Integrated Wavelength Stabilization Of Broad Area Semiconductor Lasers Using A Dual Grating Reflector

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INTEGRATED WAVELENGTH STABILIZATION OF BROAD AREA SEMICONDUCTOR LASERS USING A DUAL GRATING REFLECTOR

by

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ABSTRACT

A new fully integrated wavelength stabilization scheme based on grating-coupled surface-emitting lasers is explored. This wavelength stabilization scheme relies on two gratings. The first grating is fabricated on the p-side of the semiconductor laser in close proximity to the laser waveguide such that it couples light out of the guided mode of the waveguide into a propagating mode in the substrate; this grating is known as the grating coupler. The second grating is fabricated on the n-side of the substrate such that for the stabilization wavelength, this second grating operates in the Littrow condition and is known as the feedback grating. Furthermore with the proper design of the two gratings, the feedback grating will operate under total internal reflection conditions allowing a near unity retro-reflection of the light of the stabilization wavelength. The grating coupler and feedback grating together comprise a dual grating reflector (DGR).

The DGR wavelength stabilization scheme is investigated both theoretically by means of numerical modeling and experimentally by integration of a DGR as a wavelength selective reflector into a single quantum well semiconductor laser with a gain peak centered at 975nm. Numerical modeling predicts a peak reflection of approximately 70% including losses and a spectral width of 0.3nm. The integration of a DGR into a semiconductor laser proved both the efficacy of the scheme and also allowed us to experimentally determine the effective reflectivity to be on the order of 62%; the spectral width of light output from these devices is typically on the order of 0.2nm. Furthermore, these devices had light-current characteristic slopes greater than 0.84W/A operating under continuous wave conditions. The DGR was then modified to provide a reflection with two spectral peaks. A semiconductor device incorporating this dual wavelength
DGR was fabricated and tested. These devices showed a peak optical power of in excess of 5.5W and a light-current characteristic slope of 0.86W/A in quasi continuous wave operation; these devices also exhibit a large operating current range in which both wavelengths have comparable output powers. Another modified DGR design was investigated for the purpose of providing an even narrower spectral reflection. Devices incorporating this modified design provided an output with a spectral width as narrow as 0.06nm. DGRs were also integrated into an extremely broad area device of an unorthodox geometry; square devices that lase in two orthogonal directions were fabricated and tested. The last idea investigated was combining a DGR wavelength stabilized laser with a tapered semiconductor optical amplifier into a master oscillator power amplifier device, with the optical coupling between the two components provided by identical grating couplers disposed on the p-side surfaces of each of the devices. These master oscillator power amplifiers provide a peak power of 32W when operating under quasi continuous wave operation.
To my parents Jack and Ronda for their encouragement throughout my life and to my wife Andie for her love and support through this endeavor
ACKNOWLEDGMENTS

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<th>Abbreviation</th>
<th>Definition</th>
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<tr>
<td>ASE</td>
<td>Amplified Spontaneous Emission</td>
</tr>
<tr>
<td>AR</td>
<td>Antireflection</td>
</tr>
<tr>
<td>BOE</td>
<td>Buffered Oxide Etchant</td>
</tr>
<tr>
<td>CCD</td>
<td>Charge-Coupled Device</td>
</tr>
<tr>
<td>CW</td>
<td>Continuous Wave</td>
</tr>
<tr>
<td>DI</td>
<td>Deionized</td>
</tr>
<tr>
<td>DE</td>
<td>Diffraction Efficiency</td>
</tr>
<tr>
<td>DBR</td>
<td>Distributed Bragg Reflector</td>
</tr>
<tr>
<td>DFB</td>
<td>Distributed Feedback</td>
</tr>
<tr>
<td>DH</td>
<td>Double Heterostructure</td>
</tr>
<tr>
<td>DGR</td>
<td>Dual Grating Reflector</td>
</tr>
<tr>
<td>DWDGR</td>
<td>Dual Wavelength Dual Grating Reflector</td>
</tr>
<tr>
<td>FP</td>
<td>Fabry-Perot</td>
</tr>
<tr>
<td>FDTD</td>
<td>Finite-Difference Time Domain</td>
</tr>
<tr>
<td>FWHM</td>
<td>Full Width Half Maximum</td>
</tr>
<tr>
<td>GCSOA</td>
<td>Grating-Coupled Semiconductor Optical Amplifier</td>
</tr>
<tr>
<td>GCSEL</td>
<td>Grating-Coupled Surface-Emitting Laser</td>
</tr>
<tr>
<td>GRO</td>
<td>Grating Ring Oscillator</td>
</tr>
<tr>
<td>ICP-RIE</td>
<td>Inductively Coupled Plasma Reactive Ion Etcher</td>
</tr>
<tr>
<td>MO</td>
<td>Master Oscillator</td>
</tr>
<tr>
<td>MOPA</td>
<td>Master Oscillator Power Amplifier</td>
</tr>
<tr>
<td>MOL</td>
<td>Method of Lines</td>
</tr>
<tr>
<td>MQW</td>
<td>Multiple Quantum Well</td>
</tr>
<tr>
<td>OSA</td>
<td>Optical Spectrum Analyzer</td>
</tr>
<tr>
<td>PA</td>
<td>Power Amplifier</td>
</tr>
<tr>
<td>PML</td>
<td>Perfectly Matched Layer</td>
</tr>
<tr>
<td>QCW</td>
<td>Quasi Continuous Wave</td>
</tr>
<tr>
<td>RTA</td>
<td>Rapid Thermal Annealer</td>
</tr>
<tr>
<td>RCWA</td>
<td>Rigorous Coupled Wave Analysis</td>
</tr>
<tr>
<td>RMS</td>
<td>Root Means Squared</td>
</tr>
<tr>
<td>QD</td>
<td>Quantum Dot</td>
</tr>
<tr>
<td>SCH</td>
<td>Separate Confinement Heterostructure</td>
</tr>
<tr>
<td>SQW</td>
<td>Single Quantum Well</td>
</tr>
<tr>
<td>SQW-GRINSCH</td>
<td>Single Quantum Well Grating Refractive Index Separate Confinement Heterostructure</td>
</tr>
<tr>
<td>TEC</td>
<td>Thermo-Electric Cooler</td>
</tr>
<tr>
<td>TIR</td>
<td>Total Internal Reflection</td>
</tr>
<tr>
<td>TE</td>
<td>Transverse Electric</td>
</tr>
<tr>
<td>VCSEL</td>
<td>Vertical-Cavity Surface-Emitting Laser</td>
</tr>
</tbody>
</table>
CHAPTER 1 : INTRODUCTION

Semiconductor lasers have become a very important component of modern technology since their invention in the early 1960’s. Semiconductor lasers are crucial components of long-haul optical communications networks, barcode scanners, CD and DVD players, and metrology equipment; furthermore, semiconductor lasers have become the desired method of optically pumping most solid state lasers for high power applications. As the technology develops, semiconductor lasers have the potential to take the place of solid state lasers for many applications rather than just being a pump source.

The reason that semiconductor lasers are so attractive for high power applications is their high conversion efficiency; recent research has pushed this number beyond 70% [Kanskar, 2005]. This high efficiency means less wasted power and fewer heat management issues. The high efficiency of semiconductor lasers stems from the ability to pump them electrically.

1.1. Semiconductor Lasers

The basic features and principles of semiconductor lasers will be presented in order to explain the mechanisms behind electrically pumped semiconductor lasers, along with a phenomenological analysis of the light-current characteristics of a semiconductor laser. Then, the different emission configuration used to extract optical power from semiconductor lasers will be presented. Lastly, some of the different ways of stabilizing the wavelength of broad area semiconductor lasers will be covered, including the basic concept of a dual grating reflector.
1.1.1. Basic Principles

Typically, the fabrication of a semiconductor laser begins with a substrate of semiconductor material on which the epitaxially material that comprises the laser is grown. The epitaxial layers that make up the laser are currently grown by metal organic chemical vapor deposition, metal organic vapor phase epitaxy, or molecular beam epitaxy. The components of the epitaxial layers are typically compounds of elements of column III, such as gallium and indium, and column V, such as phosphorus and arsenic, of the periodic table; thus, these types of semiconductor materials are called III-V materials. Recently, lasers made with II-VI materials have gained interest due to the fact that these materials have higher bandgap energies and are capable of lasing in the blue.

The basic semiconductor laser manufactured today consists of higher energy bandgap material surrounding a lower energy bandgap material. The substrate is typically a heavily n-doped material; this type of material is loaded with donor atoms that readily give up electrons. On top of the substrate, n-doped material layers are typically grown that have higher energy bandgaps, followed by undoped or intrinsic layers with a lower energy bandgap, and then p-doped material layers with a higher energy bandgap are grown last. P-doped material is loaded with acceptor atoms that readily accept electrons or have holes. The structure of p-doped material, intrinsic material, and n-doped material, as shown in Figure 1.1, comprises a p-i-n diode. The intrinsic layers can be a single material as in a double heterstructure (DH) laser, or the intrinsic layers can be several materials comprising a separate confinement heterostructure (SCH) and a gain material with a lower bandgap energy than the SCH. In this case, the gain material can be a single quantum well (SQW) layer, multiple quantum well (MQW) layers, or
quantum dot (QD) layers. In both the case of the DH and the SCH, the structures created serve to optically confine the light created by the active layer or layers.

Figure 1.1: Schematic of epitaxially grown p-i-n diode material.

As voltage is applied to the p-i-n diode, with the positive terminal connected to the p-doped material and ground terminal connected to the n-doped material, electrons and holes start to flow into the intrinsic region. Due to the lower energy bandgap of the active material, the electrons get trapped in the conduction band and the holes get trapped in the valence band as depicted in Figure 1.2. With the electrons and holes present in the active region, each electron-hole pair may recombine radiatively to emit a photon having the bandgap energy. When this phenomenon occurs randomly, it is known as spontaneous emission. When a radiative event is incited by another photon, this is known as stimulated emission. When stimulated emission occurs the second photon created has the same frequency, direction, phase, and polarization as the first photon.
Lasers always consist of a gain material and a resonator, and this is no different with semiconductor lasers. The simplest resonator for a laser diode is the Fabry-Perot (FP) resonator as shown in Figure 1.3 (a). This resonator is formed by cleaving the semiconductor along one of the crystals planes to produce an extremely flat surface, and due to the large index contrast of semiconductor material and air, the reflection from this partially reflecting mirror is approximately 30%. Beyond the FP resonator, the resonator may be created by the integration of gratings operating in the Bragg condition in place of the cleaved facets as shown in Figure 1.3 (b); this type of device is known as distributed Bragg reflector (DBR) laser. In another configuration, a Bragg grating may be placed along the entire gain length of the device as shown in Figure 1.3 (c); this type of device is known as a distributed feedback (DFB) laser. Still yet,
cleaved facets may be coated with an antireflection coating and optical elements can be used to create an external resonator for the semiconductor laser.

Regardless of the resonator configuration used, as in any laser, the losses in the resonator cavity must be overcome before lasing begins. As the injection of carriers is increased, i.e. as the applied current is increased, some electron-hole pairs will nonradiatively recombine and some will radiatively recombine. Those electron-hole pairs that spontaneously radiatively recombine will produce photons that will be emitted in all directions. Photons emitted within a specific angle along the laser waveguide will be guided to one of the reflectors of the resonator. Depending on the reflectivity of the reflector, a given percentage of those photons will be redirected back into the laser cavity. Along the way, some of these photons will be absorbed, creating more electron-hole pairs and some will continue to the other reflector of the cavity,
possibly causing stimulated emission during their trip. At the injection current where the number
of photons at the beginning of a round trip equals to the number of photons at the end of the
round trip, lasing begins to occur; at this point, the gain in the cavity is equal to the losses. The
correct terminology for this injection current level is the threshold current. These phenomena are
expressed quantitatively in the next subsection.

The operational uses for semiconductor lasers can basically be broken down into two
regimes. The first being low power applications; this regime entails lasers that typically have
single transverse modes and output powers on the order of a few milliwatts. The single
transverse mode characteristic is obtained by making the active width of the laser relatively
narrow, i.e. on the order of a few microns; this small width results in a small gain volume and
hence, a small maximum output power. Theses lasers are used in fiber optic communications
networks, CD and DVD players, etc. These lasers more commonly are of the DBR or DFB
variety to provide a narrow spectral width; the feedback provided by the gratings force the laser
to operate in a single longitudinal mode. The second regime of operation is for high power
applications, such as pumping of solid state lasers and fiber lasers. High power diode lasers
generally support only a single mode along the direction of the layer growth, but are typically
broad area devices. Thus, the devices support many transverse modes in the lateral direction,
along with many longitudinal modes. Due to the large gain volume, high output powers are
possible. These high output powers are difficult to achieve to due filamentation of the gain
media. Filamentation occurs due to lateral inhomogeneities; inhomogeneities cause a slight
change in the carrier distribution, which leads to a change in the refractive index. This index
change causes spatial hole burning and temperature variations, which induces self-focusing.
This self-focusing creates a filament. Filamentation doesn’t occur at low powers and generally requires an injection current several times the threshold current. In high power diode lasers, the output beam quality also has a tendency to be rather poor, due to the high number of transverse modes and filamentation problems at higher powers. The content of this work focuses on broad area high power semiconductor lasers.

1.1.2. Light-Current Characteristics

The phenomenological analysis of the power-current characteristics presented in the following sections is based on the ideas presented by Coldren and Corzine. Basic power-current characteristics of a semiconductor laser depend on a great many things, such as the quality of the epitaxial material, the quality of the contacts fabricated, and the quality of the resonator. If we consider the optical power-current relationship for a semiconductor laser phenomenologically, we can discern the basic characteristics. We start by looking at the carriers injected into the p-i-n diode in terms of the current applied and the losses associated with injecting this current. We can view the current as a stream of carriers that we are pouring into a bucket; this bucket represents the active area of our semiconductor laser. The first loss we encounter is the carriers that do not make it into the bucket; this is known as the current leakage, as depicted in Figure 1.4. The ratio of the number carriers that actually enter the active region to the number of carriers injected into a device is known as the internal quantum efficiency or $\eta_i$. Thus, the rate at which carriers enter into or are generated in the active region is given by

$$C_{gen} = \frac{\eta_i I}{qV}$$  \hspace{1cm} (1.1)
where $I$ is the operating current, $q$ is the charge of the electron, and $V$ is the volume of the active region.

Beyond the loss associated with carriers missing the bucket, our bucket also has several holes; these holes represent the carrier leakage, $R_l$, spontaneous radiative recombination, $R_{sp}$, and nonradiative recombination, $R_{nt}$. Carrier leakage results from lack of potential barriers near the edges of the injection region. Without sufficient potential barriers, carriers near the edges will diffuse into unpumped regions and recombine. Spontaneous radiative recombination occurs when electrons and holes spontaneously recombine in the active region emitting light with random phase and random direction. Nonradiative recombination occurs when electrons and
holes recombine without emitting light radiation, but instead the energy is dissipated as heat in the crystal lattice.

As with a real bucket with holes, as the bucket fills with water and pressure builds, the streams of water flow at a faster rate, so do the streams of carriers in our carrier bucket. The rate at which carriers are lost to carrier leakage, spontaneous radiative recombination, and nonradiative recombination increases with the number of carriers as given by

$$R_i + R_{nr} = AN + CN^3, \quad R_{sp} = BN^2,$$  \hspace{1cm} (1.2)

where $A$, $B$, and $C$ are constants and $N$ is the carrier density per unit volume. The constant $A$ is known as nonradiative recombination coefficient attributed to nonradiative recombination caused by growth defects. The constant $B$ is known as the bimolecular recombination coefficient associated with spontaneous emission recombination. The constant $C$ is known as Auger recombination coefficient; Auger recombination occurs when two electrons collide, knocking one electron into the valence band and the other into a higher energy state in the conduction band. The higher energy electron then thermalizes back down to the bottom of the conduction band. The recombination rates or losses are also commonly represented in a more compact form as given by

$$\frac{N}{\tau(N)} = (A + BN + CN^2)N,$$  \hspace{1cm} (1.3)

where $\tau$ is the carrier lifetime and is a function of the carrier density.

Once our bucket is filled at a high enough rate, such that carriers fill the bucket faster than the losses take carriers away, excess carriers can recombine with the assistance of a photon to create stimulated emission; the density of carriers required to fill the bucket such that stimulated emission can occur is known as the threshold carrier density. Thus, we have another
means in which the carriers can recombine, and the rate at which this occurs is known as the stimulated emission recombination rate or $R_{str}$. This rate also depends on the density of carriers in the active region, and in addition, this rate depends on the intensity of the optical field in the active region as well. The stimulated emission recombination rate has the form

$$R_{str} = g(N) \frac{I_{op}}{\hbar \nu} = g_0 \ln \left( \frac{N + N_s}{N_p + N_s} \right) \frac{I_{op}}{\hbar \nu},$$

(1.4)

where $g_0$ is the gain coefficient, $N_s$ is the carrier density offset, $N_p$ is the transparency carrier density, and $I_{op}$ is the intensity of the optical field. In Equation (1.4), the gain has been approximated by a logarithmic function, which is a good fit for DH, SQW, and MQW lasers. Also, the gain in this equation can also be presented in terms of the current density, $J$, as

$$g(J) = g_1 \ln \left( \frac{J + J_s}{J_p + J_s} \right).$$

(1.5)

The optical field intensity may also be represented in terms of the photon density by

$$I_{op} = v_g \hbar \nu N_p,$$

(1.6)

where $v_g$ is the group velocity, $\hbar$ is Planck’s constant, $\nu$ is the frequency of the optical field or photons, and $N_p$ is the photon density.

### 1.1.2.1. Threshold Current

Threshold of the laser occurs when the loss of photons is equal to the number of photons generated in a given optical mode of the laser waveguide. This means that the electric field must replicate itself in one round trip of the cavity. Letting the electric field at the beginning of the active region be given by
\[ E(x, y, z) = E_0 U(x, y) \exp(i \omega t - i \tilde{\beta} z) \hat{y}, \]  

(1.7)

where \( E_0 \) is the peak amplitude, \( U(x, y) \) is the function describing the spatial distribution, and \( \tilde{\beta} \) is the complex propagation constant that includes gain and loss in a given section.

This complex propagation constant can be expressed as

\[ \tilde{\beta} = \beta + \frac{i}{2} (g - \alpha), \]  

(1.8)

where \( \beta \) is the real part of the complex propagation constant, \( g \) is the modal gain, and \( \alpha \) is the internal losses. Provided we have a cavity like that shown in Figure 1.5, the threshold condition requires that the total losses equal the total gain as expressed by

\[ r_1 r_2 \exp(-i2\tilde{\beta}_p L_1) \exp(-i2\tilde{\beta}_a L_2) \exp(-i2\tilde{\beta}_a L_1) = 1, \]  

(1.9)

where \( r_i \) is the field reflection from the \( i^{th} \) mirror and the subscripts \( a \) and \( p \) denote active and passive. Considering the magnitude of this equation only,

\[ \sqrt{R_1 R_2} \exp(-\alpha_p L_1) \exp(\Gamma g_a L_2 - \alpha_a L_2) \exp(-\alpha_p L_3) = 1, \]  

(1.10)
where $\Gamma$ is the field intensity overlap with the active layer, also known as the confinement factor, $g_{th}$ is the threshold gain, and $R_i$ is the power reflection from the $i^{th}$ facet. Rearranging and solving, the required threshold gain is given by

$$g_{th} = \frac{1}{\Gamma L_2} \left[ \alpha_p (L_1 + L_3) + \alpha_a L_2 + \ln \left( \frac{1}{\sqrt{R_1 R_2}} \right) \right]. \quad (1.11)$$

It is also possible to incorporate the losses associated with the passive regions into the mirrors by assuming an effective reflectivity rather than the lossless mirrors given in Equation (1.11). The threshold gain will be the same, but this equation will be given by

$$g_{th} = \frac{1}{\Gamma} \left[ \alpha_s + \frac{1}{L_2} \ln \left( \frac{1}{\sqrt{R_{eff} R_{eff}}} \right) \right] = \frac{1}{\Gamma} (\alpha_s + \alpha_m), \quad (1.12)$$

where $\alpha_m$ denotes the mirror losses. Combining with Equation (1.5) and (1.12), the required threshold current density for a device is given by

$$J_{th} = \left[ \exp \left( \frac{g_{th}}{g_s} \right) (J_v + J_s) - J_s \right]. \quad (1.13)$$

### 1.1.2.2. Light-Current Characteristic Slope

As the current is increased above threshold, the steady-state losses and steady-state carrier density are clamped. Referring back to our bucket, the pressure forcing the carriers out of the loss holes cannot increase further as the excess carriers spill over the top of the bucket and are used to create more stimulated emission. As the carrier density is clamped, then so must be the gain, since these two are directly related. Considering our device is operating in steady state,
considering the carrier injected in the active region and all loss mechanisms we have the equation

\[ \eta \frac{I}{qV} - \frac{N}{\tau(N)} - g(N) \frac{I_{op}}{h \nu} = 0. \]  \hspace{1cm} (1.14)

As previously stated, the recombination losses at threshold are clamped; thus the second term in Equation (1.14) can be written as

\[ \frac{N_{tr}}{\tau(N_{tr})} = \eta \frac{I_{th}}{qV}. \] \hspace{1cm} (1.15)

Combining Equations (1.6), (1.14), and (1.15), the photon density can be solved to be

\[ N_p = \frac{\eta (I - I_{th})}{v_g q V g_{th}}. \] \hspace{1cm} (1.16)

With the photon density, the total optical energy in the cavity can be calculated as

\[ E_{cav} = h \nu N_p V_p, \] \hspace{1cm} (1.17)

where \( V_p \) is the volume in which the photons are guided in the optical waveguide; furthermore, the energy loss rate through the mirrors is given by \( v_g \alpha_m \). Combining this energy loss rate and Equations (1.16) and (1.17), the optical power exiting the device is given by

\[ P_0 = \frac{\eta \alpha_m (I - I_{th}) V_p h \nu}{q V g_{th}}. \] \hspace{1cm} (1.18)

Knowing that \( \Gamma = V / V_p \), and using Equation (1.11), Equation (1.18) can be rewritten as

\[ P_0 = \eta \left( \frac{\alpha_m}{\alpha_s + \alpha_m} \right) \frac{h \nu}{q} (I - I_{th}). \] \hspace{1cm} (1.19)

Differentiating Equation (1.19) with respect to current, the light current characteristic slope is given by
A common parameter used in specifying the performance of a diode laser, which is related to the light current characteristic slope, is the differential quantum efficiency, and it is defined as

\[
\eta_d = \frac{q}{h\nu} \frac{dP_n}{dI} = \eta_i \left( \frac{\alpha}{\alpha_a + \alpha_m} \right).
\]  

Equation (1.21) gives the differential quantum efficiency for the device through both mirrors. To obtain the differential quantum efficiency for the device output from a single mirror, we must look at the output powers from each facet. Given the laser depicted in Figure 1.6, the power out of mirror 1 will be given by

\[
P_1 = (1 - R_{1\text{eff}})P,
\]

where \(P\) is the power incident from the inside on mirror 1. The power reflected back into the cavity will be amplified through the length of the active region, and the output through mirror 2 will be given by

\[
P_2 = (1 - R_{2\text{eff}}) \exp(L_2(\Gamma g_{\text{th}} - \alpha_a)) R_{1\text{eff}} P.
\]

Substituting Equation (1.12) into Equation (1.23), and taking the ratios of the powers through mirror 1 and mirror 2, the following power ratio is obtained

\[
K = \frac{P_1}{P_2} = \frac{(1 - R_{1\text{eff}})}{(1 - R_{2\text{eff}})} \sqrt{\frac{R_{2\text{eff}}}{R_{1\text{eff}}}}.
\]

The power ratio given in Equation (1.24) will be the same as the ratio of the efficiencies. Further, the total efficiency will be that collected from both outputs; thus the differential quantum efficiencies from the individual mirrors are given by
As with any laser, semiconductor lasers have an output, i.e. a place where light is emitted. There happen to be several different configurations to engineer the way light is emitted from a laser diode.

\[
\eta_{d1} = \frac{K}{K+1} \eta_d, \eta_{d2} = \frac{1}{K+1} \eta_d
\]  

(1.25)

1.1.3. Emission Configurations

Figure 1.6: Basic diode laser with two mirror outputs.
Figure 1.7: Some of the more common semiconductor laser cavities include (a) the Fabry-Perot resonator, (b) the distributed Bragg reflector resonator, and (c) the distributed feedback resonator.

The first configuration is the simplest; this is the cleaved facet, as shown in Figure 1.7 (a)-(c). While this configuration may be the simplest, it requires that each device or linear array of devices be cleaved from the processed wafer and may require high-reflection and antireflection coatings to get single output emission, as in the case of the FP laser. Furthermore, due to the high confinement of the light in the direction of epitaxial growth, the output light has a very high divergence that generally must be compensated for by external optics.

The second configuration allows for emission normal the wafer surface. This configuration pioneered by Soda, et. al. in 1979 is the vertical-cavity surface-emitting laser (VCSEL). While this type of device is a low power device, there has been research in recent years striving to show that the VCSEL is a suitable high power device [Miller, 2001]. The resonator reflectors of VCSEL devices are incorporated into the device through the epitaxial growth, rather than through lithographic fabrication steps as is done with other devices. Further
unlike other semiconductor lasers, the VCSEL lases perpendicular to the active layer as is shown in Figure 1.8. Typically, a VCSEL has one mirror with an extremely high reflectivity, ~99%, and one mirror with a lower reflectivity to allow for emission through the surface of the device.

![Figure 1.8: Cross section of a VCSEL showing vertical lasing.](image)

The third configuration also allows for surface emission. This configuration uses a 45° turning mirror that reflects the guided light by total internal reflection (TIR) into the substrate of or air atop the device or deflects the light already emitted from the device into the air atop the device [Evans, 1993], as shown in Figure 1.9 (a)-(c). These turning mirrors can be fabricated through a variety of techniques including wet chemical etching [Yih, 1990] and reactive ion etching [Saito, 1989]. Although this configuration does not require cleaving devices from the
wafer for use, it does require either integration of optics on the backside of the substrate, for emission into the substrate, or external optics for beam collimation.

Figure 1.9: Schematics of devices incorporating turning mirrors for emission (a) through the substrate and (b) through the superstrate and (c) a device incorporating a deflector.

The fourth configuration is again a surface emission scheme. This configuration relies on gratings fabricated in close proximity to the laser waveguide in order to couple the light into a radiating mode and are therefore referred to as grating-coupled surface-emitting laser (GCSEL). Within the category of GCSELs, there are several different configurations that exist. The grating may be a second order Bragg reflector in which the grating provides both the feedback mechanism and the emission mechanism, as shown in Figure 1.10 (a). In this configuration, the grating may be fabricated at the end of the active length of the device, as in a DBR, or it may be
fabricated over the entire length of the active device, as in a DFB. The grating may also be detuned from the second order Bragg condition, such that relatively no feedback is provided to the laser and all light incident on the grating is coupled out, as shown in Figure 1.10 (b). Due to the shortcomings of the two diffracted order from the grating, i.e. one into the substrate and one into the superstrate or air, several research endeavors have been made to enhance the directionality of the diffraction from the grating coupler. These endeavors have included fabricating the grating coupler with a blaze [Hagberg, 1995], as shown in Figure 1.11 (a); including a Bragg mirror in the epitaxial growth process to enhance directionality into the superstrate [Eriksson, 1995], as shown in Figure 1.11 (b); and fabrication of a high-reflection coating on top of the grating to enhance directionality into the substrate [Evans, 1993], as shown in Figure 1.11 (c).

Figure 1.10: GCSEL emission from (a) a grating detuned from the second order Bragg condition and (b) a grating operating at the second order Bragg condition.
1.1.4. Wavelength Stabilization Technologies

Several efforts have been made in recent years to obtain both single frequency operation and single spatial mode operation of broad area laser diodes. These efforts have been made in order to obtain high power outputs with great beam quality for uses in optical communication, metrology, and frequency conversion to blue/green sources. As mention previously, broad area laser diodes have a large number of lateral modes making it very difficult to obtain. Due to the substantial gain lengths of these laser diodes, generally greater than 500\,\mu m, they also have a
large number of longitudinal modes as well. The large number of both longitudinal and lateral modes, along with the tendency of broad area devices to have issues with filamentation, make it difficult to effectively stabilize the wavelengths of broad area laser diodes at high powers and even more difficult to obtain a single spatial mode. Beyond the previously mention applications, broad area laser diodes with stabilized wavelengths with narrow emission spectra only are useful in pumping applications. Laser diodes with spectral widths less than 1nm are used for direct resonant pumping of Nd$^{3+}$ and Er$^{3+}$, which is much more efficient than indirect pumping schemes; larger spectral widths result in lower absorption coefficients [Stoneman, 1992; Lavi, 1999]. This pumping scheme can be used in both solid state lasers and in fiber lasers doped with Nd$^{3+}$ and Er$^{3+}$.

Despite the difficulties associated with wavelength stabilization of broad area laser diodes, there are several high-power wavelength stabilization schemes for broad-area lasers that have been researched in recent years. These research efforts include fully integrated wavelength stabilization schemes, including the angled distributed feedback laser, the grating ring oscillator, and a fully integrated master oscillator power amplifier (MOPA) configuration, and also externally wavelength stabilization schemes.

The angled distributed feedback laser or α-DFB presented by Paschke, et. al. is an edge-emitting device in which the light is confined to the gain region by an angled distributed Bragg grating and cleaved facets as shown in Figure 1.12. These devices have a threshold current density of approximately 240A/cm$^2$. The devices were designed to operate at a wavelength of 1060nm. The maximum power achieved for a 160µm by 4mm device was 3.0W with an M$^2$ factor of 3.2; the maximum power achieved for a 2mm device was 2.2W. The M$^2$ factor of these
devices is in the range of 1.3-1.6 at output powers near 1W. The light-current characteristics curves of these devices were kink free up to 1.2W, with slopes of 0.51W/A for the 2mm device and 0.35W/A for the 4mm device. The spectral width of these devices was measured to be less than 6pm using a monochromator with a side mode suppression of greater than 27dB, however the spectrum is no longer single mode past 1.6W.

The grating ring oscillator (GRO) is a grating-coupled surface-emitting laser that relies on either perpendicularly patterned distributed Bragg reflectors and cleaved facets operating under total internal reflection conditions or perpendicularly patterned DBRs alone to confined the light to the active area [Dzurko, 1993], as shown in Figure 1.13. These devices have been shown to have threshold current densities less than 200A/cm² and differential efficiencies of...
greater than 60%. A single frequency output with complete spatial coherency at an optical power of 460mW has been achieved with a GRO configuration. Furthermore, an optical power of 1W with single frequency operation with a near diffraction limited output has been obtained.

Figure 1.13: Schematics of two types of grating ring oscillators, adapted from [Dzurko, 1993].

The fully integrated MOPA configuration contains a single lateral mode oscillator with a cavity formed by two distributed Bragg reflectors as shown in Figure 1.14. In this type of device investigated by O’Brien, et. al., the oscillator provides a single longitudinal mode, and thus provides a stabilized wavelength. The output from this oscillator is directly coupled to a flared amplifier that amplifies the diverging single mode output. This monolithically integrated scheme has provided an optical output with a diffraction limited lobe. The device also provided an output power in excess of 2W under CW pumping. At an output of 1W CW, 93% of the output optical power was in the diffraction limited spot in the far field with an $M^2$ factor of
approximately 1.6. The side mode suppression in this device was measured to be greater than 25dB. The differential efficiency was approximately 50%, with a wall-plug efficiency of 29%.

Figure 1.14: Schematic of an integrated MOPA.

In terms of external cavity wavelength stabilization schemes, there has been much research using the configuration shown in Figure 1.15, using an LOC tapered amplifier as the gain section, a grating operating in the Littrow condition as the stabilizing element, and the narrow input of approximately 5µm width of the amplifier as a spatial filter. The best of this research has a CW output of 2W, a differential efficiency of 72% or an L-I slope of 1.1W/A, a spectral width of 4pm, a wall plug efficiency of 40%, and an output that can be focused into a
diffraction limited spot [Chi, 2005]. Furthermore, the wavelength can be tuned by simply rotating the grating.

The wavelength stabilization technology on which this work is focused is the dual grating reflector or DGR. This technology is a fully integrated wavelength stabilization technology that forms an integrated cavity outside of the active section of the semiconductor laser using two separate gratings. The DGR wavelength stabilization technology consists of a grating coupler on the p-side and a feedback grating on the n-side of the device, see Figure 1.16. The DGR p-side grating coupler period is chosen small enough to enable the first diffraction order to exist in the substrate only. This enhances the directionality of grating coupler and eliminates the need of a high-reflection coating. Light incident on the grating coupler is diffracted into the substrate, where it propagates through the substrate to the DGR n-side feedback grating. The n-side feedback grating serves to diffract the already angularly dispersed light back into the substrate, but for a specific wavelength, $\lambda_{SW}$, the feedback grating will operate in the Littrow condition. This retro-reflected light of wavelength $\lambda_{SW}$, also denoted as the stabilization wavelength, will
travel back on its previous path through the substrate to the DGR p-side grating coupler. The DGR p-side grating coupler serves its second purpose; it couples the light incident at the proper angle and wavelength, which is the light of wavelength $\lambda_{SW}$, back into the active region of the device. Light of other wavelengths will be scattered back into the substrate by the p-side grating coupler to be absorbed, thereby providing a wavelength selective feedback. Due to the short periodicity of the p-side grating coupler, the feedback grating operates under TIR conditions on the n-side of the semiconductor laser. The TIR condition is beneficial since near unity retro-reflection can be achieved for a specific wavelength for a binary grating operating under this condition [Marciante, 2004].

An expression for the stabilization wavelength can be derived based on grating equations for the p-side grating coupler and n-side feedback grating. For a grating fabricated within close proximity to the laser waveguide, light propagating in the waveguide will be diffracted or coupled out of the waveguide. Coupled light from a first-order grating coupler will be diffracted
at an angle $\theta$ into a media of refractive index $n_s$ if incident at an angle $\phi$, given the grating coupler region has an effective index of $n_{\text{eff}}$ and a period of $\Lambda_1$, as shown in Figure 1.17 and as given by [Evans, 1993]

$$n_s^2 \sin^2 \theta = n_{\text{eff}}^2 + \frac{\lambda^2}{\Lambda_1^2} - 2n_{\text{eff}} \frac{\lambda}{\Lambda_1} \cos \phi.$$  

(1.26)

Figure 1.17: Schematic depicting out-coupling from a grating coupler with the incident light depicted by the red arrow diffracted from the grating to propagate in another direction as depicted by the green arrow into the surrounding media.

Assuming normal incidence on this grating, the grating coupler equation reduces to
\[ n, \sin \theta = \frac{\lambda}{\Lambda_1} - n_{\text{eff}}. \] (1.27)

For a feedback grating in a plane parallel and with grooves parallel to the grating coupler in Figure 1.17, the first-order conical diffraction from this feedback grating will obey

\[ (n, \sin \theta + n, \sin \theta_2) \cos \phi_2 = \frac{\lambda}{\Lambda_2}, \] (1.28)

as shown in Figure 1.18.

Figure 1.18: Schematic depicting incident light (green arrow) diffracted from feedback grating effectively redirected the light elsewhere (red arrow).
Assuming that $\phi_2$ is zero and that the Littrow condition is met and Equation (1.28) becomes

$$2n_2 \sin \theta = \frac{\lambda}{\Lambda_2} \ . \ (1.29)$$

Equation (1.29) is rearranged as

$$n_2 \sin \theta = \frac{\lambda}{2\Lambda_2} \ . \ (1.30)$$

Equation (1.30) is then plugged into Equation (1.27). Solving for the wavelength, we find an expression for the stabilization wavelength given by

$$\lambda_{sw} = \frac{2\Lambda_1 \Lambda_2}{2\Lambda_2 - \Lambda_1} n_{eff} \ (1.31)$$

### 1.2. Conclusion

In this introduction, we presented an overview of semiconductor lasers including the basic materials and structures, commonly used resonator schemes, and operational regimes and applications. We then presented a phenomenological analysis of the operation characteristics of the basic semiconductor laser; these operational characteristics include the threshold current and the light-current characteristics slope. The possible emission configurations of semiconductor lasers are then shown including cleaved facet lasers, vertical-cavity surface-emitting lasers, grating-coupled surface-emitting lasers, and turning mirror emission lasers. Lastly, we presented the wavelength stabilization technologies researched in recent years, along with the basic idea behind our wavelength stabilization scheme known as the dual grating reflector.
CHAPTER 2: RESEARCH OVERVIEW

Most of the research in this work has been on the development of an integrated wavelength stabilization scheme named the dual grating reflector (DGR) and variations on the implementation of the DGR. The DGR consisting of a grating coupler detuned from the Bragg condition on the p-side of the device combined with a feedback grating operating in the Littrow condition on the n-side surface of the semiconductor laser. This device was developed based on previous work performed by the Micro-Photonics Laboratory focusing on dual layer optics in Grating-Coupled Surface-Emitting Lasers (GCSELs). Previously, the research aimed toward enhancing the extraction from broad area GCSELs for high power application through tapering of the out-coupling grating for reduced reflection into the laser cavity and fabrication of optical structures on the n-side of the laser substrate to work in conjunction with the grating coupler [Vaissié, 2003; Vaissié, 2005]. These optical structures have included a microlens for beam shaping [Vaissié, 2003] and a sub-wavelength antireflection grating for reflection suppression and high efficiency operation [Vaissié, 2005]. The research presented in this work is an extension of this early research in that it focuses on providing a wavelength selective feedback based on the idea of dual layer optics encompassed in the DGR.

There were five research goals pursued that are presented in this work. The first goal was to prove the efficacy of the DGR wavelength stabilization scheme by integrating one of these reflectors into several semiconductor lasers and calculating the effective reflectivity of the DGR. The second goal was to see if the DGR could be adapted to produce a device capable of predictably lasing at two wavelengths. The third goal was to integrate the DGR into a different
device geometry in order to discover possible problems that would hinder a future work. The fourth goal was to explore the bandwidth limit of the DGR concept by incorporating a modified DGR design into a semiconductor laser. The fifth research goal was to obtain a high output peak power by created a hybrid master oscillator power amplifier (MOPA) configuration using a DGR laser as the master oscillator (MO) and a tapered semiconductor optical amplifier as the power amplifier (PA).

2.1. Single Wavelength Dual Grating Reflector Laser

The first research goal in the development was to prove the efficacy of the idea. Both modeling of a DGR and fabrication of devices incorporating a DGR were carried out simultaneously. Two device designs were fabricated and tested. The first device design was a broad area semiconductor laser with a DGR on one end and an out-coupling grating to provide surface emission on the other as shown in Figure 2.1. This design was pursued in order to achieve the best performance. The second design was similar to the first with a DGR on one end; however, a cleaved facet replaced the out-coupling grating on the other end. This design was pursued in an attempt to experimentally determine the effective reflectivity of the DGR section.
2.2. Dual Wavelength Dual Grating Reflector Laser

The second step in the development was to show that more than one period could be included in the feedback grating in order to force the laser to operate at multiple wavelengths simultaneously. Beyond this goal, the applications for such a device are many, including multi-wavelength interferometry [de Groot, 1993], terahertz radiation generation for sensing and imaging [Wang, 1995], and a host of optical communications technologies [Lee, 1997]. The fabrication of a dual wavelength device was accomplished by bifurcating the feedback grating along the center of the active stripe, this type of device was named the dual wavelength dual grating reflector (DWDGR) and is shown in Figure 2.2. Although this type of laser showed very good results, the fact that the different feedback reflections were spatially separated in the lateral direction, leading to the laser light being somewhat spatially separated in the lateral direction led
to some concern. Therefore, the DWDGR laser was further investigated with an alternative design as is shown in Figure 2.3.

---

Figure 2.2: Schematic of DWDGR laser showing a cross section of the device (top) and a view of the n-side of the device (bottom).
2.3. Square Dual Grating Reflector Devices

The third research goal was to show that a DGR could be integrated into different device geometries. Starting with the simplest design to fabricate, a device with a square active area surrounded by DGRs was fabricated. A schematic of this design is shown in Figure 2.4.

Figure 2.3: Schematic of DWDGR laser showing the alternative feedback grating design to allow for a laterally collocated output.
2.4. Narrower Spectral Width Dual Grating Reflector Laser

The fourth research goal was to push the limit of the DGR technology to see how narrow of a spectral width a DGR could provide. Toward this end, the DGR design was modified in such a way that the theoretical reflection spectral width of the DGR is reduced by approximately 500% from the standard design, however this tactic has strict fabrication tolerances and has more loses than a standard DGR. This modified DGR design changes the feedback grating to a redirection grating. Simultaneously, the grating coupler takes on an added function as the retro-reflection grating. Following the path of the light from the beginning, the light is incident on the grating coupler. The grating coupler diffracts the light into the substrate. The light propagates
through the substrate to the redirection grating and is diffracted at a higher angle back into the substrate. The light propagates again through the substrate and is incident on the grating coupler. Now, the angle of incidence here is such that the grating coupler period satisfies the Littrow condition for the first order for the stabilization wavelength, thus the grating coupler is also serving to retro-reflect the light of the correct wavelength. The retro-reflected light follows its path back into the laser waveguide. The path of the light of the stabilization wavelength is depicted in Figure 2.5.

![Figure 2.5: Light path for stabilized wavelength in a modified or double reflection DGR; numbers indicate the sequence of propagation in the DGR section.](image)

As previously mentioned, this scheme will have more losses than a conventional DGR due to four passes through the substrate rather than just two. Modeling results and fabrication tolerances for this design will be presented in the next section. The wavelength stabilization equation for this modified DGR scheme are derived similarly to Equation (1.31) and is given by

$$\lambda_{sw} = \frac{2\Lambda_1 \Lambda_2}{3\Lambda_2 - 2\Lambda_1} n_{\text{eff}} \quad \text{(2.1)}$$
2.5. Vertically Stacked Master Oscillator Power Amplifier

The fifth research task was undertaken with the goal of achieving high peak power was the creation of a hybrid MOPA device with the MO being a DGR laser. Various types of MOPA based on semiconductor lasers have been recently researched for high power applications, including optical pumping and medical applications. They include but are not limited to a monolithically integrated MOPA with an antireflection (AR) coated facet output [O’Brien, 1993], a monolithically integrated MOPA with a grating out-coupler providing surface emission [Carlson, 1990], [Uemukai, 1998], and a MOPA in a hybrid configuration [Schwertfeger, 2004]. The advantage of the hybrid approach over the monolithic configuration is that the MO and the PA devices can be optimized separately for better performance. However, a hybrid assembly includes coupling optics that limits the compactness of the optical head and increases the cost due to expensive mounting and alignment. Our new compact MOPA design involves vertically stacked surface-emitting devices leading to a reduced number of assembled elements and easy mounting. Optical coupling between the MO and the PA is provided by identical grating couplers integrated on both of the devices which are stacked in the vertical direction, see Figure 2.6. Broad area devices were used for both the MO and PA exhibiting large emitting and input areas. These large areas translate to a sufficiently reduced fabrication and alignment tolerance of vertically stacked chips compared with the assembly of the conventional edge-emitting diodes.

In order to obtain the high output peak power desired, we investigated pulse pumping in the quasi continuous wave (QCW) regimes of the MO and PA. The QCW regime involves pumping with pulses that have duration much longer than the carrier lifetime of the material.
2.6. Conclusion

The scope of the research included within this work has been elucidated by presenting a basic overview of the research pursued. There were five research goals pursued that are presented in this work. The first goal was the fabrication and testing of several single wavelength DGR laser to prove the efficacy of the DGR wavelength stabilization scheme and experimentally find the effective reflectivity of the DGR. The second goal involved the fabrication and testing of two different dual wavelength DGR laser designs. The third goal was to integrate the DGR into a different device geometry in order to discover possible problems that would hinder a future work. The fourth goal was to explore the bandwidth limit of the DGR by fabricating and testing a laser incorporating a modified DGR design. The fifth research goal was to obtain a high output peak power by created a hybrid MOPA configuration using a DGR laser as the MO.
CHAPTER 3 : MODELING AND DESIGN

In designing a DGR, modeling is an essential tool. Numerical modeling must be used in order to find the optimum grating parameters of both the grating coupler and the feedback grating, as there is no analytical way to do so. In this chapter, the modeling methods used will first be described. After this description, the implementation of these modeling methods will be explained, along with design parameters that must be considered when designing a DGR.

3.1. Modeling Methods

In order to model the desired grating parameters needed for the optimum reflection from the DGR, several modeling methods were employed. First, each element of the DGR was simulated individually to find the optimum parameters for that element. The grating coupler was modeled using a method of lines (MOL) algorithm [Jamid, 2002], while the feedback grating was modeled using rigorous coupled wave analysis (RCWA) [Moharam, 1995]. Through these two methods, both the optimum parameters and tolerances required on the gratings fabricated were determined for our specific laser structures and can be determined for other laser structures.

In order to find the theoretical performance of a specific DGR as a whole, two methods were used. The first of these methods is a piecewise method in which several modeling techniques were combined, these techniques include the MOL, the fast Fourier beam propagation method [Kenji, 2001], RCWA, and a numerical correlation. The reason a piecewise method is used instead of the more common all inclusive modeling algorithm, such as finite-difference time domain (FDTD) [Kenji, 2001], is due to the size of the problem window; the substrate of a
semiconductor laser is on the order of a hundred micrometers, while the length of the gratings will be on the order of several hundred micrometers. However, even though this piecewise method can simulate this large problem, it does have its shortcomings. The second method used to analyze the whole DGR is an adapted RCWA which incorporates an absorbing boundary in order to analyze the DGR structure. This method requires most of the laser substrate to be neglected.

The following sections present the modeling methods used for both the individual element simulation, as well as methods used in simulating the DGR structure as a whole.

### 3.1.1. Method of Lines Algorithm

The modeling of coupling of the light from the laser waveguide by the grating coupler is limited to the transverse electric (TE) mode. This is done because of the preferential nature of the single quantum well graded refractive index separate confinement heterostructure (SQW-GRINSCH) to only support the TE mode as a lasing mode. Furthermore, we will be limiting the modeling to two dimensions, \( x \) and \( z \). With that in mind, we start with Maxwell’s equations for source free problems.

\[
\nabla \times \vec{E} = -j \omega \mu_0 \mu \vec{H} \\
\n\nabla \times \vec{H} = j \omega \varepsilon_0 \varepsilon \vec{E}
\]

It is helpful to normalize the magnetic field so that it has the same magnitude and phase as the electric field. This normalized magnetic field is denoted as \( \tilde{H} \), and normalization of the magnetic field is carried out as follows
\[
\vec{H} = -j \sqrt{\frac{\mu_0}{\varepsilon_0}} \vec{H} \quad \rightarrow \quad \vec{H} = j \sqrt{\frac{\varepsilon_0}{\mu_0}} \vec{H}
\]  

(3.3)

Substituting this normalized magnetic field into Maxwell’s equations results in

\[
\nabla \times \vec{E} = k_0 \mu_0 \vec{H}
\]  

(3.4)

\[
\nabla \times \vec{H} = k_0 \varepsilon_0 \vec{E}
\]  

(3.5)

Expanding these equation into vector components and retaining only those essential for the TE mode, \(E_y, \vec{H}_x\), and \(\vec{H}_z\), results in the following three equations:

\[
\frac{\partial E_x}{\partial x} = k_0 \mu_0 \vec{H}_z \]  

(3.6)

\[
\frac{\partial E_z}{\partial z} = -k_0 \mu_0 \vec{H}_x \]  

(3.7)

\[
\frac{\partial \vec{H}_z}{\partial x} - \frac{\partial \vec{H}_x}{\partial z} = k_0 \varepsilon_0 E_y
\]  

(3.8)

Combining these three equations yields

\[
\frac{\partial}{\partial z} \left( \frac{1}{\mu_0} \frac{\partial E_y}{\partial z} \right) + \frac{\partial}{\partial x} \left( \frac{1}{\mu_0} \frac{\partial E_y}{\partial x} \right) + k_0^2 \varepsilon_0 E_y = 0
\]  

(3.9)

In most optical materials, \(\mu_0\) is unity. In the case of the method of lines, the quantity \(\sigma\) is used to construct an anisotropic perfectly matched layer (PML) at the problem window edge in the x direction. The equation for the electric field including \(\sigma\) becomes

\[
\frac{\partial^2 E_y}{\partial z^2} + \frac{\partial}{\partial x} \left( \frac{1}{\sigma} \frac{\partial E_y}{\partial x} \right) + k_0^2 \varepsilon_0 E_y = 0
\]  

(3.10)

Next, by applying a finite-difference approximation in x Equation (3.10) becomes
\[
\frac{\partial^2 E_{r,i,j}}{\partial \zeta^2} + \left[ \frac{1}{\sigma_i \Delta \zeta^2} \left( \frac{1}{\sqrt{\sigma_{i-1} \sigma_i}} E_{r,i-1} - 2 \frac{1}{\sqrt{\sigma_{i-1} \sigma_i \mu_{r,i}}} \frac{1}{\sqrt{\sigma_{i-1} \sigma_i}} E_{r,i} + \frac{1}{\sqrt{\sigma_{i-1} \sigma_i}} E_{r,i+1} \right) + k^2_i \varepsilon_{r,i} E_{r,i,j} \right] = 0 \tag{3.11}
\]

The longitudinal derivative is now an ordinary derivative because dependence on \( z \) has been removed from all other parameters. Within this framework, the absorbing boundary is exclusively included in \( \sigma \) and is defined as

\[
\sigma_i = \begin{cases}
1 + j \frac{\mu_0}{\varepsilon_{r,i} \varepsilon_0 k_0} \left( \frac{M + 1 - i}{M} \right)^4 & i = 1 \ldots M \\
1 + j \frac{\mu_0}{\varepsilon_{r,N} \varepsilon_0 k_0} \left( 1 - \frac{N - i}{M} \right)^4 & i = N - M + 1 \ldots N \\
1 & i = M + 1 \ldots N - M
\end{cases} \tag{3.12}
\]

A more detailed explanation of equivalent absorbing boundary condition within the method of lines can be found in [Al-Bader, 1998] and [Jamid, 2000].

The complete set of equations represented by Equation (3.11) can be written in matrix form as

\[
\frac{\partial^2 \mathbf{E}}{\partial \zeta^2} + S^2 \mathbf{E} = 0 \tag{3.13}
\]
Equation (3.13) represents a set of first-order ordinary differential equations that can be solved analytically. The solution to all of these equations can be written in matrix form as

\[ E_j = \exp(jSz)E^+_j + \exp(-jSz)E^-_j \]  

(3.15)

where, as shown in [Gerdes, 1999],

\[ \exp(jSz) = V \exp(j\lambda z)V^{-1} \]  

(3.16)

\[ S^2 = V\lambda^2 V^{-1} \]  

(3.17)

\[ S = V\lambda V^{-1} \]  

(3.18)

The matrix \(V\) is a transformation matrix with columns containing the eigenvectors of \(S^2\). It can be interpreted as a collection of the eigenmodes that can exist in the cross section of the structure represented by the sampled parameter \(\epsilon_r\). In the \(V\) matrix, the \(i^{th}\) column in the matrix is the \(i^{th}\) eigenmode or eigenvector of \(S^2\). The diagonal matrix \(\lambda^2\) is a collection of the eigenvalues of \(S^2\), where the \(i^{th}\) eigenvalue is located at the \((i,i)\) position along the diagonal of the matrix. Furthermore, the value of the quantity \(\lambda_i/k_0\) is equal to the effective refractive index of the \(i^{th}\)
eigenmode. The matrix $\exp(jS_2z)$ contains information on the amount of phase and loss that will be accumulated by the eigenmodes for a propagation distance of $z$.

Equation (3.15) is a solution for a medium that is uniform in the $z$-direction. In order to account for discontinuities in the $z$-direction, the structure must be discretized into sections which are unchanging in $z$, such as the structure shown in Figure 3.1. Once the structure is cut into slices or sections in the $z$-direction, the solution given in Equation (3.15) must be calculated for each section. Given these solutions, the reflection and transmission coefficient matrices for transitions from one section to the next may be calculated by matching boundary conditions. This is an analysis of the discontinuities of the structure, much like the analysis in [Pregla, 1993].

Given two arbitrary sections, for instance section 1 and 2, we have the solutions for the electric field given by

$$E_{y,1} = \exp(jS_1z)E_{y,1}^* + \exp(-jS_1z)E_{y,1}^- \quad \text{and} \quad E_{y,2} = \exp(jS_2z)E_{y,2}^* + \exp(-jS_2z)E_{y,2}^- \quad \text{(3.19)}$$

Applying Equation (3.7) to Equation (3.19), the expressions for the tangential magnetic fields can be written as

$$-k_0\mu_r\tilde{H}_{x,1} = S_1 \exp(jS_1z)E_{y,1}^* - S_1 \exp(-jS_1z)E_{y,1}^-$$

$$-k_0\mu_r\tilde{H}_{x,2} = S_2 \exp(jS_2z)E_{y,2}^* - S_2 \exp(-jS_2z)E_{y,2}^- \quad \text{(3.20)}$$
Given that both the tangential electric and magnetic fields must be equal at the boundary between sections, we set the boundary at the $z$ origin, and we equate both parts of (3.19) and (3.20), a system of equations can be written in matrix form as

\[
\begin{bmatrix}
1 & 1 & E_{1,1}^+ \\
S_1 & -S_1 & E_{1,1}^-
\end{bmatrix} =
\begin{bmatrix}
1 & 1 & E_{1,2}^+ \\
S_2 & -S_2 & E_{1,2}^-
\end{bmatrix}
\]  

(3.21)

Solving for the left side of Equation (3.21) yields

\[
\begin{bmatrix}
E_{1,1}^+ \\
E_{1,1}^-
\end{bmatrix} = \frac{1}{2}
\begin{bmatrix}
I + S_1^\dagger S_2 & I - S_1^\dagger S_2 \\
I - S_1^\dagger S_2 & I + S_1^\dagger S_2
\end{bmatrix}
\begin{bmatrix}
E_{1,2}^+ \\
E_{1,2}^-
\end{bmatrix}
\]  

(3.22)

Realizing that if we are only considering this single boundary and $E_{y,1}^+$ is the incident field from section 1, $E_{y,2}^-$ may be set to zero. Furthermore, $E_{y,2}^+$ is the transmitted field and is related to $E_{y,1}^+$ by the transmission coefficient $T_{12}$; likewise, $E_{y,1}^-$ is the reflected field and is related to $E_{y,1}^+$ by the reflection coefficient $R_{12}$. These relations are as follows
\[ E_{y,2}^+ = T_{12} E_{y,1}^+ \]  \hspace{1cm} (3.23)

\[ E_{y,1}^- = R_{12} E_{y,1}^+ \]  \hspace{1cm} (3.24)

Using the fact that \( E_{y,2}^- \) is zero, combining Equations (3.22) and (3.24) and solving for \( R_{12} \) yields

\[ R_{12} = (I - S_{y,1}^{-1} S_{y,2}) (I + S_{y,1}^{-1} S_{y,2})^{-1} \]  \hspace{1cm} (3.25)

Also, combining Equations (3.22) and (3.23) and solving for \( T_{12} \) yields

\[ T_{12} = 2(I + S_{y,1}^{-1} S_{y,2}) = I + R_{12} \]  \hspace{1cm} (3.26)

For the transmission and reflection coefficients associated with section 2, the same procedure can be followed starting at Equation (3.21) by solving for the right side of the equation and proceeding. The results of this are given by

\[ R_{21} = (I - S_{y,2}^{-1} S_{y,1}) (I + S_{y,2}^{-1} S_{y,1})^{-1} = -R_{12} \]  \hspace{1cm} (3.27)

\[ T_{21} = 2(I + S_{y,2}^{-1} S_{y,1}) = I - R_{12} \]  \hspace{1cm} (3.28)

At this point, the reflection and transmission coefficients at every boundary between sections in the problem can be calculated. However, these coefficients are only for a single reflection or transmission. In problems with more than just two sections, there will be multiple reflections and transmissions as the light bounces between and through discontinuities. In order to account for these multiple reflections, the scattering matrix method is employed \[\text{[Li, 1996; Jamid, 2002]}\].

Given that we have \( Y \) \( z \)-invariant sections as illustrated in Figure 3.1, we start by calculating the reflection at the boundary between the \((Y-1)^{th}\) and \(Y^{th}\) section. The imaginary \((Y+1)^{th}\) section will be assumed to be the same as the \(Y^{th}\) section. Thus our starting reflection and transmission coefficients for the boundary between the \(Y^{th}\) section and the \((Y+1)^{th}\) section are given by
The scattering matrix method treats the reflections between subsequent boundaries as a multiple reflection. These reflections are added to form a convergent infinite series. The phase accumulated between the reflections between boundaries is given by Equation (3.15) with $z$ replaced by $d_p$, the thickness of the $p^{th}$ section. Thus the reflection coefficient into the $(Y-1)^{th}$ section is found by following the path of a single incident field and following its subsequent reflections as shown in Figure 3.2; the resulting reflection coefficient is given by

\[
T_{AB}^Y = T_{BA}^Y = I \\
R_{AB}^Y = R_{BA}^Y = 0
\] (3.29)
\[ R_{AB}^{y-1} = R_{y-1} + T_{y-1} \exp(jS_yd_y)R_{AB}^{y} \exp(jS_yd_y)T_{y-1} \ldots \]
\[ + T_{y-1} \exp(jS_yd_y)R_{AB}^{y} \exp(jS_yd_y)R_{AB}^{y} \exp(jS_yd_y)T_{y-1} \ldots \]  
\[ R_{AB}^{y-1} = R_{y-1} + T_{y-1} \exp(jS_yd_y)R_{AB}^{y} \exp(jS_yd_y) \left( I - R_{y-1} \exp(jS_yd_y)R_{AB}^{y} \exp(jS_yd_y) \right)^{\dagger} T_{y-1} \ldots \]  

(3.30)

Likewise, the other remaining reflection and transmission coefficients are calculated and given as

\[ T_{AB}^{y-1} = T_{y} \exp(jS_yd_y) \left( I - R_{y-1} \exp(jS_yd_y)R_{AB}^{y} \exp(jS_yd_y) \right)^{\dagger} T_{y-1} \ldots \]  

(3.31)

\[ R_{BA}^{y-1} = R_{BA}^{y} + T_{BA}^{y} \exp(jS_yd_y)R_{y-1} \exp(jS_yd_y) \left( I - R_{BA}^{y} \exp(jS_yd_y)R_{BA}^{y} \exp(jS_yd_y) \right)^{\dagger} T_{BA}^{y-1} \ldots \]  

(3.32)

\[ T_{BA}^{y-1} = T_{y} \exp(jS_yd_y) \left( I - R_{BA}^{y} \exp(jS_yd_y)R_{y-1} \exp(jS_yd_y) \right)^{\dagger} T_{BA}^{y-1} \ldots \]  

(3.33)

Each preceding layer will be included in the reflection and transmission coefficients using Equations (3.34)-(3.37). When the last layer is reached, \( p = 1 \), the reflection and transmission coefficients for the boundary between the 1st layer and the 0th imaginary layer are

\[ R_{01} = R_{10} = 0 \text{ and } T_{10} = T_{01} = I \ldots \]  

(3.34)

\[ R_{BA}^{p-1} = R_{BA}^{p-1} + T_{BA}^{p-1} \exp(jS_yd_y)R_{BA}^{p} \exp(jS_yd_y) \left( I - R_{BA}^{p-1} \exp(jS_yd_y)R_{BA}^{p} \exp(jS_yd_y) \right)^{\dagger} T_{BA}^{p-1} \ldots \]  

(3.35)

\[ R_{AB}^{p-1} = R_{AB}^{p-1} + T_{AB}^{p-1} \exp(jS_yd_y)R_{AB}^{p} \exp(jS_yd_y) \left( I - R_{AB}^{p-1} \exp(jS_yd_y)R_{AB}^{p} \exp(jS_yd_y) \right)^{\dagger} T_{AB}^{p-1} \ldots \]  

(3.36)

\[ T_{BA}^{p-1} = T_{BA}^{p-1} \exp(jS_yd_y) \left( I - R_{BA}^{p-1} \exp(jS_yd_y)R_{BA}^{p} \exp(jS_yd_y) \right)^{\dagger} T_{BA}^{p-1} \ldots \]  

(3.37)

If the problem contains any periodicity in the propagation direction, the above procedure, Equations (3.25)-(3.37) may be carried out for a single period. With the reflection and transmission coefficients for a single period known, the coefficients for two periods may be calculated as

\[ R_{AB,d} = R_{AB,d-1} + T_{BA,d} \exp(jS_yd_y)R_{AB,d} \exp(jS_yd_y) \left( I - R_{BA,d-1} \exp(jS_yd_y)R_{AB,d} \exp(jS_yd_y) \right)^{\dagger} T_{BA,d} \ldots \]  

(3.38)
\[ T_{AB,q} = T_{AB,q-1} \left( I - R_{BA,q-1} R_{AB,q-1} \right)^{-1} T_{AB,q-1} \]  
(3.39)

\[ R_{BA,q} = R_{BA,q-1} + T_{AB,q-1} R_{BA,q-1} \left( I - R_{BA,q-1} R_{BA,q-1} \right)^{-1} T_{BA,q-1} \]  
(3.40)

\[ T_{BA,q} = T_{BA,q-1} \left( I - R_{BA,q-1} R_{BA,q-1} \right)^{-1} T_{BA,q-1} \]  
(3.41)

with \( T_{AB,0} = T_{AB}^0 \), \( T_{BA,0} = T_{BA}^0 \), \( R_{AB,0} = R_{AB}^0 \), \( R_{BA,0} = R_{BA}^0 \), and \( q = 1 \).

Equations (3.38)-(3.41) are a doubling algorithm and can be repeated as many times as desired. For the \( q \)th iteration, \( 2^q \) periods will be included in the reflection and transmission coefficients. This iteration may be repeated any number of times with very high stability.

Two structures, C and D, may be combined using variations of Equations (3.38)-(3.41), for completeness these equations are as follows

\[ R_{AB,CD} = R_{AB,C} + T_{BA,C} R_{AB,D} \left( I - R_{BA,D} R_{AB,D} \right)^{-1} T_{AB,C} \]  
(3.42)

\[ T_{AB,CD} = T_{AB,C} \left( I - R_{BA,C} R_{AB,D} \right)^{-1} T_{AB,C} \]  
(3.43)

\[ R_{BA,CD} = R_{BA,D} + T_{AB,D} R_{BA,C} \left( I - R_{AB,C} R_{BA,C} \right)^{-1} T_{BA,D} \]  
(3.44)

\[ T_{BA,CD} = T_{BA,C} \left( I - R_{AB,D} R_{BA,C} \right)^{-1} T_{BA,D} \]  
(3.45)

In the notation used, \( A \) is always the left section and \( B \) is always the right section for any discontinuity when referring to the reflection and transmission coefficient subscripts. It is apparent that any number of structures can be combined with this method. Furthermore, it must be noted that by using coefficients stored from Equations (3.38)-(3.41) for different iterations, a structure of any number of periods can be analyzed by combining the proper coefficients together and repeatedly using Equations (3.42)-(3.45).

Once the reflection and transmission coefficients are calculated for the whole structure, the reflected and transmitted fields may be found given the input fields at both ends of the
structure. These fields may be arbitrary, or either or both can be an eigenvector, a column of the eigenmode matrix \( V \) for either the 1\(^{st} \) or the \( Y \)th section. Given that the input field, or the forward traveling field, in the 1\(^{st} \) section is denoted as \( E_{j,1}^{-} \), and the input field, or the backward traveling field, in the \( Y \)th section is denoted as \( E_{j,Y}^{+} \), the transmitted/reflected fields, from the combined structure CD for instance, are given by

\[
E_{j,1}^{+} = R_{AB,CD} E_{j,1}^{-} + T_{BA,CD} E_{j,Y}^{-} \tag{3.46}
\]

\[
E_{j,Y}^{+} = T_{AB,CD} E_{j,Y}^{-} + R_{BA,CD} E_{j,Y}^{-} \tag{3.47}
\]

where \( E_{j,1}^{-} \) is the backward traveling field in the 1\(^{st} \) section and \( E_{j,Y}^{+} \) is the forward traveling field in the \( Y \)th section.

In order to calculate the field between the two structures, C and D, we must again perform a summation of transmitted and reflected fields as done in (3.30). It is necessary to have the transmission and reflection coefficients for the individual structures, C and D, in order to perform this summation. These intermediate fields will rely on the fields \( E_{j,1}^{-} \) and \( E_{j,Y}^{-} \). First, we will consider the forward going intermediate field that is a function of \( E_{j,1}^{-} \). The summation of the transmission through the structure C and indefinite reflection between the two structures, C and D, yields an intermediate coefficient

\[
\Gamma_{+}^{+} = T_{AB,C} + R_{BA,C} R_{AB,D} T_{AB,C} + R_{BA,C} R_{AB,D} R_{BA,C} R_{AB,D} T_{AB,C} + \ldots \tag{3.48}
\]

\[
\Gamma_{-}^{+} = (I - R_{BA,C} R_{AB,D})^{-1} T_{AB,C}
\]

where the superscript denotes the forward (+) or backward (-) traveling intermediate field and the subscript denotes the forward/right (+) or backward/left (-) traveling input field. No phase terms are explicitly written as they are included in the reflection and transmission coefficients themselves.
Likewise, considering the summation of backward going intermediate field that is a function of \( E_{y,1} \), results in the intermediate coefficient

\[
\Gamma_y^+ = R_{AB,D} T_{AB,C} + R_{AB,D} R_{BA,C} R_{AB,D} T_{AB,C} + R_{AB,D} R_{BA,C} R_{BA,C} R_{AB,D} T_{AB,C} + \ldots
\]

\[
\Gamma_y^- = R_{AB,D} (I - R_{BA,C} R_{AB,D})^{-1} T_{AB,C}
\]  \hspace{1cm} (3.49)

By the same token, the forward and backward going intermediate fields that are a function of \( E_{y,f} \) have intermediate coefficients that are given by

\[
\Gamma_y^+ = R_{BA,C} (I - R_{AB,D} R_{BA,C})^{-1} T_{BA,D}
\]

\[
\Gamma_y^- = (I - R_{AB,D} R_{BA,C})^{-1} T_{BA,D}
\]  \hspace{1cm} (3.50)

Thus, the forward and backward traveling fields between the structures C and D are given by

\[
E_{y,CD} = \Gamma_y^+ E_{y,1}^+ + \Gamma_y^- E_{y,1}^-
\]  \hspace{1cm} (3.52)

\[
E_{y,CD}^+ = \Gamma_y^+ E_{y,1}^+ + \Gamma_y^- E_{y,1}^-
\]

Assuming that the structure C and D are periodic with reflection coefficients calculated with iterative Equations (3.38)-(3.41) and that the results from all iterations were stored, the fields between each period can be calculated rather quickly. Using the structure C as an example, let’s assume \( q \) reached 5 such that there were 32 periods of a substructure used to construct the structure C. The intermediate coefficients for the fields between the first 16 periods and the last 16 periods, following Equations (3.48)-(3.51), are calculated as

\[
\Gamma_y^+ = (I - R_{BA,4} R_{AB,4})^{-1} T_{AB,4}
\]

\[
\Gamma_y^- = R_{BA,4} (I - R_{BA,4} R_{AB,4})^{-1} T_{AB,4}
\]  \hspace{1cm} (3.54)

\[
\Gamma_y^+ = R_{BA,4} (I - R_{BA,4} R_{AB,4})^{-1} T_{BA,4}
\]

\[
\Gamma_y^- = (I - R_{AB,4} R_{BA,4})^{-1} T_{BA,4}
\]  \hspace{1cm} (3.55)

\[
\Gamma_y^+ = R_{BA,4} (I - R_{BA,4} R_{AB,4})^{-1} T_{BA,4}
\]

\[
\Gamma_y^- = (I - R_{AB,4} R_{BA,4})^{-1} T_{BA,4}
\]  \hspace{1cm} (3.56)

\[
\Gamma_y^- = (I - R_{AB,4} R_{BA,4})^{-1} T_{BA,4}
\]  \hspace{1cm} (3.57)
Also, much like Equations (3.52) and (3.53), the intermediate fields will be given as

\[ E_{y,17}^+ = \Gamma_+^* E_{y,17}^* + \Gamma_-^* E_{y,CD} \]  

(3.58)

\[ E_{y,17}^- = \Gamma_+^* E_{y,17}^* + \Gamma_-^* E_{y,CD} \]  

(3.59)

Next, the intermediate coefficients for the fields between the first 8 periods and second 8 periods, as well as the intermediate coefficients for the fields between the third 8 periods and the fourth 8 periods are given by

\[ \Gamma_+^* = (I - R_{BA,3} R_{BA,3})^{-1} T_{AB,3} \]  

(3.60)

\[ \Gamma_-^* = R_{AB,3} (I - R_{BA,3} R_{BA,3})^{-1} T_{AB,3} \]  

(3.61)

\[ \Gamma_+^* = R_{BA,3} (I - R_{BA,3} R_{BA,3})^{-1} T_{BA,3} \]  

(3.62)

\[ \Gamma_-^* = (I - R_{BA,3} R_{BA,3})^{-1} T_{BA,3} \]  

(3.63)

With the coefficients calculated, the two sets of intermediated fields are given as

\[ E_{y,9}^+ = \Gamma_+^* E_{y,1}^* + \Gamma_-^* E_{y,17} \]  

(3.64)

\[ E_{y,9}^- = \Gamma_+^* E_{y,1}^* + \Gamma_-^* E_{y,17} \]  

(3.65)

\[ E_{y,25}^+ = \Gamma_+^* E_{y,17}^* + \Gamma_-^* E_{y,CD} \]  

(3.66)

\[ E_{y,25}^- = \Gamma_+^* E_{y,17}^* + \Gamma_-^* E_{y,CD} \]  

(3.67)

This procedure of halving the structure is repeated until the field is found between every period.

Next, the field values within the period must be obtained. An efficient way to accomplish this goal is to calculate the forward traveling field at the leftmost point of every section and calculate the backward traveling field at the rightmost point of every section. The total field value at any point within a given section can then be calculated
Figure 3.3: Single period of a structure separated into two substructure for the purpose of calculating intermediate fields within the period.

by propagating each field to the same point. As an example, given the period shown in Figure 3.3, we must first calculate intermediate coefficients for each field at each discontinuity. The forward traveling field at the leftmost point and the backward traveling field at the rightmost point in the period are known from the previous halving of the structure. Once the reflection and transmission coefficients for each discontinuity are known, as are the sections and distances, the different intermediate coefficients can be calculated. In order to obtain the coefficients for any intermediate point, the period is divided into two substructures as shown in Figure 3.3; in order to use the previous notation, these two substructures will be labeled C and D. As can be seen in Figure 3.3, no discontinuities exist in substructure C, and therefore, substructure C will only be a phase expression, with $d_i^c = d_i$. Substructure D contains both discontinuities but will not include
any phase term for the leftmost section; \( d_{1}^{\prime} \) will be set to zero. The reflection and transmission coefficients for both of these substructures are calculated applying Equations (3.29)-(3.37). Now, by applying Equations (3.48)-(3.51) the intermediate coefficients can be calculated, and by a similar application of Equation (3.52) the backward traveling field is obtained. For any intermediate point within the single period the intermediate coefficients and therefore the field can be obtained by first separating the structure into two substructures, second calculating the reflection and transmission coefficients for each of these two substructures by the application of Equations (3.29)-(3.37), third applying Equations (3.48)-(3.51) to obtain the intermediate reflection coefficients, and fourth applying Equations (3.52) and (3.53) to obtain the intermediate fields. These equations are applied in tandem to each period as to reduce computation time.

Once the forward traveling fields are known at the leftmost point of each section and the backward traveling fields are known at the rightmost point of each section, propagation to a mutual location anywhere within the section can be calculated through the phases \( e^{j S_{p} z} \), for the forward traveling field, and \( e^{j S_{p} (d_{p} - z)} \), for the backward traveling field, where \( 0 \leq z \leq d_{p} \) for each section. Thus, if for the section 1 the forward traveling field, \( E^{+} \), at the left is known and the backward traveling wave, \( E^{-} \), at the right is known, the total field value at \( d_{1} / 4 \) from the left can be calculated as

\[
E_{\text{Total}} (d_{1} / 2) = e^{j S_{1} d_{1} / 4} E^{+} + e^{j S_{1} d_{1} 3/4} E^{-}
\]  \quad (3.68)

Now that the field can be obtained anywhere within a given structure, the field over the entire expanse of the structure can be calculated as a function of both \( x \) and \( z \). The coupled field from a grating coupler can be obtained by taking a sample of the field parallel to the waveguide at some
for all $z$ a sufficient distance away from the waveguide region and not within the absorbing boundary.

### 3.1.2. Rigorous Coupled Wave Analysis

As stated previously for this problem, only TE polarization is of concern. Boundary conditions are solved using a scattering matrix method for the best computational efficiency of the waveguide grating. There are several other propagation algorithms that can be used, including the Enhanced Transfer Matrix Method [Moharam, 1995] and the R-Matrix method [Li, 1996]. Since the scattering matrix method is used here, formulation of the equations and implementation for RCWA will be very similar to that seen in the MOL. RCWA can be implemented with no absorbing boundaries such that the problem window is assumed to be infinitely periodic in the $x$-direction, or the method can be implemented with absorbing boundaries for the case of waveguide analysis [Silberstein, 2001; Moharam, 2004]. The absorbing boundaries are included by changing the relative permittivity and permeability at the analysis window edges; see [Silberstein, 2001; Moharam, 2004] for details. Imposing the condition that the relative permeability does not change in the $z$ direction, Equation (3.9) becomes

$$\frac{1}{\mu_r} \frac{\partial^2 E_y}{\partial z^2} + \frac{\partial}{\partial x} \left( \frac{1}{\mu_r} \frac{\partial E_y}{\partial x} \right) + k_0^2 \varepsilon_r E_y = 0$$  \hspace{1cm} (3.69)

RCWA is based on the transformation of functions of the spatial variable $x$ into functions of spatial frequency variable $k_x$. This is carried out by expanding all functions of $x$ into Fourier series. Thus $E_y, \varepsilon_r, \mu_r^{-1}$, and $\mu_r$ are expressed as
\[ E_j(x, z) = \sum_{m=-\infty}^{\infty} U_m(z) \exp(-jk_x^m x) \]  
(3.70)

\[ \varepsilon_j(x) = \sum_{m=-\infty}^{\infty} a_m \exp(-jk_x^m x) \]  
(3.71)

\[ \mu^{-1}_j(x) = \sum_{m=-\infty}^{\infty} b_m \exp(-jk_x^m x) \]  
(3.72)

\[ \mu_j(x) = \sum_{m=-\infty}^{\infty} c_m \exp(-jk_x^m x) \]  
(3.73)

\[ k_x^m = k_{inc} + \frac{2\pi m}{\Lambda} = k_0 n_0 \sin(\theta_{inc}) + \frac{2\pi m}{\Lambda} \]  
(3.74)

Substituting Equations (3.70)-(3.73) into Equation (3.69) and performing differentiation with respect to \( x \) results in a set of ordinary differential equations

\[ \sum_{m=-\infty}^{\infty} \sum_{n=-\infty}^{\infty} \left[ b_{n-m} \frac{\partial^2 U_m(z)}{\partial z^2} - \left( k_x^m b_{n-m} k_x^m - k_x^2 a_{n-m} \right) U_m(z) \right] \exp(-jk_x^{n+m} x) = 0 \]  
(3.75)

It is worth noting that the multiplication of the two Fourier series results in a convolution.

By truncating the number of terms retained in Equation (3.75) to \( M+1 \), where \( M \) is an even number, and multiplying out the exponential, Equation (3.75) can be written in matrix form as

\[ \frac{\partial^2 U}{\partial z^2} = S^2 U \]  
(3.76)

\[ S^2 = B^{-1} \left( K_x BK_x - \Lambda \right) \]  
(3.77)

\[ B = \begin{bmatrix}
  b_0 & b_1 & \cdot & \cdot & b_M \\
  b_{-1} & b_0 & b_1 & \cdot & b_{M-1} \\
  \cdot & \cdot & \cdot & \cdot & \cdot \\
  b_{-M+1} & \cdot & b_{-1} & b_0 & b_1 \\
  b_{-M} & \cdot & b_{-1} & b_0 & b_1
\end{bmatrix} \]  
(3.78)
As with the MOL, Equation (3.76) represents a set of ordinary differential equations that can be solved analytically. The set of solutions can be written in matrix form as

\[
\mathbf{U} = \exp(\mathbf{jS}z)\mathbf{U}^+ + \exp(-\mathbf{jS}z)\mathbf{U}^-
\]

where \( \mathbf{S} \) and \( \exp(\mathbf{jS}z) \) are defined as in Equations (3.16)-(3.18). The problem space for RCWA must be discretized into sections in which the permittivity is \( z \)-invariant. At the interface between two arbitrary sections, 1 and 2, the Fourier components of the electric field are expressed as

\[
U_1 = \exp(\mathbf{jS}_1z)U_1^+ + \exp(-\mathbf{jS}_1z)U_1^-
\]

\[
U_2 = \exp(\mathbf{jS}_2z)U_2^+ + \exp(-\mathbf{jS}_2z)U_2^-
\]

In order to get the tangential magnetic field Fourier components, we first express the tangential magnetic field as a Fourier series as

\[
\mathbf{H}_x(x,z) = \sum_{m=-\infty}^{\infty} Q_m(z) \exp(-jk_x^m x)
\]

Next, we combine Equations (3.7), (3.70), and (3.72) to find
\[ \tilde{H}_x(x, z) = -\frac{1}{k_0} \sum_{m=-\infty}^{m=\infty} \sum_{m} b_{m} \left( \frac{\partial}{\partial z} U_m(z) \right) \exp(-j k_n^m x) \]  

(3.84)

Equating Equation (3.83) and (3.84) we find that the tangential magnetic field Fourier components are related to the electric field Fourier components as

\[ Q = -\frac{1}{k_0} B \frac{\partial}{\partial z} U \]  

(3.85)

Thus the tangential magnetic field Fourier components of the two sections, 1 and 2, may be expressed as

\[ -k_0 Q_1 = B S_1 \exp(j S_1 z) U_1^* - B S_1 \exp(-j S_1 z) U_1^* \]
\[ -k_0 Q_2 = B S_2 \exp(j S_2 z) U_2^* - B S_2 \exp(-j S_2 z) U_2^* \]  

(3.86)

As done for the method of lines, the fields are then matched at the boundary between the two sections and the resulting matrix equation is

\[ \begin{bmatrix} I & I \\ B S_1 & -B S_1 \end{bmatrix} \begin{bmatrix} U_1^* \\ U_1^- \end{bmatrix} = \begin{bmatrix} I & I \\ B S_2 & -B S_2 \end{bmatrix} \begin{bmatrix} U_2^* \\ U_2^- \end{bmatrix} \]  

(3.87)

At this point, following the methodology put forth in the method of lines in Equations (3.22)-(3.37) will yield the reflection and transmission coefficients for a binary or multilayer grating or changing waveguide structure. The reflected and transmitted electric field Fourier components are then given by

\[ U_R = R_{ab} U_I \]  

(3.88)

\[ U_T = T_{ab} U_I \]  

(3.89)

where \( U_I, U_R, \) and \( U_T \) are the input, reflected, and transmitted field Fourier components vectors, respectively.
For the simulation of an infinitely periodic grating a single input plane wave having unit amplitude and having wavevector component \( k_{\text{inc}} \) in the \( x \)-direction, the \((M/2+1)\)th component of \( U_j \) will be unity and all others will be zero.

If a single input plane wave with unit amplitude is used as the input, and the diffraction efficiency (DE) into the \( i^{\text{th}} \) order of the grating is the desired quantity, it is given by the following

\[
DE_{R,i} = \left| U_{R,i(M/2+1)} \right|^2 \text{real} \left( \frac{k_x^2 n_{r,1}^2 - k_z^2}{k_x^2 n_{r,1}^2 + k_{\text{inc}}^2} \right) \tag{3.90}
\]

\[
DE_{T,i} = \left| U_{T,i(M/2+1)} \right|^2 \text{real} \left( \frac{k_x^2 n_{r,2}^2 - k_z^2}{k_x^2 n_{r,2}^2 + k_{\text{inc}}^2} \right) \tag{3.91}
\]

where \( DE_{R,i} \) is the DE into the \( i^{\text{th}} \) reflected order into the originating media of permittivity \( \varepsilon_{r,1} \) and \( DE_{T,i} \) is the DE into the \( i^{\text{th}} \) transmitted order into the output media of permittivity \( \varepsilon_{r,2} \). Furthermore, \( U_{X,i(M/2+1)} \) is the \( i+M/2+1 \) component of the reflected/transmitted field Fourier component vector \( U_X \), where \( X \) can be \( R \) or \( T \).

For the simulation of a waveguide, the input \( U_j \) is selected as a propagating mode of the waveguide. For the case when the output waveguide region is the same as the input waveguide region, the reflected and transmitted power for the same mode may be calculated by taking the square of the ratio the absolute amplitude of the output mode to the absolute amplitude of the input mode.
3.1.3. Fast Fourier Transform Beam Propagation

The electric field in a given plane parallel to the x-y plane at a distance z from the origin may be decomposed into an angular spectrum of plane waves as given by [Moharam, 1995]

\[
A_j(k_x;z) = \int_{-\infty}^{\infty} E_j(x,z) \exp[-jk_x x] dx
\]  
(3.92)

The variable \( k_x \) is the spatial frequency of the field. It is assumed that the field extends infinitely in the y-direction. Equation (3.92) is a Fourier transform, and its inverse Fourier transform is given by

\[
E_j(x,z) = \int_{-\infty}^{\infty} A_j(k_x;z) \exp[jk_x x] dk_x
\]  
(3.93)

Substituting Equation (3.93) into Equation (3.10) with \( \mu_r = 1 \) results in the following:

\[
\frac{\partial^2}{\partial z^2} A_j(k_x;z) + \left[ k_o^2 \epsilon_r - k_x^2 \right] A_j(k_x;z) = 0
\]  
(3.94)

An elementary solution to this equation is written as

\[
A_j(k_x;z) = A_j(k_x;0) \exp \left[ -j \left( \sqrt{k_o^2 \epsilon_r - k_x^2} \right) z \right]
\]  
(3.95)

Thus, the electric field at a distance z can be expressed in terms of the electric field at the origin by

\[
E_j(x,z) = \int_{-\infty}^{\infty} \left( \int_{-\infty}^{\infty} E_j(x,0) \exp[-j k_x x] dx \right) \exp \left[ -j \left( \sqrt{k_o^2 \epsilon_r - k_x^2} \right) z \right] \exp[jk_x x] dk_x
\]  
(3.96)

In a numerical implementation, \( x \to x \) and will have an even numbered of samples \( N \), and the components \( k_x \) will be related to \( x \) as shown.
 Furthermore, in the numerical implementation, fast Fourier transforms and inverse fast Fourier transforms will replace the analytic Fourier transforms, such that Equation (3.96) becomes

\[
E_y(z) = \text{IFFT} \left( \text{FFT} \left( E_y(0) \right) \exp \left[ -i \left( k_0^2 \varepsilon_r - k_x^2 \right) z \right] \right)
\]

(3.98)

where \( E_y(z) \) is a vector with components \( E_y(x_i, z) \).

### 3.1.4. Numerical Correlation

The numerical correlation used in this analysis is a mode overlap integral for two electric fields. This mode overlap integral, adapted from Heinrich gives the power coupling efficiency from an input field to the mode of a device and is given by

\[
\eta^{\text{POWER}} = \frac{\left| \int \left( E_{in}^*(x) E_{\text{mode}}(x) \right) dx \right|^2}{\int |E_{in}(x)|^2 dx \int |E_{\text{mode}}(x)|^2 dx}
\]

(3.99)

Since both the mode and the input field have been numerically calculated, the integrals will be approximated by summations over the uniformly sampled range of \( x \), which has \( X \) samples. Therefore, Equation (3.99) becomes

\[
\eta^{\text{POWER}} \approx \frac{\sum_{i=1}^{X} (E_{in}^*(x_i) E_{\text{mode}}(x_i))^2}{\sum_{i=1}^{X} |E_{in}(x_i)|^2 \sum_{i=1}^{X} |E_{\text{mode}}(x_i)|^2}
\]

(3.100)
3.2. Design and Modeling of a Standard DGR

When designing a DGR, the grating parameters of both gratings play a crucial role in the overall performance. Therefore, both gratings must first be investigated independently for the design. Once the parameters and tolerances for each grating are determined, the overall structure may be modeled.

3.2.1. Grating Parameter Optimization and Tolerances

There are several design criteria for both the grating coupler and feedback grating that must be considered. Beginning with the DGR grating coupler, two conditions must be met for the grating period. First, the grating period must be short enough for the TIR condition to be met for the feedback grating and for the diffracted order into the air of the grating coupler to be cut off. Second, the grating coupler must be significantly detuned from the Bragg condition to achieve an extremely low effective reflectivity from the grating itself [Vaissié, 2005]. The condition for the grating coupler period is given by

$$\frac{\lambda_{sw}}{2n_{eff}} < d_s < \frac{\lambda_{sw}}{n_c + n_{eff}}, \quad (3.101)$$

as long as the cover index, $n_c$, is the same on both the n-side and p-side of the device. For example, for an InGaAs strained quantum well semiconductor laser grown on a GaAs substrate with a gain peak 975nm, an effective refractive index of the waveguide of 3.24, and an air cover, an appropriate grating coupler period would be 220nm. Furthermore, given the gain peak, a feedback grating period of around 410nm would also be appropriate. Another consideration for
the grating coupler that requires attention is the grating depth. The grating should be deep enough to allow a relatively short coupling length; this length should be on the order of 100-200µm. For a coupling length of 200µm, 95% of the power will be coupled out of the waveguide after 600µm; the coupling length specifies the 1/e falloff point. The coupling length is dependent mostly on the epitaxial structure and grating depth, but the tooth shape also has a small effect if the grating is too far from perfectly binary [Vaissié, 2004]. The requirements on the grating depth are restricted from both sides; if the grating is too shallow, the coupling length will be too long, but if the grating is too deep, there will be significant scattering from the grating into the laser cavity. For a waveguide with a refractive index profile as shown in Figure 3.4 (a), the coupling length versus etch depth is shown in Figure 3.4 (b) for a 50% duty cycle. Furthermore, the coupling length versus duty cycle is shown in Figure 3.4 (c) for an etch depth of 240nm. Power reflections from the grating become greater than 1% for etch depths greater than 280nm. These parameters were determined theoretically using the MOL algorithm presented previously.
Figure 3.4 (a) The index profile of the laser waveguide where the grating coupler is fabricated, (b) the coupling length versus the groove depth or etch depth of the grating coupler given a 50% duty cycle, and (c) the coupling length versus duty cycle for a 240nm etch depth.

Given a coupling length requirement of less than 200µm and a reflection of less than 1%, from Figure 3.4 it can be determined that the etch depth should be in the range of 230-280nm and the duty cycle should be in the range of 30-55%, giving a groove width range of 65-120nm.
Therefore, the tolerances on the grating coupler are not greatly restrictive. Furthermore, a duty

cycle of less than 30% may be used, but may be difficult to fabricate due to the small size of the
grooves.

The requirements for the feedback grating depend on a variety of things. First, the
feedback grating period needs to be determined such that the desired stabilization wavelength is
retro-reflected according to Equation (1.31). Second, the grating depth and duty cycle for
maximum retro-reflection must be determined. These parameters can be determined
theoretically using RCWA. Given the angle of incidence from Equation (1.27), the desired
stabilization wavelength, and the period of the feedback grating, the diffraction efficiency into
the first order, or the fraction of the retro-reflected light, is calculated using the RCWA method.

Given the example in the previous paragraph, for a perfectly rectangular tooth profile, as seen in
Figure 3.5 (a), the diffraction efficiency versus groove depth is shown for three different duty
cycles, including the optimum 51%, in Figure 3.5 (b); the duty cycle is the groove-to-period
percentage measured at half the tooth height. Note that for the duty cycles shown, a groove
depth of anywhere from 90nm to 210nm will yield a diffraction efficiency greater than 90%. For
duty cycles outside of the range shown, diffraction efficiencies of greater than 90% can still be
obtained, but with a much greater restriction on the groove depth. Tooth shape will also have an
effect on the diffraction efficiency; however, as long as the tooth profile is close to rectangular
the diffraction efficiency will not be greatly affected. For example, if the tooth profile is as
shown in Figure 3.6 (a), the diffraction efficiency versus groove depth will be as shown in Figure
3.6 (b), which is very similar to the diffraction efficiency plot for the rectangular tooth profile.
From both Figure 3.5 (b) and 3.6 (b), it can be surmised that the tolerance is fairly tight on the
duty cycle, 209nm +/-10nm in groove width, while the tolerance on the depth is very loose, 150nm +/-60nm in groove depth. However, as mention previously, high diffraction efficiencies may still be obtained if the groove width tolerance is not met by tightening the tolerance on the groove depth. It is worth noting that for different semiconductor materials operating at different wavelengths, the DGR gratings will of course have different periods, but may also have completely different tolerances.

Figure 3.5: (a) The index profile of a rectangular grating with a 410nm period and (b) the first order diffraction efficiency versus depth of this grating when it is illuminated by a plane wave at 19.8° and a wavelength of 974nm when the grating has duty cycles of 49%, 51%, and 53%.
Figure 3.6: (a) The index profile of a more realistic grating with a 410nm period and (b) the first order diffraction efficiency versus depth of this grating when it is illuminated by a plane wave at 19.8° and a wavelength of 974nm when the grating has duty cycles of 49%, 51%, and 53%.

3.2.2. Modeling of an Entire DGR Structure

Using the grating parameters within the tolerance ranges as determined in the previous subsection, the reflection as a function of wavelength may be calculated by modeling the entire DGR structure. As previously mentioned, there were two different methods used to model an entire DGR structure. The purpose of using two different methods is to have two different solutions to compare. The first method is the piecewise methods which employs four algorithms. Each of these four algorithms plays a very important role in the piecewise approach. The first step uses the MOL algorithm to generate the electric field coupled from the laser waveguide near the top of the substrate. The FFT-BP calculates the propagation of the electric field through the substrate to the location of the feedback grating. RCWA is then used to calculate the reflected field from the feedback grating. The FFT-BP is used again to calculate the return propagation.
The numerical correlation of the coupled field and the return field is calculated in order to obtain a mode-matching efficiency. This method does not take into account any other reflections of light within the DGR structure. The second method is the RCWA method with absorbing boundaries. In this method, the substrate is reduced to on the order of 12µm, and the power reflected back into the fundamental waveguide mode from the DGR is calculated. The substrate cannot be made much larger due to computational limitations, and cannot be made any smaller as evanescent fields between the grating coupler and feedback grating will start to interact.

The details for the piecewise method will be elucidated presently. In the first step of the modeling process, the MOL algorithm described is used to calculate the coupled field from the SQW-GRINSCH structure. This structure has the real refractive index shown in Figure 3.7 (a). An image of a few periods of the grating analyzed is shown in Figure 3.7 (b); the depth of this grating is 240nm, the period is 220nm, and the duty cycle is 50/50. A wavelength of 986.9nm is used for the present example. An image of the field amplitude for the transition region from the laser waveguide to the grating coupler is shown in Figure 3.8. The coupled field is the field sampled along the black line shown in Figure 3.8 for the entire length of the grating plus the standard laser waveguide regions at the beginning and end of the grating region.
Figure 3.7: (a) Real refractive index profile of the SQW-GRINCH structure, (b) real refractive index image of a few periods of the analyzed grating coupler.

Figure 3.8: Field amplitude for transition region between ~3µm of laser waveguide and first ~3.5µm of grating coupler; black line indicated plane where coupled field is sampled.
The amplitude and phase of the coupled field is shown in Figure 3.9 (a). The phase component of the field shows a coupling angle of 20.52°. The coupled field is then propagated through 150µm of the substrate n-GaAs with refractive index of 3.52; the propagated field is shown in Figure 3.9 (b). This field is broken into its angular spectral or spatial frequency components through a fast-Fourier transform. The reflection from the feedback grating is then calculated by applying RCWA to each spatial frequency component of the field and retaining the field diffracted into the 0th and 1st order. The grating is a 400nm period binary grating with a 50/50 duty cycle and a depth of 140nm; the incident medium is n-GaAs and the secondary medium is air. Each diffracted component for each incident spatial frequency component is added to the reflected field until all incident components are included. The result of this process, after transformation through an inverse fast-Fourier transform, is shown in Figure 3.9 (c). This field is propagated back through the 150µm substrate; the propagated field is shown in Figure 3.9 (d).

Using the numerical correlation given in Equation (3.100), the fields shown in Figure 3.9 (a) and Figure 3.9 (d) are correlated. The calculation described is repeated for several other sample wavelengths to yield the coupling efficiency of the return field into the laser waveguide as a function of wavelength. The results of this calculation are presented in Figure 3.10.
Figure 3.9: (a) Field amplitude and phase coupled from laser waveguide by grating coupler, (b) field amplitude and phase after propagation through substrate, (c) field amplitude and phase after reflection from feedback grating, (d) field amplitude and phase after second propagation through substrate
Figure 3.10: Coupling efficiency as a function of wavelength for 220nm period, 240nm deep, 50/50 duty cycle grating coupler operating with 400nm, 160nm deep, 50/50 duty cycle, feedback grating separated by 150µm thick n-GaAs substrate.

As for the RCWA methods, the transmission and reflection matrices were computed for the smallest length of DGR in which both the grating coupler and feedback grating both had an integer number of periods. These matrices were used to compute the transmission and reflection matrices for two periods as described in Equations (3.38)-(3.41). This process was repeated until the DGR was at least 400µm. Then, the transmission and reflection matrices for a length of the waveguide with only the feedback grating were included following Equations (3.42)-(3.45). Along with these matrices, the fundamental mode of the waveguide was used to calculate the power reflected from the DGR back into the fundamental mode. This was repeated for several different wavelengths, the results of these calculations are shown in Figure 3.11.
Figure 3.11: Fractional reflection as a function of wavelength for 220nm period, 240nm deep, 50/50 duty cycle grating coupler operating with 400nm, 160nm deep, 50/50 duty cycle, feedback grating separated by 10µm thick n-GaAs substrate. Plots for equivalent substrate loss and no loss are shown.

The results for both methods yield a peak reflection near 90% for no losses included and full-width half-maximum spectral width of 0.3nm. The locations of reflection peaks are between 986.5nm and 987nm; the fact that the reflection peaks are not perfectly identical can be accounted for by the fact that the two different methods used may have slightly different effective indices for the waveguide due to different sampling used in the calculations. The different forms of the reflection peaks can be attributed to the single roundtrip of the light for the piecewise approach versus the multiple roundtrip of the light for the RCWA method.
3.3. Design and Modeling of a Modified DGR for Narrower Spectral Width

The design considerations and tolerances for this modified DGR structure follow much of the same methodology as that followed in the previous subsections. Again, we must first be determined the optimum grating parameters for each grating before modeling the entire structure.

3.3.1. Parameter Optimization and Tolerance for a Modified DGR

For the modified DGR design as depicted in Figure 2.7, we will first consider the specifics of the grating coupler/retro-reflection grating, and second, we will consider the specifics of the redirection grating. For the modified DGR design, careful attention must be given to the grating coupler/retro-reflecting grating, as it must be optimized to perform both of these functions. As for the standard DGR, the grating coupler period must meet the requirements imposed by Equation (3.101). As we are using the same epitaxial material, we have a gain peak of 975nm, an effective refractive index of the waveguide near 3.24, and an air cover; thus, a grating coupler period of 220nm is still appropriate. The challenges associated with the grating coupler/retro-reflection grating stem from the fact that the grating parameter requirements for near 100% diffraction efficiency into the first order must be met, while also meeting the grating parameter requirements for a coupling length of 100-200µm.

Since we must know the angle of incidence onto the retro-reflection grating, we must first consider the grating period of the redirection grating. Using Equation (2.1), a quick calculation shows a redirection grating period of 285nm would yield a peak reflection near 980nm. Furthermore, applying the grating equations for the grating coupler and redirection grating,
essentially as given by Equations (1.27) and (1.28) with $\phi$ equal to zero, the angle of incidence onto the retro-reflection grating is calculated to be 39.2°. Using this angle of incidence and RCWA, the first order diffraction efficiency for the 220nm period grating coupler was calculated; the results of this calculation are shown in Figure 3.12.

![First order diffraction efficiency versus duty cycle and depth from the grating coupler/retro-reflection grating for a plane wave with an angle of incidence of 39.2°.](image)

Next, we consider the coupling length as a function of the same grating parameters as shown in Figure 3.12. The coupling length is calculated by modeling the grating coupler using the MOL, resulting in the coupling length as a function of grating depth and duty cycle as shown in Figure 3.13.
Using the plots in Figure 3.12 and 3.13, it is clear that in order to achieve both a short coupling length and high diffraction efficiency, the depth of the grating coupler should be around 260nm with a tooth-to-period duty cycle of 32%, yielding a tooth width of 70nm. The tolerances of grating parameters are a duty cycle within the range of 30-36% for the tooth-to-period duty cycle or 64-70% for the groove-to-period duty cycle with the grating depth being having the requirement

\[(255 + 3 \cdot (36 - \text{tooth/period} \times 100))\text{nm} < \text{grating depth} < 300\text{nm}.\]

With the requirements for the grating parameters of the grating coupler/retro-reflection grating established, the grating parameters required for the redirection grating can be investigated. We have already determined from Equation (2.1) that the grating period should be
approximately 285nm. Furthermore, from Equations (1.27) and (1.28) with $\phi$ equal to zero we can calculate that the angles of incidence and reflection or vice versa are 20.2° and 39.2°. Using either of these angles of incidence and RCWA, the first order diffraction efficiency of the grating can be calculated as a function of grating depth and duty cycle. The results of these calculations are shown in Figure 3.14. The optimum grating parameter range is a depth of 290-400nm and a tooth-to-period duty cycle of 56.5-58%, yielding a tooth width of 161-165nm. Due to the difficulty of achieving this type of tolerance for the duty cycle, a secondary option would be to use a grating depth of 264-280nm and a duty cycle of 48-56%, yielding a tooth width of 137-160nm.

![Figure 3.14: First order diffraction efficiency versus duty cycle and depth from the 285nm period redirection grating a plane wave with an angle of incidence of 39.2°.](image)
3.3.2. Modeling of an Entire Modified DGR

With the grating parameters determined for both the grating coupler/retro-reflection grating and the redirection grating, the entire structure may be modeled. This modeling was carried out using RCWA only as described in the subsection 3.2.2. Modeling of an Entire DGR Structure. The results of this calculation are shown in Figure 3.15; the plot in this figure shows a peak reflection of approximately 70% without losses and a spectral width of 60pm. This spectral width shows a 500% reduction from the standard DGR modeling.

Figure 3.15: RCWA modeling of the reflection from the modified DGR design with close to optimum grating parameters; no losses were included.
3.4. Alignment Tolerances of Hybrid MOPA Configuration

It is well established for other hybrid MOPA configurations that alignment required high precision [Schwertfeger, 2004]. However, for our hybrid MOPA configuration alignment tolerances were not apparent. Therefore in order to establish approximate alignment tolerances, we resolved to use numerical modeling. The tolerances that need to be addressed are depicted in Figure 3.16, and they include longitudinal alignment, longitudinal rotation, lateral alignment, and lateral rotation.

Figure 3.16: Alignment errors that can result when aligning the MO with the PA include longitudinal displacement (top left), longitudinal rotation (top right), lateral displacement (bottom left), and lateral rotation (bottom right).
The grating couplers used to couple light between the MO and PA are 270nm period gratings covered by a high-reflectivity coating; furthermore, the first 80µm of these gratings were tapered, meaning that the groove-to-period duty cycle and grating depth were both increased from the start for beam shaping and reduced reflection [Vaissié, 2005]. These two gratings were fabricated close to identical; therefore, for the sake of calculation we assumed them to be perfectly identical. Using the MOL algorithm described previously, the optical field out-coupled from the MO was calculated; this field is shown in Figure 3.17.

![Figure 3.17: Field amplitude (top) and phase (bottom) out-coupled from MO.](image-url)
The out-coupled field is then propagated through the 150µm thick substrate of the MO, the 600µm air gap between the devices, and the 150µm thick substrate of the PA using FFT-BP. The propagated field is shown in Figure 3.18.

![Figure 3.18: Field amplitude (top) and phase (bottom) propagated from the MO to the PA grating coupler.](image)

The preferred mode or field pattern at the input of the PA will be the field shown in Figure 3.19; this is simply the complex conjugate of the out-coupled field of the MO flipped from left-to-right. The flip and complex conjugate are required due to the orientation of the MO with respect to the PA.
We now have the fields which we will use to calculate the three of the four alignment tolerances that can be specified.

First, we will calculate the optimum longitudinal alignment position, along with the alignment tolerances required. This is accomplished by calculating the numerical correlation between the propagated field incident on the PA grating coupler with the preferred input mode field of the PA as the location of the preferred input mode field is shifted, essentially changing the location of the PA. The result of this calculation is shown in Figure 3.20, where $x_0$ is the distance separation distance from the beginning of the grating on the MO and the beginning of the grating on the PA as depicted in Figure 3.16. From Figure 3.20, the optimum position of the PA with respect to the MO is when the two gratings overlap by $33\mu m$ at their beginnings; furthermore to keep the coupling efficiency within 10% of its optimum, the alignment tolerance
to this optimum positioning is +/-50µm. The optimum coupling efficiency is 65% due to the amplitude differences between the incident and input modes; the coupling efficiency could be increased by optimizing the grating coupler design for optical coupling.

![Figure 3.20: Coupling efficiency as a function of the grating offsets of the MO and PA with x₀ defined as the difference between the position of the beginning of the MO grating coupler and the beginning of the PA grating coupler.](image)

In order to calculate the longitudinal rotation tolerance, we consider the MO and PA to be optimally aligned with respect to the longitudinal alignment. We include a longitudinal rotation of the master oscillator simply by adding the appropriate linear phase function to the MO incident field. The MO incident field is then numerically correlated with the preferred input mode of the PA. The results for these numerical correlations are shown in Figure 3.21. As can be seen in this figure, the alignment must be fairly precise in terms of the longitudinal rotation;
only a deviation of +/-0.06° is allowable to stay within 10% of the optimum coupling efficiency. The deviation can be up to +/-0.15° to stay within 50% of the optimum coupling efficiency.

Figure 3.21: Coupling efficiency as a function of the longitudinal rotation of the MO with respect to the PA.

In terms of lateral displacement, we simply make the assumption that the field has a flat top profile in the lateral direction; this is generally a reliable assumption for these broad area straight stripe devices. We will also assume the phase profile in the lateral direction to be flat, a stripe width of 200µm, and optimum alignment in terms of longitudinal displacement and rotation. With these assumptions, we can say that whatever light falls on the PA grating coupler will be coupled. Therefore, a 10% drop will be experienced if a 10% shift occurs; hence, the lateral displacement alignment tolerance is +/-20µm to maintain 90% of the optimum coupling efficiency, with the optimum location being the two devices centers aligned.

In terms of the lateral rotation, we make at best a first order approximation. We assume that all other alignment is optimum. We assume that rotation of the MO will effectively result in
the field being compressed by the factor \( \cos(\varphi) \) in the longitudinal direction. This not only changes the field amplitude, but also the phase. The change in phase in the longitudinal direction is directly related to the change in polarization due to the lateral rotation. We can directly relate the lateral rotation angle to the longitudinal rotation angle by using Equation (1.26). Then using the method used for the longitudinal rotation angle, we can find the coupling efficiency. The result of these calculations is shown in Figure 3.22; from these calculations, the lateral rotation needs to be within +/-0.7° to be within 10% of the optimum coupling efficiency.

![Figure 3.22: Coupling efficiency as a function of the lateral rotation of the MO with respect to the PA.](image)

3.5. Conclusion

The modeling methods used in this work have been presented; these methods include the MOL, the fast Fourier beam propagation method, RCWA, and a numerical correlation. These methods were then used to design and model both a standard DGR and a modified DGR.
designed for narrower spectral width. This design includes modeling of each individual grating to optimize the grating parameters for the best performance and also yields the tolerances required for fabrication. The alignment tolerances between the MO and PA for the hybrid MOPA configuration were also theoretically determined using the majority of these modeling methods.
CHAPTER 4 : FABRICATION

The following sections describe the entire processing of the laser diodes starting from a supplied epitaxial wafer. The order of processing presented here is not necessarily the only order that can be or has been followed; for certain process combinations, the order does not matter. The lithographic fabrication processes for the semiconductor diode lasers include lapping and polishing of the substrate, n-contact processing, p-contact processing, mesa etching, grating fabrication, antireflection coating fabrication, and high-reflection coating fabrication. The final step in the fabrication process is the post lithographic process; this process includes the cleaving, submount bonding for thermal management, and wiring for electrical pumping.

4.1. Lapping and Polishing

The epitaxial wafer is usually a 3” or 4” n-doped GaAs wafer with epitaxial grown material providing the waveguide and gain medium, which can be either a single quantum well, multiple quantum wells, or quantum dots. For all devices presented in this work, the epitaxial material was grown on an n-GaAs substrate. The quantum well is a strained InGaAs layer with approximately 20% In. The SCH is formed by graded AlGaAs, ranging from about 70% to 0% Al concentration yielding a grating index. An InGaP layer is grown approximately 250nm above the SCH to provide an etch stop for the fabrication process. No further information about the epitaxial material beyond that provided can be given due to a nondisclosure agreement with the grower. This wafer is cleaved by hand into small blocks on the order of 2cm by 2cm. As the
wafer is approximately 650µm thick, each block is thinned to ~160µm and polished to a root mean squared (RMS) surface roughness of approximately 2nm as seen in Figure 4.1. Lapping or thinning of the wafer is necessary in order to reduce the total absorption experienced by the light passing through the substrate due to free carriers. Polishing is necessary to reduce scattering from defects that can occur at the feedback grating or output area.

For the polishing process, a block is mounted on a polishing fixture with the n-side of the epitaxial block exposed. The fixture is then placed on a South Bay Technologies Model 920 Lapping and Polishing Machine with a 30µm grit diamond pad. The block is thinned on the substrate side by removing approximately 400µm of GaAs. The pad is changed to a 9µm grit diamond pad, and 70µm of material is removed. Then, the pad is changed to a 6µm grit diamond pad, and the block is polished for 20 minutes. Then, the pad is changed to a 3µm grit diamond pad, and the block is polished for 20 minutes. Then, the pad is changed to a 1µm grit diamond pad.
pad, and the block is polished for 15 minutes. The final polishing step is carried out with a MasterTex™ polishing cloth. The block is polishing with the cloth along with 0.05µm colloidal silica slurry plus a few milliliters of a solution of diluted NaOCl. The NaOCl solution is 5% household bleach and 95% deionized (DI) water. This final step is a chemical-mechanical polishing step in which the active oxygen from the NaOCl solution reacts with the GaAs to produce Ga₂O₃ and As₂O₃ [Higuchi, 1989]. These products are then removed by the friction of the polishing cloth and colloidal silica. This final polishing step is carried out for 30-90 minutes. This polishing process results in an RMS surface roughness of less than 2nm, as previously stated.

4.2. Contact Fabrication

The p-side and n-side contact processes are very similar; therefore, the common elements will be elucidated and differences will be explicitly stated. The basic steps for contact fabrication are the lithographic definition of the contacts, metallization, liftoff, and annealing, as depicted in Figure 4.2.
The contact process begins with mounting the block, with the correct side exposed, on a slightly larger piece of silicon wafer using Futurrex PC3 planarization coating as a temporary adhesive; this provides mechanical stability for the fragile GaAs block during processing. The block is first rinsed with Acetone and isopropyl alcohol. The block is then bathed in a 10% HCl solution for 60 seconds, followed by a DI water rinse, to clean the block surface. Water should bead up and run of the GaAs surface. In some instances, a 10:1 buffered oxide etchant (BOE) solution may be used to remove difficult residues.

Once the block is mounted and properly cleaned, it is spin coated with Futurrex NR7-1000PY negative photoresist at a spin speed of 4000RPM. The resist coated block is prebaked at 150°C for 70 seconds. The block must be properly aligned to the contact mask for exposure. Typically, the p-side contact is the first to be completed. For the alignment of the p-side contact mask, crystal axes of the block must be aligned with the sides of the mask such that the block can
be cleaved into single devices after all lithographic fabrication has been completed. For the n-side contact, the mask must be aligned with previously processed contacts on the p-side of the device. This is accomplished by a front-to-back alignment feature available on the Quintel Ultra7000 µ-Line series mask aligner. This setup uses an infrared source to backlight the sample. The p-side contacts create shadows. These shadows are then aligned to the n-side mask to complete the alignment processes, as depicted in Figure 4.3. When the block has been properly aligned, the photoresist is exposed with 150mJ/cm². The block is then postbaked for 70 seconds at 100°C. After cooling, the resist is developed in a 3:1 solution of Futurrex RD6 and DI water until the exposed resist is removed from the contact areas, approximately 2 minutes and 30 seconds. The block is rinsed in DI water and blown dry with nitrogen.

![Figure 4.3: Front-to-back alignment scheme for aligning p-side and n-side contacts.](image)

Immediately before metallization, the block is bathed in a 10% HCl solution for 90 seconds, rinsed in DI water, and blown dry with nitrogen. The block is then placed in the metal deposition chamber. For the n-side contacts, the first metal layer is 4nm of nickel; this
layer serves as an adhesion layer. The second layer is 20nm of germanium; the germanium diffused into the n⁺GaAs during the annealing process to create an ohmic contact. The third layer is 250nm of gold; this layer is the highly conductive transport layer. For the p-side contact, the first layer is 20nm of titanium; this layer serves as an adhesion layer. The second is 20nm of platinum; this layer serves as a diffusion barrier so that the gold in the third layer does not diffuse into the p⁺GaAs. The third layer is 100nm of gold; this layer is again a highly conductive transport layer.

After the metal deposition is completed, the block is placed in acetone for more than 6 hours. The acetone dissolved the resist releasing the deposited metals from the non-contact areas in approximately 20 minutes; this process is also known as liftoff. Liftoff is made possible by the negative sidewall profile provided by the NR7-1000PY resist as shown in Figure 4.4. The remaining time is required for the acetone to dissolve the PC3 between the GaAs block and silicon mount. The block is removed from the acetone and rinsed in isopropyl alcohol and blown dry with nitrogen. After both contact processes have been completed, the block is annealed in a rapid thermal annealer (RTA) for 60 seconds at 400°C. This completes the contact processing.
4.3. Mesa Etching

The next step in the diode processing is the etching of the mesas; this step is depicted in Figure 4.5. The mesa etching process provides two functions. The first function is to help provide current confinement by removing the p-cladding from the unpumped areas. The second function is to remove the material on top of the grating region. This material must be removed so that the grating couplers can be fabricated in the correct proximity to the waveguide. This process, like the contact processes, begins with mounting the block p-side exposed on a slightly larger silicon piece with PC3 to provide a high mechanical stability. The block is then spin coated with Shipley 1813 positive photoresist at a spin speed of 3000RPM. The block is then prebaked at 115°C for 90 seconds. After alignment of the block to the mesa mask, the resist is exposed with 125mJ/cm². The block is then postbaked at 115°C for 60 seconds. After cooling,
the sample is developed in a 1:5 solution of 351 and DI water until the resist is cleared, approximately 2 minutes. After a DI water rinse, the block is baked for an additional 3 minutes at 130°C to reflow the resist in order to smooth the resist edges. The block is then wet etched in a 1:1:6 solution of 85% phosphoric acid (H₃PO₄), 30% hydrogen peroxide (H₂O₂), and DI water for 80 seconds and rinsed in DI water afterward. The wet etch step removes the GaAs and AlₓGa₁₋ₓAs layers down to the InₓGa₁₋ₓP etch stop. The removal rate of the GaAs and AlₓGa₁₋ₓAs is approximately 14nm/sec, whereas it takes several minutes for the etchant to start damaging the aptly named 20nm InₓGa₁₋ₓP etch stop. The resist mask is then removed with acetone and isopropyl alcohol.

Figure 4.5: Depiction of the mesa etching process steps.

A specific detail that should be noted on the wet etching of GaAs and AlₓGa₁₋ₓAs is the crystal axes dependent etching characteristics. As seen in Figure 4.6, there is a notable change in
the profile of the etched material according to the crystal axes. While this profile change may be noticeable, its impact to the device is rather small due to the high optical confinement provided by the separate confinement heterostructure. Modeling of the profiles using the MOL reveals that the reflection from the active region to the etched region into the fundamental mode is less than $10^{-7}$, and the total scattering from the transition is less than $10^{-3}$ for both etch profiles. Therefore, the orientation of the transition region between the active area and etched region should not matter; furthermore, mesas of any geometry of active area can effectively be wet etched without concerns of direction dependence due to the high confinement of the optical mode in this epitaxial material design.

![Wet etch profiles of GaAs and Al$_x$Ga$_{1-x}$As layers with respect to the crystal axes.](image)

Figure 4.6: Wet etch profiles of GaAs and Al$_x$Ga$_{1-x}$As layers with respect to the crystal axes.
4.4. Grating Fabrication

After the wet etch process, the p-side gratings can immediately be fabricated. The n-side gratings are fabricated with a very similar process; therefore, the common elements of the processing of the gratings will be elucidated and differences will be explicitly stated. The basic steps for grating fabrication are resist coating, patterning, and etching as depicted in Figure 4.7.

![Figure 4.7: Depiction of the grating fabrication process steps.](image)

The dimensions of the gratings needed for the DGR are relatively small and cannot be fabricated by standard photolithographic means. The features sizes needed for DGR fabrication are in the range of 60-210nm; these features are the grooves or teeth of a grating with periods in the range of 220-410. In order to attain these feature sizes, e-beam lithography is used. The tool used is a Leica 5000+ EBPG.
In order to prepare the sample for e-beam lithography, the block mounted on the silicon piece is spin coated with ZEP-520A electron beam resist at a spin speed of 4000RPM. The block is baked for 3:00 on a hotplate at 180°C.

Once prepared, the block is then placed on the appropriate e-beam holder, aligned, and placed into the e-beam loadlock. After pumping down the loadlock, the block is loaded into the e-beam chamber, the appropriate pattern is selected, and the resist is exposed at the appropriate locations with the appropriate dose. The appropriate dose varies according to several parameters, including the period of the grating to be written, the substrate or composition of material, the designed linewidth, the resist thickness, the writing resolution, and other parameters. Therefore, the appropriate dose is determined experimentally with a disposable sample of a given material using a dose matrix. For the dose matrix, the pattern is exposed with various doses that are known to be close to the correct dose. The disposable sample is etched, cleaned of resist, and inspected with a scanning electron microscope to determine which dose yields the required grating duty cycle for the pattern used. Examples of appropriate doses are given in Table 4.1.

<table>
<thead>
<tr>
<th>Period (nm)</th>
<th>220</th>
<th>270</th>
<th>350</th>
<th>400</th>
<th>285</th>
</tr>
</thead>
<tbody>
<tr>
<td>CAD Linewidth (nm)</td>
<td>30</td>
<td>30</td>
<td>37.5</td>
<td>170</td>
<td>45</td>
</tr>
<tr>
<td>Resolution (nm)</td>
<td>10</td>
<td>10</td>
<td>12.5</td>
<td>10</td>
<td>15</td>
</tr>
<tr>
<td>Dose (µC/cm²)</td>
<td>245</td>
<td>345</td>
<td>400</td>
<td>91</td>
<td>260</td>
</tr>
</tbody>
</table>
After exposure, the block is removed from the e-beam and developed in ZEP-RD for 90 seconds, rinsed in isopropyl alcohol, and blown dry with nitrogen.

After the patterning of the gratings in the resist, the pattern is transfer etched into the device material. This transfer etch process is carried out in a Unaxis Shuttleline ICP-RIE etcher with flow rates of 20sccm boron trichloride (BCl₃), 10sccm of argon, and 5sccm of nitrogen at a pressure of 3mT with an ICP power of 400W and an RIE power of 60W for 65 seconds for p-side gratings and 37 seconds for n-side gratings. Details on the physics and the development of this etch process are given by Vaissié, 2004. After etching, the sample is cleaned with methylene chloride, acetone, and isopropyl alcohol.

4.5. High-Reflection Coating Fabrication

After both p-side and n-side gratings have been fabricated, the p-side high-reflection coating is fabricated. The p-side high-reflection coating processes consist of a blanket deposition of nitride on the p-side, a resist masking which opens areas over the contact and DGR grating coupler, an RIE etching to remove the nitride from the contact and DGR grating coupler, a resist masking which opens areas over the contact and out-coupling grating, and a metallization; the entire high-reflection coating fabrication process is depicted in Figure 4.8.
Figure 4.8: Depiction of the high reflection coating fabrication process.

The blanket deposition is a film of silicon nitride; this nitride is deposited through a plasma enhanced chemical vapor deposition with flow rates of 8sccm of NH₃, 250sccm of SiH₄, and 650sccm of N₂ at a pressure of 40mT with an RIE power of 25W and a temperature of 250°C for 13 minutes. The deposition rate of this process is 9.4nm per minute, yielding a total thickness of 122nm.

After the deposition, the block is mounted on a slightly larger silicon wafer piece with PC3. The block is then spin coated with NR7-1000PY at a spin speed of 4000RPM. The block is prebaked at 150°C for 70 seconds. When the block has been properly aligned to the high reflection coating nitride removal mask, the photoresist is exposed with 150mJ/cm². The high reflection coating nitride removal mask creates openings on the contacts and the DGR grating coupler. The block is then postbaked for 70 seconds at 100°C. After cooling, the resist is developed in a 3:1 solution of Futurrex RD6 and DI water until the exposed resist is removed.
from the contact areas, approximately 2 minutes and 30 seconds. The block is rinsed in DI water and blown dry with nitrogen.

The block is then etched in an RIE plasma with flow rates of 36sccm of CF₄ and 4sccm of O₂ at a pressure of 40mT and an RIE power of 100W for 110 second; this etch process removes the resist from the contacts and the DGR grating coupler. The resist mask is then removed with acetone and isopropyl alcohol.

The same resist mask fabrication step described is used to create a second resist mask. This resist mask is the high reflection metallization mask; this mask creates openings over the contacts and the nitride coated out-coupling gratings. The block is then deposited with 5nm of chrome or nickel for adhesion and 250nm of gold. The block is placed in acetone to dissolve the resist mask and liftoff the unwanted metal. After rinsing in isopropyl alcohol and drying, the high-reflection coating is complete.

4.6. Antireflection Coating Fabrication

Next, the antireflection coating is fabricated on the n-side of the device. The processing for this coating is identical to the nitride deposition and removal of the high-reflection coating fabrication, except of course for the masks used. After the 13 minute silicon nitride deposition, the resist mask used for the nitride etching is fabricated; this mask opens the areas over the contacts and the feedback gratings. The same RIE plasma process used during the high-reflection coating fabrication is used to remove the unwanted nitride. After removing the resist mask with acetone and isopropyl alcohol, the antireflection coating is complete.
4.7. Post Lithographic Fabrication

With the lithographic fabrication completed, the block is cleaved into separate devices using a Dynatech automated cleaver. Individual devices are then bonded p-side down on an aluminum nitride submount with pre-deposited Au-Sn eutectic solder. Bonding p-side down makes for more efficient removal of the heat generated in the active area of the devices. The n-side contacts of the devices are then wired to a current standoff on the submount using a 1mil or 25.4µm diameter gold wire using ball/edge ultrasonic wire bonding. Multiple wire bonds are made in order to promote uniform pumping of the active region of the broad area devices. Once the devices are wired, they are ready for testing and characterization.

4.8. Conclusion

The entire fabrication process for the processing of the semiconductor lasers used in the research presented in this work has been presented. These processes include the lapping and polishing of the substrate, n-contact processing, p-contact processing, mesa etching, grating fabrication, anitreflection coating fabrication, high-reflection coating fabrication, and post lithographic processing.
CHAPTER 5: CHARACTERIZATION AND RESULTS

The fabricated devices, which are mounted p-side down on aluminum nitride submounts, are mounted on a thermo-electric cooler (TEC) mounted on a water cooled copper heatsink to help maintain the device temperature during testing. Each device is tested under pulse pumping conditions and continuous wave (CW) conditions when possible. In order to characterize the devices, several different measurements were taken. The first of these measurements was the light-current characteristics of the device. The second of these measurements is the voltage-current characteristics. The third measurement is the spectral output of the device. There are a few other measurements that may be taken beyond these primary three; these measurements include the near field, the far field, and the spectral drift of the output as a change of operation temperature. The specifics of these measurements will be explained. Following this, the experimental results of the five research efforts made, as mention in the Research Overview section, will be presented. As previously mentioned, the first research effort was the inclusion of a DGR into a laser to prove the efficacy of the DGR concept. The second effort was the inclusion of more than one period into the DGR into a laser to force the device to lase at multiple wavelengths. The third effort was to show that a DGR could be integrated into different device geometries. The fourth research effort was the design and inclusion of a modified DGR into a laser design to determine the limit of the spectral width possible from a DGR laser. The final research effort was the combination of a GCSEL DGR laser with a flared grating-coupled semiconductor optical amplifier (GCSOA) in a MOPA configuration in order to achieve a high
peak output power. The results of these research efforts will be covered in the following subsections.

5.1. Testing Methods

The light-current characteristics are measured by taking the average optical power using an Ophir 20C-SH thermal detector. For QCW pumping, the peak current is delivered by a Directed Energy PCX-7410 current driver for peak currents below 10A and a Directed Energy LDX-100 current driver for peak currents of up to 100A, depending on the pulse width and frequency. For CW pumping conditions, the current is delivered by a Newport 5600 current driver. For pulse pumping conditions, the average power measurement is used to calculate the peak power. This calculation assumes the pulse width, \( W \), of the electrical pulse and optical pulse are the same; this assumption is valid as long as the electrical pulse is significantly larger than the carrier lifetime in the material. The peak power, \( P_{\text{peak}} \), is calculated from the average power, \( P_{\text{average}} \), as given by

\[
P_{\text{peak}} = \frac{P_{\text{average}}}{W \cdot f},
\]

where \( f \) is the frequency of the pulses. Once the optical power versus current curve is recorded, the threshold current is determined by tracing the linear fit of the lasing points back to the current axis, as shown in Figure 5.1 (a). The linear fit of the lasing points has a slope that is known as the light-current characteristic slope, which has units of W/A.
The voltage-current characteristics are measured under CW conditions only. This measurement allows us to determine the serial resistance of the laser diode. The serial resistance is determined by the slope of the voltage-current characteristic slope as shown in Figure 5.1 (b).

The spectral output of a device is measured using an HP86142B Optical Spectrum Analyzer (OSA), which has a maximum resolution of 0.06nm. The light from the device is coupled into the OSA using a multimode fiber. Light is coupled into the fiber from the device within about a millimeter of the n-side surface; the fiber is oriented such that the light from the out-coupling grating is normally incident.

The near-field and far-field are measured using a charge-coupled device (CCD) camera and Spiricon image capturing software. For the near-field, the camera is focused on the emission
from the out-coupling grating with the camera oriented with respect to the device such that the light from the out-coupling grating is normally incident on the camera. Normally, a neutral density filter is placed between the device and the camera to reduce the intensity of the light on the CCD to avoid saturation. For the far-field, a screen was moved along the beams propagation direction. The camera was then focused on this screen to record the far-field image at given distances from the devices emitting area. The screen has several scale markings so that the beams divergence can be determined according to the size of the beam at given positions.

The spectral drift of the output is determined under pulse pumping conditions. For a given operation current, the spectral output of the device is recorded as the TEC operating temperature is adjusted and allowed to settle. Thus, the change in the spectral output as a function of the operating temperature is determined.

5.2. Single Wavelength Dual Grating Reflector Laser

Two different device sets were fabricated and tested to validate the idea of the DGR. The first set was a set of DGR lasers fabricated as GCSEL lasers, such that we could obtain the best light current characteristics; GCSEL outputs were used since we do not have the capability to fabricate good antireflection facet coatings. The second set of devices was fabricated with a cleaved facet output in order to estimate the effective reflectivity of the DGR section.
5.2.1. Single Wavelength DGR GCSEL Lasers

Several devices were fabricated and tested to validate the idea of the DGR; two sets of devices were fabricated on separate substrates. Figure 5.2 (a) shows a schematic of one of the devices, while Figure 5.2 (b) shows an actual device in operation. The SQW is a strained InGaAs layer on the order of 8nm thick with approximately 20% In, and the GRINSCH structure is an AlᵪGa₁₋ᵪAs linearly graded composition structure. The grating coupler period is 220nm with an effective refractive index determined to be very near 3.244. Two different feedback grating periods were used; these periods were 405nm and 410nm. The active lengths of the devices were 2mm, along with an active width of 200µm. The DGR grating lengths were 650µm, while the out-coupling grating length was 400µm followed by a cleaved facet to allow for a higher feedback reflection from the out-coupling grating section. The devices were tested under both CW and pulse pumping conditions to determine the lasing thresholds, light-current characteristic slopes, stabilized wavelengths, spectral widths, and wavelength shifts versus temperature.

![Figure 5.2: (a) Schematic of a single-wavelength DGR device and (b) a fabricated device under testing.](image)
The devices from the first substrate showed the best CW operation due to the position of the gain peak with respect to the resonant wavelengths; however, the performance could have been better since the feedback grating did not meet the intended specifications. These specifications called for a tooth-to-period duty cycle ranging from 46-51%, while the duty cycle was 42% for the first substrate and 51% for the second substrate, as shown in Figure 5.3. The second substrate had feedback gratings that meet the intended specifications; however due to a shift of the gain spectrum, the devices only worked well during pulse pumping.

![Figure 5.3: Top view of a feedback grating from (left) the first substrate and (right) the second substrate.](image)

For two devices from the first substrate, the optical power versus current was measured at a TEC temperature of 20°C. The slope of the CW light-current characteristic slopes were 0.85W/A and 0.84W/A and the current thresholds were 658mA and 649mA for the devices with the 410nm and 405nm feedback gratings, respectively, see Figure 5.4. The maximum wall plug
efficiency achieved with these devices was 31% at the peak output power. Under pulse pumping conditions, the light-current characteristic slopes were 0.88W/A and 0.84W/A for the devices with the 410nm and 405nm feedback gratings, respectively. Note that the kink in Figure 5.4 comes from the device mode hopping to a shorter wavelength further from the gain peak. This spectral mode hop is approximately 0.7nm from the original spectral mode; 0.7nm corresponds to the mode spacing of the 150µm substrate. This mode hop is thermally induced and is not seen in the pulse pumping light-current characteristics. The second device original experienced a mode hop of 0.7nm to a shorter wavelength, corresponding to the mode spacing of the 150µm substrate, at about the same operating current, but the phenomenon subsided after many hours of operation of the device.

![Figure 5.4](image.png)

Figure 5.4: Optical output power versus injection current under CW conditions at 20°C for the devices with 410nm (solid) and 405nm (dashed) periodicity feedback gratings.

The voltage-current measurements revealed a serial resistance of the devices to be 0.1-0.2Ω. The lasing spectral characteristics presented in Figure 5.5 (top) were measured at pump
currents near 2A, corresponding to output powers of 1W. The lasing wavelengths at these currents were 977.5nm and 981.3nm for the devices with the 410nm and 405nm feedback gratings, respectively. The nearest spectral peak was 30dB below the stabilized wavelength peak for both devices. The measured 3dB level spectral width for both devices was less than 0.2nm. The normalized spectral density before threshold of a single device, shown in Figure 5.5 (bottom), shows the mode spacing of approximately 0.7nm; this mode spacing corresponds to additional modes within the DGR, with the spacing determined by the thickness of the substrate.

Figure 5.5: Normalized power spectral densities (top) of the devices outputs at 1W and (bottom) of a single device near threshold.
Under pulse pumping conditions, 500nsec at 10kHz, we measured the temperature dependence of the stabilized wavelength. For the devices, the change in stabilized wavelength relative to temperature was 0.09nm/°C, while maintaining a narrow lasing spectral width; this shift is approximately 0.3nm/°C for the spontaneous emission. The change in stabilization wavelength with temperature exhibited by the DGR device is similar to that seen in DBR and DFB diode lasers. Under the same pulse pumping conditions, the stabilized wavelengths were 975.4nm and 979.6nm, which are within 0.2nm of the stabilized wavelength predicted by Equation (1.31). Regarding the lasing wavelengths under CW conditions, there is a red shift of approximately 1.9nm from those under pulse pumping conditions. This resulted from a higher junction temperature and therefore a higher effective refractive index under CW conditions.

The near-field and far-field of the device with the 410nm period feedback gratings was recorded and are shown in Figure 5.6. The divergence of the far-field perpendicular to the active stripe of the device is 0.4°, and the divergence of the far-field parallel to the active stripe of the device is 4.5° at a peak pump current of 4A.

Figure 5.6: The near-field image of one of the tested DGR lasers (left), and the far-field image shown in the inset with the profiles of the far-field parallel (blue) and perpendicular (red) to the active length of the laser showing the divergence angle of the beam (right).
The light-current characteristics and spectral characteristics of two devices from the second substrate were also tested with a TEC temperature of 20°C. Under pulse pumping conditions of 500ns and 10kHz, the light-current characteristic slopes were 0.93W/A and 0.96W/A and the current thresholds were 675mA and 699mA for the devices with the 410nm and 405nm feedback gratings, respectively, see Figure 5.7. Due to the thermal shift of the gain spectrum during CW operation, the light-current characteristic slopes reduced to 0.17W/A and 0.53W/A for the devices with the 410nm and 405nm feedback gratings, respectively. The spectral samples of these devices also had spectral widths less than 0.2nm.

Figure 5.7: Peak optical output power versus peak injection current under pulse pumping conditions for devices with 410nm (solid) and 405nm (dashed) periodicity feedback gratings.

Compared to the previously researched integrated wavelength stabilization schemes presented in the Introduction section, the DGR laser has a higher L-I slope, a minimally higher
wall plug efficiency, a lower threshold current density (except for the MOPA), and a fabrication advantage in terms of feature sizes in comparison with the grating ring oscillator and the MOPA device. We have achieved a maximum single spectral output of 1.9W CW on par with other devices. All technologies seem to have comparable side mode suppressions as well. On the negative side, the spectral width is on the order of 0.1-0.2nm, which isn’t quite as narrow as the spectral width reported for the other technologies, but is still quite good for a variety of applications. Also, the DGR laser appears to be a multimode device, and therefore, may be limited to pumping applications. Concerning the best external cavity device researched, the DGR laser has the advantage that arrays can be fabricated with multiple wavelengths with no external optics and alignment needed for stabilization. An individual DGR laser is not highly tunable like the external cavity device and some of its performance characteristics are slightly worse.

5.2.2. Single Wavelength DGR Cleaved Facet Lasers

As previously mentioned, the fabrication and testing of these cleaved facet output devices was carried out in order to estimate the effective reflectivity of the DGR section. The light-current characteristics of several devices, like that depicted in Figure 5.8, were measured under pulse pumping conditions. These devices had active widths of 200µm and active lengths of 2mm. Fabry-Perot lasers were made during the same processing with the same active areas to aid in the estimation of the DGR reflection.
The characteristics of several cleaved facet DGR lasers were measured; these devices had an average light-current characteristic slope of 0.52W/A for the cleaved facet output. The similar Fabry-Perot lasers had an average light-current characteristic slope of 0.41W/A for one of the two cleaved facet outputs. In order to eliminate the internal quantum efficiency from the calculation of the differential quantum efficiency, we use the ratio of these two light-current characteristic slopes. Using the measured light-current characteristic slopes, we have a ratio of these slopes, which is the same as the ratio of the differential quantum efficiencies, of the FP laser cleaved facet to the DGR laser cleaved facet output of 0.79. Using Equations (1.21) and (1.25), we can calculate the ratios of the differential quantum efficiencies to be

$$\frac{\eta_{FP}}{\eta_{DGR}} = \frac{1}{2} \left( 1 + \frac{R_{FP}}{R_{DGR}} \left( 1 - R_{DGR} \right) \right) \ln \frac{R_{FP}}{R_{DGR}} \frac{2 \alpha_s L - \ln R_{FP} R_{DGR}}{\alpha_s L - \ln R_{FP}},$$

where $\alpha_s$ has been specified and measured to be 2.5cm$^{-1}$, and the reflection term $R_{FP}$ has been specified to be 0.32 from FP laser characterizations. Letting $R_{DGR}$ vary and solving the Equation...
graphically for the ratio equal to 0.79, we find the power reflection of the DGR section to be 62%. This reflection is about 10% lower than predicted by the modeling and may be attributed to grating roughness resulting in a higher fraction of scattered light or higher losses than anticipated in the passive waveguide section.

The threshold current for these cleaved facet DGR lasers was on the order of 75A/cm², while the threshold current for the Fabry-Perot lasers was on the order of 65A/cm². While the DGR does indeed have a higher reflectivity, the passive section in which the DGR section is incorporated introduces initial losses that the Fabry-Perot lasers do not have to overcome. Therefore, these losses reduce the effective reflection of the DGR section at low powers until the losses are overcome.

5.3. Dual Wavelength Dual Grating Reflector Laser

The dual wavelength dual grating reflector (DWDGR) laser is much like the single wavelength DGR laser, except that the feedback grating is split in two separate areas and contains two separate periods as shown in Figure 5.9 and Figure 5.10.

The first design investigated was that shown schematically in Figure 5.9. The two periods of the feedback grating were chosen to be 408.7nm and 411.3nm; these periods yield theoretical locking wavelengths of 976.5nm and 974.2nm as determined by Equation (1.31). The device had an active length of 2mm, along with an active width of 100µm. The DGR grating lengths were 650µm, while the out-coupling grating length was 400µm followed by a cleaved facet to allow for a higher feedback reflection from the out-coupling grating section. The device
characteristics were measured under pulse pumping conditions with input current pulses of 500ns at a repetition rate of 10kHz. These measured characteristics included peak output optical power versus peak input current, the spectrum of the output light, the wavelength shift versus temperature, and the far-field.

Figure 5.9: Schematic of the first design of the DWDGR laser showing a cross section of the device (top) and a view of the n-side of the device (bottom).

Figure 5.10: Schematic of modified design DWDGR laser showing the alternative feedback grating design to allow for a laterally collocated output.
The peak output power versus peak input current device characteristics are shown in Figure 5.11. As shown, the light-current characteristic slope of the device is 0.86 W/A and the threshold current is 365mA. The thresholds for individual lasing lines were approximately the same; the relative difference was measured to be 8%, which is in the error range associated with evaluation of the threshold current by L-I characteristics. Voltage-current measurements revealed a serial resistance of the device to be 0.31Ω. The normalized emission spectrum of the device for a temperature of 20°C and a peak pump current of 3.0 A is shown in Figure 5.11. The lasing peak amplitudes remain within 25% of one another over the peak current range of 0.5-7.0A at 500ns pulse widths and a 10kHz repetition rate, with the longer wavelength dominant above threshold at lower currents and the shorter wavelength dominant at higher currents. The nearest spectral peak was measured to be 26dB below the two lasing peaks, as can be seen in Figure 5.12. The lasing wavelength peaks were measured to be 974.3nm and 976.3nm, which are within 0.2nm as determined by Equation (1.31). The 3dB level or full width at half maximum (FWHM) spectral width of the two spectral peaks is measured to be less than 0.2nm.
Figure 5.11: Light-current characteristics of DWDGR laser under 500nm/100kHz pulse pumping.

Figure 5.12: Measured spectrum for the DWDGR laser at a peak current of 3.0A and a temperature of 20°C.
The lasing wavelength peak shift versus temperature is shown in Figure 5.13 for the two wavelengths simultaneously emitted from the device. This data shows that the peaks are red shifted in relation to the temperature at a rate of about 0.09nm/°C, which is approximately one third of the common spontaneous emission shift of ~0.3nm/°C. The lasing peak shift versus temperature can be mostly attributed to a change in the effective refractive index of the grating region as a function of temperature.

![Figure 5.13: DWDGR laser spectral lasing peaks shift in wavelength versus temperature and a peak current of 1.0A/500ns/10kHz conditions.](image)

The device was also tested under DC pumping conditions. Under CW conditions, the device had a light-current characteristic slope of 0.79W/A and a threshold current of 386mA. The serial resistance was 0.3Ω. An output power of 1.2W was achieved at a current of 2.0A. Previously, the maximum amount of output power demonstrated for dual wavelength emission...
from a semiconductor laser was a peak power of 75mW with a side mode suppression of 20dB [Li, 2000].

The near-field and far-field of the device was recorded; these images are shown in Figure 5.14. The modulation in the near-field is due to an improper alignment of the neutral density filter. The two separate beams in the far-field are a result of the dispersion of the out-coupling grating. The far-field image shows that while the split of the feedback grating separates the feedback wavelengths spatially, at least some of the active area of the device amplifies and experiences both wavelengths simultaneously.

The modified design of the DWDGR laser investigated is that shown in Figure 5.10. This design was investigated in order to see if the modified design would create a collocated output in the lateral direction, as opposed to the somewhat laterally separated far field of Figure

Figure 5.14: The near-field image of the DWDGR laser (left), and the far-field image of the DWDGR laser (right).
5.14. In the modified DWDGR design, the two periods of the feedback grating were chosen to be 405nm and 410nm; these periods yield theoretical locking wavelengths of 981.5nm and 977.3nm as determined by Equation (1.31), given an effective refractive index of 3.25. The higher refractive index is due to the 220nm period grating coupler being fabricated outside of the required specifications; the grating depth is approximately 220nm. The device had an active length of 2mm, along with an active width of 200µm. The DGR grating lengths were 650µm, while the out-coupling grating length was 400µm followed by a cleaved facet to allow for a higher feedback reflection from the out-coupling grating section. The 650µm feedback grating was separated into two sections; the first section was 100µm in length with a period of 405nm, and the second section was 550µm in length with a period of 410nm. The device characteristics were measured under pulse pumping conditions with input current pulses of 500ns at a repetition rate of 100kHz. These measured characteristics included peak output optical power versus peak input current, voltage-current characteristics, the spectrum of the output light, and the far-field.

The peak output power versus peak input current device characteristics under QCW operation are shown in Figure 5.15 (left), while the voltage-current characteristics and light-current characteristics under CW operation are show in Figure 5.15 (right). The light-current characteristic slope under QCW operation of the device is 0.67 W/A at a heat sink temperature of 30°C, and the light-current characteristic slope under CW operation is 0.27W/A at a heat sink temperature of 10°C. The threshold current is approximately 1.0A under QCW operation, but appears to be about 600mA for CW operation. The serial resistance is 0.1Ω. The low light-current characteristic slope and high threshold current may be attributed to a combination of a very low effective reflectivity of the DGR due to the long coupling length of the 220nm period
grating coupler and the fact that light of the second stabilization wavelength is not reflected by the first stabilization wavelength DGR section and vice versa. The normalized emission spectrum of the device for a temperature of 20˚C with varying peak pump currents is shown in Figure 5.16. The lasing peak amplitudes remain within 25% of one another over the peak current range of 3.0-10.0A at 500ns pulse widths and a 100kHz repetition rate. The nearest spectral peak was measured to be greater than 20dB below the two lasing peaks. The lasing wavelength peaks were measured to be 977.9nm and 981.1nm, which are within 0.6nm as determined by Equation (1.31). The 3dB level or FWHM spectral width of the two spectral peaks is measured to be less than 0.3nm.

![Figure 5.15: The operation characteristics for the semiconductor laser incorporating the second dual wavelength DGR design, including (left) the light-current characteristics under QCW operation and (right) the voltage-current characteristics under CW operation, as well as the light-current characteristics under CW operation.](image-url)
Figure 5.16: Measured spectrum for the DWDGR laser with the second design of DWDGR at temperature of 20°C and peak currents of 5, 7, and 10A.

The far-field of the device was recorded; this image is shown in Figure 5.17. The two separate beams in the far-field are a result of the dispersion of the out-coupling grating. The far-field image shows that with the second design the output completely overlaps spatially in the lateral direction. Therefore, the modified design of the dual wavelength DGR overcomes the specific shortcoming of the original design, and the entire active area of the device amplifies and experiences both wavelengths simultaneously.
5.4. Square Dual Grating Reflector Devices

The square dual grating reflector laser is a square active area surrounded by DGRs followed by out-coupling gratings as shown in Figure 5.18. This device has four surface emitted outputs that overlap a few millimeters above the device in a cross pattern. Due to the lasing in orthogonal directions, the total device output will have an output with two orthogonal polarizations. Furthermore, depending on the periods chosen for the DGRs the two orthogonal directions can be either a single wavelength or two wavelengths.

Figure 5.17: Image of the far-field for the modified dual wavelength DGR laser.
Figure 5.18: Schematic of a square active area DGR device with (top left) the p-side shown, (top right) the n-side shown, and (bottom) a cross section of the device shown.

The device tested has an active area that is 2mm-by-2mm; thus, CW characterization is not much of an option due to the heat density produced under CW conditions. Attempts to characterize the device under CW conditions produced very little optical power. Therefore, the device was characterized under pulse pumping conditions only.

While this square device does not show the best of characteristics, it does show that the idea is feasible. The device shown in Figure 5.19 is a device that was tested on three separate occasions and rewired twice between testing; Figure 5.19 shows the final wiring resulting in the most uniform pumping. This device was tested under pulse pumping conditions with 500ns pulses at a frequency of 5kHz; the measured light-current characteristic curve is shown in Figure 5.20. Due to the nature of the light-current characteristic slope, it is difficult to determine
exactly what the threshold current is. This occurs as the result of not completely uniform pumping of the active region. Areas beneath the wire bonds in Figure 5.19 tend to begin lasing first, whereas other areas tend to start lasing at higher currents. This shows that a thicker deposition is needed for the n-side contact. The threshold current and the threshold current density are 5.5A and 140A/cm² as determined by the solid fit in Figure 5.20 and are 14.3A and 360A/cm² as determined by the dashed line in Figure 5.20. The light-current characteristic slope seems to be increasing past its measured value of 0.29W/A as the current reaches the limit of our measurement capabilities at 32A of peak current for the pulse width and frequency used.

Figure 5.19: Square device mounted and under operation.
Both the high threshold current and low light-current characteristic slope show that there are a lot of losses in the device and that the optical power generated is not making it into the output. Several loss mechanisms are present resulting in this low performance. The first loss mechanism is a result of the geometry of the device. Due to the longer gain length along the diagonals of the device, spontaneous emission emitted across this path will experience a high gain and take gain away from light traveling in the orthogonal directions. The second loss mechanism is a result of having DGRs on opposing sides of the active area. The peak reflection is sensitive to the effective index of the waveguide in the grating coupler region; therefore, if there are dose variations during e-beam patterning, hence depth variations during etching, during the fabrication of the grating couplers on opposite sides of the gain region, this will result in opposing DGRs operating at slightly different wavelengths. These differing reflectivity peaks
will result in a very poor cavity. Furthermore, with the feedback gratings not within specifications, scattering losses in the DGR sections will be high.

Beyond the poor light-current characteristics, the spectral output from the device is quite good. The spectral content of the outputs was measured for each orthogonal direction. The different spectral measurements for the orthogonal directions had spectral widths on the order of 0.1nm, as shown in Figure 5.21. There does seem to be different lasing wavelengths in the two orthogonal directions. This difference may be caused by slight changes in the periods of orthogonal gratings resulting from e-beam patterning due to slightly different scaling of the x-direction relative to the y-direction.

Figure 5.21: Normalized power spectral densities in the two orthogonal direction of the square DGR laser.
5.5. Narrower Spectral Width Dual Grating Reflector Devices

These modified DGR devices were fabricated similarly to the single wavelength DGR devices shown schematically in Figure 5.2 (a). Several attempts were made to fabricate devices with gratings within specifications outlined in the Design and Modeling chapter. The device with the grating parameters closest to within tolerance was selected for testing. This device had an active area of 100µm by 2mm, and the grating coupler had a duty cycle of 48% and a depth of 235nm; these grating coupler parameters will allow for a relatively short coupling length, but the DE into the first order will only be about 40%. The redirection grating duty cycle was 50% with a depth of 275nm; this combination will yield a DE into the first order of about 90%. While these parameters are not within the specification outlined in the Design and Modeling chapter, these parameters will allow for a proof of concept test.

The device measured exhibited a spectral width of 0.045nm under certain CW pumping conditions, as shown in Figure 5.22; however, the resolution of the OSA used to make the measurement is specified to be 0.06nm at 3dB. Therefore, we will safely state the spectral width is approximately 0.06nm. These stabilized wavelengths are approximately the same as that predicted by Equation 2.1. While the spectral widths shown coincide with that predicted of the spectral reflection given by modeling of the modified DGR structure, the spectral width did vary between 0.06nm and 0.12nm as the pumping conditions and temperature were changed for the devices. This type of spectral width variation was never witnessed in the standard DGR devices. This spectral width increase may be a result of the inclusion of higher order transverse modes, which are not accounted for in the modified DGR reflection versus wavelength curve shown in Figure 3.15. It could also be attributed to high thermal gradients causing changes in the effective
refractive index away from optimum conditions or surface and parameter variations of the gratings that become more of an issue as a higher number of photons are allowed to penetrate further into the DGR section.

![Normalized Spectrum](image)

Figure 5.22: Normalized spectrums of for narrower spectral width DGR laser; the device measurement was taken at 13.5°C, a current density of 250A/cm², and 220mW of optical power.

The light-current characteristic slope was low 0.4W/A measured at 13.5°C, with a threshold current of 450mA. This is likely due to several factors; the first factor is that the nitride layer of the HR and AR coatings was 80nm rather than the required 122nm. This error will increase the absorption in the out-coupling region and yield approximately a 14% power reflection at the output facet. The second factor reducing the light-current characteristic slope is the less than optimum reflection from the DGR due to the grating parameters not being within specified tolerances. Modeling of the modified DGR with the proof of concept grating
parameters give a peak reflection of approximately 30% without losses; with losses, this reflection may be on the order of 7-15%.

From the data obtained from the modified DGR device, we indeed see that the concept is sound. Further investigation of the idea could be carried out to improve the efficiency of the devices; this would include fabrication of devices with modified DGRs within tolerance.

5.6. Vertically Stacked Master Oscillator Power Amplifier

The MOPA schematic and assembly image are presented in Figure 5.23. Both the MO and PA devices were fabricated from the AlGaAs GRINSCH epitaxial wafer with a strained InGaAs single quantum well.

The MO was a single wavelength DGR GCSEL with a 220nm period grating coupler and a 410nm period feedback grating. The active section of the MO is 2mm long and 200µm wide. The total laser cavity is formed by the DGR and the cleaved facet following the grating coupler on the other side of the active section. The MO performance was tested under pulse pumping condition with a device cleaved from the same bar. The measured threshold current density was 170 A/cm², the optical power-current slope was 0.88W/A with a lasing wavelength of 975.4nm. The spectral FWHM was measured to be approximately 0.2 nm.
Figure 5.23: Schematic (top) and actual device image (bottom) of MOPA assembly incorporated a single frequency MO and a tapered PA.

For the PA, we used a tapered diode with two integrated grating couplers; fabrication details of the couplers can be found in [Vaissié, 2005]. The length of the PA active section is 4mm, with input and output aperture widths of 200µm and 650µm, respectively. The amplifier input section includes the same 270nm-periodicity grating coupler as that of the MO output. However, the PA output is provided by a grating coupler with a similar periodicity but curved grooves matched with the angle of the tapered stripe. Following our previous research, such a
curved grating improves the far-field from a tapered device. Due to the HR coating on the p-side, the input and output of the PA are provided through the GaAs substrate. The output surface is covered by an antireflection silicon nitride layer. A similar PA exhibited a broad spectrum emission with FWHM of 12nm and had no evidence of lasing at a current density up to 1 kA/cm².

The MOPA was assembled on an aluminum nitride heat sink with a patterned Au-Sn eutectic solder. The PA chip was bonded p-side down and a 500μm-thick BeO spacer was soldered close to the input coupler of the device. In contrast with the PA, the MO chip was bonded p-side up on the spacer directing the device output down to the SOA. The alignment precision of the MO chip with respect to the PA chip in terms of the longitudinal rotation, as described in subsection 3.4, is determined by the flatness of the spacer and variations in the thickness of the solder; these quantities can be very precise and well within the required precision calculated. Alignment of the MO output and the PA input were performed with a Flip-Chip technique during bonding of the MO chip. Due to the large emitting area of the MO and input area for the PA, which have dimensions of about 200x200μm², the position and angle alignments of the MO chip were performed by using the Flip-Chip technique with a lateral and longitudinal placement accuracy of 20 μm and lateral rotation angle precision of ~0.5 degrees; these alignment precisions are within those numerically predicted and described in subsection 3.4. Such a relatively low alignment precision is an advantage of our design over a MOPA assembled from conventional edge-emitting devices which incorporates a coupling lens requiring adjustment with an alignment precision of 0.5 μm [Schwertfeger, 2004].

The MO and PA were wired to different current stand-offs to allow for separate electrical
pumping of the devices. For characterization of the MOPA concept, the stacked assembly was tested under QCW conditions by electrical pulses with pulse widths of 500nsec and a duty cycle below 1%. The MO and PA were driven separately.

Efficient optical coupling between the devices was clearly observed by monitoring a spectrum of the PA output; a broad spectrum of amplified spontaneous emission (ASE) from the PA was drastically changed to a single line with a FWHM of ~0.2nm at the moment of switching on the MO driver. The wavelength of the MOPA output was measured at 975.4 nm, which matches well with the lasing wavelength provided by the MO with the previously specified DGR parameters. The nearest satellite peaks observed in the spectrum are spaced at about 0.7nm. These peaks are caused by additional Fabry-Perot modes in the GaAs substrate of the MO device. With increasing MO pumping, the ratio between the main peak and satellites also increases; this ratio was measured at 10dB at a peak current of 5A, see Figure 5.24 (right). Additionally, the ASE is reduced with increasing MO drive current, and the lasing/ASE ratio was recorded at 27dB for a MO and PA peak current of 2A and 20A, respectively.

Figure 5.24: MOPA characteristics: Optical peak power vs. PA current amplitude for different MO pumping (left) and spectrum measured at output peak power of 28W (right).
The MOPA output peak power versus PA drive current at different MO pumping levels, and therefore different MO output powers, is presented in Figure 5.24 (left). Due to the compactness of the assembly, a direct measurement of the output power from the MO is impossible; therefore, the output power was estimated from light-current characteristics obtained from a device similar to the MO. The MOPA maximum optical peak power was measured at 32W and was limited by the pulser used for PA driving. Dependence of the amplification factor versus PA drive current for the same MO pumping conditions is plotted in Figure 5.25. The maximum amplification including coupling loss was evaluated at 17 dB at a PA peak current of 60A for a low seed power from the MO; this amplification factor reduced to 9.3 dB at the maximum MOPA power output.

Figure 5.25: Amplification factor vs. PA peak current. The amplification data was evaluated from LI characteristic measured from MOPA and the device similar to the MO.
Figure 5.26 presents far-field data measured in a plane perpendicular to the output beam propagation. The beam shape is elliptical with a FWHM divergence of about 1.5 degrees and 6 degrees in perpendicular directions. The direction marked by “parallel”, see Figure 5.26, is parallel to PA p-n junction and corresponds with the lateral direction of the device. The large divergence in this direction results from a lateral multimode behavior of the broad area laser diode. The “perpendicular” direction corresponds with the fast axis of the device and so, has a better beam quality. After transformation by the grating, the divergence angle in the perpendicular direction is lowered significantly and is defined by the spectral bandwidth of the output and the out-coupling grating dispersion. Further improvements in the beam quality can be achieved through mode conditioning optics and further optimization of the coupling from the MO to the PA. All of these can be integrated into the chips through the processing of micro and nano-scale optics on the n-side, thus providing a compact hybrid MOPA structure for a wide range of applications.
5.7. Conclusion

We have presented the testing method used to evaluate the devices fabricated, along with the equipment used for each of the basic measurements. We then presented the results for each of the research goals undertaken.

The first goal was to prove the efficacy of the DGR by the fabrication and testing of semiconductor lasers incorporating DGRs. For the single wavelength DGR GCSELs, we have obtained a maximum light-current characteristic slope of 0.85W/A for CW operation and 0.96W/A for pulse operation for separate devices. These devices have a threshold current density of approximately 170A/cm². These devices had spectral outputs with spectral widths of less than 0.2nm. For single wavelength DGR cleaved facet lasers, we have experimentally determined a specific DGR to have an effective reflectivity of 62%.

Figure 5.26: MOPA output far-field profile in both parallel and perpendicular directions measured at MO and PA peak current of 5 Amps and 60 Amps. Insert is far-field image.
The second goal involved the fabrication and testing of two different dual wavelength DGR laser designs. The first design split the feedback grating down the center of the active width. A dual wavelength DGR laser incorporating this design exhibited a light current characteristic slope of 0.86 W/A under QCW operation and 0.79 W/A under CW operation. The spectral characteristics exhibited two spectral peaks; the amplitudes of these two peaks remained within 25% of one another for the peak operating current range of 0.5-7.0 A. The first design dual wavelength DGR produces an output that is not completely collocated. The second design overcomes this shortcoming by splitting the feedback grating along the length of the DGR to produce a completely collocated output. A dual wavelength DGR laser incorporating this second design indeed produced a collocated output; however, the characteristics were a bit worse. The light current characteristic slope was 0.67 W/A under QCW operation and 0.27 W/A under CW operation. This device also had a large operating current range in QCW operation with the spectral peaks staying within 25% of one another for the range of 3.0-10.0 A.

The third goal was to integrate the DGR into a square device geometry in order to discover possible problems that would hinder a future work. These devices showed that for broad area devices the contact quality and uniform current distribution are crucial to good device performance. Due to the non-uniform current density, the devices did not operate optimally. The light-current characteristic slope of one of these devices had a maximum of only 0.29 W/A; however, the spectral measurements from the two orthogonal directions had spectral widths of approximately 0.1 nm.
The fourth goal was to explore the bandwidth limit of the DGR by fabricating and testing a laser incorporating a modified DGR design. These devices exhibited a spectral width of approximately 0.06nm.

The fifth research goal was to obtain a high output peak power by creating a hybrid MOPA configuration using a DGR laser as the MO. The vertically stacked hybrid MOPA was tested in the QCW regime. Through this testing we have proved the efficacy of the optical coupling between the MO and PA. Under QCW conditions, we obtained a peak optical power of 32W with a pulse width of 500ns.
CHAPTER 6 : CONCLUSION

In this work, we presented the concept of the DGR for wavelength of broad area semiconductor lasers. Furthermore, we also presented the details on how to design, model, and fabricate a DGR for inclusion in a broad area semiconductor laser. Then, the data obtained from the testing of several different devices incorporating standard and modified DGRs was given.

6.1. Basic Concepts

In presenting the concept of the DGR, we started with an overview of semiconductor lasers including the basic materials and structures, commonly used resonator schemes, and operational regimes and applications. We then presented a phenomenological analysis of the operation characteristics of the basic semiconductor laser; these operational characteristics include the threshold current and the light-current characteristics slope. The possible emission configurations of semiconductor lasers are then shown including cleaved facet lasers, vertical-cavity surface-emitting lasers, grating-coupled surface-emitting lasers, and turning mirror emission lasers. Lastly, we presented the wavelength stabilization technologies researched in recent years, along with the basic idea behind our wavelength stabilization scheme, the DGR.
6.2. Design, Modeling, and Fabrication

In elucidating how the design and model a DGR, the modeling methods used in this work were presented; these methods include the MOL, the fast Fourier beam propagation method, RCWA, and a numerical correlation. These modeling methods were used to determine the optimum grating parameters for both grating couplers and feedback gratings of the DGRs for both standard and modified DGR configurations. Tolerance requirements were determined for the grating parameters, as well as alignment tolerances for coupling from the MO to the PA for the hybrid MOPA configuration presented.

Fabrication was then carried out with the design tolerances in mind. The entire fabrication process for the processing of the semiconductor lasers used in the research presented in this work was presented. These processes include the lapping and polishing of the substrate, n-contact processing, p-contact processing, mesa etching, grating fabrication, antireflection coating fabrication, high-reflection coating fabrication, and post lithographic processing.

6.3. Experimental Results

The data obtained from each of the research goals undertaken was presented. Each of these research goals enabled further proof of the efficacy of the DGR concept in some form.

The first goal was to prove the efficacy of the DGR by the fabrication and testing of semiconductor lasers incorporating DGRs. For the single wavelength DGR GCSELs, we have obtained a maximum light-current characteristic slope of 0.85W/A for CW operation and 0.96W/A for pulse operation for separate devices. These devices have a threshold current
density of approximately 170A/cm². These devices had spectral outputs with spectral widths of less than 0.2nm. For single wavelength DGR cleaved facet lasers, we have experimentally determined a specific DGR to have an effective reflectivity of 62%.

The second goal involved the fabrication and testing of two different dual wavelength DGR laser designs. The first design split the feedback grating down the center of the active width. A dual wavelength DGR laser incorporating this design exhibited a light current characteristic slope of 0.86W/A under QCW operation and 0.79W/A under CW operation. The spectral characteristics exhibited two spectral peaks; the amplitudes of these two peaks remained within 25% of one another for the peak operating current range of 0.5-7.0A. The first design dual wavelength DGR produces an output that is not completely collocated. The second design overcomes this shortcoming by splitting the feedback grating along the length of the DGR to produce a completely collocated output. A dual wavelength DGR laser incorporating this second design indeed produced a collocated output; however, the characteristics were a bit worse. The light current characteristic slope was 0.67W/A under QCW operation and 0.27W/A under CW operation. This device also had a large operating current range in QCW operation with the spectral peaks staying within 25% of one another for the range of 3.0-10.0A.

The third goal was to integrate the DGR into a square device geometry in order to discover possible problems that would hinder a future work. These devices showed that for broad area devices the contact quality and uniform current distribution are crucial to good device performance. Due to the non-uniform current density, the devices did not operate optimally. The light-current characteristic slope of one of these devices had a maximum of only 0.29W/A;
however, the spectral measurements from the two orthogonal directions had spectral widths on the order of 0.1nm.

The fourth goal was to explore the bandwidth limit of the DGR by fabricating and testing a laser incorporating a modified DGR design. These devices exhibited a spectral width of approximately 0.06nm.

The fifth research goal was to obtain a high output peak power by creating a hybrid MOPA configuration using a DGR laser as the MO. The vertically stacked hybrid MOPA was tested in the QCW regime. Through this testing we have proved the efficacy of the optical coupling between the MO and PA. Under QCW conditions, we obtained a peak optical power of 32W with a pulse width of 500ns.

6.4. Future Perspectives

There is still more work that may be done to push the DGR concept a bit further. There are several possibilities that may be explored.

Although it is easy to demonstrate through modeling and easy to conclude using common sense, the first future work that may be pursued is the fabrication and testing of a semiconductor lasers incorporating DGRs in several different materials to prove that the technology work effectively in differing semiconductor material systems other than the one presented in this work.

The second future work would be to explore the possibility of incorporating an annular DGR into a circular device lasing in the radial direction, as shown in Figure 6.1. Due to its circular symmetry, this type of device may produce a significantly better beam quality than that of the extremely multimode standard DGR lasers presented in this work.
Another future work that may be explored includes fabricating arrays of DGR stabilized broad area semiconductor laser, where different devices have differing wavelengths. These different wavelengths may be spectrally combined to provide an even higher output power than exhibited by a single device. Furthermore, the power of individual devices may be pushed to higher limits through modified epitaxial designs that allow a larger optical cavity, while still allowing for efficient coupling of the light from the waveguide.

Beyond the future works listed, there exists a vast sea of future applications for which the DGR may be used. With increasing integration capabilities in the future, the DGR has the possibility to become a valuable asset in making semiconductor lasers a competitor for those applications presently dominated by solid state lasers.
REFERENCES


