platform from which to construct a PBG diode-laser.

There has been some work on BRW-like lasers. Shellan et al. demonstrated a hybrid-BRW laser with only one reflector, the other cladding was Al$_{0.4}$Ga$_{0.6}$As [60]. Yang, Blood and Roberts demonstrated a laser with core surrounded by two Bragg reflectors to show reduction in spurious spontaneous emission [61]. The reflectors were designed to reduce modes at surface emission angles and not specifically designed for low-loss propagation or other laser properties. Later, Berry et al. continued upon this work to demonstrate the threshold improvement of such lasers due to modified spontaneous emission from the Purcell effect [62]. In this work, a BRW laser (BRL) will be designed by taking into account modal theory from Chapter 2, laser parameters and current VCSEL development.

5.1.1 Modal analysis with Quantum-Wells

The introduction of a quantum-well (QW) into the layer structure of a BRW is not a trivial matter. Typical laser structures place the QW at the center of the core to maximize interaction with the field peak. However, such laser modes are not as highly dispersive as Bragg modes. Thus, the introduction of a QW at the field peak would alter the modal effective index and dispersion in a significant way. The first three BRL designs did not consider these effects when incorporating the QW, assuming their effects were negligible. A subsequent study demonstrated this was false; the QW can increase leakage loss or destroy phase-matching in nonlinear structures.

Adding a QW to the modal analysis is fairly simple because of our transfer-matrix approach. In Equation 2.1, the core is considered a single physical layer. If a QW (with barrier on either side) were added to the center of the core, then this region becomes 5 distinct layers as shown in Figure 5.1. These additional interfaces contribute phases in a complicated fashion.

A simple method of analyzing the QW structure is to re-define the core and one
Figure 5.1: The BRL structure is similar to a BRW with the noted addition of a gain region in the center of the core. Here the gain is composed of a QW surrounded by barrier layers.

reflector in the TRC. Any layer in the structure can be considered the core on the condition its transverse wavevector, $k_{i,x}$, is real. All layers to the left are then considered the ‘Left Bragg reflector’ and all layers to the right are the ‘Right Bragg reflector’. In our situation with the 5 layer core, we assume the 1st layer (left-half of original core) to be the core. The left reflector remains the same. However, the right reflector now contains the barriers, QW and other half of the core as well. This is shown schematically in Figure 5.2.

Using this modification, any number of QWs, barriers or other optically thin layers can be included in the structure (e.g. superlattices or oxides). Since phase-matching requires precise knowledge of the effective-index dispersion, this method becomes quite useful. The effect of improper design can be clearly seen in Figure 5.3. Here, the matching-layer of a ML-BRW structure is varied till phase-matching is obtained. There is a 13 nm difference in layer thickness between phase-matched structures that do and don’t include the active region in the computation. The QW region is composed of a 6 nm $\text{In}_{0.20}\text{Ga}_{0.80}\text{As}$ QW surrounded by 10 nm GaAs barrier layers. The InGaAs refractive indices are computed using the binary values from GaAs and InAs and interpolated to
Figure 5.2: Breakdown of BRL structure for TRC analysis. The ‘left reflector’ remains the same. The ‘core’ is the left half of the physical core, while the ‘right reflector’ now includes the gain region and right half of the physical core.

the ternary alloy InGaAs [63]. Such an error could lead to excess leakage loss or even loss of phase-matching. For example, if the QW were placed within the phase-matched non-QW structure without any compensation, the loss would increase by 2× and the phase-matched $\lambda_s$ shifts to 1560 nm from 1550 nm.

The nonlinear process chosen for these calculations is Type-II difference frequency generation (DFG) with the BRW pump ($\lambda_p$) at 980 nm, TIR signal ($\lambda_s$) at 1550 nm and TIR idler ($\lambda_i$) at 2665 nm. The process is better explained in Equation 5.1. Many optical communication sources exist (InGaAsP diode lasers or Erbium doped fiber amplifiers) at this signal wavelength. Also, absorption bands for water and several carbon bonds lie in the wavelength range encompassing 2-3 $\mu$m [64], thus making 2665 nm a useful idler wavelength for sensing applications. These wavelengths will be revisited in the coming sections in simulating other devices.

$$\Delta \beta = 2 \cdot \pi \cdot \left( \frac{n_{eff; TE, p, BRW}}{\lambda_p} - \frac{n_{eff; TM, s, TIR}}{\lambda_s} - \frac{n_{eff; TE, i, TIR}}{\lambda_i} \right) = 0 \quad (5.1)$$
Figure 5.3: Index-mismatch versus defect-layer thickness for a ML-BRW structure with and without an active region. Here, $x_1=0.15$ and $x_2=0.40$, $x_m = 0$, $x_c=0.1$ and $d_c=600$ nm.

5.1.2 Laser parameters

As mentioned in the previous section, the QW can have a significant impact on the nonlinear performance if ignored. However, another important consideration for lasing is the overlap of the QW and Bragg mode. For efficient coupling, this overlap must be larger than that of any other guided mode in the structure. Typically, there are TIR guided modes confined to the core at the lasing wavelength as well. Thus, it is essential that the QW interacts strongly with the fundamental Bragg mode and not the fundamental TIR mode. The interaction of light with a quantum-well is a complex process and difficult to model accurately, particularly for multi-mode situations.

To simplify our understanding, we note some important properties. First, the only modes to consider are ones with peak field strength at the QW location; this need not be the global maximum [65]. Secondly, modes can only be compared on a normalized power basis [66]. This is because the complicated electric field profiles can have vastly different mode field diameter (MFD), but would still only encompass a single photon at a time. To accommodate the first point, we make use of $\Gamma_i$ as defined in Equation 5.2a, known as
the overlap factor (or confinement factor). For the second point, Equation 5.2b is used where the square of the electric field is normalized to unity. Here, $C_i$ is a normalization factor for mode $i$. If all interacting fields are kept this way, the modal fields can be more accurately compared.

$$
\Gamma_i = \frac{\int_{-\infty}^{\infty} |E_i|^2 \, dx}{\int_{-\infty}^{\infty} |E_i|^2 \, dx} \quad (5.2a)
$$

$$
C_i \cdot \int_{-\infty}^{\infty} |E_i|^2 \, dx = 1 \quad (5.2b)
$$

Let us begin with an example QW ML-BRW structure, of the properties described in Table 5.1. The field profiles are shown in Figure 5.4. Figure 5.4(a) is the Bragg mode profile while Figure 5.4(b) is the TIR mode profile for Design A. The overlap factor calculated for the Bragg and TIR modes are $\Gamma_{BRW,TE}(980 \text{ nm}) = 0.37\%$ and $\Gamma_{TIR,TE}(980 \text{ nm}) = 0.31\%$, respectively. In this design, the TIR mode and Bragg mode are almost equally ‘confined’ to the QW. This is an undesirable situation for a BRW laser since the likelihood of lasing in the Bragg mode is small due to propagation losses increasing the lasing threshold versus the TIR mode.

<table>
<thead>
<tr>
<th>$x_c$</th>
<th>$x_L$</th>
<th>$x_1$</th>
<th>$x_2$</th>
<th>$d_c$ [nm]</th>
<th>$d_L$ [nm]</th>
<th>$N_{upper}$</th>
<th>$N_{lower}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.05</td>
<td>0.00</td>
<td>0.05</td>
<td>0.45</td>
<td>600</td>
<td>300</td>
<td>8</td>
<td>8</td>
</tr>
</tbody>
</table>

There are two techniques to improve $\Gamma_{BRW,TE}$, both essentially engineering the field profile by creating a dip in the TIR mode while maintaining a peak in the Bragg mode at the center of the core. First, the core material can be reduced to a point where it is the lowest index of the structure. In this way, the TIR mode becomes dual-lobed with peaks at each defect layer (high refractive index) and minimum at the core-center (low refractive index). The benefit is shown as the open circles in Figure 5.5(a). Here, each data point is a unique structure as the quarter-wave condition is always changing the
Figure 5.4: Field profiles for the relevant modes of Design A: (a) Bragg mode $E_y$ and (b) TIR $E_y$ at $\lambda_p = 980$ nm. (c) The corresponding refractive index for the structure. The dashed line (red) is the TIR mode index while the dotted line (blue) is the Bragg mode index. Note the active region in the center and its effect on the TIR mode profile and lack of effect on the Bragg mode profile.

mirror thicknesses. Starting with Design A, the core aluminum fraction is slowly increased (decreasing refractive index). The ratio of $\Gamma_{BRW,TE}$ and $\Gamma_{TIR,TE}$ steadily increases from 1.18 to 67.0 at $x_c=0.45$ which is selected as the first optimization point. We have not gone further than 45% aluminum fraction as this is where the material changes from direct to indirect bandgap and defects can hinder performance (e.g. DX centers) [67].
Figure 5.5: Variation of the ratio $\Gamma_{BRW,TE}/\Gamma_{TIR,TE}$ with respect to core material (circles) and core thickness (squares). The ratio can be increased over 2 orders of magnitude.

Second, the core thickness can be 'stretched' to further reduce the TIR field-strength at the center, allowing the field to decay further from the peak. This is shown as open squares in Figure 5.5(a). As core thickness increases, the $\Gamma$ ratio can be increased to a peak value of 386.6 ($\Gamma_{BRW,TE}(980 \, \text{nm})=1.00\%$ and $\Gamma_{TIR,TE}(980 \, \text{nm}) = 0.003\%$), a $327\times$ increase from the original design. This maximum value will be called Design B and field profiles are shown in Figure 5.6. Through this methodology, preferential lasing on the Bragg mode is assured.

5.1.3 Power and threshold

Comparing laser designs does not just depend on the parameters listed above. Rather, operational parameters such as the output threshold or power slope are more important. This section will derive equations for determining these terms using a semi-phenomenological model of the laser. The equations will use many of the structural
properties derived so far in this chapter as well as the last, thus allowing us to compare laser BRW designs for optimization.

Estimating the output power of a diode laser is difficult due to the many interacting and complicated processes. Most diode laser modeling begins with the self-consistent coupled rate equations, describing the interaction of carriers and photons [68]. Though
very useful they are beyond the scope of this analysis, partly due to the need for simpler computation. The rate equations typically deal with the inner laser physics. In particular, terms such as the spontaneous emission lifetime of the Bragg mode or the non-radiative recombination lifetime are unknown for these lasers and may vary significantly with standard TIR lasers. As such, a quasi-phenomenological approach is used that takes into account the variation in \( \Gamma \) and \( \alpha \) of the structures and their effect on laser output. Beginning with the output efficiency equation:

\[
P_{\text{out}}(I) = (I - I_{\text{th}}) \cdot \eta_d \cdot \frac{hc}{\lambda_p \cdot e}
\]  

(5.3)

Here, \( P_{\text{out}}(I) \) is the output power of the laser at injected current \( I \). The term \( I_{\text{th}} \) is the threshold current and \( \eta_d \) is the differential efficiency. We can note that the differential efficiency, is related to the internal quantum efficiency, \( \eta_i \), by the following equation.

\[
\eta_d = \eta_i \cdot \frac{\alpha_m}{g_{\text{th}}}
\]

(5.4)

Here, \( \alpha_m \) is the mirror loss and \( g_{\text{th}} \) is the threshold gain. Further, the current \( I \) can be converted to current density \( J \) via the relation \( I = J \cdot L \cdot W \). This modifies (5.3) to the following.

\[
P_{\text{out}}(J) = \frac{LW \cdot \eta_i (J - J_{\text{th}})}{\lambda_p} \cdot \frac{hc}{e} \cdot \frac{\alpha_m}{g_{\text{th}}}
\]

(5.5)

At threshold, the gain, \( g_{\text{th}} \), is equal to the losses. Therefore, \( g_{\text{th}} = \alpha_p L + \alpha_m \), where \( \alpha_p \) is the propagation loss. The mirror loss can be further simplified by noting \( \alpha_m = -ln (R_{p,1}R_{p,2}) \). Thus, (5.5) becomes:

\[
P_{\text{out}}(J) = \frac{LW \cdot \eta_i (J - J_{\text{th}})}{\lambda_p} \cdot \frac{hc}{e} \cdot \frac{ln (R_{p,1}R_{p,2})}{ln (R_{p,1}R_{p,2}) - \alpha_p L}
\]

(5.6)

Lastly, the threshold current density can be estimated by noting the net laser gain (above threshold) satisfies the following.
Further, the QW threshold gain, $G_{th}$, has a logarithmic relation with respect to transparency and threshold current densities.

$$G_{th} = G_0 \cdot \ln \left( \frac{J_{th}}{J_{tr}} \right)$$  \hspace{1cm} (5.8)$$

Using these, the threshold current density can be isolated,

$$J_{th} = J_{tr} \cdot e^{\frac{\alpha_p L - \ln (R_{p,1} R_{p,2})}{\eta_i \Gamma L}}$$  \hspace{1cm} (5.9)$$

leading to the final result used to estimate the output power.

$$P_{out}(J) = \frac{W L \eta_i}{\lambda_p} \left( J - J_{tr} \cdot e^{\frac{\alpha_p L - \ln (R_{p,1} R_{p,2})}{\eta_i \Gamma L}} \right) \cdot \frac{h c}{e} \cdot \frac{\ln (R_{p,1} R_{p,2})}{\ln (R_{p,1} R_{p,2}) - \alpha_p L}$$  \hspace{1cm} (5.10)$$

Here, $R_{p,1}$ and $R_{p,2}$ are the facet reflection constants at the pump wavelength, $L$ is the cavity length, $W$ is the injection width, $\eta_i$ is the internal efficiency and $J_{tr}$ is the transparency current density. Note that current $I$ and current density $J$ are related by $I = J \cdot W \cdot L$. Some reasonable values for the parameters were assumed as shown in Table 5.2. The various phase-matched BRW diode laser structures can be compared in terms of laser performance using this equation hence allowing for optimization or targeted design.

Table 5.2: Typical values used for calculation of laser threshold and output power

<table>
<thead>
<tr>
<th>$\eta_i$ [%]</th>
<th>$R_{p,1}$, $R_{p,2}$</th>
<th>$J_{tr}$ [A/cm$^2$]</th>
<th>$L$ [mm]</th>
<th>$W$ [$\mu$m]</th>
<th>$G$ [cm$^{-1}$]</th>
</tr>
</thead>
<tbody>
<tr>
<td>90</td>
<td>0.3, 0.3</td>
<td>50</td>
<td>1</td>
<td>4</td>
<td>1000</td>
</tr>
</tbody>
</table>
5.1.4 Doping profile

Contrary to the designs for nonlinear conversion devices which were nominally undoped (unintentional background doped), diode lasers require a P-I-N doping profile to allow current injection into the active region. Typical diode lasers utilize n-doped GaAs substrates to grow the epitaxial layers upon. This means the lower cladding will also be n-doped, making the top cladding p-doped. Further, most diode lasers gave some grading from high doping at the extremes of the structure to nominally undoped at the core and active region. This profile allows for injection of holes and electrons into the active region by which they can be trapped by the QW.

For example, let us examine Design B from the previous section. Of the eight periods above and below, set the doping of the 7 furthest periods as \(1 \times 10^{18} \text{ cm}^{-3}\) acceptor and \(4 \times 10^{18} \text{ cm}^{-3}\) donor doping respectively. The remaining period closest to the core is set to \(4 \times 10^{17} \text{ cm}^{-3}\) acceptor and \(1 \times 10^{17} \text{ cm}^{-3}\) donor doping respectively. The core and active region are left undoped. This type of doping profile is commonly used in VCSEL’s technology. Other methods of improving the band structure includes compositional grading [69] instead of abrupt interfaces and complex doping profiles such as delta-doping [70] or modulation doping [71]. Since the growth technology available to us for this research is MOCVD, the compositional grading is inherent. However, the doping techniques are impossible or exceedingly difficult.

Utilizing the material parameters needed for calculating the band structure in [67] along with the commonly used 60:40 split of band offsets [72], the band structure of Design B can be computed. This is shown in Figure 5.7 where the P-I-N characteristic is clearly evident. All energies are plotted with respect to the GaAs valence band energy.
Chapter 5. BRW cavity design for intracavity devices

5.2 Phase-matched BRW lasers

One of the benefits of BRW based nonlinear devices is the capability for current injection and monolithic integration. This is because any layered semiconductor BRW design can be doped for conductivity. Thus, creating a BRL that is also phase-matched is possible through appropriate design. Recall Figure 5.3, where a BRW with QW is designed to have phase-mismatch $\Delta n = 0$ for DFG down-conversion. This section will expand on such devices by demonstrating the procedure for optimization of the nonlinear and active properties.

5.2.1 Difference frequency generation

Let us begin with a similar set of starting parameters as in Table 5.1, shown in Table 5.3; call this Design A. Note the matching layer thickness is not shown because it is a computed value from the phase-matching algorithm.

This design has a very poor $\Gamma$ ratio of 0.78. Following the procedure of the previous section, either reducing the core material or enlargening the core thickness can improve
Table 5.3: Example starting structure for optimization of phase-matched laser parameters

<table>
<thead>
<tr>
<th>$x_c$</th>
<th>$x_L$</th>
<th>$x_1$</th>
<th>$x_2$</th>
<th>$d_c$ [nm]</th>
<th>$N_{upper}$</th>
<th>$N_{lower}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.10</td>
<td>0.00</td>
<td>0.15</td>
<td>0.40</td>
<td>600</td>
<td>5</td>
<td>5</td>
</tr>
</tbody>
</table>

this value. The benefit is shown as the open circles in Figure 5.8(a). Starting with Design A, the core aluminum fraction is slowly increased (decreasing refractive index). The ratio of $\Gamma_{BRW,TE}$ and $\Gamma_{TIR,TE}$ steadily increases from 0.78 to 24.4 at $x_c=0.45$ which is selected as the first optimization point. The open squares in Figure 5.8(a) shows how stretching the core thickness can further improve the $\Gamma$ ratio of phase-matched laser structures. Here, the ratio has been increased to a peak value of 36.3 ($\Gamma_{BRW,TE}(980 \text{ nm})=1.18\%$ and $\Gamma_{TIR,TE}(980 \text{ nm}) = 0.027\%$), a $46\times$ increase from Design A. This structure will be called Design B and field profiles are shown in Figure 5.9. Note the significant dip in the TIR mode at $\lambda_p$ (Figure 5.9b) while a peak exists for the Bragg mode (Figure 5.9a). The signal and idler modes are shown in Figures 5.9c and 5.9d respectively.

The various phase-matched BRW-ML structures can also be compared in terms of laser performance as derived in Equations 5.9 and 5.10. Figure 5.8(b) demonstrates how changing core thickness ($x_c=0.45$) will affect laser threshold, shown as circles. The output power of the laser, chosen at an arbitrary above-threshold current of 100 mA, is shown as squares. There is a wide variation in performance due to structural variations with threshold currents varying from 10 mA all the way to 55 mA. This attests to the wide tunability of Bragg-type modes.

### 5.2.2 Nonlinear parameters

The previous section explored the optimization of the BRW-ML structure for lasing, but did not include any nonlinear characteristics. Efficient nonlinear conversion is also dependent on modal field profiles and propagation losses, though not necessarily in ways
**Chapter 5. BRW cavity design for intracavity devices**

Figure 5.8: (a) Variation of the ratio $\Gamma_{\text{BRW,TE}}/\Gamma_{\text{TIR,TE}}$ with respect to core material (circles) and core thickness (squares). (b) Variation of the threshold current (circles) and output power at 100 mA (squares) with core thickness.

beneficial to lasing. A balance is required between optimum laser design and optimum nonlinear conversion design. This section will detail how to re-design the structures from the previous section to optimize the conversion process using just a single parameter which takes into account all elements.

In nonlinear optics, several measures are available to compare the efficacy of different structures. Of these, the nonlinear effective area, $A_{\text{eff},2}$, and the effective structural nonlinear constant, $d_{\text{eff}}$, are important parameters. The former contains the overlap of the various interacting mode-profiles and the latter averages the bulk nonlinearity, weighted by the field profiles. The equations for both are shown below.

\[
d_{\text{eff}} = \frac{\int E_p E_s E_i d(x) dxdy}{\int E_p^2 E_s E_i dxdy} \quad (5.11a)
\]

\[
A_{\text{eff},2} = \frac{\int E_p^2 dxdy \cdot \int E_s^2 dxdy \cdot \int E_i^2 dxdy}{(\int E_p E_s E_i dxdy)^2} \quad (5.11b)
\]

To compute $d_{\text{eff}}$, the bulk nonlinear constant for each material, $d$, is used as mea-
Figure 5.9: Field profiles for the relevant modes of Design B: (a) BRW $E_y$ and (b) TIR $E_y$ at $\lambda_p$, (c) the TIR $H_y$ at $\lambda_s$ and (d) TIR $E_y$ at $\lambda_i$.

measured by Ohashi et al. [73]. The fields required in both equations are 2-dimensional (2-D) transverse profiles. A simple method to compute these is via the effective index approximation [74]. Here, ridge waveguides of width 4 $\mu$m are assumed. Utilizing these parameters, an equation for conversion efficiency can be determined.

The coupled mode equations with no pump depletion, perfect phase-matching and weak conversion approximation are defined in Equations 5.12 below.

\[
\frac{\partial A_p}{\partial z} = i \frac{\kappa}{\lambda_p} A_s A_i - \frac{\alpha_p}{2} A_p \approx 0 \quad (5.12a)
\]
\[
\frac{\partial A_s}{\partial z} = - i \frac{\kappa}{\lambda_s} A_p A_i^* - \frac{\alpha_s}{2} A_s \approx - \frac{\alpha_s}{2} A_s \quad (5.12b)
\]
\[
\frac{\partial A_i}{\partial z} = - i \frac{\kappa}{\lambda_i} A_p A_s^* - \frac{\alpha_s}{2} A_s \quad (5.12c)
\]
\[
\kappa = \frac{4\pi \cdot d_{eff}}{\sqrt{2c\epsilon_0 \cdot n_{eff,p} \cdot n_{eff,s} \cdot n_{eff,i} \cdot A_{eff}}} \quad (5.12d)
\]
Here, $A_x$ are the envelope amplitudes and normalized such that $P_x=|A_x|^2$. Note Equation 5.12a is simplified to zero because gain saturation / clamping within the laser will compensate for deviations in the pump power from losses due to nonlinear down-conversion. This is a specific consequence of having the pump generated via laser action within the cavity; a safe assumption since the laser gain is several orders stronger than the nonlinear gain. Also, Equation 5.12b is simplified by ignoring the first term (nonlinear component) because $A_{iij}A_s$. The solution to these equations can readily be found, as shown in Equation 5.13.

$$A_p(z) = A_{p,0} \quad (5.13a)$$

$$A_s(z) = A_{s,0} \cdot e^{-\alpha_s z} \quad (5.13b)$$

$$A_i(z) = -i\frac{\kappa}{\lambda_i} A_{s,0}^* \cdot A_{p,0}^* \cdot e^{-\alpha_p z} \cdot \frac{e^{-\frac{1}{2} (\alpha_s + \alpha_i) z}}{\frac{1}{2} (\alpha_s + \alpha_i) z} \quad (5.13c)$$

The boundary conditions are $A_p(z=0)=A_{p,0}$, $A_s(z=0)=A_{s,0}$, $A_i(z=0)=0$. Using these formulas, the conversion efficiency, $\eta$, can be derived in (5.14a), shown below.

$$\eta = \frac{P_i}{P_p \cdot P_s}$$

$$= \frac{\kappa^2 \cdot L^2}{\lambda_i^2} \cdot e^{-\frac{1}{2} (\alpha_s + \alpha_i) L} \cdot \frac{sinh^2 \left(\frac{1}{4} [\alpha_s - \alpha_i] L\right)}{\left(\frac{1}{4} [\alpha_s - \alpha_i] L\right)^2} \quad (5.14a)$$

$$\eta' = \eta \cdot P_{p,\text{internal}} \quad (5.14b)$$

Equation 5.14a takes into account both $d_{eff}$ and $A_{eff}$ but does not take into account the laser parameters such as $\Gamma$ and $\alpha_p$. For this, another efficiency parameter is defined in 5.14b. Here, $P_{p,\text{internal}}=P_p/\sqrt{T_{p,1}T_{p,2}}$ where $P_p$ is the estimated output power of the laser derived in Equation 5.10 and $T_{p,1}$ and $T_{p,2}$ are the transmission coefficients. This
Figure 5.10: Change in efficiencies $\eta$ and $\eta'$ with core thickness. Here, the device length $L=1$ mm and injected current $I=100$ mA.

The two efficiencies, $\eta'$ and $\eta$, have been calculated by implementing the following procedure: First, the signal and idler leakage losses can be estimated via the imaginary component of the effective index. By placing a high-index GaAs substrate at the end of the structure, the complex effective index can be found. Keeping with transfer matrix methods, we have utilized a complex root-finding algorithm based on Newton optimization. Second, the assumptions detailed in Table 5.2 are utilized. The relative efficiencies with respect to core thickness are shown in Figure 5.10. Here, the peak in $\eta'$ occurs at a core thickness of 650 nm, call this Design C; the best design thus far within our limited search space. A simple calculation shows that for a 10 mW internal signal power, 68 $\mu$W idler power can be generated within a 1 mm sample.

### 5.2.3 Tuning

Diode lasers have a varying emission wavelength due to heating and band-renormalization effects. Further, wavelength tunability can be implemented via numerous methods [75].
Figure 5.11: (a) Tuning of the phase-matched signal and idler wavelengths as the pump wavelength is varied. With decreasing pump wavelength, larger idler wavelengths are accessible, well past 3 $\mu$m. (b) Change of conversion efficiency with pump wavelength.

Thus, the tuning characteristics of the phase-matching have also been investigated to understand the range of tunability attainable with these structures. By varying the pump wavelength, a set of phase-matched signal and idler wavelengths can be found by a zero-finding search. The tuning curve for Design C along with the variation in $\eta$ are shown in Figure 5.11. At shorter laser wavelengths, larger idler wavelengths are accessible. Also, the degeneracy point occurs for longer laser wavelengths at $\approx 1010$ nm. The efficiency at these longer wavelengths also increases substantially due to better overlap of the interacting modes.

### 5.2.4 Parametric oscillation

This section will explore the possibility and requirements for parametric oscillation within these devices. Initially, only leakage losses will be included in the calculations such that their effect on OPO threshold can be minimized. Later in the section, other propagation losses will be included to obtain more realistic threshold values. The lossless parametric gain of a nonlinear element is described by Equation 5.15.
Figure 5.12: Contour plots of OPO threshold powers in Watts for (a) signal SRO and (b) DRO as a function of core thickness and device length. The mirror reflectivities are 99.9% and 95% for both signal and idler.

\[ g = \cosh (\Gamma_{NL} L) \]  \hspace{2cm} (5.15)

\[ \Gamma_{NL} = \sqrt[4]{\frac{P_p}{\lambda_s \lambda_i}} \]

When the gain equals the total cavity loss, oscillation can occur, this is the threshold condition. Two types of OPOs will be explored, the singly resonant oscillator (SRO) and the doubly resonant oscillator (DRO). The threshold conditions are described by Equations 5.16a and 5.16b, respectively.

\[ SRO : P_{p,th} = \frac{\lambda_s \lambda_i}{\kappa^2 L^2} \left[ \cosh^{-1} \left( e^{\alpha_s t L} \right) \right]^2 \]  \hspace{2cm} (5.16a)

\[ DRO : P_{p,th} = \frac{\lambda_s \lambda_i}{\kappa^2 L^2} \left[ \cosh^{-1} \left( \frac{e^{\alpha_s t L} e^{\alpha_i t L} + 1}{e^{\alpha_s t L} + e^{\alpha_i t L}} \right) \right]^2 \]  \hspace{2cm} (5.16b)

\[ \alpha_{s,t} = \alpha_s - \ln (R_{s,1} R_{s,2}) \]

\[ \alpha_{i,t} = \alpha_i - \ln (R_{i,1} R_{i,2}) \]
Contour plots of threshold power as a function of sample length and core thickness are shown in Figure 5.12 for (a) the case of SRO for the signal and (b) the case of DRO. Though most designs have very large CW threshold pump powers, some longer devices have more accessible requirements and can be achieved by present day single-mode diode lasers. For example, Design C with a cavity length of 3 mm has an SRO threshold of 978 mW. Note that there are design challenges with such long laser lengths such as decreased differential efficiency and difficulty in fabrication uniformity. Nonetheless, this demonstrates that BRW-ML based OPO chips are possible and can be practically implemented with present day technology.

However, these ideal threshold values do not take into account practical losses, particularly absorption from dopants and scattering from roughness. These factors typically dominate the loss in ridge waveguide lasers. With respect to OPO thresholds, realistic signal and idler losses are needed, as seen in Equations 5.16a and 5.16b. Since these wavelengths are far from the QW absorption band, the dopant contribution to absorption is negligible and only scattering is a major factor.
A more realistic value is $2 \text{ cm}^{-1}$ for the TIR mode from a device tested using the Fabry-Pérot technique for propagation loss at 1550 nm in a similar structure [49]. If the idler loss is assumed to be similar, then more realistic OPO thresholds can be estimated.

A similar contour plot is shown in Figure 5.13. There are some notable differences between these thresholds and those in Figure 5.12. First, the thresholds have all increased by at least one order of magnitude and there are no sub-watt threshold OPOs. Second, the benefit of DRO OPOs can be seen in these higher loss scenarios as their thresholds are far lower than those of SRO OPOs. Here, the optimum configuration is for a 3-5 mm chip with 650 nm core width having threshold just over 4 Watts. Such instantaneous pump powers can be easily obtained if the pump laser is mode-locked. Nonetheless, it is important to note the effects of realistic propagation losses and not just leakage loss.
Chapter 6

Bragg reflection waveguide diode lasers

A platform for monolithic integration is not complete without the demonstration of an active device, such as a laser. In fact, this is even more crucial in BRW based platforms because a Bragg mode cannot be excited through traditional means (e.g. prism coupling, facet coupling) due to its many nodes and anti-nodes. This means any nonlinear process requiring a Bragg mode input will also require a BRW based laser to create the mode. For example, down-converting from $2\omega$ to $\omega$ would require the input of a Bragg mode to output the TIR mode. As such, the demonstration of such a laser is paramount to any integration scheme involving the Bragg mode.

The theoretical framework for lasers based upon a BRW cavity was detailed in Chapter 5. This chapter will go further, specifically delving into diode-lasers and the many technical / practical complications (e.g. doping, interface charge bunching). Our initial attempt to fabricate a BRL was less than ideal, with a slightly modified design had to be re-grown. This chapter will detail the work done in designing, fabricating and demonstrating our results of the first double-sided BRLs [76]. The characterization results such as electrical, optical and thermal will also be discussed.
Chapter 6. Bragg reflection waveguide diode lasers

6.1 Laser cavity design

The first BRW laser (BRL) design, called BRL1, was based on the quarter-wave BRW. Thus, the mode Equation 2.6d derived in Chapter 2 can be utilized to compute the modal properties. We restricted the choice of AlGaAs to less than 0.37 aluminum fraction to reduce the number of DX-centers within the structure. However, to maintain the contrast in the mirrors the lowest aluminum fraction used is 0 (GaAs).

Table 6.1: BRL1 epitaxial structure design

<table>
<thead>
<tr>
<th>x_c</th>
<th>x_1</th>
<th>x_2</th>
<th>d_c [nm]</th>
<th>N_{upper}</th>
<th>N_{lower}</th>
<th>QW material</th>
<th>QW #</th>
<th>QW gap [nm]</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.37</td>
<td>0.00</td>
<td>0.30</td>
<td>700</td>
<td>8</td>
<td>8</td>
<td>In_{0.2}Ga_{0.8}As</td>
<td>2</td>
<td>2</td>
</tr>
</tbody>
</table>

The structure properties are summarized in Table 6.1. Note two exceptional properties of this design. First, the core is the lowest-index material. In the Chapter 4, a high-index core is used to support both TIR modes as well as Bragg modes within the same structure. However, such a structure would definitely lase in the fundamental TIR mode due to the lower losses and larger confinement factor. Thus, this design employs a
low-index core (anti-guided). Second, the core is fairly large compared to similar diode laser designs. Typical lasers are restricted by the transverse single-mode condition which is significantly eased in the case of Bragg mode lasers [57].

The structure was grown using Metal Organic Chemical Vapour Deposition (MOCVD) on 2° off n-GaAs substrates through CMC microsystems. All interfaces within the mirrors were linearly graded in composition over a distance of 25 nm, the minimum capable by the grower. The bottom reflector was n-doped with Silicon at a level of $1.2 \times 10^{18}$ cm$^{-3}$ and the top reflector was p-doped with Carbon at a level of $1.0 \times 10^{18}$ cm$^{-3}$. One reflector period adjacent to the core on the p-side and two periods on the n-side had reduced doping to reduce optical losses, specifically $1.2 \times 10^{17}$ cm$^{-3}$ and $5 \times 10^{17}$ cm$^{-3}$ for the n and p-type, respectively. The structure was capped with a a 50 nm GaAs contact layer, doped to $4 \times 10^{18}$ cm$^{-3}$ (p++). A complete epitaxial growth list is provided in Appendix C.2.

The active region was designed by CMC microsystems for emission at 980 nm. The active region is composed of two 20% InGaAs QWs separated by 2 nm of GaAs. Though not evident at the time, this separation is insufficient to decouple the QW states. The possible effect of this on performance will be discussed further in the next section.

Utilizing the quarter-wave equation for mode-index, we find the Bragg mode effective
index is 3.199. From this, the TE electric field mode profile ($E_y$) can be computed. This is shown in Figure 6.1 along with the refractive index profile for the structure. Note the Bragg mode-effective index is below all material indices, as expected. Using the Ghatak technique mentioned in chapter 2, the leakage loss of this structure is estimated to be $0.83 \text{ cm}^{-1}$.

Samples from the grown wafers were processed into ridge waveguide lasers through the procedure described in Appendix A. Fabricated ridge widths ranged from 3 to 4 µm and cavity lengths between 0.5 to 1.2 mm. A typical SEM cross-section of the ridge is shown in figure 6.2(a), and a typical side-wall is shown in Figure 6.2(b). All laser facets were left uncoated. This could potentially leave many surface states leading to unwanted recombination and eventual catastrophic optical damage. However, the Bragg mode volume is large compared to typical TIR modes leading to low photon density at the facet. Further, the cavity volume is fairly large allowing for sufficient gain to compensate for the uncoated facet.

### 6.1.1 Characterization

Testing was performed in our pulsed diode laser characterization setup, described in Appendix B. The devices readily lased at room temperature in CW. A typical light versus current (L-I) and voltage versus current (V-I) curve is shown in Figure 6.3 for a 685 µm long device, operating at 20°C. Threshold occurs at 16.8 mA, or 816 A/cm² in terms of current density; this is higher than average threshold compared to similar diode lasers. Further, output power from a single facet is quite low, typically below 5 mW. Thermal rollover is also evident in all devices as seen in the L-I curve at above 50 mA injection. The voltage is slightly elevated, exceeding 4 V for some devices at high-injection.

This performance is sub-par to what is typical and expected of diode lasers at 980 nm. Several attempts at fabrication yielded similar results hence removing any single-run
fabrication errors as the reason. By chance, a red light was observed to be emitting from the device when room lights were turned off. This red-light was observed from above the laser and no such light was evident in the beam. Spectral analysis of the beam confirms this.

To collect this emission, a multimode fiber was brought normal to the beam axis (from above) and then sent to an Ocean Optics USB2000 spectrometer for analysis. The red light was found to be the tail end of emission peaking at 870 nm. Further, this peak was found to increase with injection current while other features did not, as shown in Figure 6.4. This implied a leakage of the carriers to some GaAs layer, possibly the 2 nm barrier between the QWs or the substrate. Due to these issues in performance, a redesign and new growth of the BRL was warranted and will be detailed in the next section.

### 6.2 Redesign of cavity

The redesigned BRW laser, called BRL2, had some slight modifications compared to BRL1. First, to reduce optical leakage into the substrate, the number of lower periods
Figure 6.4: Off-axis (from above) spectral measurement of BRL1. Note the emission at 870 nm which is carrier dependent. The tail of this peak is visible as red light in a darkened room.

was increased from 8 to 9. This prohibitively increased the epitaxial thickness and the upper periods had to be reduced from 8 to 7. The active region was redesigned with a more standard 10 nm GaAs barrier, hence decoupling the QW states. All materials and other thicknesses were kept the same in the new re-growth. A complete epitaxial growth list is provided in Appendix C.3.

Simulations reveal the leakage loss to substrate in this redesign is $0.29 \text{ cm}^{-1}$. Wafers of BRL2 were processed in the same procedure as BRL1 resulting in very similar ridge widths and cavity lengths. An example cross-section and side-wall of a fully fabricated BRL2 laser is shown in Figure 6.5.

6.2.1 Characterization

Light-Current-Voltage

Testing of the new devices revealed BRL2 to perform better than BRL1. Output power was higher and the off-axis red light was no longer visible. The devices were thus further tested in terms of electrical, optical, spectral and modal properties to ascertain various
Chapter 6. Bragg reflection waveguide diode lasers

(a) Cross-section of ridge waveguide laser.  (b) Side-wall of ridge waveguide laser.

Figure 6.5: SEM micrographs of fabricated BRL2 lasers.

internal laser parameters as well as verification of the BRW mode.

LIV curves of three laser cavity lengths of BRL2 are shown in Figure 6.6 operating at 20°C in CW mode. The lowest threshold for these devices is 13 mA (418 A/cm²), while the output power peaks just over 15 mW before thermal rollover. This output power is about 5 times larger than what was observed in BRL1. The threshold is about half that of BRL1, indicating reduced losses. The threshold current density is well within the average of typical InGaAs QW diode lasers.

Near and Far Field

In order to verify that the laser is operating in the PBG mode, near-field (NF) and far-field (FF) were examined and compared with theory. To obtain the NF profile, a 60× microscope objective was used. The theoretical calculation, illustrated in Figure 6.7-(a), can be compared with the obtained images shown in Figure 6.7-(b). The two profiles are qualitatively similar. In the center, a bright peak is evident, with adjacent peaks above and below that are separated by nodes. Further peaks and nodes are evident but less pronounced, due to the limitations of the optics and camera dynamic range.

A FF is typically represented in terms of angle from the source. However, to facilitate
Figure 6.6: Light-current-voltage curves for the redesigned BRW laser, BRL2, operating at 20°C. Lasers with three cavity lengths are shown: 500 μm (solid), 580 μm (dash) and 970 μm (dash-dot). The lowest threshold for these devices is 13 mA, or 418 A/cm², for the 970 μm device [76]

the characterization of the extremely divergent PBG mode, planar far-fields were used for comparison. The planar FF was captured by bringing the camera as close as 5 mm from the laser facet while minimizing the camera gain. A typical FF profile is shown in Figure 6.7-(d) with the theoretical planar FF profile in Figure 6.7-(c) calculated at a distance of 5 mm. Both NF and FF were computed using a full-vectorial commercial mode solver [77]. Theory and experiment show vertical beams, albeit the fine features seen in Figure 6.7-(d) could not be resolved in the measurement. This is likely due to saturation and a finite dynamic range effects in the camera.

To further verify the far-field, a sample BRL2 laser was sent to Prof. Hanquin of the Institute of Semiconductors at the Chinese Academy of Sciences. There, a standard angular far-field instrument was used to measure the far-field pattern, shown in Figure 6.8(a). Here, the vertical direction has two lobes at highly divergent angles, horizontal has a single lobe centered at zero. Theoretically computed far-fields in terms of angle, also derived from Lumerical, are shown in Figures 6.8(b) and 6.8(c) for the
vertical and horizontal directions, respectively. Upon comparison, there are significant similarities, particularly in the dual lobe nature of the vertical far-field. Further, the smaller peaks at $\pm 35^\circ$ and $0^\circ$ are also slightly evident. Nonetheless, the similarities in near and both far-field measurements provide convincing evidence that lasing is taking place in the Bragg mode.

**Mode profile insensitivity**

One of the prime benefits cited for PBG defect-waveguide lasers is the emission insensitivity. This stems from the large spacing of modal effective indices when compared to traditional TIR modes [57]. Note, the only modes that should be considered are those with antinode at the location of the QW. As such, the lowest orders to have this property are the zero and second order modes. For TIR modes in AlGaAs waveguides, this mode spacing (in effective index) depends heavily on the structure and materials, but would typically not exceed 0.01. On the other hand, for BRL2, this spacing is $\approx 0.6$. This makes lasing in higher order modes extremely unlikely as such modes would incur giant leakage losses. Calculation of the Ghatak loss of the second-order TE Bragg mode leads to a value exceeding 1000 cm$^{-1}$. Further, due to the anti-guided nature of the core,
(a) Measured angular far-field. Vertical direction has two lobes at highly divergent angles, horizontal has a single lobe centered at zero.

(b) Computed vertical far-field.  
(c) Computed horizontal far-field.

Figure 6.8: Theoretical and measured angular far-field of BRL2. Measurements were performed at the Institute of Semiconductors at the Chinese Academy of Sciences.

The laser mode is more insensitive to filamentation or heating as the mode-profile is not determined solely by the index of the core but also the reflectance of the Bragg mirrors.

Our collaborators at the Chinese Academy of Sciences utilized their angular far-field instrument to compare far-fields at various injection current levels from 20 mA to 100 mA, or $>5 \times$ threshold.
Chapter 6. Bragg Reflection Waveguide Diode Lasers

Figure 6.9: Change of far-field with current injection. Threshold for this device is below 20 mA.

**Propagation Loss**

Spectral analysis of sub-threshold spectra can elucidate valuable information about internal laser and waveguide parameters [78]. This is particularly useful because of the unique nature of the mode. There have been no direct measurements of the propagation loss of Bragg modes. Through this technique the modal loss, group index and laser transparency current density can be determined.

The CW laser emission is coupled into a bare cleaved fiber and sent to a high-resolution spectrometer (8 pm resolution). A sample sub-threshold spectrum is shown in Figure 6.10(a). The group index can be found from the peak spacing, shown in Figure 6.10(b), as $3.89 \pm 0.02$. This is very similar to the expected value of 3.93. Through Fourier transform of the sub-threshold spectrum, the cavity propagation gain/loss, $K$, can then be determined. Figure 6.11(a) shows an example Fourier transform. A simple interpretation of the decaying peaks is the amount of light exiting the laser from multiple cavity round trips. The decay slope of these peaks is related to $K$.

By obtaining $K$ at different sub-threshold currents, the laser gain versus carrier relationship can be measured, as shown in Fig. 6.11(b). The current at which $K = 0$
(a) High-finesse peaks of the Bragg mode in the Fabry-Pérot cavity. This is the high-gain region where the laser mode appears.

(b) Group index of Bragg mode derived from peak spacing.

Figure 6.10: Example sub-threshold spectrum of BRL2 [76].

on this curve is the transparency current density. This point is found to be at a value of 460 A/cm². The cavity mode gain/loss data can be fit to the logarithmic relation: K=G₀⋅ln(I/I₀)-αᵢ, which relates the current to the cavity mode gain/loss. From this fit a modal propagation loss of αᵢ=14.1 cm⁻¹ is obtained.

The loss value was also confirmed using an independent technique, which uses the dependence of the laser properties on the cavity length. This is a fundamentally different technique as it relies on the averaging over many devices and cannot be applied to single lasers. Several lasers from a single chip with different cavity lengths were tested and the differential efficiency, ηᵯ, was extracted. Note however that this method has inherent limitations due to high variance from uncoated FP lasers. The slope fit is only used to verify the order of magnitude of the loss determined from the sub-threshold spectra.

The differential efficiency and cavity length are related to each other via Equation 6.1 [67]. Here, ηstaking is the stimulated emission efficiency, R is the facet reflectivity and αᵢ is the propagation loss.
(a) Example FFT of sub-threshold spectrum. The slope of these peaks on a semilog scale is related to the modal gain.

(b) Derived laser parameters from Fourier analysis of sub-threshold spectra. The internal propagation loss is measured as 14.1 cm\(^{-1}\) and transparency current density is 460 A/cm\(^2\).

Figure 6.11: Fourier transform analysis of sub-threshold spectra to determine internal laser parameters.

\[
\frac{1}{\eta_D} = \frac{1}{\eta_{stim}} \left(1 - \frac{\alpha_i \cdot L}{\ln(R)}\right) \tag{6.1}
\]

By plotting the inverse differential efficiency against length, \(\alpha_i\) can be found through the slope as shown in Figure 6.12. From the fitted line (solid), the propagation losses from this method were calculated to be 13.2 cm\(^{-1}\). For the calculations, \(R\) was derived from the Fresnel reflectance and the mode index using \(R=(n_{eff}-1)^2/(n_{eff}+1)^2\).
Figure 6.12: Inverse-efficiency curve of BRL2 using several cavity lengths. The slope of the line is used to derive a propagation loss of 13.2 cm$^{-1}$. Note that this technique has high variation inherently and was only used to verify the order of magnitude of the sub-threshold loss calculation.

Spectrum

The laser typically emits single transverse mode near threshold, usually $< 4 \times$ threshold. This occurs because heating effects have not hampered laser performance significantly. This can be seen in Fig. 6.13 where spectra are taken from 30 to 80 mA in 10 mA steps. Though the spectra shown are single moded, the evidence of other modes gaining power is evident at higher currents. Nonetheless, the main laser peak is always 20 dB larger than the side modes. The onset of thermal rollover takes place at approximately $6 \times$ threshold where the spectrum becomes multi-moded or erratic due to heating. The wavelength red-shifts at a rate of about 0.25 nm/mA due to carrier induced effects, about one order of magnitude larger than what has been reported in literature [79].

As current is injected into the laser, the quantum well active region rises in temperature. The ratio of this increase to the net power input to the laser is defined as the thermal impedance, $R_{th}$. This parameter is useful to determine the strength of self-heating, particularly towards device reliability and lifetime. In the case of BRL2, it will assist in gauging the self-heating that has been observed in the spectral shift. Thermal
Figure 6.13: Emission spectra of a BRL2 laser at 20 C operating in CW mode. Spectra are taken in steps of 10 mA starting from 30 mA. The device is 608 µm long with threshold at 19.5 mA.

impedance can be calculated via Equation 6.2. Here ΔT is the change in temperature of the active region caused by a change in input power ΔP. $P_{out}$ is the optical power emitted from the laser, hence IV-$P_{out}$ is the power dissipated to the active region. Sidewall roughness can also add to this through non-radiative recombination at defect states. This reduces the injection efficiency of the laser while also generating heat, further degrading the device performance. To determine the strength of this effect, large ridge-waveguide lasers would need to be tested. This effectively reduces the sidewall contribution from the injection efficiency. At the moment, photolithography masks are not available with these patterns to verify this hypothesis.

$$R_{th} = \frac{\Delta T}{\Delta P} = \frac{\Delta T}{IV - P_{out}}$$  \hspace{1cm} (6.2)

A simple method to calculate $R_{th}$ is to use a combination of both pulsed and CW mode [80]. Since pulsed mode removes the effect of self-heating, the change in power between CW and pulsed modes represents the reduction due to self-heating. Then, while keeping the laser operational in CW mode and cooling the heat sink, we find the
temperature at which the laser emits the same power as in pulsed mode at the original temperature. This change in temperature can then be said to be rise in temperature, \( \Delta T \), of the active region due to self-heating.

A BRL2 laser with 438 \( \mu \)m cavity length and 14.5 mA threshold current was used to measure thermal impedance. The laser was turned on at 25 mA at 20°C in pulsed mode with 4 \( \mu \)s pulses and 1 ms delay. The total output power of the laser was 4.99 mW. Upon switching to CW mode, the total output power of the laser was reduced to 4.63 mW with a voltage of 2.37. Then, the heat sink temperature was slowly decreased till the CW output power returned to 4.99 mW. This occurred at 14.4°C, a total change of 6.6°C. The calculation for thermal impedance is shown in Equation 6.3

\[
R_{th} = \frac{6.6^\circ C}{(0.025 \, A)(2.37 \, V) - 4.63 \, mW} = 0.1209^\circ C/mW = 120.9 \, K/W \quad (6.3)
\]

This value is much higher than similar InGaAs edge-emitting diode lasers that have thermal impedance around 5 K/W [81]. However, it is much lower than similar VCSEL’s that are usually between \( \approx \)1000-4000 K/W [82, 83]. This is to be expected though because BRL’s have cavity volumes similar to edge-emitters, but have the same vertical structure as surface-emitters. As such, the \( R_{th} \) measured is not surprising. Nonetheless, it provides some insight into the strength of self-heating within BRL2.

**Heat sink bonding**

These negative effects of heating on output power and spectral shift can be mitigated via bonding of the laser to a larger heat sink. Though testing of the laser is always performed on a TEC cooled copper block, the thermal contact between the two is poor. To increase the performance of thermal sinking, some laser chips were bonded to copper pieces using Indium metal. The copper pieces measured roughly 20 mm \( \times \) 5 mm \( \times \) 3 mm and were sanded and cleaned prior to bonding. The Indium and bonding was performed manually.
Figure 6.14: Light-current curves comparing unbonded and bonded BRL2. The linear region has increased due to improved heat dissipation.

and requires some level of dexterity and patience. First, the copper was raised to 160°C and Indium was placed atop it. The Indium quickly melts and was spread into a thin even layer using a thick wooden dowel. Note the melting point of Indium is roughly 157°C. The chip is then placed on the liquid Indium layer, just at the edge of the copper block to allow easy access. Finally, the block is allowed to cool and the laser is washed thoroughly in DI water and iso-propanol.

The positive impact of bonding was readily observed. For comparison, results from the same laser tested in the previous section will the shown. First, the onset of thermal rollover occurs at over $10 \times$ threshold rather than $6 \times$ threshold before. The linear region of the L-I curve has also been extended thus allowing far higher output powers. Other lasers on the same chip demonstrate over 50 mW peak single-facet output after bonding, a significant improvement over the unbonded case. LI curves for the bonded and unbonded are shown in Figure 6.14 for comparison.

Secondly, the emission wavelength shift have been reduced to 0.12 nm/mA from 0.25 nm/mA. A comparison of the shift of wavelength peak before and after bonding is shown in Figure 6.15. Lastly, the emission wavelength itself has been blue-shifted towards the 980 nm target. Recall, the unbonded emission wavelength was 989 nm at threshold.
Figure 6.15: Laser peak wavelength shift comparing unbonded and bonded BRL2. Bonding has reduced the wavelength shift by 50%. This implies a lower temperature and increase in temperature of the active region.

but after bonding, the emission does not reach 989 nm till 70 mA, or $> 3\times$ threshold. Spectra were captured for the bonded case, shown in Figure 6.16, at the same conditions and current levels as those in Figure 6.13. This allows for easy comparison. Note the wavelength range is now closer to 980 nm. Also, the side-mode suppression has been improved, beginning at 25 dB near threshold to over 30 dB at higher injection currents.

These results, when compared with those prior to bonding, demonstrate that these lasers are generating a lot of heat. This is not too surprising due to the abnormally high voltage that can cause detrimental Joule heating. However, the underlying cause of the high-voltage is still unclear.

**Thermal sensitivity**

Though the results of the previous section show significant generation of heat, the low-index design of this BRL affords some thermal benefits. This is due to reduced carrier leakage from the quantum-wells into the barriers and core. The 37% AlGaAs core has a large bandgap which acts as a second barrier to carriers. Typical InGaAs QW lasers utilize a GaAs high-index core to act as the separate confinement heterostructure (SCH).
Figure 6.16: Emission spectra of a bonded BRL2 laser at 20 C operating in CW mode. Spectra are taken in steps of 10 mA starting from 30 mA. The device is 608 μm long with threshold at 19.5 mA. Bonding reduces the wavelength shift significantly when compared to the unbonded case in Figure 6.13.

This is the same material used as the QW barrier and hence cannot provide the same benefit. As such, hot carriers cannot escape as readily in such anti-guided lasers, a factor unique to BRWs due to their ability to guide in low-index cores.

The band diagram of the active region of BRL2 is shown in Figure 6.17. Traditional InGaAs/GaAs diode lasers have a GaAs core, providing a QW barrier-height of <168 meV. In BRL2, the core is inherently a larger bandgap material due to the low-index guiding mechanism employed. As such, the barrier is 277 meV larger and carrier confinement is increased leading to longer carrier leakage lifetimes and weaker sensitivity to temperature.

A laser diode’s sensitivity to temperature can be represented by two values, the threshold characteristic temperature, $T_0$, and the slope characteristic temperature, $T_1$. As the labels suggest, they represent the sensitivity of the laser threshold and slope efficiency to temperature, respectively. The characteristic temperatures $T_0$ and $T_1$ are governed by Equations 6.4. In Equation 6.4a, $I_{th}(T)$ is the threshold current at temperature $T$. 
Figure 6.17: Band diagram of the active region at the center of the core. The 37% AlGaAs core provides an additional 277 meV barrier to carrier leakage [6].

and $I_0$ is a laser parameter that can be interpreted as the threshold current at absolute zero. Similarly, in Equation 6.4b, $\eta_{s\text{lope}}(T)$ is the slope efficiency at temperature $T$ and $\eta_{s\text{lope},0}$ is the slope efficiency at absolute zero. Note $T$, $T_0$ and $T_1$ in these equations are in Kelvin units.

$$I_{th}(T) = I_{th,0} \cdot e^{\left(\frac{x}{T_0}\right)}$$ (6.4a)

$$\eta_{s\text{lope}}(T) = \eta_{s\text{lope},0} \cdot e^{\left(\frac{x}{T_1}\right)}$$ (6.4b)

The bonded BRL2 was tested for its temperature sensitivity by varying the temperature of the TEC controlled copper block. To remove the inherent heat generation of the laser itself, these measurements must be performed in pulsed mode. Here, we have used 2 μs pulses with over 1 ms delay between pulses. This represents a duty cycle of less than 0.2%, allowing the laser to cool between successive pulses. This effectively removes the interference of the internally generated heat from the sensitivity measurement. BRL2 was then operated at temperatures from 15°C to 100°C. The measured LI curves are shown in Figure 6.18. From these curves, $T_0$ and $T_1$ were calculated as 215 K and 216 K respectively. These values are on the order of the highest reported for this material.
Figure 6.18: Light-current curves for BRL2 at temperatures ranging from 15°C to 100°C. These were measured in pulsed mode using 2 μs pulses.

Another possible explanation is due to tuning of the TBR wavelength and angle with temperature. As the gain shifts with heating, so does the reflector. It is possible that the change in one is compensated by the other, allowing for thermally stable operation. This is known as detuning the reflector, a well-known principle in distributed feedback lasers [85]. This effect could have been incorporated within our devices unintentionally during epitaxial growth. Further, the thermal insensitivity is expected to increase even by designing BRW lasers with reduced heat generation.

6.3 Summary / Discussion

This chapter has detailed the design and characterization of the first quarter-wave BRW laser. Although the first design was sub-optimal due to current leakage, the re-designed wafer and subsequent lasers performed much better. Single facet power was measured to exceed 20 mW in CW mode at room temperature and the lowest threshold current density
was 418 A/cm$^2$. Spectral analysis found significant heating in the devices leading to poor performance and thermal rollover at just 6× threshold. Bonding the lasers to copper using Indium greatly improved performance and maximum power could now exceed 50 mW in CW mode. Propagation losses were measured for the first time to be 14.1 cm$^{-1}$ for the Bragg mode. Lastly, the thermal performance of the bonded laser was found to be very good. This is surprising considering the significant heating which still hampers the efficiency. Characteristic temperatures $T_0$ and $T_1$ were found to be 215 K and 216 K respectively. It is expected that there is significant room for improvement in these lasers in terms of power, spectral purity and thermal performance via optimization of the heterostructure and layer design to reduce heating.
Chapter 7

Intracavity frequency conversion:
Degenerate design

With the experimental demonstrations of BRW-based nonlinear conversion in Chapter 4 and diode lasers in Chapter 6, the next step is integration of these functionalities. In the next two chapters, my technique of utilizing intracavity frequency conversion within a diode laser will be detailed. Utilizing the same cavity for lasing and frequency conversion is an elegant solution to the integration problem. Though individual components integrated sequentially can allow for larger functionality on a complete chip, the process of nonlinear conversion benefits greatly from the use of intracavity conversion.

The literature is filled with examples on the use of a single cavity for lasing and nonlinear conversion. Tranbachu and Broyer developed equations governing intracavity optical parametric oscillators (OPO) and demonstrated one experimentally [86]. There, the main benefit of an intracavity design is in accessing the strong laser fields circulating within the cavity, hence enhancing nonlinear interaction. This should allow for greater converted powers and reduced OPO threshold. Debuisschert et al. predict over 80% power conversion can be attained between the pump and signal pulses [87]. More recently, continuous-wave (CW) intracavity OPO designs have been explored [88]. This is
particularly impressive in light of the lower peak powers of such a CW laser compared to traditional mode-locked OPO sources.

Examples of intracavity nonlinear interaction within semiconductors are also evident in the literature. Quantum cascade lasers operating in the mid-IR generating a strong second harmonic signal, with efficiency as high as 100 $\mu$W/W$^2$, have been demonstrated [89]. There have also been demonstrations of blue generation within near-infrared vertical cavity surface emitting lasers (VCSEL) via second harmonic generation [90]. These demonstrations were monolithic and intracavity within a semiconductor laser but were not phase-matched and thus difficult to compare to phase-matched BRW designs. Further, they were discovered by chance and can be difficult to design towards a tunable source.

Some phase-matched designs have also been proposed in literature. Averkiev et al. theoretically analyzed the performance of difference-frequency generation (DFG) within a semiconductor heterostructure laser [91]. Lastly, the dynamics of an all-semiconductor intracavity OPO were explored by Khurgin, Rosencher and Ding [1]. However, neither provided a platform or design for the materials proposed within their schemes. As such, there is need of a suitable platform from which to design nonlinear devices. The Bragg reflection waveguide fills this role well, particularly due to targeted frequency conversion via design of the vertical structure. The coming sections will describe the design, fabrication and characterization of first attempt at a BRW laser with intracavity down-conversion.

### 7.1 Device design

The first BRW structure for intracavity frequency conversion, called BRL3, was designed for degenerate down-conversion. This was chosen because the degenerate case is the essentially the reverse process of SHG, sometimes termed half-harmonic generation (HHG), which had already been demonstrated. Thus, degenerate down-conversion is not a signif-
significant jump from previous experiments. Specifically, the BRL3 structure was again made with InGaAs quantum-wells emitting at 980 nm and converting to 1960 nm through parametric fluorescence. The device would essentially convert the pump radiation internally when the laser is turned on. The design was built upon the double matching-layer BRW structure (DML-BRW), described in Section 2.2.2 and has improved nonlinear interaction [92]. The structural parameters of BRL3 are shown in Table 7.1. For simplicity
of calibration and growth, the entire design is composed of only three AlGaAs alloys (excluding the active region). The core has been further enlarged compared to BRL1 and BRL2 from 700 nm to 1100 nm. This leads to a value of 0.64% per well for the confinement factor $\Gamma$ of the Bragg mode while ensuring no modes are confined to the core. This is due to the large low-index core separating the high-index GaAs matching layers. The field profiles of the interacting modes and refractive index profiles are shown in Figure 7.1. Note the structure was designed for 975 nm rather than 980 because our past SHG experiments have always shown a slight shift of phase-matching to longer wavelengths, possibly due to the Gehrsitz refractive index model used [23].

Utilizing the computational procedure detailed in Chapter 2 and 5, the modal effective

<table>
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<th>$x_c$</th>
<th>$x_1$</th>
<th>$x_2$</th>
<th>$x_a$</th>
<th>$x_L$</th>
<th>$d_c$ [nm]</th>
<th>$d_a$ [nm]</th>
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<tbody>
<tr>
<td>0.52</td>
<td>0.30</td>
<td>0.52</td>
<td>0.00</td>
<td>0.52</td>
<td>1200</td>
<td>275</td>
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Table 7.1: BRL3 epitaxial structure design
indices of the BRW pump, TIR signal and idler are 3.1658, 3.1613 and 3.1702 respectively. The calculated leakage loss of the Bragg mode is 0.5 cm$^{-1}$ using the Ghatak method. The structure effective nonlinear coefficient, $d_{eff}$ is 11.3 pm/V and the 2nd order nonlinear effective area, $A_{eff}$ is 89.3 um$^2$.

The structure was again grown using Metal Organic Chemical Vapour Deposition (MOCVD) on 2° off n-GaAs substrates through CMC microsystems. All interfaces within the mirrors were linearly graded in composition over a distance of 25 nm, the minimum capable by the grower. The bottom reflector was n-doped with Silicon at a level of $1.2 \times 10^{18}$ cm$^{-3}$ and the top reflector was p-doped with Carbon at a level of $1.0 \times 10^{18}$ cm$^{-3}$. One reflector period adjacent to the core on the p-side and two periods on the n-side had reduced doping to reduce optical losses, specifically $1.2 \times 10^{17}$ cm$^{-3}$ and $5 \times 10^{17}$ cm$^{-3}$ for the n and p-type, respectively. The structure was capped with a a 50 nm GaAs contact layer, doped to $4 \times 10^{18}$ cm$^{-3}$ (p++). The core is also slightly doped; 495 nm on each side of the active-region is doped $1.2 \times 10^{17}$ cm$^{-3}$ and $1 \times 10^{17}$ cm$^{-3}$ for the n and p-type, respectively. The active region was designed by CMC microsystems for emission at 980 nm. The active region is composed of two 20% InGaAs QWs, roughly 6 nm, separated by 10 nm of GaAs. A complete epitaxial growth list is provided in Appendix C.4.

Samples from the grown wafers were processed into ridge waveguide lasers through the procedure described in Appendix A. Fabricated ridge widths ranged from 2.5 to 4 μm and cavity lengths between 0.5 to 1.3 mm. The etch depth was roughly 3.75 μm for the tested lasers. A typical SEM cross-section of the ridge is shown in figure 7.2(a), and typical side-wall is shown in Figure 7.2(b).
7.2 Laser Characterization

7.2.1 Light-current-voltage characteristics

The devices were tested in our pulsed diode laser characterization setup, described in Appendix B. Initial attempts at current injection were unable to lase BRL3 in CW mode. However, pulsed mode was able to induce lasing which implied the devices operated very hot. This behaviour persisted even after multiple attempts of fabrication. At the same time, several attempts at BRL2 fabrication were successful hence ruling out the fabrication process as the cause.

By operating BRL3 below the moisture dew point, the first clue was found. Water droplets begin forming on the entire device except for the region near the waveguide being tested. This shows the lasers are operating hot. Another cue was found by observing the power utilized in maintaining the heat sink temperature. For example, the heat sink consumes $70\pm20$ mW to maintain the set point for an unbonded laser operating at 150 mA with 1 $\mu$s pulses with 20 $\mu$s delay at $15^\circ$C; this is fairly high since short duty cycle and pulses should remove self-heating of the device. Several typical L-I and V-I curves for BRL3 are shown in Figure 7.3(a) and Figure 7.3(b) respectively. From the V-I, the device voltage can exceed 7 V and is likely cause of device heating. The high voltage induces Joule heating as carriers are forced to the quantum-wells over heterobarriers. It is possible there are large, unanticipated heterobarriers in the grown structure.

7.2.2 Laser spectrum

The spectrum of the laser was measured by collimating the beam using a 60× objective lens, then coupled to a multi-mode fiber. The coupling was optimized through the use of a fiber power meter. Spectra were obtained using a Horiba spectrometer (1800 line/mm grating) with TE cooled Silicon CCD. This spectrometer is more suitable than the OSA because the laser is operating in pulsed mode and optical powers are too low for fiber
Chapter 7. Intracavity frequency conversion: Degenerate design

Figure 7.3: Typical LIV curves for bonded BRL3 lasers operating in pulsed mode with 10 $\mu$s pulses. Solid lines are 745 $\mu$m cavity length, dash-dot lines are 1078 $\mu$m cavity length.

collection. Figure 7.4 shows the spectra obtained at several above-threshold currents for a 1078 $\mu$m cavity length device. At threshold, BRL3 lases at 965 nm and eventually has a second mode lasing near 980 nm. It is unclear if the shift is due to poorly grown QWs or due to mismatch of the mirror cavity resonance and PL peak. Such mismatch is typical in VCSEL’s and complex calibration at growth is required to overcome it.

7.2.3 Off-axis spectrum and Power factor

To rule out single carrier recombination or Auger recombination, both non-radiative, the 90° off-axis sub-threshold spectra were examined. By analysis of the unamplified spontaneous emission spectrum (UASE) at various current levels, the power factor can be determined. The power factor, $z$, describes the relationship between the injected current, $I$, and carrier density, $N$, as described in Equation 7.1 [93]. If single carrier recombination dominates, $z$ would be close to 1. If Auger recombination dominates, $z$ would lean towards 3. Radiative recombination, called bimolecular recombination, utilizes 2 carriers (electron and hole).
Figure 7.4: Normalized laser spectra at several injection currents from 25 mA to 55 mA in 5 mA steps. Note the laser initially emits at 965 nm with few longitudinal modes. At higher currents, more longitudinal modes participate and eventually a second transverse mode appears near 980 nm.

\[ I = C \cdot N^z \]  

(7.1)

The UASE was collected via an objective lens focused on the ridge waveguide. Though a window in the top contact is usually required to obtain unaltered UASE, this measurement only requires relative UASE spectra between injection levels. The off-axis spectra as a function of current are shown in Figure 7.5(a). These are not the actual UASE spectra as they are modified by the transmission of the top contact. However, the total relative UASE power at various injection levels can be found by integrating the area un-
der each spectra. The integrated power is normalized to the maximum value and plotted on a log-log plot. The slope of this curve is related to the power factor $z$, as derived in Equation 7.2. From this data, the power factor is found to be 2.06, hence verifying the bimolecular recombination.

$$z = 2 \cdot \frac{\partial \ln(I)}{\partial \ln(P_{sp})} \quad (7.2)$$

### 7.2.4 Analysis

Through conversations with the growers, the probable cause of the high voltage was determined to be the activated doping level. Though the requested doping was sufficient for efficient lasers, the MOCVD reactor in question had very low activation at AlGaAs with Al% above 35%. This is a well known effect due to DX centers caused by the shift from direct to indirect bandgap. The grower supplied activation curve is shown in Figure 7.6; this curve was unknown to us before growth. Note that the minimum activation, less than 1%, occurs near 48% AlGaAs. This is fairly close to the 52% AlGaAs used in our structure. Hence, less than 1% activated doping must be expected
Figure 7.6: Variation of Si doping activation with composition for the CMC MOCVD reactor. Note activation is less than 1% for the 52% AlGaAs used in BRL3.

from all these layers. Further, 30% AlGaAs has an activation of \( \approx 50\% \). This implies the entire mirror is less than half the designed doping level which led to the following performance issues:

1. Increased voltage, at times over 7 V

2. Inoperable in CW mode

3. Significant self-heating even in pulsed mode

4. Lasing at 965 nm rather than 980 nm from calibrated PL before growth

Though the lasers performed well below expectations, experiments were continued to determine if any parametric fluorescence was present in the laser emission. The following section will describe the experiments and results.
Figure 7.7: TE linear loss of a 686 μm long BRL3 sample from Fabry-Pérot transmission measurements. The measured propagation loss is $2.53 \text{ cm}^{-1}$. The solid line is a fit of the FP Airy function.

### 7.3 Parametric Fluorescence

Parametric fluorescence (PF) is the opposite process of SHG, where a single high-energy photon is converted into two lower-energy photons. The following section will describe how measurements of the nonlinear down-conversion was performed. Initially, the device was characterized linearly to ascertain the effect of losses on any nonlinear performance. Next, the fluorescence power was measured by first removing interference from the laser emission and then performing low power measurements of any infrared power in the beam output from the laser. Lastly, the down-converted emission was characterized spectrally through the use of a Fourier-transform infrared (FT-IR) spectrometer. This final measurement was the convincing piece of evidence that down-conversion was indeed taking place within BRL3.
7.3.1 Linear loss at long wavelengths

The linear loss at down-converted wavelengths is important to gauge and compare the down-converted powers with other cases in literature, particularly those with almost lossless propagation such as LiNbO$_3$ QPM waveguides. To determine this, Fabry-Pérot transmission (FP) measurements were performed at 1550 nm. This is because finely tunable lasers are readily available for this range. Though the losses will be different at 1.96 $\mu$m (design), it should not vary drastically because there are no new absorption peaks for AlGaAs in this range.

A cleaved bare fiber was brought to the facet of a 686 $\mu$m long BRL3 sample and coupled into a waveguide. The polarization was controlled via paddles that modify the stress in the fiber and then monitored using a polarization beam-cube splitter at the output. The fiber launch method was used because it was difficult for an objective to access the bonded laser. FP fringes were obtained by finely tuning the tunable laser (JDS Uniphase SWS15101) and monitoring the transmitted power on an InGaAs detector. The result of a scan using TE polarized input is shown in Figure 7.7 where the fringes are clearly visible. From the contrast of these fringes, the propagation loss can be determined [94]. Using this method, the loss was calculated as 2.53 cm$^{-1}$. A fit of the FP Airy function resulted in a similar value of 2.56 cm$^{-1}$. The fit is shown as the solid line in Figure 7.7.

These propagation loss values are very similar to measurements performed in other BRW waveguides designed by our research group. Though the value is fairly large for AlGaAs waveguides at this wavelength, it is important to note the semiconductor is deeply etched, doped and coated in metal. Hence this value is not unexpected. However, this loss value would certainly degrade the conversion performance of the device.
Figure 7.8: Test setup for PF detection. The Silicon and long-pass filters are used to attenuate the laser wavelength while passing the PF wavelengths.

### 7.3.2 Fluorescence power

The setup used is shown in Figure 7.8. Because all near- and mid-infrared detectors have some detectivity at the laser wavelength, detecting PF requires some filtering before the detector. In literature, some reports use absorptive and long-pass filters [16, 95] while others utilize a monochromator [96]. Here, two double-side polished Silicon wafers were used as filters to strongly absorb the laser wavelength. Transmission tests show over 30 dB absorption per filter. A long-pass filter by Andover Corp. with cut-on at 1.65 μm was also placed after the Si filters with over 40 dB rejection of the laser wavelength. This assures over 100 dB reduction in the laser emission reaching the detector. A chopper is placed in line of the beam to allow phase-sensitive detection in case of extremely weak or noisy PF signal.

The detector used was a thermo-electrically cooled (-30°C) extended InGaAs detector by Electro-optic systems. The detector features detectivity of 1 V/μW at 2.2 μm, detection capable up to 2.5 μm. The 3-dB bandwidth is 1000 Hz and the digital synchronous filter of the SR830 Lock-in amplifier is 200 Hz. Hence the chopper was typically set
Figure 7.9: PF L-I curves from a bonded 578 μm BRL3 laser at 10° at several pulse duty cycles. Values shown are compensated for pulse duty cycle and represent pulse peak powers.

below 200 Hz for the PF measurements. Note the short pulses from the diode laser will be seen as a DC voltage by the detector as they are too fast for the detector electronics to resolve.

A signal was readily observed on the detector when the laser was turned on. The L-I dependence for this signal differed greatly from a typical L-I curve for the laser wavelength. An example of this signal L-I is shown in Figure 7.9. Note these curves are of peak pulse powers and have been compensated for spectral dependence of the signal/idler determined by spectra, shown later in this section. Similar to the laser L-I, the change in slope represents the laser threshold current, in this case \( \approx 43 \) mA. However, in contrast to typical laser behaviour, the before threshold slope is larger than the after threshold slope; this implies poorer efficiency after threshold for this detected signal. The 10 \( \mu \)s pulses have the weakest peak pulse powers, possibly due to heating. Note however, the average power was still largest for the 10 \( \mu \)s pulses as the off-time of the pulse cycle is less. This allowed for easier detection of the down converted signal.
Figure 7.10: PF power versus laser power showing linear dependence. This is characteristic of PF. The PF efficiency is $1.04 \times 10^{-7}$ W PF per W pump.

When the detected power is plotted against the laser power, shown in Figure 7.10, a linear relation is evident. This is an indication that the detected power is PF. The slope of this curve is $1.04 \times 10^{-7}$ W/W which is on the order of other reported values of PF in AlGaAs waveguides [96] or LiNbO$_3$ QPM waveguides [97]. The PF efficiency, $\eta_{PF}$, is defined as the signal power, $P_s$, divided by the pump power (laser), $P_p$. Assuming half the detected power is the signal, $\eta_{PF}=5.2 \times 10^{-8}$ W/W. However, as will be noted from the spectra, the detectivity at the signal wavelength was weak and this $\eta_{PF}$ is likely underestimated.

### 7.3.3 Fluorescence spectrum

Further analysis of the power measurements cannot be done without first understanding the spectrum of this emission. This is because the nature of this infrared light is still unknown. A complete understanding requires spectral measurements as evidence. For this, Prof. Burch’s group within the Physics department provided the use of their FT-IR instrument. The setup was originally designed for IR absorption measurements of
Figure 7.11: Spectrum of PF in a 1078 μm long BRL3 at 150 mA using a FT-IR spectrometer. The laser (pump), signal and idler are clearly visible. (inset) A close-up of the idler taken at 50 mA showing a FWHM of approximately 2 nm.

materials, but was used without a sample. One of the FT-IR lamp sources was replaced with the BRL3 beam and aligned properly into the interferometer. A room-temperature extended InGaAs was used for the measurements.

The interferometer was set for a resolution of 8 cm⁻¹ and a rate of 10 kHz at the reference wavelength of the interferometer (632.8 nm HeNe laser). The laser emission was easily found in the spectra. However, some fine alignment was required to observe the infrared emission observed in the power measurements of the previous section. The power of the laser had to also be increased by decreasing the pulse duty cycle; 40 μs pulses with 20 μs delay were used. An example of the spectrum is shown in Figure 7.11; the laser, signal and idler are clearly visible. The laser wavelength was measured as 976 nm at low injection currents which is slightly inaccurate. Re-evaluation of the laser using two separate spectrometers confirms lasing initially occurs at 967 nm; leading to a correction factor of 1.0093. A close-up spectrum of the idler is shown in the inset. The FWHM is extremely small, approximately 5 nm, encompassing less than 10 longitudinal modes. Weaker surrounding modes are also visible. The narrow bandwidth of the BRW
Figure 7.12: Normalized PF spectra in a 1078 μm long BRL3 at several injection levels. The signal and idler are marked with arrows. The injected current tunes the signal to shorter wavelengths and the idler to longer wavelengths.

phase-matching would likely not contribute to this width [39].

7.3.4 Analysis

Comparison with simulations

From Figure 7.11, the signal and idler wavelengths are found to tune as current is increased. By analyzing the peak position of both as a function of current, an injection tuning curve can be constructed as shown in Figure 7.13. The signal wavelength varies from 1715 nm at low injection to 1634 nm at high injection. Similarly, the idler varies
Figure 7.13: Measured current tuning curve for a 1078 μm long BRL3. The difference in signal and idler wavelength increases with current.

from 2263 nm at low injection to 2502 nm at high injection. Each signal and idler point is found to track the laser wavelength. This is shown clearly in Figure 7.14(a) where the sum of signal and idler photon energy is plotted against the laser photon energy. The two measurements match up almost exactly and show the same dependence on current. This is evidence that the laser line is participating in the nonlinear interaction and not side modes or amplified spontaneous emission.

These values in the tuning curve are quite far from the designed degeneracy point for down-conversion. There are two possible explanations for this deviation. First, as noted in the previous section, the laser runs very hot due to the high voltage. This modifies the refractive indices of all layers and shifts the degeneracy phase-matching point to longer wavelengths. Secondly, the emission wavelength of the laser is far from design as shown in Figure 7.4. These shorter pump wavelengths have phase-matching at non-degenerate wavelengths. For example, at low injection currents, the laser emits around 967 nm. Based on simulations, this leads to a room temperature signal and idler at 1718 nm and 2212 nm, respectively. Therefore, the observed values are within expected values from simulations. The phase-matching curves for several temperatures between 20°C to 180°C.
(a) Comparison of laser and down-converted photon energy. The combined signal+idler photon energy matches almost exactly with the laser photon energy proving the laser is the pump.

(b) Simulated phase-matching curves for temperatures between 20°C and 180°C in 40°C steps.

Figure 7.14

are shown in Figure 7.14(b)

Conversion efficiency

The spectral analysis was incorporated in the power measurements of the previous sections to account for responsivity and transmission. Since the transmission spectrum of the objective lens is unknown, it is assumed constant at 30%. Note, it is likely the transmission is lower for the idler than signal due to glass IR absorption.

A reasonable assumption is that the detected power is equally distributed between the signal and idler photons. The quantum efficiency, defined as the probability a pump photon will be down converted, is $\eta_Q = \eta_{PF} \cdot \omega_p / \omega_s$. Using the spectral data for the frequency, $\eta_Q = 8.59 \times 10^{-6} \pm 0.18 \times 10^{-6}$ %. The error takes into account the spectral variation observed in the tuning curve. The external normalized conversion efficiency can be
calculated using Equation 7.3.

\[
\eta_{\text{ext,norm}} = \frac{P_s}{P_p \cdot P_0^i \cdot L^2}
\]  

(7.3)

Here, \(L\) is the device length, \(P_s\) and \(P_p\) are the signal and pump powers, respectively. \(P_0^i\) is the initial idler power and is generally assumed as quantum noise in PF experiments. For waveguides, this can be computed by placing a single photon in each signal mode and dividing the resulting energy by the cavity transit time, \(\tau = L \cdot n_g / c\). To calculate this, we note the ratio \(P_s / P_p\) has been calculated in Section 7.3.2 as \(5.2 \times 10^{-8}\). The group index can be found through simulations; at 2300 nm idler \(n_g\) is 3.248. From the spectrum at 50 mA, the number of modes participating in the idler can be estimated as 27 ± 5, leading to \(P_0^i = 378 \pm 70\) nW. The count was performed by adding the bandwidth of the main idler peak and side peaks, then dividing by the free spectral range (FSR). There is a small error due to lack of clarity of other peaks within the spectrum. However, it is unlikely such weak modes contribute significantly. The device length for the power measurements is 578 μm long. From these values \(\eta_{\text{ext,norm}} = 4176 \pm 817\) %/Wcm\(^2\), far larger than other reports of PF in AlGaAs [96] (1000 %/Wcm\(^2\)), GaP [98] (16 %/Wcm\(^2\)) or LiNbO\(_3\) [97] (13 %/Wcm\(^2\)) waveguides. Our conversion efficiencies are much larger due to the short cavity length compared to these other demonstrations.

From simulations of a 967 nm pump in BRL3 at room temperature \(A_{\text{eff}}\), the second-order nonlinear effective area, is found to be 114 μm\(^2\). Utilizing this, the effective nonlinearity, \(d_{\text{eff}}\), can be calculated by through Equation 7.4a and Equation 7.4b to obtain Equation 7.4c.

\[
g^2 = \frac{2 \omega_i \omega_s}{\epsilon_0 \cdot c^3 \cdot n_{\text{eff,p}} n_{\text{eff,s}} n_{\text{eff,i}}} \frac{d_{\text{eff}}^2 \cdot P_p}{A_{\text{eff}}} \]  

(7.4a)

\[
g^2 P_p = \frac{\omega_i}{\omega_i} \cdot \eta_{\text{ext,norm}} \]  

(7.4b)

\[
d_{\text{eff}}^2 = \frac{\epsilon_0 \cdot c^3 \cdot n_{\text{eff,p}} n_{\text{eff,s}} n_{\text{eff,i}}}{2 \omega_s^2} \eta_{\text{ext,norm}} \]  

(7.4c)
Here, $g$ is the loss-less parametric gain. Substituting the measured values into Equation 7.4c, $d_{eff} = 38.7 \pm 3.6 \text{ pm/V}$. This is roughly $3 \times$ larger than the theoretical value of $11.3 \text{ pm/V}$. A possible explanation is the lack of accurate AlGaAs bulk nonlinearity for the theoretical calculation. Another possibility is due to the slight cavity enhancement caused by the facets. Nonetheless, it should be noted these numbers are likely underestimated as they do not take into account the linear losses.

### 7.4 Summary / Discussion

In summary, phase-matched diode lasers based on the DML-BRW structure were designed for intracavity degenerate down-conversion from 980 nm to 1960 nm. Due to poor activation of the n-doping, the lasers had significant performance issues due to high voltage. The lasers could not operate in CW, but only pulsed mode due to self-heating. Laser emission was at 965 nm rather than 980 nm as designed. Nonetheless, parametric fluorescence (PF) was detectable from these lasers. The detected power was found to scale at a rate of $1.04 \times 10^{-7} \text{ W PF/W of pump}$. Through the use of an FT-IR, the PF was found to be non-degenerate with signal in the 1650-1750 nm range and the idler in 2300-2500 nm range. The observation of non-degenerate PF rather than the designed degenerate PF was likely due to the shifted laser emission and self-heating. Simulations validate this hypothesis.

The normalized conversion efficiency of this process was calculated to be $4176 \pm 817 \% / \text{Wcm}^2$, a very high value owing to the intracavity design. This leads to a calculated effective nonlinearity, $d_{eff}$, of $38.7 \pm 3.6 \text{ pm/V}$. These large efficiency and nonlinearity values attest to the intracavity design. By placing an active medium within an appropriately designed phase-matched cavity, the interaction has been significantly increased.
Chapter 8

Intracavity frequency conversion: Non-degenerate design

The results from the previous section forced us to reconsider the parametric fluorescence (PF) experiment and waveguide design. Though BRL3 was designed for degenerate down-conversion, actual operation was non-degenerate and both wavelengths were $> 200$ nm from target. A new experiment was devised to create a PF structure for non-degenerate down-conversion with the signal wavelength in the telecommunication C-band, chosen as $1550$ nm for design. This wavelength range is important in telecommunications since it lies within the gain bandwidth of Erbium doped fiber amplifiers (EDFAs). Further, many tunable CW and pulsed sources exist for the C-band. Through the use of such lasers, additional experiments can be performed. For example, by coupling an external laser into the diode ridge waveguide at the phase-matched frequency, the parametric gain can be ascertained. Such a versatile structure would be an important step to designing practical down-conversion devices. This chapter will discuss the design and experiments performed towards this goal.
(a) Normalized fields for the BRW mode at 990 nm, TIR mode at 990 nm, signal at 1550 nm and idler at 2740 nm.

(b) Refractive index profile at 990 nm, dashed line is the Bragg modal effective index and dotted line is the TIR modal effective index.

(c) Refractive index profile at 1550 nm, dashed line is the TM signal modal effective index.

(d) Refractive index profile at 2740 nm, dashed line is the TE idler modal effective index.

Figure 8.1: Fields and refractive index profiles for BRL4.

8.1 Device design

The non-degenerate structure was designed with the failures of BRL3 in consideration. The high-voltage (Figure 7.3(a)) and subsequent self-heating were the limiting factors in laser performance. It was believed the n-doping activation mentioned in Section 7.2.4 was the cause of this. As such, the new design was chosen with AlGaAs materials <
Chapter 8. Intracavity frequency conversion: Non-degenerate design

35%, guaranteeing at least 8% activation. This structure was called BRL4 and again made with InGaAs quantum-wells emitting near 980 nm. However, based on the results of BRL2, heating is known to push the emission to longer wavelengths, hence the double-matching layer BRW (DML-BRW) was designed to be quarter-wave at 990 nm. The down-converted radiation would occur at 1550 nm and 2740 nm through intracavity parametric fluorescence. This process is better described by the momentum conservation condition in Equation 8.1.

$$\Delta k = k_{BRW, 990\text{nm}}^{TE} - k_{TIR, 1550\text{nm}}^{TM} - k_{TIR, 2740\text{nm}}^{TE} = 0$$ (8.1)

The structural parameters of BRL4 are shown in Table 8.1. For simplicity of calibration and growth, the design is composed of four AlGaAs alloys (excluding the active region). The core is slightly smaller than BRL3 at 1100 nm compared to 1200 nm; this is still a large value compared to typical diode lasers. The field profiles of the interacting modes and refractive index profiles are shown in Figure 8.1. Note the QWs in the center of the core region. BRL4 was the first structure to utilize the theoretical framework of including QWs to the transfer matrix calculations mentioned in chapter 5. The per well confinement factor, $\Gamma$, is 0.59% for the Bragg mode and 0.002% for the TIR mode, a ratio of 388. This is due to the large low-index core separating the high-index GaAs matching layers which virtually guarantee complete lasing in the Bragg mode.

Utilizing the computational procedure detailed in Chapter 2 and 5, the modal effective

<table>
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<th>$x_c$</th>
<th>$x_1$</th>
<th>$x_2$</th>
<th>$x_a$</th>
<th>$x_L$</th>
<th>$d_c$ [nm]</th>
<th>$d_a$ [nm]</th>
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<td>1100</td>
<td>400</td>
</tr>
<tr>
<td>$N_{upper}$</td>
<td>$N_{lower}$</td>
<td>QW material</td>
<td>QW #</td>
<td>QW gap [nm]</td>
<td>Signal pol.</td>
<td>Idler pol.</td>
</tr>
<tr>
<td>4</td>
<td>5</td>
<td>In$<em>{0.2}$Ga$</em>{0.8}$As</td>
<td>2</td>
<td>10</td>
<td>TM</td>
<td>TE</td>
</tr>
</tbody>
</table>
indices of the BRW pump, TIR signal and idler are 3.2487, 3.2705 and 3.2100 respectively. The calculated leakage loss of the Bragg mode is 0.19 cm$^{-1}$ using the Ghatak method. The structure effective nonlinear coefficient, $d_{\text{eff}}$, is 15.2 pm/V and the 2nd order nonlinear effective area, $A_{\text{eff}}$, is 701.7 um$^2$. The effective area is large because of the poor overlap caused by the weakly confined idler mode. This design was chosen after much optimization because it demonstrated a good balance between leakage loss of the idler, nonlinear overlap and total epitaxial thickness. From Equation 5.10, the expected CW laser output power from BRL4 is 95 mW for 100 mA input. In a DFG configuration, this leads to a down-converted power of 487 $\mu$W at the idler for a 1 mW input of signal. Note, this assumes good operation of the laser and low signal / idler losses.

The structure was again grown using Metal Organic Chemical Vapour Deposition (MOCVD) on 2$^\circ$ off n-GaAs substrates through CMC Microsystems. All interfaces within the mirrors were linearly graded in composition over a distance of 25 nm, the minimum capable by the grower. Each interface was also highly doped in a technique called ‘modulation doping’. This method was found to reduce voltage of barriers in VCSELs [99]. The bottom reflector was n-doped with Silicon at a level of $4.0 \times 10^{18}$ cm$^{-3}$ and $3.0 \times 10^{17}$ cm$^{-3}$ for Al$_{0.35}$Ga$_{0.65}$As and GaAs layers, respectively. The high doping level or the low-index layer of the mirror is to compensate for the 8% activation. The top reflector was p-doped with Carbon at a level of $5.0 \times 10^{18}$ cm$^{-3}$ and $3.0 \times 10^{18}$ cm$^{-3}$ for Al$_{0.35}$Ga$_{0.65}$As and GaAs layers, respectively. Each interface was doped at $4.0 \times 10^{18}$ and $1.0 \times 10^{19}$ cm$^{-3}$ for the n and p side, respective. The structure was capped with a 100 nm GaAs contact layer, doped to $3 \times 10^{19}$ (p++). The core is also slightly doped; 429 nm on each side of the active-region is doped $6.0 \times 10^{17}$ and $3.0 \times 10^{17}$ for the n and p-type, respectively. The active region was designed by CMC Microsystems for emission at 980 nm. The active region is composed of two 20% InGaAs QWs, roughly 6 nm, separated by 10 nm of GaAs. A complete epitaxial growth list is provided in Appendix C.5.

Samples from the grown wafers were processed into ridge waveguide lasers through
the procedure described in Appendix A. Fabricated ridge widths ranged from 3.0 to 4 \( \mu m \) and cavity lengths between 0.5 to 1.1 mm. The etch depth was roughly 3.7 \( \mu m \) for the tested lasers. A typical SEM cross-section of the ridge is shown in figure 8.2(a), and typical side-wall is shown in Figure 8.2(b).

8.2 Characterization

8.2.1 Light-current-voltage characteristics

BRL4 laser bars were tested in our pulsed diode laser characterization setup, described in Appendix B. Similar to BRL3, attempts at DC current injection were unable to induce lasing. However, pulsed mode could, which again implied the devices operated very hot. One device was chosen for its high maximum power characteristics and indium bonded to a copper block. Several typical L-I and V-I curves from this 980 \( \mu m \) bonded BRL4 are shown in Figure 8.3(a) and Figure 8.3(b) respectively. The voltage is \( \approx 4 \) V from the V-I, much reduced compared to BRL3 but still higher than BRL2. This is likely causing some detrimental self-heating. Further testing of the devices were performed in pulsed mode.
Chapter 8. Intracavity frequency conversion: Non-degenerate design

Figure 8.3: Typical LIV curves for a 980 µm bonded BRL4 laser operating in pulsed mode with 40 µs pulses. There are many kinks in the L-I which imply non-uniformities and other non-ideal laser properties. Nonetheless, the voltage is much lower than BRL3 and heating is reduced.

8.2.2 Laser spectrum

The spectrum of the laser was measured by collimating the beam using a 60× objective lens, then coupled to a multi-mode fiber. The coupling was optimized through the use of a fiber power meter. Spectra were obtained using a Horiba spectrometer (1800 line/mm grating) with TE cooled Silicon CCD. This spectrometer is more suitable because the laser is operating in pulsed mode. Figure 8.4 shows the spectra obtained at several above-threshold currents using 40 µs pulses with 20 µs delay for a 980 µm cavity length device. Near threshold, BRL4 lases in multiple modes around 985 nm; it is unclear if these are different longitudinal or transverse modes. At higher currents, the spectral bandwidth continues to increase to longer wavelengths. This may be due to wavelength chirping as the laser heats up in the duration of a pulse.
Chapter 8. Intracavity frequency conversion: Non-degenerate design

Figure 8.4: Normalized laser spectra at several injection currents from 25 mA to 55 mA in 5 mA steps (pulsed mode with 40 μs pulses). Note the laser initially emits at 985 nm with few longitudinal modes. At higher currents, more longitudinal modes participate at longer wavelengths, possibly due to heating.

8.3 Parametric Fluorescence

In Chapter 7, it was found that BRL3 converts photons at the laser frequency into two photons in the infrared. This process was found to occur naturally within the laser cavity, a significant feat because the device is fully monolithic and electrically injected. Similar PF experiments require large lasers and complex setups to couple pump light into the waveguide [96, 98]. It is expected that BRL4 will exhibit the same PF emission. This section will detail the results of PF power, spectral and efficiency experiments.
8.3.1 Linear loss at long wavelengths

As with testing BRL3, the linear loss at down-converted wavelengths is important to gauge the efficiency of the device and compare it with other cases in literature. Many examples have almost lossless propagation, such as within LiNbO$_3$ QPM waveguides. To determine this, Fabry-Pérot transmission (FP) measurements were performed at 1550 nm where the signal was designed using the same methodology used in Section 7.3.1. The result of a scan using TM polarized input is shown in Figure 8.5 where the fringes are clearly visible. Using the method in [94], the loss was calculated as 10.8 cm$^{-1}$. A fit of the FP Airy function, shown as the solid line, resulted in a similar value. This propagation loss value is far larger than BRL3. It is unclear where this loss originates. By comparing the SEM for BRL3 (Figure 7.2(b)) and BRL4 (Figure 8.2(b)) sidewall roughness, there is no significant visual difference. In terms of epitaxial design, the loss could originate by scattering from the highly doped interfaces. Though VCSELs demonstrate lower voltages, there is no mention of enhanced propagation loss possibly
8.3.2 Fluorescence spectrum

The output spectrum from BRL4 was measured using the same FT-IR instrument (Prof. Burch’s group within the Physics department) used for BRL3 in Section 7.3.3. The setup was originally designed for IR absorption measurements of materials, but was used without a sample. One of the FT-IR lamp sources was replaced with the output of BRL4 and aligned properly into the interferometer. A room-temperature extended InGaAs was used for the measurements.

The interferometer was set for a resolution of 1 cm$^{-1}$ and a rate of 10 kHz at the reference wavelength of the interferometer (632.8 nm HeNe laser). Though the laser emission was easily found in the spectra, some fine alignment was required to maximize the PF peaks. Unlike BRL3, BRL4 can operate at larger pulse duty cycles; 80 μs pulses with 20 μs delay were used to obtain clear spectra. Further, the TEC could maintain a
Figure 8.7: Close-up spectra of same BRL4 device at 110 mA. The multi-moded shape of the pump is translated into the signal and idler, further evidence of the parametric down-conversion process.

lower temperature. As such, spectra were taken at 10°C to assure the chip does not fail while testing. An example spectrum is shown in Figure 8.6; the laser, signal and idler are clearly visible. The correction factor of 1.0093 determined in Chapter 7 has again been utilized.

Close-up spectra of the pump, signal and idler are shown in the Figure 8.7. Similar to the spectra in Figure 8.4, the pump (laser emission) has a strong peak near 985 nm with modes on either side, shown in Figure 8.7(a). This shape is roughly translated into the signal and idler spectra, shown in Figures 8.7(b) and 8.7(c), respectively. This is evidence of the parametric down-conversion process as the pump modes are participating in the nonlinear interaction. The spectrum also shows two small peaks, just above the noise floor, situated at wavelengths between the pump and signal. It is not clear through which process these frequencies are generated as they do not correspond to any simple second-order nonlinear process. These generated wavelengths could represent higher-order processes such as four-wave mixing.

By measuring spectra at various injection levels, the current tuning curve can be
Figure 8.8: BRL4 current tuning curve and verification of energy conservation.

Calculated. This is done by plotting the signal and idler wavelengths as a function of injected current. Here, the tuning mechanism is the shift in pump wavelength due to self-heating effects. The current tuning curve for BRL4 is shown in Figure 8.8(a). The signal can tune from 1725 nm to 1750 nm while the idler can tune from 2215 nm to 2305 nm. This tuning range is smaller than that of BRL3 due mainly to the reduced self-heating. BRL3 was able to tune drastically due to the large shift in laser wavelength with current. Here, the improved laser performance has hindered BRL4’s tuning range.

Figure 8.8(b) compares the energy of the pump photon with that of the down-converted photons. The two are nearly identical and vary in the same direction with current, further proof that the laser emission is the nonlinear pump.

The stage temperature can also be tuned via the TEC and feedback thermistor. By plotting the signal and idler wavelengths as the stage temperature is varied, the temperature tuning curve can be obtained. Note, this temperature is not the actual
active region temperature. As the stage changed temperature, expands or contracts and the device moves out of alignment with the interferometer. Thus, spectra from only a few temperatures between 5°C and 20°C were captured. The resulting tuning curve is shown in Figure 8.9. The idler at some temperatures was too weak to ascertain the wavelength and were ignored in the plot.

Both the current and temperature tuning curves allow separate control of the output wavelength. This is primarily accomplished by modification of the laser temperature. Such controls would be important towards a widely tunable monolithic source of coherent radiation.

### 8.3.3 Fluorescence power

Now that the spectral properties of the down-conversion have been obtained, the strength of the PF can be determined. By knowing the wavelengths of the signal and idler, the detectors can be calibrated. The same measurement setup for PF power in BRL3 was
Figure 8.10: BRL4 PF output power dependence with current and pump strength.

used (Figure 7.8). The only exception is that three Silicon filters were used to reject the laser radiation as opposed to two. The transmission of the third filter was 51% for the PF signal, slightly lower than the other two. This is because the filter came from a separate filter of different thickness. Together, these should provide over 130 dB reduction of the laser wavelength. After the experiment, it was verified that the 100 dB reduction of two filters would have been sufficient. The same thermoelectrically cooled (-30°C) extended InGaAs detector by Electro-optic systems was utilized. Since the idler does not extend past 2300 nm, this detector is sufficient.

A PF signal was readily detected when the laser was turned on. Similar to BRL3, the PF L-I dependence differs from the laser L-I as shown in Figure 8.10(a). The laser threshold is marked and is where the PF slope changes. Note the L-I goes up and down due to the poor L-I dependence of the laser itself (refer to Figure 8.3(a)). In contrast to laser L-I curves, the below threshold slope is higher than the above threshold slope. This
could be due to a much larger number of modes in the amplified spontaneous emission participating in the down-conversion.

A linear relation is noticeable when the detected power is plotted against the laser power, as shown in Figure 8.10(b). This is an indication that the detected power is PF. The slope of this curve is $1.38 \times 10^{-7}$ W/W, slightly larger than BRL3 and on the order of similar PF experiments in waveguides [96, 97, 98]. The PF efficiency, $\eta_{PF}$, is defined as the signal power, $P_s$, divided by the pump power (laser), $P_p$. Assuming half the detected power is the signal, $\eta_{PF} = 6.89 \times 10^{-8}$ W/W. This is likely underestimated as the objective has lower transmission for the idler, hence, a higher percentage of the detected power is the signal.

### 8.4 Analysis

The spectral analysis was incorporated in the power measurements of the previous sections to account for responsivity and transmission. Since the transmission spectrum of the objective lens is unknown, it is assumed constant at 30%. As before, the detected power is assumed to be equally distributed between signal and idler wavelengths. The quantum efficiency, defined as the probability a pump photon will be down-converted, is $\eta_Q = \eta_{PF} \cdot \omega_p / \omega_s$. Using the spectral data for the frequency, $\eta_Q = 1.218 \times 10^{-5} \pm 0.013 \times 10^{-5}$ %. The error takes into account the spectral variation observed in the tuning curve. The quantum efficiency is one order of magnitude larger than that of BRL3, an impressive feat considering the much higher propagation losses. This implies improvement in the pump laser performance is vital to efficient down-conversion.

The external normalized conversion efficiency can be found using Equation 7.3. To calculate this, note the ratio $P_s/P_p$ has been calculated in the previous section 7.3.2 as $6.89 \times 10^{-8}$. The group index can be found through simulations; at the average idler wavelength, 2260 nm, $n_g$ is 3.313. Utilizing the spectrum near threshold, the number of
idler modes participating in PF can be determined. Here, 80 mA was chosen because the signal-to-noise ratio is good and the idler spectrum is large; this will provide a safe lower estimate of the conversion efficiency. For this current, a count of the idler bandwidth leads 102±10 modes. Error is due to lack of clarity of other peaks within the spectrum. By placing one photon in each mode, the initial idler power is 826±81 nW. From these values \( \eta_{\text{ext, norm}} = 874 \pm 86 \% / \text{Wcm}^2 \), much lower than BRL3. This is expected due to the high linear losses of the signal and idler. From Equation 7.4c, \( d_{\text{eff}} = 27.1 \pm 1.3 \text{ pm/V} \). This is again lower than BRL3, but still larger than comparable waveguide technologies, attesting to the larger nonlinearities within compound semiconductors.

### 8.5 Summary / Discussion

In summary, diode lasers (BRL4) based on the DML-BRW structure for phase-matched non-degenerate down-conversion were designed, fabricated and tested. These integrated devices performed lasing and down-conversion within the same cavity (intracavity). The laser emission at 990 nm was designed to couple through the second order nonlinearity to produce 1550 nm and 2740 nm. The laser itself was found to have lower voltage characteristics compared to BRL3 due in part to the considerations taken during design. However, poor L-I properties such as kinks were observed. Further, the lasers could not operate in CW, but only pulsed mode due to self-heating. Laser emission was at 985 nm. Through the use of an FT-IR, the PF was found to be non-degenerate with signal in the 1700-1750 nm range and the idler in 2200-2300 nm range. These values are roughly 150-200 nm away from design and can be attributed to poor understanding of the QW indices, tolerances in growth and self-heating. Nonetheless, parametric fluorescence (PF) power in the range of nW was detectable from these lasers. The detected power was found to scale at a rate of \( 1.38 \times 10^{-7} \text{ W PF/W of pump} \).

The normalized conversion efficiency of this process was calculated to be 874 ± 86
%/Wcm², far lower than BRL3. This is due to the significant linear losses for the signal and idler, measured at >10 cm⁻¹. From the conversion efficiency, \( d_{eff} \) was computed to be of 27.1±1.3 pm/V. These large efficiency and nonlinearity values attest to the intracavity design and nonlinearity of compound semiconductors. The PF wavelengths were found to be tunable using both current and stage temperature, thus providing useful tools towards practical monolithic integrated nonlinear sources.
Chapter 9

Future directions

The work described in this thesis demonstrates that Bragg reflection waveguides (BRW) are a versatile platform for the integration of nonlinear and active components while maintaining efficiency. From theory to demonstration, the thesis provides a complete picture of how to design such integrated devices within BRWs. The work culminated with the clear observation of efficient parametric fluorescence (PF) within the active cavity of a BRW diode lasers. There are some clear paths to future work and improvements based upon this work towards viable sources that are useful to the community.

The diode lasers tested here are sub-optimal and require further development to improve their performance. Lasers built upon the BRW platform are expected to have some significant benefits compared to traditional waveguide counterparts. This includes improved single-mode behaviour due to greater mode spacing, increased light-matter interaction and higher output powers due to larger mode volumes. However, none of these benefits were observed within our lasers due to poor output performance of the lasers. Other active structures can also be explored such as semiconductor optical amplifiers (SOAs). By tilting the direction of the waveguide with respect to the facet, the underlying nonlinear properties can be explored without any enhancements from the cavity.

The Bragg mode within BRWs have fairly large modal volumes when compared to
traditional waveguides due to the penetration of the mode into the Bragg mirrors. This leads to a reduction of photon density within the waveguide and hence higher threshold for detrimental nonlinear effects such as spectral hole burning and filamentation. Similar reduction in photon density in fibers have lead to demonstrations of multi-kW single-mode lasers. A similar effort within BRW diode lasers could lead to increases in single-mode output power. In this work, optimization of the design and fabrication within BRL2 lead to improvements in power compared to BRL1. Most importantly, the CW output power from a single facet reached $\approx 50$ mW in some bonded devices. The high voltages of all tested devices point to a problem at wafer design or growth leading to detrimental heterostructure barriers. BRL2 could exceed 4 V and BRL3 could exceed over 8 V; for reference, most lasers in literature (VCSEL and edge-emitting) are below 2 V. By improving the voltage characteristics, many of the output power and self-heating issues may be alleviated. However, it is unclear exactly where the epitaxial issue lies. The designs used in this thesis can provide a starting point from which to diagnose the performance and reach the eventual goal of multi-W single mode diode lasers.

Investigating some unique types of PBG waveguides built atop BRWs could also yield benefits. Currently, 2-D confinement is achieved through total internal reflection by the ridge waveguide. A more versatile method would be to create a surface 2-D air-hole structure with a defect that defines the waveguide. Essentially, this would be a quasi 3-D (sometimes called 2.5-D) confinement PBG waveguide. There have been many theorized benefits from 2-D air hole structures, in particular slow light [100]. It is also known that slow-light can enhance nonlinear interactions [101]. Hence, such a design could further increase in conversion efficiency while allowing for additional tuning of modal properties through structure.

One of the goals of the intracavity PF devices was to target the down-converted wavelength. In this thesis, two structures of different design principles were fabricated to this goal. BRL3 for degenerate PF and BRL4 for non-degenerate PF, however neither
device was near the designed target. The down-converted photons of BRL3 were non-degenerate and about 300 nm from the designed degeneracy point. Conversely, BRL4 was designed non-degenerate but the down-converted photons were about 200 nm from the designed point within the telecommunication C-band. One possible reason for this is a mismatch of the BRW cavity resonance with the gain peak of the quantum-wells, a typical problem in VCSELs. Evidence of this can be seen in BRL3 where the calibration PL during growth was $\approx 980$ nm, yet the laser emission was at 965 nm. This shift is a typical sign of mismatched cavities within VCSELs. By appropriate simulation, design and grower calibration, it may be possible to reduce the effects of this and target the designed down-converted wavelength. With this, tailored wavelength sources for specific applications could be realized.

Lastly, a widely tunable down-conversion source would rely on a tunable diode laser pump. To facilitate this, distributed Bragg reflectors (DBR) can be added to the laser design. These DBRs can be electrically tuned to control their resonance point and hence the laser wavelength. Since the laser is the pump for nonlinear interaction, precise control of the laser leads to precise control of the down-converted photons. Further, since small changes in pump wavelength can lead to large changes in down-converted photons, such a widely tunable DBR laser could provide hundreds of nanometers in signal / idler tunability.

The future directions mentioned here require considerable effort in terms of improvements in structure design and fabrication. However, the effort is warranted as the benefits are likely feasible. PF is one of the weakest nonlinear processes since it relies on quantum noise within the sample to provide an initial spark for down-conversion, similar to spontaneous emission. Nonetheless, the PF signal was readily detected in both power and spectrum from these diode lasers attesting to efficiency of the platform. By improving upon the laser performance and with more targeted designs, the dream of an electrically pumped, semiconductor monolithic OPO may soon be realized.
Appendix A

Detailed fabrication procedure

A.1 Stage 1: Fabricating the ridge waveguides

1. Inspect the wafer and locate a suitable area to cut a sample from. Be sure the area is large enough to further cleave the number of 1x1 cm samples you require. Cut this piece from the wafer using a diamond scribe and ruler.

2. Clean the piece using the nitrogen gun to remove any dust created during the cutting. Further clean the sample using acetone and isopropanol (IPA), ultrasonic bath in IPA then dry using the nitrogen gun. IPA should be the final solvent used as it leaves no residue and quickly evaporates.

3. Prepare the Oxford Plasmalab 100 for deposition. This includes turning on the instrument, cleaning the chamber and setting the table temperature to 400°C.

4. Insert the substrate into the Oxford Plasmalab loadlock chamber on a silicon wafer. Place shards of silicon around the piece to eliminate edge effects. Deposit silica (SiO₂) for 5 minutes at 400°C. Inspect the result to ensure no defects. If the silica is “bad”, the photolithography later will be impossible.

5. Use the clean recipe in the Oxford Plasmalab 100 and follow the shut-down proce-
Appendix A. Detailed fabrication procedure

dure.

6. Cleave individual 1x1 cm samples from the larger piece. Clean each piece with acetone and iso-propanol (IPA).

7. Bake each piece at 100°C for at least 5 minutes.

8. Spin P-20 primer on a sample at 3000 RPM for 45 seconds. Set ACL to 9.

9. Spin S1818 photoresist on the sample at 4000 RPM for 45 seconds. Set ACL to 9. Inspect for defects, bubble streaks or other inconsistencies.

10. Soft-bake the sample at 102-104°C for 4 minutes. Let sample return to room temperature for 1 minute.

11. Prepare the Karl Suss MA-6 mask aligner for use. Insert the chrome-on-glass mask and center the ridge waveguide pattern for exposure.

12. Align the sample edges (assumed to be flat from good cleaving) to the ridge waveguides. This will assure the pattern is along the crystal axes.

13. Expose the photoresist using the soft-contact setting, for 6.5 seconds.

14. Develop the sample in MF-321 developer solution for 45 seconds or till pattern appears developed. Immediately quench the sample into de-ionized (DI) water.

15. Inspect the pattern under the microscope; be sure to filter UV light using the reflection filter on the table. If the sample is under-developed, dip in developer again for 3-5 seconds. If the sample is over-developed, it is left to the user to determine if it needs to be repeated.

16. Repeat for all samples. Clean mask with acetone and IPA every 3-5 exposures as it can get dirty from the contact lithography. Bake the mask at 120°C for at least 15 minutes each time.

18. Hard bake the samples using an increasing temperature profile. Initially bake at 100°C and slowly increase the temperature to 105°C over 10 minutes (or every 2 minutes).

19. Prepare the Trion Phantom etcher by physically cleaning the chamber with IPA. Nitrogen blow gun fry the chamber and run the oxygen clean recipe (titled “CLEAN”) for 5 minutes.

20. Run the silica etch recipe without the sample to prepare the chamber. Settings are: 400 W ICP power, 70 W RIE power, 15 mTorr pressure, 50 sccm CHF$_3$ flowrate, 8 sccm He flowrate and 80 second time (titled Bhavin_sio2_v2).

21. Vent chamber and affix all samples to the black anodized aluminum carrier using Santovac 5 vacuum grease. Clean samples on carrier lightly using nitrogen gun.

22. Place carrier back into chamber and close lid. Evacuate the chamber to vacuum using the manual controls for at least 5 minutes. Run silica etch recipe as mentioned above.

23. Vent chamber and remove samples. Gently clean back of samples to remove Santovac 5 on cleanroom cloth that has IPA on it.

24. Clean chamber using oxygen clean recipe.

25. Inspect sample under the microscope for any new damage or defects.

26. Set up wet-bench for use of 10:1 buffered oxide etchant (BOE). Dip each sample between 15-20 seconds into BOE and quickly quench with DI-water. Be careful of the dangers of BOE / Hydrofluoric acid (HF).
27. Prepare Trion Mini-lock etcher for AlGaAs etching. Open chlorine (Cl\textsubscript{2}) gas cylinder in the service corridor behind the etcher. Turn on both RF power supplies. Reduce the chiller temperature to 5\textdegree C.

28. Place the 8” clear quartz carrier into the chamber. Run both the hydrogen clean and oxygen clean recipes for 15 and 10 minutes respectively (titled “H\textsubscript{2}-O\textsubscript{2} clean”). Both recipes require manual tuning. Keep an eye on the reflected power routinely.

29. Remove quartz carrier and insert the 8” black graphite carrier with 3” quartz plate into the chamber. Be sure to clean it with IPA before hand. Run the oxygen clean recipe for 5 minutes.

30. Prepare the chamber by running the etch recipe for 45 seconds. Settings are 200 W ICP power, 50 W RIE power, 5 mTorr pressure, 8 sccm Ar flowrate, 4.5 sccm Cl\textsubscript{2} flowrate, 5 sccm BCl\textsubscript{3} flowrate.

31. Pre-bake one sample for 5 minutes at 100\textdegree C to remove any surface moisture.

32. Remove the carrier with quartz plate. Affix the sample onto the quartz using Santovac 5 vacuum grease. Clean the sample of any dust using the nitrogen gun.

33. Place the quartz back onto the graphite carrier and return them both to the chamber. Leave the chamber under vacuum for 10 minutes. This is not just to reduce the base pressure but to also give the chamber a chance to cool down.

34. Run the etch recipe in a pulsed mode of 75-90 second etching bursts and leave 150-180 seconds for between successive bursts. This is because the sample can become quite hot with this recipe.

35. Remove the sample and inspect for damage, micro-masking and other features under the microscope.

36. Clean the chamber as before and repeat for all samples.
37. Follow shut-down procedure for Mini-lock etcher. Close chlorine cylinder in back service room.

38. Heat AZ300T photoresist stripper in a petri dish to 80°C. Place the samples in the stripper for 2 minutes. Ultrasonic the samples with the stripper for 2 minutes in ultrasonic. Clean with acetone and IPA.

39. Place the samples in BOE for 3 minutes to remove the SiO$_2$ hard mask. Clean with acetone and IPA.

A.2 Stage 2: Electrical Isolation of ridges and patterning oxide opening

1. Prepare the Oxford Plasmalab 100 for deposition. This includes turning on the instrument, cleaning the chamber and setting the table temperature to 400°C.

2. Insert all samples into the Oxford Plasmalab loadlock chamber on a silicon wafer. Place shards of silicon around the samples to eliminate edge effects. Deposit silica (SiO$_2$) for 3 minutes at 400°C. Inspect the result to ensure no defects. If the silica is “bad”, the photolithography later will be impossible.

3. Use the clean recipe in the Oxford Plasmalab 100 and follow the shut-down procedure.

4. Spin P-20 primer on a sample at 3000 RPM for 45 seconds. Set ACL to 9.

5. Spin S1818 photoresist on the sample at 5000 RPM for 45 seconds. Set ACL to 9. Inspect for defects, bubble streaks or other inconsistencies.

6. Soft-bake the sample at 102-104°C for 4 minutes. Let sample return to room temperature for 1 minute.
7. Prepare the Karl Suss MA-6 mask aligner for use. Insert the chrome-on-glass mask and center the oxide opening pattern for exposure.

8. The ridge waveguides from Stage 1 are about 0.5 mm longer than the oxide opening pattern. This allows for some of the ridges to be seen out of the pattern for alignment. Rotate and align the openings just above the ridge waveguides.

9. Expose the photoresist using the soft-contact setting, for 8 seconds.

10. Develop the sample in MF-321 developer solution for 45 seconds or till pattern appears developed. Immediately quench the sample into de-ionized (DI) water.

11. Inspect the opening under the microscope; be sure to filter UV light using the reflection filter on the table. If the opening is under-developed or closes at points along the ridge, dip in developer again for 5 seconds. If the sample is over-developed, it is left to the user to determine if it needs to be repeated.

12. Repeat for all samples. Clean mask with acetone and IPA every 3-5 exposures as it can get dirty from the contact lithography. Bake the mask at 120°C for at least 15 minutes each time.


14. Prepare the Trion Phantom etcher by physically cleaning the chamber with IPA. Nitrogen blow gun fry the chamber and run the oxygen clean recipe (titled “CLEAN”) for 5 minutes.

15. Run the silica etch recipe without the sample to prepare the chamber. Settings are: 400 W ICP power, 70 W RIE power, 15 mTorr pressure, 50 sccm CHF$_3$ flowrate, 8 sccm He flowrate and 70 second time (titled Bhavin_sio2_v2).

16. Vent chamber and affix all samples to the black anodized aluminum carrier using Santovac 5 vacuum grease. Clean samples on carrier lightly using nitrogen gun.
17. Place carrier back into chamber and close lid. Evacuate the chamber to vacuum using the manual controls for at least 5 minutes. Run silica etch recipe as mentioned above.

18. Vent chamber and remove samples. Gently clean back of samples to remove Santovac 5 on cleanroom cloth that has IPA on it.

19. Clean chamber using oxygen clean recipe.

20. Set up wet-bench for use of buffered oxide etchant (BOE). Dip each sample between 15-20 seconds into BOE and quickly quench with DI-water. Be careful of the dangers of BOE / Hydrofluoric acid (HF).

21. Inspect sample under the microscope for any new damage or defects.

22. Heat AZ300T photoresist stripper in a petri dish to 80°C. Place the samples in the stripper for 2 minutes. Ultrasonic the samples with the stripper for 2 minutes in ultrasonic. Clean with acetone and IPA.

A.3 Stage 3: Contacts deposition, thinning and cleaving

1. Spin P-20 primer on a sample at 3000 RPM for 45 seconds. Set ACL to 9.

2. Spin S1811 photoresist on the sample at 4000 RPM for 45 seconds. Set ACL to 9. Inspect for defects, bubble streaks or other inconsistencies.

3. Soft-bake the sample at 102-104°C for 4 minutes. Let sample return to room temperature for 1 minute.

4. Prepare the Karl Suss MA-6 mask aligner for use. Insert the chrome-on-glass mask and center the contact pattern for exposure.
5. Rotate and align the contact pattern such that the ridge waveguides are in the center of the gap and roughly straight.

6. Expose the photoresist using the soft-contact setting, for 12 seconds.

7. Dip the sample in toluene for 10 minutes. This hardens the surface and creates an undercut useful for lift-off.

8. Remove from the toluene and blow dry with the nitrogen gun.

9. Bake on the hotplate for 1 minute at 100°C. Develop in MF-321 developer for 2 minutes (120 seconds). It takes much longer to develop because of the toluene. Immediately quench the sample into de-ionized (DI) water.

10. Deposit the top p-type contact. Currently, this is done by packaging and shipping the samples to Sherbrooke University in Quebec, Canada. The deposition is of Ti-Au layers, performed at an angle with rotation.

11. Place samples with top contact into petri dish with acetone. Let sit for 5 minutes. Place in ultra-sonic bath till photo-resist peels off completely. Do not put in ultra-sonic bath for greater than 20 seconds as the ridges could be damaged. Remove left-over photoresist with swab.

12. Prepare lapping machine for sample thinning. Clean surface pad and ensure there is 30 μm and 5 μm alumina powder for thinning. Wear two or three layers of nitrile gloves for protection as well as a face mask.

13. Heat sample holder to 110°C and melt mounting wax onto it. Affix samples to holder and turn off hotplate.

14. Periodically flatten samples to holder with tweezers as mounting wax cools. This will ensure flatness. Wait 5 minutes.
15. Set lapping fixture to a setting of 0.16 inches and attach sample holder to fixture with screw. Place some 30 \( \mu m \) alumina powder and water onto the lapping surface, mix till it is a paste. Begin rotation and set voltage to 15 V.

16. Carefully bring fixture to contact with rotating surface. Slowly apply force with your hands and body and be sure to move the fixture slowly allowing for various angles of thinning and to utilize all the alumina paste.

17. Continue for 10 minutes or till sample has reached thickness setting.

18. Clean lapping surface and fixture with water to remove used alumina.

19. Set lapping fixture to a setting of 0.14 inches. Place some 5 \( \mu m \) alumina powder and water onto the lapping surface, mix till it is a paste. Begin rotation and set voltage to 20-25 V.

20. Repeat thinning procedure for another 10 minutes or till sample has reached thickness setting.

21. Clean lapping surface and fixture with water to remove used alumina. Remove sample holder from fixture and place on hotplate. Set hotplate to a setting of 110°C to melt mounting wax.

22. Carefully remove thinning samples. Note their thickness and ease of damage.

23. Clean area and lapping machine. Follow shut-down procedure.

24. Place samples into a petri dish with acetone for 10 minutes. Gently agitate the dish to allow all the mounting wax to dissolve away. Clean with IPA.

25. Deposit the bottom n-type contact. Currently, this is done by packaging and shipping the samples to Sherbrooke University in Quebec, Canada. The deposition is of a stack of Au-Ge-Ni-Au layers. The sample is then annealed at 380-400°C for 1 minute in nitrogen.
26. Cleave the samples by utilizing a two layer plastic sheet. One side should have a mild adhesive to hold the sample. With the sample on the adhesive, carefully mark it with a diamond scribe at the lengths you wish to cleave.

27. Place the second layer atop the first, effectively confining the sample.

28. Place the sample onto a glass slide. Using a microscope, carefully push the sample over the edge of the glass slide. This should cleave at the scribe marked lengths.

29. Carefully remove the cleaved devices. Inspect the facets and measure the device lengths under a high-magnification microscope.

30. Place cleaved devices in a suitable package for transportation such as a gel pack.
Appendix B

Pulsed diode laser characterization setup

At the beginning of my graduate studies, there was no setup to test and characterize diode lasers in the Photonics group. Since my research topic was built heavily upon diode laser research, it was important to build and assemble a suitable testbed. This required many hours of research in the literature, using online sources and scouring manufacturers databases. The setup that was eventually built by myself is extremely reliable and capable of a wide range of diode laser tests. This appendix will go into some detail about the setup itself and its capabilities.

B.1 Diode testing setup

This test setup is capable to testing bare, unpackaged diode laser chips or bars. This could include bonded or unbonded lasers as the mount is flexible to many configurations. A diagram of the setup is shown in Figure B.1. Here, a current source drives the laser via probes controlled by manipulators. Probes are brought into contact using a microscope. This current source is capable of pulsed and DC current sourcing. The same source module can also bias and read the photocurrent of a photodiode placed in the laser
Appendix B. Pulsed diode laser characterization setup

Figure B.1: High-level diagram of the diode-laser test setup

The laser sits atop a copper block that is thermo-electrically cooled (TEC). The TEC is driven by a temperature controller that uses a feedback PID control mechanism through a thermistor inserted within the copper block. A 3-axis stage is next to copper block with axis height within range of the copper block. This way, optics, fibers or detectors can access the laser emission directly and the position can be optimized via the stage controls.

B.1.1 Keithley 2520 Pulsed diode-laser test system

The main piece of equipment in the setup is the Keithley 2520 pulsed diode-laser test system, image shown in Figure B.2(a). This comprises of a control box connected to a test-head, shown in Figure B.2(b) and B.2(c), respectively. The 2520 setup has the capability of sourcing current to the laser in both DC and pulsed modes. In pulsed mode, the 2520 can source pulses as small as 500 ns and as large as 5 ms with delay between 20 µs and 500 ms. The current range is as high as 1 A for DC mode and 5 A for pulsed mode. Internally, the 2520 can perform staircase sweeps of the current, averaging of the data and arbitrary current patterns. The control box receives the setup information
either from the 2520 front screen or via GPIB. The output itself is performed by the testhead which has the four BNC coaxial connectors on it. Two of these connectors are for output, the other two for reading and feedback control. The 2520 uses the read ports to sample the voltage and current at 100 ns intervals. This data can also be directly accessed for diagnostics of the setup for impedance verification. This will be shown in the next section.

The 2520 testhead can also accept two photodiodes via TNC triaxial cable connectors. The triaxial cables are for low-noise measurements. The 2520 can bias the detectors internally up to 20 V and read currents as high as 100 mA. Upon triggering of a pulse, the system internally determines when the pulse has stabilized to within 10% of the setpoint and reads the detected photocurrent at that point. This way, pulse and measurement timing are coupled and pulsed LIVs are simplified.
Appendix B. Pulsed diode laser characterization setup

B.1.2 Laser testblock

The interface between the Keithley 2520 and the laser occurs on a copper stage, custom built for this purpose. This stage is shown in Figure B.3(a) with a closeup in Figure B.3(b). The copper piece was affixed using thermal epoxy upon a 15 mm x 23 mm sealed TEC from Custom Thermoelectric (part # 04711-5L31-03CFJ). The TEC is rated for a maximum of 3 A and 7 V. This setup can maintain over 100°C at the high end, but only 5°C on the low end. This low end value is suitable for most cases since the dew-point of water in the air is above 5°C. Operating under this point runs the risk of shorting and damaging the equipment or laser.

The probes are coaxial until the final few millimeters before the shield is exposed where the tip is 20 μm. This ensures minimal distortion of the pulse shape by the injection hardware itself. The probe holders are SSMC terminated with two connectors on each probe holder. Both the probe holder (part# 74CJ-APT-KS/200) and probes (part#
Appendix B. Pulsed diode laser characterization setup

Figure B.4: Images of the cables connecting the probes to the testhead

73CT-APTA/200) are from American probe. The cables connecting the Keithley 2520 testhead to the probes are shown in Figure B.4(a). They are custom manufactured by Applied Specialties (part# RG178-SSMRA-BNC-3FT) using RG178 high-bandwidth coaxial cable. One end is BNC terminated as shown in Figure B.4(b) and the other is SSMC terminated as shown in Figure B.4(c). Though initially we used the supplied low-impedance cables supplied by Keithley, the connectors were soldered manually by myself and came off repeatedly. Hence, these professionally made cables were made to ensure reliable measurements.

B.1.3 Keithley 2510-AT Temperature controller

The TEC is controlled using the Keithley 2510-AT Autotune temperature controller and a thermistor. The 2510-AT utilizes a PID (Proportional-Integral-Derivative) controller in a feedback loop to provide control down to 0.001°, in most cases. Further, the benefit of the -AT model is the capability of autotuning the control constants. An image of the 2510-AT is shown in Figure B.5(a), and a schematic of the front face in Figure B.5(b). The 2510-AT can source 10 V at up to 5 A to the TEC. For the feedback mechanism, the 2510-AT measures the resistance of a thermistor placed within the side of the copper stage. This hole is visible in Figure B.3(b). The thermistor chosen is a 30 Ω model,
Appendix B. Pulsed diode laser characterization setup

Figure B.5: Keithley 2510 Autotune temperature controller

(b) Diagram of the 2510 control box

(bought from Digikey (part# 235-1015-ND). The autotune procedure of the controller was then used to configure the PID constants for the chosen equipment.

B.1.4 Detection

Several detectors were used and tested in the duration of this thesis. The fastest detector was a 3mm InGaAs PIN photodiode from GPD-IR (part# GAP-3000). However, it required constant alignment due to its small size. Unfortunately, a connection on the back of the TO can fell off and is no longer usable. Another InGaAs PIN photodiode was bought from Judson Teledyne (part# J16-8ND-R05M-HS). This had a ND filter on the TO can allowing high power to be measured. Lastly, a large area Silicon PIN detector was bought from Silicon Sensor (part# 500103). Due to its large area of 50 mm$^2$, this detector was highly used because of the minimal alignment necessary. However, due to its large size, the capacitance was prohibitive to high speed measurement and it is recommended that a bias voltage of -20 V and >5 μs pulses are used.

On occasion, a collimated beam was necessary. For this, a 60× objective lens from Newport (part# M-60X) was used. This lens featured a high numerical aperture and short working distance; a particularly useful feature for the highly divergent beams of
Figure B.6: Labview interface to the diode laser testbed. A sample L-I curve is shown.

Bragg mode lasers. Note the transmission of this lens at 980 nm was found to be only 59%.

### B.1.5 Labview control program

Both the Keithley 2520 and 2510-AT were controlled using Labview through GPIB to make interfacing simple. No usable code for either device was readily available at the time. As such, I made an interfacing program in Labview. An event driven interface was found best as this provided a quick response time and simple block diagram code. The setup can perform sweeps, single current and traces while controlling the temperature of the stage if needed. The measured data can be displayed in multiple formats and saved
Appendix B. Pulsed diode laser characterization setup

Note risetime is 4 data points until it “settles” within 10% of the final (Orange oval). These values are thrown out and not used to report the measurement. The last value (in red) is the only one reported as the voltage for that pulse value.

(a) Voltage trace of a 500 ns pulse (b) Voltage trace of a 1 μs pulse (c) Voltage trace of a 5 μs pulse

Figure B.7: Voltage trace of several pulses. Note the Keithley 2520 samples at 100 ns intervals.

to file. A screen shot of this program is shown in Figure B.6.

B.2 Characterization

B.2.1 Pulsed source verification

Upon building of the setup, it became vital to verify the injection behaviour of the pulsed source. Large impedance mismatches could cause oscillations and distort the actual current shape received by the diode laser. Testing short pulses, i.e. <1 μs, is actually recommended by Keithley. A sample BRL2 laser (refer to Chapter 6) was driven in pulsed current mode and voltage traces were measured. The resulting traces are shown for 500 ns, 1 μs and 5 μs pulses shown in Figures B.7(a), B.7(b) and B.7(c), respectively. The rise time is noticeable in the 500 ns pulse, shown by the tilted ellipse. However, the final result output by the 2520 is shown by the circle. This value is suitable as it is within 10% of the actual value which can be determined from the 1 μs pulse trace. This verifies the setup is capable of sourcing short pulses to the lasers with pulse duration >1 μs. Shorter 500 ns pulses may be suitable, however, it is very close to the edge of capability due to the rise time.
Appendix B. Pulsed diode laser characterization setup

Figure B.8: Photocurrent trace of several pulses. Note the Keithley 2520 samples at 100 ns intervals.

The light detection speed can also be tested in a similar fashion. Using the GPD-IR InGaAs detector and a production grade IBM laser, several pulse durations were again tested. The resulting photocurrent traces for 500 ns, 1 µs and 5 µs pulses shown in Figures B.8(a), B.8(b) and B.8(c), respectively. Here, the photocurrent is shown as circles and voltage as squares. It can be seen that the photocurrent and voltage follow each other reasonably for this laser and there is almost no risetime.

Figure B.9: Calibration of the thermistor and fitting the results to the Steinhart and Hart equation. The fit coefficients are shown. Open squares are measured data and the solid line is the fit.
B.2.2 Thermistor calibration

The 2510-AT utilizes the Steinhart and Hart thermistor model to determine the actual temperature from the resistance, shown in Equation B.1. Here, T is the temperature in Kelvin, R is the resistance in ohms and A, B, C are model coefficients. This thermistor was manually calibrated using an external sensor across a broad range of temperatures. The results were then fit to the Steinhart and Hart equation, as shown in Figure B.9.

\[
\frac{1}{T} = A + B (\ln R) + C (\ln R)^3 \tag{B.1}
\]
Appendix C

Epitaxial designs

C.1 Wafer 1: SH1

Table C.1: SH1 epitaxial structure

<table>
<thead>
<tr>
<th>Layer #</th>
<th>Composition</th>
<th>Thickness (nm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>GaAs (substrate)</td>
<td>-</td>
</tr>
<tr>
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### C.2 Wafer 2: BRL1

Table C.2: BRL1 epitaxial structure

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<td>Grade Al$<em>{0.30}$Ga$</em>{0.70}$As to GaAs</td>
<td>25</td>
<td>1.0$\times$10$^{18}$</td>
<td>p (C)</td>
</tr>
<tr>
<td>69</td>
<td>GaAs</td>
<td>154.4</td>
<td>1.0$\times$10$^{18}$</td>
<td>p (C)</td>
</tr>
</tbody>
</table>
### Appendix C. Epitaxial designs

C.3 Wafer 3: BRL2

Table C.3: BRL2 epitaxial structure

<table>
<thead>
<tr>
<th>Layer #</th>
<th>Composition</th>
<th>Thickness (nm)</th>
<th>Doping (cm(^{-3}))</th>
<th>Doping type</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>2°-off GaAs (substrate)</td>
<td>-</td>
<td>-</td>
<td>n+ (Si)</td>
</tr>
<tr>
<td>1</td>
<td>GaAs</td>
<td>100</td>
<td>4x10(^{18})</td>
<td>n+</td>
</tr>
<tr>
<td>2</td>
<td>Al(<em>{0.30})Ga(</em>{0.70})As</td>
<td>249.7</td>
<td>1.2x10(^{18})</td>
<td>n (Si)</td>
</tr>
<tr>
<td>3</td>
<td>Grade Al(<em>{0.30})Ga(</em>{0.70})As to GaAs</td>
<td>25</td>
<td>1.2x10(^{18})</td>
<td>n (Si)</td>
</tr>
<tr>
<td>4</td>
<td>GaAs</td>
<td>148.4</td>
<td>1.2x10(^{18})</td>
<td>n (Si)</td>
</tr>
<tr>
<td>5</td>
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<td>25</td>
<td>1.2x10(^{18})</td>
<td>n (Si)</td>
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<tr>
<td>6</td>
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<td>1.2x10(^{18})</td>
<td>n (Si)</td>
</tr>
<tr>
<td>7</td>
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<td>1.2x10(^{18})</td>
<td>n (Si)</td>
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<tr>
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</tr>
<tr>
<td>9</td>
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<td>n (Si)</td>
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<td>n (Si)</td>
</tr>
<tr>
<td>11</td>
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<td>25</td>
<td>1.2x10(^{18})</td>
<td>n (Si)</td>
</tr>
<tr>
<td>12</td>
<td>GaAs</td>
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<td>1.2x10(^{18})</td>
<td>n (Si)</td>
</tr>
<tr>
<td>13</td>
<td>Grade GaAs to Al(<em>{0.30})Ga(</em>{0.70})As</td>
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<td>1.2x10(^{18})</td>
<td>n (Si)</td>
</tr>
<tr>
<td>14</td>
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<td>1.2x10(^{18})</td>
<td>n (Si)</td>
</tr>
<tr>
<td>15</td>
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<td>1.2x10(^{18})</td>
<td>n (Si)</td>
</tr>
<tr>
<td></td>
<td>Material</td>
<td>Composition</td>
<td>Carrier Density</td>
<td>Layer Type</td>
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<td>$1.2 \times 10^{18}$</td>
<td>n (Si)</td>
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<tr>
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</tr>
<tr>
<td>18</td>
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</tr>
<tr>
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<td>$1.2 \times 10^{18}$</td>
<td>n (Si)</td>
</tr>
<tr>
<td>21</td>
<td>Grade GaAs to Al$<em>{0.30}$Ga$</em>{0.70}$As</td>
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<td>n (Si)</td>
</tr>
<tr>
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<td>Al$<em>{0.30}$Ga$</em>{0.70}$As</td>
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<td>n (Si)</td>
</tr>
<tr>
<td>23</td>
<td>Grade Al$<em>{0.30}$Ga$</em>{0.70}$As to GaAs</td>
<td>25</td>
<td>$1.2 \times 10^{18}$</td>
<td>n (Si)</td>
</tr>
<tr>
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<td>$1.2 \times 10^{18}$</td>
<td>n (Si)</td>
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<tr>
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<td>Grade GaAs to Al$<em>{0.30}$Ga$</em>{0.70}$As</td>
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<td>n (Si)</td>
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<tr>
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<tr>
<td>27</td>
<td>Grade Al$<em>{0.30}$Ga$</em>{0.70}$As to GaAs</td>
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<td>n (Si)</td>
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<tr>
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<tr>
<td>29</td>
<td>Grade GaAs to Al$<em>{0.30}$Ga$</em>{0.70}$As</td>
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<tr>
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<tr>
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<td>Comments</td>
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<td>$1.2 \times 10^{17}$</td>
<td>n (Si)</td>
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<td>47</td>
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<td>6</td>
<td>-</td>
<td>undoped</td>
</tr>
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<td>48</td>
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<td>-</td>
<td>undoped</td>
</tr>
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<td>49</td>
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<td>p (C)</td>
</tr>
<tr>
<td>52</td>
<td>GaAs</td>
<td>148.4</td>
<td>$5.0 \times 10^{17}$</td>
<td>p (C)</td>
</tr>
<tr>
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<td>$5.0 \times 10^{17}$</td>
<td>p (C)</td>
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<td>p (C)</td>
</tr>
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<td>p (C)</td>
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<td>$1.0 \times 10^{18}$</td>
<td>p (C)</td>
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<td>p (C)</td>
</tr>
<tr>
<td>58</td>
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<td>p (C)</td>
</tr>
<tr>
<td>59</td>
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<td>$1.0 \times 10^{18}$</td>
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<td>$1.0 \times 10^{18}$</td>
<td>p (C)</td>
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<tr>
<td>62</td>
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<td>p (C)</td>
</tr>
<tr>
<td>63</td>
<td>Grade $\text{Al}<em>{0.30}\text{Ga}</em>{0.70}\text{As}$ to GaAs</td>
<td>25</td>
<td>$1.0 \times 10^{18}$</td>
<td>p (C)</td>
</tr>
<tr>
<td>64</td>
<td>GaAs</td>
<td>148.4</td>
<td>$1.0 \times 10^{18}$</td>
<td>p (C)</td>
</tr>
<tr>
<td>65</td>
<td>Grade GaAs to $\text{Al}<em>{0.30}\text{Ga}</em>{0.70}\text{As}$</td>
<td>25</td>
<td>$1.0 \times 10^{18}$</td>
<td>p (C)</td>
</tr>
<tr>
<td>66</td>
<td>$\text{Al}<em>{0.30}\text{Ga}</em>{0.70}\text{As}$</td>
<td>249.7</td>
<td>$1.0 \times 10^{18}$</td>
<td>p (C)</td>
</tr>
<tr>
<td>67</td>
<td>Grade $\text{Al}<em>{0.30}\text{Ga}</em>{0.70}\text{As}$ to GaAs</td>
<td>25</td>
<td>$1.0 \times 10^{18}$</td>
<td>p (C)</td>
</tr>
</tbody>
</table>
### Appendix C. Epitaxial designs

#### C.4 Wafer 4: BRL3

Table C.4: BRL3 epitaxial structure

<table>
<thead>
<tr>
<th>Layer #</th>
<th>Composition</th>
<th>Thickness (nm)</th>
<th>Doping ($cm^{-3}$)</th>
<th>Doping type</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>2°-off GaAs (substrate)</td>
<td>-</td>
<td>-</td>
<td>n+</td>
</tr>
<tr>
<td>1</td>
<td>GaAs</td>
<td>200</td>
<td>4.0x10^{18}</td>
<td>n+ (Si)</td>
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<tr>
<td>2</td>
<td>Grade GaAs to Al$<em>{0.52}$Ga$</em>{0.48}$As</td>
<td>25</td>
<td>4.0x10^{18}</td>
<td>n+ (Si)</td>
</tr>
<tr>
<td>3</td>
<td>Al$<em>{0.52}$Ga$</em>{0.48}$As</td>
<td>569.2</td>
<td>1.2x10^{18}</td>
<td>n (Si)</td>
</tr>
<tr>
<td>4</td>
<td>Grade Al$<em>{0.52}$Ga$</em>{0.48}$As to Al$<em>{0.30}$Ga$</em>{0.70}$As</td>
<td>25</td>
<td>1.2x10^{18}</td>
<td>n (Si)</td>
</tr>
<tr>
<td>5</td>
<td>Al$<em>{0.30}$Ga$</em>{0.70}$As</td>
<td>221.1</td>
<td>1.2x10^{18}</td>
<td>n (Si)</td>
</tr>
<tr>
<td>6</td>
<td>Grade Al$<em>{0.30}$Ga$</em>{0.70}$As to Al$<em>{0.52}$Ga$</em>{0.48}$As</td>
<td>25</td>
<td>1.2x10^{18}</td>
<td>n (Si)</td>
</tr>
<tr>
<td>7</td>
<td>Al$<em>{0.52}$Ga$</em>{0.48}$As</td>
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<td>1.2x10^{18}</td>
<td>n (Si)</td>
</tr>
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<td>8</td>
<td>Grade Al$<em>{0.52}$Ga$</em>{0.48}$As to Al$<em>{0.30}$Ga$</em>{0.70}$As</td>
<td>25</td>
<td>1.2x10^{18}</td>
<td>n (Si)</td>
</tr>
<tr>
<td>9</td>
<td>Al$<em>{0.30}$Ga$</em>{0.70}$As</td>
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<td>1.2x10^{18}</td>
<td>n (Si)</td>
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<td>Grade Al$<em>{0.30}$Ga$</em>{0.70}$As to Al$<em>{0.52}$Ga$</em>{0.48}$As</td>
<td>25</td>
<td>1.2x10^{18}</td>
<td>n (Si)</td>
</tr>
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<td>Material</td>
<td>Composition</td>
<td>Energy (eV)</td>
<td>Charge (cm⁻³)</td>
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<td>1.2x10⁻¹⁸</td>
<td>n (Si)</td>
</tr>
<tr>
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<td>Grade Al₀.₅₂Ga₀.₄₈As to Al₀.₃₀Ga₀.₇₀As</td>
<td>25</td>
<td>1.2x10⁻¹⁸</td>
<td>n (Si)</td>
</tr>
<tr>
<td>13</td>
<td>Al₀.₃₀Ga₀.₇₀As</td>
<td>221.1</td>
<td>1.2x10⁻¹⁸</td>
<td>n (Si)</td>
</tr>
<tr>
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<td>Grade Al₀.₃₀Ga₀.₇₀As to Al₀.₅₂Ga₀.₄₈As</td>
<td>25</td>
<td>1.2x10⁻¹⁷</td>
<td>n (Si)</td>
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<tr>
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<td>Al₀.₅₂Ga₀.₄₈As</td>
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<td>1.2x10⁻¹⁷</td>
<td>n (Si)</td>
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<td>1.2x10⁻¹⁷</td>
<td>n (Si)</td>
</tr>
<tr>
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<td>Al₀.₃₀Ga₀.₇₀As</td>
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<td>1.2x10⁻¹⁷</td>
<td>n (Si)</td>
</tr>
<tr>
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<td>Grade Al₀.₃₀Ga₀.₇₀As to Al₀.₅₂Ga₀.₄₈As</td>
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<td>1.2x10⁻¹⁷</td>
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<td>1.2x10⁻¹⁷</td>
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### C.5 Wafer 5: BRL4

**Table C.5: BRL4 epitaxial structure**

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<td>Thickness (Å)</td>
<td>Carrier Concentration (cm⁻³)</td>
<td>Type</td>
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Appendix D

Publications and conference contributions

D.1 Peer-reviewed journal publications


(5.) A. S. Helmy, P. Abolghasem, J. S. Aitchison, B. J. Bijlani, J. Han, B. M. Holmes, D. C. Hutchings, U. Younis and S. J. Wagner, “Recent Advances in Phase-Matching


(8.) P. Abolghasem, J. Han, **B. J. Bijlani** and A. S. Helmy, “Type-0 second order nonlinear interaction in monolithic waveguides of isotropic semiconductors,” Opt. Express, vol. 18, 12681 (2010).


Appendix D. Publications and conference contributions


D.2 Peer-reviewed conference contributions

* indicates the presentation was given by me


Bibliography


[38] S. J. Ullal, A. R. Godfrey, E. Edelberg, L. Braly, V. Vahedi, and E. S. Aydil, “Effect of chamber wall conditions on Cl and Cl$_2$ concentrations in an inductively coupled


[63] G. Aers, geof.aers@nrc-cnrc.gc.ca.


