Surface–normal multiple quantum well
electroabsorption modulators based on
GaAs–related materials

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Cover picture: Detail of a spatial light modulator illuminated by a monochromatic source.

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Abstract

Electroabsorption is the physical phenomenon by which absorption in a medium can be controlled by applying an electric field. The Quantum-Confinement Stark Effect, which makes the absorption band-edge in quantum wells very-field dependent, together with the strong absorption peak provided by excitons, are the reasons for the success of electroabsorption modulators based on quantum well structures.

This thesis describes the design and fabrication of surface-normal modulation devices. The techniques needed to understand the conception and fabrication of surface-normal, multiple quantum well-based optical modulators are introduced, as are the various characterisation techniques used during and after the fabrication.

Large-area modulators for free-space optical communication were developed, with an active area of 15mm×15mm and a modulation speed of several Megahertz. Contrast ratios up to 5:1 on full modulator areas were measured. Problems limiting the yield and modulation speed of such devices are presented and solutions are presented and demonstrated.

Two-dimensional arrays of 128×128-pixel amplitude modulators have been fabricated and characterised. Speeds of up to 11700 frames per second were observed, limited by the driving electronics.

The use of multiple quantum well optical modulators in a free-space optical retro-communication system has been studied and an opto-mechanical design for a modulating retro-reflector is described, allowing large field-of-view in one direction using reflecting, resonant-cavity modulators for high contrast-ratios.

Keywords: spatial light modulators, quantum wells, optical resonator, Fabry–Pérot, electroabsorption modulator, free-space optical communication.
Preface

The work presented in this thesis is the result of team work. It is presented as such in the body of the thesis, to keep the unity of the work. The author’s contributions are detailed below:

The author performed the modelling of all modulators presented, wrote the recipes for the structures and some calibration runs (sometimes with the assistance of the group in charge of the MOVPE). The characterisation of all freshly-grown modulator structures and most of the calibration runs, in particular for X-ray diffraction, Hall effect and spectrophotometry, was the responsibility of the author.

The author did not do any processing work and was seldom in the clean room, although he was heavily involved in discussions concerning process choices. Processing was done by Qin Wang, Susanne Almqvist and Daniel Ågren. The author usually took over the devices after fabrication for optical characterisation.

SIMS measurements were performed by a commercial company and interpreted with their help.

The work presented on large-area modulators, and in particular the solution to yield- and modulation speed-related problems is the result of a collegial work.

The characterisation of SLM is entirely the work of the author, with the exception of the driving electronics and some of the programming needed to drive the device.

The original idea for the modulating retro–reflector stemmed from Lars Sjökvist at FOI. The design work presented is entirely that of the author. The prototype delivered to FOI, however, is very much the result of group work.
Acknowledgements

The work presented in this thesis is the result not only of my own work and efforts, but also the fruit of intense collaboration work within Acero and with other entities.

First of all, I would like to thank Lars Thylén for accepting me as a PhD student. It has been a very interesting experience to have one foot in KTH and get to know the Swedish education and research world.

Jan Andersson accepted the responsibility of becoming my supervisor at Acero along with his duties as Department manager. I am grateful for his help, his advice and his time.

Bertrand Noharet has been my group manager, project manager and technical leader on a day-to-day basis. Bertrand, I really appreciated your leadership. You were here to encourage me and celebrate our successes. You also were here and listened to me when things were not so easy. I want to thank both the boss and the friend.

I am deeply indebted to Qin Wang, who has been a close colleague and one of the main driving forces behind our activities on modulators, overseeing the processing. I want to thank her for our technical and non-technical discussions, for pushing me again and again, and for teaching me some Chinese!

Daniel Ågren started working with us as a Master student before being employed at Acero. His dynamism and technical contributions have been a driving force for our modulator activities.

Susanne Almqvist deserves my thanks and apologies. She has been amazing in the clean room, doing a lot of meticulous work. He has also saved the situation more than once, fixing the mess every time I managed to damage devices, usually destroying the wirebonds or putting my fingerprints on the optical area.

None of the work presented here would have been accomplished without the tremendous help from the group responsible for the MOVPE. They grew the structures for us, made sure that the equipment was in the best working conditions at all time, and they provided us with much needed support. Hedda Malm, in particular, explained me in length the art of calibrating and growing structures, and writing recipes. Carl Asplund joined her later and his help was also of great value. I also want to thank Jan Borglind and Smilja Becanovic who have been very helpful.

I want to thank Leif Kjellberg for his help. He has been a constant support on the technical side with everything related to experiments. He has been my guru in electronics
and mechanics and many measurements would have been impossible without his help.

Our work on free-space optical communication was a collaboration with Totalförsvarets forskningsinstitut (FOI) and Chalmers and in particular with Lars Sjökvist, Johan Ögren, Emil Hallström, Per Rudqvist, David Engström and the late Sverker Hård. It has proved pleasing and fruitful to work with all of you.

I want to thank the QWIP department for their help when we started the development of SLM. The ASIC driving the modulator array is the work of JuanHua Guo and Henk Martijn. Our optical chip would not have been of much use without the quality of your work. Jörgen Alverbro has also been of valuable help when discussing the initial characteristics of the optical chip.

I shared the office with Clara Fredén–Klenfeldt in 2003, when she was working on her Master Thesis on quantum dots. It was a very pleasant experience and I really appreciated her dynamism and kindness. Clara was on holidays in Thailand with her family last Christmas. She has been reported missing, together with her mother and younger brother, after a Tsunami devastated that region. All my thoughts go to her family and friends.

I want to thank all my colleagues at Acreo. They have made my work enjoyable. In particular Linda Höglund, Daniel Selberg, Ludovic Coppel, Thierry Corman, Andy Scholes, Bengt Jacobsson Nissar and Maria Kindlundh, whose friendship has been well appreciated.

No research work can be performed without substantial financing. I want to thank FOI and FMV (Försvarsmaterielverk) for financing our activities in free-space optical communication. I also want to thank the Swedish Knowledge Foundation, KK–Stiftelsen, for the grant I received and in particular Carola Olmér for renewing my grant for one more year in 2004, allowing me to put my research work into a state where it could be presented in this thesis.

Finally, I want to thank my parents Lucien and Christiane, my sister Karine, her children Tomy–Lee and Lou–Lyne, and my brother Guillaume for their love and support.
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<td>AlAs</td>
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<td>AlGaAs</td>
<td>Aluminium Gallium Arsenide</td>
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<td>ASIC</td>
<td>Application Specific Integrated Circuit</td>
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<td>CAD</td>
<td>Computer Aided Design</td>
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<td>CCD</td>
<td>Charge Coupled Device</td>
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<td>CMOS</td>
<td>Complementary Metal Oxide Semiconductor</td>
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<td>CR</td>
<td>Contrast Ratio</td>
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<td>DBR</td>
<td>Distributed Bragg Mirror</td>
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<td>DOE</td>
<td>Diffractive optical element</td>
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<td>EIT</td>
<td>Electromagnetically-Induced Transparency</td>
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<td>fps</td>
<td>Frames Per Second</td>
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<td>FT</td>
<td>Fourier Transform</td>
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<td>FWHM</td>
<td>Full Width Half Minimum</td>
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<td>GaAs</td>
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<td>ICD</td>
<td>Integrated Circuit driver</td>
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<td>InP</td>
<td>Indium Phosphide</td>
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<td>LC</td>
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<td>MBE</td>
<td>Molecular Beam Epitaxy</td>
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<td>Micro-Electro-Mechanical System</td>
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<td>OSA</td>
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<td>Optical Transfer Matrix</td>
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<td>QCSE</td>
<td>Quantum–Confined Stark Effect</td>
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<td>SLD</td>
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<td>SLM</td>
<td>Spatial Light Modulator</td>
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<td>UAV</td>
<td>Unmanned Aerial Vehicle</td>
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<td>VCSEL</td>
<td>Vertical Cavity Surface Emitting Laser</td>
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<td>C</td>
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<td>d</td>
<td>Thickness of an optical layer</td>
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<td>f3dB</td>
<td>Cut–off frequency</td>
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<tr>
<td>i</td>
<td>The purely imaginary complex number of modulus -l</td>
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<td>k</td>
<td>Cavity length of an optical resonator in units of half the resonance wavelength (integer)</td>
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<td>k'</td>
<td>Number of pixels in a subdivided modulator</td>
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<tr>
<td>keV</td>
<td>Kilo electron–volts</td>
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<td>l</td>
<td>Number of layers in a Distributed Bragg Reflector</td>
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<td>M</td>
<td>Optical transfer matrix of a material layer</td>
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<td>n</td>
<td>Refractive index</td>
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<tr>
<td>n_i</td>
<td>Imaginary part of the refractive index in a lossy medium</td>
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<td>n_s</td>
<td>Refractive index of the substrate</td>
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<td>n_E</td>
<td>Effective refractive index</td>
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<tr>
<td>n_0</td>
<td>Refractive index in the medium of incidence of the beam</td>
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<tr>
<td>P</td>
<td>Product of Optical Transfer matrices</td>
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<td>P (D)</td>
<td>Plane in which the viewing angle is measured</td>
<td>50</td>
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<tr>
<td>r</td>
<td>Internal resistance of a signal generator</td>
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<td>R</td>
<td>Reflectance of an interface or a stack of layers</td>
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<td>R_b</td>
<td>Reflectance of the back mirror in a Fabry–Pérot cavity</td>
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<td>R_b'</td>
<td>Effective reflectance of the back mirror in a Fabry–Pérot cavity</td>
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<td>R_f</td>
<td>Reflectance of the front mirror in a Fabry–Pérot cavity</td>
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<td>R</td>
<td>Resistance</td>
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<td>S</td>
<td>Area of a device</td>
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<td>S</td>
<td>Focus spot</td>
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<tr>
<td>t</td>
<td>Thickness of the depleted region of a diode</td>
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<td>W</td>
<td>Vector parallel to the incident beam at maximum viewing angle</td>
<td>50</td>
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<td>Y</td>
<td>Optical admittance</td>
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<td>α</td>
<td>absorption in a multiple quantum well structure</td>
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<tr>
<td>$\alpha$</td>
<td>Absorption coefficient</td>
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<td>$\alpha$</td>
<td>Angle between the normal to the modulator surface and the projection of the incident beam to plane (xOz).</td>
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<tr>
<td>$\beta$</td>
<td>Viewing angle</td>
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<td>$\beta_{\text{max}}$</td>
<td>Maximum value of the viewing angle</td>
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<td>$\delta_0$</td>
<td>Variations of the angle between the normal to the modulator surface and the projection of the incident beam to plane (xOz).</td>
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<tr>
<td>$\delta_n$</td>
<td>Differential refractive index in a lossy medium</td>
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<td>$\varepsilon_0$</td>
<td>Dielectric constant of vacuum</td>
<td>37</td>
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<tr>
<td>$\varepsilon_r$</td>
<td>Relative dielectric constant of a material</td>
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<tr>
<td>$\phi$</td>
<td>Phase shift imposed on a reflected beam</td>
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<td>$\kappa$</td>
<td>Percentage of a device area used for contacts</td>
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<td>$\lambda$</td>
<td>Wavelength in vacuum of an optical beam</td>
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<td>$\lambda_0$</td>
<td>Resonance wavelength of an optical resonator</td>
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<td>$\Lambda$</td>
<td>Length of the absorbing medium in a Fabry–Pérot cavity</td>
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<td>$\Lambda_0$</td>
<td>Optical length of a resonator</td>
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<td>$\rho$</td>
<td>Contact resistivity</td>
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<td>Angle between the incident beam and the sample surface in a rocking curve measurement</td>
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<tr>
<td>$\omega - 2\theta$</td>
<td>Type of scanning using X–ray diffraction, also known as &quot;rocking curve&quot;</td>
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<td>$\theta$</td>
<td>Angle of incidence of a light beam</td>
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<td>$\gamma$</td>
<td>Angle of incidence of the beam on the modulator surface</td>
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<td>$\tau_{\text{device}}$</td>
<td>Electrical time constant of a device</td>
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1 Introduction

The goal of this thesis is to develop surface-normal semiconductor optical modulators based on the electroabsorption effect in quantum wells. Gallium Arsenide (GaAs)-related materials have been the main focus of this work and devices presented are made of GaAs and Aluminium Gallium Arsenide (AlGaAs).

Electro-absorption is the physical phenomenon by which absorption in a medium can be controlled by applying an electric field. A mechanism for electro-absorption in semiconductors was proposed by Franz and Keldish in 1958 [1][2]. It was, however, a weak effect with limited practical use. In 1985, Miller observed strong electro-absorption effects in quantum wells [3]. His observations became the starting point for the development of semiconductor electro-absorption modulators. There are two reasons for the success of optical modulators using quantum wells: the first one is the Stark effect. When an electric field is applied across a semiconductor, its bandgap energy is shifted, in an effect called the Stark effect. While weak in bulk material, the effect is much stronger in quantum wells and has been called the Quantum-Confined Stark Effect (QCSE). The second reason for the success of such modulators is the presence of excitons. Excitons are hydrogenoid entities formed by an electron and a hole orbiting around each other. As these entities can be very stable, electronic transitions that create them are likely, giving rise to absorption peaks. Excitons are long-lived in quantum wells, due to the confinement of the electron and hole wavefunctions. Even better, they are still long lived and with only a moderate broadening in quantum wells when an electric field is applied, again due to the confinement[4]. These two mechanisms, the QCSE and the presence of strong excitonic absorption, are the reason for the success of semiconductor electroabsorption modulators.

Surface-normal devices are devices accessed through the epitaxial surface, as opposed to longitudinal devices, which are accessed from cleaved surfaces. Devices designed for surface-normal operation are strong contenders when mass production is considered: it is possible to fabricate arrays, allowing a high degree of integration; and it is possible to test devices when they are still on the wafer. The latter point is important to keep the costs down, as non-working devices are not packaged. In contrast, longitudinal devices have to be packaged before they are tested. Also, surface-normal modulators are insensitive to the polarisation of the incident light beam, as the electric field is always coplanar with the quantum wells. This is opposed to longitudinal modulators such as the ones based on Indium Phosphide (InP) wells and used in telecommunication applications, which, despite high contrast ratios, are plagued by a sensitivity to the polarisation as only one polarisation direction is absorbed by the first excitonic peak.

There are already devices in production for surface-normal access. Vertical Cavity Surface Emitting Lasers (VCSELs) are a common example of such devices. There has also been a lot of published work on surface-normal modulators based on GaAs [5] and InP [6] material as well as GaAs-based modulator arrays [7][8][9].
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Competing modulator array technologies include mainly Micro-Electro-Mechanical System–based mirrors (MEMS) [10] and Liquid Crystal (LC) modulators [11][12]. LC modulators have been successfully used for 8-bit amplitude and 8-bit phase modulator, including in two-dimensional arrays and are available commercially. They are not sensitive to moderate variations of the illumination wavelength, which can be a strong advantage. The technologies main drawback is its modulation speed, limited to tens of kilohertz due to the material viscosity, and sensitivity to the polarisation of the optical beam for some of the LCs. MEMS modulator arrays are also available commercially. They can be used to modulate the light amplitude or phase, depending on the design, and are largely wavelength–independent. The technologies main drawback is that they usually deflect the light, rather than absorbing it, introducing parasitic light to systems that use them. They are also limited to the kilohertz–range for the modulation speed, as mechanical parts have to be moved back and forth. In contrast, modulators based on electro–absorption in quantum wells are wavelength–sensitive, but they have potential for very high modulation speeds, in excess of 40 Ghz [13][14]. It makes them very attractive for photonics applications using monochromatic sources.

In the longer run, several promising technologies could replace quantum well–based electro–absorption for photonics devices. There has been a fast development of quantum dots in the recent years, and it will be very exciting to see how these can be used in optical modulators. Another area of intense research is modulators based on Electromagnetically–Induced Transparency (EIT). Since they use an optical signal as a command, they may not cover the same applications as electro–absorption devices. They are nonetheless a very exciting research area in optical modulation.

Surface–normal electroabsorption modulators based on GaAs material have been demonstrated more than a decade ago and the possibility of high amplitude modulation and high modulation speed have long been shown. Despite this, and despite the potential for low–cost production provided by surface–normal access, there is very little published work related to the fabrication of such devices at the wafer level or other aspects of volume production. The author's contribution to this field has been in this very direction: devices have been designed taking into account the uniformity of epilayers and its impact on the performance of single modulators and on wafer yields; device designs have been optimised to allow fabrication at the wafer level; large–area modulators, with more than 1 cm² of active area, have been designed and yield–related issues have been studied. Finally, a reflecting retro–reflector for free–space optical communication has been demonstrated using specially optimised, large–area, reflective, resonant–cavity modulator. It was the first time, to the author's knowledge, that such a modulator design was used in a reflecting retro–reflector.

This thesis introduces the techniques needed to understand the design and fabrication of surface–normal, Multiple Quantum Well (MQW)–based optical modulators.
Chapter 1: Introduction

Chapter 2 introduces the design of modulators and some of the physics involved in this process. Chapter 3 describes the fabrication steps and the various characterisation techniques used during and after the fabrication. Chapter 4 presents some devices developed, a large-area modulator for free-space optical communication and a large, two-dimensional array of amplitude modulators. The main characteristics of these devices are discussed. Chapter 5 is system-oriented. The use of MQW optical modulators in a free-space optical retro-communication system is presented and an opto-mechanical design for a modulating retro-reflector is described. Follow chapter 6 with an introduction to the material published in scientific journals and conferences and a conclusion for the thesis in chapter 7.
2 Design of MQW modulators

The fabrication of MQW modulators relies on an accurate understanding of the optical, electrical and structural properties of thin–film semiconductor structures. This chapter starts by introducing the physical properties of GaAs–based quantum–well structures and how they can be calculated. It carries on by describing how MQW structures are incorporated into p–i–n diodes. The properties of optical resonators — Fabry–Pérot cavities — are introduced, and their optical properties and relevance for amplitude modulators are discussed. A modulator structure is presented and its optical properties described. Phase modulation using resonant–cavity modulators is introduced and some attractive applications of such modulators are presented.

2.1 Absorption in GaAs MQW structures

GaAs is a very mature material for optoelectronic devices. High–quality substrates are commonly available in diameters of 3, 4 and 6 inches. Growth of epistuctures by Molecular Beam Epitaxy (MBE), Metal–Organic Vapour Phase Epitaxy (MOVPE) and other techniques is mature and used in production of VCSELs and Light Emitting Diodes (LEDs). GaAs can be mixed freely with Aluminium Arsenide (AlAs) to form AlGa1−xAs alloys with a bandgap between that of GaAs and AlAs. Both binaries have almost the same lattice parameter (the difference is around 0.14 %, see table 1) and thick structures can be grown without strain. This translates into low densities of defects in the epilayers.

A quantum well is a thin layer of a shallow–bandgap material between two layers of a wider–bandgap one. Due to their properties, as well as well–developed processing techniques, AlGaAs alloys are very popular for the fabrication of MQW structures. The wells are generally in GaAs and the barriers in AlGaAs with an aluminium fraction of x = 0.30, although AlGaAs wells and AlAs barriers are possible and have been used.

<table>
<thead>
<tr>
<th></th>
<th>GaAs</th>
<th>AlAs</th>
<th>AlxGa1−xAs</th>
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</thead>
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<td>Lattice parameter (Å)</td>
<td>5.6533</td>
<td>5.6611</td>
<td>5.6533 + 0.0078x</td>
</tr>
<tr>
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<td>3.018</td>
<td>1.424 + 1.247x</td>
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<tr>
<td></td>
<td></td>
<td></td>
<td>1.424 + 1.247x + 1.147(x−0.45)^2 for x&lt;0.45</td>
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<td></td>
<td>1.424 + 1.247x + 1.147(x−0.45)^2 for x&gt;0.45</td>
</tr>
</tbody>
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*Table 1: Material properties of AlGaAs at room temperature. After S. Adachi, J. Appl. Phys. 53, p8775 (1982)*

2.1.a Quantum wells with no electric field
Chapter 2: Design of MQW modulators

A quantum well is depicted in figure 1 (A). Due to the small size of the well, there is not a continuum of energy levels in the growth direction, which we denote z. Instead, discrete levels appear. Their numbers and positions depend on the well width w and the barrier height. In the conduction band, these levels can host electrons. In the valence band, charge carriers are holes, which are really electron vacancies. There are two types of holes, heavy and light ones, with each their own set of energy levels.

![Diagram of quantum well](image)

Figure 1: A quantum well without (A) and with (B) an applied electric field. VB and CB are the valence and conduction band; $E_n$ denotes the electron potential energy; $z$ is the growth direction of the layer stack; $e_1$ and $e_2$ the first and second electron energy level; $hh_1$ and $lh_1$ are the first heavy hole and light hole energy levels.

When interband absorption of light can occur, an electron is promoted from its hole energy level in the valence band to an electron level of same parity in the conduction band: for example from the first or third heavy–hole or light–hole levels to the first electron level; or from the second heavy–hole or light–hole levels to the second electron level. Levels of different parity do not give rise to absorption: the absorption probability is proportional to the overlap between the level wavefunctions, which is zero for levels of different parity with no applied electric field.

There also exists an absorption when an electron does not quite reach its level in the conduction band, but instead remains bound to the positive vacancy it has left in the valence band. This electron–hole entity can be seen as an hydrogenoid atom, with the negative and positive charge orbiting around their centre of gravity. It is called an exciton. There exists for excitons an optimal electron–hole distance for which the exciton energy is minimised, making the exciton stable and likely to exist during a measurable amount of time. In practice, excitons are observed in wells of good crystalline quality in the form of strong absorption peaks at energies lower than the level–to–level transition energies by the exciton energy. The strength of the excitonic peak can be considered as a sign of the crystalline quality and material purity, as defects and impurities allow the electron–hole pair to recombine faster, decreasing the exciton lifetime. More about excitons can be found in [15]. A complete review of excitons in semiconductors can be found in [16].
2.1.b Quantum wells with an electric field

When an electric field is applied on a bulk semiconductor, a small shift of the bandgap energy is observed, called the Stark effect. In quantum wells, this energy shift is much greater and is called the Quantum–Confined Stark Effect (QCSE). Figure 1 (B) shows the same wells as previously, when an electric field is applied. The QCSE shifts the absorption inside the Quantum Wells (QW) towards longer wavelengths. At the same time, the field pushes the electron and hole wavefunctions in opposite directions, which decreasing the overlapping and therefore the absorption strength.

2.1.c Calculation of the absorption profile

The absorption spectrum of a real MQW structure cannot be calculated analytically. The numerical calculation is usually done by discretising the Schrödinger equation to find the energy levels and corresponding wavefunctions. This calculation is done three times, once for each carrier type in its band.

Once the wavefunctions are known, the excitonic binding for each interband transition can be calculated. Several mathematical expressions for the exciton wavefunction have been proposed by Bastard [4] (see also his book [17]). The absorption due to each transition and excitonic state is then calculated.

Finally, when the absorption changes in a medium, so does its refractive index. Both quantities are related and can be calculated from each other by the Kramers–Krönig

![Graphs showing absorption coefficient and differential refractive index](image)

Figure 2: (A) modelled absorption profile of a multiple quantum well structure and (B) differential refractive index of the same structure calculated using the Kramers–Krönig relation.
relations [18]. The last step is thus to calculate the refractive index variation, as it is needed when modelling modulator structures. The variation of the refractive index in the MQW structure changes its optical length. An example of modelled absorption spectra with the corresponding refractive index variations is shown in figure 2(A) and (B). A very valuable resource for the calculation of electronic and optical properties of semiconductor heterostructures is the book of Harrison [19].

2.2 Modulator design

The design of a modulator has to accommodate electrical and optical constraints into a device structure: the device has to allow an electric field to be applied to the MQW structure; the electrical path has to be as conductive as possible to allow high modulation frequencies; and the optical arrangement has to minimise insertion losses, allow reflective and transmissive designs and allow optical resonators to be used or minimised. Compromises that define these constraints are presented and discussed.

To use a QW structure as part of an optical modulator, the device has to allow an electric field to be applied across the wells. This is achieved by placing the MQWs inside a diode and applying a reverse bias to the diode. We have placed our MQW in the intrinsic region of a p-i-n diode, which is the most popular choice.

As far as the optical design is concerned, there are mainly two main choices to be done: should the light reflect on the device or transmit through it; and should it have a resonant cavity or not.

In a transmissive, non–resonant surface–normal modulator, the optical signal propagates through the diode and is absorbed in the MQWs depending on the bias applied to the device. The diode is covered with an anti-reflective coating on both air–semiconductor interfaces to avoid reflections. This type of modulator is appealing from a system point-of-view, as it can be placed almost anywhere in the beam path and puts minimal constraints to the optical system.

A reflective, non–resonant modulator structure is similar to its transmissive counterpart, but one of the air–semiconductor interfaces is replaced by a mirror, either a metallic layer or a semiconductor Distributed Bragg Reflector (DBR). The light beam then goes twice through the MQW structure, which increases the absorption. Non-resonant modulators, however, cannot reach high contrast ratios, due to the limited absorption taking place in the MQW structure. An example of reflectance / transmittance profiles for these two types of modulators is shown in figure 3 using a modelled MQW structure with 60 quantum wells.
2.2.a Asymmetric Fabry–Pérot resonators

Embedding the absorbing medium inside an asymmetric Fabry–Pérot (FP) resonator is a powerful way of increasing the Contrast Ratio (CR): the cavity reflectance varies in a non-linear fashion with respect to that of the mirrors.

In a reflective FP modulator, the reflectance is minimal at the resonance wavelength, which allows it to achieve near zero reflectance in the low-reflectance state. This significantly increases the contrast at the cost of some higher insertion loss. In a transmissive FP modulator, the transmittance is maximum at the resonance wavelength, keeping insertion losses low but providing poor contrast ratio. Due to their low CR, transmissive FP modulator are not of interest for us and are not discussed further.

In a FP cavity studied in reflective mode, the equivalent back mirror reflectance is decreased by the absorptior taking place inside the cavity, as illustrated in figure 4. The equivalent back-mirror reflectance is:

\[ R_b' = R_b e^{-2 \alpha \cdot L} \]

where \( R_b' \) is the effective reflectance of the back mirror, \( R_b \) the reflectance of the back mirror, \( \alpha \) the absorption coefficient of the medium and \( L \) the medium length. Figure 5 shows how the cavity reflectance varies with the reflectance of the back mirror for a fixed set of front mirrors of reflectance \( R_f \). As is evidenced by these curves, it is advantageous for a modulator to use high-reflectance mirrors on both sides: a high device
reflectance is accessible, meaning low insertion losses; and the slope of the curve is steep, so a small change in the back-mirror translate into a large change in device reflectance.

However, there are other parameters to take into account when using a resonator. The most important one is probably the selectivity \([20][21][22]\), which describes the spectral width of the resonator. We use the Full Width Half Minimum (FWHM) of the cavity. Another popular measure is called the finesse (see, for example [23] p 130). Figure 6 (A) illustrates how the selectivity increases with the reflectance of the front mirror; figure 6 (B) shows how the selectivity varies with the cavity length, where the optical
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length of the resonator is \( \Lambda_0 \) with:

\[
\Lambda_0 = \frac{k}{2} \lambda_0 ,
\]

where \( k \) is an integer and \( \lambda_0 \) the resonance wavelength. The FWHM of the resonance dip is plotted as a function of the front mirror reflectance and as a function of \( k \) in figure 7 (A) and (B), respectively. In the modulator structures we have fabricated, \( R_f = 30\% \) to \( R_f = 50\% \), \( k = 11 \) and \( R_b > 95\% \) were used.

(A)  
Figure 6: Examples of reflectance of Fabry–Pérot cavities when (A) the back mirror has a reflectance of 95\% and the cavity a length of \( k/2=5.5 \); and (B) both mirrors have a reflectance of 30\%.

(B)

Figure 7: Variation of the Full Width Half Minimum (FWHM) of the resonance dip of a Fabry–Pérot cavity: (A) as a function of the front mirror reflectance for a cavity length of \( k/2=5.5 \) times the resonance; and (B) as a function of \( k \) for a cavity with front and back mirrors of 30\% and 95\% of reflectance, respectively.
Chapter 2: Design of MQW modulators

The cavity FWHM is an extremely important parameter, as it limits the device tolerance [24]:

- Variations across the device of the layer thickness can shift the cavity resonance so much that no single wavelength is suitable on the whole device. This is especially true on large-area devices.
- The resonance wavelength varies with the angle of incidence of the light beam. If a tolerance in angle of incidence is needed, the selectivity has to be decreased accordingly.

2.3 Modelling of modulator structures

2.3.a Optical modelling

The optical modelling has been performed using the Optical Transfer Matrix (OTM) method, which can be found for example in [18] or [25]. The OTM method is well adapted to thin-film optics as amplitude and phase of reflected and transmitted signals can be calculated, for both polarisations.

Using the OTM, each material layer is described by a matrix $M$, as illustrated in figure 8:

$$M = \begin{pmatrix}
    \cos(\delta) & \frac{i \sin(\delta)}{n_{pol}} \\
    i \sin(\delta) \cdot n_{pol} & \cos(\delta)
\end{pmatrix}$$

with

$$\delta = \frac{2 \pi n d \cos(\theta)}{\lambda}$$

and

$$n_{pol} = n \cdot \cos(\theta)$$  for transverse electric polarisation
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\[ \eta_{pol} = \frac{n}{\cos(\theta)} \]  
for transverse magnetic polarisation

where \( n \) is the refractive index, \( i \) imaginary the complex number, \( d \) the layer thickness, \( \theta \) the angle of incidence in the layer, and \( \lambda \) the wavelength in vacuum.

A layer stack is described by a matrix product \( P \), where layer 1 is met first by the beam and layer \( p \) lays on a substrate of refractive index \( n_s \). The optical admittance \( Y \) of the layer stack is straightforward to calculate:

\[
P = M_1 \cdot M_2 \cdots M_p , \]

\[
\begin{pmatrix} B \\ C \end{pmatrix} = P \begin{pmatrix} 1 \\ n_s \end{pmatrix}
\]

and

\[ Y = \frac{C}{B} \]

If the medium of the incoming beam has a refractive index \( n_0 \), the reflectance \( R \) and phase shift \( \phi \) associated with the beam reflected by the layer stack are:

\[
R = \begin{pmatrix} n_0 - Y & n_0 - Y \\ n_0 + Y & n_0 + Y \end{pmatrix}
\]

Figure 8: Sketch of the layer stack corresponding to the optical transfer matrices described in the text.
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\[ \phi = \frac{\text{Im} (Y)}{\text{Re} (Y)} \]

Losses in absorbing media are taken into account by using complex refractive indices. A MQW is described by the sum of three components \( n = (n) + \delta n - i n \)

- The effective refractive index \( \langle n \rangle \), which is the weighted average of real part of the refractive indices of the barriers and wells. An effective index can be used because the optical thickness of each layer of the stack is in the order of 30 nm, which is much smaller than the considered wavelength of 850 nm.

- The absorption is taken into account by \( n_i = \frac{\alpha \cdot \lambda}{4 \pi} \)

- \( \delta n \) is the detuning appearing due to the variation of the absorption and calculated by the Kramers–Krönig relation [18].

An example of modulator structure is shown in figure 9 (A). The front mirrors is either the air–semiconductor interface or (as shown here) a DBR with up to 5 pairs of layers. The resonator cavity consists of an n–doped buffer and the MQW structure. The buffer is about 0.6 μm–thick and used both as a contact layer for the devices and an adjustment for the cavity length. The MQW structure is undoped and contains generally 50 to 60 wells to

![Diagram of modulator structure](image)

Figure 9: (A) Example of modulator structure as modelled by the optical transfer matrix method; and (B) example of modelled reflectance for applied electric fields between 0 and 120 kV/cm.
provide enough absorption while keeping the needed bias voltage below 10 V. The back mirror is a p–doped DBR with usually 25 pairs and provides a reflectance over 98 % as well as good conductivity thanks to very high doping levels. Figure 9 (B) shows a typical modelled reflectance for applied electric fields between 0 and 120 kV/cm.

2.4 Phase modulation

2.4.a Need for high–speed, phase modulator

Modulation of the phase of an optical signal, as opposed to modulation of its amplitude, is attractive in a number of applications. In optical communications, the link can be made more resilient to noise and other signal perturbations if data is keyed to the phase instead of the amplitude. It is also of interest when the beam shape has to be altered in some way, but the beam should be attenuated as little as possible: non–mechanical beam steering, adaptive optics, and coherent optical processing applications such as optical correlation.

For beam steering applications, the device displays a phase pattern which diffracts the beam to a specific direction [26]. It is possible to use an amplitude modulator array, but artefacts appear in the diffracted beam, as some diffraction orders cannot be efficiently eliminated.

In beam shaping applications, the beam is transformed to have a given amplitude profile (a “shape”) in a given plane positioned after the device. A typical example of beam shaping are the diffractive optical elements (DOEs) placed in front of laser pointers to allow them to project a particular sign such as a company logo. Another example is optical tweezers, which are becoming increasingly popular in micro/nano–biology laboratories: a specific amplitude profile, usually a light spot or a ring, is formed in a plane containing biological particles in suspension in a thin liquid film. It is possible, using the radiation pressure of light, to manipulate these particles and move them around without resorting to mechanical tweezers [27][28][29][30]. Currently, LC displays and other techniques are used for light shaping, but they are limited in that they can only move a handful of particles at the same time, due to their slow modulation speed. High–speed modulators would allow controlling many particles in parallel though time slicing. Near infrared is also well adapted to biology applications, as there is little absorption in this range [31].
Although not as popular as it used to be, optical correlation was for decades the primary application, which had the optical community hope that optics would someday become the dominant technique for signal processing at the expense of silicon-based electronics. This vision was based on the peculiar properties of optical computing:

- In the optical world, data processing is instantaneous: a light pulse goes through all the elements of the processing unit (essentially displays, lenses and filters) at the speed of light, whereas in electronics data travels successively through blocks, the speed of which is limited by the switching time of transistors;

- In the optical world, data is treated in parallel, whereas in electronics data has to be serialised and each chunk of data has to be processed in turn;

- For the same processing power, optics can make the system lighter and less power-hungry.

The VanderLugt correlator (also known as the 4-f correlator) is a popular choice for a large range of image-processing application based on correlation, such as pattern recognition. A VanderLugt correlator is depicted in figure 10. It is based on the principle that if an image placed in the object plane of a lens is illuminated with a monochromatic beam, the Fourier Transform (FT) of the image appears in the plane where the beam would focus if there was no object. Since the beam is most often collimated, that plane is the image plane of the lens. The image to be processed is displayed on the input Spatial Light Modulator (SLM) and its FT is projected on the second SLM. The second SLM displays a filter, usually a modified FT of the object being looked for, so these two FT are multiplied pixel-by-pixel to each other. The resulting pattern is Fourier Transformed by the second lens, resulting in a correlation operation between the original image and the object the filter is based on. The correlation pattern is recorded by a camera sensor. If the object described by the filter is present in the original image, a peak appears in the correlation at a position corresponding to the object location.

Since the object is only detected if its orientation is the same in the image and the filter, many filters may need to be tested against the image to detect one object. If the presence of several objects has to be tested, it can amount to hundreds of thousands of filters per image. Hence, the filter SLM has to be significantly faster than the image SLM. Furthermore, the filter SLM has to be able to display complex values: the filter is based on the FT of the object that is searched for and is composed of complex numbers. However, as is discussed in Paper A, the coding domain of the filter SLM can be reduced to 4 values: 0, 1, $e^{2\pi i}$ and $e^{4\pi i}$ with only little effect on the quality of the correlation. Reducing further the coding domain to 3 values: +1, 0 and -1 somewhat degrades the quality of the correlation, but it still remains far better than when using binary amplitude coding or even continuous, phase-only coding with no zero value. This simplification of the coding
domain to 3 values has 2 major advantages:

- It becomes possible to design SLMs based on MQW modulators, provided that a phase shift of π can be achieved (continuous pure phase modulation is not discussed as it is not currently possible with MQW-based modulators, to the best of the author’s knowledge).

- The amount of data to feed the SLM with is limited to 2 bits per pixel (or 3 bits for 2 pixel in case of data packing). This is a very important advantage as the amount of data to send to the device would soon become a bottleneck with increased frame-rates, as it is today with Charge Coupled Devices (CCDs) and Complementary Metal Oxide Semiconductor (CMOS) detectors used in optical correlators.

Clearly, there is an identified need for fast, amplitude and phase, ternary (and quaternary) modulators.

2.4.6 Principle of phase modulation using a MQW structure in a reflective, resonant–cavity modulator

A possible modulator structure for a phase modulator was introduced by Trezza in 1994 [32]. It is a reflective, resonant cavity structure with a high-reflectance back mirror and a moderate-reflectance front mirror, as shown in figure 9(A). Trezza argued qualitatively that such a structure should provide a phase shift of π radians between 2 states. He also presented experimental results which demonstrated phase modulation reaching the expected π radians with close reflected intensity between the two states.
The principle of phase modulation is as follows: in the first state, no voltage is applied to the modulator. There is no absorption in the cavity at the working wavelength and, since the back mirror has the highest reflectance, most of the light is reflected from it. In the second state, an electric field is applied, which shifts the excitonic peak of the MQW structure to the cavity resonance. In this state, absorption in the cavity is so strong as to not allow light to reflect on the back mirror and leave the cavity. Hence, most of the light reflected from the device is reflected at the front mirror.

To compare the two states, optical indices of the respective layers have to be introduced. The outer medium is air and has an index of \( n_a = 1 \); layers in the DBRs have indices \( n_1 \) and \( n_2 \) respectively, with \( n_1 < n_1 < n_2 \). Finally, the cavity has an average index of \( n_c = n_2 \).

In the first state, the optical path followed by the beam on its way to the back mirror is \( l \pi \) for the propagation inside the front mirror (\( l \) pairs of \( \lambda/4 \) layers) plus \( k \pi \) inside the cavity (the cavity length is \( k\lambda/2 \)), where \( l \) and \( k \) are two integers. The beam is reflected at the interface with the first layer of the back mirror, of refractive index \( n_b \). There is no phase shift upon reflection, as \( n_b < n_c \). The propagation on the way back induces the same phase shift, leading to a total of \( 2l(k+k)\pi \). This amounts to no shift at all, as it is congruent with \( 2\pi \). In the second state, the beam sees a single reflection at the air–semiconductor interface, leading to a phase shift of \( \pi \). The phase difference between the two states is thus \( \pi \).

### 2.4.c Modelling of phase modulators

Although the previous model shows that phase modulation should be possible, it is too limited to provide quantitative information: the contribution, in each state, from the non-dominant mirror is neglected, just as is the cavity detuning as an electric field is applied across the MQW structure. As was discussed in 2.1, the variation of the refractive index in the MQW structure is calculated indirectly though the Kramers–Krönig equation.

Figure 11 shows a modelled phase modulator with a structure as shown in figure 9 (A). The front and back mirror contain 3 and 25 pairs of layers, respectively and the MQW structure is made of 50 wells. Figure 11 (A) shows the path of a phase modulator in the complex plane, as the applied voltage is varied. The radius represents the reflected intensity and the angle the phase shift of the reflected beam with regards to an arbitrary offset. Figure 11 (B) shows the reflectance of the structure at three specific operating points. Two of them are high–reflectance states with a phase difference of \( \pi \). The third state is a low–reflectance state. Although the reflected intensity is not the same between the two phase states, it should be close enough for practical purposes if it can be obtained
experimentally on arrays of modulators. The tolerance in wavelength, of 3 nm, is large enough to indicate that the effect is not an artefact of the modelling. Whether or not it is large enough to be used in devices may well depend on the fabrication accuracy and in particular on the uniformity of the devices.
3 Fabrication of MQW modulator devices

The fabrication of semiconductor devices can be described as a two-step process. The first step focuses on the vertical dimension: the structure is grown by an epitaxy technique, in our case MOVPE. The second deals with delimiting the lateral dimensions of the structures to define discrete devices. This involves removing material and depositing others, essentially metals to form contacts and isolators to passivate the surface.

In each step, characterisations have to be performed to checks that every parameter is as it should. This chapter presents an overview of the main fabrication and characterisation techniques that have been used to make our modulators.

3.1 The growth of epilayers by MOVPE technique

MOVPE is a high-performance, production-grade epitaxy equipment. Good calibration procedures allow for the repeatable growth of uniform structures with a high crystalline quality, sharp transitions between successive material layers and high doping levels.

3.1.a The MOVPE Growth technique

MOVPE is a form of chemical vapour deposition. A substrate wafer, acting as a support for the structure to be grown, is placed in a growth chamber (or reactor) and heated to the growth temperature, generally between 650 and 750 degrees for GaAs-related materials. Active gases are transported to the growth chamber by a carrier gas and react at the substrate surface to form the epilayer.

Active gases are obtained by cracking so-called precursors: organic compounds for the III–species, trimethyl–gallium ((CH₃)₃Ga) and trimethylaluminum ((CH₃)₃Al) and often hydrides for the V–species, for example arsine AsH₃ for arsenic. The carrier gas is a non-reactive gas, usually H₂.

The growth process is sketched by figure 12, showing a vertical reactor similar to the one used. The substrate is placed on a susceptor, which rotates around its axis to provide better growth uniformity. Gases enter the chamber through three pipes marked A, B and C. They are placed at different radial positions in the chamber. This allows adjusting flows in different regions of the chamber by balancing the flows in the pipes. Gases go through a diffuser to even out pressure differences and produce a homogeneous
flow in the chamber. Due to the pressure in the chamber, between 20 and 1000 mbar, and the gas–material frictions, there is a thin film of stagnant gas against the substrate, where the chemical reactions take place. This gas film, called the boundary layer, is shown as a hashed layer on the wafer. Used gases leave the chamber through the exhaust situated under the susceptor.

Active gases reaching the boundary layer have to diffuse through it to participate in the chemical reaction. This is a slow process and the growth is thus diffusion limited. It also has consequences on which parameters affect the growth and how they do so.

The growth is done in excess of the V–species (arsenic in our case) and the flows and proportions of the other species (gallium, aluminium) determine the growth rate. Flow rates also determine how much species are incorporated with regards to each other.

The growth temperature is an important parameter, as it increases the diffusion process in the boundary layer. The temperature is often not exactly the same across the wafer, and maintaining a uniform temperature is paramount to achieving growth of uniform layers. The growth temperature has also an incidence on doping. It is easier to p–dope GaAs material at a lower growth temperature than that used for intrinsic and n–doped material.

Finally, the flow repartition between pipes A, B and C is essential to a good

![Diagram](image)

*Figure 12: Sketch of a vertical MOVPE reactor. Gases enter the chamber through pipes A, B and C and leave through the exhaust under the susceptor. The boundary layer, where the chemical reactions take place on the substrate, is marked by a hashed layer.*

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material uniformity, as it determines the flow of active gases reaching the boundary layer at a given radial position.

3.1.2 Calibration of the growth parameters

The calibration to grow a new structure is generally done in three steps: calibration of each bulk material, calibration of the periodic sub-structures (DBRs and QW structure) and growth of one full structure as a test.

The calibration of separate materials has as goal to find the right parameters to obtain the desired Al fraction and doping levels. A 1 μm layer is grown on a substrate and X-Ray Diffraction (XRD) is used to assess the Al fraction, usually at several positions along the wafer radius to control the composition uniformity. XRD is discussed in detail in 3.2. If the material is doped, the doping level is controlled by Hall measurement.

Once all the materials related to a DBR are calibrated, the periodic structure itself is grown. XRD is used at several radial positions (usually every 10 mm) to measure the period and evaluate the uniformity. XRD provides the physical thickness of the period and, if of good quality, of each of the two layers of the period. The reflectance is also measured at several radial position, by a spectrophotometer. It provides the optical thickness of the period. While the refractive index of undoped AlGaAs alloys is readily available in tables [33], doped material is subject to higher inaccuracies.

The growth of QW structures requires only the calibration of the Al fraction in the barriers. Test QW structures are grown on top of a thin Bragg mirror, to ease the optical characterisation. XRD is performed as for DBRs. Reflectance measurements are also performed similarly and the position of the excitonic peak used as a confirmation of the data obtained by XRD.

The modulator structure contains one non-periodic feature, its n-doped buffer, which acts both as a layer for n-type contacts and as a spacer to achieve the right optical cavity length. The growth parameters are the same as those of the n-type DBR, so there is no need for a separate calibration of the thickness uniformity. The Al fraction and growth speed are calibrated by growing a 1 μm-thick layer of material. The growth speed is measured in-situ by realTemp [34], which is reasonably accurate for thick layers (but not for thin ones such as those in DBRs). The Al fraction is measured after growth by XRD. A second, more accurate evaluation of the growth speed is performed by growing a full structure and measuring its reflectance by spectrophotometry.
3.2 Characterisation by X-ray diffraction

XRD is a popular characterisation technique for a variety of materials, ranging from solids in crystalline form to liquids, amorphous solids and gases. When used on crystals, it is possible to extract many qualitative and quantitative parameters such as stochiometry, stress, layer thickness or the amount of crystalline defects in the material. The rocking–curve technique is presented and some results obtained with it are presented and discussed.

3.2.a Principle of X-ray diffraction

When an X-ray radiation interacts with atoms, part of it is absorbed, part continues to propagate in the same direction and part is diffracted. In ordered materials, the diffracted contribution of neighbouring atoms can sum up constructively, given the right distance between them and angle of incidence of the beam, resulting in detectable peaks in certain directions. The phenomenon, illustrated by figure 13, is similar to DBRs in visible optics, excepts that it reflects on planes of atoms instead of material layers.

![Diagram of X-ray diffraction](image)

*Figure 13: Diffraction of X-rays by the atoms (solid spots) in a crystal. Source: Shi–Li Zhang, Laboratory exercises on X-ray diffraction, Dpt of Electronics, KTH (2001)*

Rocking–curve, also known as ω – 2θ scanning, is a very common method to assess material compositions, thickness of monolayers, strain and more. A rocking curve is performed by shining a specific wavelength at a sample and measuring the diffracted
beam, as shown figure 14. As $\omega$ is varied, $2\theta$ is changed accordingly to maintain $\omega = \theta$. When the scan interval contains angles for which there is constructive diffraction from the material, a peak is detected. Materials with similar lattice parameters give rise to diffraction peaks with close values of $\omega$. The angular distance between the two peaks is then used to calculate the difference in lattice parameter between the materials, making it possible to assess such things as material composition and strain.

3.2.6 Characterisation of GaAs–based material

Rocking curves have been measured in plane (0 0 4) to characterise material composition and in plane (0 0 2) for periodic structures and full modulator epilayers.

The (0 0 4) plane is commonly used to measure single layers of material. A typical diffractogram is shown in figure 15. The GaAs peak comes from the substrate and is used as a the reference. The peak to its left has been diffracted by the AlGaAs epilayer and is shifted from the GaAs peak due to the small difference in lattice parameter. The angular distance between the two peaks is a measure of the Al fraction in the epilayer. The

![Figure 15: X-ray diffractogram of a 1 μm AlGaAs layer on a GaAs substrate. The substrate top is at the right and the layer top at the left. The angular distance between the two peaks is a measure of the Al fraction.](image-url)
sharpness and high intensity of the peak, similar to that of the substrate, are an indication of a constant stoichiometry and good crystal quality. Rocking curve scans have been performed on material calibration wafers at several radial distances to evaluate the variation in composition.

We have generally found variations of the Al fraction between 0.005 and 0.025, or up to 3.3% of the incorporated fraction. The consequences of these variations on the optical properties are negligible compared to the effect of thickness variations. Figure 16 shows the modelled reflectance of a 25-pair, p-doped DBR using the extremal values of the Al fraction measured by XRD. The shift in wavelength is below 3 nm.

The (0 0 2) plane is of interest when small satellite peaks are to be investigated: the substrate peak is not as strong and the scan can be performed without attenuator, resulting in a higher beam intensity meeting the sample.

Figure 17 shows the rocking curve of a modulator structure in the (00 2) plane. Only the central part of the scan is shown for clarity, although more than three times the range was measured with a good quality. The substrate peak is visible, but not dominating the graph. Other material peaks are also visible, in particular the high- and low-Al fraction alloys used in the Bragg mirrors, approximately 0.20 and 0.75, respectively. The material used in the n-doped buffer, containing an Al fraction of 0.35, is also visible. The alloy used for the barriers of the quantum wells cannot be seen on the figure, although it is also present as a side lobe of the low-Al fraction peak.

The satellites on both sides of the main peaks are due to higher-order interferences from the periodic elements of the structure, namely the Bragg mirrors (marked as DBR on the scan) and the QW structure (marked QW). Their positions and intensities provide a very accurate assessment of the structure geometries. In the case of the DBR, the

![Graph showing reflectance vs. wavelength](image)

*Figure 16: Modelled reflectance of the p-doped Bragg mirror, taking into account the variation of the material composition across the wafer: each curve use extrema values of the composition as measured by X-ray diffraction.*
thickness of a pair is given by the periodicity of the peaks. The repartition between the two layers forming the period can be extracted from the intensity modulation of the peaks [35]. The period of the QW structure is almost ten times as small as that of the DBR, and

Figure 17: Rocking curve of a full modulator structure measured in the (0 0 2) plane. Peaks due to the material composition of the successive structure layers are indicated as such at the centre of the graph. Satellite peaks generated by the quantum well structure and the diffracted Bragg reflector are marked (QW) and (DBR), respectively.

Figure 18: Thickness variation of the periodic elements of a full modulator structure over the radius of a 4 inch wafer, measured by rocking curve in the (0 0 2) plane: (A) absolute and (B) relative variations.
only a handful of peaks are measurable. The QW period can be obtained from the peak positions, but no information on the separation between the barriers and wells can be extracted from this scan. The sharpness of the satellites is a sign of the good crystalline quality of the epilayer scanned.

Rocking curve scans have been performed on full modulator structures at several radial distances to evaluate the uniformity of the periodic elements of the modulators. Thickness variations of 1% to 2% have been generally obtained between the centre and a radial distance of 40 mm. Figure 18 shows the radial variation of the DBR and the QW structure extracted from a series of rocking-curves on the full structure.

3.3 Characterisation by Secondary ion mass spectroscopy

Secondary Ion Mass Spectroscopy (SIMS) is a method to profile the composition of solids as a function of depth. It is destructive, as the ion beam etches the device to reach deeper layers. It has a very high detection sensitivity, up to one particle per billion (or $10^{12}$ atoms/cm$^2$) and a very high depth resolution, up to 20 Å. It has been used to control the composition of epilayers and look for unwanted impurities and doping diffusion.

3.3.a Principle of SIMS

The principle of SIMS is to bombard the surface of a sample with ions, to extract secondary ions. The primary ions are usually caesium $^{133}$Cs$^+$, with an energy in the order of 1 to 20 kilo electron–volts (keV). Other types of ions are also possible, of which argon $^{40}$Ar$^+$ and ionised oxygen molecules $^{16}$O$^+$ are common. The bombardment causes the sample to sputter out atoms, of which about 1% are ionised. These secondary ions are captured by an electric field and send through a mass spectrometer to an array of detectors.

The extraction rate of secondary ions depends on a variety of parameters. When low–concentration atoms are looked for, their extraction rate depends on the matrix they are implanted in, and the rates are different between, for example, GaAs and Si matrices. It is possible to calibrate that rate by first measuring a sample that has been implanted by a known dose of the element of interest. However, it is often sufficient to have a qualitative measurement and compare the concentrations between different depths of the sample.
A SIMS system is shown in figure 19. It contains two sources of primary ions (1 and 2) targeting the sample (5). Sputtered secondary ions are focused by the transfer optical system (7) to the mass spectrometer (12). At the output of the spectrometer, a detection system records the hits of selected ions.

3.3.3 SIMS measurement of a modulator structure

One of our earlier structures was sent for analysis to a commercial SIMS company. That structure had no front DBR and the air–semiconductor interface acted as the front mirror. The epilayer presented poor structural quality. The p–doped DBR was suspected as the root of the problem, as some of the DBRs grown for calibration presented a lot of structural defects. Another concern was the low excitonic absorption inside the quantum wells.

Figure 20 shows the analysis curves with from left to right, the structure features from the air interface towards the GaAs substrate. The Al fraction can be used to separate the successive zones of the structure. The first part, called zone A on the figure, is a thick, n–doped Al<sub>0.9</sub>Ga<sub>0.01</sub>As buffer and appears with a constant Al fraction. Zone B is the QW structure, with alternating layers of GaAs and Al<sub>0.9</sub>Ga<sub>0.01</sub>As. Zone C is the p–doped DBR,
with alternating layers of high- and low-Al fraction AlGaAs layers. The As scan follows a similar pattern, although it is less well-defined at the beginning. This was interpreted as an artefact of the measurement. Zone D is an AlGaAs buffer that was grown at the bottom of the epilayer. Finally, zone E is the GaAs substrate.

The hydrogen curve is a typical example of non-detection, with a flat value on a sizeable part of the scan and a few peaks barely above that value in the rest of the scan.

The silicon curve, responsible for the n-type doping, is particularly interesting: it shows that an important diffusion of dopant occurred to the quantum wells. Approximately 140 nm of the QW structure has been doped, out of 875 nm. It also shows that the doping level is over $1 \times 10^{19}$, and is much higher than the free-carrier concentration of $10^{17}$ measured by Hall effect. This discrepancy was attributed to an inaccuracy in the quantitative value obtained by SIMS due to the difference in matrix extraction between GaAs and AlAs, as all concentrations were calibrated for GaAs.

The carbon curve, responsible for the p-type doping, shows high doping levels, although it is difficult to know how accurate the values are. Periodic variations in the DBR could be due to a difference in doping, or to the difference between the two matrices it is extracted from.

Finally, an unexpectedly high level of oxygen is measured in the structure, in particular in the QW structure (zone B) and the DBR. This is a good explanation for both the low absorption in the quantum wells and for the structural defects in the DBR.

Following this result, the diffusion of n-type dopant was taken care of by adding an undoped buffer layer between the QW structure and the n-doped region. The presence of oxygen was confirmed in other structures. Oxygen is carried into the reaction chamber by the sources. In was removed from subsequent structure by adapting the filtering of the precursors. Finally, it was confirmed recently that the silicon concentration of over $10^{19}$ cm$^3$ makes sense: low carrier concentration in n-type material, measured by Hall effect, was due to an excessive doping of silicon. Atoms in excess replaced gallium atom instead of only arsenic, which resulted in a secondary p-type doping and decrease the number of available carriers.

3.4 Characterisation by spectrophotometry
Figure 20: SIMS measurement on an early structure, showing doping diffusion from the n-doped region (zone A) to the quantum wells (zone B), and a high level of oxygen in the intrinsic and p-doped regions.
Chapter 3: Fabrication of MQW modulator devices

Reflectance measurements were performed with a spectrophotometer. Reflectance is a particularly important technique as it provides a direct means of controlling the features of the modulator structure, unlike XRD. One important factor of these measurements was the feedback to the structure modelling, in particular for the refractive index of doped layers. We found the refractive index to be consistently a factor of 0.982 times that of undoped material, both for n- and p-type doping.

The main drawback of our reflectance measurements is the beam size of the instrument we used. The beam was rectangular in shape, 5x10 mm in size, which is very large compared to the thickness variations measured by XRD.

Figure 21 shows reflectance scans performed on a wafer with a full modulator structure, at radial positions from 0 to 35 mm in steps of 5 mm. In this interval, the excitonic absorption peak remains steadily at 842 nm, while the resonant cavity shifts between 862 and 854 nm.

Another setup has been used to measure the reflectance of modulators. A pigtailed Super-Luminescent Diode (SLD) centred on 850 nm with a spectral bandwidth of 80 nm was connected to a fibred collimator to illuminate the device. The reflected beam was coupled back to a fibre through another collimator and sent to an Optical Spectrum Analyser (OSA). The illumination spot used was usually below 1 mm in diameter and the measured signal of good quality. Much smaller beam spots are also attainable, depending on the collimator used. The major drawback of this system is the alignment time.

![Reflectance Measurement Diagram](image)

*Figure 21: Variation of the modulator reflectance, measured by a spectrophotometer at several radial positions on an unprocessed wafer.*

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3.5 Clean–room processing

The processing of grown structures starts by a visual inspection of the epilayer. The structure is then measured by XRD and a reflectance spectrum is optionally performed. The wafer then goes back to the clean room and is processed into devices.

3.5.a Crystalline defects in the epilayer

We have been confronted, in the early development of the modulator structures, with high densities of defects. Defects in the crystalline quality can be caused by many factors, the primary ones being the quality of the GaAs substrate (supplier of lesser quality or “bad batches”), inadequate growth parameters or impurities. The epilayer for our full structure is also rather large (over 4 μm–thick), which exacerbates the problem. We observed a clear improvement when the incorporation of oxygen in the structures was eliminated: the defect density decreased sharply and electrical properties of devices improved, with higher breakdown voltages and lower leakage currents of reverse–biased diodes.

Figure 22(A) shows a picture of an epilayer taken with a microscope. A high density of small, bubble–alike defects is visible, as well as a few larger ones. Figure 22(B) is a picture taken by Atomic Force Microscopy (AFM), showing the shape of one of the bigger defects.

While the density in smaller defects is definitely related to the leakage current, we first supposed that the bigger ones caused such high current flows that they provoked the thermal death of the devices. This is of special concern for our large–area devices: we ended up dividing large modulators into pixels to increase the yield, as discussed in chapter 4.1. However, a closer study on several pixellated devices showed that it is not so. No correlation between dead devices and the presence of large defects was found.

![Figure 22](image)

*Figure 22: (A) microscope picture of an epilayer showing a myriad of small crystalline defects uniformly scattered across the surface, as well as a few, bigger defects; and (B) atomic force microscope picture of one of the bigger defects.*
3.5.b Processing of simple modulators

The processing is depicted in figure 23; the newly grown structure is shown in figure 23 (A), and may or may not contain an n-doped DBR. If it does not, the air–semiconductor interface acts as a mirror of reflectivity of around 30%.

The first step is to define the n contacts. Although etching through the front DBR should not be necessary, as it is doped, we often chose to do so: we obtained until recently mitigated results with n–type doping, due to too much Si incorporation, as mentioned in chapter 3.3.b. Having the contacts go through the heterojunctions formed by the DBR would have increased even more the resistance of the n–type region of the devices. Once trenches are etched to the n–contact region, metal is deposited in them. We used typically AuGe/Ni/Au. Figure 23(B) shows a device after the n–mesa has been etched and the n–contacts defined.

The second step consists in etching through the structure down to the p–doped region to define devices. P–contacts are then defined inside the etched region, as shown in figure 23(C), and metal layers are deposited, typically Ti/Pt/Au.

Finally, the device is annealed to turn the metal depositions into good, ohmic contacts. Devices are then tested electrically: I–V characteristics are measured. Breakdown voltages and current densities in reverse bias are used to evaluate the electrical quality of the devices. P–p and n–n contacts resistances are also measured as a way to check that contacts are really ohmic.

Figure 23: Processing of a wafer into devices: (A) the full, unprocessed wafer; (B) a device after definition of the n–type contacts; and (C) a device after definition of the mesa and the p–type contacts.
4 Examples of modulators

Modulators suitable for various applications and with very different requirements have been developed from the same basic structure features. This chapter describes specifically two types of devices that have been fabricated and what challenges were faced during development. The first type is large-area, reflective, resonant cavity modulators for use in Modulating Retro-Reflectors (MRR) and other free-space optics applications. The second type is a large, two-dimensional array of amplitude modulators, also called a Spatial Light Modulators (SLM).

4.1 Large-area modulators

Large-area modulators are attractive for related to free-space optics. This is in strong contrast to the well-developed guided optics applications, for which fast modulators with a sub-millimetre active area are the rule. The fabrication of large-area modulators is hindered by several practical problems related to material defects, electrical constants and uniformity. These issues are the central subject of Paper D. The devices discussed were fabricated from a structure like the one shown in figure 23(A), containing a front-mirror formed from a n-doped, 3-pair DBR, an n-doped contact layer, a 50-well QW structure and a p-doped, 25-pair DBR as the back mirror. All have a chip area of 16×16 mm² and an active area of 15×15 mm², the difference being due to the contact area. Four devices were integrated with the retro-communication unit described in chapter 5.

4.1.a Pixellation and yield

The yield is limited by the density of fatal defects on the wafer. With a monolithic device, the presence of one such defect short-circuits the chip and effectively destroys it. With a pixellated chip, one pixel at most is destroyed per defect. The number of pixels to divide the device into depends on the defect density and the minimum functional area needed to keep the device. Functional pixels are wire bonded to the chip carrier so they can be driven electrically.

Devices of 1, 4, 28 and 64 pixels, called type A, B, C and D, respectively, were fabricated and tested. They are shown in figure 24. A pixel was considered functional if its breakdown voltage was higher than 8 V. It can be considered that devices of type A and B have the same yield, as removing one pixel out of 4 (25% of the modulating area) is not an option. Yield for these devices was below 50%. Types C and D, on the other hand, allow the removal of several pixels with limited effect on the overall optical performance of the device. For example, excluding 5 pixels from a C-type modulator corresponds to decreasing the fill factor to 82%. For these modulators, a yield of 100% was observed.
4.1.b Pixellation and electrical limitations

The problem described here is the one of scaling devices to smaller dimensions to improve the performance, as the modulation speed is limited by their RC constant. There are two situations to consider: the standalone device and its intrinsic performance limitations, and the complete electrical circuit composed of the device and its driving electronics. Figure 25 shows a simple model of a modulator device attached to a signal generator. The modulator is modelled as simply as possible, as a serial RC circuit, which supposes, among others, that it is not illuminated (as no photocurrent is included).

Using the parallel plate capacitor model, the device capacitance can be written as

$$C = \frac{\varepsilon_0 \varepsilon_r S}{t} = \eta S$$
where $\varepsilon_0$ is the dielectric constant of vacuum, $\varepsilon_r$ is the mean value of the relative dielectric constant in the depleted region of the diode (i.e. the QW structure), $S$ is the device area and $t$ the thickness of the depleted region. The second notation introduces 

$$\eta = \varepsilon_0 \varepsilon_r \cdot S / t$$

It is practical as only $S$ varies when the device size is scaled down.

The device resistance usually has the contact resistance as its main contribution. It can be written as

$$R = R_n + R_p = \frac{\rho_n \kappa_n}{S} + \frac{\rho_p \kappa_p}{S} = \frac{X}{S}$$

where $\rho_n$ and $\rho_p$ is the contact resistivity in the n-type and p-type regions, respectively and $\kappa_n$ and $\kappa_p$ are the percentage of $S$ that are used for the respective contacts and $X = (\rho_n \kappa_n + \rho_p \kappa_p)$. Hence, the device time constant $\tau_{device}$ can be written as:

$$\tau_{device} = R \cdot C = \frac{X}{S} \cdot \eta \cdot S = X \cdot \eta$$

and it is independent of its size; isomorphic devices have the same time constant. $\tau_{device}$ characterises how fast the voltage across the capacitor reacts to a voltage applied to the RC circuit. Since the MQW structure resides between the plates of the capacitor, $\tau_{device}$ is a measure of how fast the electric field can be changed across the MQWs. The cut-off frequency associated with $\tau_{device}$ is $f_{3dB}$:

$$f_{3dB} = \frac{1}{2\pi \cdot \tau_{device}} = \frac{1}{2\pi \cdot X \cdot \eta}$$
Chapter 4: Examples of modulators

This constant is the best attainable time constant for any device with this geometry, independently of the scaling.

However, when the complete electrical circuit is taken into account, the picture is quite different. The time constant of the modulator with its driver can be written as:

\[ \tau_{\text{circuit}} = (r + R) \cdot C = (r + \frac{X}{S}) \cdot \eta \cdot S = \tau_{\text{device}} + r \cdot \eta \cdot S \]

If the contact areas are sufficiently large, the internal resistance of the signal generator dominates the resistive term and \( \tau_{\text{circuit}} \) varies linearly with the modulator area. The internal resistance of the generator is usually 50 \( \Omega \) and decreasing it below a few Ohms is a difficult task. In this circumstance, scaling down the device trades \( C \) for \( R \), and decreases \( \tau_{\text{circuit}} \) towards \( \tau_{\text{device}} \) by decreasing the impact of \( r \) in the circuit.

If the modulator size and geometry are to be kept unchanged, the signal generator has to be modified to reach higher modulation speeds. Driving generators in parallel directly is not recommended, as although the equivalent power generator has a lower impedance, individual generators are never exactly balanced and the stronger ones force current into the weaker ones, degrading performance and lifetimes.

Dividing a modulator into independent pixels allows the device to be driven by a set of independent signal generators. Figure 26 illustrates the case of a device composed of \( k \) pixels, each driven by its generator. Each pixel has a capacitance and an \( n \)-type resistance of \( C/k \) and \( kR \), respectively, as shown figure 26(A). The \( p \)-type contact is common. Since the pixels and generators are identical, potentials at points \( C_i \) to \( C_s \) are identical at all times. Hence, all capacitors can be considered as being plugged in parallel and equivalent to one capacitor of value \( C_{\text{eq}} = k \cdot C / k = C \). Likewise for potentials at points \( B_i \) to \( B_s \) and \( C_i \) to \( C_s \). Figure 26(B) shows the resulting equivalent circuit. The device has the same time constant as before the pixellation. The internal resistance of the power supply has been reduced by a factor \( k \).

It is worth noting that when only one one pixel is driven, the pixel and circuit time constants are:

\[ \tau_{\text{pixel}} = (k \cdot R_n + R_p) \cdot \frac{C}{k} = (R_n + \frac{R_p}{k}) \cdot C \]
\[ \tau_{\text{pixel circuit}} = \left( r + k \cdot R_n + R_p \right) \frac{C}{k} = \frac{r \cdot C}{k} + \tau_{\text{pixel}} \]

The pixel time constant is lower than that of the full device, because the p-contact has not been scaled down. The lower capacitance also lowers the impact of the internal impedance of the signal generator.

![Electrical model of a modulator divided into k, equivalent pixels each connected to its own driver. (A) shows the initial model with each pixel. (B) shows an equivalent circuit.](image)

**Figure 26:** Electrical model of a modulator divided into \( k \), equivalent pixels each connected to its own driver. (A) shows the initial model with each pixel. (B) shows an equivalent circuit.

### 4.1.1 Uniformity of large-area modulators

Device uniformity severely limits the optical performance of large-area modulators based on resonant-cavity designs. Although the position of the excitonic peak can be considered constant across a full 4 inch wafer, the cavity thickness does vary by a measurable amount across a single device.

The high-reflectance level remains weakly sensitive to the cavity variations. For a mean reflectance of 60% to 70%, reflectance variations were generally observed below 10% of the illumination power, translating to a 15% to 20% variation of the reflected

39
power across the device for the high–reflectance state. In contrast, the low–reflectance state is very sensitive to geometrical variations: the reflectance can be close to 0.2% (CR over 300:1 have been measured on small devices) or over 10% of the illumination power. This translates into variations of the reflected power in the order of 5000% of the low–reflectance state. In a large–area modulator, it does not matter that a small area reaches very good extinction ratios if not all of the device does. The power reflected by the lower–performance area is enough to decrease the extinction ratio of the modulator. Hence, the worst–performing area dictates the optical performance of the modulator.

A 2×2–pixel modulator, shown in figure 24(B), was investigated in detail. This investigation was reported in Paper F. The device was scanned along 5 horizontal lines and the reflectance measured at each mm with a beam of 0.5 mm in diameter. The cavity resonance was found to vary by 6 nm or 0.7% across the device. The wavelength and driving voltage providing the best CR on a span of incidence angle of at least 3 degrees was looked for. A CR in excess of 5:1 was measured using an illumination at 854 nm covering the whole modulator area and voltages of 0 and 8.5 V. Graphs of uniformity measurements and CR as a function of the incidence angle are shown in figure 27(A) and (B), respectively.

![Graphs of uniformity measurements and CR as a function of the incidence angle](image)

*Figure 27: (A) Measurement of the cavity resonance wavelength along 5 lines at a distance of 1, 3, 6, 11 and 13 mm from the upper edge and (B) measurement of the contrast ratio as a function of the angle of incidence of the light beam using voltage levels of 0 and 8.5 V and an illumination at 854 nm covering the whole modulator area.*

### 4.2 Arrays of amplitude modulators

This chapter discusses briefly the need for arrays of fast modulators, describes the prior art and presents our contribution. A few key characteristics of the devices we fabricated are presented.

Chapter 2.4.a discussed how arrays of fast modulators are of interest in a variety of
applications, focusing on phase modulation. Fast amplitude modulator arrays are also of interest in applications such as board-to-board optical communication [36] or vector-matrix multiplications [37]. In the latter, a row of light emitters, VCSELs for instance, illuminate each their column of a two-dimensional modulator array. Pixels from a same modulator raw are summed optically and the value detected by a detector array. The principle is sketched in figure 28. The modulator array, being two-dimensional, is the most complex device of the system. The computational throughput is limited by the data rate of the slowest element, which is obviously the SLM due to the amount of data it must be provided with.

![Figure 28: Principle of an optical vector-matrix multiplier. Source: www.lenslet.com](image)

### 4.2.a Prior art

The first step towards large arrays of GaAs–based modulator devices happened in the mid–90s at Hughes with the work by Efron on modulator arrays [7] and by Goossen at Lucent on the integration of a small modulator array with a CMOS circuit driver[38].

In 1996, Worchesky at Lockheed Martin Corp. (now British Aerospace) published work on a 256×256–pixel array that could attain 300,000 frames per second (fps) [8].

In the late 90s, the U.S company Sanders (which later became part of British Aerospace) pushed the performance of devices with 8–bit, grey–level modulator arrays and devices that can be used as light emitters, modulators, and detectors [39]. Their SLMs have been tested in optical correlators by independent groups[40] but it is unclear how they are used today.

The Israeli company Lenslet [37] introduced in 2003 an optical vector–matrix multiplier using a line of VCSELs, an SLM and a line of detectors. The SLM is a 288×132–pixel array of 8–bit, amplitude modulators and reaches 50 kfps [9].
4.2.2 The process lines

Two process lines have been explored, each with advantages and drawbacks. These process lines are the subject of Paper C. An Integrated Circuit Driver (ICD) was developed to drive the modulator array. It is an Application Specific Integrated Circuit (ASIC) using standard CMOS technology and capable of applying a bias of up to 50 V to the individual pixels of the optical chip, with a voltage swing of 5 V. The ICD is connected to the optical chip by flip–chip bonding technique during the last steps of the fabrication process.

In the first line, the modulator structure is grown, from the substrate to the top, with a p–doped contact layer, a 25–pair, p–doped DBR (the back mirror), the QW structure, an n–contact layer buffer and finally a 5–pair, n–doped DBR (the front mirror). The wafer is bonded against a transparent substrate and the GaAs substrate is removed by mechanical lapping and selective chemical etching, uncovering the p–doped side of the epilayer. The structure is then processed into devices, and pixels and contacts are formed. The wafer is finally diced into individual devices, which are flip–chip bonded against their ICD. Figure 29 shows (A) the wafer after bonding against a transparent substrate and (B) a device detail after flip–chip bonding against an ICD.

In the second line, the modulator structure is grown upside down, with the n–doped, 5–pair DBR against the substrate and the p–doped back mirror on top. There is therefore no need for a transparent substrate. The structure is processed directly, after

![Diagrams](image)

Figure 29: Sketch of process lines 1 – figures (A) and (B) – and 2 – figures (C) and (D): (A) a wafer after bonding against a transparent ; (B) a device detail after processing, with one common n–contact (left pixel) and two modulators; (C) a substrate before processing; and (D) a device detail.
which the wafer is diced into individual devices. Each device is flip–chip bonded against its ICD. Finally, the GaAs substrate is removed from the device by mechanical lapping and selective chemical etching. Figure 29 shows (C) the wafer before processing and (D) a device detail after flip–chip bonding against an ICD.

In the second process line, the interface between the air and the device is issued from an etching process and its optical quality could be put into question. Furthermore, the 4 μm–thick epilayer is mechanically supported by the ICD on which it rests. It is questionable whether the obtained is flat enough, at least in the case of phase modulators.

In the first process line, the epilayer is mechanically supported by the transparent substrate. While it is supposed to be better, it has been difficult to achieve in practice: the GaAs and glass substrate have very different thermal expansion coefficients and even bonding the two has proved problematic, as the substrate bends when the temperature is cycled to reach adhesion.

SLMs were successfully fabricated in wafer scale using the second process line. They were characterised and reported on in Paper F. The devices are approximately 6 ×6 mm in size. Arrays contain 128×128 pixels with a square pixel pitch of 38 μm and a fill factor of 50 %. The low fill factor is due to the choice of wet chemical etching to process the devices. Although wet etching is a more simple technique than dry etching, it has the disadvantage of etching isotropically. This effect is particularly visible when thick structures, such as the p–doped mirror and the QW structure of our modulator, which total over 3 μm, are to be etched.

*Figure 30: Picture of a few pixels of the optical chip, before flip–chip bonding against a circuit driver. Large gaps between the pixels are clearly visible. The round shapes on top of each pixel are the metal bumps used to contact the pixels to the circuit driver.*
4.2.c A 128×128–pixel, amplitude modulator array

A device issued from the second process line was extensively characterised. The device was scanned along three lines with a beam of 1 mm in diameter and the position of the resonant cavity extracted from the reflectance profiles. The cavity length varies by less than 1 nm across the device, as shown figure 31. Although this figure is much lower than for large–area modulators, the consequence on the contrast ratio – or, more accurately, on the low–reflectance level – is still important. The reflected optical power was measured at the operating wavelength as a function of the applied bias at three important positions of the device: at the corner where the cavity is longest, the corner where it is shortest and at the centre of the device. The results are shown in figure 32. The reflected power in the corner is 70 % higher than at the centre. The direct consequence is that the number of separate grey levels at the chip level is limited, five in our case. Part of the reason for these high reflectance values is the low fill factor, as the inter–pixel area reflects a non–negligible amount of light.

![Figure 31: Position of the Fabry–Pérot cavity vs the horizontal position on the chip for three lines parallel to the pixel rows: at 1.5 mm from the top edge; in the middle of the chip; and at 1.5 mm from the bottom edge.](image)

The modulation speed of a device was measured and reached 11700 frames per second (fps). This is more than the 10 kfps the ICD was designed for. The modulation speed was limited by the computer card used to feed the SLM with data. The modulation signal measured optically when the SLM displayed alternating black and white images at full speed is shown in figure 33. Pictures taken with a CCD camera zooming on a small region of the SLM are shown in figure 34. The reflected light in the inter–pixel area is clearly visible.
Chapter 4: Examples of modulators

Figure 32: Reflected optical power vs bias voltage measured at the chip center and at the two corners where the cavity position is most extreme. Arrows show the bias voltages that should be used to have 5 grey levels through the device. For each gray level, a rectangles indicates the minimum and maximum reflected power. The insert shows 10 consecutive measurements at the central point, illustrating the repeatability of the method.

Figure 33: Maximum frequency modulation on an SLM, measured by displaying alternatively black and white pictures. The highest frame rate measured is 11700 fps.
Chapter 4: Examples of modulators

Figure 34: Detail of the pixel array of an SLM displaying an image. The inter-pixel region is clearly visible.
5 A modulating retro–reflector for free–space, optical communication

This chapter presents the principles of free–space, optical retro–communication, and the motivation for developing such a system. Our work focused on specific design problems and compromises related to the retro–communication module, the MRR. Prior art of such modules is discussed and our proposed solution is described.

Radio frequency–based communications, although a proven and very mature technology, have a number of limitations in certain circumstances: they are easily detected and susceptible to eavesdropping as they are not unidirectional, even though encryption can be used as a stop–gap; they can be jammed; and the unit sending data bears the burden of providing the power for the transmission, which can translate into large power–dissipation and power source requirements.

Asymmetric free–space optical links can be made to have none of these drawbacks and thus be a strong contender in this niche application. The idea underlying asymmetric links is to have a base station querying a unit for data. The queried unit can be a fixed, camouflaged sensor gathering data or an Unmanned Aerial Vehicle (UAV) with embarked sensors. The base station finds the unit location, directs an interrogating light beam to it and collects the reflected, modulated beam on its way back. The queried unit modulates the interrogating beam and reflects it back to the base station.

5.1 Prior art in free–space, optical retro–communication modules

The MRR is the opto–mechanical arrangement in charge of modulating the interrogating beam and reflecting it back to the right direction. The group of Gilbreath at the U.S. Naval Research Laboratory (NRL) has been the most active in this field. Two major types of designs have been proposed to date: focal–plane and corner–cube retro–reflectors.

5.1.a Focal–plane retro–reflectors

The solution involving focal–plane retro–reflectors is illustrated figure 35. The interrogating beam $B_i$ is directed at the lens $L$, which focuses it to a spot $S$ on its image focal plane. A reflecting device $R$, placed at the image focal plane, reflects the beam back into a beam $B_o$ through the lens to the direction it originates. If the modulation device is
transmissive, it can be placed in the beam path either close to the lens or between the lens and the reflector. If the device is a reflective modulator, it can be used as the reflector.

Beside their simplicity, solutions using focal–plane retro–reflectors have the advantage of providing a two–directional (2D) field–of–view (FOV). Also, as the usable focal plane area can be small depending on the focal length, small modulators can be used, resulting in a high achievable modulation speed — and a high link bandwidth. Over 16 Mb/s, limited by the control electronics, with a CR of 160:1 has been demonstrated by FOI [41]. Such systems have, however, a FOV limited to a few degrees and the reflected intensity depends on the viewing angle.

To overcome the FOV–limitation, several cat–eye designs were proposed. Biermann [42] proposed a diffraction–limited system using a parabolic reflector as the focal surface. A 2D FOV of 30 degrees in each direction is reported. However, since putting reflective modulators on a parabolic surface is not practical, the design can only accommodate large–area, transmissive modulators. A schematic of the design is shown

figure 36(A). Rabinovitch [43] proposed a cat-eye design using a telecentric lens pair and a flat focal surface. It uses a plane mirror in the focal plane and an array of small, transmissive modulators placed against the mirror. The reported half-power FOV is 30 degrees for short distances and 20 degrees for longer ones (the design is not diffraction-limited). A schematic of the design is shown figure 36(B).

5.1.2 Corner–cube retro–reflectors

A corner–cube is an assembly made of three mirrors placed perpendicularly to each other, as depicted figure 37. Commercial corner–cubes are available in the form of glass piece with three gold–covered faces and a disk–shaped entry surface. Gilbreath has reported on a free–space, optical link using a modulating retro–reflector composed of a corner–cube and a large–area, transmissive modulator placed at the entry surface of the corner cube. A FOV of 20 degrees and contrast ratios of 1.75:1 and 4:1 are reported for an applied bias between 12 V and 25 V. The system was demonstrated with the MRR embarked on a UAV [44].

5.2 Proposal for a modulating retro–reflector for free–space, optical retro–communication

5.2.a Geometrical design of the modulating retro–reflector

The existing designs of MRR focus on transmissive modulators, choosing to trade off the contrast ratio for a larger FOV. Our requirements when starting to study MRRs were
Chapter 5: A modulating retro-reflector for free-space, optical communication

substantially different from the literature at the time that we could not reuse an existing design as:

• A CR of at least 10:1 was expected for a maximum voltage swing of 10 V. This requirement pushed for the use of reflective, cavity–resonant modulators;

• The risk involved with developing the system, from the opto-mechanical design to the fabrication of a prototype, should be minimised. Reflective modulators are clearly easier to fabricate, especially at 850 nm, where the GaAs substrate is not transparent and has to be removed for transmissive modulators;

• The actual FOV to be obtained was not a hard constraint. Besides, it was possible to pack several MRR together to reach the specification.

Based on these specifications, a design using a reflective modulator and a corner cube was developed, in which the interrogating beam reflects on the large–area modulator, enters the corner cube and is retro–reflected back to the modulator and towards the interrogator, as shown figure 38(A). Although the modulator is sensitive to the angle of incidence, it quickly became apparent that it is possible to overcome this limitation.

If the beam is incident on the modulator at angle $\alpha$, as shown figure 38(A), then a variation of the viewing angle by $\delta\alpha$ in plane (xOz) results in a variation of the incidence of the same amount. If, however, the variation of the viewing angle happens in a different plane, for example in $P \parallel D$, a larger variation of the viewing angle is possible for the same constraints in incidence. The situation is illustrated in figure 38(B): the modulator is symbolised by the grey square centred on (xOy). The angle of incidence of the beam is initially along $V_{xz}$, forming an angle $\alpha$ with the normal (Oz) to the modulator surface. The viewing angle $\beta$ is varied in the plane containing the disk $D$ between $\beta = 0$ and $\beta = \beta_{\text{max}}$, the latter being pictured by vector $W$. Meanwhile, the angle of incidence on the modulator surface is given by:

$$\gamma = A\cos(\cos(\alpha) \cdot \cos(\beta))$$

and varies between $\gamma_{\text{min}} = \alpha$ and $\gamma_{\text{max}} = A\cos(\cos(\alpha) \cdot \cos(\beta_{\text{max}}))$.

As the viewing angle varies, so does the reflected intensity: when $\gamma \neq 0$, part of the beam reflecting on the modulator either misses the corner cube or the modulator on its way back. $\beta_{\text{max}}$ is defined as the smallest value of the viewing angle for which no power is reflected back. $\beta_{\text{max}}$ is a function of the distance between the modulator and the cube, as is discussed in Paper F. As a rule of thumb, we defined OP in figure 38(A) as the
Figure 38: (A): Geometrical arrangement for a modulating retro-reflector using a reflective modulator and a corner cube, and (B) 3D angles characterising the module. $\alpha$ is the initial angle of incidence of the beam when centred on the module and is the main design parameter of the module. $\beta$ is the viewing angle and varies between $-\beta_{\text{max}}$ and $+\beta_{\text{max}}$ (symbolised by vector $\mathbf{W}$). The angle of incidence of the beam on the modulator surface is $\gamma$.

The smallest distance which does not induce the cube to shadow the modulator. Indeed, a short distance is desirable: the shorter it is, the larger the FOV. On the other hand, shadowing the modulator is deemed unacceptable as part of the modulator is never used, which is costly in terms of money (yield, number of chips per wafer, etc) and performance (RC constant).

Figures 39 and 40 show how $\gamma$ and the reflected power, respectively, vary with the viewing angle. The reflected power varies almost linearly with $\beta$, providing a half-power FOV of 8 and 26 degrees for an $\alpha$ of 12 and 45 degrees, respectively. The variation of the incidence angle experienced by the modulator is very limited and within the constraints of resonant–cavity devices: 2.3 and 5.5 degrees for $\alpha = 12$ and 45 degrees, respectively. If it is not, it is possible to adjust it to a lower value by increasing the modulator–corner cube distance. This operation comes at a cost, however, as the FOV decreases.

Because the power varies linearly with the viewing angle, modules can be combined together, pointing at directions offset by $\beta_{\text{max}}$, providing a large FOV of constant reflected power. Figure 41 illustrates the case of a four–module system for...
Chapter 5: A modulating retro-reflector for free-space, optical communication

Figure 39: Angle of incidence $\gamma$ of the beam on the modulator surface as a function of the viewing angle $\beta$, for several values of the $\alpha$ design parameter.

values of $\alpha$ of 12 and 45 degrees: full-power FOVs of 24 and 78 degrees and half-power FOVs of 32 and 104 degrees are obtained.

The FOV in other direction (rotation along (Oy)) has not been discussed so far. It does not benefit from the same effect as in $\mathcal{P}(\mathcal{D})$ and a variation of $\alpha$ impacts $\gamma$ by the same amount. Hence, the proposed design is well adapted for applications needing a substantial FOV in one direction only.

Figure 40: Reflected power as a function of the viewing angle $\beta$, for several values of the $\alpha$ design parameter.
5.2.6 Fabrication of a four-module system

A mechanical assembly, composed of four MRR in a protective box was designed and fabricated. Each MRR assembly is adjustable to accommodate the characteristics of individual modulators: $\alpha$ is adjustable by two screws and the distance between the modulator and the cube can be changed by replacing a spacer. A drawing taken from the Computer Aided Design (CAD) modelling of the system is shown in figure 42.

Pixellated modulators were used, as described in chapter 4.1. To provide temperature stability, the devices were mounted on Peltier elements and actively cooled. The system was tested successfully with transfer of pseudo-random data at 8Mbit/s over a 100 m link. CAD drawings of the full system are shown in figure 43 and a picture of the four-module system can be seen in figure 44.
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Figure 42 CAD modelling of a modulating retro-reflector, as part of a 4-modulator system.

(A) (B)

Figure 43: CAD drawings of the four-module retro-communication system: (A) side view of a two-module part; and (B) top view of the assembled system, without its top cover.
Chapter 5: A modulating retro-reflect for free-space, optical communication

Figure 44: Picture of an assembly consisting of four modulating retro-reflectors, as part of a free-space, optical retro-communication system.
6 Guide to the papers

Paper A: Multiple quantum well spatial light modulators for correlation–based processors

This paper reviews the requirements set by optical correlators used as pattern recognition systems on the performance of SLM. The performance of different coding domains are evaluated. Designs of MQW electro–absorption modulators are proposed and their coding domains discussed. The performance of the time–averaged pseudo–random encoding technique is evaluated. It is shown that it is well adapted to the coding domains of MQW SLMs.

**Contribution of the author:** modelling of the modulators and calculation of their coding domains, writing of eight pages (40 %) of the article.

Paper B: Multiple quantum well spatial light modulators: design, fabrication, characterization

This paper was a report of the initial work at Acreo on MQW SLMs in 2001. Results on single pixel amplitude modulators and initial work on a ternary, amplitude and phase modulator array is presented.

**Contribution of the author:** optical modelling of the modulators, all characterisation, writing of the article.

Paper C: Two–dimensional GaAs/AlGaAs multiple quantum well spatial light modulators

This paper compares two process lines for the fabrication of MQW SLMs. In the first line, the top side of the epilayer is the one to be in contact with the circuit driver. The epilayer is directly processed into pixellated chips, the wafer is diced into devices, devices are flip–chip bonded to their circuit driver and the GaAs substrate is finally removed from the optical chip. In the second process line, the top side of the epilayer is the optical surface. It is bonded to a transparent substrate and the GaAs substrate is removed. The epilayer is then processed into pixellated chips, diced into devices, and devices are flip–chip bonded to their circuit driver.
Chapter 6: Guide to the papers

**Contribution of the author:** optical modelling of the modulators, all characterisation to prepare the structure epitaxy, part of the discussions on the two processing lines.

**Paper D: Fabry–Pérot Electroabsorption Modulators for High-Speed Free-Space Optical Communication**

This paper discusses yield and modulation speed issues of large-area, reflective MQW modulators. The modulators presented have 15×15 mm active areas and exhibit contrast ratios of 8 dB for a voltage swing of 8 V. A modulation frequency in excess of 10 Mhz was measured. A wafer-level fabrication process was used, and devices were pixellated to increase the yield and modulation speed.

**Contribution of the author:** optical modelling of the modulators, all characterisation to prepare the structure epitaxy, part of the discussions on yield and speed improvements.

**Paper E: GaAs–based multiple quantum well spatial light modulators fabricated by a wafer–scale process**

This paper presents the design, fabrication and characterization of large, two-dimensional multiple quantum–well modulator arrays. Such arrays present potential for very high modulation speeds, being limited only by the RC constant of the pixels. The design compromises to reach high–contrast, low–voltage swing optical structures compatible with CMOS–based integrated circuits are discussed and experimental results are present. Contrast ratio of 5:1 (limited by the fill factor), variations in uniformity below 1 nm and frame rates in excess of 10 kHz are demonstrated. Technology maturity for volume production is also discussed.

**Contribution of the author:** optical modelling of the modulators, all characterisation to prepare the structure epitaxy, all characterisation of the devices, writing of the paper.

**Paper F: A modulating retro–reflector for free–space optical communication**

This paper presents the modelling of a free–space, optical retro–communication module
Chapter 6: Guide to the papers

composed of a reflective, resonant–cavity modulator and a corner cube. Although resonant–cavity modulators are sensitive to the angle of incidence of the light beam, we show that with the right geometrical arrangement the module can have a field-of-view more that 10–fold that of the modulator. The module modelling is validated by experimental data using a corner cube and a 14mm×4mm MQW modulator.

Contribution of the author: optical modelling of the modulators, all characterisation to prepare the structure epitaxy, optical characterisation of the device, design of the opto–mechanical arrangement, writing of the paper.


7 Conclusion

7.1 Achievements

This thesis described the successive steps needed to design, fabricate and characterise surface-normal, reflective resonant-cavity optical modulators based on GaAs material using a wafer-scale process.

The modelling tools used to design modulator structures have been presented, and the main compromises in structure design – in particular those related to the selectivity of the resonant cavity – have been discussed. The key fabrication methods and characterisation techniques: growth by MOVPE, SIMS, XRD, reflectance profiles have been introduced and their impact on device performance has been presented. Effects related to device uniformity have been presented, as they are one of the main concerns with resonant-cavity modulators and particularly with the large-area ones.

The author’s contribution to the field of surface-normal, electroabsorption modulators has been in addressing some uniformity aspects of modulator designs to allow the fabrication of devices on full 4 inch wafers. The most evident achievements of the work presented are the two devices presented in chapter 4, both of which have been fabricated using a wafer-level process. With the fabrication of large-area modulators, issues related to device yield and RC limitations of the modulation frequency have been addressed. On the design side, a limited cavity selectivity has been chosen. It has made devices less sensitive to variations of the resonance wavelength and growth non-uniformity. A modulated optical signal of 8 Mb/s has been measured on such devices. Paper F reported on the optical characterisation of one such device.

The other device presented is a 128×128-pixel amplitude modulator array. Paper E reported on the fabrication and characterisation of such a device. A frame-rate of over 11 000 fps was demonstrated with a contrast ratio of 5:1. The devices were driven by a standard CMOS circuit driver applying a voltage swing of only 5 V.

The opto-mechanics for a free-space, optical retro-communication receiver composed of four modulating retro-reflectors (MRR) was designed and fabricated. Paper F reported on the opto-mechanical design of one such module and the achieved contrast ratio of 25:1 for one MRR. The design originality is its leverage of the high contrast ratio attainable with reflective, resonant-cavity modulators in an MRR. To the author’s knowledge, it is the only demonstration of a reflective, resonant-cavity modulator in a reflecting retro-reflector.
7.2 Future work

Phase modulators: there is a clear interest in fast, phase-flip modulators and especially two-dimensional arrays of modulators for coherent free-space optics. Although single-pixel phase-flip modulators have been demonstrated by Trezza [32], no work on arrays has been reported. There are certain hurdles to overcome to achieve working arrays; the variation in electric field across the MQW structure between the two phase states is more than twice that of amplitude modulator, which make it difficult to drive by standard CMOS circuit drivers. More efficient modulator structures, requiring lower voltage swings need to be designed and fabricated. At the processing level, the uniformity across the devices has to be sharply increased, as a uniform reflectance is a key to turning displayed phase patterns into accurate intensity shapes needed by applications such as optical tweezers.

Advanced structures: the modulator designs have to be improved to increase contrast ratios while at the same time making the devices more robust to variation of the layer thickness within the device or other process-related inaccuracies. Devices need also to be less sensitive to the incidence of the light beam. Coupled-cavities have been proposed to decrease the selectivity of resonant devices. Also, several types of advanced shapes of quantum wells and coupled wells have been proposed to increase the absorption or change the absorption/phase shift behaviour of modulators [45][46][47][48][49].

Other absorbing media: Other absorbing media should be investigated and their potential for amplitude or phase modulators evaluated. In particular, quantum dots [50] might be adapted to the requirements of such devices.
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