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OPTIMIZATION OF QUANTUM WELL OPTOELECTRONIC MODULATORS

A DISSERTATION
SUBMITTED TO THE DEPARTMENT
OF ELECTRICAL ENGINEERING
AND THE COMMITTEE ON GRADUATE STUDIES
OF STANFORD UNIVERSITY
IN PARTIAL FULFILLMENT OF THE REQUIREMENTS
FOR THE DEGREE OF
DOCTOR OF PHILOSOPHY
IN
ELECTRICAL ENGINEERING

John Alfred Trezza
February, 1995
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I certify that I have read this dissertation and that in my opinion it is fully adequate, in scope and quality, as a dissertation for the degree of Doctor of Philosophy.

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ABSTRACT

The development of semiconductor lasers and the advancement of fiber optic communications has fueled an increasing interest in optoelectronics in both research and development groups. To date, optical switching has been performed primarily by either direct modulation of semiconductor lasers or by the conversion of optical signals to electrical signals which are then switched and converted back to optical signals. External optical switches are currently technologically desirable for long-haul fiber switching, local area networks, consumer electronics, imaging and display technology. Some of the necessary characteristics of a switching system in which external optical modulators display distinct advantages are: low chirp parameter, low power requirements and large contrast ratio. In addition, such optical modulators should have desirable optical bandwidth, and be photon conserving and reversible. External optical switches have been previously created, but those devices were fabricated mostly in waveguide formats incompatible with dense integration and have always utilized absorption in a manner which inefficiently modulates incoming optical beams. This thesis examines quantum well optoelectronic modulators in the GaAs/AlGaAs/InGaAs materials system from both the electronic and optical viewpoints to eliminate the previous inefficiencies and to meet all of the above desirable switching criteria.

Experimental results with quantum well opto-electroabsorption utilizing either the quantum-confined Stark effect or field induced carrier separation are discussed. These two techniques provide the framework for creating large absorption changes with little or no refractive index changes (zero chirp). Tradeoffs between band to band transitions in single quantum wells versus more complex coupled quantum well architectures are described and developed. Additional attributes such as optical multistate behavior will also be detailed.

These quantum well elements are then used in several types of experimental optical modulator structures to further enhance optical switching. Zero chirp reflection modulators (which use increasing absorption to either increase or decrease reflectivity and thus modulate amplitude), vertical cavity phase flip modulators (which modulate reflected phase by 180° while keeping intensity constant), and vertical cavity X-modulators (which are reversible directional modulators that route optical beams rather than absorbing in one of the switched states) will be explained and demonstrated. Explanations of simple combinations of devices for future system applications will also be made.
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1. Introduction

The title of this work is “Optimization of Quantum Well Optoelectronic Modulators.” Much work has been done studying and advancing electronic switches. Here, though, a ‘modulator’ refers to an optical switching element; something which accepts photons as input and alters these photons when ‘switched.’ Such optical switches have been extensively investigated, albeit less than their electronic counterparts. Ideally, the three types of modulators one would like are:

1) A pure amplitude modulator which would alter the amplitude of the incident light without affecting the phase of the light between the two states.
2) A pure phase modulator which would alter the phase of the incident light from 0° to 180° without affecting the amplitude during switching.
3) A pure direction modulator, which would route photons without affecting the other characteristics of the light.

This work produced these three types of switching elements and this thesis describes how these modulators were conceived, modeled, designed, and produced. The structures described here were grown epitaxially by molecular beam epitaxy (MBE). Details of this growth technique are plentiful and will not be discussed here. Traditionally, modulators have employed epitaxial and lithographic techniques to form waveguide devices as shown in Figure 1-1a. In these structures, the light beam passes through the structure parallel to the plane of the epitaxial layers. This allows the formation of integrated 1-D arrays of devices and other structures such as Mach-Zehnder interferometers which can be monolithically fabricated.

![Figure 1-1: (a) Waveguide and (b) vertical configurations for optoelectronic modulators.](image)

Figure 1-1b shows another optical modulator format. In this configuration the incident light impinges perpendicular (more correctly it is just not parallel) to the planes of the
grown layers. This later format is compatible with the formation of dense, 2-D arrays of devices since light is incident from outside of the plane of the substrate. In addition, the vertical format permits wafer stacking if the devices operate at wavelengths at which the substrates are transparent. By stacking wafers, 3-D arrays of devices are realizable.

This thesis examines the optimization issues of optical modulators from both the electronic and optical cavity viewpoints. Electronically this is achieved by investigating various quantum well structures—where quantum wells are used as the active material in the devices; they are what actually causes the ‘switching.’ These optimizations are applicable to both the waveguide and vertical cavity configurations. On the other hand, the optical optimizations focus on how to use quantum wells in the vertical configuration device to improve performance. Issues such as operating voltage, chirp (parasitic refractive index change), multi-state switching behavior, photon conservation behavior, reversibility, optical bandwidth, and modulation ratio will be examined.

Optical modulators have and will increasingly have an important role in many applications. These include fiber optic switching for long-haul telecommunications networks\(^\text{10}\) and local area networks\(^\text{11}\). Other applications cover consumer electronics, imaging and display technology,\(^\text{12}\) neural networks,\(^\text{13}\) and board to board optical interconnects.\(^\text{14}\)

This investigation begins with a background on quantum wells, matter-light interaction and the creation of excitons, and the relationship between absorption and refractive index. This analysis will be conducted in Chapter 2. Chapter 3 will then introduce the electronic optimizations.

Previously, single quantum wells were used for absorption modulation.\(^\text{15}\) However, parasitic refractive index changes between the on and off states (high chirp parameters) limited the switching rate by adding unwanted frequency components. In addition, this parasitic effect made them unsuitable for the phase flip modulators described later. This work presents the means for using single quantum wells for absorption modulation with zero parasitic refractive index changes between two voltages. This will allow phase modulators to be realized.

Following single well devices, double well devices will be discussed (sections 3.2 and 3.3). Previously, coupled quantum well structures have been used for nonlinear optics applications.\(^\text{16}\) Here, coupled quantum wells will be analyzed for their absorption characteristics and these are experimentally demonstrated. In particular, the use of coupled quantum wells for low-voltage absorption modulation with zero parasitic refractive index change over the entire switching cycle (rather than just between two voltages) will be demonstrated. In addition, multistate behavior will be demonstrated. Finally, partially
doped coupled quantum well structures will be shown and their experimental results discussed.

After describing these two coupled quantum well structures, the use of multiple quantum wells or doped quantum wells for extremely low electric field operation and the ability to further enhance or suppress parasitic refractive index changes will be described in section 3.4 and 3.5.

Once the benefits of an optimized quantum well structure have been delineated, attention will turn toward the optimization of the optical cavity structures. Chapter 4 begins with an introduction to the generalized Fabry-Perot equations and continues with discussions of numerical modeling, cavities, and cavity-exciton interactions. After this, sections 5.1 and 5.2 will contain a discussion of the optimization of reflection modulators. Previously, reflection modulators have been made using Fabry-Perot cavities, but these devices were not optimized for zero chirp behavior. They thus had undesired phase modulation in addition to their amplitude modulation. Here zero chirp reflection modulators are described. These devices produced pure amplitude modulation, the first of the three ideal switches.

Subsequently, section 5.3 will contain a treatment of phase modulation in cavity devices. Previously, attempts to make phase modulators out of semiconductor cavity configurations appeared very promising. While the low reflectivities the early structures displayed could be improved simply with better design, the phase changes they exhibited were limited by parasitic effects in the device and were thus much more problematic to correct. Here true 180° phase flip devices are shown. These represent the second of the three desirable types of switching elements. In addition, in section 5.5 a description of arrays of phase modulators for beam steering, a very efficient successor to reflectivity gratings, will be given. Both theoretical and experimental results of gratings will be presented where the simulations themselves were based upon the experimental single device responses.

Finally, the problem of photon routing will be tackled in section 5.6. This will be experimentally demonstrated using a device which allows incident photons to be either transmitted or reflected. In addition, the device allows photons to be incident from either the front or the back of the wafer, making the device reversible. In addition to the single device characteristics, results from stacked devices will be given.

It is difficult for authors to perform an information 'core dump'. Therefore any written documentation of events, even a thesis, can only be expected to cover a portion of the work actually accomplished. It is hoped that this review will touch upon most of the main topics that I have investigated at Stanford. The rest I leave for the reader to look for
in the literature or to discuss with me at a conference or electronically over the future, digital, optical 'information superhighway.'
2. Background for Electronic Optimization

2.1 Introduction

All of the devices that are considered here utilize quantum wells as the active region. These quantum wells are structures which display significant changes in optical properties with applied electric fields. A schematic picture of a quantum well is given in Figure 2-1.

![Diagram of a quantum well](image)

**Figure 2-1:** Schematic of Quantum Well

A quantum well consists of a small bandgap material (here 50Å of In_{0.26}Ga_{0.74}As) surrounded by barriers of a larger bandgap material (say Al_{0.33}Ga_{0.67}As). This generally forms a potential well in both the conduction band and valence band into which carriers can fall. Each of the two wells, because of their small size, contain quantized energy levels. Electrons and holes can thus be captured and coupled via their strong coulomb interaction. This forms an extended, distributed positive charge-negative charge state with dipole moment equivalent to that of a single electron and hole. Due to the strong confinement in quantum wells, these particles, called excitons, have very strong and very sharp absorption resonances at wavelengths equivalent to the energy level difference between the two levels from which the exciton arose minus a binding energy. In terms of Figure 2-1 above, this energy is $E_o - E_p$, where $E_o$ is the binding energy. Binding energies are typically around 10meV. Further discussions of the mathematics of quantum wells will be discussed in...
section 4.5. Exciton absorption characteristics are typically modified through the use of an electric field.

### 2.2 Photorefractive vs. Electrorefractive

The use of quantum wells as an active region for optoelectronic switching has followed two paths. The first path uses the quantum well region in a structure which promotes a photorefractive effect. Such a structure is shown in Figure 2-2. Here, the quantum wells are bounded on either side by an insulating region (for example phosphosilicate glass, PSG). Chromium Tin Oxide (CTO) is a transparent conductor which allows electrical contacts and optical penetration. In operation, an electric field is applied across the structure, causing a decrease in absorption at the zero bias exciton peak (via the Quantum confined Stark effect—discussed in section 3.1—in which an electric field decreases the absorption at the zero bias exciton peak).

#### Photorefractive Electrorefractive

A strong "write" beam is then projected onto the sample in certain spatial locations. Where the intensity of this write beam is large, carriers are generated in the quantum well region and are swept toward the contacts of the device by the applied electric field. The carriers become pinned and do not reach the contact regions because of the PSG barrier. These pinned carriers screen the applied electric field, reducing the perceived electric field in the active region. The lower applied field allows the absorption to increase. Typically samples are several millimeters in diameter and large patterns can be optically written.
The second technique is in essence similar and is also shown in Figure 2-2. Here, the structure consists solely of a p-i-n diode which is reverse biased in order to apply an electric field across the quantum wells. Instead of applying a fixed voltage across these devices and using optical input to screen the applied electric field, the applied electric field is varied directly through an external power supply. This direct electronic modulation varies the optical properties of the quantum well active region—thus performing optical modulation. Device sizes are typically between 1μm and 1mm. This technique is used when electrically addressable pixel arrays are desired. This later technique is the one that will be considered here.

2.3 Effects of Growth Error

The development of reliable cavity devices depends upon a growth methodology which produces reliable and reproducible results. The devices considered here operate at wavelengths near 1μm. A fabrication (growth) error of 1% will shift the wavelengths of an optically resonant cavity by 100Å. This is typically larger than the full width at half maximum of the wavelength over which most resonant cavity devices can expect to operate. In order to deal with variations inherent in current MBE technology, an iterative design and development process was developed. The first step in this process consists of modeling the device. This is done with a thin-films program that is discussed further in section 4.5. This modeling provides a basis for comparison of theory with the 'as-grown' wafer. The second step consists of partially growing the device in the MBE and performing an in-situ optical reflectivity measurement. Modeling of the partially grown device can be performed and compared with the in-situ measurement. Any discrepancies can be accounted for by differences between the expected and actual growth rates. Adjustments in MBE growth times for the individual layers can then be adjusted for the remainder of the structure to compensate for the previous differences. This process can be repeated so that the thickness of the final structure can be exact to within 0.2%.22

Once the wafer is grown, the simulation program can be used to predict how the optical properties of the wafer would be affected by post-growth etching of the top layers. Such etching may be critical for fabricating arrays of non-identical device types or for integrating optical detectors with transistors.23

2.4 Coupling of Light and Matter

In this section, the interaction between light and matter will be discussed. In particular, this will lead to generalized expressions for exciton absorption. This will
provide a framework for seeing how exciton absorption is proportional to the overlap of the electron and hole wavefunctions in the quantum well. The hope is to demystify the quantum mechanics behind excitons. They can be looked at quite simply. The section begins with an introduction to the dipole approximation—which is usually made when discussing semiconductor optoelectronic materials.

2.4.1 Dipole Approximation

The Hamiltonian which relates the interaction of light to matter is found by replacing the momentum term, p, by p-(e/c)A in the standard kinetic energy term. This gives:

$$H = \frac{1}{2m_0} \left[ p - \frac{e}{c} A \right]^2 + W(r) + e\varphi$$  \hspace{1cm} Eq. 2-1

Where A is the E-M field vector potential and \( \varphi \) is the scalar potential of any applied electric field, \( B = \nabla \times A \). \( W(r) \) is the potential energy of the system. These equations alone are insufficient to determine a unique solution to a particular problem, so a specific choice of boundary conditions, or gauge, is needed. In dealing with excitons, the coulomb gauge is typically used. This specifies that the field is transverse, and so \( \nabla \cdot A = 0 \). Note that there is nothing 'magical' about this choice of gauge. Another could be chosen. Choosing a gauge merely means choosing a boundary condition which fulfills some physical intuition. Given this, if the term in brackets in the hamiltonian is expanded, and the dc field term is neglected, then:

$$H = \frac{p^2}{2m_0} + W(r) - \frac{e}{m_0c} A \cdot p + \frac{e^2}{2m_0c^2} A^2$$  \hspace{1cm} Eq. 2-2

The term containing \( A^2 \) is small and unimportant for linear absorption and can be neglected for the current purposes. The first two terms on the right side are the typical free space hamiltonian for a particle. The third term represents the light-matter interaction that will be analyzed in the absorption properties of excitons in semiconductors. Note that this term can be rewritten as:

$$H_{\text{int}} = -\frac{e}{m_0c} A \cdot p = e\mathbf{r} \cdot \mathbf{E} = -d\mathbf{E} = -E_0 \bar{e}_k \mathbf{d} \cos(kr - \omega t)$$  \hspace{1cm} Eq. 2-3

$$= \frac{-E_0}{2} \left( e^{ikr - \omega t} + e^{-ikr - \omega t} \right) \bar{e}_k \mathbf{d}$$
For simplicity, the position dependent parts of the exponential terms can be expanded: 
\[ e^{i\vec{k} \cdot \vec{r}} = 1 + i \vec{k} \cdot \vec{r} + \ldots \]. When only the first term in the expression is used (i.e. the ‘1’), the calculation is known as the dipole approximation. This is sufficient for the study of excitons when the wavelength of light for band to band transitions is much longer than the diameter of the excitons themselves \( (\lambda >> a_0) \). For the case when \( \lambda \sim a_0 \), the second term is needed (this case is referred to as the quadrupole approximation). The matrix element under the dipole approximation is:

\[
\left\langle \varphi_n | H_{\text{int}} | \varphi_1 \right\rangle = \frac{-E_0}{2} \left( e^{-i\omega t} + e^{i\omega t} \right) \left\langle \varphi_n | \vec{\varepsilon}_k \cdot \vec{d} | \varphi_1 \right\rangle = \frac{-E_0}{2} \left( e^{-i\omega t} + e^{i\omega t} \right) d_{nl}
\]

Eq. 2-4

Here \( d_{nl} \) is the dipole matrix element between generic states \( n \) and \( l \). If a semiconductor system with valence and conduction bands is considered, then the transition will occur between two states such as:

\[
\varphi_{v,k} = u_{v,k}(r) \frac{e^{i\vec{k} \cdot \vec{r}}}{\sqrt{V}}, \quad \varphi_{c,k} = u_{c,k}(r) \frac{e^{i\vec{k} \cdot \vec{r}}}{\sqrt{V}}.
\]

Eq. 2-5

Here the \( u_{ck} \) and \( u_{vk} \) represent the conduction and valence band Block functions, respectively. Given these wavefunctions, the dipole matrix element becomes

\[
d_{cv}(k) = \left\langle \varphi_{c,k} | \vec{\varepsilon}_q \cdot \vec{d} | \varphi_{c,k} \right\rangle.
\]

Eq. 2-6

Realizing that a dipole can be rewritten in terms of the momentum:

\[
\vec{d} = \left( \frac{e}{im_0 \omega} \vec{p} \right); \quad \vec{p} = \frac{\hbar}{i} \vec{V}
\]

Eq. 2-7

then using the product rule for derivatives on the full wavefunction, the matrix element can be expanded as shown:

\[
d_{cv}(k) = \frac{-e\hbar}{m_0 \omega} \left[ \vec{\varepsilon}_q \cdot i\vec{k} \left( u_{ck} | u_{vk} \right) + \left( u_{ck} | \vec{\varepsilon}_q \cdot \nabla | u_{vk} \right) \right]
\]

Eq. 2-8

The first term in the square brackets is zero (block functions originating from different bands are orthogonal). Noting the above relationship between the dipole element and momentum, the matrix element can be rewritten:

\[
d_{cv}(k) = \frac{e}{im_0 \omega} \left( u_{ck} | \vec{\varepsilon}_q \cdot \vec{p} | u_{vk} \right).
\]

Eq. 2-9
By performing a Taylor expansion on this term around the gamma point (k=0) the following equation is obtained:

\[
d_{cv}(0) = \frac{e}{m_\text{e} \omega} \left[ \langle u_{\text{co}} | e_q \cdot p | u_{\text{vo}} \rangle + k \frac{\partial}{\partial k} \langle u_{\text{co}} | e_q \cdot p | u_{\text{vo}} \rangle \right] + \ldots \text{ Eq. 2-10}
\]

A bit of terminology should be explained now. If the conduction and valence bands have different parity, then the system is said to be a first class (first order) dipole and the first term of the above expression dominates. However, this first term is zero if the conduction and valence bands have the same parity. In this case, the second term is the dominant term and the system is said to be a second class (second order) dipole. Looking at a general semiconductor system from conservation of angular momentum considerations, if one accepts that the photon imparts a momentum (l=1), then the electronic system must obey a \(\Delta l = \pm 1\) during absorption. This can be split up between the angular momentum of the Bloch states and the envelope wavefunctions. Now, if the valence and conduction bands both have s-like bands (same parity), or if one band were s-like and the other d-like, then \(\Delta l_{\text{Bloch}}=0\) or \(\pm 2\). In these cases, the envelope portion of the system would have to display \(\Delta l_{\text{envel.}} = \pm 1\) (the exciton would have to be p-like for example). These systems will only result in second class dipole transitions, and the resulting exciton absorption will be quite weak. However, in systems, such as the (InAlGa)As system currently being studied, the valence band states are primarily p-like while the conduction band is primarily s-like (different parity), producing a system which in general has \(\Delta l_{\text{Bloch}} = \pm 1\). This allows the exciton envelope wavefunctions to have \(\Delta l_{\text{envel.}}=0\). The excitons are s-like. This situation produces strong first class dipole absorption. It is, in fact, responsible for the large lowest-level observed exciton transitions.

Note that this is not the end of the story regarding conservation of momentum: in the GaAs system, holes with different momentum can produce excitons with different absorptive strengths. For example, different hole states couple with TM polarized light differently.\(^{27,28}\) Some differences between light-hole and heavy-hole exciton transitions will be discussed in conjunction with the angular dependence of Fabry-Perot cavities in section 5.6.4.
2.4.2 Exciton Absorption

In this section, the strength of optical absorption will be related to the strength of the exciton transition. From time dependent perturbation theory, the transition probability between two states \( m \) and \( l \) is given as: \(^{29}\)

\[
 w_{ml} = \left| \frac{1}{i\hbar} \int_0^t dt' \left( \phi_m \mid H_{\text{int}} \mid \phi_l \right) e^{i(\omega_m - \omega_l)t} \right|. \tag{2.11}
\]

The value for the term in brackets, which is given in Eq. 2-4 can be inserted into this equation. Integrating this expression (assuming long times so that sinc functions can be approximated by delta functions) and then integrating \( w_{ml} \) over a 3-D density of states, one can obtain the absorption coefficient from the transition probability. It should be noted that the absorption coefficient is \( w_{ml} \hbar \omega / 2\pi S \), where \( S \) is the pointing vector, \( S = n_c E^2 / 8\pi \), and \( n_c \) is the index of refraction of the material while \( |E|^2 \) and \( c \) are the field intensity and speed of light, respectively. For a semiconductor valence band to conduction band transition, then, absorption is:

\[
 \alpha = \frac{\omega}{\pi n_{\text{sub}} c} |d_{cv}|^2 \int_0^\infty d(\hbar \omega_{cv}) \frac{4\pi k^2}{d(\hbar \omega_{cv})} \delta(\hbar \omega_{cv} - \hbar \omega) \tag{2.12}
\]

Rewriting the dipole matrix element in terms of momentum, converting \( k \) dependent terms to energy dependent terms, and integrating the above expression, the absorption at \( k=0 \) becomes\(^{30}\).

\[
 \alpha = \frac{2e^2}{n_{\text{sub}} c \omega \rho_{cv}(0)} \left[ \frac{2m_r}{\hbar^2} \right]^{1.5} \Theta(\hbar \omega - E_g)(\hbar \omega - E_g)^{0.5} \tag{2.13}
\]

Stepping back for a moment, using the Bloch function approach, exciton wavefunctions can be written generally as

\[
 \psi = \sum_{k \in \mathbb{K}} \phi(k_e, k_h) u_{c, k_e} u_{v, k_h} e^{i(k_e r_e + k_h r_h)} = u_{c, 0} u_{v, 0} \sum_{k \in \mathbb{K}} \phi(k_e, k_h) e^{i(k_e r_e + k_h r_h)}
\]
Eq. 2-14

Here, \( \phi \) is the envelope wavefunction for the two particle system and the \( u \)'s are the Bloch functions. The approximate equality holds if the Bloch functions \( u_{co}, u_{vo} \) vary slowly with their wavevectors, \( k_e \) and \( k_h \). The summation term in the approximate expression represents the exciton envelope wavefunction. If one takes the above generalized wavefunctions, and assumes low level optical excitation (few free electrons and holes, therefore no exciton-exciton interactions) then the absorption coefficient can be written in terms of these wavefunctions as:

\[
\alpha(\omega) = \frac{4\pi^2 \omega}{n_{sub} c} \left| d_{cv}(0) \right|^2 \sum_n \phi_n(r = 0) \left\langle 0 \left| \Delta \left( \hbar \omega - E_g + \frac{E_B}{n^2} \right) \right| \phi_n \right\rangle^2 \tag{2-15}
\]

This equation is known as the Elliott equation.\(^{31}\) The \( \phi_n^2 \) term is known as the Sommerfeld enhancement factor.\(^{32}\) In quantum well systems, where the symmetry is broken in the \( z \) direction (the growth direction), this Sommerfeld enhancement factor can be split into a \( z \) direction term and an \( x-y \) ‘in-plane’ term as:

\[
\left| \phi_n(r = 0) \right|^2 = \left| \langle \gamma(z) | \gamma(z_n) \rangle \right|^2 \left| \phi_n^{xy}(r_{xy} = 0) \right|^2 \tag{2-16}
\]

The conclusion to be derived is that \textit{exciton absorption is proportional to the overlap integral of the electron and hole envelope wavefunctions in the ‘z’ direction (i.e. the term with the \( \gamma \)'s)}. This will be critical to the discussion of the field induced carrier separation modulation scheme introduced in section 3.2.

2.4.3 Wannier Equation

The Schrödinger equation for a two particle system can be written in terms of a center of mass and relative coordinates for the two particles, just like a hydrogen atom. The corresponding equation is known as the Wannier Equation.

For a bulk crystal:

\[
\left[ -\frac{\hbar^2}{2m_e} \nabla^2 - \frac{e^2}{\varepsilon_0 r} \right] \phi(r) = \xi \phi(r) \tag{2-17}
\]
In 3-d, then the bound state energies are $E_n = E_0/n^2$, while in a pure 2-d system, the energies are $E_n = E_0/(n+0.5)^2$. Here $E_0$ is the exciton Rydberg: $h^2/8\pi\hbar m^*a^2$, where $m^*$ is the reduced effective mass, and $a^*$ is the exciton Bohr radius.

These quantities can be related to other material properties. For example, as $E_0$ increases, the dielectric constant decreases, which decreases the Bohr radius and increases the binding energy. Hence, GaAs with a 1.5 eV bandgap has a bulk exciton binding energy of 4.2 meV, while ZnSe has an exciton binding energy of 18 meV, and CuCl, with a bandgap of 3.4 eV has an exciton binding energy of 200 meV. The exciton states being dealt with here are somewhere between 3-D and a purely 2-D system since the quantum wells confining the electrons and holes have some non-zero width.

### 2.5 Material Systems and Determining Absorption

By changing the width and depth of the quantum well regions, accurate placement of the lowest energy absorption edge can be realized. With this type of control, exciton absorption can be realized at a variety of wavelengths. In this work, the focus has been on the red to near infra-red region of the spectrum (from wavelengths of 6300 Å to 11000 Å). Because all of the epitaxial material in this study was grown on GaAs substrates, different techniques need to be developed for determining the absorptive coefficients for exciton transitions above and below the GaAs bandgap value of 8900 Å.

At energies below the GaAs bandgap (wavelengths longer than 8900 Å) a semiconductor sample can be anti-reflection coated on both sides of the wafer with single quarter wave layers of silicon nitride. Then a transmission experiment can be performed and absorption can be obtained through the [Beer-Lambert rule](https://en.wikipedia.org/wiki/Beer%E2%80%93Lambert_law): $I(d) = I(0)e^{-\alpha d}$, where $d$ is the thickness of the active medium (the quantum well region). The Beer-Lambert method is used for Indium-containing quantum wells which are either very wide or contain high Indium concentrations (> 15%).

High indium content structures are often desirable. For example, excitons made with 75 Å In$_{0.25}$Ga$_{0.75}$As/200 Å Al$_{0.33}$Ga$_{0.67}$As quantum wells are used to obtain modulation in the 1.06 μm range (useful for Q-switching of Nd:YAG or Nd:YVO3 lasers). Growth of these long wavelength materials is complicated because of a large mismatch in the atomic spacing between the GaAs substrate and the epitaxial layers. This mismatch determines the maximum Indium concentration allowed for direct InGaAs growth on GaAs substrates. Higher Indium concentrations require the use of complex growth techniques to achieve high quality exciton resonances. Quantum well systems were created as part of this work at wavelengths of 1.3 μm$^{34}$ and 1.55 μm$^{33}$. Such wavelengths can be reached

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with high indium concentration quantum wells using graded buffers to achieve reasonable quality material.\textsuperscript{34} It should be noted that for indium concentrations below 25%, typically thick barriers were used in this work (200Å) in order to reduce the average concentration of indium and prevent strain induced lattice dislocations. Graded buffers could reduce this barrier width and thus reduce significantly the required operating voltage.

For excitons with energies above the GaAs bandgap, two regimes can be identified. The first regime is applicable if part of the exciton's absorptive tail extends below the bandgap. In this case, the method for obtaining the absorptive spectra entails performing a photocurrent measurement over the entire wavelength region and then normalizing this photocurrent data to an absorption measurement of the exciton tail using the Beer-Lambert method. This hybrid approach is useful for Indium containing quantum wells which are either very narrow or have very low Indium concentrations.

Exciton resonances with wavelengths between 6000Å and 8800Å are quite common using the GaAs/AlGaAs quantum well system. For this wavelength regime, the above methods will not work since the GaAs substrate is opaque. Two methods of analysis are available. The reflectivity method involves growing a quarter wave-stack dielectric mirror below the active region and performing a reflectivity measurement. If the mirror stack is created with materials whose bandgaps are of higher energy than the exciton transition, then the incident beam will not be absorbed by any epitaxial material other than the quantum wells (the beam will be reflected by the non absorbing mirror and thus not pass through the absorbent substrate). This technique requires a precise knowledge of the mirror reflectivity.

\[
\int_{\lambda_{\text{max}}-\text{HWHM}}^{\lambda_{\text{max}}+\text{HWHM}} d\lambda \alpha(\lambda)
\]

\textbf{Eq. 2-18}

The second technique, the absorptive area method, relies upon the knowledge that the integrated absorption area for the lowest exciton peak (plus or minus its half width at half maximum, HWHM) remains roughly constant between quantum wells of slightly different composition.\textsuperscript{35} Therefore, if photocurrent measurements are performed on a new quantum well sample, and the spectral width of the zero bias, lowest energy exciton transition can be extracted from this photocurrent measurement, then the maximum absorption of this transition can be derived from comparison with absorptive values for a known quantum well system.\textsuperscript{36} Note that there is a scaling factor associated with a comparison between quantum wells with differing barrier height since these provide different amounts of electrical confinement, $\zeta$, (assume that the barriers are wide enough that small changes in width will be negligible). Under these conditions:
\[ \alpha_{\text{new QW system}} = \frac{\zeta_{\text{new QW sys}} \cdot \text{HWHM}_{\text{new QW sys}}}{\zeta_{\text{known QW sys}} \cdot \text{HWHM}_{\text{known QW sys}}} \cdot \alpha_{\text{MAX}_{\text{known QW sys}}} \]  

Eq. 2-19

For reference, the ratio of the confinement factors for GaAs quantum wells containing AlAs barriers versus those with Al_{0.33}Ga_{0.67}As barriers is 1.125, with AlAs having the higher confinement. Therefore, given previous data or the data in the literature, reliable absorptive values can be obtained for slightly different material compositions. This approach gave values which were extremely reliable for predicting the energy levels and absorption peaks for a variety of MBE grown quantum well structures.

2.6 Kramers Kronig Relationship

The final portion of this electronic optimization background section covers the relationship between changes in refractive index and changes in absorption. Understanding this interaction is crucial to understanding zero chirp modulation.

Neglecting non-linear material effects, the relationship between the polarization of a material and the applied electric field is given by the complex susceptibility:

\[ P(\omega) = (\chi' + i\chi'')(\omega)E(\omega) \]  

where \( P \) is the polarization, \( E \) is the electric field and \( \chi' \) and \( \chi'' \) are the real and imaginary parts of the complex susceptibility. The real and imaginary parts of any linear causal system can be related by the Kramers-Kronig relationship:

\[ \chi'(\omega) = \frac{2}{\pi} \int_{0}^{\infty} d\omega' \frac{\omega' \chi''(\omega')}{\omega'^2 - \omega^2} \]  

\[ \chi''(\omega) = -\frac{2}{\pi} \int_{0}^{\infty} d\omega' \frac{\chi'(\omega')}{\omega'^2 - \omega^2} \]  

Eq. 2-21

The 'P' in this expression denotes that the principle value of the integral is taken (omit the '0' point in the definite integral). For the quantum well semiconductor structures utilized in this study, one would like to obtain relationships between readily measurable quantities, like the refractive index and absorption coefficient, which can be obtained from reflectivity measurements. Given the complex dielectric constant for a material, \( \varepsilon = \varepsilon' + i\varepsilon'' \), which is directly related to \( \chi' \) and \( \chi'' \), one can derive the refractive index, \( n \), and the absorption coefficient \( \alpha \) for a material.
\[ n(\omega) = \sqrt{0.5\left[\varepsilon'(\omega) + \sqrt{\varepsilon'^2(\omega) + \varepsilon''^2(\omega)}\right]} \quad \text{Eq. 2-22} \]

\[ \alpha(\omega) = \frac{\omega}{n(\omega)c} \varepsilon''(\omega) \quad \text{Eq. 2-23} \]

For semiconductors, though, one typically finds that \( \varepsilon' \ll \varepsilon'' \) for the wavelength ranges of interest. Under these conditions, the above equations can be approximated as:

\[ n(\omega) \approx \sqrt{\varepsilon'(\omega)} \quad \text{Eq. 2-24} \]

\[ \alpha(\omega) \approx \frac{\omega}{n_0 c} \varepsilon'(\omega) = \frac{4\pi\omega}{n_0 c} \chi''(\omega) \quad \text{Eq. 2-25} \]

Using these semiconductor approximations to rewrite the Kramers-Kronig relationship, one obtains:

\[ \Delta n(\lambda_o) = \frac{c}{\pi} \int_0^\infty d\lambda \frac{\Delta \alpha(\lambda)}{1 - (\lambda / \lambda_o)^2} \quad \text{Eq. 2-26} \]

This is the form of the relationship used to derive refractive index changes from the difference in the two absorption curves in the next chapter. Hence, if a quantum well sample has different absorption vs. wavelength curves when under two different electric fields, the difference of those absorption curves could be used to determine the difference in refractive index induced by the electric field.

The essential points to realize about the above relationship are the following: The denominator samples the changes of absorption in an anti-symmetric manner around the wavelength of interest, \( \lambda_o \). In addition the sampling drops off roughly as \( \lambda^2 \) around \( \lambda_o \). Thus, usually only a relatively narrow wavelength range around \( \lambda_o \) is important for determining the changes in refractive index. Given this, refractive index changes will be zero when the changes in absorption on either side of \( \lambda_o \) in wavelength are equal (over a small wavelength range). Because of the antisymmetric denominator of the Kramers-Kronig relationship, if \( \Delta \alpha \) is a symmetric function around \( \lambda_o \), the above integral will be zero. For example, if the change in absorption between two states has a local maximum, the change in refractive index would be zero if that local maximum was large and broad.
enough so that the denominator of the above equation dropped off more quickly than the full width at full maximum of the Δα curve. Specific examples of this relationship will be given in conjunction with the zero chirp single quantum well and coupled quantum well systems.
3. Zero Chirp Absorption Modulation

This chapter will discuss the means for obtaining zero chirp absorption modulation. In this context, chirp is defined as the change in refractive index divided by the change in absorption, \( \Delta n/\Delta \alpha \). Chirp is a deleterious effect in optical switching for a number of reasons. Most notably, changes in refractive index induce changes in the optical thickness of the device and hence induce changes in the phase of the output light. These phase changes induce spurious wavelengths into the output signal. This can be understood with a simple illustration. An optical wave can be described simply as having an electric field:

\[
E = E_o \cos \left( \omega t + \varphi \right)
\]

Eq. 3-1

Taking a little liberty with this equation, it could, for small time changes, be considered as:

\[
E = E_o \cos \left( \left( \omega + \frac{\partial \varphi}{\partial r'} \right) \Delta t \right)
\]

Eq. 3-2

The point of this illustration is to demonstrate that a change in refractive index during switching (i.e. a condition with chirp), which is equivalent to a change in phase during switching, induces a change in the frequency of an optical beam. Because different frequencies travel at different rates through media (for example plastic or glass optical fibers), pulses of light containing multiple wavelengths will spread during signal propagation. This spreading of signal pulses limits the rate at which bits can be transmitted optically. In addition, refractive index changes are detrimental to switching devices which simply require parasitic effects to be minimized. Two examples of such devices are arrays of pure amplitude modulators used for efficient spatial light modulation, and phase flip modulators which encode information on the phase of an optical wave. These device types will be discussed in sections 5.2, 5.3 and 5.4.

3.1 Single Quantum Well Systems

As described in chapter 2, when a low bandgap material is placed between high bandgap materials, a quantum well is formed and exciton-type absorption can be observed. Semiconductor properties, such as bandgap, are bulk properties and derivations of such bulk properties typically assume infinite crystals. Nevertheless, a typical analysis of quantum wells often assumes that each section of the well has essentially the same bandgap
as these bulk materials. More correctly, bandgaps and other properties of quantum wells, such as effective mass, often only use a perturbative approach to determine the small deviations from bulk parameters induced by such effects as strain. In addition, although the well and barrier materials have different Bloch functions, the problem of matching these Bloch functions at the material boundaries is almost never addressed in the analysis of GaAs/InGaAs/AlGaAs quantum wells. Despite the often claimed similarities between GaAs, InGaAs, and AlGaAs, there is no reason to believe that all of these approximations in the analysis of quantum wells should be expected to produce accurate quantitative results. From this perspective, the fact that accurate quantitative results can be found through such techniques for typical quantum wells (50Å to 100Å wide) is remarkable. While 50Å of GaAs can be thus approximated by a series of slightly modified bulk parameters and then modeled within a quantum well configuration, the question of how much material is required for such an analysis to be valid still remained.

![Graphs showing absorption versus wavelength for different quantum well thicknesses.](image)

**Figure 3-1:** Experimental Absorption versus Wavelength curves at two different voltages for various thickness of GaAs 'quantum wells'. Layer thicknesses up to and including one unit cell are shown.

In an effort to determine the onset of the applicability of a bulk-like-parameter quantum well analysis, several thin "quantum wells" were grown. Figure 3-1 shows the experimental effects of placing thin GaAs (low bandgap) layers between layers of Al$_{0.42}$Ga$_{0.58}$As in three experimentally grown wafers. As shown in Figure 3-1, for what is nominally 1.46Å of GaAs (or about 1/2 of 1 monolayer of material, which means the wafer
is not even entirely covered) a small change can be observed in the absorption vs. wavelength curve when voltage is applied. However, the observed change is indicative of a bulk change in absorption--known as the Franz-Keldysh effect.\textsuperscript{40} This is about what would be expected for a bulk Al\textsubscript{0.42}Ga\textsubscript{0.57}As layer. With one monolayer or approximately 2.8\AA{} of GaAs, a small effect of the quantum well exciton absorption can be seen. Once a full unit cell of GaAs is deposited, around 5.7\AA{} of material, definite absorptive characteristics related to this confined region can be seen. This is the onset of true exciton absorption. While a 5.7\AA{} GaAs layer may not be as close to bulk-like as a 50\AA{} quantum well, it is clear from this experiment that a 5.7\AA{} GaAs layer does have enough band structure of its own to enable a distinct exciton absorption. Such an absorption requires confinement in a potential well and points to the GaAs layer as the location of this well. For wells larger than one unit cell, the typically employed method for dealing with 50\AA{} quantum wells can likely be used with little adjustment (assuming one accounts for the energy dependent effective masses resulting from the high lying subbands in such thin quantum wells).

Since typical sized quantum wells contain several confined states, there are various exciton transitions which are possible. The lowest transition occurs, naturally, between the lowest lying electron and highest lying hole quantum well subbands. With the application of bias, individual exciton transitions can be shifted in wavelength or quenched in maximum amplitude, or even reduced in total absorptive area. The three sum rules which provide guidelines for understanding absorptive changes are:\textsuperscript{41}

- If integrated over the entire wavelength spectra, the total change in absorption with applied electric field will be zero.

- The total absorption from a given valence to conduction subband is approximately proportional to the square of the overlap of electron and hole envelope wavefunctions.

- The sum of all of the overlap integrals from any one conduction (valence) subband to all the valence (conduction) subbands is conserved.

The remainder of this chapter will discuss the various modulation schemes; including those for single quantum wells, coupled double quantum wells, multiple quantum well schemes, and doped quantum wells.
3.1.1 Quantum Confined Stark Effect

This section will give a brief overview of the work done using the most common method of quantum well electro-absorptive modulation.

As alluded to earlier, the exciton state basically consists of extended electron and hole wavefunctions which are correlated by the Coulomb interaction. The 3-D treatment in a bulk semiconductor is remarkably similar to the treatment of a hydrogenic state.\textsuperscript{20}

Unlike 3-D states, when writing the Schrödinger equations in 2-D, for example for excitons in quantum wells, the system cannot be transformed into center of mass and relative coordinates in the direction perpendicular to the epitaxial layers because the absolute electron and hole positions are important (i.e. specific, quantum well induced boundary conditions must be met). If the system is in the regime where the confinement imparted by the barriers is larger than the coulomb energy of the electron-hole system, then the exciton wavefunction can be separated into electron and hole wavefunctions in the direction perpendicular to the epitaxial layers (the $z$ direction) and a wavefunction containing the $x$-$y$ plane dependencies: $\varphi(r) = \psi_e(z)(z)\psi_h(z)\varphi_{xy}(x,y)$.

With an applied electric field, the Schrödinger equations for the $z$-direction wavefunctions must be solved:

$$
\left[-\frac{1}{2m_{e,h}} \frac{\delta^2}{\delta z^2} + \frac{\delta}{\delta z} + e\varepsilon z + V_{e,h}(z)\right] \psi_{e,h}(z) = E_{e,h}\psi_{e,h}(z)
$$

Eq. 3-3

Here $\varepsilon$ is the applied electric field and $E$ is the eigenenergy of the system.

**Zero Applied Bias**

**With Applied Bias**

![Graph showing effect of electric field on quantum well states](image)

*Figure 3-2: Effect of electric field on Quantum Well states.*
Figure 3-2 shows the effect of the electric field on the electron and hole wavefunctions (neglecting Coulomb interactions). Several things occur with the application of the applied electric field. First, the energy of the lowest transition (lowest electron level, to the highest heavy hole level) is reduced by the application of the electric field ($E_i < E_h$). At low electric fields this band tilting effect shifts the energy levels approximately quadratically with voltage. Second, the applied electric field separates the carriers and thus decreases the binding energy of the electron-hole pair. This acts to increase the transition energy and operates against the band tilting effect. The band tilting effect dominates in this conflict. Third, the overlap integral of the electron and hole envelope wavefunctions decreases. This decrease lowers the maximum absorption value for the exciton transition. Finally, the electrons and holes will experience greater barrier sampling. The roughness of epitaxial interfaces, on the order of 1 or 2 monolayers, thus increases the linewidth of the exciton transitions and decreases the maximum absorption with bias.

![Image](image-url)

**Figure 3-3:** (a) Absorption versus Wavelength at 2 voltages and (b) change in refractive index between those two voltages. Data is for an experimental 75Å GaAs/35Å Al$_{0.31}$Ga$_{0.69}$As quantum well.

Both the shifting of the exciton peak, the increase in linewidth, and the decrease in absorption peak are depicted in Figure 3-3a, which shows experimental data for a 75Å GaAs quantum well. These characteristics are indicative of the QCSE. The location of the lowest exciton absorption peak is circled at the two biases and the shifting and quenching behavior are apparent. One should also note how much stronger the resonances are in these experimental 75Å quantum wells relative to the 5.7Å quantum wells of Figure 3-1. This stronger resonance occurs primarily since in larger wells the electrons and hole wavefunctions sample the GaAs/AlGaAs interfaces much less. These interfaces are inherently rough and degrade the quality of the exciton, particularly with bias.
Looking at Figure 3-3a, one can take the difference between the two absorption curves to obtain the change in absorption versus wavelength. In such a curve, there would be a local maxima at 8390Å. From the previous discussion, it is clear that this would produce a zero in the change of refractive index between the two voltages. Figure 3-3b shows that this is indeed the case. Thus the quantum confined Stark effect can be used to obtain large changes in absorption with zero changes in refractive index (zero chirp) but only between two voltages. In a typical design process, one would specify the wavelength, the total absorption of the structure, and the operating voltage. The structure would then be grown with an appropriate number of quantum wells whose zero volt exciton peak was the appropriate distance, in wavelength, from the desired operating wavelength so that the desired operating voltage could be used. In this experimental device, operation at 8390Å between these two voltages results in increases in absorption with applied bias (positive differential absorption modulation, PDAM). However, the single well system could also be used at a different wavelength, such as 8100Å, where absorption decreases with increasing absorption (negative differential absorption modulation, NDAM). The problem is that in order to obtain zero chirp using NDAM, the device, when ‘on’, often has to be biased so that the second lowest absorption peak (called the light hole exciton) is almost directly underneath the lowest order absorption peak. This represents a lower operating voltage than the condition displayed in Figure 3-3, since the excitons don’t have to be shifted as much, but the change in absorption is usually only around 50% of the maximum absorption.$^3$ Hence using the QCSE only modest $\Delta \alpha$ is achievable with an NDAM configuration.

3.2 GaAs/AlGaAs/InGaAs Asymmetric Quantum Wells.

3.2.1 Introduction / Theory

As described earlier, optoelectronic devices which use quantum wells typically employ the Quantum Confined Stark Effect (QCSE).$^4$ This technique was detailed in the preceding section. As was briefly mentioned above, negative differential absorption modulation (NDAM), which entails high absorption at zero field and lower absorption with applied bias, is limited in standard single-well devices due to the shifting of light hole excitons. In conventional structures, the strong zero bias absorption is due to electron-first heavy hole (HH1) excitons which are shifted to longer wavelength and quenched (red-shifted) with applied bias. Unfortunately, just as the HH1 exciton is red-shifted, so are other exciton pairs, most notably, the electron-first light hole exciton (LH1), which is red-
shifted toward the original operating wavelength. Hence, although absorption due to the HH1 exciton resonance decreases at the operating wavelength, the LH1 exciton resonance shifts toward that energy and limits the magnitude of NDAM.

This section describes how three step asymmetric coupled quantum wells are used to obtain a higher degree of NDAM than is obtainable through the conventional QCSE and at a far lower voltage than is typically required by the QCSE. In addition, these asymmetric coupled quantum wells can be utilized in devices at other wavelengths where the same structure displays positive differential absorption modulation (PDAM). Finally, the devices can display absorptive bistate behavior as well as a zero electro-refractive effect. The latter effect makes this type of quantum well structure particularly useful for low chirp amplitude modulation because there is little or no real index change with bias voltage. Taken together, these characteristics make these quantum wells uniquely suited for use in vertical cavity modulators, self electro-optic effect devices (SEEDs), and waveguide devices, as well as a variety of new devices.

As a reminder, to first order, exciton absorption is proportional to the overlap integral of the electron and hole envelope wavefunctions. The most often used method for determining the strength of the absorption and the binding energy of the exciton involves application of variational techniques upon an approximate exciton wavefunction, such as:

\[ \Psi_{\text{exciton}}(r) = \Psi_e \Psi_h \sqrt{\frac{2}{\pi}} \frac{2}{a_b} \exp\left[-\frac{2r}{a_b}\right] \]  

**Eq. 3-4**

where \( \Psi_e \) and \( \Psi_h \) represent the independently solved electron and hole wavefunctions for a specific exciton pair, \( a_b \) is the effective exciton radius and \( r \) is the polar coordinate of distance. By using trial wavefunctions together with an appropriate Hamiltonian—which accounts for both quantum confinement and Coulomb binding energies—the strength of the exciton can be found. The above technique is valid only if the quantum confinement energy is significantly larger than the Coulomb term in the Hamiltonian; otherwise, the separation of the envelope wavefunctions from the terms which account for Coulomb attraction could not be justified. For example, in the conduction band of the wells at zero bias, the confinement energies are around 250meV while the Coulomb binding energies are around 5meV. Using such an assumption, it is clear that the greater the overlap between the electron and hole envelope wavefunctions, the better defined the electron-hole system is and, hence, the greater the absorption peak. This was described mathematically in the previous chapter. A structure, which under bias, alters the overlap of the two particles will then affect the magnitude of the optical absorption. Optical modulation is thus obtained. In
contrast with devices relying strictly upon the QCSE, this mechanism does not require the exciton resonance wavelength to shift in order to obtain a decrease in absorption. However, even for minute biases there will always be some small wavelength shift with bias as the bands tilt. In the current structure, an applied bias which decreases the overlap integral for an exciton, decreases the absorption at that exciton’s resonant wavelength. Conversely, absorption will rise if the overlap increases. In this section a number of device structures which have been created to observe these effects will be described. Next the theoretical aspects and predictions of device operation will be detailed, contrasting this device with work previously done. Following this will be the experimental results of the structures and an examination of the correlation of this data with the theoretical predictions. Next, a general discussion of three-step asymmetric coupled quantum wells, including how small modifications of asymmetric coupled quantum wells can give one of eight different permutations suitable for device operation will be given. Finally, I will discuss how the initial empirical device (hereafter referred to as a type IA device) relates to the other device types available with this set of structures.

3.2.2 Device Design

To realize the field induced carrier separation modulation effect, three-step asymmetric coupled quantum wells were designed. The devices were grown by molecular beam epitaxy with a quantum well band structure shown in Figure 3-4. The active quantum well region consisted of 20 coupled wells, each containing a 50Å GaAs well and a 20Å In$_{0.2}$Ga$_{0.8}$As well separated by a 10Å Al$_{0.33}$Ga$_{0.67}$As barrier with 200Å Al$_{0.33}$Ga$_{0.67}$As barriers separating adjacent coupled wells. A 2000Å, 5.5x10$^{18}$cm$^{-3}$ Silicon doped n-type Al$_{0.33}$Ga$_{0.67}$As layer was grown below the wells while a combination of a 1500Å, 5x10$^{18}$cm$^{-3}$ Beryllium doped layer and a 2500Å 5x10$^{19}$cm$^{-3}$ Beryllium doped layer (p-type Al$_{0.33}$Ga$_{0.67}$As) was grown above the wells. The result was a p-i-n structure which could be reverse biased to apply an electric field without substantial carrier injection. A 50Å, 7x10$^{19}$cm$^{-3}$ p-doped cap layer was grown to prevent surface degradation typically caused by unprotected AlGaAs surfaces. The large barriers between pairs of coupled wells were chosen to minimize both the possibility of strain related defects and any built-in field across the wells under zero bias. The latter was important in order to obtain a nearly flat-band condition to match the assumption in the theory. The entire structure was grown by molecular beam epitaxy at 485°C.
The choice of growth temperature was influenced by several considerations. While it is true that low growth temperature typically adversely affects the optical quality of AlGaAs, the result of this degradation is primarily limited to the optical emission properties of a structure. Previous work has shown that while InGaAs/AlGaAs structures do suffer emission degradation, exciton absorption characteristics are not significantly harmed by low growth temperatures.\(^{45}\) In addition, it has been shown that optical characteristics are limited by the AlGaAs/InGaAs interface quality and not by the overall quality of the AlGaAs barrier regions.\(^{46}\) Working at a slightly higher temperature would not significantly enhance this interface quality. In fact, for 30% Indium wells, a change in temperature from 490°C to 535°C (still well below the Indium desorption temperature of 550°C) was found to degrade the optical characteristics of quantum wells.\(^{47}\) In an effort to avoid this degradation and to create a process compatible with future devices containing higher Indium concentrations, the structures were grown at 485°C.

To form devices, 200µm square mesas were created by wet etching the sample down to the n-type region. Subsequently, electrical connections were made through an alloyed Au/Ge/Ni/Au contact to the n-type region while Ti/Au contacts were made to the p-type material. The p-type contact encircled the perimeter of the top of the mesa and thus allowed optical access at normal incidence. Microprobes were used to contact these metallic regions. This eliminated the need for bonding and packaging. The optical input was achieved by passing a white light source through a spectrometer and focusing the output onto the device.
3.2.3 Theoretical Analysis

In the simplest view, the type IA coupled well device can be modeled as a multi-particle system described by a linear combination of two excitons, one centered in each of the two wells:

$$\psi_{\text{exciton}} = A\psi_{e1}\psi_{h1}\sqrt{\frac{2}{\pi}}\frac{2}{a_{b1}}\exp\left[-\frac{2r}{a_{b1}}\right] + B\psi_{e2}\psi_{h2}\sqrt{\frac{2}{\pi}}\frac{2}{a_{b2}}\exp\left[-\frac{2(r-d)}{a_{b2}}\right]$$  

Eq. 3-5

Here d is the separation between the two excitons. In essence, this is the simplest, tight-binding type approach to the solution of a multiparticle system. Interaction terms would have to be included in the overall Hamiltonian for this trial wavefunction of a four particle system.

![Image of band structure graphs](image)

Figure 3-5: Band structure and energy levels for coupled quantum well system's (a) conduction band at 0 bias, (b) valence band at zero bias, (c) conduction band at 4V bias, (d) valence band at 4V bias. Dotted lines are levels without coupling.

In the present case, however, it is still reasonable to consider the entire construct as a single exciton described by a single-well exciton wavefunction. A more complete treatment will be given in section 3.3.6. In this case, $\psi_e$ and $\psi_h$ describe the extended electron and hole
envelope wavefunctions over the two wells. As long as the central perturbing barrier is not large compared with the Coulomb terms, this extended state approach will give reasonable results. A type IA device, the one considered here, has conduction and valence band levels as shown in Figure 3-5a and Figure 3-5b at zero volts and in Figure 3-5c and Figure 3-5d at 4 V (72kV/cm) bias. Here the dashed lines correspond to the energy levels of the coupled system while the solid lines correspond to the energy levels if the two coupled wells are separated to infinity. By observing these uncoupled energy levels, one can determine which well is the main contributor to the corresponding coupled energy level.

For coupled systems with appropriate central barrier discontinuities, it is useful to think that particles primarily reside in the well whose uncoupled energy level corresponds to the coupled system level. This can be more clearly seen in Figure 3-6. Here at zero bias, the lowest electron level is primarily in the GaAs well while the highest heavy hole (HH1) and second highest heavy hole (HH2) are primarily in the GaAs and InGaAs wells respectively. Since the Type IA device forces the electron and HH1 particles into the GaAs well, the overlap integral between these particles will be large and a strong resonance is predicted. Conversely, a relatively weak overlap between the electron and HH2 states here indicates a relatively weak absorption for this exciton system. As seen in Figure 3-6c and Figure 3-6d, under applied bias, the HH1 level becomes associated with the InGaAs well. In effect, the HH1 and HH2 have exchanged wells. In this configuration, the original electron-HH1 exciton which had a large overlap at zero bias would be quenched while the previously unfavorable electron-HH2 exciton resonance would become enhanced. Figure 3-6a-c show the calculated electron and hole envelope wavefunction probability amplitudes ($\Psi^*\Psi$) for various applied biases on the type IA device. The wavefunctions were obtained by a piecewise step potential transfer matrix technique which is described more fully in Section 4.5.1. 49 The electron wave function is initially contained largely in the GaAs well and as bias is applied, the electron becomes even more tightly confined to this well. The HH1 at zero bias is indeed mainly contained in the GaAs well, but at a field of 72kV/cm (4V), the hole has been swept into the InGaAs well. Note that the electric field tends to pull holes toward the InGaAs well in this design. Looking at the HH2 exciton, at zero bias, this particle is clearly contained in the InGaAs well.
Figure 3-6: Probability amplitude \( \psi^* \psi \) for the (a) electron, (b) highest and (c) second highest hole states in the experimental structure as a function of applied bias. The separation of wavefunctions with applied bias can be seen.

However, at 4 Volts bias, the HH2 moves against the electric field and shifts into the GaAs well. Since at this voltage both the electron and HH1 would exist in the same well, an increasing absorption peak would be expected, corresponding to this more localized exciton as bias is applied. On the other hand, at higher voltages (above 6 volts for this sample) the electron-HH2 exciton behaves as if it were in a single 50Å GaAs quantum well. Here the wavefunctions shift to opposite sides of the well and their energy levels shift in a manner which exemplifies the QCSE. If this single well behavior shifts the higher energy excitons to the resonance wavelength of the original electron-HH1 exciton, then absorptive bistate behavior can be obtained.

Previously, coupled wells with two GaAs wells of differing width separated by an AlGaAs or AlAs barrier were used to analyze some of the properties of coupled wells.\(^{50}\) While these two-step asymmetric coupled quantum wells did display some wavefunction shifting properties, the three-step system has several important advantages. First, the three-step system is more flexible. In addition to controlling the relative width of the wells and the barrier, the relative depth of the two wells can be controlled. In contrast to the two-
step structures, three-step structures enable one to place the lowest electron or hole level in either the narrower or the wider well. Another difference is the use of InGaAs. This incorporates strain into the structure since InGaAs on GaAs or AlGaAs cannot be grown lattice matched. This enhances the separation of the HH1 and LH1 energy levels.\textsuperscript{51} In such a system one expects substantial separation of the HH1 and LH1 exciton energy levels at zero applied electric field. This is done in an effort to remove the influence of the LH1 exciton on device operation. In addition, since one would expect the LH1 exciton to red-shift at lower voltages than the HH2 excitons, due to their lighter mass, the LH1 and HH2 excitons should occur at the same wavelength for some bias. The type IA device explores the transition between GaAs/AlGaAs coupled wells and two coupled InGaAs wells with differing Indium concentration, which would allow transmission modulators on GaAs substrates to be made.

3.2.4 Experimental Results

The absorption spectrum for the type IA device at low voltage is shown in Figure 3-7a. The measured photocurrent is normalized to account for quantum efficiency variations with applied bias. This normalized data is proportional to the absorption spectrum. Photocurrent at 8175Å drops to 30% of its maximum value for an applied bias of 4 volts (72kV/cm). This NDAM corresponds to the electron-HH1 transition described earlier. In addition, the absorption due to an exciton resonance at 8125Å increases by 70% with an applied bias of 6V (109kV/cm), demonstrating PDAM. The higher energy electron-HH2 transition is responsible for this resonance. At 8175Å, the ratio of percentage change in absorption to applied field is 96 μm/kV where this ‘efficiency ratio’ is

\[
\text{Efficiency ratio} = \frac{(\alpha_{\text{high}} - \alpha_{\text{low}})}{\alpha_{\text{high}}} / E_{\text{max}}
\]

Eq. 3-6

Here \(\alpha_{\text{low}}\) and \(\alpha_{\text{high}}\) are obtained from the minimum and maximum photocurrent values and \(E_{\text{max}}\) is the field applied to achieve this modulation. In contrast, when the QCSE is used in GaAs/AlGaAs quantum well systems which have similar operating wavelengths to those of this device, absorption typically drops to around 50% of maximum for fields near 300kV/cm.\textsuperscript{36} The efficiency ratio of these QCSE dependent devices is 17 μm/kV. Substantially improved NDAM performance is achieved at a significantly lower voltage than is realizable using the QCSE. In addition, in the region of PDAM, the efficiency ratio is 38 μm/kV which is viable for device applications.
Figure 3-7: Absorptive characteristics in (a) low field regime (carrier separation regime) and (b) high field regime (QCSE) regime. (c) composite picture with absorptive "bistate" behavior.

While at low biases the changes in absorption at the two wavelengths of interest are dominated by the change in overlap integral, the QCSE begins to affect the behavior of the excitons at higher biases as shown in Figure 3-7b. Here the exciton which displayed PDAM at low bias begins to red shift with further increases in the applied field. This is the regime where the electron and HH2 are both located in the GaAs well and are pulled to opposite sides of the well by the electric field. The benefit of such an effect is demonstrated in Figure 3-7c. At 8175Å, for example, the photocurrent at 0V and at 11V is quite large while at 6V, a minimum in photocurrent occurs. Similarly, at 8125Å, absorption is low at 0V and at 11V and becomes large for intermediate voltages. This absorptive-bistate behavior is ideally suited to many optical switching situations. Now examining the HH1 and HH2 levels more closely, the HH1 exciton is more significantly red shifted than the HH2 exciton since the particles comprising the HH1 exciton are located in opposite wells at higher bias and hence experience a larger effective band tilting. In essence, this exciton sees a wider 'effective well'. At 6V, for example, the HH1 exciton resonance is shifted nominally to 8350Å. Furthermore, at voltages just above those required to shift the HH1 to the InGaAs well, anti-crossing repulsion of energy levels
causes the HH1 exciton to red-shift further, while this effect would tend to blue-shift the HH2 exciton. In other words, the energy difference between the two lowest hole levels in the coupled system will be substantially larger than the difference between the two lowest unp

![Graph showing phase change versus wavelength for varying applied bias](image)

**Figure 3-8:** Relative Phase Change versus Wavelength for varying applied bias. Low phase change over varying bias points can be obtained.

It should be noted that since this device operates primarily through the movement of heavy holes, whose effective mass is quite large, this level splitting behavior is less than if the devices used the movement of electrons as the means of modulation (note the difference in Figure 3-5a between the electron uncoupled and coupled levels while the hole levels are very similar for coupled and uncoupled states for similar energy separations). The net result is that the lack of appreciable blue shift in the HH2 exciton at low bias results from a counterbalance between the small energy level repulsion blue-shift and a small band tilting induced (QCSE) red-shift.

Absorption ($\alpha$) and refractive index ($n$) are related by the Kramers-Kronig relations as described in the previous chapter. Figure 3-8 uses these relations to depict how the experimental phase changes with applied bias. For this figure, the absorption data was used to calculate the change in the device refractive index as a function of wavelength for varying biases. At wavelengths near the NDAM and PDAM peaks, the refractive index
change (relative to the zero bias case) is extremely low (nearly zero) over all bias points. While devices operating at \( \lambda_0 \) using the QCSE could display low phase shift, the ability to quench the exciton resonance with low bias means there is also little red-shift of the higher lying resonances. In effect, these devices produce the same change in absorption associated with a high voltage using the QCSE with at least as small a phase change as the QCSE would give at low voltage. The low phase modulation indicates a very low chirp parameter, where chirp is again defined as the ratio of phase modulation (refractive index modulation) to absorption modulation (\( \Delta n/\Delta \alpha \)). More will be said about this in Section 3.3.

Finally, the data depicts the role of the light hole exciton. In Figure 3-7a, the light hole exciton is observed at 8025\( \text{Å} \) at zero bias. This is at a substantially higher energy than the HH2 exciton level. As bias is applied, the light hole exciton is QCSE red-shifted much faster than the HH2 exciton. At an applied bias of 6V, the light hole exciton is co-resonant with the HH2 exciton. However, since the QCSE is the dominant effect in this bias regime, as the resonant energy is red-shifted, the amplitude of the resonance decreases, so that at higher biases, the light hole resonance is not distinguishable.

### 3.2.5 Discussion

The basic three-step asymmetric coupled quantum well configuration utilizes the lowest electron state and the two highest heavy hole (HH1 and HH2) states. Through appropriate design and biasing considerations, eight different permutations can be realized—depending upon which of the coupled wells the above three states each reside in at zero applied bias (flatband condition) and which direction the bias is applied. Since it is desirable to minimize carrier injection into the device active area during operation, the quantum wells are placed in the intrinsic region of a p-i-n diode which is reverse biased. Reverse biased diodes are desired since injected carriers would complicate the device operation by introducing screening potentials as well as by limiting the maximum intensity of light that the devices could modulate. The unfortunate consequence of desiring reversed biased diodes is that in order to obtain both directions of electric field biasing requires the growth of two wafers grown with the active regions inverted relative to one another.

In Figure 3-9, for a given device type (here type I), the two bias directions are labeled as subtype A and B where the direction of field can be seen from the band sloping in the figure.
Table 1: The permutations of the three-step asymmetric coupled quantum well. The locations of the various particles are as indicated. “E” refers to electrons, HH1 to the lowest heavy hole, and HH2 to the second lowest heavy hole.

<table>
<thead>
<tr>
<th>General Device Type</th>
<th>Zero Bias Particle location</th>
<th>Subtype A Particle Location (under bias)</th>
<th>Subtype B Particle Location (under bias)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Wider Well</td>
<td>Thinner Well</td>
<td>Wider Well</td>
</tr>
<tr>
<td>Type I</td>
<td>E, HH1</td>
<td>HH2</td>
<td>E, HH2</td>
</tr>
<tr>
<td>Type II</td>
<td>HH2</td>
<td>E, HH1</td>
<td>E, HH2</td>
</tr>
<tr>
<td>Type III</td>
<td>HH1</td>
<td>E, HH2</td>
<td>E, HH2</td>
</tr>
<tr>
<td>Type IV</td>
<td>E, HH2</td>
<td>HH1</td>
<td>E, HH2</td>
</tr>
</tbody>
</table>

As described earlier, the type IA device begins with the electron and HH1 primarily in the wider well (the GaAs well) while the HH2 is in the narrower (InGaAs) well. With bias, the HH1 and HH2 effectively switch wells. A type IB device begins with the particles in the same locations as the type IA device, but with bias it shifts the electron from the wide well to the narrow well. This device would also show quenching of the HH1 exciton and enhancement of the HH2 exciton. However, since the electron wavefunctions are not as well confined as hole wavefunctions, the transitions are not as abrupt or as large. This will be discussed shortly.

Table 1 depicts the eight permutations of devices (type IA through type IVB). For each device type (I, II, III, IV) the zero bias particle positions are the same for the two subtypes (A,B). The subtypes refer to the direction of bias where the direction of the field follows the same convention as shown in Figure 3-9. Hence, by comparing the zero bias locations for a particular type to the positions for a subtype (corresponding to a bias with a particular direction), the particles which shift can be determined.

When a well contains a particular electron and hole, the absorption peak is large for the exciton corresponding to that pair. The analysis of the other permutations follows directly from the chart. Note that in order to achieve the positioning of the three particles at zero bias, the relative depth and width of the two wells must be adjusted in addition to the barrier heights.
Figure 3-9: Schematic representation of band structure and electron and hole locations for the type I devices. Type IA and type IB refer to the devices under the biases shown in the figure. "E" refers to the electrons primary location while "HH1" and "HH2" refer to the highest and second highest hole states, respectively.

Two devices of particular interest are the type IIA and the type IVB devices. The type IIA device begins with the HH1 exciton confined to the thin well (one could think of this as a very deep InGaAs well relative to a wider GaAs well). When bias is applied, this HH1 exciton is quenched and the HH2 exciton is excited as the electron switches wells. It has the same qualitative behavior as the type IA device. However, since the HH1 exciton is originally confined to the thinner well, its absorption peak will be greater than a type IA device at zero bias. Hence one could achieve greater modulation with this device.

The type IVB device, in contrast, begins with the a HH2 exciton in a wide well and shifts both particles to the thinner well with bias. Thus, the HH2 absorption maxima should remain relatively strong with bias since even at biases where appreciable red-shift occurs due to the QCSE, the two particles will still be confined to a very small well. This double-well QCSE method might prove useful for obtaining larger PDAM than conventional, single-well QCSE devices.
3.2.6 Conclusion

In conclusion, three-step asymmetric quantum wells are better suited for negative differential absorption modulation than are devices based upon the QCSE. This method also allows for positive differential absorption modulation and shows absorptive bistate behavior. Furthermore, the device exhibits a zero electro-refractive effect. This translates into low phase modulation with applied bias and a far better chirp parameter than conventional quantum well devices. The foundation of these devices is the ability to switch particles from one well to an adjacent one with applied bias. While either electrons or holes could be moved, the device just discussed switches the HH1 and HH2 levels causing the observed absorption changes. With a slightly altered design, devices with original resonances in the smaller (InGaAs) well which are then quenched with bias could be created. Such devices should show even greater absorption modulation since an exciton confined by the smaller and deeper InGaAs well would give the electron-hole pair a greater binding energy and hence an originally larger absorptive peak that would be quenched. Devices which exhibit persistently high absorption peaks even with high bias could be useful for double well QCSE experiments.

3.3 Electron and Hole Swapping: InGaAs/InGaAs coupled QW’s

3.3.1 Introduction

In this section coupled InGaAs quantum well systems which use field induced spatial separation of both electron and hole states to modulate the magnitude of exciton optical absorption and hence transmission are theoretically analyzed and experimentally demonstrated. The samples consisted of p-i-n diodes with an active region of twenty coupled wells, each coupled well structure containing a 50Å In$_{0.3}$Ga$_{0.7}$As well and a 30Å In$_{0.15}$Ga$_{0.85}$As well separated by a 10Å Al$_{0.33}$Ga$_{0.67}$As barrier. One structure was grown with the thinner well on the n-type side of each coupled quantum well while in the other sample, the thinner well was oriented toward the p-type side. By applying bias to the structures, either the lowest exciton or hole states effectively switch wells, thereby enhancing certain exciton resonances and quenching others. The two devices grown, despite their similar structure, operate through the field induced switching of opposite carrier types. As in the devices of the previous section, this method of modulation does not require the excitons to Stark-shift; the device can produce large absorption/transmission changes with zero refractive index change under bias.
The initial GaAs/InGaAs structure of the previous section was limited to use in reflection devices since it contained GaAs quantum wells and operated well above the bandgap of the GaAs substrate. *Here both type IIA and type IIB coupled InGaAs quantum well systems where the two wells have different widths and Indium compositions are discussed.* At zero bias, the lowest energy exciton transitions for both the type IIA and type IIB devices are associated with the deeper/thinner of the two wells. This is in contrast with coupled wells composed of identical composition material or in type I devices where the lowest energy levels are always associated with the wider wells. With bias the two lowest electron states effectively switch wells in the type IIA device, and the two lowest hole states switch wells in the type IIB device. Thus it displays control of spatial overlap of the lowest electron and hole states and modulates absorption. Both strained growth and bandgap properties are used to an advantage. The use of InGaAs in each well both shifts the light hole absorption edge to very high energy, thus removing it from consideration in device operation, and results in a device which can be operated at wavelengths below the bandgap of GaAs. These experimental devices operate beyond 0.9μm and thus they operate as transmission modulators. In addition to its present use as a transmission modulator operating on GaAs, the quantum well structure may also be used for both Fabry-Perot and waveguide modulator systems. Following a discussion of device design, the method through which type IIA and IIB coupled quantum wells modulate via field induced carrier separation is depicted. Higher energy states in the valence band are shown, and their influence on the absorption spectra is also investigated. Finally a comparison of theoretical models with experimentally obtained absorption data (which corresponds to transmission data) will be made and applications for low chirp operation and absorptive bistate behavior will be described.

### 3.3.2 Device Design

The basic design was described in the previous section. To recap, in the type IIA device, the wider, In$_{0.3}$Ga$_{0.7}$As wells were grown on the n-type side of each coupled quantum well. Conversely, in the IIB devices, the wider wells were grown on the p-type side. The inverted coupled quantum well growth allows electric fields to be applied in the opposite direction across the coupled well system. Although the structures appear quite similar, modulation in type IIA and IIB devices is a result of field induced control of opposite carrier types. Because the quantum wells are located in the intrinsic region of a $p$-$i$-$n$ diode which is *reverse* biased to prevent significant carrier injection, two separately grown wafers are required to obtain this bi-directional field capability. Both type IIA and IIB device operation can be obtained with the same coupled quantum well system.
The structure was grown at 485°C for reasons identical to those described in the previous section. Transmission measurements were taken by passing a white light source through a spectrometer and using the resultant monochromatic light to measure transmission below the GaAs bandgap energy. The absorption was then calculated and normalized to account for multiple interface reflections.\textsuperscript{52} In addition, photocurrent was measured both above and below the bandgap and the resultant curve was fitted to the absorption data in order to obtain quantitative absorption data for the coupled well system both above and below the GaAs bandgap. In this way it is possible to obtain reliable information about the high energy subbands. Agreement between the lineshapes of absorption and photocurrent was extremely good.

### 3.3.3 Device Analysis

Figure 3-10 and Figure 3-11 show the band structure and energy levels (shown dotted) for the conduction and valence bands of the type IIA and IIB coupled well systems at three different biases. The solid lines refer to the location of the energy levels if the two wells were uncoupled.

By noting which solid line corresponds to each dotted line, it can be determined in which well the original energy level was lowest and thus which well primarily contains the particle associated with that energy level. In the type IIA coupled quantum well at zero applied bias (Figure 3-10a), both the lowest electron and lowest heavy hole (HH1) states are mainly contained in the thinner (30Å In\textsubscript{0.15}Ga\textsubscript{0.85}As) well while the second lowest heavy hole state (HH2) is primarily in the wider (50Å In\textsubscript{0.3}Ga\textsubscript{0.7}As) well. A large electron-HH1 resonant absorption is then expected since there is a large overlap and a relatively weak electron-HH2 absorption is predicted since the two particles are in opposite wells and thus spatially separated. As shown in Figure 3-10b and Figure 3-10e, in a type IIA device at low bias (4\textnu = 72 kV/μm), the lowest electron level is now associated with the wider well while the highest two hole states do not switch wells. In essence, before the anticrossing of the two lowest electron energy levels the lowest electron state is tightly bound to the thinner well. As the two energy levels approach one another, mixing between the levels alters the character of each of the two lowest states. Both states become extended; associated with both wells to some degree. At high enough fields, the mixing between the two states decreases, but the lowest energy state (n=0) is now bound tightly in the larger well. For example, Figure 3-12a shows the probability amplitude for the lowest electron level at various biases in the type IIA device. Here the switching behavior can be clearly seen. Since the two highest hole levels do not experience this switching in the type
IIA device, the electron shift causes the overlap integrals between the lowest electron and two highest hole states to change.

![Graphs showing energy levels](image)

**Figure 3-10:** Energy levels in the type-IIA coupled quantum well systems for (a) valence band at 0V, (b) valence band at 4V, (c) valence band at 10V, (d) conduction band at 0V, (e) conduction band at 4V. Dotted lines correspond to coupled energy levels; solid lines to the energy levels in the absence of coupling. Energy levels and particle locations for each level are as indicated. Arrows drawn between two names (HH3 and HH4, for example) indicate that the applied bias is near the anticrossing of these two states.
Figure 3-11: Energy levels in the type-IIIB coupled quantum well system for (a) valence band at 4V, (b) valence band at 10V, (c) conduction band at 4V. Zero volt situation is the same as in Figure 3-10. Dotted and solid lines have the same meaning as in Figure 3-10.

Wavefunction calculations were performed for all states via piecewise step potential transmission matrix techniques. Strain induced band splitting effects have been taken into account in the calculation. The net result is a field induced quenching of the electron-HH1 exciton absorption and an enhancement of the electron-HH2 absorption. In this particular type IIA structure, at zero bias, both the HH2 and HH3 are located in the thinner well and thus the E-HH2 and E-HH3 excitons provide only weak absorption. Examining the lower hole states with applied bias, near 4V there is an anti crossing of the HH3 and HH4 states (see Figure 3-10b). Hence, above 4V, the HH3 state will be located primarily in the thinner well and the HH4 primarily in the wider well. In this type IIA device, the electron is already in the wider well under a 4V applied potential, so the HH3-HH4 anticrossing results in a quenching of the HH3 exciton and an enhancement of the HH4 exciton.
At higher biases (near 10V, see Figure 3-10c) there is an anticrossing of the HH3 state in the thinner well and the HH2 state in the wider well. Beyond this bias level, the HH2 will be associated with the thinner well and the HH3 once again associated with the wider well. The result of this additional anticrossing is that the HH2, which at 4V had been enhanced, will once again be quenched while the HH3 which had been quenched will now be enhanced. For completeness, the lowest light hole level is shown. It, too, shows similar well switching behavior. In the current design, the light hole is pushed to very high energy by the lattice mismatch induced strain. This beneficial effect allows us to ignore the light hole in the analysis of device operation.

The band structure and energy levels for the type IIB device are shown in Figure 3-11. The significance of the solid and dotted lines is the same as in Figure 3-10 for the type IIA device. At zero applied electric field, the energy levels in the type IIB device should be nominally identical to those in the type IIA structure. However, because the wells are grown 'upside down' compared with the type IIA device, the built-in field of the diode will be dropped across the quantum well pair in the opposite direction from the type IIA device. Despite this, the structures were grown conservatively so that the locations of each of the particles should be identical: HH1 and E1 are located in the thinner well, while the HH2 and E2 are found in the wider well. A type IIB structure is characterized by an anticrossing of the two lowest hole states with bias. As shown in Figure 3-11b and Figure 3-12b, even at a bias of 72kV/cm (4V), the HH1 becomes associated with the wider well while the HH2 is located primarily in the thinner well. Figure 3-11d and Figure 3-11e show that the
electrons do not switch wells. The result of this is a field induced quenching of the electron-HH1 exciton absorption and an enhancement of the electron-HH2 absorption. It should be noted that at 4V bias, the electron-HH3 system is inter-well and therefore a relatively weak transition (see Figure 3-11b). At about 6V bias, however, the anti-crossing of the HH2 and HH3 levels occur. Above this bias, the HH2 becomes associated with the wider well, thereby quenching the HH2 exciton absorption, while the HH3 becomes a direct transition, and thus provides enhanced absorption. As shown in Figure 3-11c, by 10V bias, the HH1 and HH2 transitions are strongly inter-well while the HH3 is intra-well (remember that the electron state is confined to the narrow well). Above 10V, the tightly confined HH3 exciton should act as though it were confined to a single 30Å 30% InGaAs well system and should display QCSE behavior: red-shifting and quenching. In addition, analysis shows that the LH1 transition should act like an indirect transition. Hence, the LH1 should QCSE red shift faster than the HH3 transition. Inter-well transitions red-shift faster than the HH3 (intra-well) transition since the spatial extent is larger as is the amount of band tilt. Also note that the strain induced lifting of heavy and light hole states has indeed shifted the light hole exciton to sufficiently high energy that it does not affect device operation.

3.3.4 Experimental Results

Figure 3-13 shows the experimental absorption versus wavelength curves for the type II A device structure at both low and high biases. At zero bias, the large HH1 exciton peak is readily discernible at 9125Å while the HH2 peak is not observable. The HH3 exciton is associated with the wide well and its resonance contributes to the large peak near 8600Å. With applied bias, behavior in agreement with the theoretical calculations is observed. For example, as depicted, the HH1 is quenched with bias. In addition, since the transition becomes spatially separated, a large red-shift in the absorption edge is observed. As noted earlier, this shift is similar to the observed red-shift in the QCSE. The HH2 exciton at 9050Å is also enhanced with bias. Although at biases between 4V and 10V, the electron-HH2 overlap is quite strong due to the movement of the electron state, the resonance is not as pronounced as the electron-HH1 resonance. This makes sense since the electron-HH2 resonance at 4V is associated with the wider well and the overlap is not as strong as the electron-HH1 resonance at 0V which is located in the thinner well.
Figure 3-13: *Experimental absorption spectra for the type-IIA device at various applied voltages. Shown are (a) low bias region (spatial overlap absorption modulation) and (b) high bias (quantum confined Stark effect) region. Labels depict the transition responsible for the various peaks.*

Consequently, the peak is not as large. Because the quantum confinement energies for these two resonances are comparable (because the thinner well is deeper) broadening and peak reduction is not as observable as it is in coupled wells of equal depth, where higher energy levels are less strongly confined. In addition, the HH3 resonance discernible near 8600Å is initially quenched and red-shifted. Beyond 10V, an enhanced and persistent absorption of the HH3 transition is seen while the HH2 transition is quenched, as expected. Absorption data is reported as $\alpha L$.

As reported by Fox et. al., a simple variational calculation revealed that exciton effects will slightly alter the fields at which the crossing behavior occurs$^{44}$. However, this shift, which is approximately equal to the ratio of the difference in intra and inter well exciton binding energies, and the difference in the energy levels for the two transitions, is only a few percent for this structure and does not significantly affect the results. At 9140Å, with an applied bias of 72kV/cm (4V), the absorption of the quenched HH1 exciton decreased by 79μm/kV, where, again, this efficiency ratio is defined as $[(a_{\text{high}} - a_{\text{low}})/a_{\text{high}}]/E_{\text{max}}$. The absorptive suppression per applied field in this non-optimized sample was three times greater than with conventional InGaAs quantum well samples previously investigated.$^{45}$ Thus transmission modulators on GaAs could operate at considerably lower voltage than currently used. In triple wells, the magnitude of $\alpha L$ is comparable to that of single quantum well systems, although the change in absorption can be made much higher than is possible in a single well system.
Figure 3-14: Experimental absorption spectra for the type IIB device at various applied voltages. Shown are (a) low-bias region (spatial overlap absorption modulation), (b) high-bias (quantum confined Stark effect) region, and (c) absorptive bistate behavior from the combination of the two modulation schemes. Labels depict the transition responsible for the peaks.

Further, there is an unusual persistence of the HH3 transition at fields up to 360kV/cm (near the dielectric breakdown of the device). One would expect the electron-HH3 pair to act like an exciton in a single 50Å well at these high biases and see a QCSE red-shift and a decrease in overlap with bias. The high energy of the hole (n=3), seems to make it less susceptible to high field spatial separation that is typically observed with the QCSE in this field regime, although some red-shift is still evident.

Figure 3-14a and Figure 3-14b show the experimental absorption versus wavelength curves for the type IIB device at low and high bias. While one would expect a higher zero applied bias HH1 exciton peak, a combination of a slightly lower Indium flux during growth (even 2% would be enough) and the small but non-zero built-in field of the p-i-n diode is sufficient to partially 'quench' the HH1 exciton from its flatband absorption
value to the value observed with zero applied bias. A forward bias of 0.6V was enough in this type IIB device to increase the HH1 absorption peak to an αL of 0.24.

![Graph showing change in refractive index versus wavelength for various voltages in the type II-A device.](image)

*Figure 3-15: Change In Refractive Index (relative to 0V applied bias) versus Wavelength for various voltages in the type II-A device. At 9135Å the region of zero refractive index change can be seen.*

In any event, the basic theoretical predictions are upheld. At zero applied bias, the HH1 peak is readily discernible at about 9200Å. The HH2 peak at 9200Å, while enhanced, is below its peak value. The HH3 exciton is now associated with the large well and weak absorption can be seen near 8800Å. With applied bias, the characteristic quenching of the HH1 resonance is observed as it is considerably red-shifted. The HH2 particle is enhanced slightly with bias, and can be seen at 9050Å at 4V (72kV/cm) bias.

With increasing bias, the HH1 remains inter-well and continues to be quenched with bias. The HH2 transition remains intra-well until 6V. The HH3 is higher in energy than the other two levels at zero bias and so is less tightly confined. The HH3 wavefunction penetrates into the thinner well more substantially than the HH2 penetrates the wider well at a given bias before the anti-crossing point (where the splitting between the two levels is a minimum). Enhancement of the HH3 occurs before 6V bias is reached.

At around 6V bias (108kV/cm), the HH2 is quickly quenched while the HH3 transition is appreciably enhanced. By 8V, the absorption peak found near 8950Å is entirely due to the HH3 exciton transition. Above this bias, the HH3 exciton in the type
IIB coupled device acts like a single well exciton system in the 30Å 15% Indium well. This is very similar to what was observed with the double quantum wells in the previous chapter. The HH3 undergoes a QCSE red-shift and resonant quenching. However, since the energy states reside in such a deep, narrow well, the confinement energy is quite high and the spatial overlap is large until very large biases are applied. Hence the red-shift is not appreciable and the overlap quenching is also small. At 24V, near the device breakdown, an appreciable, broad exciton peak at 9100Å is seen. This peak is a combination of a large HH3 exciton, the first light hole transition and the inter-well heavy hole transitions which have been appreciably red-shifted.

At 9200Å an efficiency ratio of 77 µm/kV is achieved with a bias of 5V. Again, the type IIB device gives superior transmission modulation to the single quantum well devices. The absorptive suppression per applied field in the type IIB sample is, like the IIA sample, nearly three times greater than with single InGaAs quantum well samples. The radial extent of each exciton is very bias dependent so that the length scale 'L' changes with voltage.

3.3.5 Absorptive Bistate behavior and Low Chirp Characteristics

The result of the low field optical modulation through spatial overlap adjustment and the high field modulation dominated by single well QCSE effects is shown for the type IIB device in Figure 3-14c. At 9100Å, what is referred to as absorptive bistate behavior can be seen in this device. In the present context, absorptive bistate behavior refers to a situation where the low field absorption and the high field absorption are quite high while intermediate voltages produce extremely low absorption values. It is the combination of absorptive quenching without appreciable red-shift of all resonances at low bias and the large red-shift of higher energy transitions at higher biases that make this possible. This type of behavior has many potential applications for optical latches as well as multi-state logic circuitry.

The Kramers-Kronig relationship was used to analyze the absorption data over a wider range of wavelengths than is shown in the absorption figures, using bulk material parameters as a reference. The change in refractive index versus wavelength at various applied biases was thus obtained. Exciton width (L) was assumed to be 90Å (width of two wells plus barrier) for the presentation of this data. This assumption does not affect the conclusions. Figure 3-15 shows the changes in refractive index for the type IIA device, which is typical for all of the coupled well systems. Since not all excitons red-shift simultaneously, the characteristic zero in refractive index change is seen at 9135Å, the absorption change maximum. If one creates coupled well systems which require low voltages to achieve the anticrossing of two resonant states, then this low field will not
Stark-shift the higher energy levels. Hence, the wavelength (energy) at which the extrapolated anticrossing occurs will be very close to the wavelength of the original HH1 exciton maxima (at zero applied field). With field, the lowest two energy states reach the anticrossing condition. At this point, the lowest energy level begins to significantly red-shift as it becomes an inter-well transition. Simultaneously, the second lowest transition becomes inter-well, and is prevented from red-shifting (some blue-shifting will be present, the magnitude of which depends upon the strength of the coupling between the two resonant levels). This removes this high energy transition from the immediate vicinity of the operating wavelength. The net result is that the change in absorption area for a small wavelength range on either side of the extrapolated anticrossing wavelength is held approximately constant. Knowing this, from earlier discussions of the Kramers-Kronig relationship, the change in refractive index will be zero at the anticrossing wavelength. In contrast with optimized, low-chirp devices which exploit the QCSE to achieve zero $\Delta n$ at two bias points, the coupled well structure will give low chirp operation over the entire range of applied bias. Note that in this particular device, the PDAM region did not have a zero chirp regime (see 9000Å in Figure 3-15 and Figure 3-13). The GaAs/InGaAs coupled quantum wells of the previous chapter had PDAM regions that were well defined and displayed changes in absorption with local maxima. However, looking at the NDAM region, the low chirp behavior over the entire voltage swing makes this structure uniquely suited for minimal dispersion in absorption modulation devices. In addition, other wavelengths, such as 9050Å, have minimal $\Delta \omega$ with considerable $\Delta n$. Such features could be exploited in waveguide or Fabry-Perot modulators for use as phase modulators. While obtaining low voltage transmission modulation is important for high frequency optical modulation, the ability to change transmission without changing refractive index is the significant effect which makes this device structure extremely important for device applications. Further optimization will allow lower voltage operation to be obtained, but even this unoptimized sample displays zero chirp behavior.

3.3.6 Theoretical Quantum Well Optimization

Optimization of the type II coupled quantum well systems is best achieved by making one well thin enough to ensure high E1-HH1 overlap in the zero bias condition, yet deep enough to ensure a large confinement energy. The lowest energy level of the thinner/deeper well should be below the bottom of the shallower well so that the exciton is tightly confined to the thin well. Finally the shallower well should be quite wide to ensure that the lowest level in the wide well is quite low so that the energy level difference between the lowest levels in the two wells is small. This ensures very low voltage operation.
Finally the barrier should be constructed so that it is thick enough to confine the carriers, yet thin enough to ensure adequate coupling. Strong coupling is needed to split the lowest two energy resonances and ensure a nice regime where zero phase change can occur during the voltage swing. Keep in mind that if the wider well is close to a multiple of the width of the thinner well, coherent quantum mechanical reflections make the effective barrier height lower than as constructed. In the current structure, better performance at the same wavelength could be achieved by using a larger difference in indium compositions (10% and 30% for example) so the lowest level in the deep well is below the bottom of the shallower well and using a larger (for example 100Å) shallower well to ensure low voltage operation. To design the experimental devices, calculations of relative absorption strength were performed by a variational technique which accounted for coupling between the lowest two electron and hole states as well as for exciton interactions. The wavefunctions used were:

\[
\psi_{\pm\pm} = \left[ a \psi_{e1} + \sqrt{\left( e^{i \alpha} - a^2 \right)} \psi_{e2} \right] \left[ b \psi_{h1} + \sqrt{\left( e^{i \beta} - b^2 \right)} \psi_{h2} \right]
\]

Eq. 3-7

\[
\psi_{\pm-} = \left[ a \psi_{e1} + \sqrt{\left( e^{i \alpha} - a^2 \right)} \psi_{e2} \right] \left[ -\sqrt{\left( e^{i \beta} - b^2 \right)} \psi_{h1} + b \psi_{h2} \right]
\]

Eq. 3-8

\[
\psi_{\pm+} = \left[ -\sqrt{\left( e^{i \alpha} - a^2 \right)} \psi_{e1} + a \psi_{e2} \right] \left[ b \psi_{h1} + \sqrt{\left( e^{i \beta} - b^2 \right)} \psi_{h2} \right]
\]

Eq. 3-9

\[
\psi_{\mp} = \left[ -\sqrt{\left( e^{i \alpha} - a^2 \right)} \psi_{e1} + a \psi_{e2} \right] \left[ -\sqrt{\left( e^{i \beta} - b^2 \right)} \psi_{h1} + b \psi_{h2} \right]
\]

Eq. 3-10

\[
\phi_{1s}(\lambda) = \sqrt{\frac{\sigma}{\pi}} \frac{1}{\lambda} \exp \left[ -\frac{\sqrt{(x^2 + y^2)}}{\lambda} \right]
\]

Eq. 3-11

While the Hamiltonian was:

\[
H = \frac{\hbar^2}{2 \mu_{xy}} \nabla_{xy}^2 - \frac{\hbar^2}{2 m_e} \frac{\partial^2}{\partial x_e^2} - \frac{\hbar^2}{2 m_h} \frac{\partial^2}{\partial x_h^2} - \frac{e^2}{4 \pi \epsilon_0 \epsilon_r r} - eF_z + V(z)
\]

Eq. 3-12

In this case, \(\psi_{e1}, \psi_{e2}, \psi_{h1}, \psi_{h2}\) are the four complex wavefunctions in the absence of coupling, \(\mu_{xy}\) is the reduced mass of the electron hole system, \(m_e\) and \(m_h\) are the electron and hole effective masses, \(\lambda\) is the effective exciton radius, \(r = x^2 + y^2\) is the polar coordinate of
distance, and $a$ and $b$ are the complex coupling parameters. ‘F’ represents the external electric field while $z$ is the distance coordinate in the $z$ direction. Without coupling between the lowest electron and hole states, $a$ and $b$ have a magnitude of 1.0 and one obtains wave functions which resemble single well wave functions. The $e^{a}$ and $e^{b}$ terms are taken to have the same phase as $a^{2}$ and $b^{2}$, respectively. Using such a technique, one can obtain better estimates of the relative absorption strength than a simple overlap integral of the pure, uncoupled, electron and hole states provides. With this theoretical calculation, for optimized structures, efficiency ratios of 400$\mu$m/kV or more may be possible with two coupled wells ($\alpha_{\text{max}}=.25$, $\alpha_{\text{min}}=.04$, $E_{\text{max}}=20$kV/cm). Note that this is well over an order of magnitude better than for single well systems. This calculation method is a further extension of the tight binding method.

With the above wavefunctions and Hamiltonian, several exciton characteristics can be found. Given $\psi_{e1}, \psi_{e2}, \psi_{h1}, \psi_{h2}$ at various applied voltages, the exciton wavefunctions can be determined at each voltage by using variational techniques to find the optimal values for the real and imaginary parts of the $a$ and $b$ coefficients as well as for the value of the exciton radius, $R$. This technique requires minimization of the energy with respect to 5 parameters. Since even for a computer this could become a long problem, the initial attempt assumed $a$ and $b$ parameters and found a minimum for $R$. Next, using this value for $R$, the optimum values for the complex parts of $a$ and $b$ were found. Then these were used to find $R$ again and the process was iterated. However, it was found that this system of equations had only one minimum over the 5 parameter space, so later calculations were performed by choosing a course grid of points in 5 dimensional space, finding the minimum, then making a finer mesh grid around that point and finding a minimum again, and repeating until the minimum was achieved with reasonable accuracy. Neither method proved more accurate and the decision to change techniques was chosen purely on the basis of convenience and integrability with previous computer code. Using this technique, the wavelength of the four lowest excitons, their binding energy and radii were found. Most importantly, though, by looking at these parameters, the approximate applied electric field at which the anticrossing between the lowest energy levels occurs were found. The computer program was used primarily as a qualitative tool, although the voltages at which anticrossing occurred were found accurately. Quantitative discrepancies of 5% to 15% in the other values between experiment and theory were likely a result of two factors. First, energy dependent effective masses were not used for any of the theoretical calculations. For very thin wells, energy levels are quite high in the valence band and changes in mass due to band nonparabolicity could be important. Second, because of the thin dimensions of some of the quantum wells and the sensitivity of energy levels to small changes in
thickness, even an accurate model would have disagreed with an, at times, finicky growth technique. With the subsequent improvements in reproducibility in the lab, future iterations of growth and design adjustment should be all that is necessary to obtain better agreement between theory and experimental results. Figure 3-16 plots some of the parameters for the four lowest exciton transitions to give a flavor for the type of results obtained. More points versus voltage are needed to perhaps get a clearer picture of some of the smaller features. For design purposes, though, all that was being investigated was the changes in the anticrossing energy as a result of the Coulomb interaction.

![Graphs showing binding energy and exciton diameter as a function of applied electric field.](image)

*Figure 3-16:* Simulation of coupled InGaAs quantum wells showing (a) binding energy (b) exciton diameter as a function of applied electric field. Simulation is of an 30Å In$_{0.15}$Ga$_{0.85}$As and a 50Å In$_{0.5}$Ga$_{0.7}$As coupled quantum well with 15Å Al$_{0.33}$Ga$_{0.67}$As barrier.

The differences in switching voltage between calculations without coupling and including the variational techniques proved to be smaller than variations due to growth error. As mentioned, all of the devices use p-i-n diodes to apply an electric field. These devices must be reverse biased in order to prevent current injection (which would quench exciton resonances. Table I shows that the same quantum well structure could be used to provide either hole or electron switching with bias. Therefore, if a structure were built which allowed application of bi-directional fields, a single device could switch electrons and holes. Using the combined results from two experimental p-i-n structures with identical quantum well attributes, absorption at the NDAM wavelength was plotted versus applied electric field.
Figure 3-17: Absorption versus Voltage at the NDAM wavelength. These experimental results show the combined data from two p-i-n structures to illustrate the response possible if the quantum wells were embedded in a structure which allowed bi-directional fields.

The result is shown in Figure 3-17. This clearly shows that multi-state behavior is possible with a single quantum well structure. Here the changes in absorption are much greater than possible using the QCSE in a NDAM region.

3.3.7 Conclusion

In conclusion, this section demonstrates the use of coupled InGaAs quantum wells for transmission modulators on GaAs using both type IIA and type IIB quantum well configurations. Results of the last chapter were elaborated upon and several new issues were discussed. The foundation of these devices is the ability to switch the lowest electron level from one well to an adjacent one in type IIA devices while a spatial switching of hole states is utilized in the type IIB devices. In addition, low chirp absorption modulation over large voltage swings were demonstrated. This significant achievement is not realizable in single well systems since many exciton resonances red-shift concurrently in single well structures. Furthermore, properly designed devices can display absorptive/transmissive bistate behavior. This section has also provided a theoretical description of device operation, explaining the different transitions and how overlap integrals are controlled to achieve device operation. Finally experimental results and theoretical predictions
demonstrated good agreement, even with higher energy heavy hole states and light hole exciton states.

3.4 Advanced Quantum Well Systems

3.4.1 Introduction

The previous sections described the processes behind three-step asymmetric coupled quantum wells (for this section they shall be referred to as TACQWs). Using field induced spatial separation of charges, they demonstrated changes in absorption per unit applied bias seven times greater than obtainable through the quantum confined Stark effect (QCSE). In addition, these multi-step well systems displayed zero refractive index change at the active wavelength over the entire operating voltage swing, thus allowing zero chirp optical modulation. Furthermore, these devices exhibited multistate behavior with large differentials in absorption.

Despite the desirable characteristics of three-step asymmetric coupled quantum wells (TACQWs), there are several unresolved issues regarding optical modulation systems which these initial results on TACQWs did not address. First, although TACQWs permit zero refractive index change over the entire voltage swing at the active wavelength, for small wavelength deviations from that wavelength, the refractive index changes can be on the order of 0.05. For 1μm wavelength light (wavelength in air) traveling through a 3μm long GaAs waveguide (or a typical cavity device with near unity back mirror reflectivity and 90% front mirror reflectivity), this refractive index change can produce phase changes of 50°. This parasitic phase change is significant enough to warrant consideration. Second, unlike electrical systems, which carry a signal ground for voltages, single beam optical systems do not have such a reference. This makes it difficult to provide low noise switching and account for system induced parasitics. Dual beam systems have been investigated by others55 and such systems could be used to accommodate the ground problem. One configuration which eliminates scattering loss resulting from the ‘ground’ signal transmitting through etched surfaces requires two closely spaced wavelengths to pass through the device. One wavelength would be affected by the active medium, the other would be below the band edge and pass through unaffected. However, the two wavelengths would be close enough together so that their response to system induced parasitic scattering and bulk material characteristics would be nearly identical. TACQW’s are not compatible with the need for two closely spaced wavelengths since when the device is switched, the lowest order transition is significantly red-shifted. This results in
substantial absorption over a large wavelength range, causing degradation of the reference beam. In addition, field induced carrier separation is not an effective means of modulation when the wells are shallow; at zero bias, electrons are not well confined. Since carrier sweep out times are much shorter for shallow wells,\textsuperscript{56,57} they are desirable for high frequency devices. Quantum well systems which contain multiple coupled wells or greater variation in material composition are the key to eliminating the above limitations of TACQW's. These more advanced structures are discussed in the following sections.

3.4.2 Device Design and Theory for Triple Wells

To eliminate the significant red-shift of the lowest order absorption edge and to test structures compatible with shallow wells, p-i-n devices whose intrinsic region contained 20 coupled triple wells were investigated. These wells consisted of a 40Å In\textsubscript{0.2}Ga\textsubscript{0.8}As well, a 60Å GaAs well, and a 40Å In\textsubscript{0.5}Ga\textsubscript{0.7}As well separated by 14Å Al\textsubscript{0.41}Ga\textsubscript{0.59}As barriers. The triple well regions were separated from one another by large, 200Å, Al\textsubscript{0.41}Ga\textsubscript{0.59}As barriers to reduce the deleterious effects of strain and prevent the formation of undesirable dislocation networks. Like TACQW's, the coupled triple well structures modulate light via carrier induced separation of carriers. However the lowest and second lowest electron levels, corresponding to the 40Å In\textsubscript{0.3}Ga\textsubscript{0.7}As and 40Å In\textsubscript{0.2}Ga\textsubscript{0.8}As wells respectively, have much lower coupling than a double well structure. In terms of general variational wavefunctions:

\[
\psi_{2\text{well}} = \left[ a\psi_{e1} + \sqrt{(e^{i\alpha} - a^2)} \psi_{e2} \right] b\psi_{h1} + \sqrt{(e^{i\beta} - b^2)} \psi_{h2}\]

Eq. 3-13

\[
\psi_{3\text{well}} = \left[ a\psi_{e1} + b\psi_{e2} + \sqrt{(e^{i\alpha} - a^2 - b^2)} \psi_{e3} \right] c\psi_{h1} + d\psi_{h2} + \sqrt{(e^{i\beta} - c^2 - d^2)} \psi_{h3}\]

Eq. 3-14

The 'a' coefficients are much larger at zero bias for the triple well system. Here the \(\psi\)'s are the complex wavefunctions in the absence of coupling and \(\alpha\) and \(\beta\) can be taken to have the phase of \((a^2+b^2)\) and \((c^2+d^2)\), respectively.

The larger bandgap of the central well creates a large effective barrier between the two outer wells at zero bias. This leads to more tightly confined electron and hole wavefunctions in the outer wells and a greater electron-hole envelope wavefunction overlap integral \(\langle \phi_e | \phi_h \rangle\), creating well defined excitons. As shown in Figure 3-18, the wavefunctions of the three lowest electron levels are tightly confined to their respective wells. While these wells are not shallow, triple well structures with their weak coupling
and strong spatial separation should make carrier separation modulation accessible for very shallow wells (say GaAs-In0.02Ga0.98As wells).

Figure 3-18: *Conduction band offsets under positive bias (diode reverse biased) and zero bias conditions showing the location of the lowest three electron levels in both cases. In addition, the wavefunctions under the two bias conditions are shown.*

### 3.4.3 Experimental results

The current wells were designed so that the lowest energy levels were very close to the bottom of the GaAs well while the second lowest electron level was slightly above the GaAs well minimum. When voltage is applied to reverse bias the diode, the coupling of the two outer wells significantly increases via coupling through the central well. The voltage induced band bending decreases the effective barrier during anticrossing of the two lowest electron levels (the 'a' and 'b' coefficients become nearly equal). With further applied bias, the lowest two levels switch wells (so that 'b' is unity). Again the large separation between the outer wells afforded by the central well causes the wavefunctions to be tightly confined to their respective wells. Thus while the lowest hole wavefunction remains tightly confined in the opposite In0.3Ga0.7As well with bias, the lowest electron level becomes extremely well confined to the In0.2Ga0.8As well. Furthermore, because of the large spatial separation of the outer two wells, the electron wavefunctions can be abruptly switched. Figure 3-18 shows how the electron wavefunctions shift and are then tightly confined. Figure 3-19a displays how the electron wavefunction can be switched
completely from the In$_{0.3}$Ga$_{0.7}$As well to the In$_{0.2}$Ga$_{0.8}$As well with only a differential electric field of 50kV/cm. Using the previously defined modulation efficiency, \([\alpha_{\text{high}} - \alpha_{\text{low}}]/\alpha_{\text{high}}\)\(E_{\text{max}}\), then this ratio is 250 \(\mu\)m/kV, compared to about 100\(\mu\)m/kV for double wells and 17\(\mu\)m/kV for single wells.\(^{38}\)

Figure 3-19: (a) absorption and (b) dispersion characteristics of the triple well system. The applied electric fields are as shown.

The current device displays two additional important types of behavior. First, because switching occurs over a small differential field swing (50kV/cm) and uses a small overall field (180kV/cm), and because the reduced coupling between the outer well levels reduces the energy level induced splitting, there is no significant red-shift of the lowest electron level. The lower energy level is only shifted about 200\(\AA\) (30 meV) at these wavelengths. This is significantly less than the 500\(\AA\) or more (70 meV) seen in TACQWs. Thus the coupled triple well device is more suitable for the dual beam systems described in section 3.4.1. However, because the central well decreases the coupling off-resonance between the lowest energy levels of the side wells, the anticrossing repulsion of energy levels is not nearly as strong as in double well systems. As shown in Figure 3-19b, this negates the balance of absorptive area around the anticrossing energy. In essence, the zero \(\Delta n\) over all voltages which is seen in TACQWs is not fully realized here. The refractive index changes by as much as 0.015 over the voltage swing at the operating wavelength. In such a case, 1\(\mu\)m wavelength light (wavelength in air) traveling down a 3\(\mu\)m GaAs waveguide (or the cavity device briefly described in section 3.4.1) would experience a 15\(^{\circ}\) phase shift due to this parasitic refractive index change. Optimization of the well structure may be able to compensate for this shortcoming.
3.4.4 Design and Theory of ‘Effectively Graded’ Structure

A second two well coupled device consisted of “effectively graded” quantum wells containing of a series of 5 Å, 10 Å, 20 Å, and 30 Å GaAs co-wells with 5 Å Al$_{0.34}$Ga$_{0.66}$As barriers and a 10 Å and 5 Å In$_{0.2}$Ga$_{0.8}$As set of co-wells with similar barriers. The series of GaAs wells and In$_{0.2}$Ga$_{0.8}$As wells were separated from one another by 30 Å Al$_{0.34}$Ga$_{0.66}$As barriers. The active region is composed of twenty of these complex coupled well sets in the intrinsic region of a $p$-$i$-$n$ diode and each well set was separated from one another by 150 Å Al$_{0.34}$Ga$_{0.66}$As barriers to minimize the effects of strain from the In$_{0.2}$Ga$_{0.8}$As. A schematic of the well structure is shown in Figure 3-20.

![Figure 3-20: Conduction and Valence band offsets for the “effective graded” quantum well device under zero bias and with an applied electric field. The inset schematically depicts the way the device effectively operates.](image)

The best way to view this structure is to keep in mind the picture of “effectively graded” structures using chirping techniques for MBE growth; the well structure can be thought of as essentially an 80 Å QW and a 20 Å InGaAs QW with compositional grading across each of the wells. Note that while the individual InGaAs co-wells and the GaAs co-wells are strongly coupled together within themselves, the two co-well sets are far less tightly coupled. This makes the effective bandgap across the two ‘wells’ appear to vary across the structure as shown in the inset in Figure 3-20. This effective compositional grading across the structure acts to ‘pre-bias’ the structure; making, for example, the conduction band looks as it would with non-graded wells and an applied electric field across the structure. 59
Since switching is dependent upon the lowest level for electrons in the conduction band, the relation of the hole band is of secondary importance.

3.4.5 Experimental Results

The device operates through spatial separation of carriers. At zero applied bias, the lowest electron and hole levels exist in the InGaAs co-wells and display a large exciton resonant absorption, as shown in Figure 3-21a. However, when bias is applied across the wells in the opposite direction to the conduction band 'pre-biasing', this has two effects: first, as the pre-bias is negated, the conduction band energy levels blue-shift (for reasons analogous to the causes of red-shifting from the QCSE).

![Graphs showing absorption and dispersion characteristics of the "effective graded" quantum well system.](image)

Figure 3-21: (a) absorption and (b) dispersion characteristics of the "effective graded" quantum well system.

However, as the energy levels of the InGaAs co-wells and the GaAs co-wells approach each other, energy level repulsion attempts to simultaneously red-shift the lowest levels. This is in contrast with TACQWs, where both effects act in the same direction. The effect of this interaction is shown in Figure 3-21a. With application of bias, the strong absorption peak is quenched and significantly broadened. However, the location of the resonant maximum remains at almost constant wavelength as a result of the near cancelation of the two opposing energy level shifts described above. Note that the heavy mass of the hole and the lack of well swapping between the lowest hole levels precludes these levels from shifting appreciably. While the absorptive efficiency ratios for these devices are not significantly better than for single quantum wells using the QCSE, the dispersion characteristics are improved. As shown in Figure 3-21b, lack of significant exciton resonance shifting decreases the refractive index changes at wavelengths shorter.
than the exciton resonance to less than 0.015 over the entire voltage swing and over the 500Å range where absorptive changes are appreciable. Note that there is a corresponding increase in the refractive index at longer λ. This would be particularly useful for photorefractive devices. While the total area under the Δn curve is not significantly changed, the changes in absorption have been shifted from being equally distributed above and below the zero refractive index point to being concentrated at longer wavelength. This is unlike either single quantum well systems using the QCSE or TACQW devices where a refractive index changes of 0.05 or greater is observed on both sides of any zero refractive index change crossings. Further optimization should further reduce residual Δn.

3.4.6 Conclusion

In summary, advanced QW schemes improve such characteristics as optical modulation efficiency ratios and bandwidth over which a low Δn exists. Such structures are also more compatible with the use of dual beam propagation for carrying optical signal ground and with the use of shallow wells for high speed modulation. Given the precise structures available with a combination of computer control and in-situ characterization for MBE grown material, fabricating advanced quantum well systems is no more difficult than creating a series of single wells and there are clear performance advantages.

3.5 Doped Coupled Quantum Wells

There are alternative methods for quantum well absorption modulation aside from the QCSE and field induced carrier separation. One class of devices utilizes dopants as a means of modulation. Depending upon the doping scheme, these dopants introduce carriers into the quantum wells or simply provide a location for fixed charge. In either case, these charges screen the exciton electron-hole interaction. This reduces the exciton lifetime, increases the width of the exciton transition (Heisenburg Uncertainty Principle) and decreases the height of the absorption maxima.

Figure 3-22 shows a schematic picture of a new method of using carriers in coupled quantum wells to produce modulation. In this scheme, the thinner of two wells is doped while the wider well is undoped. Thus, while the lowest order transition would be washed out, the transition to the wider well would remain strong. Here the energy levels are spaced closely enough so that low switching voltages are achieved and the coupling between the wells is low enough so that there is minimal leakage of the carriers from one well to another at zero bias. With applied bias, the carriers from the one well are “spilled” into the adjacent well, thus screening that transition.
Figure 3-22: Doped, coupled quantum well sample (a) without bias and (b) with bias. The circles in the plot represent the carriers in the wells. These carriers screen coulomb interactions.

Two structures were experimentally grown and the results of these experiments are shown in Figure 3-23. Both experiments contained 50Å GaAs wells and 30Å In$_{0.2}$Ga$_{0.8}$As quantum wells. Figure 3-23a depicts a device with n-type dopant while Figure 3-23b is for a device with p-type doping. Both experimental structures had dopant levels of $1 \times 10^{18}$ cm$^{-3}$. In both cases the applied bias quenches the exciton transition, demonstrating this dopant modulation scheme.

In the experimental data, absorption tails beyond 8200Å can be seen. Such large tails are not observable in undoped samples and reflect the influence of absorption in the thinner, doped well.

While this technique provides an alternative method of absorptive modulation, it does not provide absorptive changes as large as those produced by undoped coupled quantum wells. In addition, the required voltages are no lower than undoped wells. Furthermore, even for optical systems which use low optical input powers, large numbers of charges need to be moved. This will limit the switching speed of these devices relative to that of undoped wells.
Figure 3-23: Experimental results for doped, coupled quantum well sample. Here only the thinner, deeper well was doped with (a) silicon (n-type) and (b) carbon (p-type). Quenching of the resonance at 8150Å can be seen.

While these disadvantages are significant and may preclude these devices from use in strictly electrically controlled devices, there may be alternative uses for these structures. For example, because the relative widths and depths of the two wells can be controlled, the energy difference between various sub-levels in the coupled quantum well system can be controlled--at zero bias this is by design, but bias can be used to tune this difference. Intersubband wavelength light can be used at this energy difference to control interband absorption transitions (by removing carriers from lower subband levels using an intersubband transition, the lowest interband exciton interband transitions can be enhanced). Small amounts of bias can change energy differences and tune the structure to different intersubband wavelengths. A series of devices could be biased slightly differently to use various wavelengths of mid infra red light to control near infra red light absorption characteristics. More work needs to be done in this area though, but the prospect of using light rather than voltage as a controlling medium is often desirable. In addition to doped samples, it should be interesting to investigate if and how intersubband transitions in undoped wells could control interband transitions. This, however, will not be discussed further here.
4. Quantum Well and Optical Cavity Simulation

This chapter describes the general analytic equations governing Fabry-Perot cavities, numerical methods for quantum well state determination and the simulation of Fabry-Perot cavities, including exciton states. Furthermore, it explores the interaction of excitons and Fabry-Perot cavities to affect the width of the Fabry-Perot cavity optical reflectivity minima. In addition, the theory behind the simulation of arrays of devices for spatial light modulation will be discussed.

4.1 Fabry-Perot Cavities

A Fabry-Perot cavity array consists of two or more reflective layers enclosing cavity regions. An example of such an array is shown in Figure 4-1. Here $E_i$ is the incident electric field, $E_r$ the overall reflected electric field, $E_t$ the overall transmitted field, and the $E_{in}$ are the internal fields at some specified location in the cavity. The r's and t's refer to the electric field reflectivities and transmissivities of the cavity boundary layers (mirrors). The array can have as many cavities as desired, but typical MBE-grown optoelectronic modulators limit the number of cavities to one or two in order to limit the fabrication complexity.

![Figure 4-1: Schematic representation of a generalized Fabry-Perot cavity array.](image)

Using the above picture, if the L's are defined as the lengths of the individual cavities and $E_{int}$ is defined as the electric field in the cavity just after reflection from the 'left' side mirror of its respective cavity, then for normally incident light, the boundary conditions can be written recursively as:
\[ E_{\text{int}n} = r_n^E_{\text{int}n + 1} E_{\text{int}n} e^{-\left( \frac{j \omega}{c} n(\lambda, V_n) + 2 \alpha(\lambda, V_n) \right) L_n} + j n E_{\text{int}n - 1} e^{-\left( \frac{j \omega}{c} n(\lambda, V_{n-1}) + 2 \alpha(\lambda, V_{n-1}) \right) L_{n-1}} + j n^2 r_n^E_{\text{int}n} e^{-\left( n \alpha(\lambda, V_n) \right) L_{n+1}} + \left( \frac{j \omega}{c} n(\lambda, V_n) + 2 \alpha(\lambda, V_n) \right) L_n \]

\text{Eq. 4-1}

\[ E_T = \sum_{n=1}^{n_{\text{max}}} \left( j^{n-1} r_n^E_{\text{int}n} e^{-\left( \frac{j \omega}{c} n(\lambda, V_n) + 2 \alpha(\lambda, V_n) \right) L_n} \prod_{m=1}^{n-1} \left[ j n^2 r_n^E_{\text{int}n} e^{-\left( n \alpha(\lambda, V_m) + \alpha(\lambda, V_m) \right) L_m} \right] \right) \]

\text{Eq. 4-2}

\[ E_t = j n^2 r_n^E_{\text{int}n_{\text{max}}} e^{-\left( \frac{j \omega}{c} n(\lambda, V_{n_{\text{max}}}) + \alpha(\lambda, V_{n_{\text{max}}}) \right) L_{n_{\text{max}}}} \]

\text{Eq. 4-3}

Here \( E_{\text{int}0} = E_t \) and \( L_0 = 0 \).

It is possible to eliminate the interior electric field terms and derive the overall reflectivity of the device from the \( n \)th interface as a function of the reflectivity of the \( n+1 \)st interface. Thus the overall reflectivity can be obtained through this recursive function:

\[ \frac{E_{r n}}{E_{i n}} = \frac{r_n - E_T(n+1) e^{-\left( \frac{j \omega}{c} n(\lambda, V_n) + 2 \alpha(\lambda, V_n) \right) L_n}}{1 - r_n E_T(n+1) e^{-\left( \frac{j \omega}{c} n(\lambda, V_n) + 2 \alpha(\lambda, V_n) \right) L_n}} \]

\text{Eq. 4-4}

For example, if there were only one cavity, then \( E_T(n+1) = r_2 \), the reflectivity of the right side mirror, and the above expression becomes

\[ E_{r 1} = \frac{r_1 - r_2 e^{-\left( \frac{j \omega}{c} n(\lambda, V_1) + 2 \alpha(\lambda, V_1) \right) L_1}}{1 - r_1 r_2 e^{-\left( \frac{j \omega}{c} n(\lambda, V_1) + 2 \alpha(\lambda, V_1) \right) L_1}} \]

\text{Eq. 4-5}
Similarly, for the transmission of a single cavity, the expression for a single cavity becomes:

$$E_t = \frac{-r_1 t_2 e^{-\left(j \frac{2\phi}{c} n(\lambda, V_1) + 2\alpha(\lambda, V_1)\right)L_1}}{1 - r_1 r_2 e^{-\left(j \frac{2\phi}{c} n(\lambda, V_1) + 2\alpha(\lambda, V_1)\right)L_1}} \quad \text{Eq. 4-6}$$

Remember that the reflected intensity (optical power) is equal to $E^*E$, where $E$ is given by the above expressions.

### 4.2 Optical Bandwidth

The previous discussion provided expressions for reflection from and transmission through a Fabry-Perot cavity. Here, the generalized equations for optical bandwidth will be given.

As a starting point, the points for half maximum power (or field intensity) for a Fabry-Perot cavity can be obtained through a simple expression$^{60}$:

$$F \cos^2\left(\frac{2\pi D}{\lambda} \right) - \varphi = 1 \quad \text{Eq. 4-7}$$

Here $F$ is the finesse of the cavity, $\lambda$ is the wavelength, $\varphi$ is the optical phase, and $D$ is an integer. Making the approximation that the relation between the change in wavelength and the change in the phase is linear and small, then the following relations can be used:

$$\varphi = \varphi_o + \frac{d\varphi}{dg} \Delta g \quad \text{and} \quad \frac{2\pi D}{\lambda} = m\pi(1 + \Delta g) \quad \text{where} \quad g \text{ is defined by the relation} \quad \frac{1}{2\Delta g} = \frac{\Delta \lambda}{\lambda_o}$$

Using these approximations in the above expression, then optical half-width (where this halfwidth $=2\Delta g$), can be written as:

$$\frac{\Delta \lambda}{\lambda_o} = \frac{2 \cos^{-1}(F^{-0.5})}{m\pi - \frac{d\varphi}{dg}} \quad \text{Eq. 4-8}$$

Macleod$^{60}$ has derived a simple, approximate expression to determine the phase change due to changes in wavelength imposed by the quarter wave stack dielectric mirrors.

$$\theta = \tan^{-1}\left(\frac{-\pi n_h n_L (g - 1)}{n_C(n_h - n_L)}\right) \quad \text{Eq. 4-9}$$
Here, \(n_e\) is the refractive index of the cavity region. It is assumed that the change of refractive index with wavelength of the cavity is small over the width of the Fabry-Perot resonance. This is NOT necessarily true when an exciton and Fabry-Perot resonance are coincident. The results of such a situation will be discussed later. Using the expression for \(\theta\) above in the expression for half width of the cavity resonance, gives:

\[
\frac{\Delta \lambda}{\lambda_0} = 2 \cos^{-1}(F^{-0.5}) \left( \frac{n_H - n_L + \frac{\pi^2 n_H^2 n_L^2 (g - 1)^2}{n_C(n_H - n_L)}}{mn \left( n_H - n_L + \frac{n_H n_L}{mn_C} + \frac{\pi^2 n_H^2 n_L^2 (g - 1)^2}{n_C(n_H - n_L)} \right)} \right)
\]

Eq. 4-10

For simplification, note that the resultant expressions are themselves functions of \(g\) and that in this case, \(g\) is very close to 1. Thus the terms containing \(g\) can be neglected, giving analytic expressions which are extremely good approximations to the actual bandwidths that are measured. For greater accuracy, a matrix technique is usually required and will be discussed later.

### 4.3 Before vs. Beyond the matching condition

By modeling an optical cavity as a thin front mirror and an ‘effective back mirror’ which accounts for the bottom quarter wave stack mirror reflectivity and the absorption of the quantum well active material at a particular bias, the reflectivity of the device as a whole at the cavity’s resonant wavelength can be simulated.61

The ‘matching condition’ occurs when the front mirror reflectivity, \(r_f\), is equal to the effective back mirror reflectivity, \(r_b e^{-2\alpha L}\), where \(r_b\) is the value of the bottom quarter wave dielectric stack reflectivity. When a device is operated before the matching condition, for a given front mirror reflectivity (for example \(R_f = 50\%\)), increasing absorption decreases device reflectivity. Recall that the value of absorption is determined at a wavelength by the voltage across quantum wells, and hence the exciton locations. These quantum wells are in the optical cavity. Before the matching condition, the front mirror reflectivity is lower than the effective back mirror reflectivity and so reflectivity is dominated by the back mirror. In this case, increases in cavity absorption decrease the amount of light reflected. Conversely, if the device is operated beyond the matching condition, increasing absorption increases device reflectivity. Here the effective back mirror is less reflective than the front mirror and
so reflectivity will be dominated by the front mirror. Increases in cavity absorption make the front mirror appear more reflective so overall device reflectivity increases.

Figure 4-2  Total Reflectivity versus Effective Back Mirror Reflectivity for asymmetric Fabry-Perot devices employing 95% and 50% reflective front mirrors are depicted. Regions corresponding to before and beyond the matching condition for the 50% front mirror device are as shown.

The previous chapters described how applying a voltage across quantum wells could increase or decrease absorption (NDAM and PDAM) at a particular wavelength. Now it should be noted that a cavity which has a resonant frequency set to either a NDAM or PDAM wavelength can experience either increasing or decreasing reflectivity, regardless of the direction of the change in absorption.

4.4 Effect of Exciton Width on F-P Width

The above derivation for Fabry-Perot optical bandwidth relied upon the approximation that the change of the cavity refractive index with wavelength is small over
the range of the optical bandwidth. However, when the exciton and Fabry-Perot resonances are coincident, or nearly so, then the exciton can create a large \(dn/d\lambda\) around that wavelength region. This interaction tends to widen the width of the F-P region if the exciton resonance is wider than the F-P resonance. This is indeed the case for most reasonable semiconductor design. Figure 4-3 shows the result of exciton resonant linewidth on the width of the Fabry-Perot resonance.

![Graph](image)

**Figure 4-3:** Simulation of the effect of exciton width (Lorentzian lineshape) on the width a Fabry-Perot minima when both resonances are coincident in wavelength.

Here, the Fabry-Perot resonance is designed to have an optical full width at half maximum (FWHM) optical bandwidth of 120\(\text{Å}\) around the central wavelength of 8500\(\text{Å}\). The reflectivity of the device is shown with zero exciton absorption and with excitons having a maximum absorption of 5000\(\text{cm}^{-1}\) centered at 8500\(\text{Å}\). Recall that for different material systems with equivalent material quality, under similar conditions and similar design, the total absorptive area for a single transition will be approximately the same. For excitons with linewidths above 75\(\text{Å}\) or so, the overall reflective dip (which now consists of a coupled exciton-photon resonant system) is widened considerably. For 200\(\text{Å}\) exciton linewidths, for example, the coupled system has a resultant reflectivity dip containing a FWHM of 325\(\text{Å}\). Note that the relationship between exciton width and the increased width of the reflectivity dip is a non-linear function. It is also a function of the values of the front and back mirrors (which determine the finesse of the cavity). The change in
bandwidth between situations where no exciton is present and where an exciton of FWHM of 400Å (around 8500Å) exists reflects the difference between 400Å and an infinitely wide absorption.

4.5 Numerical Methods for Quantum Wells and Optical Cavities

The simulations of the Fabry-Perot cavities and uncoupled quantum well energy levels were performed using transfer matrix techniques. The transfer matrix technique basically presupposes waves impinging upon a ‘surface’. In the case of a quantum well, the structure is examined in terms of the potential energies of the different layers. For a Fabry-Perot cavity, the relevant material parameter is the complex dispersion (absorption plus refractive index). In both cases, the layer thicknesses must be given. The percent of the wave which is transmitted and reflected at each material interface is determined as the wave travels the length of the material. By varying the incident energy of the wave and determining the energies at which the maximum transmission occurs for the structure, bound states can be found. In the case of quantum wells, these roughly correspond to the stationary quantized states of the well. In the case of optical cavities, it corresponds to the wavelength of the Fabry-Perot resonances. Energies not corresponding to the maximum transmission can be used to map out the response of the structure at other wavelengths (in the optical case). Here a very brief overview of the relevant equations for both the electronic and optical cases is given.

4.5.1 Electronic states

Propagation of waves across interfaces requires two things. First, usable wavefunctions which can express transmission and reflection characteristics are needed. Second, good boundary conditions are required. For electronic transitions across potential energy barriers, the boundary conditions which are usually employed are continuity of the wavefunction and continuity of flux: \( \psi \) and \((1/m)(d\psi/dx)\) where ‘x’ is the length variable and \( m \) is effective mass in the appropriate materials.\(^{62}\) There is nothing magical about this choice of boundary conditions. The only reason they are chosen is that they happen to do well at predicting behavior. In fact, it has been suggested that in certain situations other boundary conditions (such as \((1/m)^{0.5} (d\psi/dx)\)) might be more appropriate.\(^{63}\)

Given the ‘standard’ boundary conditions, appropriate wavefunctions are chosen:

\[
\psi_{\text{left}} = Ae^{kx} + Be^{-kx}
\]

Eq. 4-11

67
\[ \psi_{\text{right}} = Ce^{kx} + Be^{-kx} \]  

Eq. 4-12

Here the \( k \) and \( k' \) represent the complex wave number on the appropriate side of the step. ‘Left’ and ‘right’ refer to the corresponding side of the step.

\[ k = \left[ \frac{2m}{\hbar} \left( V_0 - E \right) \right]^{0.5} \]

Eq. 4-13

Given two joined materials with mass and wave number (\( m \) and \( k \)) on the left side of the boundary between the materials and (\( m' \) and \( k' \)) on the right side of the boundary with an interface located at \( x_o \), then the coefficients \( A, B, C, D \) are related:\(^{49}\):

\[
\begin{pmatrix}
A \\
B
\end{pmatrix} = \left( \frac{1}{2} \right) \begin{pmatrix}
1 + \frac{mk'}{mk}e^{x_o(k' - k)} & 1 - \frac{mk'}{mk}e^{-x_o(k' + k)} \\
1 - \frac{mk'}{mk}e^{x_o(k' + k)} & 1 + \frac{mk'}{mk}e^{-x_o(k' - k)}
\end{pmatrix} \begin{pmatrix}
C \\
D
\end{pmatrix}
\]

Eq. 4-14

This equation can be used to determine the amount of a wave that is transmitted and reflected from each interface. A structure can be approximated as a series of constant potential energy regions (which merely advance the waves phase) separated by potential interfaces. Thus the total transmission of a wave through a structure can be determined. For example, if the ‘A’ parameter on the leftmost interface is assumed to be unity, then the ‘C’ parameter on the rightmost side of the rightmost interface can be used to determine the transmission.

4.5.2 Optical structures

An analogous treatment can be produced for optical waves. Here, instead of the wave representing the probability amplitude, it represents, for example, the electric field vector on either side of a step.
\[
\begin{align*}
\text{Left side} & \quad E = A e^{ikx} + B e^{-ikx} & \text{Eq. 4-15} \\
\text{Right side} & \quad E = Ce^{ik'x} + De^{-ik'x} & \text{Eq. 4-16}
\end{align*}
\]

Here the boundary conditions (say for TE polarized modes—where there is no E field component in the direction of propagation) are that E and dE/dx must be continuous. An equation very similar to that of the previous subsection can then be found for the transfer matrix in this way:

\[
\begin{pmatrix}
A \\
B
\end{pmatrix} = \frac{1}{2} \begin{pmatrix}
1 + \frac{k'}{k}e^{i(k' - k)x_0} & (1 - \frac{k'}{k})e^{-i(k' + k)x_0} \\
(1 - \frac{k'}{k})e^{i(k' + k)x_0} & 1 + \frac{k'}{k}e^{i(k' - k)x_0}
\end{pmatrix} \begin{pmatrix}
C \\
D
\end{pmatrix}
\]

\text{Eq. 4-17}

An alternative version of this equation for optical waves, and the one actually used for the simulations shown in chapter 5, employed a transfer matrix technique which examines the individual layers and, essentially, rewrites the equation in terms of more familiar parameters: the complex refractive index \(n\) which incorporates absorption and dispersion, the incident angle \(\theta\), the wavelength \(\lambda\), the thickness of each layer \(x\), the refractive index of the incident medium \(n_o\), and the complex admittance, \(Y\).

\[
\left(\begin{array}{c}
A \\
B
\end{array}\right) = \prod_{n = 1}^{n_{\text{max}}} \begin{pmatrix}
\cos\left(\frac{2\pi n x}{\lambda} \sqrt{n^2 - n_0^2 \sin^2(\theta)}\right) & i \sin\left(\frac{2\pi n x}{\lambda} \sqrt{n^2 - n_0^2 \sin^2(\theta)}\right) \\
i \sin\left(\frac{2\pi n x}{\lambda} \sqrt{n^2 - n_0^2 \sin^2(\theta)}\right) & \cos\left(\frac{2\pi n x}{\lambda} \sqrt{n^2 - n_0^2 \sin^2(\theta)}\right)
\end{pmatrix} \begin{pmatrix}
1 \\
Y_{ns}
\end{pmatrix}
\]

\text{Eq. 4-18}

\[P = \frac{Y_n^2}{\sqrt{n^2 - n_0^2 \sin^2 \theta}} \quad \text{Eq. 4-19}
\]
while for TE modes: \[ P = Y\sqrt{n^2 - n_0^2 \sin^2 \theta} \] \hspace{1cm} \text{Eq. 4-20}

Then, for example, reflectivity is:

\[
R = \left( \frac{Yn_0A - B}{Yn_0A + B} \right)^2
\]

\hspace{1cm} \text{Eq. 4-21}

A and B here represent the admittance of the entire set of device layers. The matrix techniques are the same except that the total reflectivity is now obtained by multiplying the matrices for each of the individual layers together, starting with an initial condition for \( n_s \), the refractive index of the substrate. The program used complex refractive index values for all layers; for the quantum wells, empirical absorption and refractive index data as a function of wavelength and applied electric field were incorporated into the model to accurately predict the effects of exciton lineshape and complex dispersion on such parameters as chirp and optical bandwidth.

### 4.6 Development of the Equation used to Simulate Array Response.

The final section of this chapter describes the method used to simulate the response from an array of devices. To first order, the far field pattern reflected from an array will look like the Fourier transform of the reflected electric field from the surface of the array.\(^{67}\) Since the computer model simulates the empirical single device responses, both the near and far field behavior of a device array under a variety of processing conditions can be calculated.

In an attempt to develop a simulation which would be capable of determining both the near and far field response, the origins of diffraction theory were investigated. Here a brief outline of the development of the equation used to model arrays is given. The analysis begins with Green’s Theorem.

**Green’s Theorem:** Let \( U(P) \) and \( G(P) \) be any two complex valued functions of position. Let \( S \) be a closed surface surrounding a volume \( V \). Let \( U, G, \) and their first two derivatives be continuous and single valued. Then:

\[ \int_S \nabla \times \nabla \cdot G \, dS = \int_V \nabla \cdot (\nabla \times G) \, dV - \oint_{\partial V} \nabla \times G \cdot n \, dS \]

70
\[
\int \int \int_{\mathcal{V}} \left(G \nabla^2 U - UV^2 G\right) dv = \int \int_{\mathcal{S}} \left(G \frac{\partial U}{\partial n} - U \frac{\partial G}{\partial n}\right) ds \quad \text{Eq. 4-22}
\]

If \( U \) and \( G \) satisfy the Helmholtz equation: \( \left( \nabla^2 + k^2 \right)G = 0 \) then the volume integral becomes zero. The next step involves splitting \( \mathcal{S} \) into two parts, an outer part \( \mathcal{S}' \) which goes to infinity and an inner part \( \mathcal{S}'' \) (which becomes infinitely small around a point \( P_0 \)). Then looking at \( \mathcal{S}'' \) and rearranging the Greens integral, the integral theorem of Helmholtz and Kirchhoff is obtained:

\[
U(P_0) = \frac{1}{4\pi} \int \int_{\mathcal{S}} \left( \frac{\partial U}{\partial n} G - \frac{\partial G}{\partial n} U \right) ds \quad \text{Eq. 4-23}
\]

This equation relates the electric field at a point, \( P_0 \), to the values of the field at a boundary surrounding that point.

Given a diffracting medium, for example a screen as shown in Figure 4-4, integration is done over is \( \mathcal{S}_a + \mathcal{S}_b \) (where these surfaces are defined in Figure 4-4). However, \( \mathcal{S}_b \) can be made to go to infinity, and, if the Sommerfeld radiation condition holds:

\[
\lim_{R \to \infty} R \left( \frac{\partial U}{\partial n} - jkU \right) = 0 \quad \text{Eq. 4-24}
\]

then the integral over \( \mathcal{S}_a \) goes to zero and only \( \mathcal{S}_a \) need be of concern. A Green's function is picked to satisfy the following conditions:

a) Across the screen opening, \( U \) and its derivative are the same as they would be in the absence of the screen.

b) Across the screen where it is unopened, either \( U \) or its derivative are zero.

c) Either \( G \) or its derivative vanishes over the entire surface \( \mathcal{S}_a \)

One such Green’s function, proposed by Sommerfeld, is:
\[ G(p_1) = \frac{e^{jkr_{01}}}{r_{01}} - \frac{e^{j\tilde{r}_{01}}}{\tilde{r}_{01}} \]

*Eq. 4-25*

Which, when used in the integral theorem of Helmholtz and Kirchhoff, gives the generalized equation which was used for this program.

\[ U(p_0) = \frac{1}{2\pi} \int \int_{P_1} U(p_1) \left( \frac{2\pi}{j\lambda} + \frac{1}{r_{01}} \right) e^{jkr_{01}} \cos(n,\tilde{r}_{01}) ds \]

*Eq. 4-26*

Where \( P_1 \) represents the points on \( S_n \).

*Figure 4-4: Schematic for derivation of the diffraction formula used in the array simulations.*

In the above equation, the argument for the cosine term is the angle between the \( r_{01} \) vector and the normal to the surface of the screen. It should be noted that if the \( 1/r \) term in the parenthesis is eliminated (assuming \( r \gg \lambda \)) and \( U(p_1) \) is assumed to be an expanding spherical wave, then the Rayleigh-Sommerfeld diffraction formula is obtained. However, in an effort to make the simulation more general and capable of predicting near-field diffraction patterns, the more general expression above was used in the array simulation.
In the simulated experiments, U(P1) represents the characteristics of the array. The array is specified as a series of individual devices of given width and pitch, each of which has its own reflectivity and phase. The array is then built laterally by specifying a number of these regions for a given wavelength. Distance from the array can be specified so that either near field or far field patterns can be obtained. Figure 4-5 shows the near and far field diffraction patterns for an array of phase modulators.

![Nearfield pattern (z=10μm) vs Farfield pattern (z=10000μm)](image)

*Figure 4-5: Near and far field patterns for an array of phase flip modulators (described in chapter 5)*

The above modeled array consists of 24, 4μm wide phase modulators with 2μm spaces separating these devices. For Figure 4-5, the array is in the 01010101... state (meaning that the first stripe is reflecting with 0° phase, the second with 180° phase, the third with 0° phase, and so on). Note that the diffraction patterns are not symmetric around 0° angle since the array itself is not quite symmetric (the 'leftmost' stripe reflects 0° while the 'rightmost' stripe reflects 180°). To see this more clearly, if the first 0° stripe is neglected (the leftmost 6μm of the array are ignored to produce a symmetric array, 10101...), then the center of the symmetric array is 3μm removed from the center of the entire physical array. For the nearfield pattern viewed at a distance of 10μm, a 3μm shift of the array center moves the symmetry point for the diffraction pattern to \( \tan^{-1}(0.3) = 16.7° \). As can be seen in Figure 4-5, this is where the symmetry occurs. The farfield pattern viewed at 100000μm gives a diffraction pattern centered around \( \tan^{-1}(3 \times 10^{-5}) = 1.7 \times 10^{-3} \) (which is why it appears centered around 0°).
5. Fabry-Perot Optoelectronic Modulators

5.1 Modulation schemes

A number of optical modulation schemes will be investigated here. Figure 5-1 summarizes these device types. They can be broken down broadly into two categories.

![Modulation schemes diagram](image)

*Figure 5-1: Modulation Schemes using Quantum wells and Cavities.*

The first category, consisting of 'high loss' devices, operates by attenuating an incoming signal to transmit incoming information. The two main types of devices which comprise this category are the reflection-electroabsorption modulator and the transmission modulator. The latter of these two operates strictly through absorption. The device is epitaxially grown on a GaAs substrate and consists of a p-i-n structure. Anti-reflection coatings are placed on both sides of the wafer and the device is created to operate at the wavelength at which the absorption changes with bias (using QCSE or field induced carrier separation). The incident optical signal is either transmitted through the device unchanged in amplitude or is attenuated. Attenuation occurs in the manner described by the Beer-Lambert rule where attenuation is a function of both operating wavelength and operating voltage. The reflection-electro absorption modulator is a Fabry-Perot device and operates via the principles described in Chapter 4. Increasing absorption at the Fabry-Perot wavelength $\lambda_{f-p}$ can either increase or decrease the intensity of the reflectivity of the incoming beam. Thus
in one of the two device states, the reflected signal will have a large amplitude while in the other operating state, the reflected beam will be strongly attenuated. In both of these devices, information is transmitted by amplitude modulation. The drawback of amplitude modulation is that it is a destructive modulation method (non-conservative modulation method). In the low state, the optical input is absorbed by the semiconductor material and is therefore lost. These devices are incompatible with systems which require signal output from one device to be directly input to subsequent devices since there is no output signal from a 'low' state device.

In contrast, Figure 5-1 also displays low loss devices. These devices are non-destructive (they are conservative) in that there is a large amplitude optical output in both the on and off states of the device. This large optical output can then be routed for further processing in subsequent switching or logic stages. The two conservative methods that will be examined are the phase flip modulator, which provides a large optical output and transmits information by altering the phase of the reflected beam between 0° and 180°, and the transmission-reflection modulator (and a superset of it called the X-modulator) which routes incident signals rather than absorbing incident light.

5.2 Zero Chirp Reflection Modulator Before the Matching Condition

By analyzing the exciton lineshapes of quantum wells, the wavelengths and biases at which they exhibit large absorption changes and zero refractive index changes relative to zero bias can be found. To use this effect, GaAs/AlGaAs quantum wells were placed in the intrinsic region of a reverse-biased p-i-n diode with an asymmetric Fabry-Perot cavity. A particularly advantageous sample was developed which could be post-growth processed to optimize all relevant parameters. Computer simulation was used to determine the exact post-growth correction required and this approach yielded reflection modulators with 90% reflection change and zero relative phase change.

5.2.1 Introduction

Optoelectronic switches have recently been intensely studied. Reflection modulators based upon large absorption changes in quantum wells have shown high contrast ratios while exhibiting lower parasitic phase modulation than conventional waveguide modulators. While quantum wells are capable of large absorption changes (Δα), they also typically exhibit large refractive index changes (Δn). Understanding the physics of quantum well excitons and their real and imaginary dielectric functions is
crucial for high-speed optical switching since such switching will be critically limited by \( \Delta n \)-induced pulse broadening. As mentioned earlier, the ratio of changes in refractive index to changes in absorption can be defined as a chirp parameter. Changes in refractive index change optical path lengths and thus cause changes in optical phase. A low chirp parameter is desirable for low-dispersion amplitude modulation. This section describes how to eliminate parasitic \( \Delta n \) in a novel, optimized structure thus yielding a pure reflection modulator with zero chirp parameter. At the operating wavelength, such a device would exhibit a high reflectivity change and zero phase change when switched between two bias points. These devices are designed and developed by analyzing exciton lineshapes, numerically simulating the structures, including quantum well absorption and dispersion effects, and creating a flexible modulator design which allows for final optimization after molecular beam epitaxial growth.

5.2.2 Background

As described in Chapter 2.6, the Kramers-Kronig relation can be used to calculate \( \Delta n \) given \( \Delta \alpha \). Figure 3-3 showed the absorption spectrum of 75Å GaAs/35Å AlAs quantum wells. The wells were biased by placing them in the intrinsic region of a \( p-i-n \) diode. By looking at the change in absorption between two bias points versus wavelength, \( \Delta n \) versus wavelength at an applied voltage was extracted. Noting the exciton maximum at around 8400Å under 34V applied bias, it can be seen that there exists a wavelength where zero index change will be observed. This is ideal for a pure reflection (zero-chirp) vertical-cavity modulator. To take full advantage of this situation in an asymmetric Fabry-Perot modulator, three parameters must be optimized simultaneously. First, the Fabry-Perot (F-P) dip of the modulator cavity must be tuned to the wavelength where \( \Delta n = 0 \). Next, the modulator must be designed with the correct total \( \Delta \alpha \) to achieve a high contrast modulation. This entails choosing an appropriate well width and number of wells. Finally, the well width must be designed to shift the exciton to the desired wavelength at the required voltage.

To obtain numerical simulations of device performance, a thin films program based upon the system in Eq. 4-19 was developed. It calculated reflection, transmission, and absorption as a function of bias. To model changes with voltage, the experimental absorption spectra for 75Å GaAs/35Å AlAs quantum wells that were previously characterized were employed.\(^4\) Using the Kramers-Kronig relation, the dispersion of these wells was also incorporated. Thus, the experimental spectra of previously grown samples was used to simulate how future samples should perform.
5.2.3 Experimental Results

To confirm the theoretical predictions and the simulated results, a structure with 92 quantum wells with the aforementioned characteristics was grown. The wells were placed between a bottom quarter wave stack mirror containing 25.5 periods of AlAs/Al_{0.33}Ga_{0.67}As and a top mirror consisting of 6 periods of AlAs/Al_{0.33}Ga_{0.67}As. An additional quarter-wave layer of Al_{0.33}Ga_{0.67}As was placed on the top surface as an anti-reflection coating. By etching this top layer, the final top mirror reflectivity could be changed from about 5% to 77%. This etching provides the ability to tune exactly to the matching condition and post-process the devices for maximum contrast ratio. Hence, after shifting the exciton to obtain Δn=0 at the F-P wavelength, the front mirror reflectivity was adjusted to give the maximum reflectivity change for the available Δα at that bias. Once the structure was grown, the simulation was adjusted to account for fluctuation in the molecular beam epitaxial growth to obtain the optimal etch depth. This was achieved by using the in-situ technique discussed briefly at the beginning of this thesis. By matching the simulation to this zero-bias reflectivity spectrum, the expected reflectivity spectrum for other biases could be calculated and hence the amount of etching required on the top quarter wave mirror layer could be determined. The top layer was etched 190Å to yield a top mirror reflectivity of 31%. This was calculated to give the largest change in reflectivity. Thus, through careful, empirically-assisted simulation, precise post-growth processing requirements could be determined and carried out. Maximum performance is thus ensured. Figure 5-2 shows the simulated reflectivity spectrum at several applied biases after a 190Å etch on the top quarter wave layer.

Experimental results of the total reflectivity versus wavelength are shown in Figure 5-3 for the device after the 190Å etch post-processing. Reflectivity changes from 94% to 6% were obtained at 8375Å. Simulations show agreement within 2% at wavelengths near the F-P minimum. As the exciton shifts toward the F-P minimum, that minimum shifts to longer wavelength since the refractive index is increased by the exciton. At the Δn=0 bias, here 34V, the F-P dip is again at the same wavelength as at zero bias. The simulation matches the experimental results over all bias conditions remarkably well. Since the Kramers-Kronig relationships connect dispersion at a particular wavelength to absorption over all wavelengths, the values of Δn become increasingly inaccurate at wavelengths near the ends of the empirically recorded absorption data. This becomes apparent in the
Figure 5-2: Simulation of Reflectivity versus Wavelength as a function of bias. The simulation included an empirically derived approximation of the behavior of the quantum wells and was used to predict the spectrum after the top mirror period had been etched 190Å.

Figure 5-3: Experimental Reflectivity versus Wavelength as a function of bias. The vertical arrows depict the approximate location of the Fabry-Perot wavelength as a function of bias. The curves agree quite well with the simulation.
simulation where the discrepancy in reflectivity value becomes larger near the ends of the wavelength range.

Figure 5-4 shows reflectivity and phase versus bias at 8375Å. The phase increases as the exciton approaches the F-P dip, as one would expect, but drops to zero when it is at the F-P wavelength. This occurred at about 34V bias. The phase was measured with a Michelson interferometer where the device acts as the mirror in one of the arms while the other mirror is mounted on a piezoelectric mount which can be swept to produce sinusoidal distance variation. In this way, the phase change with voltage could be measured directly to within an accuracy of 2%. The phase was measured in 2 Volt increments from 0 to 40 Volts. The experimental curves agree quite closely with the phase values predicted by the simulation. The figure also confirms that etching accurately placed the reflectivity minimum at this same bias.

![Graph showing phase and reflectivity versus bias at 8375Å. Reflectivity changes from 94% to between these two bias points. Dots are simulated phase shift.]

5.2.4 Conclusion

In conclusion, this section has laid the theoretical and experimental basis for the optimal design and development of zero-chirp high contrast reflection modulators which are operated before the matching condition. Post-processing combined with empirical data assisted simulation yielded accurate optimization of device parameters which satisfy multiple design specifications. The theory for eliminating $\Delta n$ is also applicable to quantum
wells in waveguide modulators. Finally, a device which displays a reflectivity change from 94% to 6% while retaining zero phase shift between the two bias points was demonstrated.

5.3 Zero Chirp Reflection Modulators After the Matching Condition

5.3.1 Introduction/Theoretical Background

This section discusses asymmetric Fabry-Perot reflection modulators (AFPM) using both InGaAs and GaAs quantum wells whose cavities operate beyond the matching condition and whose modulation characteristics exhibit zero phase change (zero chirp) when switched. These devices are structurally similar to devices which operate before the matching condition, but with incorporation of an additional etch step, enable realization of zero phase change modulators. Thus modulators operating before and beyond the matching condition with reflection at zero and 180° out of phase can be achieved with a single growth. This section also briefly describes how the observation of the reflectivity spectrum can provide quick information about the voltage necessary to obtain this zero chirp behavior. These structures provide a basis for low chirp optical switching, beam steering, and spatial light modulation.

The previous section demonstrated a modulator in which the reflectivity changed from 90% to 6% with no relative phase change between the on and off states (zero chirp). It used GaAs/AlAs quantum wells and operated before the matching condition, where increasing absorption decreases the total device reflectivity and the reflectivity of the device is dominated by the back mirror. Here, two AFPM's which utilize GaAs/AlGaAs and InGaAs/AlGaAs quantum wells using the zero phase change technique operate beyond the matching condition. Recall that devices operating beyond the matching condition achieve an increase in reflectivity with increasing absorption and are dominated by the front mirror reflectivity. The basic device design for the GaAs/AlGaAs modulator is shown in Figure 5-5. The InGaAs/AlGaAs modulator has the same general structure (see device design section for exact specifications). While the theoretical analysis for zero chirp operation requires accurate accounting of both absorption and dispersion of exciton resonances, as described in Section 4.3, the difference between devices operating before and beyond the matching condition can be understood solely on the basis of absorption considerations. Because different mirrors dominate, the reflectivity of the devices before and beyond the matching condition, the reflected beam will switch between zero and exactly 180 degrees out of phase if zero refractive index changes in the cavity are obtained. Arrays of the earlier devices, which operated before the matching condition and these present devices
which operate beyond the matching condition could be used to make a primitive phase grating for beam steering applications.

\[\text{Figure 5-5: Schematic of the asymmetric Fabry-Perot modulator.}\]

Such a scheme could be realized by growing devices to operate beyond the matching condition (with high front mirror reflectivity) and then using lithographic techniques to make alternate devices operate before the matching condition by etching the front mirror. By switching off various devices, an amplitude modulated phase grating effect would be achieved. This type of beam steering is more efficient than a pure amplitude grating because, in general, steering can be performed with a greater number of devices in the highly reflective state. This is because steering is performed with a combination of variable pitch phase and variable pitch amplitude. However, this technique while superior to pure amplitude gratings is inferior to the pure phase gratings which will be discussed in Section 5.2.

The crux of the current individual device operation rests upon the need to obtain zero refractive index changes in the cavity when bias is applied. This technique was described in the previous chapter and applies equally here (aside from the change in wavelength).

In order to realize zero chirp reflection modulation beyond the matching condition, several conditions must be met. First, the Fabry-Perot (F-P) dip of the modulator cavity must be tuned to the wavelength where \(\Delta n = 0\) and the change in absorption (\(\Delta \alpha\)) is large.
Next, the relative front and back mirror reflectivities must be fabricated to operate the device beyond the matching condition. In addition, the modulator must be designed with the correct total $\Delta \alpha L$ product to achieve high contrast modulation. Finally, the quantum wells must be grown to operate at the appropriate wavelength. Because the devices always operate beyond the matching condition and reflectivity is dominated by the front mirror at all times, there will be zero relative phase change between the on and off states when bias is applied if the device is operated within the bias and wavelength constraints mentioned above.

5.3.2 Device Design

Two devices were grown by molecular beam epitaxy. The general structure for each device is shown in Figure 5-5. The first device consisted of a 24.5 period quarter wave stack back mirror ($R_b$) and a 7 period front mirror ($R_f$), both comprised of AlAs/Al$_{0.33}$Ga$_{0.67}$As. The structure was a $p$-$i$-$n$ diode with an intrinsic region consisting of 95 75Å GaAs/35Å AlAs quantum wells. The second structure contained a 10.5 period back mirror and a 7 period front mirror both composed of AlAs/Al$_{0.33}$Ga$_{0.67}$As with 45 75Å In$_{0.2}$Ga$_{0.8}$As/35Å Al$_{0.33}$Ga$_{0.67}$As quantum wells in the intrinsic region. The GaAs/AlAs sample was grown at 600°C while the InGaAs/AlGaAs sample was grown at 485°C.

As in the previous chapter, if the top mirror consists of many pairs of quarter wave mirror stacks so that the Fabry-Perot resonance is well defined, then by etching the top mirror's topmost quarter wave layer, the reflectivity of that mirror can be altered without substantially altering the wavelength of the Fabry-Perot resonance. Top mirror reflectivities from 83% to 10% for the 8375Å sample and 90% to 28% in the 9660Å sample are possible with such mirror pair design. To determine the optimal etch, the thin films program was again used. To model changes with voltage, the experimental absorption spectra of quantum wells that had been previously characterized was used. As in the previous chapter, using the Kramers-Kronig relation, dispersion is incorporated in the calculation. Inclusion of this additional information allows very accurate modeling of devices. Zero bias reflectivity spectra are taken in-situ and this data is fit with the simulation. The necessary etch depth can then be determined.

5.3.3 Experimental Results

In the GaAs/AlAs quantum well modulator, the top mirror was etched 80Å to slightly decrease the top mirror reflectivity and slightly enhance the change in the device
reflectivity ($\Delta R = R_{\text{max}} - R_{\text{min}}$). Because the device is operating beyond the matching condition with a relatively low reflectivity front mirror, the maximum possible change in reflectivity ($\Delta R$) of this device as a function of bias was relatively small.

![Graphs showing reflectivity and phase shift vs. wavelength and voltage](image)

**Figure 5-6:** (a) Reflectivity versus Wavelength at various biases and (b) reflectivity and phase shift (relative to zero bias) vs. Bias at 8375Å. Data shown is for the GaAs/AlAs quantum well device. Zero chirp modulation is achieved when operating between 0 and 15.75V.

Figure 4-2 shows that it requires front mirror reflectivities as high as 95% to achieve the same change in reflectivity per unit change in absorption beyond the matching condition as can be obtained with 50% front mirror reflectivity in devices operated before the matching condition. Note that the situation becomes complicated if quantum well dispersion is incorporated as it was in the thin film numerical simulation program. Because the present devices, which were operated beyond the matching condition, had front mirror reflectivities around 75%, future device performance could be significantly improved by using a higher reflectivity front mirror. This would increase the change in reflectivity although if it were not accompanied by a decrease in the back mirror reflectivity, the optical bandwidth would decrease through such a scheme. Tradeoffs in design will be briefly covered in Section 5.6.2. Regardless, even this less-than-optimal structure displays all the relevant design considerations and achieves zero chirp performance. Figure 5-6a and Figure 5-6b show the experimental reflectivity vs. wavelength as a function of bias and the experimental reflectivity and phase versus bias at the 0V Fabry-Perot wavelength (8375Å) for the GaAs/AlAs quantum well device. As depicted in Figure 5-6a, the device reflectivity at the Fabry-Perot wavelength changes from about 33% to 60% with an applied bias of 16V. The reflectivity maximum surrounded by two local minima in the on state is characteristic.
of devices operating beyond the matching condition. When the exciton and Fabry-Perot wavelengths coincide at the applied voltage where zero phase change is obtained (note that they never exactly coincide due to Rabi splitting between exciton and Fabry-Perot resonances, but Rabi splitting is not easily observable at room temperature in devices with high absorption) the reflectivity at the Fabry-Perot dip is higher than it is at zero applied bias. However, the maximum reflectivity is achieved when the exciton maxima is coincident in wavelength with the zero bias Fabry-Perot resonance. In the GaAs/AlGaAs quantum well structure, for example, this occurs at 8375 Å. Away from this wavelength, absorption will be lower and hence reflectivity will be lower, giving two local reflectivity minima. A good method of checking for the zero phase condition entails finding the voltage at which the wavelength of the reflectivity maxima (with applied bias) and the wavelength of the 0V Fabry-Perot dip coincide. This type of check can be understood since refractive index and the logarithm of reflectivity are related by the Kramers-Kronig relation. In such relations, when near sufficiently broad, symmetric reflectivity maxima or minima, the magnitude of the change in one observable is related to the change in the slope of the other observable. If one observes reflectivity at a wavelength where the slope of the logarithm of reflectivity versus wavelength does not change between two bias points, then there will be no change in refractive index at that wavelength between those two bias points. At zero applied bias, at the Fabry-Perot dip minima, the reflectivity versus wavelength curve has a zero slope. Therefore, in order to have zero refractive index change, one must obtain either a local maxima or minima in the reflectivity curve at the zero bias Fabry-Perot wavelength; with 16V bias, the device is just beyond this condition. Dynamically, as the exciton wavelength shifts toward the Fabry-Perot wavelength, the Fabry-Perot reflectivity dip is red-shifted due to exciton induced refractive index changes from the shifting exciton. This creates a pseudo ‘anticrossing’ between what is perceived as the exciton minima and the Fabry-Perot minima (the two local minima). Figure 5-7 shows the energy of the two local minima as a function of bias and clearly depicts the ‘anticrossing’ behavior in both devices. At low bias, the lower energy minimum corresponds to the F-P resonance and the higher energy minimum to the exciton resonance. Beyond the zero phase condition, these two levels are switched so that the lower resonance is now the F-P dip. Looking at the ‘anticrossing’ between the two minima, the wavelength and bias at which the zero relative phase change will occur can be predicted solely from the reflectivity data. The straight lines in Figure 5-7 depict the movement of the exciton and Fabry-Perot levels as extracted from the anticrossing of the local minima. These lines intersect at the voltage and energy at which zero relative phase change is achieved.
Figure 5-7: The Fabry-Perot and exciton induced minima as a function of bias voltage. Data is shown for (a) GaAs/AlAs quantum well device and (b) InGaAs/AlGaAs quantum well devices. The thin, straight lines indicate the movement of the Fabry-Perot and exciton resonances. Their intersection depicts the applied bias and operating energy (wavelength) where zero chirp is achieved.

Because the absorption changes on either side of the 0V F-P minima wavelength are equal at this voltage, by the Kramers-Kronig relationship, \( \Delta n = 0 \). The previously mentioned method of observing the condition where the slopes of the two reflectivity curves are equal requires broad, symmetric peaks to be strictly valid. If the reflectivity maxima in the sample were asymmetric and narrow enough, then the earlier statement about equal slope would not hold. In addition, determining the zero phase voltage by this method requires repeated reflectivity measurements until the zero phase condition is extracted. In contrast, observing the anticrossing between local minima requires only two measurements at very low bias, after which the required data can be extrapolated easily. Furthermore, because the reflectivity minima are more widely separated, it provides a more accurate measure of the weights of the reflectivity around the anticrossing wavelength (which corresponds to the operating wavelength) than simply observing the reflectivity maxima. While direct phase measurements via the Michelson setup are certainly more accurate, this extrapolation of the anticrossing point provides a means of using a simple reflectivity setup to obtain a very quick, good check of actual phase measurements.

The actual phase data extracted from the Michelson interferometer experiment is shown in Figure 5-9b as is the reflectivity as a function of voltage. As this data shows, there is zero phase change between the 0V and 15.75V. Furthermore, between these two bias points, almost the maximum possible reflectivity change (33% to 60%) is achieved for the post-etched device. This sample is not optimum because the 0V exciton is somewhat closer to the F-P dip than had been intended.
Figure 5-8  (a) Reflectivity versus Wavelength at various biases and (b) reflectivity and phase shift (relative to zero bias) for the GaAs/AlGaAs quantum well device. Zero chirp modulation is achieved between 0 and 21.8V.

Figure 5-9: (a) Reflectivity versus Wavelength at various biases and (b) reflectivity and phase shift (relative to zero bias) vs. Bias at 9660Å. Data shown is for the InGaAs/AlGaAs quantum well device. Zero chirp modulation is achieved when operating between 0 and 21.8V.

The close exciton results in both a non-trivial phase shift at 0V bias (relative to what would exist in the absence of the exciton) and in the inability to achieve maximum reflectivity in the on state with zero phase shift. This inability could be remedied either by operating this device at lower temperature or by growing a new structure where the F-P dip is farther from the 0V exciton resonance. This device is identical to those of the previous section which operated before the matching condition, with the exception of a different front mirror reflectivity. Although a new wafer was grown to achieve this, a single wafer could be
grown and an array of devices processed with alternating devices etched to operate before the matching condition (through reduced Rf) and non-etched devices operating beyond the matching condition.

Figure 5-9 shows the reflectivity and phase data for the In\(_{0.2}\)Ga\(_{0.8}\)As/Al\(_{0.33}\)Ga\(_{0.67}\)As quantum well sample after a 70\(\text{Å}\) etch. The use of InGaAs allows the device to operate at longer wavelengths (here 9660\(\text{Å}\)) which are compatible with InGaAs laser diodes. This data also displays the expected behavior: lineup of the on-state maximum reflectivity wavelength with the 0V F-P dip and zero relative phase change between the on and off states. In this sample, the reflectivity increases from 23% to 48% with increasing absorption (application of 21.8V bias) while still obtaining zero relative phase change between the two applied biases. Again, the mirror reflectivities of this device could be enhanced to provide a larger \(\Delta R\) for a given change in absorption \(\Delta\alpha\). In addition, the 0V heavy hole exciton resonance was also close enough to the F-P dip to provide an easily measurable phase difference between the 0V reflected phase and what the phase of the device would have been in the absence of the quantum wells. This situation could be easily remedied with only very minor adjustments to the cavity length. The devices show reflectivity changes which are comparable with previous devices which operated before the matching condition. Higher reflectivity changes in both types of devices can be realized through an increase the front mirror reflectivity. Such a higher front mirror would have two effects. First, the higher Q-factor for the cavity results in decreased optical bandwidth. On the other hand, lower absorption changes are required to achieve the desired performance so instead of a 2\(\lambda\) length cavity, perhaps only a \(\lambda/2\) cavity would be required. Shorter cavities result in increased bandwidth. The same considerations must be made in both types of devices. One attraction of operating beyond the matching condition is the desire to have high contrast modulators which reflect 180° out of phase with the conventional modulator configuration. A more important attraction is the desire to create X-modulators, which will be discussed later.

5.3.4 Conclusion

In conclusion, asymmetric Fabry-Perot reflection modulators operating beyond the matching condition which were adjusted to produce significant reflectivity changes while providing zero relative phase change when switched have been demonstrated. Devices using both InGaAs and GaAs quantum wells were demonstrated. In addition to making direct reflectivity and phase measurements, it was shown that by determining the anticrossing point between the two induced local minima created by refractive index effects on the exciton and Fabry-Perot resonances, one can determine the on state voltage and
wavelength at which the zero relative phase change occurs. Because these devices operate beyond the matching condition, their phase upon reflection is 180° different from previous devices operated before the matching condition. Because the top mirror reflectivity determines which of the two device types exists and since only the topmost quarter wave layer need be etched to obtain large top mirror reflectivity changes, a single wafer could be grown and processed to make an array containing both types of devices.

5.4 Vertical Cavity Phase Flip Modulators

5.4.1 Introduction

Since absorption changes and refractive index changes are integrally coupled (the Kramers-Kronig relationship describes this mathematically), the QCSE could be used to directly perform phase modulation by altering the refractive index and hence the path length of a material containing quantum wells. However, precisely because absorption and refraction are related, in order to achieve high phase change per unit distance, the penalty is high absorption per unit distance. The result is that in order to obtain a 180 degree phase change in a short waveguide device (several microns long), the absorption would be so large that little or no usable signal would propagate through the structure. Quantum well phase modulators have thus evolved to operate at wavelengths far from the exciton peak where attenuation is low. In such devices, waveguides several millimeters long are then constructed to get an appreciable phase change.\textsuperscript{79,80} Clearly, such large dimensions are incompatible with high-density on-chip integration as well as with any spatial light modulation systems.

In this chapter, the realization of a vertical cavity phase flip modulator (VCPF M) is presented. This represents an alternative approach for achieving 180 degree phase modulation and is based upon the ability to obtain large absorption changes with zero refractive index change (zero chirp modulation). When this technique is combined with the ability to design vertical Fabry-Perot modulators which alternate between operation before and beyond the matching condition\textsuperscript{73}, a phase change of exactly 180 degrees with little or no reflectivity change is obtained with an active region only 5000Å long. This chapter describes how a cavity is created which alternates the dominant mirror for reflection. Next the method to eliminate parasitic refractive index effects in these structures and how this is translated into a phase flip modulator is explained. Finally, experimental results, optimization considerations and additional theoretical aspects of these devices are discussed. Since these phase flip modulators are created vertically, they can be made quite small and placed into large arrays. This opens the door to pure phase change modulation
for high density switching or spatial light modulation. In addition, the ability to flexibly perform complex logic functions using multiple modulators is realizable. With intensity modulation, the off state has very low reflectivity. This results in the inability to take the output of one device and use it as the input for a second device. With phase modulators, the device has a high, non-changing reflectivity so that the output of one device can be used as the input for subsequent devices. In addition, optimization can make the device operate as a low-reflectivity-change analog phase change modulator. The properties of VCPFM's make them unique for many applications.

### 5.4.2 Theoretical Considerations

Recalling the simple model where a cavity is thought of as a thin front mirror (closest to the incident light) with electric field reflectivity, $r_f$, a back mirror with electric field reflectivity $r_b$, and a cavity with an absorption coefficient $\alpha$, the resultant intensity can be written analytically:

$$I = \left| \frac{r_f - r_b e^{-2\alpha L}}{1 - r_f r_b e^{-2\alpha L}} \right|^2 \quad \text{Eq. 5-1}$$

Where the intensity is given for the "Fabry-Perot" point, where the round trip phase within the cavity is an integer multiple of $2\pi$. The consequence of the above formula is that for a given reflected intensity, one can solve for the absorption coefficient, $\alpha$, as:

$$\alpha_{\text{low}} = \frac{1}{2L} \ln \left[ \pm \sqrt{I - r_f} \right] \quad \text{Eq. 5-2}$$

There are thus two absorptive solutions for a given reflected intensity since the signs in front of the two square root terms can be either both positive or both negative. The two points correspond to regions before and beyond the matching condition. Assuming no other cavity changes, a device which can alternate between the two values of absorption given by Eq. 5-2 will have the same reflected intensity. However because different mirrors dominate the reflectivity, the phase difference between the two points will be exactly $180^\circ$. This can be seen from Eq. 5-1 in the following way. Since the electric field reflectivity is the square root of the intensity, the numerator of Eq. 5-1 can switch from positive (zero phase change) to negative ($180^\circ$ phase change) and yet have the same magnitude. This is the simplest picture for the phase flip modulator. In practice, the mirrors are comprised of quarter wave dielectric stacks, and the thin films program is used to model actual device response.
In the absence of additional effects, shifting the magnitude of absorption and thus switching the device from operating before to operating beyond the matching condition would produce exactly 180° phase shift. However, the use of quantum wells to provide the variable absorption material introduces the notorious parasitic dispersive effect which deleteriously affects device behavior. However, as described earlier, the judicious use of quantum wells in a controlled manner can create situations which allow large absorption change; zero refractive index change operation. When the parasitic phase shift is eliminated, 180° phase change can be achieved and understood entirely through Fabry-Perot effects. The parasitic refractive index changes, then, add additional changes in phase to the device response and force the change in phase between the on and the off states to be less than 180°. Thus for the phase flip modulator to obtain maximum phase change, refractive index changes must be eliminated.

The requirements that must be simultaneously satisfied to produce phase flip modulators are: Given a wavelength (λd), a desired voltage swing, and a required reflected intensity (I), front and back mirror reflectivities (rf and rb) are chosen and then quantum wells are designed so that with applied bias, the desired absorptive values are obtained (with the simple model of Eq 5-2, these are αhigh and αlow). In addition to achieving the desired absorptive values, the design must ensure zero parasitic phase change. Using the QCSE, this means ensuring both low absorption at zero bias and maximum exciton absorption at the desired voltage.

5.4.3 Device Design

In order to observe the above effects, the device shown in Figure 5-10 was grown by molecular beam epitaxy. The device is a p-i-n diode with an n-doped back mirror consisting of a 24.5 period quarter wave stack and a p-doped front mirror consisting of a 10 period quarter wave mirror stack. Both mirror stacks consisted of Al0.33GaAs/AlAs layers. The cavity was undoped and contained 48 75Å GaAs quantum wells separated by 35Å AlAs barriers. In-situ reflectivity measurements were used after the first 5 periods of the bottom mirror and again just after the cavity was completed to ensure that device layers were accurately grown during the critical segments of the wafer. By placing the Fabry-Perot dip about 175Å from the heavy hole resonance midway between the center and the edges of the wafer, the probability of good device yield from the wafers is increased. The entire structure was grown at 600°C.
5.4.4 Experimental Results

Reflectivity measurements were made normal to the surface using a white light source, spectrometer, and standard lock-in techniques. Figure 5-11 shows the total device reflectivity spectra near the Fabry-Perot dip for a typical device on the wafer. At zero applied bias, the Fabry-Perot dip has a reflectivity of 65% at the operating wavelength of 8330Å ($\lambda_{op}$). As the exciton resonance is red-shifted with applied bias, both the absorption and the refractive index increase near $\lambda_{op}$. Since $\alpha$ is low and the device operates before the matching condition ($r_f < r_b e^{-2d}$), increases in absorption decrease reflectivity in this absorption range. In terms of the simple model given by Eq 5-1, increases in absorption decrease the magnitude of the numerator and thus decreases the device reflectivity. In this low-loss regime, device reflectivity is dominated by the back mirror. In addition, though, the increase in refractive index increases the effective cavity length ($L$) and therefore shifts the Fabry-Perot resonance to longer wavelength. These two effects can be seen in Figure 5-11 at 7 volts. Increasing bias increases absorption, which decreases reflectivity and red-shifts the Fabry-Perot resonance.

As the exciton is further red-shifted toward $\lambda_{op}$, the device passes through the matching condition (where $r_f = r_b e^{-2d}$ and total device reflectivity reaches a minima) into the high absorption regime beyond the matching condition $r_f > r_b e^{-2d}$. In this region, front mirror reflectivity dominates and increasing absorption increases total device reflectivity. Thus, the numerator of Eq 5-1 is positive so that increasing absorption increases the magnitude of the total device reflectivity. However, refractive effects are still determined
by the exciton. Whether or not the rate of change in refractive index (relative to the unbiased case) increases or decreases depends upon when the inflection point of the electron-heavy hole exciton absorption curve passes through $\lambda_{\text{op}}$.

![Graph](image)

*Figure 5.11: Experimental Reflectivity versus Wavelength near the Fabry-Perot minima at several bias points.*

As Figure 5-11 shows, at 10 Volts, the device is beyond the matching condition (since reflectivity has increased with respect to the 7 volt case), but the change in refractive index is still increasing (since the 10V Fabry-Perot minima is at a longer wavelength than it is at 7V). Further increases in voltage continue to red-shift the exciton toward $\lambda_{\text{op}}$. The device continues to operate beyond the matching condition, and as the exciton maxima approaches $\lambda_{\text{op}}$, the change in refractive index (relative to at 0V) decreases to zero. At 14 Volts, for example, the Fabry-Perot dip is roughly at $\lambda_{\text{op}}$ and so the parasitic phase shift should be zero. This is an easy way to use reflectivity to obtain a rough estimate of the voltage at which exactly 180° phase flip is achieved.

Further applied bias red-shifts the exciton beyond $\lambda_{\text{op}}$. As described earlier, this decreases the absorption at $\lambda_{\text{op}}$ (which decreases reflectivity since the device operates beyond the matching condition), and decreases the refractive index (relative to the zero bias
case). Thus the Fabry-Perot resonance will be blue-shifted from $\lambda_{op}$. Indeed, this response is exactly what is observed, for example, at 20V.

When measuring phase directly, the quantum well induced parasitic refractive index changes introduce phase shifts in the reflectivity. For this experiment, the reflected phase at the Fabry-Perot minima at zero applied bias is defined as having zero phase. All phase shifts are measured from 0° to 360° relative to the zero bias condition. When the exciton increases the effective cavity refractive index, the effective cavity length is increased. When a device is operated before the matching condition and reflection is from the back mirror at the Fabry-Perot wavelength, this increase in cavity length causes a phase shift relative to the zero bias condition. Since the zero bias condition is defined as zero phase shift, increases in refractive index when before the matching condition result in a small positive phase. When the device is operated beyond the matching condition, reflectivity is from the front mirror and is 180° in the absence of parasitics. Changes in the quantum well refractive index affect the penetration depth of the wave into the cavity (changing the boundary conditions within the cavity). Here, increases in refractive index decrease the reflected phase below 180° while decreases in quantum well refractive index increase the reflected phase beyond 180°. Experimental phase measurements were taken in 0.5V steps over the range shown in Figure 5-12.

![Graph showing phase and reflectivity vs. applied voltage](image)

*Figure 5-12: Experimental Reflectivity and Phase versus Voltage for the device at 8330Å*

In addition, the reflectivity in 1V steps is shown at the same wavelength over the same voltage range. The phase of the device changes as expected. At low bias, the phase
has a positive component from the increased refractive index. As voltage is increased, a
switch in the dominant mirror occurs and the phase moves to a point somewhat below
180°, since the refractive index is still greater than its zero bias value. As the exciton
maxima passes through λop, the parasitic refractive index becomes zero, giving exactly
180° phase change. For the present device, this occurs at 13.5V. As the exciton goes
beyond λop, the refractive index is below its zero bias value and phase increases above
180°. The reflectivity of the device at λop remains relatively uniform, despite the fact that
the Fabry-Perot resonance passes through zero in order to go from before to beyond the
matching condition. This is a result of several influences. First, the high Q of the cavity
makes the matching condition a very sensitive function of bias. A small change in
absorption can switch the device from being highly reflective before the matching condition
to highly reflective beyond the matching condition. In this device, the matching condition
occurred between 7 and 8 volts. Hence at low bias, the reflectivity is quite high at all
wavelengths except between these voltages. Second, because the heavy hole exciton
causes a red-shift in the Fabry-Perot resonance as it approaches λop, when the absorption is
at the level required to meet the matching condition, the Fabry-Perot resonance occurs at a
longer wavelength than the zero bias Fabry-Perot wavelength, λop. Hence, when the
device is at the matching condition, reflectivity sampling occurs on the side of the Fabry-
Perot dip, not at the minima. Thus, the observed change in the reflectivity at λop is not
large. When far beyond the matching condition (near the 180° phase flip voltage), the
combination of a relatively quenched exciton, and the shift of the resonance due to
refractive index changes combine to create a voltage region where total device reflectivity
changes are small. For this device, when the 180° phase flip condition is achieved, the
reflectivity is 63% (compared with 65% at zero applied bias). Hence this phase flip device
displays exactly 180° phase flip characteristics at 8330Å with a bias of 13.5V. The change
in reflectivity between the on and off states is 2% absolute (reflectivity changes from 65%
to 63%). Note that from 10V to 20V, the reflectivity is within 5% of the zero bias value.
However, over this same voltage range, the phase changes by almost 100°. Whether this is
detrimental or advantageous depends upon the application.

5.4.5 Analysis away from the zero volt Fabry-Perot dip
Because refractive index and the logarithm of reflectivity are related by the
Kramers-Kronig relationship an approximate picture of the exciton induced parasitic
phase change beyond the matching condition can be extracted from the reflectivity
spectrum. From this, the phase upon reflection can be obtained. In the present case,
Kramers-Kronig analysis was performed on the data in Figure 5-11 and the measured phase given in Figure 5-12 to make sure that the conversion was scaled appropriately. Because the reflectivity spectra only cover a narrow wavelength range around the Fabry-Perot point, the data cannot substitute for a rigorously measured phase over all wavelength regions; the accuracy of this technique drops off rapidly when moving away from the Fabry-Perot point. Nevertheless, this technique provides a quick way of obtaining an estimate of reflected phase over a large voltage and wavelength range. Figure 5-13 depicts the absolute reflected phase from the device at several voltages when the device is operated beyond the matching condition. The inset shows the phase of the sample at zero applied electric field where at the Fabry-Perot minima the phase passes through zero.

Figure 5-13: Reflected Phase versus Wavelength at several bias points beyond the matching condition. These were obtained by performing a Kramers-Kronig transformation on the data of Figure 5-11 and scaling to make sure the data fit the data of Figure 5-12 at 8330Å. Inset shows reflected phase versus wavelength at zero applied bias.

The total change in phase at a given wavelength from the off to on states is the difference between the main part of Figure 5-13 and the inset. As shown in the figure, as the exciton shifts toward the Fabry-Perot wavelength, the point where 180° reflectivity is obtained is red-shifted (due to refractive index changes). As the applied biases approaches 14V, the
exciton coincides with $\lambda_{op}$, and the reflected phase at the 8330Å is exactly 180°. With further bias, the 180° reflectivity point (the zero parasitic phase point) is shifted toward shorter wavelength. Note that 180° phase in the "on-state" only creates a phase-flip device if the "off-state" has 0° phase upon reflection. This occurs only at the zero bias Fabry-Perot minima. On the other hand, because of the parasitic phase shift, the difference between the on and the off states can become exactly 180° for wavelengths other than $\lambda_{op}$, by operating at voltages different than the voltage which optimizes for the Fabry-Perot wavelength. However, reproducibility of such structures would be reduced since it relies on exact, a-priori knowledge of the magnitudes of the slopes of the Fabry-Perot dip and on the width of the exciton resonance rather than simply upon the existence of a maxima.

Despite the exciton induced shifts in the Fabry-Perot minima, the total shift of the 180° reflection point is only 40Å. However, because of the high finesse of the cavity, this can produce large changes in the phase of the device. At 20V, for example, the 210° reflected phase represents a 30° parasitic shift of the 180° point, which is an increase in the effective optical length of 20Å. Improvement could be achieved by operating with a lower finesse cavity (a cavity with wider bandwidth), or by using coupled quantum wells (which can inherently give zero parasitic refractive index change over a wide voltage range). Furthermore, a broad exciton resonance was obtained which increases the sensitivity of the phase to voltage around the zero parasitic point. When operating beyond the matching condition, the Fabry-Perot dip typically contains a local maxima surrounded by two local minima. However, this is not observed in the experimental data. The thin-films program was used to understand how the quality of the exciton resonance (the width of the zero bias exciton peak) affects the observation of this behavior. In Figure 5-14, the results of simulations are shown for the cavity structure operating beyond the matching condition at the zero parasitic point. This figure shows that for a cavity containing narrow excitons (at 14V bias = 230kV/cm) with a HWHM of about 7meV (about 40Å at this wavelength range), the typical absorption maxima surrounded by two local minima is readily observable. In contrast, slightly larger excitons with a HWHM of 10meV (about 60Å at this wavelength range) produce only an absorption minima and the double minima behavior is washed out because the exciton peak is very large compared to the width of the Fabry-Perot resonance. In the simulation, the exciton maxima were kept at the same value for ease of comparison, although it is often more appropriate to make the approximation that the absorption area ($\text{exciton width} \times \text{absorption maxima}$ product) is constant.

The influence of the double minima behavior on the phase properties can be seen in Figure 5-14 where the reflected phase in the narrow exciton device has a plateau around
180° due to the influence of the narrow exciton Fabry-Perot cavity interaction (shallow phase behavior).

![Graph showing theoretical reflectivity versus wavelength](image)

**Figure 5-14:** Theoretical Reflectivity versus Wavelength for the experimental cavity structure containing either narrow excitons (HWHM=7meV) or wide (HWHM=10meV) excitons biased to the zero parasitic point beyond the matching condition. In addition, the phase for the narrow exciton case showing the slowly changing phase behavior induced by narrow excitons around the 180° point is displayed.

This is in contrast to the experimental data of Figure 5-13, where the broad exciton resonance causes a steep change in phase near the Fabry-Perot point. The exciton resonance data used for the narrow exciton case in Figure 5-14 was taken from the previously grown devices which operated beyond the matching condition. Recall that the double minima behavior had been observed in these devices, so that obtaining this predicted shallow phase behavior is readily realizable. The shallow phase behavior means that phase will change very little if the applied voltage is somewhat off from the exact 180° voltage. From Figure 5-13 the 180° point only shifted 40Å over the 12V to 20V range and over this wavelength range, the phase change in Figure 5-14 only changes by about 1°; this is a significant effect. In addition, the simulation of Figure 5-14 shows that over a bandwidth from 8275Å to 8375Å, the parasitic phase change is less than 10°. Figure 5-15 extends this theoretical analysis to other operating conditions. This figure shows the predicted phase behavior at a variety of voltages of a device consisting of the cavity
structure but containing the narrow excitons of Figure 5-14. At zero applied bias, the phase at 8330Å is zero, and at the 180° flip point (which in the experimental device corresponds to 13.5V) the condition depicted in Figure 5-14. exists.

Figure 5-15: Theoretical Phase versus Wavelength curves for the experimental cavity structure but containing narrow excitons at a variety of bias points. Voltages which correspond to those of the experimental device are given for comparison.

When the device is biased at the matching condition where the shifted Fabry-Perot point has zero reflectivity but the reflectivity is higher at the operating wavelength as described above, the parasitic at 8330Å is about 20°. This point corresponds to between 7 and 8 volts in the device. However, over the voltage range corresponding to 10 to 13.5 volts in the experimental structure where reflectivity changes little, the parasitic phase change is less than 10°. Thus sharper excitons should make the phase versus voltage curve of Figure 5-12 contain a more abrupt transition from 0 to 180°. Note that for digital applications, having an abrupt phase change might be important while for other applications a shallow switch from 0 to 180° might be advantageous. The later device might be useful for an analog switch which converts small signal voltage changes (over which the phase change versus voltage is roughly linear) to a phase modulated optical beam. In any event, while the cavity structure can affect the abruptness of the transition, the width of the exciton
resonance is also of paramount importance in determining device performance. While one does not design structures based upon the quality of the exciton, the heavy hole exciton resonance always broadens with bias when the QCSE is employed. Thus by creating a device which operates either closer to or farther from the zero bias exciton peak, the relative width of the exciton can be adjusted. Thus the devices can be optimized for the correct exciton $\alpha_{\text{max}}$ and $\alpha_{\text{min}}$ and absorption linewidth for a given application.

5.4.6 Conclusion

In conclusion, vertical cavity phase flip modulators have been demonstrated both theoretically and experimentally. The device relies on the combination of a cavity in which the dominant mirror responsible for reflection can be switched and a quantum well system which can be operated between the on and off states with no parasitic refractive index change. This is in contrast to typical phase modulators which inherently utilize small refractive index changes and long physical path lengths to obtain phase shifts. The device presented here produces a 180° phase shift (relative to the phase shift at zero applied bias) at 13.5V. Although the phase changes by 180°, the device reflectivity only changes from 65% to 63% between these two bias points. The combination of a high finesse cavity and exciton electro-absorption and electro-refractive effects results in a device which has a relatively flat reflectivity versus voltage response once the device is beyond the matching condition. Over the flat reflectivity range, though, the phase can be tuned over 100° due to the broad excitons which produce a shallow transition from 0 to 180° because of enhanced parasitics away from the 180° phase flip point. Hence some optimization could result in a constant reflectivity tunable analog phase modulator. This tunability could be enhanced by operating in a higher finesse cavity. Conversely, the abruptness of the 0 to 180° transition with voltage could be enhanced by reducing or eliminating the parasitic refractive index changes at voltages away from the 180° voltage—by taking care to ensure good exciton quality or by utilizing coupled quantum wells respectively. Which of those choices is preferable depends upon the application. The current phase flip modulator achieves the 180° phase flip condition required for high-frequency, high-efficiency optical switching. In contrast with amplitude switches, for which the output cannot be fed to subsequent devices because an ‘off’ state produces no output, these devices have high reflectivity in both the on and off states and can thus be stacked. Hence much more complicated optical logic becomes possible. The vertical cavities allow large arrays of devices to be made (in contrast with waveguide devices). This paves the way for vertical cavity phase flip modulator array spatial light modulation. Such arrays are far more efficient than amplitude modulator arrays since far less incident light is lost.
5.5 Etching effects on diffraction efficiency

As mentioned, the vertical cavity phase flip modulators of the previous section have a very special property: they encode information on phase so their reflectivity in both the on and off states is large; this yields very efficient spatial light modulators. Also recall that the far field pattern of the reflected light from an array of modulators will, in general, look like the spatial Fourier transform of the light reflected from the surface of the array (if the reflected light is passed through a lens, then this pattern can be observed at the focal plane of the lens).\textsuperscript{68} In general, though, the reflected intensity can be found as a function of distance from the sample via the simulation techniques described in Section 4.6.

Previously, arrays were created using the photorefractive effect\textsuperscript{81,82} or with arrays of individual reflection modulators which were non-optimized for zero chirp. The later design permitted a variable pitch amplitude grating to be formed--allowing light to be diffracted in a number of modes.\textsuperscript{19} The design was only about 7% efficient for two main reasons. The lack of a zero chirp condition created spurious modes; light which was to be diffracted into the primary modes was thus lost. In addition, because the modulator varies reflected amplitude, incident light which impinges upon the device elements which are 'off' is lost.

The use of phase flip modulators allows all devices to be highly reflective in both states. In operation, each device can switch between exactly 0 and 180 degrees. Note that one could use both intensity and phase modulators in an analog mode where each device can exist in a state between fully on and off. For the phase modulators, though, this tends to introduce some amplitude modulation and hinders performance. For phase modulators with 65% reflectivity, 26% of the incident light can be put into each of the two first order modes (making total diffraction into first order modes over 50% efficient). Obviously individual devices with higher reflectivity will produce even more efficient gratings.

These gratings were experimentally fabricated using an array of the vertical cavity phase flip modulators described in the previous section. Areas of 4\textmu m x 100\textmu m were wet etched to form mesas which were spaced 2\textmu m apart from one another. Etching was performed with a 5:1:10 solution of H\textsubscript{2}SO\textsubscript{4}: H\textsubscript{2}O\textsubscript{2}:H\textsubscript{2}O. The entire device structure is approximately 3\textmu m thick (top mirror=1.5\textmu m, active area=0.5\textmu m, bottom mirror=2\textmu m). The problem with wet etches is that they can be quite isotropic; causing a degradation of the lateral pattern dimensions. In an effort to predict this degradation, simulations were performed. For comparison, an ideal anisotropic etch would produce the result displayed
in Figure 5-16. However, this type of etch profile would not be produced by the wet etching that was performed.

Figure 5-16: Simulated diffraction pattern for 24 element array of phase modulators (4μm wide 2μm spacing. '0' represents 0° phase shift, 1 represents 180° phase shift. Simulations were performed using the single device response for the VCPF of Section 5.4.4. (a) and (b) give different grating configurations.

One etch profile that would be applicable if an n-type substrate were used is shown in the inset to Figure 5-17. In this etching scheme, the top mirrors of the p-i-n diode (the p-type region) would be etched down to electrically isolate the p-type contacts. It is assumed that the effects of the fringing fields through the insulating active region between the devices is negligible so that each device is controlled independently and the unetched active region does not support much field. It is also assumed that the p-i-p structure is not conducting. Figure 5-17 shows the results of the etching on array performance. As can be seen by comparing this with Figure 5-16, the locations of the diffraction peaks are not affected by this form of etching. However, the strengths of the individual peaks are
degraded by this etching pattern. This is a result of the increased absorption in the regions which were more reflective in the ideal etched case. Despite this decrease in efficiency, if the assumption that neglecting fringing field effects is valid, this type of etching scheme would be adequate for producing beam steering arrays with superior performance to that of amplitude modulator arrays. However, this is not a very reasonable assumption for the array's small lateral dimensions.

Figure 5-17:  Simulation of array response with isotropic etch through the top mirror. Assumes that the active areas between devices are isolated. (a) and (b) match the same grating configurations as Figure 5-17.

Because of non-negligible effects of fringing fields, the active areas of each of the devices must be etched to isolate the individual sets of quantum wells. The resulting etch structure is shown schematically in Figure 5-18.
Isotropic etching through the active region results in a degradation of both the phase and intensity characteristics of the reflected light. In addition, a deeper vertical etch creates a larger lateral etch; decreasing the ratio of pixel size to pixel spacing. Figure 5-18 shows that the results create an unacceptable array response for good beam steering characteristics. Figure 5-19 shows the experimental results from an array formed by isotropic etching through the active region. Good agreement between theory and experiment is shown. This provides two important pieces of information. First, more work needs to be done to improve the anisotropy of the mesa formation--perhaps by dry chemical etching. Second, the good agreement between theory and experiment demonstrates that the simulation techniques are accurate and can be used to simulate and optimize structural array design. Thus the above predictions for highly isotropic etches are extremely encouraging for realizing beam steering arrays.

![Image](image.png)

**Figure 5-18:** Simulation of array performance with isotropic etching through the entire active region. Severe degradation is observed as many of the diffraction modes overlap in an unusable fashion.
5.6 Vertical Cavity X-Modulators

The previous sections have depicted the first two of the three ideal switching elements described in the introduction to this thesis: pure amplitude and pure phase modulators. This section describes the third of the three switching elements: the photon routing device (pure direction modulator).

In this section a photon conserving, reversible intensity switch is described. In this device, known as an X-modulator, the incident power is either transmitted through or reflected from the device. Reversibility means that the device response for light incident from both the top and bottom of the structure are nearly identical. By being both conservative and reversible, the device is uniquely capable of performing complex optical switching, routing, and logic. Furthermore, a large fan out is possible. In essence, this device is an electro-optical realization of an X-gate (sometimes referred to as a Fredkin Gate) which is a primitive structure into which all logic functions can be decomposed.
5.6.1 Structure and Single Device Response

The general structure of the X-modulator consists of a slightly asymmetric Fabry-Perot cavity containing top and bottom mirrors of 10 and 12.5 period GaAs/AlAs quarter wave stacks surrounding an undoped cavity of 45, 75Å In$_{0.2}$Ga$_{0.8}$As quantum wells. The top and bottom mirrors were doped p and n type respectively. In-situ measurements and corrections were made three times during the growth. The bottom of the wafer was antireflection coated with a 1/2 wave layer of SiN$_x$ to remove any effects of the semi-insulating substrate from transmission properties. Mesas were etched to form devices, and transmission and reflection measurements were performed by using a white light source and a spectrometer to obtain monochromatic light for probing. Standard lock-in techniques were used.

Device modeling was performed using the thin-films program described several times earlier. Modulation was performed with the quantum confined Stark effect, using the techniques to achieve large, zero chirp, increases in absorption. The device operates beyond the matching condition. At zero applied bias, the device is near the matching condition. With little reflectivity and little exciton absorption, the device is highly transmissive. With bias, absorption at the active wavelength increases. This increase in absorption moves the device further beyond the matching condition, increasing reflectivity, and simultaneously decreasing transmission. Furthermore, the quantum wells are designed so that at zero bias, when α is low, $r_t - r_b$ and the position of the front and back mirrors can be thought of as interchangeable. The device is thus reversible.

![Figure 5-20](image)

*Figure 5-20*: (a) Theoretical and (b) experimental curves for Reflection and Transmission versus Wavelength of the X-modulator. “On” indicates response with an applied electric field.
Figure 5-21: Modulation Ratio and Reflectivity Change versus Voltage parameter space plot for the X-modulator. All of the shown points are possible design specifications given these three characteristics. Reversibility difference of <5% is assumed.

Figure 5-20 shows the theoretical prediction before growth and the experimental results from this first device. When switched, with an applied bias of 40V, the device modulates from (T ~ 60%, R~ 6%) to (T ~ 6%, R~ 60%). In addition, with incident light taken from the bottom, the structure shows characteristics with reflectivity and transmission values within 1.5% of those using top incident light. The designed optical bandwidth of the devices was 2nm, which is intermediate between the wide bandwidth needs for high temperature stability devices (these are good to ±8°C) and WDM applications, which desire narrower bandwidths (< 1nm)\textsuperscript{85}. Furthermore, the device shows zero relative phase change between the off and on states for both the reflected and transmitted waves. Note that the structures used 200Å GaAs barriers to eliminate strain induced material degradation. This degradation is induced by the accumulated strain of many stacked lattice mismatched InGaAs quantum wells. If phosphorus were used in the barriers (InGaP) to perform strain compensation\textsuperscript{86}, then barriers of 35Å could be used and the voltage would be reduced by 40% without any redesign of the device. Such strain compensation could also be performed by using a graded buffer layer\textsuperscript{87} to create an effective substrate composition between that of the well and barrier layers. For example, a substrate which is graded to In\textsubscript{0.12}Ga\textsubscript{0.88}As will produce a compressive strain on a 75Å In\textsubscript{0.2}Ga\textsubscript{0.8}As quantum
well which would be exactly compensated by the tensile strain induced by 50Å GaAs barriers. In this case, many wells could be stacked with no net accumulated strain.

5.6.2 Parameter Space

Fabry-Perot devices are optically characterized primarily by voltage, optical bandwidth (OB), modulation ratio (MR), reflectivity change (ΔR) (related to insertion loss), and reflected phase. Figure 5-21 and Figure 5-22 show a portion of the parameter space for X-modulator. Figure 5-23 defines the relevant parameters. As is shown, for these simulations, modulation ratios well over 1000 and voltages of 5V are possible with changes in reflectivity above 60%. (These voltages can all be reduced by 0.6 if strain compensation using phosphorus in the barrier regions or graded buffer layers are used).

![Graph showing parameter space for X-modulator.](image)

*Figure 5-22: Optical bandwidth and Reflectivity Change versus Voltage parameter space plot for the X-modulator.*

In general:

- For a fixed voltage, as MR increases, ΔR increases and OB decreases.
- For a fixed DR, as voltage increases, OB increases and MR decreases.
- For a fixed MR, as voltage increases, OB increases and DR decreases.
Figure 5-23 shows a generic reflectivity response versus wavelength at two voltages (not for the current X-modulator) to help define the relevant characteristics. Modulation ratio is defined as $R_{\text{high}}/R_{\text{low}}$. Change in reflectivity is defined as $R_{\text{high}}-R_{\text{low}}$. Optical bandwidth is shown and is measured here in Angstroms. Through design the following can be controlled: front and back mirror reflectivities, cavity length, distance (in wavelength) of zero bias exciton peak from the Fabry-Perot peak, and maximum and minimum exciton absorption.

![Figure 5-23: Generic modulator reflectivity spectrum showing some of the relevant parameters.](image)

5.6.3 Stacked Devices

The optical properties of two stacked 200μm x 200μm square X-modulators were theoretically predicted and experimentally verified. Several logic functions are achievable with such a configuration (shown schematically in the Figure 5-24 inset). White light incident at 21° off normal incidence was used with lenses below and between the devices to keep the light as columnar as possible—dispersion in incident angle broadens the measured optical bandwidth. Figure 5-24 shows the experimental results. The system takes two electrical and up to three optical inputs and provides three optical outputs. The incident angle imparted a 50Å blue shift to the Fabry-Perot resonance wavelength. Inputs A, B, and C represent optical inputs for this device while D and E are electrical inputs to this optoelectronic system. For the measurements, only A was an ‘on’ optical signal, making: D, D_E, and D_E the effective outputs for 1, 2 and 3 respectively. Output ‘1’ represents the single device reflectivity response and was similar to that of Figure 5-20. Figure 5-24
also shows the logic high and some of the various logic low levels at the Fabry-Perot wavelength for the outputs 2 and 3, given the different combinations of the electrical inputs. Stacked wafers, each of which contains large 2-D arrays of devices would be able to perform extremely efficient complex switching, routing and logic

![Diagram](image)

**Figure 5-24:** Measured Signal versus Wavelength for output 2 and output 3 (shown schematically in inset) of a dual stacked X-modulator system. Output 1 is similar to the plots shown in Figure 5-20 with the appropriate wavelength shift.

### 5.6.4 Angular Dependence

The creation of large arrays of X-modulators to perform complex optical switching depends upon the ability to design devices to operate at specific angles. Figure 4 shows the angular dependence of the 'off' state reflectivity for both TE and TM light incident on an X-modulator whose normal incidence Fabry-Perot minima is at 9840Å. Because the cavity mode shifts, but the exciton absorption wavelength does not, for incident angles in excess of 21°, the contrast ratio will begin to degrade and a TE-TM split will be observed. Clearly for arrays of interconnected devices, angles larger than 21° might be desired. Angular distortion can be compensated for by fabricating a device with a wider cavity. Figure 5-25 also shows the normal incidence spectra for a wider cavity device designed to be matched to the 9840Å device with an incident angle of 25°. This type of design is the key to array fabrication. Care must be taken when designing structures for operation at non-normal incidence. Since the lowest heavy hole state (momentum = 3/2; angular momentum = ±3/2) has no net wave component in the direction perpendicular to the growth direction,
TM polarized light propagating within the plane of the quantum wells (parallel to the growth direction) will not interact with the heavy hole to produce a heavy hole exciton.

![Graph showing reflectivity vs wavelength for TE and TM polarizations at various angles](image)

*Figure 5-25: X-modulator transmission response for a given range of input angles. This demonstrates the degradation of contrast ratio and the TE-TM mode split. The effect of a wider cavity is also shown.*

Conversely, the lowest light hole exciton experiences a slightly enhanced absorption for the TM polarized light component traveling in the plane of the quantum wells. Thus for non-normal incident light, the value of exciton absorption at a wavelength could be affected if TE polarized light is not used.

### 5.6.5 Conclusion

In conclusion, this section discussed the design, fabrication and testing of vertical cavity X-modulators—a structure which allows for both reversible and conservative switching. This represents the third of the three desired switching elements introduced in the introduction to this thesis. The experimental device displayed changes in reflection and transmission of over 55% each. The devices were fabricated to accept incident light from both the bottom and top of the structure, making them reversible. In addition, optimization conditions, results for multi-device configurations, and angular input issues have been discussed. The unique properties of X-modulators will have a significant impact on efficient switching, 3-D array optical routing and optical logic.
6. Summary and Suggestions for Future Work

6.1 Summary

Both the optical and electrical properties of quantum well optoelectronic modulators were investigated in this thesis. It was asserted that while optical switching elements have been and continue to be heavily investigated for a number of applications, ideal switching properties have never been realized. The culmination of this work was the development of the three ideal classes of optical switching elements: pure amplitude modulator, pure phase modulator, and pure direction modulator.

The early sections of this thesis demonstrated first the onset of quantum well absorption in very narrow wells. Then the quantum confined Stark effect was shown to have properties which could be used to achieve zero parasitic refractive index changes between two voltages. Coupled quantum wells were investigated and shown to exhibit high modulation efficiency and zero chirp behavior over the entire voltage swing. Modulation with electron and hole swapping was then demonstrated with coupled InGaAs wells. These proved quite promising, but changes in our MBE system eliminated the ability to pursue these further. More complex quantum well structures were shown to enhance either the modulation efficiency or the optical bandwidth over which low chirp behavior existed. Finally, partially doped coupled quantum wells were discussed as an alternative modulation scheme which might have potential for optically controlled absorptive modulation.

The later portion of this work investigated cavity devices which used single quantum wells to obtain pure amplitude modulators before and beyond the matching condition with zero relative phase change between the on and off states. These show promise for ideal spatial light modulation. Next, attention was turned to the phase flip modulator which produce 180° phase changes with almost no amplitude modulation. Characteristics away from the Fabry-Perot minima were investigated, and exciton characteristics were shown to be useful for optimizing these structures for either digital or analog applications. Finally, the X-modulator demonstrated photon routing. This device was designed to accept input from either the top or the bottom of the device structure. Stacking of these devices was performed and showed that complex arrangements of these devices could prove powerful for optical routing or logic. The parameter space of such devices was also investigated and the tradeoffs analyzed.
Throughout the work, the theory of light-matter interactions, excitons, and Fabry-Perot cavities was developed. Simulations of both the electronic and optical components of these optoelectronic modulators were described and performed. Coupled quantum well devices were also investigated from a theoretical perspective. All of the experimental structures were first designed using these simulation tools and then grown with the aid of in-situ measurements. The complexity of these growths necessitated the use of both of these techniques in order to realize the novel and useful device structures that are the basis of this thesis.

6.2 Future work

There are various issues to be resolved and various avenues for future work:

Within the area of coupled quantum wells, much can be done to optimize quantum well structures for other purposes. For example, photorefractive devices rely on large refractive index changes with voltage. Coupled quantum well systems could be optimized to create large refractive index changes with small absorptive changes. In addition, some work combining coupled quantum wells with cavity structures would be useful to make better digital switching phase flip modulators. They could also be used to lower the voltage of all cavity devices.

In addition, the coupling of intersubband and interband transitions allow an interesting method of using optical inputs to control these devices. Thus, a long wavelength light could modulate a shorter wavelength (higher energy) transition. An interesting experiment would be to use valence band intersubband transitions (with normal incidence light) to modulate interband absorption. In doped quantum wells, this should present no problem. It would be interesting to see if virtual transitions in undoped quantum wells would provide enough of an effect to cause a change in interband absorption. Such a mechanism could operate via a principle similar to the optical Stark effect.42

Phase flip modulator gratings would be very useful for steering input beams to multiple optical fibers. Certainly more work needs to be done to improve these devices. However, gratings composed of X-modulators are also quite intriguing since a single grating could accept two input beams and simultaneously provide four outputs (two from each input); each of which could be steered. Also, combinations of gratings made from the more simple amplitude modulators could provide very useful output characteristics while being faster to grow and tailored for easier fabrication.

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The X-modulators and phase flip modulators can also be configured in three dimensional arrays—by stacking wafers containing two dimensional arrays. Because each of the individual devices is designed to provide large output signal, complex routing, switching, and optical logic can be performed. The architectures afforded and the simple systems which are producible must be further explored.

On the more practical side, stacking modulators on top of one another, growing modulators on top of silicon circuitry, and growing modulators on top of a vertical cavity laser structure to perform Q-switching in a single package are all useful avenues to explore.

Since all modulators need light sources, some thought could be given to novel sources. In particular, it would be interesting to fabricate nonlinear optical material on top of GaAs light emitting diodes. Such material could be be deposited through MBE, chemical vapor deposition, or pulsed laser deposition, for example. Frequency doubling or halving could be performed if particular materials were chosen which had near lattice match with the substrate and allowed the appropriate wavevector matching necessary for frequency conversion. In these cases, the nonlinear material choice need not be limited to semiconductors. In another direction, light sources using organic materials such as hydroxynine aluminum emit broad luminescent spectra across the visible wavelengths. Furthermore such materials can be deposited on glass or semiconductor substrates by techniques as potentially simple as dipping wafers or using photoresist spinners. Combinations of semiconductor and organic technologies could prove quite useful.

Other active modulation materials can be investigated. For example quantum dots could have extremely interesting linear and nonlinear absorptive properties. Finally, all of the cavity structures could be investigated in various material systems; from Silicon/Germanium to Gallium Nitride/Aluminum Nitride.

There are countless other possible avenues for exploration; and much of the fun of research is trying to discover the best ones.
REFERENCES

1 Multitudes of review articles are available about CMOS technology for example. One recent one is:


6 A fourth technique, polarization modulation, can be performed, although it is not as easily performed with vertical cavity quantum well devices. Some simple polarization effects can be obtained. See section 5.6.4.

7 Again, many books and articles exist. An example is: NATO Advanced Study Institute on Molecular Beam Epitaxy (MBE) and Heterostructures (1983 : Erice, Sicily)


30. The author has done this, but omits the details here.


33. S. Kim, J. A. Trezza, Submitted to Journal of Vacuum Science and Technology.


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