Photonic Devices and Applications based on Intersubband Transitions and Electromagnetically Induced Transparency

PETER JÄNES

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Abstract

Although photonic devices have experienced a rapid development lately, there is still room for substantial improvements in performance. From a telecommunications perspective, improvements in speed, size, integration and power consumption are desired. There is also a general interest in photonic devices with new functionalities.

Being a key component in fiber-optic systems, high-speed optical modulators often initiate the development towards higher bit-rates. The technology of current state-of-the-art modulators have matured suggesting new paths of development. In this thesis we investigate the potential of modulators based on intersubband (IS) transitions in quantum wells (QWs). Specific QW designs are suggested and complete modulator structures are simulated. IS absorption is also experimentally characterized. Absorption linewidth is critical for IS modulator performance since narrow linewidth implies high bandwidth and/or small driving voltage. High material quality is important, since linewidth is typically limited by well-width fluctuations and interface roughness.

A mid-IR AlGaAs/GaAs-modulator is proposed having a RC-limited bandwidth of 130 GHz and a peak-to-peak voltage of 0.9 V. Experimentally, Stark shift is measured in InAlAs/InGaAs step QWs at $\lambda \sim 6 \mu m$ predicting that an IS modulator based on this material would have a bandwidth of 90 GHz and a peak-to-peak voltage of 0.9 V.

IS absorption at 1.55 $\mu m$ requires material combinations with high conduction-band offset. Simulations of an InGaAs/InAlAs/InGaAs step QWs predict a bandwidth of 90 GHz and a peak-to-peak voltage of 2.0 V. Experimental studies of IS absorption in AlN/GaN QWs are presented. IS absorption at 1.5-3.4 $\mu m$ with linewidth below 100 meV is measured for well widths between 15-54 Å. Subpeaks corresponding to well-width fluctuations on the monolayer scale are identified with linewidths of $\sim 60$ meV. Agreement between theoretical calculations and measured spectra is encouraging. Theoretical simulations together with measured absorption linewidths suggest that high performance IS modulators operating at 1.55 $\mu m$ are realizable.

Photonic devices with new functionalities are addressed by investigating electromagnetically induced transparency (EIT) theoretically and considering potential applications based on EIT. Simulations of two-dimensional pulse-propagation based on the Maxwell-Bloch equations are performed with a focus on storing and reading out optical pulses. We explicitly formulate the phase-matching conditions for reading out stored pulses in a new direction and propose a serial-to-parallel converter based on this.

For slow-light devices, e.g., optical buffers, we identify and analyze two main limitations on the medium bandwidth: the frequency dependent absorption and the group velocity dispersion. Since large bandwidth and large delay are contradictory requirements, the delay bandwidth product is considered. Analytical expressions are derived and analyzed and verified by simulations on pulse propagation. Insertion of parameters relevant for semiconductors indicates that development of materials with long coherence times are necessary for realizing optical buffers based on EIT.
Acknowledgement

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List of publications

The thesis is based on the following publications, which will be referred to by their letters:

A P. Jänes, P. Holmström, and U. Ekenberg
A High-speed intersubband modulator based on quantum interference in double quantum wells,

B P. Holmström, P. Jänes, U. Ekenberg, and L. Thylén
Design of intersubband optical modulators,

C P. Jänes and P. Holmström
High-speed optical modulator based on intersubband transitions in InGaAs/InAlAs/AlAsSb coupled quantum wells,

D P. Holmström, P. Jänes, U. Ekenberg, L. Thylén
Strong electroabsorption using intersubband transitions in InGaAs/InAlGaAs/InAlAs step quantum wells,

E X.Y. Liu, P. Holmström, P. Jänes, L. Thylén, and T.G. Andersson
Intersubband absorption at 1.5-3.5 µm in GaN/AlN multiple quantum wells grown by molecular beam epitaxy on sapphire,
Submitted to Physica Status Solidi (a)
LIST OF PUBLICATIONS

F X.Y. Liu, T. Aggerstam, P. Jänes, P. Holmström, S. Lourdudoss, L. Thylén, and T.G. Andersson
Investigation of intersubband absorption of GaN/AlN multiple quantum wells grown on different substrates by molecular beam epitaxy, accepted for publication in J. Crys. Growth, also presented at 14th Int. conf. on Molecular Beam Epitaxy (MBE 2006), Tokyo, Japan, Sept. 2006.

G P. Arve, P. Jänes and L. Thylén
Propagation of two-dimensional pulses in electromagnetically induced transparency media

H P. Jänes, P. Arve and L. Thylén
All optical serial to parallel converter utilizing electromagnetically induced transparency

I P. Jänes, J. Tidström, and L. Thylén
Limits on optical pulse compression and delay bandwidth product in electromagnetically induced transparency media
J. Lightwave Technol., vol. 23, no. 11, pp. 3893-3899, 2005

J J. Tidström, P. Jänes, and L. M. Andersson
Delay bandwidth product of electromagnetically induced transparency media
Submitted to Phys. Rev. A

Related publications not included in the thesis:

P. Holmström, P. Jänes, S. Irmscher, H. Kim, and T. G. Andersson
High-speed optical modulator using intersubband transitions in GaN/AlGaN step quantum wells,

Structural and optical properties of GaN/AlN multiple quantum
wells for intersubband applications,

P. Holmström, S. Matsui, H. Uchida, T. Nakazato, P. Jänes, T. Aggerstam,
A. Kikuchi, and K. Kishino
Electroabsorption modulator based on intersubband transitions in
(Al)(Ga)N step quantum wells considering intermixing,
Paper 91 in proceedings of the 8th Int. Conf. Intersubband Transitions in
Quantum Wells (ITQW 2005), Cape Cod, USA, Sept. 2005

X.Y. Liu, P. Jänes, P. Holmström, T. Aggerstam, S. Lourdudoss, L. Thylén
and T.G. Andersson
Growth of GaN and GaN/AlN multiple quantum wells on sapphire,
Si and GaN template by molecular beam epitaxy,
paper TuP-07, 1st Int. Symp. on the Growth of III-Nitrides (ISGN-1),

U. Westergren, Y. Yu, P. Jänes, P. Holmström, and L. Thylén
Efficient and compact light-intensity modulators for high frequen-
cies and high bitrates,
pp. 142-145 (Invited paper) in proceedings of the 8th International Confer-
ence on Transparent Optical Networks (ICTON 2006), Nottingham, United
Kingdom, 2006.

J. Tidström, P. Jänes, and L.M. Andersson
Pulse-distortion in EIT medium
Paper WB6 in Slow and Fast Light 2006 Technical Digest (Optical Society of
America, Washington, DC, 2006)
## List of Acronyms

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<th>Description</th>
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<tbody>
<tr>
<td>EIT</td>
<td>electromagnetically induced transparency</td>
</tr>
<tr>
<td>DIPF</td>
<td>doping induced potential fluctuations</td>
</tr>
<tr>
<td>FTIR</td>
<td>Fourier transform infrared</td>
</tr>
<tr>
<td>GVD</td>
<td>group velocity dispersion</td>
</tr>
<tr>
<td>IR</td>
<td>infrared</td>
</tr>
<tr>
<td>IS</td>
<td>intersubband</td>
</tr>
<tr>
<td>LO</td>
<td>longitudinal optical</td>
</tr>
<tr>
<td>MBE</td>
<td>molecular beam epitaxy</td>
</tr>
<tr>
<td>MOVPE</td>
<td>metal-organic chemical vapor-phase epitaxy</td>
</tr>
<tr>
<td>MQW</td>
<td>multi quantum-well</td>
</tr>
<tr>
<td>TE</td>
<td>transverse electric</td>
</tr>
<tr>
<td>TM</td>
<td>transverse magnetic</td>
</tr>
<tr>
<td>QD</td>
<td>quantum dot</td>
</tr>
<tr>
<td>QW</td>
<td>quantum well</td>
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<tr>
<td>QWIP</td>
<td>quantum well infrared photodetector</td>
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Chapter 1

Introduction

1.1 Background

Despite the ups and downs experienced by the telecommunication industry the internet data traffic continues to grow and approximately doubles each year. The drive for such a development is an increased range of services demanding more and more bandwidth. Although such a growth naturally cannot continue in the long run, this expansion of data traffic is expected to persist for at least some years ahead.

Fiber optic communication forms the basis of modern telecommunication and has proven quite successful in meeting and surpassing the requirements set by the rapid growth of data traffic. Wireless and mobile technology have become important parts of telecommunication but when it comes to transporting high speed data over long distances, the only viable solution is fiber-optics. A consequence of the continuous increase of data traffic is a continuous demand for faster and more versatile optical communication systems.

Photonics has since long outperformed electronics when it comes to high-speed data transmission. Transmitting high bit-rates (>10 Gb/s) over long distances (>100 km) is today standard in fiber-optic systems. But there is still an incentive to investigate the possibilities to further increase the speed (bandwidth) of photonic devices.

Electronics, on the other hand, is superior to photonics regarding functionality. In a typical communication system today, transmission of the data is carried out optically while all the switching and all data processing are done electronically resulting in numerous electronic-optical and optical-electronic conversions. If more functions would be performed in the optical domain, the complexity, size, cost, power consumption, etc are expected to be reduced. Much effort has been put in research on all-optical networks and with some success, but still some functionalities are difficult to implement with photonic devices resulting in ineffective solutions. Buffering is an example of such a functionality. Buffering is important
in a switch/router when a data packet has to be delayed for some reason, e.g. the out-going route is momentarily occupied. Today optical buffering is carried out using fiber loops, a non-flexible and quite bulky solution. Another functionality that simply does not exist optically is memories. Consequently much remains to be done in the field of optical information processing. Whether photonics will outperform electronics in this respect remains to be seen. Electronics has so far shown a remarkable ability to adapt and present effective solutions to complicated problems, still it is undoubtedly photonics that has the largest potential for improvement in the sense that it is less mature than electronics.

In addition to speed and functionality, other challenges also awaits photonic devices, such as reducing size, reducing power consumption and increasing integration.

This thesis focuses on the issues of speed and functionality of photonic devices and also size is addressed. Specific physical phenomena are investigated as potential paths of development. In the case of speed, intersubband transitions are considered for high speed optical modulators. Furthermore, electromagnetically induced transparency is analyzed to investigate its promising potential to allow new functionalities in photonic devices.

1.2 Speed

The development of high-speed photonic devices in general is often preceded by the development of high-speed transmitters. The most straightforward implementation of a transmitter is a laser (or even a light emitting diode) that is simply switched on and off, consequently generating an intensity modulation of the transmitted light. But for high modulation speeds ($\geq 10 \text{ Gb/s}$) it is more effective to use an external modulator that generates an intensity modulation by varying the transmission through the modulator. Current state-of-the-art high-speed modulators are typically based on either electroabsorption in quantum well interband transitions or on the electro-optic effect in e.g. $\text{LiNbO}_3$.

Interband electroabsorption modulators has proven quite successful allowing high speed ($\sim 80 \text{ Gb/s}$) with relatively modest driving voltage ($\sim 3 \text{ V}$) [1]. Low driving-voltage is an important issue for high-speed modulators since it becomes increasingly difficult to generate large driving voltages for large bandwidths. Being semiconductor based, interband electroabsorption modulators also allows integration with semiconductor lasers making them a cost-effective solution. One drawback of these modulators is the difficulty in achieving a negative chirp. As the amplitude of the light is modulated, there is a simultaneous modulation of the phase of the light called chirp. A negative chirp can to some extent compensate for the chromatic dispersion of the optical fiber increasing the maximum transmission distance. Another drawback is the modest saturation intensity limiting the launched power into the fiber.
1.3. FUNCTIONALITY

Electro-optic Mach-Zehnder modulators, on the other hand, does not suffer from these drawbacks. However, the required driving voltage is quite large (\(\sim 5-10V\)) making them difficult to drive at high bandwidths. Electro-optic modulators are also quite large, typically several centimeters long.

The device technology of these modulators are today relatively mature offering limited improvement of performance. Instead it seems necessary to consider some different modulation mechanisms in order to further push the modulator performance. Intersubband (IS) transitions have been suggested as an interesting candidate for optical modulators [2, 3, 4]. In this thesis the potential of IS modulators for high-speed applications is investigated. Specific modulator designs are suggested and simulated. IS electroabsorption at mid-IR as well as IS absorption at 1.55 \(\mu\)m is characterized. It is concluded that IS modulators has the potential to outperform current state-of-the-art modulators especially regarding speed and required voltage swing, but also that the chirp characteristics and saturation intensities are advantageous.

1.3 Functionality

Another path of the technical development of optical communication involves devices with novel functionalities. Electromagnetically induced transparency (EIT) is a promising phenomenon which may prove successful in implementing functionalities which today can be realized only with poor performance or complex devices or not at all.

The physics of EIT is a complex matter and will be discussed in greater detail in chapter 5, but in short the induced transparency is associated with a large reduction of group velocity which can be used to delay optical pulses. Experiments have shown delay times close to milliseconds [5, 6] and it seems attractive to consider an optical buffer based on EIT. In this thesis limitations on such a buffer are investigated theoretically and important restrictions on bandwidth and delay times are derived and material limitations are discussed. Associated with slow group velocity is also a significant spatial compression of optical pulses inducing a substantial reduction of the size of such devices. Further, EIT also allows an optical pulse to be stored as a coherent material excitation with a storage time limited by the coherence time of the excitation. Storage times as long as a second have been shown experimentally [7]. An interesting feature analyzed in this thesis is the possibility to read out a stored pulse in a direction different from the original direction of propagation and applications are proposed.

1.4 Outline of the thesis

This thesis addresses performance improvement of photonic devices as well as novel applications. More specifically intersubband transitions in quantum wells are considered for enhancing the performance and increasing the speed of optical modu-
lators. Further, potential applications based on electromagnetically induced transparency are investigated as well as the limitations and constraints of such devices.

In chapter 2, the physics of intersubband transitions is briefly summarized motivating the investigation of exploiting IS transitions in an optical modulator. Further, in chapter 3 different modulation mechanisms are presented and the modeling of quantum wells are explained as well as the extraction of parameters describing modulator performance. Design issues are discussed after that and some results from simulations are presented. Moreover, the choice of material and material considerations are discussed. The design and simulation of different modulator structures in different materials are treated in paper A-C. Following the discussion on materials and growth is a presentation of the methods for characterizing IS structures experimentally. The discussion on IS modulators is finalized with a presentation of experimental results based on the results from paper D-F.

In chapter 4 the physics of EIT is explained from the perspective of the Maxwell-Bloch equations. Further, the susceptibility is introduced which simplifies the analysis of a static EIT system. In chapter 5 potential applications of EIT are set forth. Pulse propagation and slow light are considered and the importance of bandwidth and delay bandwidth product are emphasized, two parameters considered in detail in papers I and J. A presentation of orthogonal read-out of stored pulses follows after that, which is introduced in paper G and applied in paper H. Potential EIT media is then discussed followed by a brief description of the simulation program. The chapter is concluded by considering some specific devices. Discussion and conclusions are provided in chapter 6 while chapter 7 contains brief summaries of the papers forming the basis of this thesis.
Chapter 2

Intersubband physics

2.1 Basic physics

The wavefunction $\psi(r)$ of an electron satisfies the time-independent Schrödinger equation

$$\hat{H}\psi(r) = E\psi(r) \quad (2.1)$$

where $\hat{H}$ is the Hamiltonian operator of the system and $E$ is the total energy of the electron. If no forces act on the electron it is called a "free electron" and the electron has only kinetic energy given by

$$E(k) = \frac{\hbar^2 k^2}{2m}. \quad (2.2)$$

It is of limited interest to consider a free electron, and it is more relevant to describe electrons moving in periodic crystal structures. When considering electrons in a periodic potential it is found [8] that the energy dispersion for small $k$ is well described by the parabolic expression of Eq. 2.2 but with an effective mass, $m^*$, different from the free-electron mass, $m$. Moreover, there are energy bands that are "forbidden" forming energy gaps for the electrons.

The energy dispersion of real semiconductor materials is quite complex, but for most photonic applications there are two features that are central. The bandgap ($E_g$), the forbidden energy gap between the conduction band and the valence band of a semiconductor is important for many optical devices in that a transition across the bandgap sets limitations on the photon energy involved. The effective mass, or the curvature of the parabolic dispersion for small $k$ plays a crucial role for many physical processes.

By surrounding a thin layer of a low bandgap material with a high bandgap material, a quantum well (QW) is formed 2.1a. In a QW the carriers are confined to move in only two direction and the energy is quantized in the third direction forming atomic-like energy levels. A photon can be absorbed by the medium inducing an
excitation of an electron in the valence band to the conduction band. In addition to these interband transitions, transitions between the energy levels within a band (intersubband transitions) are also possible.

2.2 Intersubband transitions

In this thesis we are concerned with intersubband (IS) transition within the conduction band. There are a few major differences between interband and IS transitions which we will illuminate since they imply benefits when designing modulators based on intersubband transitions instead of interband transitions.

Why an intersubband modulator?

From the schematic energy dispersion diagram of Fig. 2.1 we note that the subbands in the conduction band are almost parallel. This implies that the transition energy is almost independent of the electron k-vector, resulting in a narrow absorption peak. In contrast, due to the opposite curvature of the valence- and conduction bands, the interband QW absorption spectrum is a step-like function with some exciton peaks.

A narrow and strong IS absorption peak implies that an IS based modulator can be made short resulting in a reduced capacitance and an increased RC-limited bandwidth. It also allows the voltage swing required for modulation to be reduced.

Another important feature of IS absorption is the fast relaxation rates compared to interband absorption. IS relaxation is mediated through rapid LO-phonon interaction in the picosecond or even sub-picosecond range. For a modulator this rapid relaxation implies that the modulator becomes less sensitive to saturation, a property important when high intensities are to be launched into the fiber.

More on intersubband transitions

The potential benefits of an IS based modulator motivates a thorough investigation of IS transitions.

It is easy to realize that the absorption linewidth is important for the performance of the modulator and we will motivate this further below. There are a number of different mechanisms determining the width of the absorption peak. There is homogeneous broadening caused by the finite lifetime of the electron states and is mainly due to electron-electron scattering, LO-phonon scattering, interface roughness scattering and impurity scattering. There is also inhomogeneous broadening since different electrons experience slightly different IS transition energies. This inhomogeneous broadening is caused by non-parabolic subbands, well-width fluctuations and inhomogenities in the material.

In a one-particle picture, the inhomogeneous broadening seems to be quite detrimental for the absorption linewidth. It has however been found experimentally and
2.2. INTERSUBBAND TRANSITIONS

Figure 2.1: a) A quantum well is formed by surrounding a low-bandgap material with a high-bandgap material. b) Schematic potential profile of a quantum well containing two bound states in the conduction band. c) In-plane energy dispersion of a quantum well. Intersubband (IS) transition energy is relatively independent of k-vector, which is not the case for interband (IB) transitions. IS relaxation is mediated through LO-phonon interaction.

explained theoretically, that the collective nature of the IS resonance can effectively cancel inhomogeneous broadening to some degree resulting in quite narrow absorption spectra even with a high degree of nonparabolicity [9].

Another important property of IS absorption is that, according to the polarization selection rule [10], only light polarized normal to the growth direction of the QW can be absorbed. For a modulator this is not major problem, since there are ways to control the polarization of the input light and the light travels in-plane. For characterization purposes, this polarization dependence is important, since absorption in TM-polarized light and not in TE-polarized light is often considered proof of IS absorption.
Chapter 3

Intersubband modulators

Considerable effort has been put into developing lasers and detectors based on IS transitions, and with great success [11, 12]. The large interest in these devices is driven by the potential applications. In the case of quantum cascade lasers, there is a demand for mid-IR sources used for gas sensing, and the desired wavelength in an IS based device can be easily reached by correct design of the quantum wells. Regarding quantum well infrared photo-detectors (QWIPs) they are successfully used in gas detection and thermal imaging.

Developing modulators based on IS transitions has attracted less attention. There are however a number of potential modulator applications at the wavelength range offered by mature III-V materials, such as on-chip communication, free space communication etc. Mature III-V materials only allow IS absorption at wavelengths above $\sim 4 \mu m$ due to the limited conduction band offset. But it might be even more attractive to consider IS modulators for short wavelength (1.55 $\mu m$) telecommunications. Such short wavelengths require materials with large conduction-band offsets.

3.1 Principle of operation

As mentioned above, in an IS modulator, transitions within the conduction- (or valence-) band are used for modulation. There are, however, three different mechanisms to be used for modulation: carrier density modulation, quantum interference and Stark effect.

In a carrier density modulator, absorption modulation is achieved by modulating the number of electrons available for absorption. Modulation speed is limited by carrier transport and simulations have predicted that the carrier density modulator will be considerably slower than modulators based on the other mechanisms [13].

In a quantum interference modulator, modulation originates from an interference between coherent electronic states due to an applied electric field. When explicitly considering a coupled QW this quantum interference can equally well be viewed as a modulation of the oscillator strength. In Paper A we considered a coupled quantum
well where the two lowest states can be tuned in and out of resonance by applying an electric field resulting in an electric field dependent oscillator strength of the transitions from these two states to a third state. Quantum interference modulation can be achieved in various QW constellations with many different states interfering (e.g. Fig. 4b in Paper B). Keeping the QW structure as simple as possible is of course beneficial from a manufacturing point of view. It is also possible to combine the quantum interference modulation mechanism with Stark effect (Paper C) which can be advantageous for the chirp properties of the modulator.

When applying an electric field, the energy levels of the confined states in a QW are shifted. This energy shift is called Stark effect and can effectively be used for modulation since a shifted absorption peak results in an absorption modulation at a given wavelength. The Stark shift is significant in asymmetrical QWs such as the step Qws described in Paper B and D.

### 3.2 Quantum well design and simulations

When trying to predict the performance of an IS modulator the first requirement is an accurate model of the electron states in the QWs. Having such a model allows the IS transition energies and oscillator strengths to be calculated which in turn enables calculation of the absorption and refractive index of the QWs. When the optical characteristics of the active layer is known, a waveguide simulation is performed enabling macroscopic parameters describing the performance of the device to be calculated.

#### Modeling of the quantum wells

Let us begin with modeling of the QWs. The energy levels and wavefunctions are calculated from the Schrödinger equation

\[
\frac{-\hbar^2}{2m_e(z)} \frac{\partial}{\partial z} \psi_n(z) + V(z) \psi_n = E_n \psi_n
\]  
(3.1)

where \(E_n\) is the energy of the bound state \(n\) in the quantum well and \(\psi_n\) its envelope function. Writing the Schrödinger equation in this form allows for a position and energy dependent effective mass, \(m_e\) (see below). The total potential energy is given by

\[
V(z) = V_c(z) + V_H(z)
\]  
(3.2)

where \(V_c(z)\) is the conduction band edge and \(V_H(z)\) the Hartree potential which is calculated by solving the Poisson equation

\[
\frac{\partial^2 V_H(z)}{\partial z^2} = \frac{\rho(z)}{\varepsilon_0 \varepsilon_r(z)}
\]  
(3.3)
\( \rho(z) \) is the density of charges due to ionized donors and electrons confined in the QWs. Since the electrons interact with the ionized donors, the Schrödinger and Poisson equations have to be solved self-consistently. In the first step, the Schrödinger equation is solved for an unperturbed potential, then the population in each state is calculated which enables a calculation of a new potential profile from the Poisson equation. This new potential is then used in the next iteration continuing until the energy levels has converged to a steady value.

For nitrides it is also necessary to consider built-in fields due to spontaneous and strain-induced material polarization. These built-in fields are quite strong resulting in a substantial modification of the potential profile [14]. For instance, a single QW becomes more similar to a triangular well than a square well, see e.g. Fig. 9 in paper E.

When solving equation 3.1 we also have to take into account that the conduction bands are not exactly parabolic. Nonparabolicity is most significant in narrow wells and for higher subbands when the quantized state energy becomes comparable with the energy gap. It is important to distinguish between orthogonal mass and parallel mass [15]. The orthogonal effective mass is used when calculating the energy states and the oscillator strengths and we take nonparabolicity into account by introducing an energy dependent effective mass [16]

\[
m_e(E) = m_e \left(1 + \frac{E - V_e}{E_g + \Delta_0/3}\right)
\]

where \( \Delta_0 \) is the energy difference between the light-hole and split-off valence bands. Using an energy and position dependent effective mass complicates matter when calculating the oscillator strength of the transitions of interest. This is due to the fact that the calculated envelope functions become non-orthogonal. An approach proposed in [17] and [18] must be taken, yielding orthogonality by considering coupling to the light-hole and split-off bands.

The nonparabolicity of the parallel mass gives rise to a broadening of the single-particle transition because transitions with different k-values have slightly different transition energies. This parallel nonparabolicity can be modeled by describing \( E(k) \) up to higher orders than \( k^2 \) introducing new parameters [15] allowing the broadening to be calculated. But since the IS resonance is a collective excitation this inhomogeneous broadening mechanisms turns out to be effectively canceled [9]. The resulting linewidth is difficult to model since it is affected by a number of additional factors (interface roughness, well-width fluctuations etc). Instead it is more accurate to use a phenomenological linewidth based on experimental results, in the simulations.

Another result of the many-body interactions is a shift of the IS resonance. The many-body interactions include exchange-correlation interaction, excitonic interaction and depolarization shift becoming increasingly important at high doping.

The exchange-correlation interaction can be included as a correction to the potential [19] adding an extra term in Eq. 3.2
CHAPTER 3. INTERSUBBAND MODULATORS

\[ V_{xc}(n(z)) = -\frac{2}{\pi r_s} \left( \frac{9\pi}{4} \right)^{1/3} \frac{e^2}{8\pi\epsilon_r\epsilon_0 a_0} \left[ 1 + 0.7734 \frac{r_s}{21} \ln \left( 1 + \frac{21}{r_s} \right) \right] \]  

(3.5)

where \( r_s = \left[ \frac{3}{4\pi\epsilon_0 a_0(n(z))} \right]^{1/3} \) and \( a_0 = \epsilon_r(m_0/m^*)a_B \), \( a_B \) being the Bohr radius.

The depolarization shift arises from resonant screening of the electromagnetic field from the electron gas, while the exciton shift reflects the Coulomb interaction of the excited electron and the corresponding "hole" in the ground state. The total shift of the transition energy can be expressed as

\[ E_{12,\text{shifted}} = E_{12} \sqrt{1 + \alpha - \beta} \]  

(3.6)

where \( \alpha \) accounts for the depolarization shift and \( \beta \) the exciton shift and is given by [20]

\[ \alpha = \frac{2e^2n_s}{\epsilon_r\epsilon_0 E_{12}} \int_{-\infty}^{+\infty} dz \left( \int_{-\infty}^{z} dz' \psi_1(z')\psi_2(z') \right)^2 \]  

(3.7)

and

\[ \beta = -\frac{2n_s}{E_{12}} \int_{-\infty}^{+\infty} dz \psi_1(z)^2\psi_2(z)^2 \frac{\partial V_{xc}(n(z))}{\partial n(z)}. \]  

(3.8)

where \( n_s \) is the sheet carrier density.

For low and moderately doped structures where \( n_s \) is small, these many-body effects are small, but in IS modulator structures a high doping (yielding a stronger absorption) is often preferred making many-body effects necessary to include. In papers A-C, the depolarization shift is accounted for in the model [21]. In the theoretical calculations of paper D and E all many-body effects mentioned above are taken into account. A nice agreement between calculated and experimental transition energies is found (Fig. 6 in paper E).

Linewidth

As mentioned above, the absorption linewidth is limited by material quality such as interface roughness, well-width fluctuations, doping induced potential fluctuations (DIPF) making it difficult to model. In papers A-C we instead use a phenomenological linewidth in our simulations based on experimentally published data on similar structures.

In paper A we also address the issue of DIPF by introducing an electric field dependent linewidth. The reason is simple; if the transition energy is very dependent on the electric field it is naturally sensitive to local variations in the electric field due to fluctuations in the doping. A Stark-effect modulator, where the basis of modulation is an electric field dependent transition energy, is more sensitive to DIPF than a quantum interference modulator where the transition energy can be almost independent of the electric field.
3.3. DEVICE DESIGN

Calculating modulator characteristics

Once the transition energies and oscillator strengths have been calculated and the absorption linewidth has been estimated, the complex dielectric function, $\epsilon_r(\omega)$ for the QW stack can be calculated (see Eq. 1 and 2 in paper A). Together with the dielectric functions of the surrounding layers, the optical mode is solved by using the transfer matrix method. From the complex propagation factor, $\beta = b - ai$, the modal absorption spectra can be determined (see e.g. Fig. 5 in paper A). Having the modal absorption for different applied electric fields, it is easy to calculate the extinction ratio for different voltage swing and insertion loss, parameters that are central for the performance of a modulator. Requiring an extinction ratio of 10 dB gives a relation between the change in modal absorption, $\Delta \alpha_m$ and the modulator length as

$$\Delta \alpha_m L = 2.3.$$ (3.9)

The length, $L$, together with the mesa width, $w$ allows us to calculate the capacitance of the modulator from

$$C = \epsilon_0 \epsilon_r \frac{wL}{d},$$ (3.10)

where $\epsilon_r$ is the dielectric constant of the QWs and $d$ is the thickness of the QW stack. The capacitance is the main limiting factor of the modulator bandwidth (see below).

From $\beta$, it is also straightforward to calculate the chirp parameter, $\alpha_{ch}$, since

$$\alpha_{ch}(V) = \frac{\partial (\text{Re}(\beta))}{\partial F} = \frac{\partial (\text{Im}(\beta))}{\partial F} = \frac{-db}{da},$$ (3.11)

where $F$ is the applied electric field. The chirp parameter is simply the phase modulation divided by the amplitude modulation. The chirp of the pulse is of great importance for the transmission on optical fiber [22]. Due to the chromatic dispersion of the fiber, a spectrally wide pulse will be broadened during propagation and this broadening often limits the maximum propagation distance. However, if the pulse is chirped correctly it can to some extent counteract the chromatic dispersion and extend the propagation distance. For standard single-mode fiber, this means that $\alpha_{ch}$ should be negative.

3.3 Device design

Lumped devices

In this work we are mainly interested in the benefits offered by, and problems arising when, utilizing intersubband transitions to design an electroabsorption modulator. The main effort has thus been put into optimizing the active layer of the modulator. Since comparison with other modulators is necessary in order to establish whether
IS modulators would be competitive or not, a complete modulator structure has to
be simulated in order to extract relevant parameters such as modulation bandwidth,
chirp extinction ratio etc. The simplest modulator design is that of a lumped device
(Fig. 3.1). The light is input in the modulator waveguide and the optical mode
has an overlap with the active layer enabling a modulation of the absorption of the
mode.

The electrical characteristics of the modulator is modeled as a capacitance, $C$
over the active layer in series with a small resistance, $R_s$ (Fig. 3.2). Since no slow
carrier transport is involved, it is this capacitance of the modulator that limits the
bandwidth of the modulator. $R_s$ is due to contact resistance and other resistances
in the MQW, and is comparably small usually a few $\Omega$.

We define the bandwidth of the modulator as the frequency at which the power
of the electrical signal in an ideal detector has decreased by 3 dB compared to
low frequencies. This corresponds to a decrease in optical intensity modulation by
a factor $\sqrt{2}$ if the received signal current is proportional to the optical intensity,
which is usually the case in modern communication systems. Since the intensity
modulation can be considered linearly dependent on the modulator voltage, the
bandwidth of the modulator becomes

$$f_{3dB} = \frac{1}{2\pi RC}$$

(3.12)

where $R = R_g + R_s$, see Fig. 3.2. The bandwidth of the transmitter can be
considerably improved by employing a shunt resistance, $R_{sh}$. But for a given driver,
this is at the expense of valuable modulation voltage. In our papers we present the
bandwidth without any shunt resistor (i.e. using Eq. 3.12) setting $R$ to the common
50$\Omega$. 

Figure 3.1: Schematic picture of lumped modulator.
3.3. DEVICE DESIGN

Figure 3.2: Model of modulator-driver circuit. The modulator is electrically modeled as a capacitance, $C$, in series with a small resistance, $R_s$. To improve the bandwidth a shunt resistance, $R_{sh}$ can be employed at the expense of modulation voltage.

Traveling wave devices

When deploying the structure in a real modulator much can be gained by considering the high-frequency properties of the device. By employing a so called traveling wave design of the modulator, where the applied electric field travels in conjunction with the optical field the modulator is no longer a lumped, RC-limited, device but can rather be seen as a piece of transmission line, resulting in a substantial improvement of the electrical properties of the modulator.

The traveling wave design has successfully been introduced in interband electroabsorption modulators [23]. Lumped interband modulators are typically RC-limited to bandwidths of roughly 40 GHz while it seems possible to push the bandwidth above 100 GHz employing a traveling wave design [24]. It is therefore natural to expect that IS based modulators also would benefit from such a device design resulting in further improvement of modulator bandwidth. The bandwidth of interband traveling wave modulators has been found to be partly restricted due to a limited conductivity of the p-doped layer in the p-i-n structure [25]. Noteworthy is that no p-doping is necessary in an IS modulator and an IS based traveling wave modulator would thus not suffer from such a limitation.

Since a traveling wave design would allow a longer modulator, the heating [14] and the saturation effects (paper C) can be even further reduced.
CHAPTER 3. INTERSUBBAND MODULATORS

Alternative waveguides

In conventional modulators a confined optical mode is achieved by having a waveguide surrounded by a cladding with a slightly lower refractive index.

For long wavelengths the confinement can be improved by using a surface plasmon waveguide. A surface plasmon is an electromagnetic surface wave propagating at the interface between two materials having different signs of the dielectric constant (e.g. metal and semiconductor) [26]. Only a TM mode exists and the mode profile is an exponentially decaying amplitude on both sides of the surface (Fig. 3.3). In the case of a metal-semiconductor interface, the mode decays much more rapidly in the metal resulting in a significantly smaller penetration of the metal. A surface plasmon waveguide is easily achieved by simply applying a metal cladding on top of the quantum well structure. A metal has of course large losses but at the long wavelengths and short modulator lengths studied in Paper A the losses are acceptable. Another problem of a plasmon waveguide is the coupling of the light into the modulator. Although there are solutions to this problem involving prisms or gratings [27], the most effective way would be to integrate the modulator with a quantum cascade laser having a surface plasmon waveguide.

The loss in a metal plasmon waveguide increases as the wavelength is reduced making them impractical for 1.55 \( \mu m \). It is instead possible to use a so called plasma effect waveguide [28]. By high doping, the refractive index of the cladding material can be reduced significantly hence increasing the mode confinement and consequently the overlap between the optical mode and the active layer. Care must however be taken since a large doping also results in increased loss due to free carrier absorption.

3.4 Active layer design

Given the necessary tools to calculate the optical properties of the QWs as well as the parameters of interest in a complete modulator as presented above, we can
3.4. ACTIVE LAYER DESIGN

simulate the performance of an intersubband modulator. In papers A-C we present the performance of specific modulator designs to illustrate the capacity of IS based modulators and to show the potential to achieve a high performance device. The presented modulators are optimized in the sense that they are designed to have high bandwidth at a reasonably low voltage swing while at the same time not sacrificing any other vital parameter such as insertion loss or chirp. Designing a modulator for a more specified application makes the criteria for optimization more well defined and although the examples in the papers are illustrative, the most important thing is understanding how the different parameters are connected and the trade-offs that have to be considered between different parameters.

In order to reduce the complexity of the parameter regime, it is convenient to specify a required extinction ratio and only study the trade-off between bandwidth and applied voltage. Both parameters are quite important for high speed application since it becomes increasingly difficult to generate a large voltage swing at high bandwidths. From a design point-of-view there are two parameters, the number of quantum wells, \( n_{\text{well}} \), and the length of the active layer, \( L \), that affect the bandwidth and the required peak-to-peak voltage, \( V_{pp} \). When discussing trade-offs it is relevant to assume that the modulation of the electric field across the QWs is optimized and held constant when varying other parameters. Further, the overlap between the optical mode and the active layer is assumed to be proportional to the number of QWs. This is a valid assumption if the width of the optical mode is much larger than, and independent of, the width of the active layer. For interband modulators, on the other hand, the active layer often constitutes the waveguide making such an assumption invalid. For a fixed extinction ratio, there is a trade-off between high bandwidth and small \( V_{pp} \), as noted in paper A. The relation

\[
C \sim \frac{1}{V_{pp}^2}
\]  

(3.13)

is readily obtained by assuming a change in \( n_{\text{well}} \) (or \( L \)) and considering the effect on \( L \) (or \( n_{\text{well}} \)), \( C \) and required \( V_{pp} \).

In paper A an additional important design issue for the quantum interference modulator is discussed, namely the width of the barrier separating the coupled wells. A wide barrier reduces the energy difference of the two lowest levels at anticrossing and increases the change in oscillator strength with applied field. This would be beneficial for the modulation strength but the absorption linewidth limits the minimum energy difference since the absorption peaks has to be resolved.

Chirp is a parameter that is highly affected by the design of the QWs. This is realized from Eq. 3.11 and the fact that the change of absorption with electric field is strongly dependent on the QW design. Any change in absorption results in a change in refractive index realized through Kramers-Kronigs relations. For transmission over standard single-mode fiber, a negative chirp is beneficial since it counters the dispersive broadening of the fiber. Comparing different plots of absorption spectra in papers A-C it is evident that there is a great possibility to
affect the changes in absorption and consequently also refractive index simply by designing the QWs properly. In Fig. 4 of paper C it is shown that a negative chirp is achieved at high transmittance. In contrast, the step-like absorption spectra of interband modulators offers only limited possibilities to modify the chirp resulting in negative chirp only at large negative bias with the simultaneous large insertion loss.

### 3.5 Performance limitations

The perhaps most important limitation of the performance of an IS modulator is imposed by the absorption linewidth. The implications of the linewidth on modulator performance is apparent in that a reduced absorption linewidth, $\Gamma$, increases the peak absorption. In fact in paper A we find by simple reasoning that for a quantum interference modulator

$$C \sim \Gamma^3.$$

hence for a given voltage swing, a reduction of $\Gamma$ by e.g. a factor of 2 results in a reduced capacitance by a factor of 8 since the device length can be reduced together with a simultaneous increase in active layer thickness.

In [2] the same relation was found for an IS based Stark effect modulator by the following argument. A reduced $\Gamma$ increases the absorption strength allowing a decreased modulator length. Simultaneously the electric field modulation can be reduced (since a smaller shift of the absorption peak is necessary) allowing an thicker active layer (more QWs) for a given voltage swing. The result is a further reduction in modulator length. The capacitance reduction due to the decreased length and increased active layer thickness follows the same relation as in equation 3.14.

Given the short relaxation times of excited carriers and the fact that there is no carrier transport involved in the IS modulators, saturation of the absorption does not appear to be a major concern. Still, it is of course interesting to estimate the saturation effect. To avoid saturation, the excitation rate of electrons in the ground state must be much less than the IS relaxation rate. The saturation intensity of a two-level system is [29]

$$I_s = \frac{\hbar \omega}{2 \sigma T_1},$$

where $T_1$ is the IS relaxation time and $\sigma$ is the absorption cross-section. Relating the saturation intensity to the saturation power, $P_s$ of the modulator we get equation (1) of paper B allowing $P_s$ to be calculated. For the InGaAs/InAlAs/AlAsSb modulator in paper C, $T_1$ is of the order of 2 ps resulting in a saturation power of 50 mW. For a GaN based modulator the relaxation time is of the order of hundred fs resulting in a saturation power of several Watt. Noteworthy is that a traveling wave
modulator design would allow an increased modulator length and a consequently a reduced modal absorption, $\alpha_m$ significantly increasing the saturation power.

### 3.6 Simulated results

Let us now briefly summarize the results obtained from simulations on specific modulator structures.

For mid-IR applications, there are quite a few mature III-V materials to choose from. Depending on the exact wavelength regime of interest one may be more suitable than another but in all, the results from simulations on different materials are quite similar. In paper A an AlGaAs/GaAs modulator based on quantum interference modulator in 6 double quantum wells is analyzed. A modulation bandwidth of 130 GHz with $V_{pp} = 0.9\text{V}$ is predicted. Similar performance was attained for a Stark effect modulator with an active layer of 8 InGaAs/InAlGaAs/InAlAs step QWs (Paper B, see also [2]). The main uncertainty of performance lies in the assumed absorption linewidths as realized from Eq. 3.14, but in the simulations values on $\Gamma$ were taken from experimental results on similar structures.

For telecommunication wavelengths ($\lambda \sim 1.55\ \mu\text{m}$) materials offering a large conduction band offset ($\sim 2\ \text{eV}$) are required, making it necessary to consider more immature materials. In Paper C we propose a modulator with an active layer of 4 periods of InGaAs/InAlAs/AlAsSb coupled quantum wells where modulation is achieved by a combination of Stark effect and quantum interference. The calculated performance of such a modulator is quite competitive compared to state-of-the-art interband electroabsorption modulators with a bandwidth of 90 GHz and a voltage swing of 2.0 V. Note that this simulated IS modulator is a lumped device, while interband modulators with such large bandwidths have a traveling wave design.

Another material offering IS transition at 1.55 $\mu\text{m}$ is Al(Ga)N/GaN. In paper B a step QW structure is briefly considered assuming a rather pessimistic linewidth of 120 meV. Still the performance is comparable to that of interband modulators.

In our experimental work on single AlN/GaN quantum wells we have achieved linewidths below 100 meV (paper E,F) comparable to other published results [30, 31]. The expected performance of AlGaN/GaN modulators assuming a linewidths of 100 meV is similar to that of the antimonide based ([14]).

### 3.7 Materials

Following the discussion about linewidth and conduction band offset is the importance of material choice. The desired wavelength sets a condition on the smallest conduction band offset. In the range of materials fulfilling this condition, the choice of material is the one offering the smallest absorption linewidth which most likely is that which offers the best material quality (i.e. interface roughness, well-width fluctuations etc).
For mid-IR applications, (~ 4-12 \( \mu m \)), conventional III-V materials are an attractive choice. By conventional we mean III-V materials commonly used in commercial lasers, detectors, etc. These mature III-Vs consequently offer quite good material quality. Examples of such material combinations are AlGaAs/GaAs (paper A) or InGaAs/InAlAs (paper D).

Reaching shorter wavelengths, more specifically \( \sim 1.55 \mu m \) it becomes necessary to consider materials with larger conduction band offset which however is less mature in the context that they have not been equally investigated and developed resulting in a lower material quality. Unfortunately it also becomes increasingly important with material quality at shorter wavelengths since the quantum well width has to be smaller to enable a larger energy separation of the bound states. The energy levels in a well that is only a few monolayers thick is naturally more sensitive to fluctuations on the monolayer scale than in a well being tens of monolayers thick.

AlGaN/GaN is an example of a large conduction band offset material promising for IS modulators operating at 1.55 \( \mu m \). A complication with the III-nitrides (in the wurtzite structure) is the strong built-in fields due to a substantial spontaneous polarization as well as strain induced polarization. Another problem is the lack of low cost, high quality GaN substrates but fortunately there are other alternatives such as Si(111) and sapphire. The experimental results on AlN/GaN structures in this paper is from growth on sapphire substrates, and the best results are from growth on templates (where a thick GaN layer is grown on the sapphire substrate by MOVPE). In paper B a nitride based IS modulator is considered theoretically and papers E and F report on our experimental results.

Another promising alternative for short wavelength modulation is InGaAs/AlAsSb and IS absorption at a wavelength as short as 1.35 \( \mu m \) has been measured [32]. An advantage of the antimonide based structures is that they may be grown lattice matched to InP which may prove useful for integration purposes. A problem is the difficulty to achieve high quality interfaces at high doping densities due to doping induced interdiffusion [33]. In paper C an antimonide based modulator is analyzed.

Short wavelength IS absorption has also been shown in ZnSe/BeTe QWs [34].

3.8 Growth and processing

So far we have focused on simulations and theoretical predictions of IS absorption. Following is a description on the experimental work.

Growth

Growth of QW structures can be performed by either Metal-Organic Vapor-Phase Epitaxy (MOVPE) or Molecular Beam Epitaxy (MBE).

In MOVPE, growth is carried out in gas phase, where the desired atoms are deposited by chemical reactions of organic compounds or metal hydrides at the semiconductor surface. In contrast, in MBE growth occurs by physical deposition
3.9 METHODS OF CHARACTERIZATION

of the atoms in ultra-high vacuum. The source material is evaporated and then condensed on the wafer.

MBE is considered to allow better control of the layer thicknesses (on the monolayer scale) and to give abrupt hetero-interfaces. The lower growth temperature also reduces atom diffusion across the interfaces. A well defined and controlled QW thickness becomes increasingly important for the narrow quantum wells necessary for transition energies at 800 meV ($\lambda = 1.55 \, \mu m$) making MBE the natural choice for these structures.

For IS transition energies in the mid-IR range, MOVPE is still an attractive alternative, and in paper D the growth was made with MOVPE.

For Al(Ga)N/GaN growth it turns out that MOVPE offers a solution to the substrate problem. Since commercial GaN-substrates with low dislocation densities have become available only recently, growth is most commonly carried out on sapphire substrates. By first growing a thick GaN layer by MOVPE on the sapphire substrate before growing the QW stack with MBE the material quality is increased resulting in reduced absorption linewidth and increased absorbance (paper F).

Processing

There is no need for any processing when simply characterizing the grown material and the IS absorbance spectra. But in order to analyze the change in absorption under the application of an electric field (the electroabsorption) some simple processing is necessary in order to apply electrodes.

For the InGaAs/InAlGaAs/InAlAs structure characterized in paper D, standard processing was carried out in order to achieve a bottom contact. After lithography, dry-etching and metallization contacts on top of and below the active layers were attained allowing application of a voltage across the wells (Fig. 3.5). For the AlN/GaN material, similar processing was carried out. However it was found that leakage current in large area devices was considerable due to a substantial density of screw dislocations. Consequently electroabsorption characterization was not possible. This problem is expected to be suppressed in real modulators having significantly smaller area while the material quality also is continuously improved.

A more advanced design and more process steps are necessary in order to manufacture modulators operating at high frequencies. In this thesis we only report on characterization of electroabsorption but processing of high-frequency modulators is in progress.

3.9 Methods of characterization

In simulations and theoretical calculations, it is relatively straightforward to determine what affects the IS transition energy (quantum well width, barrier height, effective mass etc). When characterizing grown material it is important to analyze what has actually been grown in order to enable any comparison with theory. Furthermore, sometimes additional complications arise due to uncertainties in some of
the involved physical processes during growth, such as the relaxation behavior of GaN/AlN as discussed in paper E. Consequently there are a number of different methods of characterization that are important.

From a material perspective, X-ray diffraction is the single most important tool of characterization yielding information on the dimensions as well as quality of the grown layers. Other valuable tools include atomic force microscopy, photoluminescence measurements, transmission electron microscopy, etc.

However, what ultimately decides the performance of an IS modulator is the shape and strength of the absorption peak. In that respect, measuring the absorption spectra is perhaps the most important tool of characterization.

**Absorption measurements**

In dispersive spectroscopic techniques, the wavelength is scanned using e.g. a grating and the intensity for each wavelength is measured individually. Superior to the dispersive techniques in many ways is Fourier-transform infrared (FTIR) spectroscopy which allows a quick and more sensitive measurement of the spectra. In a FTIR spectrometer the light from a spectrally wide source passes through an interferometer with a moving mirror. The result is a so-called interferogram which can be viewed as a Fourier transform of the light source spectra. The output passes through the sample and the intensity as function of mirror position is measured. The spectrum is then calculated by performing a Fourier transform of the measured interferogram, consequently moving from the time domain back to the frequency domain.

When characterizing the absorption in the QWs a so called multi-pass waveguide geometry is used (Fig. 3.4). No time-consuming waveguide processing is necessary. A piece of the wafer is cut (typically 5 x 7 mm) and the bottom is polished and two opposite edges are polished in a 45° angle. This geometry allows a beam incident on one of the beveled edges to be internally reflected several times and finally leaving the sample at the other beveled edge after multiple passages through the QW stack. An advantage of the multi-pass waveguide is consequently an increased interaction with the active layer resulting in a stronger measured peak. The drawback is that any differences in refractive index between epitaxial layer and substrate, which is the case for AlN/GaN on sapphire, cause extra reflections resulting in an interference pattern in the absorption spectra. This interference pattern can be suppressed by measuring at an angle larger than the 45° corresponding to normal incidence to the beveled edge resulting in fewer internal reflections and a weaker interference pattern at the expense of a more difficult alignment.

When evaluating the samples, it is usually only the IS absorption that is of interest. An effective way of isolating this is to normalize with a reference and calculating the absorbance as

$$A = -\log_{10} \frac{T_{\text{sample}}}{T_{\text{reference}}}$$  \hspace{1cm} (3.16)
Figure 3.4: Geometry of a multi-pass waveguide. Light is incident on a beveled edge and exits the sample after multiple internal reflections increasing the interaction with the active layer. Only light with an electric field component orthogonal to the QW plane experience IS absorption.

where \( T_{\text{sample}} \) and \( T_{\text{reference}} \) is the measured transmission spectrum of the sample and the reference, respectively. The reference is ideally an identical sample with the same quantum well structure but without any doping, hence the IS absorption is isolated. However, generally it is sufficient to use a substrate without epitaxial layers as reference. Since IS absorption occurs only for TM polarized light, i.e. light with the electric field in the growth direction, it is also possible to use TE polarized light through the same sample as reference. However any polarization dependence of the light source, mirrors etc must be compensated for by introducing a correction to Eq. 3.16.

**Electroabsorption measurements**

Once an intersubband absorption peak has been found it is of course interesting to characterize the absorption change with applied electric field (electroabsorption). It is straightforward to do this in a multipass waveguide by applying contacts on top of and below the QW stack, Fig. 3.5. An alternative would be to process a complete ridge-waveguide modulator structure. The benefit of a contacted multipass waveguide is that the processing is fairly easy and absorption measurements can be performed by FTIR. The drawback is that no high-frequency measurements can be performed with a multi-pass waveguide. For materials with small conduction band offset it is also necessary to perform electroabsorption measurements on multipass waveguides at low temperature in order to avoid leakage current due to thermionic emission, (see paper D). For the nitrides we have also found that the low material quality and high dislocation density yields large leakage currents in such a large area component making a ridge-waveguide structure the best choice for electroabsorption characterization of Al(Ga)N/GaN QWs.
3.10 Experimental results

Given all the necessary tools to characterize the grown quantum wells we may validate the theoretical models through experimental studies.

**InGaAs/InAlGaAs/AlGaAs**

For mature III-V material systems, the material properties are well known from literature and growth is well controlled. Consequently less uncertainties lie in the input parameters used in calculations. In paper D the Stark shift in InGaAs/InAlGaAs/AlGaAs step QWs is characterized in a multipass waveguide. It is found that due to the leakage current in this large area device, the measured Stark shift is smaller than calculated (Fig. 4 in paper D). Still, in this multipass geometry an absorption modulation of 6 dB was measured at a low voltage swing of ±0.5 V. The results imply that it should be possible to realize a modulator based on this structure with a bandwidth of ∼ 90 GHz requiring a peak-to-peak voltage of only 0.9 V.

**AlN/GaN**

When growing less mature materials, such as the nitrides considered in papers E and F, additional challenges arise. Great effort has been put into developing a stable growth process allowing well-defined and narrow QWs of sufficient quality. The uncertainties in material properties (conduction band offset, material polarization etc) together with uncertainties in material quality (interface quality, doping levels etc) make systematic examination of the dependence of growth parameters on the intersubband absorption necessary. In papers E and F we present such studies.

We found that not only the well width affects the IS transition energy, but also the barrier width since it greatly affects the strain-induced electric field in the well. This dependence is stronger for narrow barriers.
3.10. EXPERIMENTAL RESULTS

Figure 3.6: FTIR absorption spectrum of a sample with 10 AlN/GaN QWs measured in a multipass geometry. The well and barrier widths are 2.8 nm and 4.1 nm respectively. (Sample S1372 from paper F).

Absorption linewidths of about 100 meV is repeatedly achieved for wavelengths around 1.55 µm, with the best result of 93 meV (Table 1 of paper F), which is comparable with other published results [30, 31]. Comparison with theoretical simulations (paper C and [14]) indicate that Γ ~ 100 meV is sufficient for a high performance IS modulator. For many samples it is also found that the absorption peak consists of several subpeaks. This is attributed to monolayer fluctuations where each subpeak corresponds to a specific local well-width. By performing a fit of a sum of Lorentzian peaks, each peak energy can be compared with a theoretical calculation of the transition energy for different well widths in discrete monolayer steps (see Fig. 6 in paper E). Encouraging agreement between measurements and calculations is found justifying our theoretical models. These subpeaks indicate that a further improvement of material quality, i.e. reducing well-width fluctuations, will allow improvement of the absorption linewidth.

Growing the QW stack on MOVPE grown GaN templates rather than directly on the sapphire substrate was found to significantly improve the material quality and consequently the strength and linewidth of the IS absorption peaks (paper F). In combination with a strong δ-doping, the resulting absorption peaks seem promising for modulator applications. In Fig. 3.6 the absorption spectrum of sample S1372 from paper F is plotted as an illustrative example showing a strong absorption with reasonable linewidth (~ 105 meV). The peak energy is 765 meV making it suitable for modulation at 800 meV (1.55 µm).

The experimental results so far is limited to single GaN wells with AlN barriers. Due to the strong built-in fields these single wells will experience a linear Stark-shift
of the transition between the ground and first excited state (see e.g. Fig 9 in paper E). But for an increased Stark effect, a step QW is preferable in a modulator.
Chapter 4

EIT Physics

4.1 Introduction

The term Electromagnetically Induced Transparency (EIT) was first introduced by Harris et al. [35]. As indicated by the terminology, EIT means that an otherwise opaque medium becomes transparent for an electromagnetic probe field by applying another strong electromagnetic control field. In conjunction with this transparency, the medium exhibits extremely low group velocity as well as other interesting phenomena such as enhanced nonlinear properties [36].

EIT is typically achieved in a three-level atomic-like system with two pairs of levels that are dipole coupled but the transition between the third pair is dipole forbidden. In Fig. 4.1a a so-called Λ-system is shown where the two lower levels are dipole coupled to a common upper level but without any coupling between the lower levels. EIT can also be observed in a V-scheme (Fig. 4.1b) or ladder-scheme (Fig. 4.1c). We will focus on the Λ-system which is the most studied case, both theoretically as well as experimentally.

A simple understanding of the origin of the transparency is gained by considering

![Energy level schemes for EIT](image)

Figure 4.1: Energy level schemes for EIT: a) Λ, b) V and c) ladder
Figure 4.2: The Λ-system, where the highest energy level is coupled to two lower meta-stable levels. The Rabi frequency of the control (probe) field is denoted $\Omega_c$ ($\Omega_p$) while $\delta_c$ ($\delta_p$) is the detuning of the control (probe) field.

the Λ-system, Fig 4.2. The absorption spectra of the probe field without any control field consists of a single Lorentzian peak at the frequency $\omega_{ab}$ (Fig. 4.3). When applying a strong resonant control field two dressed states are created with a splitting equal to the Rabi frequency of the control field, $\Omega_c$ [37]. The absorption of a resonant probe field is then canceled by interference between the two dressed states. The absorption spectrum of the probe field consequently consists of two peaks with a separation equal to $\Omega_c$ with transparency at resonance (Fig. 4.3).

4.2 Maxwell-Bloch equations

For a more comprehensive description of EIT it is necessary to consider in detail how the electromagnetic fields interact with the three-level system in the medium. We use the density matrix, $\rho$, to describe the state of the system, where

$$\rho_{ij} = \langle i | \rho | j \rangle. \quad (4.1)$$

The diagonal elements, $\rho_{ii}$, represent the probability of being in state $i$, while the off-diagonal elements $\rho_{ij}$ describe the atomic polarization. The time evolution of the density matrix is given by the equation of motion

$$\frac{\partial \rho_{ij}}{\partial t} = -\frac{i}{\hbar} [H, \rho_{ij}] - \gamma_{ij} \rho_{ij} \quad (4.2)$$

where we have introduced a relaxation rate $\gamma_{ij}$ including all contributions (population relaxation, dephasing etc) to the decay of $\rho_{ij}$. The Hamiltonian of the three-
4.2. MAXWELL-BLOCH EQUATIONS

Figure 4.3: Real (thin lines) and imaginary (bold lines) parts of the susceptibility as function of probe field detuning, $\delta_p = \omega_p - \omega_{ab}$, for a $\Lambda$-system (see Fig. 4.2). Dashed lines represent susceptibility without any control field applied while the solid lines represent susceptibility with a control-field strength $\Omega_c = 4\gamma_{ab}$.

level system in Fig. 4.2 can be written as $H = H_0 + H_1$ where $H_0$ is the Hamiltonian for the bare "atom" and $H_1$ for the interaction with the electromagnetic fields. In the rotating wave approximation (i.e. neglecting terms far off resonance) the total Hamiltonian becomes

$$H = \begin{pmatrix} E_a & h\Omega_{ba} & h\Omega_{ac} \\ h\Omega_{ab} & E_b & 0 \\ h\Omega_{ca} & 0 & E_c \end{pmatrix}$$ \hspace{1cm} (4.3)

where $\Omega_{ij} = \varphi_{ij}\mathcal{E}_{ij}/\hbar$ is the Rabi-frequency for the $i-j$ transition, $\varphi_{ij}$ is the dipole matrix element, $\mathcal{E}_{ij}$ is the amplitude of the optical field resonant with the $i-j$ transition. $E_i$ is the energy level of the bare atom.

The connection between electromagnetic field and the response of the medium lies in the polarization of the medium

$$P = N\varphi_{ij}\rho_{ji}. \hspace{1cm} (4.4)$$

and the wave equation

$$c^2 \nabla^2 \mathcal{E} - \frac{\partial^2 \mathcal{E}}{\partial t^2} = \frac{1}{\varepsilon_0} \frac{\partial^2 P}{\partial t^2} \hspace{1cm} (4.5)$$

where $N$ is the density of excitation centers (atoms, quantum dots, etc) and $P$ is the polarization of the medium. Combining equations 4.2 and 4.5 we get the Maxwell-Bloch equations, a powerful set of equations describing the interaction between the electromagnetic fields and the medium. In a rotating frame (i.e. introducing
\[ \dot{\rho}_{ij} = \rho_{ij} \exp(\omega_{ij} t) \] and employing the slowly varying envelope approximation we explicitly get

\[ \frac{\partial \hat{\rho}_{aa}}{\partial t} = \text{Im} \left[ \Omega_p^{*} \hat{\rho}_{ab} + \Omega_c^{*} \hat{\rho}_{ac} \right] - \gamma_{aa} \hat{\rho}_{aa} \quad (4.6) \]

\[ \frac{\partial \hat{\rho}_{bb}}{\partial t} = -\text{Im} \left[ \Omega_p^{*} \hat{\rho}_{ab} \right] + b_{ab} \gamma_{aa} \hat{\rho}_{aa} + \gamma_{cc} \hat{\rho}_{cc} \quad (4.7) \]

\[ \frac{\partial \hat{\rho}_{cc}}{\partial t} = -\text{Im} \left[ \Omega_c^{*} \hat{\rho}_{ac} \right] + b_{ac} \gamma_{aa} \hat{\rho}_{aa} - \gamma_{cc} \hat{\rho}_{cc} \quad (4.8) \]

\[ \frac{\partial \hat{\rho}_{ab}}{\partial t} = -\frac{i}{2} \left[ \Omega_p (\hat{\rho}_{aa} - \hat{\rho}_{bb}) - \Omega_c \hat{\rho}_{bc} \right] - \gamma_{ab} \hat{\rho}_{ab} \quad (4.9) \]

\[ \frac{\partial \hat{\rho}_{ac}}{\partial t} = -\frac{i}{2} \left[ \Omega_c (\hat{\rho}_{aa} - \hat{\rho}_{cc}) - \Omega_p \hat{\rho}_{bc} \right] - \gamma_{ac} \hat{\rho}_{ac} \quad (4.10) \]

\[ \frac{\partial \hat{\rho}_{bc}}{\partial t} = -\frac{i}{2} \left[ \Omega_c \hat{\rho}_{ab} - \Omega_p \hat{\rho}_{ac} \right] - \gamma_{bc} \hat{\rho}_{bc} \quad (4.11) \]

By formulating Eq. 4.6 - 4.12 in a simulation program in a spatial grid, complex two dimensional pulse propagation can be simulated as in paper G and H.

### 4.3 Susceptibility

Although powerful, the Maxwell-Bloch equations are quite complex to handle and simulations based on them can be time consuming. For situations with time-varying control field, such as storing pulses, they are necessary (although alternative approaches have been suggested [38]). For a static control field it is often sufficient to describe the medium by its susceptibility. Studying the susceptibility is also illustrative since it enables a simple interpretation of the response of the medium. Although the slow propagation of the probe pulse can be understood from the Maxwell-Bloch equations (see Eq. 27-28 in paper G), the susceptibility offers a more comprehensive analysis of the medium bandwidth.

The susceptibility, \( \chi \), is defined as

\[ \mathcal{P} = \epsilon_0 \mathcal{E} \chi \quad (4.14) \]

where \( \mathcal{P} \) is the slowly varying envelope of the polarization [39] and is given by

\[ \mathcal{P} = 2N \phi_{ab} \rho_{ab} \quad (4.15) \]

\( \rho_{ab} \) is given by the Maxwell-Bloch equations.
4.3. SUSCEPTIBILITY

From eq. 4.14 and 4.15 the susceptibility can be expressed as function of $\Omega_c$ and $\rho_{ab}$. Since we are considering the steady state situation, we may set $\partial \rho_{ij}/\partial t = 0$ in the Maxwell-Bloch equations and explicitly write the susceptibility as

$$\chi = -\kappa \frac{\delta_p + i\gamma_{bc}}{(\delta_p + i\gamma_{bc})(\delta_p + i\gamma_{ab}) - \frac{\Omega_c^2}{\Omega}}$$

(4.16)

where we have introduced a material constant

$$\kappa = \frac{N|\rho_{ab}|^2}{\epsilon_0 \bar{\hbar}}.$$  

(4.17)

and the detuning of the probe field, $\delta_p = \omega_p - \omega_{ab}$ as illustrated in Fig. 4.2. The control field is assumed to be on resonance, i.e. $\delta_c = 0$.

In papers G, H and I we use the notation of the relaxation rates and decoherence rates as described above, while in paper J a different definition is used, to emphasize the mechanisms behind the decoherences (see Fig. 1 in J). The population decay rates are described in the same way although the notation differs between the papers. Instead the difference lies in the description of the decoherence rates. In many papers, including paper G, H and I, the underlying mechanisms for loss of coherence between two states are ignored and instead a total “dephasing” rate or decoherence rate $\gamma_{ij}$ is defined which simply describes the total rate at which the coherence is lost. This is a convenient description when experimental values of the dephasing rates are used to determine the susceptibilities. Usually experimentally determined dephasing rates are the sum of the loss of coherence due to population relaxation and "population conserved" dephasing (pure dephasing). But in paper J the decoherence due to relaxation and decoherence due to pure dephasing are considered separately resulting in an expression of the susceptibility that explicitly shows this dependence (Eq. 1 in paper J).

As mentioned above, the susceptibility allows us to predict many properties of the EIT medium with a constant control field. Usually we are interested in the pulse propagation in an EIT medium. The pulse shape after propagating a distance $z$ in a dispersive absorbing media is given by

$$\mathcal{E}(z, t) = \mathcal{E}(0, t) \cdot e^{i\beta z}$$

(4.18)

where $\beta$ is the propagation “constant”

$$\beta(\omega) = \frac{\omega n}{c} = \frac{\omega \sqrt{1 + \chi(\omega)/\epsilon}}{c}.$$  

(4.19)

Having $\beta$ it is possible to calculate the group velocity of a pulse with carrier frequency $\omega_0$ since (see e.g. [40])

$$\frac{d\beta}{d\omega} \bigg|_{\omega_0} = \frac{1}{v_g}$$

(4.20)
and we get the same result as from the Maxwell-Bloch equations (see paper G), namely

\[ v_g = c \frac{\Omega_e^2}{\Omega_e^2 + 2\omega_p \kappa}. \]  

(4.21)

Other important parameters, such as group velocity dispersion (GVD) and absorption can be derived from the susceptibility and paper I as well as paper J uses the susceptibility expressions to derive analytical expressions on the limitations of pulse propagation in an EIT media.
Chapter 5

Applications

5.1 Pulse propagation

From Eq. 4.21 or by simply looking at a plot of the real part of the susceptibility (Fig. 4.3) it is clear that the group velocity of the probe pulse is reduced with a reduced control field strength. This velocity reduction is however at the expense of the medium bandwidth since the separation of the absorption peaks is equal to $\Omega_c$. This limitation of the bandwidth of the medium is apparent since a pulse with a spectrum broader than the transparency window will naturally experience a large absorption of the frequencies outside of this window. But there are other limitations on the bandwidth of an EIT medium, such as group velocity dispersion (GVD) and the fact that the absorption within the window is frequency dependent. But before these factors are considered in greater detail (section 5.2) it may be instructive to clarify the difference between the static and dynamic control field and between medium bandwidth and pulse bandwidth.

Static control field

As a probe pulse enters an EIT medium, the group velocity is reduced at the medium boundary resulting in a spatial compression of the pulse. The temporal pulse-length is however not affected and consequently the pulse bandwidth is preserved. But after propagating in the medium the pulse may be distorted resulting in a change also in pulse bandwidth.

Dynamic control field

If a (slow) probe pulse propagates in an EIT medium and the (fast) control field is temporally ramped down, the group velocity of the entire pulse is simultaneously reduced. No spatial compression of the pulse occurs, hence the reduced group velocity results in an increased temporal pulse-length corresponding to a reduction of the pulse bandwidth.
Medium bandwidth and pulse bandwidth

Although it may be obvious we emphasize the difference between the pulse bandwidth and the medium bandwidth.

The pulse bandwidth is simply the bandwidth of the pulse. When entering an EIT medium, the pulse bandwidth is unchanged. The pulse bandwidth is however affected by a temporal change in control field since it (usually) means that the entire pulse experiences a simultaneous change in group velocity. Propagation in an EIT medium also affects the pulse bandwidth due to a frequency dependent absorption and/or due to GVD.

The bandwidth of the medium is often discussed when examining the usefulness of EIT for applications. By medium bandwidth we mean the maximum bandwidth a pulse propagating through the medium can have experiencing acceptable distortion, broadening and attenuation. This measure is quite dependent on how much pulse distortion and pulse attenuation that can be allowed.

5.2 Slow light

There is much effort put into the research field of slow light since there are a number of potential applications. A device where optical pulses can be delayed for a controllable time is of great interest for telecommunication applications. The application can be optical instead of electronical buffering of pulses arriving at a router, synchronization, etc. Today any optical buffering is done with long fiber loops, a bulky and inflexible solution.

Slow light can be realized in many ways, coherent population oscillations \[41\], microcavities, Bragg grating resonators, spectral hole-burning \[42\]. EIT offers a versatile solution to slow light since extensive pulse manipulation also is possible.

The bandwidth and length of the probe pulse can be manipulated by appropriately varying the control field \[43\]. If, for example, a probe pulse enters an EIT medium with a weak control field, it is spatially compressed but retaining its temporal width. If the control field then is increased, the velocity of the pulse increases while the compressed spatial width is preserved. Consequently the probe pulse exiting the medium has a reduced temporal width and an increased pulse bandwidth.

Bandwidth

One important measure for slow light applications is the bandwidth of the device. By studying Fig. 4.3 a rough estimation of the bandwidth of the media, \(\omega_{\text{media}}\) seems to be equal to the control field Rabi frequency, \(\Omega_c\), since the distance between the two absorption peaks equals \(\Omega_c\). As a first rough approximation this holds true, a pulse with a bandwidth greater than the transmission window will undoubtedly experience a strong absorption. In a more refined picture, the bandwidth of the medium becomes a quite complex parameter. First, it is necessary to define how
much distortion, broadening and attenuation of a pulse that has propagated through
the medium can be accepted. When this has been defined, the next step is to
consider the pulse propagation in the medium. The basis of the analytical analysis
of pulse propagation in paper I and J is an expansion of the propagation constant,
\( \beta \), similar to what is performed for propagation in optical fibers in many text
books (see e.g. [40]). Since \( \beta \) to a good approximation can be considered \( \sim \chi \) the
expansion is explicitly done for the susceptibility.

\[
\chi(\delta_p) = \chi_0(\delta_0) + \chi_1(\delta_0)\delta_p + \chi_2(\delta_0)\delta_p^2 + \chi_3(\delta_0)\delta_p^3 + O(\delta_p^4) \tag{5.1}
\]

It turns out that there are three factors limiting the bandwidth of the medium:

- Attenuation
- Frequency dependent absorption
- Group velocity dispersion

By attenuation we here mean that the pulse is simply attenuated but the pulse
shape is preserved. It is \( \chi_0 \) that is responsible for the attenuation and using the
notation of Eq. 4.16 it becomes

\[
\chi_0 = i\kappa \frac{\gamma_{bc}}{\gamma_{bc}\gamma_{ab} + \frac{\Omega_c^2}{4}} \tag{5.2}
\]

The attenuation is small if \( \Omega_c \) is large compared to the decoherence rates.

The frequency dependent absorption, apparent from the imaginary part of the
susceptibility (Fig. 4.3), results in a higher attenuation of the high-frequency com-
ponents of the pulse. The consequence is a bandwidth reduction and a temporal
pulse broadening. This frequency dependent absorption is easily modeled analyti-
cally by simply considering the second order term in the expansion of the suscep-
tibility (\( \chi_2 \)) and using a standard Fourier transform method [40] to calculate the
pulse bandwidth after propagation as is done in paper J.

Another pulse broadening or rather pulse distorting mechanism is the group
velocity dispersion (GVD). In Fig. 4.3 it can be seen that the real part of the
susceptibility is not exactly linear in the transparency window. Remembering equation
4.20 it is apparent that the group velocity is frequency dependent, i.e. different fre-
quency components of the pulse travels with different velocities, hence the pulse
is distorted and broadened. It is important to note that GVD in an EIT medium
diffs from that of a normal dispersive medium, such as a fiber, since here the
GVD is an odd function dominated by the third order term in the susceptibility
expansion, \( \chi_3 \). As a consequence the center frequency travels slower than the rest
of the pulse or faster than the rest of the pulse. The resulting distortion includes
a ringing tail as seen in e.g. Fig. 4 in paper I. In paper J it is shown that if
\( \Omega_c/\gamma_{aa} = 1 \) the third order GVD is equal to zero. In that case, higher order terms
of the susceptibility expansion have to be considered in order to describe the GVD.
This is however not necessary since pulse propagation will instead be limited by the frequency dependent absorption. Consequently it turns out that expanding the susceptibility to third order is sufficient to analytically investigate the bandwidth of an EIT medium.

Whether attenuation, frequency dependent absorption, GVD or a combination of them will limit the bandwidth depends highly on the chosen parameters. Analytically it is possible to study these bandwidth limitations individually which is important for predicting the bandwidth of an EIT medium.

In paper I and J we define the bandwidth by allowing the pulse width to increase by a factor 2. For the frequency dependent absorption this is a straightforward criterion since the broadening of a gaussian pulse can be analytically calculated from $\chi_2$. Calculating the pulse broadening due to GVD cannot be done analytically since GVD originates from the third order term, $\chi_3$. Instead we compare the propagation time for different frequency components of the pulse, relate this difference in propagation time to the pulse broadening and attain an expression for the bandwidth limitation due to GVD (Eq. 4 in paper I and Eq. 11 in paper J). Maxwell-Bloch simulations studying pulse broadening due to GVD have shown that this is a reasonable description of GVD limited bandwidth (paper I).

In paper I we study the situation of a strong control field, in particular $\Omega_c \gg \gamma$, and find that GVD or attenuation limits the bandwidth and do not consider frequency dependent absorption. A strong control field makes the imaginary part of the susceptibility relatively flat in the center of the transparency window suppressing the frequency dependent absorption. The simulated pulse shapes in paper I using the Maxwell-Bloch equations confirm this fact.

In paper J a different situation is studied with a more moderate control field and where the pure dephasing of the coherence between the two lower states is small compared to decoherence due to relaxation. Under these conditions it is found that the frequency dependent absorption has to be taken into account.

The results of the different papers converge when a strong control field is considered.

It is however clear from Eq. 6 in paper I and Eq. 7-10 in paper J that regardless of what limits the medium bandwidth, it increases with control field strength. On the other hand the delay time decreases (Eq. 4.21) with an increased control field strength. We have consequently two contradictory requirements on our slow light device; large delay time and large bandwidth. It is therefore useful to consider the product of these two quantities, the delay bandwidth product, as a measure of the performance of a slow light device.

**Delay bandwidth product**

The delay bandwidth product (DBP) is an important parameter when discussing the performance of a slow light device and is simply the product of the bandwidth and the delay time.
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\[
DBP = \text{delay time} \cdot \text{medium bandwidth} = t_{\text{delay}} \cdot \omega_{\text{medium}}.
\] (5.3)

and obviously a large DBP is strived for. It can also be related to the number of pulses that can be stored in a system (paper J). A closely related parameter sometimes used is fractional delay which is simply the delay time divided by pulse width \((t_{\text{delay}}/t_0)\) and is proportional to DBP.

If considering a real application the DBP would likely have to be maximized at a given bandwidth. In paper I and J, DBP is analyzed in conjunction with the bandwidth as described above. Similar parameter regimes are found where either the GVD, frequency dependent absorption or attenuation are limiting factors. In paper J an extensive analysis of DBP and limiting parameters are carried out. It is found that for a moderate \(\Omega_c\) (compared to \(\gamma\)), the frequency dependent absorption forms an upper limit of the DBP. This limit is independent of \(\Omega_c\). The GVD limits DBP for larger \(\Omega\) (see Fig. 4 of paper J). The analysis in paper J is carried out in normalized parameters allowing easy insertion of specific examples.

In paper I as well as paper J relevant parameters for atomic systems as well as potential semiconductor media are considered resulting in DBPs typically less than 100 for relevant bandwidths, depending on the exact assumed parameters. From an application perspective, this is a quite modest result raising relevant questions on whether EIT will be an alternative for optical buffering applications. For the situation of a strong \(\Omega_c\) where the frequency dependent absorption is small (paper I), the possibility of GVD compensation or other "tricks" may offer a solution. Compensating for frequency dependent absorption is also possible by introducing gain in the system, but this undoubtedly adds noise. Nevertheless, other applications for slow light in EIT, such as synchronization, are still of interest, and the analysis of bandwidth of DBP is to some extent general and highly relevant for other EIT applications.

Pulse compression

The limits on the bandwidth and delay time in EIT media is a central issue ultimately determining the feasibility of EIT based devices. Another interesting parameter studied in detail in paper I is the limit on pulse compression. Today photonic devices are relatively bulky due to the large lateral and transversal size of the optical pulses as well as a weak interaction with these pulses forcing long interaction lengths. Reducing the size of photonic devices is vital for the success of the same. Additionally, an increased integration in photonics requires the devices to be smaller than today which brings us to the concept of the spatial limit of an optical pulse. In EIT media, or any other slow light media for that matter, a pulse is compressed spatially upon entrance. The limit of this compression is tightly connected to the bandwidth discussion above, since a strong compression (i.e. small \(v_g\)) is followed by a reduced bandwidth. The limit of the spatial pulse compression is determined by the allowed distortion and the required propagation length. In-
Interesting to note is however, that a substantial compression is possible and in one example of paper I a 50 ps pulse is spatially compressed from 15 mm to roughly 50 \( \mu \)m and may still propagate 100 \( \mu \)m under acceptable distortion. In paper H where an EIT based serial to parallel converter is analyzed, the total device length is approximately 5 mm for processing of four 5 ps pulses.

### 5.3 Pulse storage and read-out

As mentioned above, not only is it possible to slow down a light pulse by EIT, but it is also possible to stop the pulse, store it for some time, and then release it again.

If a probe pulse is propagating in an EIT medium, it can be slowed down simply by reducing the control field strength. If the control field is turned off completely, the pulse is brought to a complete stop and stored as a coherent material excitation. When the control field is turned on again, the probe pulse is revived and continues to propagate.

A few things are worth emphasizing here. First of all it is not the photons of the probe field that are slowed down and stored, instead it is the coherence of the two lower states, \( \rho_{bc} \) in the \( \Lambda \)-system that is responsible for the storage. The pulse can be viewed as a superposition of a photonic pulse and a material excitation termed polariton [44, 45]. This is apparent in Fig. 2 and 5 in paper G where the amplitude of the probe pulse, \( E_p \), is plotted together with \( \rho_{bc} \) when storing and reading out a pulse.

Moreover, the storage time is limited by the decay rate of the \( |b\rangle \) and \( |c\rangle \) coherence. For atomic systems this means storage times typically on order of \( \mu \)s or more [46] but storage times longer than 1 s has been demonstrated in cold prae-sodymium doped crystals [7]. For semiconductors the situation is worse due to the large decoherence rates and so far storage of pulses has yet not been demonstrated experimentally in semiconductors.

This storage and read-out process has been studied extensively [47, 48] for the one-dimensional situation. In paper G we extend the pulse propagation and storage to a two-dimensional situation. This allows us to study the situation with a probe and control field having different propagation directions. In paper G we show that a stored pulse can be read out in a direction different from the original propagation direction. The key to this change in propagation direction before and after storage is found in the Maxwell-Bloch equations and the phase of \( \rho_{bc} \). When the pulse is stored, the spatial phase of \( \rho_{bc} \) is given by the difference in the probe field and control field k-vectors.

\[
\mathbf{k}_{bc} = \mathbf{k}_p - \mathbf{k}_c
\]  

(5.4)

The read-out control field can now be applied in any direction where the vector relation in Eq. 5.4 is fulfilled, reading out the probe pulse in a new direction. This can be viewed as a phase-matching condition which has to be fulfilled for the
5.3. PULSE STORAGE AND READ-OUT

Figure 5.1: Phase-matching condition for changing propagation direction at pulse read-out.

The probe pulse is distorted as a consequence of changing the direction of the control field and the finite group velocity difference between the probe- and the control-field. The part of the probe pulse first hit by the trailing edge of the control field slows down and stops first while the rest of the pulse continues to propagate until the whole pulse experiences a turned-off control field. If the direction of the read-out control field is not changed, this spreading is compensated by the corresponding compression when the pulse is read out. On the other hand if the control field direction is changed, the pulse is first broadened in the direction of the control field before storing and then compressed in the direction of the read-out control field. This effect is clear in Fig. 2 and 5 in paper G where the shape of the read-out probe pulse is skewed. The distortion can be reduced by having a slower switching time of the control field. If the group velocity difference between the control and probe field is large, which is the case for a weak control field, the distortion also becomes small.

The concept of changing the propagation direction of a probe pulse by the control field offers many exciting applications. In paper H we propose a serial to parallel converter based on this possibility, where a series of probe pulses are stored and read out orthogonally hence creating a serial to parallel conversion. The concept is quite simple and comprehensible and in paper H a complete Maxwell-Bloch simulation of a semiconductor based device is presented. The simulation shows that such a device is feasible although there are some issues to be resolved before realization. The problem of realizing EIT in semiconductors is perhaps the most challenging which brings us to the interesting area of different physical
realizations of EIT media.

5.4 EIT-Media

Atomic systems

Atomic systems are the most commonly used in EIT experiments. This is mainly due to their sufficiently long coherence times but also since atomic systems generally are quite well characterized. EIT has been shown in a variety of hot atomic systems vapors, such as lead [49], strontium [50] and rubidium [6]. The first observation of slow light in an EIT system was in an ultra cold gas of sodium atoms [5] where the group velocity was reduced to 17 m/s.

A complication arising in hot atomic vapors is the inherent doppler broadening. However, if the probe- and control-field are copropagating and the base of the $\Lambda$-system consists of two hyperfine split states EIT can be observed. Further, the influence of Doppler broadening is also small if the control field is strong [36].

Storage of pulses has also been carried out in praseodymium doped crystals [7].

Semiconductors

The atomic systems offer important possibilities to investigate the physics of EIT, they offer a tool for investigating concepts of applications and are the basis of many exciting experiment. But if any EIT based devices for telecommunication or other more voluminous applications are to become competitive, they will most likely have to be based on semiconductors. The main reason for this is cost. Semiconductors can be cost effectively manufactured in large volumes. But also flexibility and robustness are important. In the atomic systems, the energy levels and dipole moments are given by nature. In the semiconductors, we can design our quantum wells or quantum dots to match a desired wavelength or dipole moment. Moreover, these energy levels and dipole moments can easily be manipulated by applying a voltage and thus adding an extra feature. In atomic systems such tunability is much more difficult to achieve. The density of excitation centers is also larger in a semiconductor than in a gas or a doped crystal leading to more compact devices.

There are however a number of issues that have to be resolved before semiconductors are a realistic alternative for EIT devices. The main problem with EIT in semiconductors is the large dephasing rates. A large dephasing rate leads to a rapid loss of coherence limiting the storage time of a pulse as well as the group velocity reduction. In an ideal atomic system, the dephasing times are typically on the order of nanoseconds or more, enabling storage times of that magnitude. In semiconductors, dephasing processes are typically dominated by carrier-carrier and carrier-phonon scattering leading to considerably higher dephasing rates, $\sim 10^{11} - 10^{14}$ s$^{-1}$ [51].

There are a number of ways to achieve a three-level EIT-system in semiconductors. QW as well as QD bound states have been suggested but also excitonic three-level systems and spin-based systems are possible to use. In fact, the energy
levels in the double QW of the IS modulator in paper A can be viewed as a Λ system.

EIT in semiconductor QWs has been studied theoretically [52, 53] as well as shown experimentally [54, 55]. Although encouraging, the observed transparencies are still too weak to be practically used, at least in the applications we consider here. This is usually attributed to the short dephasing times of a few hundred femtoseconds associated with IS excitations. Recent results show however that the dephasing rate of the dipole forbidden transition can be significantly smaller than the other dephasing rates [56] which is promising since it is this dephasing rate that is most detrimental for EIT.

Although EIT has not yet been achieved in QDs, they seem promising as an EIT medium given their longer coherence times compared to QWs. At low T, interband dephasing times of a few hundred picoseconds have been observed [57] but with a strong temperature dependence resulting in subpicosecond dephasing times at room temperature. Using intersublevel excitations instead, room temperature dephasing times of several picoseconds has been reported [58]. The dephasing seem to be dominated by carrier interactions or impurity scattering. In a QD system it is also important to minimize the coupling between the different dots. Simulations have predicted that EIT in a QD system is distorted when many-body effects is taken into account and that too large dot densities should be avoided to reduce couplings between different dots [51].

In paper I and J we have included some numerical examples in our studies of pulse compression and delay bandwidth product. Realistic dot densities and dipole moments are easily assumed while achievable dephasing rates are more difficult to predict. A range of dephasing rates are therefore considered with the purpose to illuminate what requirements the applications put on the semiconductor medium.

Given the importance of long coherence times, it is interesting to consider alternatives to EIT in QW or QD bound states and promising results have been found using excitonic resonances [59] as well as the electron spin [60, 61].

Another problem arising with the usage of EIT in semiconductors is inhomogeneous broadening. Any inhomogenities in QD size, QW width, etc will introduce a detuning of the probe- and/or control-field (Fig. 4.2). But if the two-photon detuning is small, i.e. $\delta_\rho \approx \delta_\sigma$, the shape of the susceptibility is mainly preserved [36]. This would be the situation with dot-size fluctuations in an EIT medium based on QD intersublevels, a variation in dot size affects the transition energies similarly.

5.5 Simulations

The analytical relations derived in papers G,I and J yield an understanding in how different parameters scale with each other. These analytical expressions are valid under some approximations or in certain parameter regimes. In order to verify the validity of the analytical results, numerical calculations and simulations are
performed. Further, some situations cannot be analyzed other than by simulations (e.g. the device in paper H).

The simplest numerical calculations are the ones in which the susceptibility (Eq. 4.16) is used in standard Fourier-transform pulse propagation calculations. This method is however limited to situations involving a static control field.

A more complete analysis of the dynamics in an EIT system requires solving the Maxwell-Bloch equations (Eq. 4.6-4.13) providing information on the density matrix as well as the electromagnetical fields. We have developed a simulation program numerically solving the Maxwell-Bloch equations in two dimensions in the slowly-varying envelope approximation. Such a simulation tool is necessary in order analyze situations as storage and retrieval of pulses in different directions as well as other scenarios involving a time-varying control field.

5.6 Potential devices

There are a number of potential devices based on EIT. We have considered two of them, optical buffer/delay line (paper I,J) and serial-to-parallel converter (paper H).

The optical buffer is undoubtedly the most studied EIT application mainly due to the strong need for such a device for telecommunication purposes. Much of the analysis of optical buffers concerning bandwidth and DBP can be applied on other slow-light devices. Regarding the theoretical predictions as well as experimental results on EIT based optical buffers, it is apparent that many issues remain to be resolved before such a device is a reality. There is today a large gap between the desired performance set by system requirements and the experimental results regarding DBP. The main problem is the short coherence times of the different media considered.

Another telecommunication application is the serial-to-parallel converter proposed in paper H. Although the simulations predict that such a device is feasible and that it would be less complicated than a corresponding electronic one (at least for high bit-rates), the conclusions is also here that development of (semiconductor-) materials with long coherence times is necessary.

Other potential applications include pulse manipulation such as spatial and temporal compression [43], quantum information processing [62], optical memories [45] nonlinear applications [35].
Chapter 6

Discussion and conclusions

The most important areas for the development of photonic devices in telecommunication appear to be speed, functionality, size, power consumption and integration. In this thesis the first three of them are addressed.

In the field of developing high-speed optical transmitters, the current techniques of interband optical modulators have shown to be highly successful. Modulation speeds of 100 Gbit/s have been demonstrated. However, in order to further improve the performance of the modulators (increasing speed and reducing driving voltage) it appears necessary to improve the modulation mechanism rather than the already well developed device design. We have found that intersubband transitions offer such an improvement of the modulation mechanism. Simulations of complete modulator structures predict an increased bandwidth as well as a reduced driving voltage. Experimentally we have shown that our models can predict the absorption spectra and the absorption modulation supporting the results from simulations of complete devices. Although we have shown electroabsorption experimentally, a complete high-speed IS based modulator remains to be demonstrated.

For mid-IR applications, such as free space communication, IS modulators based on mature III-V materials are already a realistic alternative, since a sufficiently high material quality is achievable. Other intersubband based mid-IR devices such as quantum cascade lasers and QWIPs are already implemented.

However, for short wavelength applications (\(~ 1.55 \mu m\)) some work remains, mainly concerning material development. One question to be answered is what material system will offer the best performance. Much of our experimental work has focussed on Al(Ga)N/GaN, but the antimonide based structures (which we have treated theoretically) are also interesting. Due to the faster carrier relaxation rate in the nitrides, they promise superior saturation intensities. But another factor that may be decisive is the fact that the antimonide structures can be grown on InP substrates offering advantages in integration with lasers. Most important, however, is which material system produces the most narrow absorption linewidth.

The success of IS based modulators will mainly be decided by the achievable
absorption linewidth which in turn is limited by the attainable material quality. The experimental results show that the achieved linewidths and absorbances already would allow performance competitive with current state-of-the-art interband modulators. For the AlN/GaN MQWs we measure linewidths of \( \sim 100 \text{ meV} \) which has been predicted to be sufficient for a competitive modulator. But in order for IS modulators to compete with already well established technologies, it has to be better and consequently an improved linewidth is necessary. Improvements on linewidth seems plausible since much of the measured broadening can be attributed to well-width fluctuations and interface roughness and there is still room for improvements of growth. We have found that the absorption peaks in fact consist of several sub-peaks with transition energies corresponding to monolayer fluctuations of the well width and that these subpeaks have a linewidth of 60-70 meV.

Modulation of the IS absorption can be achieved with different mechanisms. Whether the choice of modulation mechanism will be Stark effect or quantum interference (or both) remains to be seen, but the decision will likely be based on the achievable linewidth and manufacturing.

The IS modulators simulated in this thesis are lumped devices, still the predicted performance is as good as or better than what is achieved in traveling wave interband modulators. Employing a traveling wave IS modulator will presumably enhance the performance further.

Given these promising features, it is likely that modulators with bandwidths exceeding 100 GHz will be based on IS transitions rather than interband transitions.

Regarding functionality, and also to some extent size, electromagnetically induced transparency (EIT) offer many exciting opportunities for photonic devices and we have touched upon some of them. We have focused on whether EIT is a realistic alternative for applications by investigating theoretically the limitations on bandwidth and delay bandwidth product. For optical buffers it is realistic to expect only relatively modest delay bandwidth products. Buffering large packets of data might therefore not be a potential application, but rather synchronization or other applications where buffering of more moderate numbers of bits is sufficient. Once again the material issue is central and the performance of EIT based buffers are ultimately limited by the decoherence rate of the material excitation. Although atomic systems offer the longest decoherence times, EIT devices will most likely have to be based on semiconductor materials since energy levels, dipole moments etc can be controlled. However, decoherence rates in semiconductor materials still are quite large which will limit the performance (bandwidth and delay) of such devices. Any major material breakthrough will revise these conclusions on EIT based optical buffers and given the rapid development in materials research this may very well happen. Another functionality considered, is coherent storage of optical pulses. We have shown that EIT offers the possibility of changing the propagation direction when reading out stored pulses and also presented simulations of a device based on this feature. Moreover, we have analyzed the limitations of spatial pulse compression in EIT media and found the similar bandwidth limitations as for optical buffers.
A common issue of the progress of IS modulators and EIT devices is materials and material quality. It is apparent that critical for the success of most devices is a well controlled and understood manufacturing process as well as a thorough understanding of material physics. By that it is not said that theoretical predictions and speculations are unimportant. On the contrary, without new ideas of applications based on different kinds of physical phenomena, there is less drive for material development.
Chapter 7

Summary of the original work

Here follows a brief description of the publications forming the basis of this thesis.

Paper A, "A High-speed intersubband modulator based on quantum interference in double quantum wells"

In this paper we propose an AlGaAs/GaAs based IS modulator operating at 8.4 $\mu$m. The modulation mechanism is quantum interference in double quantum wells and the optimization of the width of the middle barrier is discussed. A complete modulator structure with a surface plasmon waveguide is simulated and a RC limited bandwidth of 130 GHz is predicted at a voltage swing of 0.9 V. The importance of absorption linewidth for the performance of a quantum interference modulator is shown.

Contributions by the author of the present thesis: Modulator design, developing simulation program, performing simulations and writing the paper. The relation between capacitance and linewidth was derived by P. Holmström. The analysis of the modulator design was discussed by all authors.

Paper B, "Design of intersubband optical modulators"

This paper is a review of our theoretical work on the modulator designs including paper A and discusses the properties of IS modulators based on different modulation mechanisms. We also present some preliminary results from simulations on material systems allowing IS absorption at 1.55 $\mu$m including Stark effect in GaN/AlGaN/AlN step QWs and quantum interference in InGaAs/AlAsSb coupled quantum wells.

Contributions by the author of the present thesis: Simulations on InGaAs/AlAsSb QWs and some contributions to the writing. The paper was mainly written by U. Ekenberg.
Paper C, "High-speed optical modulator based on intersubband transitions in InGaAs/InAlAs/AlAsSb coupled quantum wells"

In this paper an IS modulator operating at 1.55 µm is proposed. The active layer consists of 4 periods of InGaAs/InAlAs/InAlAsSb double quantum wells. Modulation is achieved with a combination of Stark shift and quantum interference resulting in a negative chirp at high transmission. Assuming a realistic absorption linewidth results in a bandwidth of 90 GHz for a voltage swing of 2 V.

Contributions by the author of the present thesis: The design and simulation of the modulator. The paper was jointly written by P. Jänes and P. Holmström.

Paper D, "Strong electroabsorption using intersubband transition in InGaAs/InAlGaAs/InGaAs step quantum wells"

In this paper we experimentally characterize the Stark shift in InGaAs/InAlGaAs/InGaAs step quantum wells with IS absorption at $\sim 6$ µm. In a multipass waveguide an absorption modulation of 6 dB is measured at a low voltage swing of $\pm 0.5$ V. The results imply that it should be possible to realize a modulator based on this structure with a bandwidth of $\sim 90$ GHz requiring a peak-to-peak voltage of only 0.9 V.

Contributions by the author of the present thesis: Processing of the modulator, measurements and experimental analysis. Design and simulations were made by P. Holmström who wrote the paper with some contributions by P. Jänes.

Paper E, "Intersubband absorption at 1.5-3.5 µm in GaN/AlN multiple quantum wells grown by molecular beam epitaxy on sapphire"

In this paper AlN/GaN quantum wells with different barrier and well widths are characterized regarding material quality as well as IS absorption. It is found that not only the well width, but also the barrier width affects the IS transition energy since the barrier width influences the built-in fields. The IS absorption peaks are found to be made up of several subpeaks corresponding to monolayer fluctuations and an encouraging agreement with calculated IS transition energies are found. Further we find that the uniformity of the MQW over the whole wafer is good with a variation of IS transition energy less than 1.

Contributions by the author of the present thesis: Measurements, experimental analysis and parts of the writing. The systematic study was initiated and analyzed by all authors. Growth was performed by X.Y. Liu. Simulations by P. Holmström.
Paper F, "Investigation of intersubband absorption of GaN/AlN multiple quantum wells grown on different substrates by molecular beam epitaxy"

In this paper we show that the IS absorption strength as well as the linewidth are improved if the MQWs are grown on MOVPE grown GaN templates rather than on sapphire substrates. This is due to an improved crystalline quality confirmed by XRD measurements.

Contributions by the author of the present thesis: Measurements and experimental analysis. Some contributions to the writing. Growth was performed by T. Aggerstam and X. Y. Liu.

Paper G, "Propagation of two-dimensional pulses in electromagnetically induced transparency media"

In this paper we analyze two-dimensional pulse propagation in EIT media analytically as well as through simulations of the Maxwell-Bloch equations. It is shown that a stored probe pulse can be read out in a new direction, and a phase-matching condition for this change of direction is derived. Adiabatic and nonadiabatic pulse storage is compared, and it is found that a nonadiabatic switching of the control field results in a substantial pulse distortion.

Contributions by the author of the present thesis: Derivation of phase-matching condition for changing propagation direction of the probe pulse. Writing parts of simulation program. Simulations were performed by P. Arve who wrote the main part of the paper with some contributions by P. Jänes.

Paper H, "All optical serial to parallel converter utilizing electromagnetically induced transparency"

In this paper an optical to serial converter based on the findings of paper G is proposed. Simulations of storing a sequence of 4 gaussian pulses and reading them out orthogonally is presented. Parameters relevant for a semiconductor medium is used in the simulations indicating the feasibility of such a device.

Contributions by the author of the present thesis: Development of simulation program, performing simulations, the analysis of the results, and writing the paper. Original idea of achieving a serial to parallel conversion by reading out the pulses orthogonally was proposed by L. Thylén.

Paper I, "Limits on optical pulse compression and delay bandwidth product in electromagnetically induced transparency media"

In this paper we analyze the limitation on spatial pulse compression in EIT media as well as limitations on bandwidth and DBP. We show that for a strong control
field it is GVD and attenuation that are limiting factors.

Contributions by the author of the present thesis: Model for medium bandwidth and DBP. Performing simulations. Parts of the calculations. Writing of the paper. The analysis of the results was treated by all authors.

Paper J, "Delay bandwidth product of electromagnetically induced transparency media"

In this paper we present an extensive analysis of the limitations on DBP for slow light devices based on EIT. The treatment of the bandwidth limitation due to GVD is similar to the one in paper I, but in this paper we consider a situation with a weaker control field and find that we also have to take the frequency dependence of the absorption into account. Analytical expressions of the DBP are derived and analyzed and their validity is verified by Maxwell-Bloch simulations.

Contributions by the author of the present thesis: Performing simulations. The analysis and results were discussed jointly by all authors. The calculations and model was mainly developed by J. Tidström who also wrote the paper.
Bibliography


