FOI
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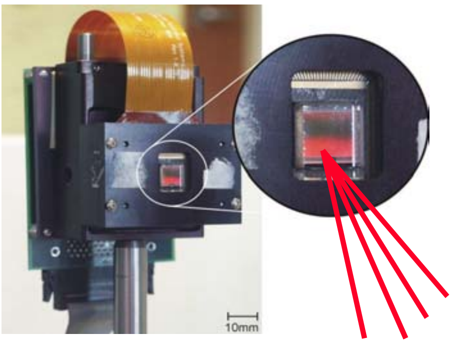
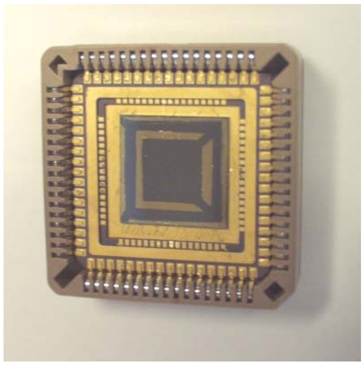
FOI-R--1220--SE
March 2004
ISSN 1650-1942

User report

Lars Sjöqvist, Emil Hällstig, Johan Öhgren, Lars Allard

Retrocommunication - final report





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Issuing organization	Report number, ISRN	Report type
FOI – Swedish Defence Research Agency Sensor Technology P.O. Box 1165 SE-581 11 Linköping	FOI-R--1220--SE	User report
	Research area code 4. C4ISR	
	Month year March 2004	**Project no.** E3831
	Customers code 5. Commissioned Research	
	Sub area code 41 C4I	
Author/s (editor/s) Lars Sjöqvist Emil Hällstig Johan Öhgren Lars Allard	**Project manager** Lars Sjöqvist **Approved by** Svante Ödman **Sponsoring agency** FMV/HKV **Scientifically and technically responsible** Lars Sjöqvist	

Report title

Retrocommunication - final report

Abstract (not more than 200 words)

Novel techniques for free-space optical communication at high data transfer rates are of interest for future military application. Retrocommunication provides a technique to transfer data from small platforms using an asymmetric data link. Retrocommunication has been a sub-project within the Swedish Defence Photonics project and this report contains a summary of the main results obtained within the project.

The novel technologies studied were multiple quantum well (MQW) optical modulators for communication and spatial light modulators (SLMs) based on liquid crystal materials for non-mechanical beam steering. Within the project reflective MQW modulators with high contrast and capable of high data rates have been developed. Non-mechanical beam steering techniques were evaluated experimentally and by developing performance models. A retroreceiver based on MQW modulators and a transceiver using non-mechanical beam steering were developed and fabricated.

In the final phase of the project a retrocommunication link using MQW modulators and non-mechanical beam steering was demonstrated. Link establishment and tracking of the movable retroreceiver during data transfer were shown. The link was in real time capable of transferring audio signals and images captured by a CCD camera.

Keywords

Retrocommunication, MQW, quantum wells, beam steering, SLM

Further bibliographic information	Language English
ISSN 1650-1942	**Pages** 25 p.
	Price acc. to pricelist

Utgivare
Totalförsvarets Forskningsinstitut - FOI
Sensorteknik
Box 1165
581 11 Linköping

Rapportnummer, ISRN
FOI-R--1220--SE

Klassificering
Användarrapport

Forskningsområde
4. Spaning och ledning

Månad, år
Mars 2004

Projektnummer
E3831

Verksamhetsgren
5. Uppdragsfinansierad verksamhet

Delområde
41 Ledning med samband och telekom och IT-system

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Uppdragsgivare/kundbeteckning
FMV/HKV

Tekniskt och/eller vetenskapligt ansvarig
Lars Sjöqvist

Rapportens titel (i översättning)
Retrokommunikation - slutrapport

Sammanfattning (högst 200 ord)

Ny teknik för fri optisk kommunikation med höga överföringshastigheter är av stort intresse för framtida militära tillämpningar. Retrokommunikation erbjuder en teknik att överföra data från små plattformar genom att använda en asymmetrisk länk. Retrokommunikation har varit ett delprojekt inom Försvarsmaktens fotonikprojekt och den här rapporten summerar resultat som erhållits inom projektet.

Nya teknologier för kommunikation baserade på optiska kvantbrunnsmodulatorer (MQW) och ljusmodulatorer (SLM:er) som utnyttjar vätskekristaller för icke-mekanisk strålstyrning har studerats. Inom projektet har reflektiva MQW-modulatorer med hög kontrast samt med höga bandbredder utvecklats. Icke-mekanisk strålstyrning utvärderades experimentellt och genom att utveckla prestandamodeller. En retromottagare baserad på MQW-modulatorer och en transceiver som använder sig av icke-mekanisk strålstyrning utvecklades och tillverkades.

I den slutliga delen av projektet demonstrarades en retrokommunikationslänk som använder MQW-modulatorer och icke-mekanisk strålstyrning. Länketablering och målföljning av den mobila retromottagaren under dataöverföring visades. Via länken överfördes i realtid audiosignaler och bilder som registrerats med en CCD-kamera.

Nyckelord
Retrokommunikation, MQW, kvantbrunnar, strålstyrning, SLM

Övriga bibliografiska uppgifter

Språk Engelska

ISSN 1650-1942

Antal sidor: 25 s.

Distribution enligt missiv

Pris: Enligt prislista

CONTENT

1. INTRODUCTION

Novel photonics component technologies provide new opportunities for free-space optical communication links in military applications. The increasing demand for high data transfer rates makes optical communication links interesting in future communication networks. New sensors that generate high amount of data need fast information transfer to provide e.g. the command and control functions with information for fast decisions. Retrocommunication is a technique that has attracted a lot of interest recently[1]. This new technique has been studied and evaluated as a sub-project within the *Swedish Defence Photonics Project*. Retrocommunication is based on the principle that an interrogating laser is used to extract information from a retromodulating receiver where the laser light is modulated and reflected (in the same direction) back to the transmitting unit (Figure 1). The retromodulating receiver consists of an array of retromodulators. In the retrocommunication project new multiple quantum well (MQW) modulators have been developed and fabricated. In addition, techniques for non-mechanical beam steering using liquid crystal (LC) spatial light modulators (SLM's) have been studied.

State of the art technology based on MQW technology is capable of transferring data of the order of tens of Mbits/s. Naval Research Laboratory (NRL), USA, has demonstrated a data link to an unmanned aerial vehicle (UAV) over shorter distances[2]. Advantages using this technique include e.g. low weight and small volume, low power consumption, technical simple solution and a large field of view reducing the pointing requirement for the interrogating laser transceiver (i.e. mechanical stabilisation of the retromodulator can be neglected). Since no active transmitter is used by the retroreceiver the risk for revealing link is low. Asymmetric communication using MQW technology has several interesting tactical applications in future military heterogeneous communication networks. Transfer of information from small low weight airborne platforms, or temporary installed information nodes in tactical positions, communication to buoys on the water surface utilised by submarines for information exchange, are some examples of applications. This technology can also be used for identification purposes in order to recognise friend or foe of selected target. Future links may include transfer of data from an UAV to the ground or vice versa, between airborne platforms, between combat vehicles, from UAVs to individual combat units (soldiers) etc.

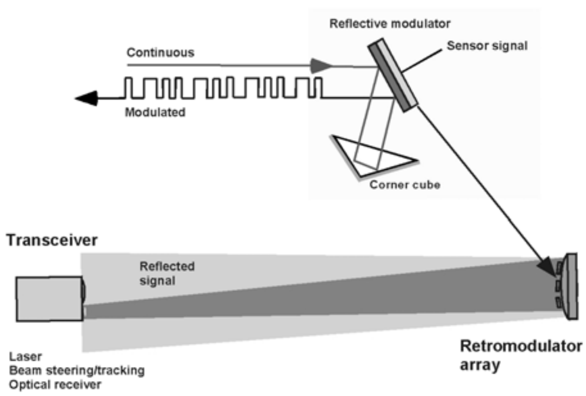


Figure 1 Principle of retrocommunication.

New technology for laser beam steering and tracking is of considerable interest for several military laser applications[3,4]. Optical phased array techniques utilise phase modulation and alter the properties of the light. Spatial light modulators have been evaluated for beam steering and shaping. Several SLM technologies such as; micro mechanical mirrors, MQWs and liquid crystals, have developed rapidly during the recent years. Liquid crystal components are one class of devices exhibiting attractive features for future beam steering devices. From the application point of view, traditional systems based on mechanical mirrors and gimbals are complex, expensive, occupies relative large volume, possess high weight and have high power consumption.

This report summarises the results from the retrocommunication project obtained during 2001 to 2003. During the project technology for MQW retromodulators were developed and a retromodulating receiver was fabricated. Techniques for non-mechanical beam steering and tracking have been presented utilising LC SLMs. A transmitter/receiver unit based on non-mechanical beam steering was developed and evaluated. The project was completed by a technical demonstration showing non-mechanical beam steering and tracking implemented in a retrocommunication link.

2. PROJECT ORGANISATION AND OBJECTIVES

The project was divided into two phases, where basic component technologies were investigated during the first two years[5]. The third year was devoted to a technical demonstration showing the principle of retrocommunication combined by non-mechanical beam steering[6].

The main objectives of the retrocommunication project, as defined in the project definition, were[5]:

- Demonstrate retrocommunication in combination with non-mechanical laser beam control
- Demonstrate laser beam control function such as e.g. link establishment, target tracking and simultaneous data transfer up to approximately 1 km range
- Demonstrate retromodulating techniques capable of transferring data rates of the order 10 Mbits/s
- Evaluate SLM techniques based on liquid crystals for laser beam control in the retrocommunication application
- Evaluate techniques based on MQW modulators for implementation in retrocommunication.

The two component technologies studied in the project were: SLMs based on LC materials and MQW optical modulators. During the first two years of the project three separate main activities were carried out; evaluation and performance studies of novel LC SLM techniques for beam steering, development of MQW optical modulators and experimental and theoretical work on evaluating sub-components. In addition a system study was completed during the first year of the project. After two years the results from the component studies were reviewed and the appropriate techniques for laser beam control and retromodulation were chosen.

The technical demonstration aimed to show the component technologies studied during period I in a retrocommunication function demonstrator link. The technical demonstration objectives were slightly altered compared to the goals defined above[7]. The main difference was the range for the communication link, which was limited to 180 m allowing the demonstration to be performed indoor at the "roof" laboratory at FOI. The purpose of the technical demonstration was to demonstrate principles and functions of the novel communication system described to outline future capabilities.

Three different organisations participated in the project: FOI (Dept. of Laser Systems), ACREO (Dept. of Imaging) and Chalmers University of Technology – CTH (Photonics Laboratory, Diffractive optics group, Liquid Crystal group). The main responsibilities and activities within each organisation were as follows:

FOI
Project coordination
Responsible for a systems study in the initial project phase
Evaluation of nematic LC SLMs for beam control
Fabrication of a transceiver module based on non-mechanical beam steering
Evaluation of MQW optical modulator performance
Responsible for the technical demonstration (together with the optics group at CTH)

ACREO
Responsible for development of MQW optical modulators
Development of performance/design models
Modulator processing
Evaluation of optical and electrical properties of MWQ modulators
Development and fabrication of retromodulating receiver

CTH Liquid Crystal Group
Development of a ferroelectric (FLC) SLM beam steerer based on novel high tilt angle principles
Evaluation of new materials for beam control using anti-ferroelectric LC
Evaluation of a material for beam steering using V-shaped switching FLC
Development of a beam steering SLM based on V-shaped switching FLC
Studies of driving wave forms for novel LC materials

CTH Diffractive Optics Group
Evaluation of optical characteristics of a beam steerer using high tilt FLC material
Tracking and scanning principles using LC SLM's
Algorithms for tracking and beam steering
Experimental studies of performance properties of beam steering and tracking using LC SLMs

3. DEVELOPMENT OF QUANTUM WELL MODULATORS

The technology preferred for retromodulators is based on multiple quantum wells (MQW) using the AlGaAs/GaAs material combination. A reflective layout of the component was chosen in order to obtain a high contrast ratio. Moreover, the process technology used favoured fabrication of reflective devices. In addition to MQW retromodulators, transmissive modulators based on ferroelectric LC materials were studied initially in the project focusing on system issues and principles of retrocommunication. The final part of the project involved development of a retromodulating receiver with corresponding optics, mechanical assembly and control electronics.

3.1. Reflective MQW modulators

Multiple quantum well modulators utilises a phenomenon called the quantum confined Stark effect to alter the reflectivity of the component. This effect is also named electro-absorption. Altering the electrical field over the quantum well structure controls the reflectivity of the modulator. Drive voltages of the order, 8 to 12 V, is required to change the reflectivity. The change in the electrical field causes a shift in the absorption features (or reflectivity) with respect to wavelength. The MQW modulator has a narrow wavelength band (approximately 1-2 nm) and operates in the region λ = 845 to 860 nm when the material combination AlGaAs/GaAs is used. The operating wavelength is determined by the geometrical and material properties of the modulator. The basic principles for the MQW modulator technology has been presented in ref.[8,9].

3.1.1. Modulator configuration

The developed MQW modulators utilised a reflective design where the quantum wells were placed between two Bragg mirrors constituting a Fabry-Perot (FP) cavity. The reflective AlGaAs/GaAs structure is grown on a GaAs substrate (Figure 2). The FP cavity was incorporated in order to maximize the optical contrast of modulator. In the first phase of the project models were developed to simulate electro-absorption, electro-refraction and resonance effects. The models were used to optimize geometric parameters affecting the performance of the modulators. Fabricated test structures were compared with the models in order to tune the modulator parameters to obtain optimal performance. The developed models consisted of a suite of programs described in detail previously[8]. Simulated performance parameters were e.g. contrast ratio, response time, reflectivity, etc.

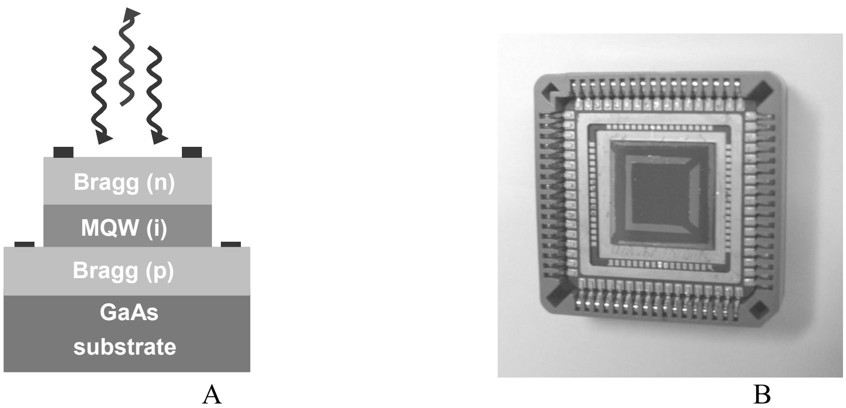


Figure 2 A) Schematic structure of a reflective AlGaAs/GaAs MQW modulator. B) Photograph depicting a reflective AlGaAs/GaAs MQW modulator. From ref. [9].

Optimisation techniques based on simulated annealing were utilised in the optimisation process. In addition, models to simulate the electrical characteristics were developed. The electrical characteristic provides information about the temporal properties of the modulators. Extensive calculations were performed to optimise the modulator structure with respect to the angle of incident of the light impinging on the modulator [9]. An optical model of the final retromodulator receiver was developed and the structure of the optical assembly was optimised[10].

3.1.2. *Fabrication*

The modulators were fabricated using standard metal organic vapour phase epitaxi (MOVPE). The fabrication procedures have been described in detail elsewhere[8]. In the first phase of MQW modulator design single chip processing techniques were utilised. An iterative procedure was used between successive fabrication, evaluation and simulation steps. Different layouts of the modulator structures were investigated. Initially large aperture (~10x10 mm^2) modulators were fabricated. However, problems with yield (several modulator structures appeared to have short-circuits) and limited response time suggested multi-pixel structures. An example showing typical structures investigated is show in Figure 3. As illustrated both single- and multi-pixel structures were fabricated. Small single-pixel (dimensions ranging from 3x3 to 0.25x0.25 mm^2) modulators were considered for focal-plane applications. After optimisation of the structures and processing parameters full wafer processing were utilised providing a considerably higher yield of modulators to be characterized.

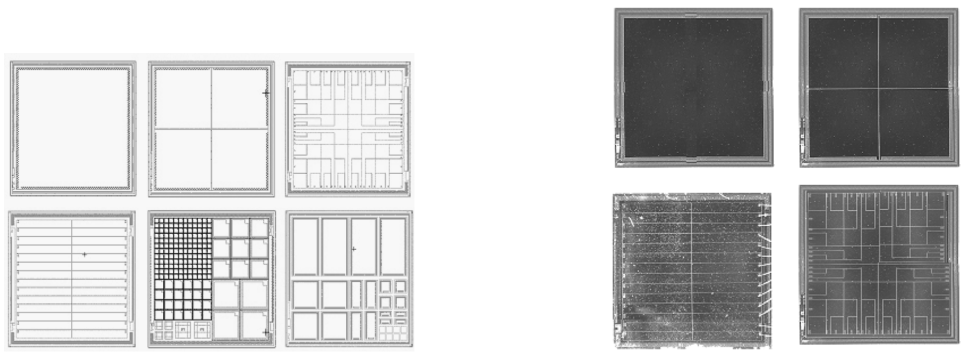
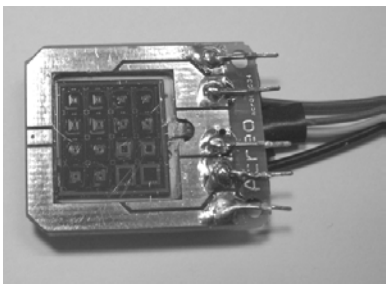


Figure 3 A) Lithographic mask sets showing fabricated and evaluated modulator structures. B) Fabricated modulators.

An example of fabricated focal plane single pixel MQW modulators is depicted in Figure 4A. Different dimensions were investigated and a simple experimental setup for the focal plane was used as exemplified in Figure 4B. Some experimental results showing modulation properties of focal plane retromodulators are presented in ref.[11]. One advantage of using smaller pixel dimensions and several pixels driven in parallel is the increased speed of the modulator.



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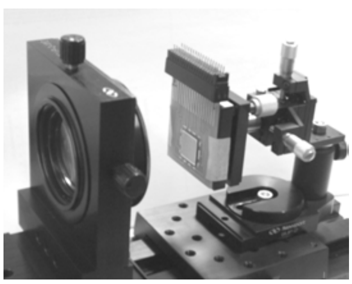

B

Figure 4 A) Example showing fabricated MQW focal plane modulators. B) Example of a focal plane experimental evaluation setup.

3.1.3. Characterisation of modulator properties

Several characterisation methods were utilised during the optimisation and fabrication of the MQW modulators[8,9,12,13]. For example, SIMS, Photoluminescence, X-ray diffraction and Spectrophotometry were employed. One simple and powerful method for characterising MQW modulators is to study the I-V characteristic of the p-i-n structure. I-V measurements provide information about the electrical contacts (which may limit the speed of the modulator) and the characteristic electrical response of the modulator. Examples of results from characterisation and evaluation of different MQW structures can be found in previous reports[8,9]. Emphasis was also concentrated on the electric drive electronics of the modulators. If high speed (above 10 MHz) is required attention is required regarding the drive electronics. During optimisation of reflective optical modulators dedicated drive electronics was considered and developed. The goal was to construct drive electronics that did not limit the response time of the MQW modulators.

3.2. Evaluation of performance

Several properties of the MQW modulators were studied experimentally. These studies were performed in an iterative manner providing feedback to the design and fabrication steps. The most important factors related to the performance of the modulators are; the temporal bandwidth, contrast ratio and the influence from the angle of incidence. In addition, polarisation properties of the MQW modulators were investigated[14]. Performance was studied both in experimental set-ups on the optical table and over longer ranges (up to 180 m)[15]. An example showing contrast behaviour and temporal response of the MQW modulators is depicted in Figure 5.

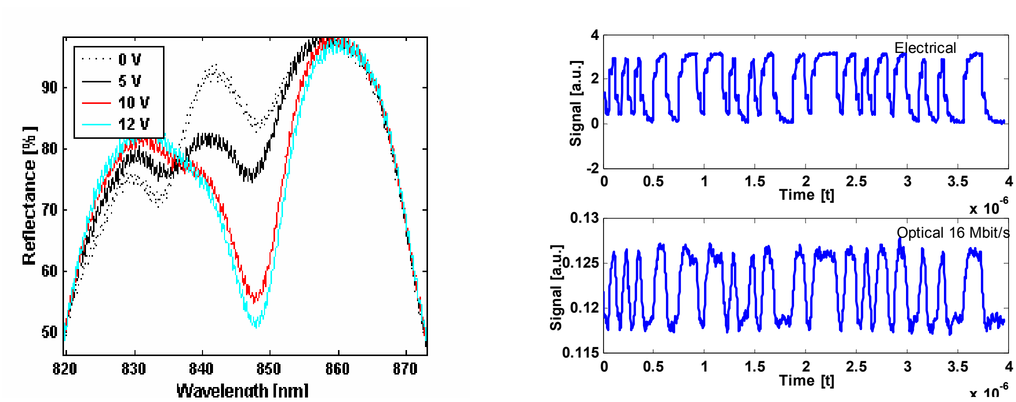

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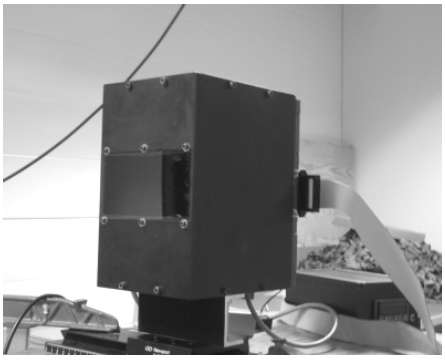
Figure 5 A) Example showing alterations in the reflectivity as a function of the modulator drive voltage. B) Example of temporal response of small single-pixel modulators using a bit stream as electrical signal at 16 Mbit/s. From ref.[9,11].

The large aperture MQW modulators showed excellent modulation properties (studying bit streams) up to approximately 7-8 Mbit/s. Considering the smaller MQW modulator structures transfer rates up to 16 Mbit/s has been demonstrated. In the retrocommunication application the reflective MQW modulator is combined with a retroreflector to constitute a part of the retromodulating receiver (see below). Contrast ratios of the order 10:1 have been obtained using the combined MQW modulator and retroreflector. Using single MQW modulators contrast ratios as high as 160:1 has been observed. Another important performance characteristic is the effective field of view. Since the developed structures utilises a FP design the angle of incidence is a critical parameter. Experimental results have shown that the best performance was obtained for an angle of incidence of 20 degrees (of the light impinging on the modulator). The field of view of the optimised modulators was ±10 degrees.

3.3. Development of a retromodulating receiver

The final objectives with the optimisation and fabrication of reflective MQW modulators described above were to construct a retromodulating receiver capable of demonstrating the technology in a novel retrocommunication link (Figure 6). The retromodulating receiver contains mainly three parts; the mechanical housing and assembly, the optical modulators with corresponding retroreflectors and the control and drive electronics. A thorough description of the development of the retromodulating receiver has been presented in ref. [10].

A geometrical model was developed to investigate design parameters for the mechanical assembly housing the optical sub-components. Moreover, the optical design of the retromodulator receiver was studied by modelling the combined MQW modulator and the retroreflector in an optical ray-tracing program (Zemax). The final design of the retromodulating receiver consisted of four separate optical modulators having individually adjustment possibilities with respect to the optical axis. Each modulator unit consisted of a pixelated (14x2 rectangular pixels) reflective MQW modulator and a retroreflector. Details about the geometrical features of the retroreceiver can be found ref. [10]. The retromodulating receiver had a ±10 degrees field of view. The field of view was adjustable by moving each separate sub-modulator independently. The mechanical assembly was modelled using a CAD software. Optimised MQW modulators were implemented in the retroreceiver and the performance has been described [10]. The operating wavelength of the receiver was 850 nm.



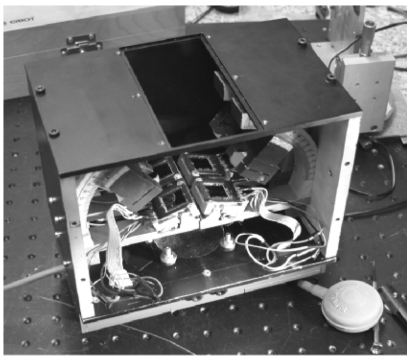


Figure 6 A) Retromodulating receiver assembly. B) Four reflective MQW modulators and retroreflectors constituting the optical assembly. From ref.[10].

In addition to the mechanical and optical sub-systems, control and drive electronics were developed. Separate temperature controllers were used to stabilise the temperature of each MQW modulator. Drive electronics was designed and fabricated capable of providing accurate signals to the modulators from bit streams generated by a computer or a pseudo random bit sequencer

(PRBS). All parts were mounted in a housing with an optical window to provide a device relatively insensitive to mechanical perturbations.

The fabricated retroreceiver was evaluated over longer ranges (up to 180 m) transmitting bit streams generated by a PRBS. Transfer rates up to 7-8 Mbits/s have been demonstrated with the present device. Performance was investigated varying parameters such as e.g. angle of incidence of the light, FOV of the retroreceiver, polarisation and data rates etc. planning for the technical demonstration of the retrocommunication link.

Summarising the results related to development of MQW optical modulators; reflective modulators have been optimised and fabricated, high contrast ratios have obtained and data rates up to 20 Mbit/s have been demonstrated (limited by drive electronics). Several novel geometries have been developed and evaluated. Proof of principles has been demonstrated by transferring signals at 180 m range.

4. NON-MECHANICAL BEAM STEERING

Another novel component technology studied in this project was non-mechanical laser beam steering and control using liquid crystal SLMs [16]. Basically this activity has been divided into two tasks; evaluation of state of the art nematic LC SLMs available as commercial components and development and evaluation of new LC SLMs for beam steering utilising novel materials and concepts. In the first phase of the project both efforts were concentrated on both these two activities. However, during the final phase, related to the technical demonstration, the major emphasis was on implementing nematic LC SLMs into a transceiver capable of non-mechanical beam control. The principles for non-mechanical beam steering have been described in detail previously and the reader is referred to ref [3].

4.1. Nematic liquid crystal spatial light modulators

Nematic LC SLMs have the advantage that analogue phase modulation of light can be accomplished. The drawback of these devices is the relative slow response time, order of 10-30 ms, limiting the applicability in applications that requires a fast response. Nematic SLMs fabricated on silicon backplane addressing circuits are available commercially for evaluation. In this project, a 128x128 two-dimensional and 1x4096 one-dimensional reflective devices have been studied for beam control and beam steering (Figure 7A). From the application point of view beam control means link establishment and tracking.

Nematic liquid crystal SLMs have been studied with respect to properties such as beam steering efficiency, phase and space quantisation effects [17,18,19,20,21]. The main objective with the extensive evaluation of NLC SLMs was to optimise the performance. The common method to perform beam steering utilise blazed phase gratings as modulation patterns. Since the voltage to phase relationship (transfer function) is not known the first step is to measure it for the individual SLM, see Figure 7B. Several methods aiming to determine the phase to voltage relationship have been studied[17]. Moreover, properties of the SLMs such as phase quantisation due to limited number of bits and spatial quantisation due to pixelation effects cause intensity variations and reduced beam steering efficiency[20].

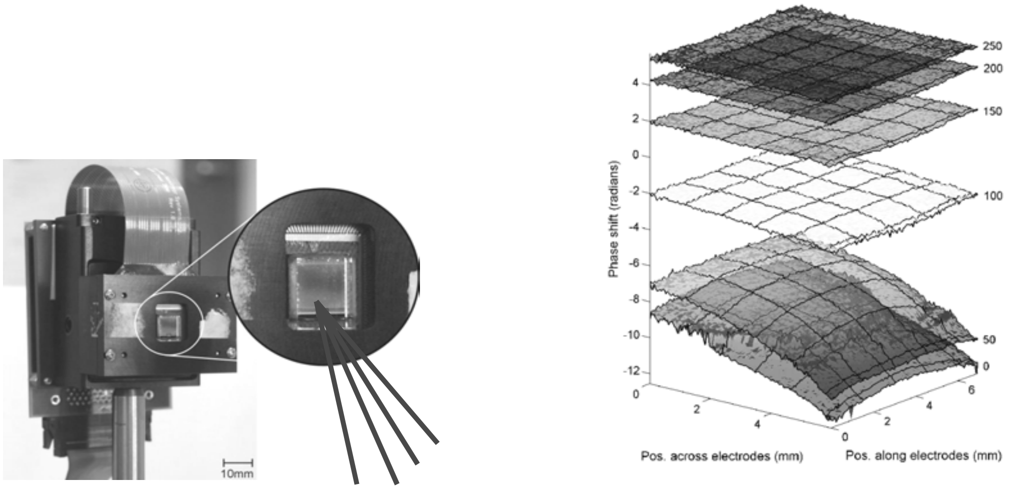


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Figure 7 A) Photograph showing a reflective NLC SLM designed for phase modulation. B) Example showing the phase modulation as a function of the applied voltage for different electrodes on a 1x4096 SLM. The command voltage, ranging from 0 to 250, is proportional to the actual addressing voltage on the electrodes.

Different methods to optimise the performance of a 1x4096 NLC SLM having small pixel dimensions have been studied[22]. The developed methods improved the beam steering efficiency. The effective maximal beam deflection angle was of the order ±2 degrees. Different tracking methods and algorithms have been studied experimentally using SLMs for beam steering[22,23 ,25]. An optimised beam steering NLC SLM was characterised for implementation in a transceiver unit. The SLM operated at 30 Hz frame rate, 850 nm wavelength and utilised dedicated software for control of individual pixels.

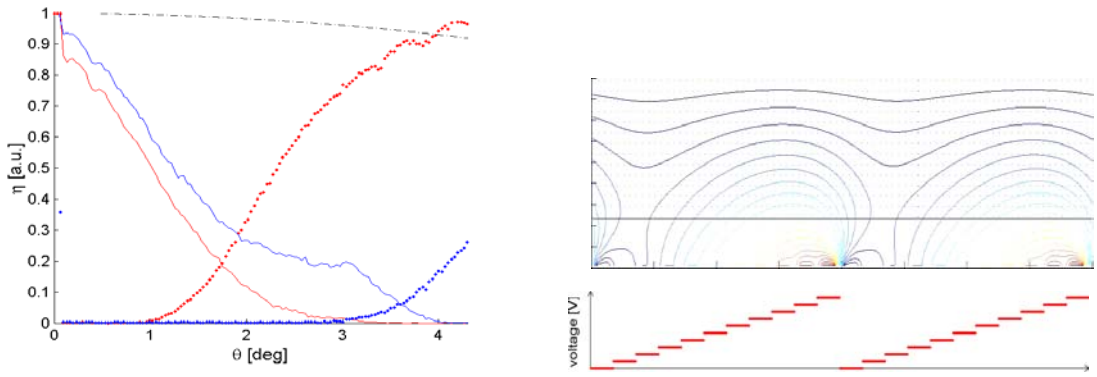

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Figure 8 A) Beam steering efficiency using a 1x4096 NLC SLM showing the steering efficiency of the first and zero orders as a function of deflection angle (solid – first order, dotted – zero order). The blue curve show optimised performance whereas red is un-optimised. B) Example showing the electrical field within the LC layer in a nematic SLM used for modelling fringing field effects [18].

Performance limiting effects appearing in form of fringing fields have been studied experimentally and by developing models for the LC dynamics and optical field propagation through the SLM. The model is based on solving equations governing the visco-dynamics in presence of an electrical field and finite difference time domain (FDTD) methods for propagation of the optical field[18,24]. Using the model and experimental results knowledge of methods to improve the performance of the beam steering device was extracted. In addition, polarisation effects occurring during light propagation through NLC SLMs have been studied[24].

4.2. Ferroelectric liquid crystal modulators

During the project a novel beam steering component developed at CTH using two cascaded ferroelectric LC (FLC) SLMs was developed and evaluated, see Figure 9[25,26,27]. The FLC SLMs uses a high tilt angle FLC material capable of phase-only modulation without losses in the optical power. The principle of the beam steering device is to image the first SLM onto the second on a 1:1 pixel basis (Figure 9B). Using this scheme four discrete phase levels are obtained. In addition to the optical part of the component drive electronics and control software (using a PC) were developed. The high tilt angle FLC beam steerer has been described in detail previously and thoroughly evaluated experimentally focussing on alignment procedures and performance regarding beam steering efficiency[27]. The advantage of using FLC materials compared to nematic is the reduced time response of the former. The beam steering schemes using four phase levels were also studied for tracking experiments using the FLC beam steerer and a nematic SLM to simulate four discrete phase levels[25].

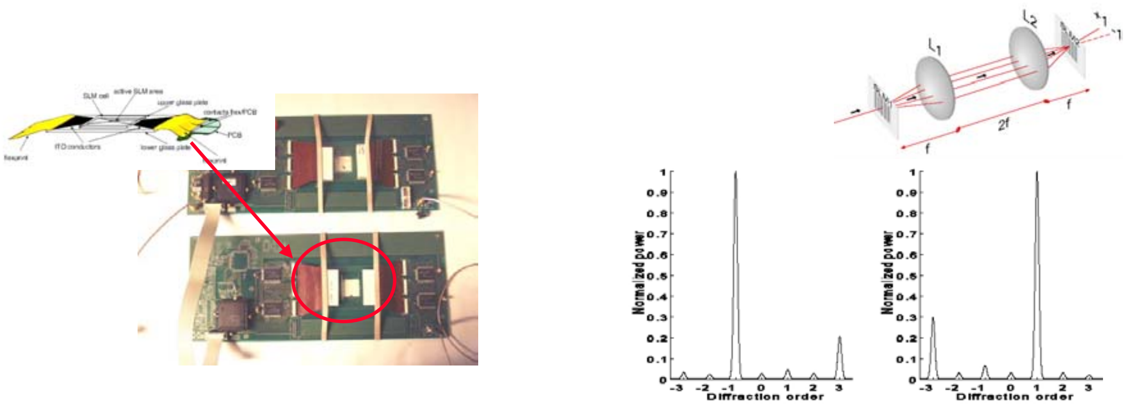

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Figure 9 A) Laser beam steerer based on two cascaded FLC SLMs using high tilt angle. B) Optical setup and example of far-field beam steering efficiency.

4.3. New liquid crystal materials for beam steering

New novel liquid crystal materials and schemes for laser beam steering were studied during within the project. The main activities (excluding high tilt FLC SLMs described above) were focused on evaluating antiferroelectric liquid crystal (AFLC) material and V-shaped switching FLC for beam steering applications. The results from these studies have been summarised in ref.[28].

The advantage of AFLC materials is the potential to develop a SLM capable of phase-modulation using three discrete phase-levels. Within the project several orthoconic AFLC materials were investigated[29]. One problem related to orthoconic AFLC is the surface stabilisation process. In order to operate in a beam steering application the helical pitch of the material needs to be of the order of the cell thickness. However, the investigated materials exhibited too short helical pitch, less than 1 μm, to be used in a cell with 2.7 μm thickness[30]. The conclusion from the studies of AFLCs is that present materials do not fulfil requirements to be implemented in beam steering applications. New material exhibiting longer helical pitch needs to be synthesized for this particular application.

A new type of material based on the principle of V-shaped switching FLC has been studied extensively during the last phase of the project. This new principle seems suitable for beam steering since analogue phase-only modulation at fast temporal response can be achievable. The basic physic of the electro-optic effect, alignment issues, tuning of LC and cell parameters, characterising of switching etc. have been investigated carefully[30]. An example showing analogue switching in a V-shaped FLC cell is illustrated in Figure 10. The studied material was capable of 312 degree phase modulation (reflective structure/circular polarised light) and exhibit sub-millisecond temporal response. Using principles of V-shaped switching a 1x256 SLM has been developed, fabricated and demonstrated within the project (see paragraph below).

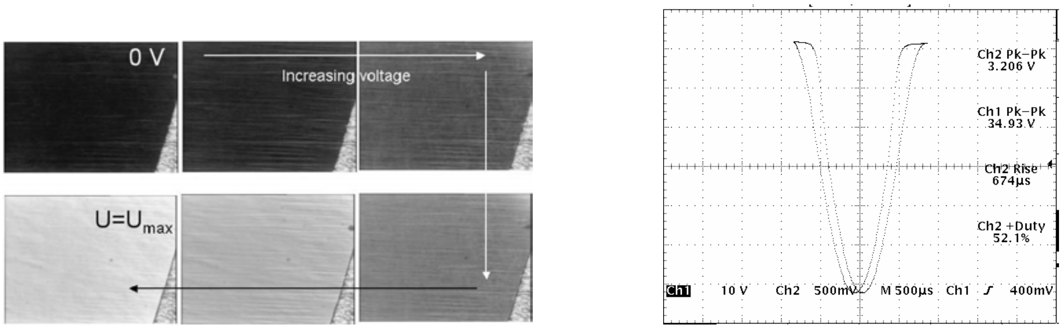

Figure 10 A) Analogue switching in V-shaped FLC. B) Transmission vs. voltage for a test cell containing V-shaped switching FLC. From ref. [28].

4.4. Transceiver for retrocommunication

The final goal of the performance studies of LC SLM was to implement a non-mechanical beam steering component into a transceiver as part of the retrocommunication link to be demonstrated. After the evaluations described above a reflective 1x4096 NLC SLM to be implemented in the transceiver was specified. The SLM was optimised to operate at 850 nm wavelength and with 30 Hz framerate. The SLM manufacturer developed dedicated software capable of addressing individual pixels at 30 Hz.

The developed transceiver consists of an optical mono-static transmit/receive channel utilising lenses for beam transfer (Figure 11). A tuneable external cavity laser having narrow linewidth (less than the MQW modulator) was used as source. The NLC SLM was implemented into the beam path to provide the beam steering and tracking function. The optical layout of the transceiver was optimised using standard ray-tracing techniques. Tracking was performed using a CCD camera with high frame rate (600 Hz) and the FOV of the receive channel was controlled by the SLM by placing the spatial tracker after the SLM. By using information from the CCD (centroid motion) control signals to the beam steering SLM were generated in a feedback loop running at 30 Hz (limited by the SLM). Dedicated software for beam steering and tracking was developed and run on a PC. The communication signal was registered using a separate photodetector. Details about the transceiver have been presented in ref. [11].

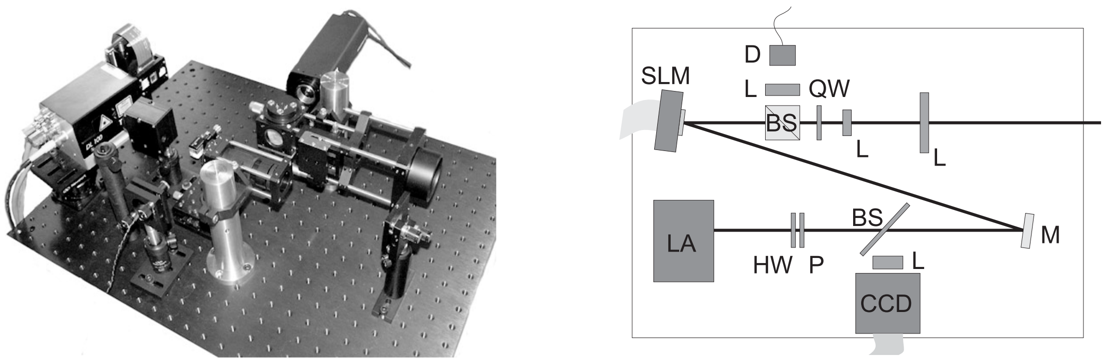

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Figure 11 A) Photograph showing one example of an evaluated transceiver configuration with the 1x4096 NLC SLM and the optics for the transmit/receive channels. B) Schematic layout of the transceiver unit. The following abbreviations are used: SLM = 1x4096 NLC SLM, LA = laser, P = polarizer, D = photodetector, M = mirror, BS = beam splitter, L = lens, CCD = camera. Note that the left figure shows a preliminary set-up. For the final transceiver the CCD was mounted after the SLM and a photodiode for the communication channel was inserted (right).

The developed transceiver has been used to study different beam steering and tracking schemes[25,31]. Measurements were performed at long ranges (up to 180 m) indoors. Factors such as beam profile quality at long ranges, tracking and beam steering accuracy, beam stability, steering efficiency, tracking speed etc. were investigated. The motivation for these studies was to predict performance of the transceiver for the technical demonstration. Different schemes for beam steering and tracking was also discussed in detail[25].

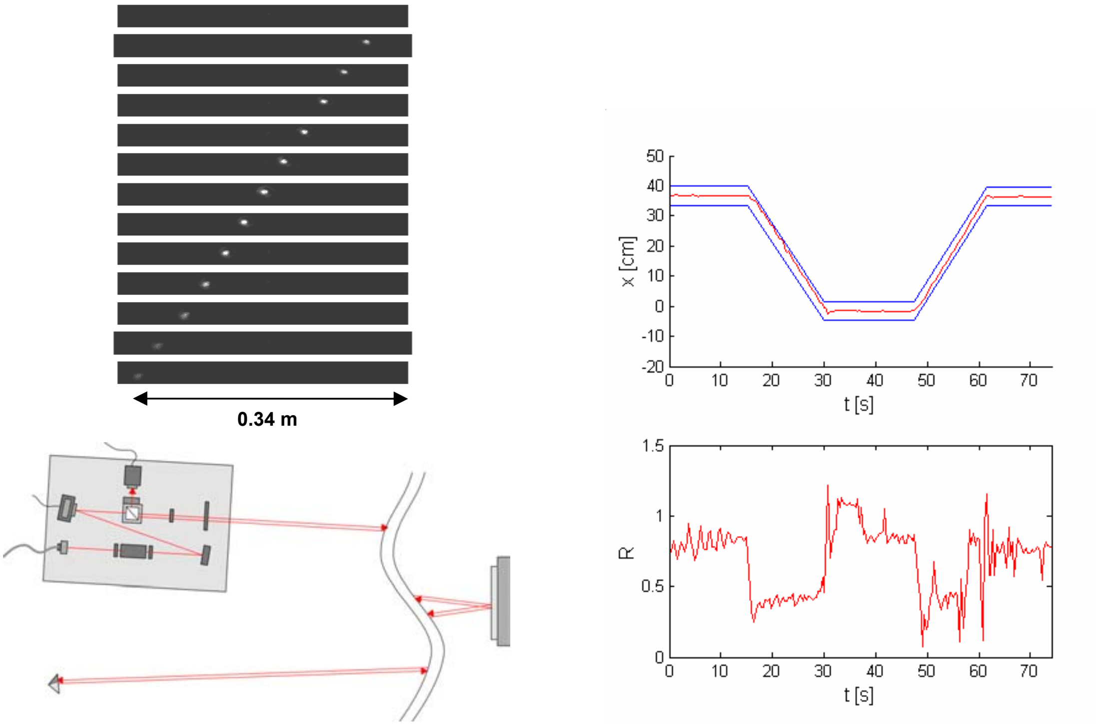


Figure 12 A) Example showing non-mechanical laser beam steering at 90 m. B) Tracking of a moving retroreflector at 180 m. The solid blue curves show the actual position of the reflector and the red curve shows the beam position (upper). Reflected intensity plotted as a function of time (lower).

The transceiver unit was also utilised to study the performance of the developed retromodulating receiver over longer range (100-180 m)[11]. Parameters such signal to noise ratio, variation in the SNR depending on the angle of incidence (on retroreceiver), data transfer rates and polarisation sensitivity were investigated. Using the retroreceiver data rates up to 5 Mbit/s was possible. In addition, the performance of focal plane MQW modulators was studied and in this case transfer rates up to 16 Mbit/s was observed and the maximal rate was limited by the modulator drive electronics.

Summarising the results from the activities related to non-mechanical beam steering the following main results were obtained; performance of NLC SLMs have been evaluated for non-mechanical beam steering, beam steering has been demonstrated at 180 m range, tracking possible at 30 Hz frame rate, performance limiting factors have been identified, optical properties of NLC SLM's have been modelled and methods to improve steering efficiency have been developed. In addition new LC materials have been evaluated for beam steering.

5. TECHNICAL DEMONSTRATION

The technical demonstration was divided into three separate parts where the demonstration of the retrocommunication link was emphasised. The two other activities included illustration of laser beam forming and control using a two-dimensional nematic SLM and demonstration of beam steering using a novel 1x256 SLM based on V-shaped switching FLC.

5.1. Retrocommunication combined with non-mechanical beam steering

The demonstration of the retrocommunication link aimed to show the following functions of the novel link: link establishment and tracking using non-mechanical beam steering, transfer of data at data rates of the order ~5-10 Mbit/s, transfer of data during the retroreceiver is moving in one dimension and, finally, transferring real-time audio and video signals.

5.1.1. Technical description of the retrocommunication link

The technical demonstration was performed at 100 m range using separate control computers (PC) for the transceiver and retro receiver control. A schematic showing the set-up for the demonstration is depicted in Figure 13. Two separate computers were used to control the beam steering/spatial tracking function and the communication channel, respectively. The RS232 interface was used to send information and receive information in the communication channel. A LabView interface was developed both for controlling and feed the retroreceiver with data and to decode data from the optical receiver channel. For the tracker separate software was developed in C++ capable of extracting information from the CCD at high rates and providing the SLM with control signals in a feedback loop. Dedicated hardware was developed to take variations in the receive signal into account coding the analogue optical communication (receive) into a bit stream adapted for the RS232. Audio data or images (collected by a frame grabber card) could be transmitted via the retrocommunication link. In addition, a PRBS was used to demonstrate transfer of information at higher data rates since the RS232 is limited to 115 kbit/s. The retromodulating receiver was placed on translational stage capable of moving the retromodulator head in the horizontal direction approximately 50 cm.

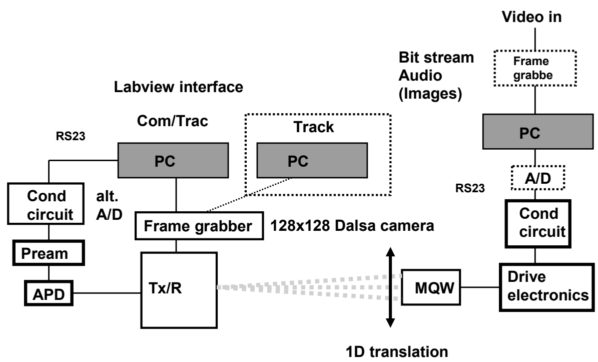


Figure 13 Schematic of the set-up for the technical demonstration of the retrocommunication link.

5.1.2. Experimental results

The demonstration was divided into several steps focusing on properties of non-mechanical beam steering and data transfer using the retromodulating receiver. Firstly, scanning the beam over the stationary retroreceiver and subsequently locking the beam onto the MQW modulators and optimising the reflected signal proved link establishment. An example, showing the beam locked onto the MQW modulators is depicted in Figure 14A. Tracking of the retroreceiver was verified by viewing the moving retroreceiver and the beam simultaneously using a CCD camera. The tracking algorithm was designed to start scanning the beam searching for the optical signal in order to re-lock if the signal was lost temporarily.

Audio signals, generated live by a microphone or by recorded music, were transferred via the link both in stationary and in dynamic (moving retroreceiver) cases. If the link was broken (by introducing a obscuration) it was automatically re-established when the obscuration was removed. The retroreceiver moved rather slowly, ~ 1-2 dm/s, due to limitations of the translation stage. However, the principles of non-mechanical beam steering and tracking were evidently demonstrated. An example, showing the detected optical signal having various strengths during tracking is shown in Figure 14B and Figure 15A.

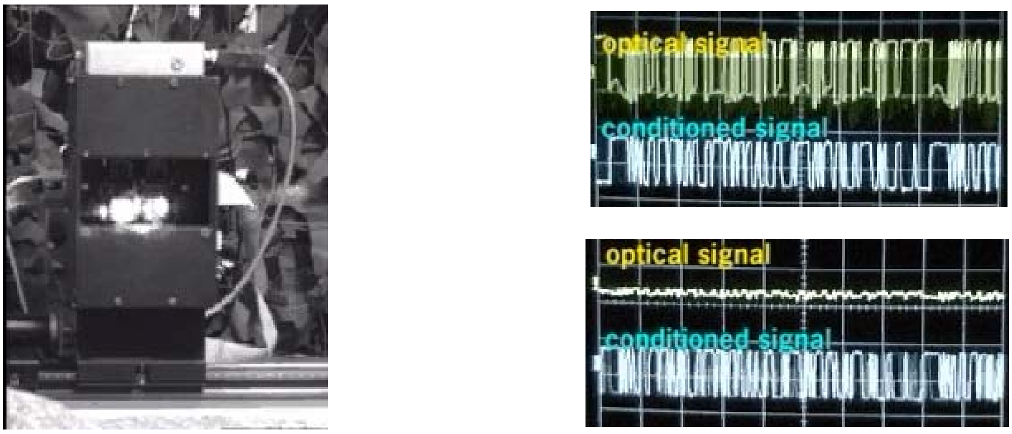
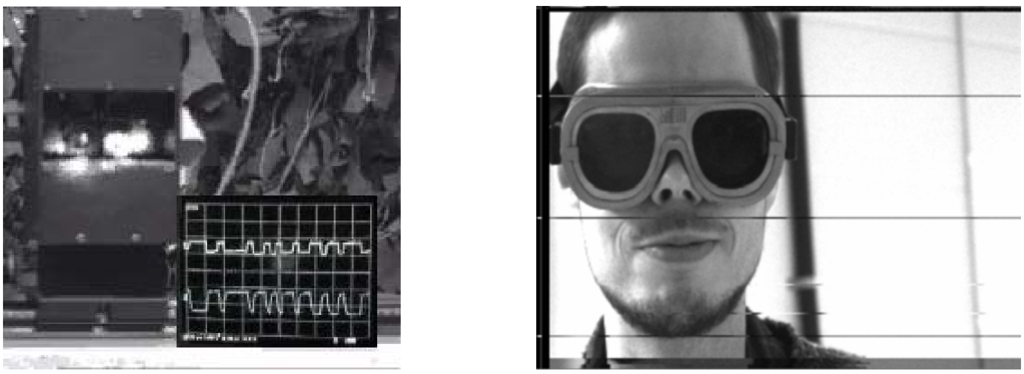


Figure 14 A) Laser beam locked on MQW modulators after link establishment. B) Example showing the detected optical and conditioned signal during tracking of the retroreceiver in case of strong (upper) and weak (lower) optical signal.

Using the RS232 interface video images were transferred via the retrocommunication link at limited rate (Figure 15B). The images were scrolled over the monitoring window on the receive computer at rate 1 image/s. However, the rate is only limited by the specific interface (computer, electronics etc.) used in this particular case. If dedicated hardware is implemented real time video is feasible.



A B

Figure 15 A) Retroreceiver and optical signal detected by the transceiver during tracking. B) Transferred image using the retrocommunication link.

The final part of the demonstration consisted of transferring data at high speed using a PRBS generator. In this case data transfers of bit streams up to 8 Mbit/s have been demonstrated using the retroreceiver. At 8 Mbit/s, however, the signal to noise ratio declines making a rate of approximately 5 Mbit/s more realistic if a low bit error rate is required. Eye-plot describing the data transfer characteristics at 1 and 4 MHz are shown in Figure 16. The corresponding approximate bit error rates were $4{\cdot}10^{-30}$ and 10^{-10}, respectively.

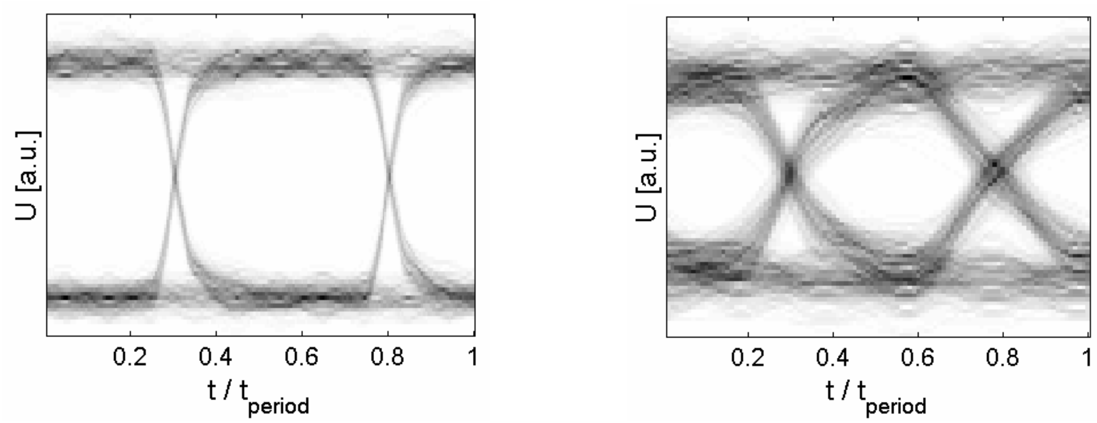


Figure 16 A) Eye plot at 1 MHz rate. B) Eye-plot at 4 MHz rate. The x-axis shows time modulus the time for one period and y-axis the detector signal. From ref.[32].

Detailed results from the technical demonstration and further experiments describing the link performance are planned to be presented elsewhere[32].

5.2. Laser beam steering and control using a two-dimensional SLM

Examples of advanced laser beam control and beam steering were demonstrated using a two-dimensional transmissive NLC SLM with high pixel density (VGA resolution). The SLM was capable of approximately 2π phase modulation at 532 nm wavelength. Pre-defined phase patterns, calculated by a phase-retrieval method, were used to show advanced beam steering capabilities. An ordinary laptop PC controlled the SLM and the VGA output was used for distributing the phase patterns to the SLM. The device operated at maximum 25 Hz. An optical breadboard set up was used to project the laser beam patterns on a screen. The demonstrated examples included e.g. electronic focusing/defocusing, multiple beam steering, arbitrary beam pointing and beam splitting into multiple beams. The main objective of the demonstration was show future potential for using two-dimensional SLM's in laser communication applications.

5.3. Beam steering using V-shaped switching FLC SLMs

During the technical demonstration of the retrocommunication link a novel beam steering device based on a 1x256 SLM using a V-shaped switching FLC material was presented. Simple beam steering based on analogue phase modulation was shown using limited control electronics. However, the technique shows promising features for future beam steering devices based on LC

SLMs. The main advantages are analogue phase modulation and a fast temporal response operating below the millisecond region.

6. DISCUSSION AND CONCLUSIONS

During the course of the project new concepts for MQW retromodulators have been discussed[9,10]. New optical designs were discussed showing promising features for improving the efficiency and simplify the optical layout. One drawback with the solution chosen in this project was the complications introduced by the use of a reflective FP structure. New optical designs may include e.g. corner cube configuration where on side of the corner cube has been replaced by a MQW modulator or different designs combining cat-eye optics with smaller MQW modulators in order to increase the time response. Another improvement which has high importance is shifting the operating wavelength of the modulator from 850 to 1550 nm. Using 1550 nm has the advantage of using eye-safe laser radiation making the practical use of the link more feasible. Moreover, at 1550 nm high quality photonics components are available due to the overlap with the telecommunication (fibre) field. Processing technologies for fabrication of MQW modulators using 1550 nm are available. Example of interesting material combinations are in this case InGaAs/InP, InGaAsP/InGaAsP and AlGaInAs/AlGaInAs. Another interesting matter is to compare different concepts for MQW modulators designed at 1550 nm e.g. reflective vs. transmissive. Wavelength multiplexing is one attractive concept that may be used to increase the bandwidth in retrocommunication links.

Comparing the objectives stated in the planning of the project the goal of implementing non-mechanical beam steering in a retrocommunication link application has been fulfilled. Principles such as link establishment and tracking during data transfer have been demonstrated. Limiting factors such as temporal response and steering efficiency have been thoroughly studied. Optical MQW modulators have been developed where modulators having small dimensions fulfil the initial goals i.e. capable of data transfer rates above 10 Mbit/s. The data rate for the small MQW modulators was limited by the drive electronics. The retroreceiver is limited to a data rate of approximately 5 Mbit/s which is less than the initial goal. Retrocommunication has been demonstrated at range 180 m which is shorter than the initial goal of approximately 1 km. However, the range of the retrocommunication link can rather easily be extended, from a technical point of view, by improving the sensitivity of the transceiver and the retroreceiver.

Non-mechanical beam steering show promising feature for implementation in future systems using active laser technology. The present components need to be improved before implementation into system applications is achievable. Important parameters are steering efficiency and temporal response. Frame rates above 1 kHz are required for several applications. New evolving component technologies based on e.g. micro-mechanical mirror SLMs are of interest to be evaluated for beam control applications. Moreover, development of new LC materials shows interesting features. Another important issue is to utilise two-dimensional components to fully be able to gain the capabilities phase modulation of light provides. Concerning non-mechanical beam steering one goal is to evaluate and identify suitable components to be used at 1550 nm. The international interest for non-mechanical laser beam control is high and several international project, both in USA and Europe, are ongoing aiming to develop new technologies and components. In this project non-mechanical beam steering has been combined with a laser communication application for the first time.

Free-space optical communication is believed to be a crucial part in high speed data links between movable platforms in the future communication network. Retrocommunication provides a new technology for asymmetric communication links which possesses several interesting features for e.g. small light weight airborne platforms such as unmanned aerial vehicles (UAV). Retrocommunication has potential to be an important part of a future heterogeneous communication network for military applications. High data rates and secure communication are two key words that are commonly used in this respect. Of particular interest is transfer of sensor information from e.g. small UAVs used in reconnaissance purposes.

The retrocommunication project has created a network between the university groups (CTH-O, CTH-V), research institutes (ACREO) and governmental laboratories (FOI). Fundamental research issues related to development of new photonic components and studies of new optical materials have been carried out by CTH and ACREO having facilities for these activities. Evaluation of the new techniques and components has been performed by FOI providing knowledge about system aspects. The foundation of this network is beneficial for all parts providing an efficient use of resources. One important goal of the Swedish Photonics Projects was to initiate and maintain a network between defence related research and activities ongoing at the universities and research institutes. Within the retrocommunication project competence and equipment available at CTH and ACREO have been used for evaluation in a specific application. It is important to maintain activities within this field and use established networks by e.g. incorporating graduate students in continuing activities.

The following recommendations are summarised for future activities within the field of retrocommunication and non-mechanical beam steering:

- Development of modulators operating at 1.55 µm wavelength with simplified optical structure

- Study new design and structures for MQW modulators based on e.g. cat-eye configurations combined with small MQW modulator arrays

- Investigate and evaluate new components aiming to demonstrate two-dimensional beam control at 1550 nm at high frame rates and high beam steering efficiency

- Incorporate the non-mechanical beam steering and retrocommunication activities focusing on new technology within the research programmes (FoT structure)

- Demonstrate the technologies in different field applications including e.g. a retrocommunication link (MQW modulators) or active imaging (non-mechanical beam steering)

In conclusion, retrocommunication based on MQW technology has been demonstrated in combination with non-mechanical laser beam steering using LC SLMs. These two new technologies show promising features to be implemented in future novel laser communication systems.

7. References

[1] L. Sjöqvist, S. Hård, S. Junique, B. Noharet and P. Rudquist, ”Retroreflective Free-Space Optical Communication. System analysis and performance”, FOI Report, FOI-R--0344--SE, 2001.

[2] G. C. Gilbreath et al., ”Large-Aperture Multiple Quantum Well Modulating Retroreflector for Free-Space Optical Data Transfer on Unmanned Aerial Vehicles", *Opt. Eng.* Vol. 40(7), pp. 1348-1356, 2001.

[3] S. Hård, S. Jacobsson, B. Löfving, U. Olin, P. Rudquist, L. Sjöqvist, O. Steinvall and S. Walles, “Laser Beam Steering-An Introductory Study”, ISNN 1101-9154, FOA Report, *FOA-R--99-01158-408--SE*, 1999.

[4] L. Sjöqvist,”Novel technologies for free-space optical communication by combining multiple quantum well modulators and non-mechanical beam steering“, Northern Optics 2003, Invited talk, Helsinki university of Technology Publications in Engineering Physics, *TKK-F-A822*, 2003.

[5] L. Sjöqvist, “Retroreflective free-space optical communication. Project plan *FOA MEMO 00-4832/L*, Oct. 2000.

[6] L. Sjöqvist, S. Hård, B. Noharet and P. Rudquist, Retroreflective free-space optical communication. Project plan – Technical demonstration“, *Document RC038*, Swedish Defence Photonics Project, Feb. 2003.

[7] L. Sjöqvist, S. Hård, B. Noharet and P. Rudquist, Retroreflective free-space optical communication. Project plan – Technical demonstration“, *Document RC038*, Swedish Defence Photonics Project, Feb. 2003.

[8] S. Junique, B. Noharet, Q. Wang and D. Ågren, ” Status report WPB2.2 - Fabrication and Evaluation of MQW Modulators”, *Document RC030*, Swedish Defence Photonics Project, April 2002.

[9] D. Ågren, S. Junique and Q. Wang,“Final Report WP B2 – MQW Retromodulators”, *Document RC042*, Swedish Defence Photonics Project, Nov. 2002.

[10] D. Ågren, S. Junique, Q. Wang and B. Jacobsson , ”MQW retro-modulator receiver module. Delivery D2”, *Document RC052*, Swedish Defence Photonics Project, Oct. 2003.

[11] L. Sjöqvist, E. Hällstig and J. Öhgren, ”Retrocommunication – Transceiver fabrication and evaluation. Delivery D1”, *Document RC053*, Swedish Defence Photonics Project, *FOI Report, FOI-D-0117-SE*, Oct, 2003.

[12] S. Junique, Q. Wang, H. Martijn, J. Guo, B. Noharet, J. Borglind, B. Hirschauer, H. Malm, D. Ågren, O. Öberg and J. Andersson, “Multiple quantum well spatial light modulators. Design-Fabrication-Characterization”, SPIE 46th Annual Meeting, Spatial Light Modulators: Technology and Applications”, San Diego, 2001.

[13] Q. Wang, S. Junique, D. Ågren, B. Noharet, H. Malm, J. Borglind, J. Andersson, L. Sjöqvist and J. Öhgren, "Wide-aperture GaAs/AlGaAs multiple quantum well electro-optic modulators", *Proc. SPIE*, vol. 4947, April 2003.

[14] J. Öhgren, "Measurements on MQW modulators and retroreflectors for work packages B2 and C3 during period I", *Document RC040*, Swedish Defence Photonics Project, Nov. 2002.

[15] J. Öhgren and L. Sjöqvist, "Performance of MQW retromodulators", *Document RC032*, Swedish Defence Photonics Project, April, 2002.

[16] E. Hällstig, L. Sjöqvist and M. Lindgren, "Novel photonics technology in defence applications-spatial light modulation devices", Nordic symposium on military electro-optics, Proc. on CD, publ. No. 4, Laser Applications, Helsinki, Oct. 2001, *FOI-S--0152--SE*.

[17] E. Hällstig, M. Lindgren and L. Sjöqvist, "Study of a zero-twist nematic 128x128 SLM, FOI Report, FOI-R--0345--SE, 2001.

[18] E. Hällstig, J. Stigwall, T. Martin, L. Sjöqvist and M. Lindgren, "Fringing fields in a liquid crystal spatial light modulator for beam steering", In press, *J. Modern Optics*, March 2004.

[19] E. Hällstig, M. Lindgren and L. Sjöqvist, "Characterization of a liquid crystal spatial light modulator for beam steering",*Proc SPIE*., vol. 4632 , pp. 187-196, 2002.

[20] E. Hällstig, L. Sjöqvist and M. Lindgren, "Beam intensity variations using a quantized spatial light modulator for non-mechanical beam steering", *Opt. Eng*., vol. 42, pp. 613-619,2003.

[21] E. Hällstig, J. Stigwall, M. Lindgren and L. Sjöqvist, "Laser Beam Steering using a Liquid Crystal Spatial Light Modulator" *Proc. SPIE*, vol. 5087, 2003.

[22] J. Stiqwall, "Optimization of a spatial light modulator for beam steering and tracking applications", *FOI Report*, FOI-R--0552--SE, August, 2002.

[23] M. Johansson, S. Hård, B. Robertson, I. Manolis, T. Wilkinson and W. Crossland, "Adaptive beam steering implemented in an FLC-SLM free-space optical switch", *Appl. Optics*, vol. 41, pp. 4904-4911, 2002.

[24] E. Hällstig, T. Martin, L. Sjöqvist and M. Lindgren, "Polarization properties of a liquid crystal spatial light modulator for phase modulation", In manuscript, March 2004.

[25] See D. Engström, "Beam steering using liquid crystal based spatial light modulators", Tek. Lic, Chalmers Tekniska högskola, 2003 and references therein.

[26] D. Engström, A. Magnusson, S. Hård, P. Rudquist, K. D'Havé, T, Matuszczyck, L. Sjöqvist and E. Hällstig, "Beam steering by combination of two binary liquid crystal SLM's", EOS Topical Meeting on Diffractive Optics, Budapest, Oct. 2001.

[27] D. Engström, S. Hård, P. Rudquist, K. D'havé, T. Matuszczyk, M. Skeren, and B. Löfving, "Beam Steering Experiment with Two Cascaded Ferroelectric Liquid-Crystal Spatial Light Modulators," *Appl. Opt.,*vol. 43, pp. 1559-1569, 2004.

[28] P. Rudquist, K. D'havé, A. Hammarquist and M. Matuszczyk, " Multiphase and analog modulation by chiral smectic liquid crystals for fast non-mechanical beam steering", *Document RC054*, Swedish Defence Photonics Project, March, 2004.

[29] P. Rudquist, "Status report WP A2.1 – Results and possibilities for AFLC SLM's", *Document RC033*, Swedish Defence Photonics Project, April, 2002.

[30] P. Rudquist, K. D'havé, A. Hammarquist and M. Matuszczyk, " Multiphase and analog modulation by chiral smectic liquid crystals for fast non-mechanical beam steering", *Document RC054*, Swedish Defence Photonics Project, March, 2004.

[31] See E. Hällstig, "Characterization of liquid crystal spatial light modulators for laser beam steering", Tek. Lic., FOI/Uppsala universitet, 2003 and references therein.

[32] E. Hällstig, D. Engström, J. Öhgren, L. Allard, D. Ågren, S. Junique, Q. Wang and L. Sjöqvist, "A novel free-space retrocommunication link based on multiple quantum well modulators and non-mechanical beam steering", In manuscript, March 2004.