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Report title

Retrocommunication with Ferroelectric Liquid Crystal Modulators - Preliminary Results

Abstract (not more than 200 words)

We have demonstrated a free-space laser communication link based on retromodulation. The communication is difficult to overhear and highly directional. A potential application is in an all-optical link from air to submarines. A text message was transmitted from a retromodulator to a transceiver by one-way communication. The transfer rate was 10 kbit/s and the distance was 8 m.

The modulator utilised a ferroelectric liquid crystal (FLC) cell, which was manufactured at FOI. The optical anisotropic property of the smectic C* phase was used for amplitude modulation. The modulator response (optical contrast) was measured with respect to drive amplitude, frequency, temperature, and different FLC materials. The optical contrast was greater than 3 in a frequency range up to 20 kHz. At higher frequencies, the response was distorted due to limited switch time of the FLC.

The transceiver was arranged using fibre-optic components, which made a flexible system. It consisted of a 1.55-µm-semiconductor laser, an optical circulator, a fibre coupling port, a beam expander and a detector. A link budget was calculated for the combined transceiver-retromodulator system.

The communication performance was limited by 42 dB attenuation (low signal-to-noise ratio) and distortion of modulator response. Important factors affecting the link performance included the FLC material and drive voltage; cell thickness and temperature; overall attenuation; precise alignment of fibre port and beam expander; and laser beam divergence.

Keywords

retrocommunication, link, laser, free-space, liquid crystal, FLC, modulation, fibre

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Retrokommunikation med ferroelektriska vätskekristallmodulatorer - Inledande resultat

Sammanfattning (högst 200 ord)

Vi har byggt en optisk länk som demonstrerar retrokommunikation med laser. Kommunikationen är svår att avlyssna och är i hög grad riktad. En möjlig tillämpning är som del i en optisk länk från luft till undervattensfarkoster. Ett textmeddelande sändes enkelriktat från en retromodulator till en lasermottagare/-sändare. Överföringshastigheten var 10 kbit/s och avståndet 8 m.

Modulatorn byggde på en cell med ferroelektriska vätskekristaller (FLC). Cellen hade tillverkats på FOI. De anisotropiska optiska egenskaperna i smektisk C*-fas utnyttjades för amplitudmodulering. Modulatorns optiska svar (kontrast i ljusintensitet) mättes med avseende på drivspänningens amplitud och frekvens, temperaturen och olika FLC-material. Kontrasten var bättre än 3 för frekvenser upp till 20 kHz, men högre frekvenser förvrängde svaret på grund av begränsningar i vätskekristallens omslagstid.

Lasermottagaren/-sändaren gjordes lätthanterlig genom att inkludera fiberoptik. Den bestod av en 1,55 µm halvledarlaser, en optisk cirkulator, fiberport, strålbreddare och en detektor. Länkförluster uppskattades för hela systemet inkluderande lasermottagare/-sändare och retromodulator.

Kommunikationsförmågan begränsades av en dämpning på 42 dB (lågt signal-till-brus-förhållande) och förvrängning av modulatorns svar. Viktiga faktorer var FLC-materialet och drivspänningen, celltjockleken och temperaturen, dämpning i länken, linjering av fiberporten och strålbreddaren samt spridningen hos laserstrålen.

Nyckelord
retrokommunikation, samband, länk, laser, vätskekristall, FLC, modulering, modulation, fiber

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Contents

1. Introduction

More developed communication abilities from land and air to submarine vessels and underwater systems, as well as communication entirely beneath the water surface, is believed to become important in the future [1]. An interesting way to communicate is to use a laser, which is difficult to overhear (highly directional), has a long range and the ability to transfer information with high speed. Unlike radio waves the blue-green laser wavelength can be transmitted several tenths of meters in the water. Other wavelengths can be used for the part of the communication from the air to the water surface, for example, IR above 1.5 µm, which is invisible and eye-safe. One concept is laser communication in a retrosystem: one operator has a laser transmitter/receiver (transceiver) while the other makes use of a retroreflector and a modulator that encodes information. The operator makes benefits in reduced weight, volume and power consumption for this retromodulator.

This report evaluates the use of retrocommunication in certain aspects. A free-space communication link is studied, which could be one part of a link from air into water. The link utilises a laser with a 1.55 µm wavelength and a retromodulator consisting of a modulator and a retroreflector. The modulator is optical and based on liquid crystal technology. The reflector is realised using a cube corner prism. Some aspects of research are [1]:

- Performance of optical modulators based on ferroelectric liquid crystal cells (FLC cells)
- Transmission for various optical components
- The directional sensitivity of the retroreceiver
- Steering electronics/computer programming for encoding information

The objective of the study is to construct a demonstrator showing “proof of principles” for a retrocommunication free-space link. The construction makes use of novel technology and can be seen as a first step towards a functional system. At this point, short distances and moderate communication speed are accepted. Of importance is to show that the principles work and to explore some of the technological and physical limits.

2. Retrocommunication System Performance

2.1.1. Overview of the Communication System

The two operating parts of the system were assembled in an indoor laboratory environment and separated 8 m. Figure 1 shows the principles of the system.

The first part, the *transceiver*, is controlled by an operator who sends out a laser beam and collects it after modulation. At this place, the communication is restricted to *listening*. A beam from a diode laser, operating at 1.55 µm wavelength, is directed via an optical fibre to the free-space using a fibre port. In close connection to the port is a beam expander located. The port and the expander constitute the transmitting and receiving optics (Figure 1), which is mobile with respect to the other equipment because of the fibre. Technical details and aspects of this sub-system are discussed in Chapter 4.

The expander also collects the reflected and modulated beam and transfers it to the fibre port and into the fibre. An optical circulator redirects the received beam to a detector. The detector signal is then subject to data acquisition and decoding.

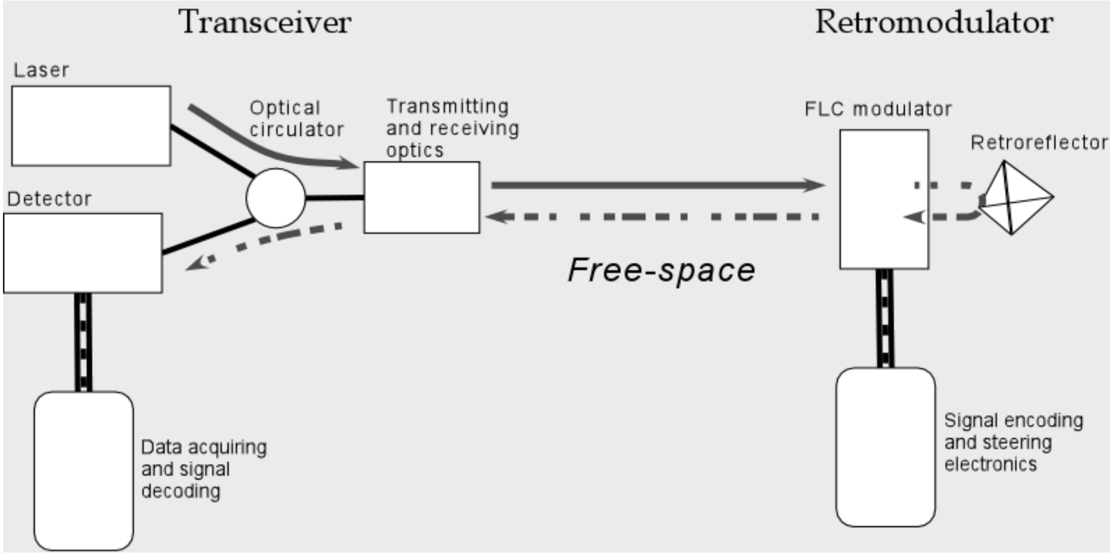

Figure 1 The transceiving sub-system transfers a laser beam via an optical fibre through an optical circulator to the transmitting and receiving optics. The retromodulating sub-system modulates the beam with an encoded message and reflects it back. The transceiver collects the beam, passing it through the same fibre. The optical circulator redirects it to a detector. The signal is read and decoded into the message.

The second part, the *retromodulator*, is controlled by an operator who modulates the laser beam and sends it back. At this place, only *talking* is performed. The message is encoded into an electrical signal controlling the modulator. As the laser beam hits the modulator it will be amplitude modulated. It is then reflected by the retroreflector back to the transceiver. The retroreflector has the property to send the beam back along the direction of incidence independently of the angle of arrival, within its field of view. The beam will pass the modulator once more directly after reflection. Technical details of this sub-system are discussed in Chapter 3.

The one-way communication described might be extended to a two-way communication, by adding a modulator to the transceiver and an optical receiver on the retromodulator side.

2.1.2. Transmitted Information

Information is added to the link by two-level amplitude modulation of the laser beam. It is therefore natural to use binary encoded information. However, there are several ways to encode information, including code systems, bit representations, start and stop sequences, code packages etc.

A simple choice of encoding and information was made for the preliminary link transmission: the information is a text message less than 100 characters, which is sent only once. Each character is ASCII encoded into 8 bits. A start bit sequence is sent first with the message bits following subsequently without interruption. Logical ones are converted to +60 V and zeroes to –60 V. These voltages drive directly the FLC modulator. No space is allowed between two bits, resulting in no change of voltage during the time that bits of the same level are sent. For writing the message, encoding it and transmitting it, we used common PC software[1] together with a DAQ-card[2].

The same software was used for decoding of the received information. At this step, however, some new aspects had to be considered. As there is no common trigger in a retrocommunication system, the program instead listens to the received signal, waiting for the start bit sequence. When it comes, it triggers the program to sample and retrieve data. The start sequence is now no longer of interest and can be rejected. One way to do that is to introduce a one-off time delay before sampling. The sample rate is only once per bit, which is the lowest possible. To be sure to sample at stabilised signal levels and not at the flanks, the time delay could be adjusted. The received data is then converted back to characters via ASCII, and the message reappears.

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[1] National Instruments: LabVIEW 6.0

[2] National Instruments: PCI-MIO-16E-4

2.1.3. Link Budget Estimation

In order to determine the power requirements for the laser, a link budget calculation considering the attenuation in the entire system is performed. All parts of the retrocommunication system, from the laser via the retroreflector back to the detector in the transceiver, are listed, and the transmission for critical components is calculated.

Table 1 Calculated transmittance for the retrocommunication system.

Component	**Transmittance**		**Comments**
	ratio	**ratio in dB**	
fibres connecting the laser and the polarisation controller			neglected
polarisation controller	(0.97)	–0.1	value from Thorlabs FPC031 (the same manufacturer)
fibres connecting the polarisation controller and the optical circulator			neglected
optical circulator 1-2	(0.83)	–0.76	product sheet
fibre, fibre port and beam expander			neglected
incidence at modulator	0.0576	–12.3	assumption of beam diameter 5 cm and retro reflector diameter 12 mm
polariser I	0.57	(–2.4)	measured
liquid crystal cell	0.66	(–1.8)	measured
polariser II	0.57	(–2.4)	measured
cube corner prism			neglected
polariser II	0.57	(–2.4)	measured
liquid crystal cell	0.66	(–1.8)	measured
polariser I	0.57	(–2.4)	measured
incidence at beam expander			neglected
beam expander, fibre port and fibre			neglected
optical circulator 2-3	(0.81)	–0.87	product sheet
fibre connecting the optical circulator and the detector			neglected
entire system	1.7×10^{-3}	–27.5	total transmittance

The beam expander used is not optimised for the system, and the beam leaving it could be diverging instead of collimated. Thus, the beam area will be larger at the modulator. This explains the relatively large calculated loss at this surface.

The calculation shows that the laser and the detector have to manage 30 dB of attenuation. Our laser has an output power of about one milliwatt, and the photodetector has a typical responsivity of 0.8 A / W and a conversion gain of 1.6×10^6 V / A, so the received signal should be clearly recognisable.

2.1.4. Communication Results

We have successfully transferred a 100-character text message from the retromodulator to the transceiver at a rate of 10 kbit / s over a distance of 8 m.

A major limiting factor is the signal-to-noise ratio and signal distortion. The received irradiance at the detector was 76 nW and the emitted irradiance 1.3 mW, so the attenuation is larger than calculated. The detector might perform better at a higher power level. The attenuation may be caused by insufficient anti-reflection coating of the beam expander; large divergence of laser beam; misalignment of the beam expander to the fibre port etc. The latter manifest itself as variation in contrast when the expander is subject to slight mechanical stress. The relatively large noise showed fast, periodical oscillations. This was mainly due to the vibrations the modulator was exposed to. Also, reflections gave rise to interferometric beat noise.

The distance seem to have little impact on the signal contrast for distances ranging up to 8 m. Rather, a larger distance in combination with a laser beam divergence makes it easier to establish contact. On the other hand, the divergence will make the irradiance decrease at large distances.

The retromodulator can be tilted several degrees without signal loss. A more precise measurement was not performed at this stage. It can also be moved off-axis by a lateral translation less than 5 mm with retained signal.

The transmission rate is limited by the FLC response time. A higher modulation frequency results in a distorted, sinusoidal signal with lower contrast, having peaks lagging in time relative to the electrical impulse (compare Figure 10). This makes it harder to sample at the right time-position, resulting in bit errors. A gradual increase of bit errors is noticed in the text message as the transmission rate is increased. One improvement would be to find another FLC-cell with better characteristics or to change the data acquisition rate. The present acquisition is made at a minimum (only one sample per bit). It could be increased to capture the signal more completely, after which signal processing could be used to find the peaks and valleys. The utilised data acquisition hardware and software is capable of data rates of up to 500 kbit / s and imposes no restrictions.

3. Retromodulating Receiver

3.1. Cube Corner Retroreflector

In order to reflect the laser beam after modulation, a cube corner glass prism is placed behind the modulator. The cube corner has the geometrical property of reflecting an incident beam exactly in the reverse direction, within its field of view. A thin beam will also be translated, but that is not regarded in retrocommunication, which uses a relatively wide beam.

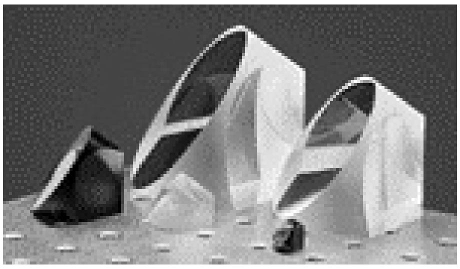

Figure 2 Cube corner retroreflectors. From Edmund Industrial Optics.

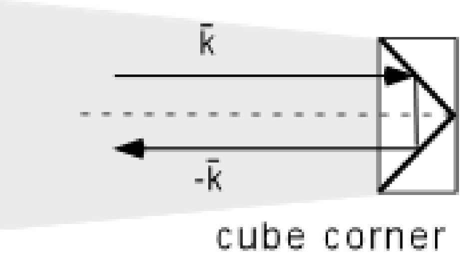

Figure 3 Retroreflection from a cube corner prism. In practice three reflections will take place as there are three reflecting surfaces.

The cube corner reflector[3] in our study had an entrance diameter of 12.7 mm and an angle tolerance of 3 arcsec (14 µrad) with respect to an ideal corner.

3.2. Ferroelectric Liquid Crystal Modulators

3.2.1. Operating principles

Liquid crystal (LC) materials are characterised by long cigar shaped molecules with preferential orientation order defining a symmetry axis. The structure of a typical LC molecule is shown in Figure 4 (left). The LC exhibits physical properties resembling both a liquid and a solid material. The liquid crystal can exist in different phases with each phase defining exclusive properties of the material. The two most common materials (phases) are nematic and smectic (Figure 4). The phase transitions occur at specific temperatures. At increased temperature the directions of the molecules become randomly ordered and the LC is considered to be isotropic. Nematic materials have all molecules aligned in the same direction (parallel) with randomly located centers within a volume element. In a smectic phase, on the other hand, the volume element is divided into separate layers where molecules in each layer are aligned parallel to the layer surface normal. Nematic liquid crystals have been used in most applications, predominantly in LCD displays. In this paragraph attention is focused on smectic LC materials, and in particular smectic C* which are also labelled ferroelectric liquid crystals (FLC). The characteristic feature of the FLC is the permanent dipole moment present in the material. Within a specific phase, physical properties such as the optical anisotropy or the viscosity can be altered by regulation of the temperature. The viscosity partly affects the optical response time of the material.

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[3] Edmund Industrial Optics: Prism Corner Cube, 12.7 mm, silver coating, NT45-202

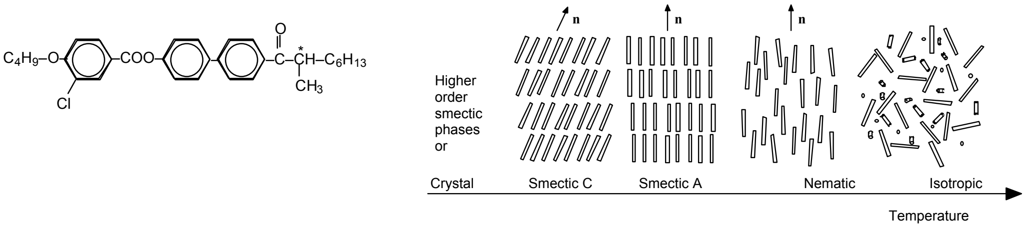

Figure 4 Structure formula of a liquid crystal molecule (left). Common phases observed in liquid crystals (right).

Liquid crystals are optically anisotropic (birefringent) and the optical properties can be altered using an external electric field (E). The orientation of the LC molecules can be changed by the E-field. In nematic liquid crystals a spontaneous dipole moment is induced while the ferroelectric exhibit a permanent dipole moment. The torque generated by the applied E-field causes the LC molecules to change direction. The birefringence defined as the difference in refractive index between the extraordinary and ordinary axis, $\Delta n = n_e$-n_o, is of the order 0.1 to 0.3 for LC materials. The extraordinary axis is commonly parallel to the long axis of the molecule. An AC-field is used to alter the effective retardation of light passing through an optical cell filled with a nematic liquid crystal. The optical response of a nematic LC is analogue. Ferroelectric liquid crystals, on the other hand, exhibit a binary optical response in presence of an electric field. The FLC molecule can be described by moving on a cone about the symmetry axis. The symmetry axis defines the normal vector to the smectic layer. Two specific states exist defined by the tilt angle ±θ (Figure 5). The permanent dipole moment causes the molecule to switch between the two states when a DC field with different polarity is applied.

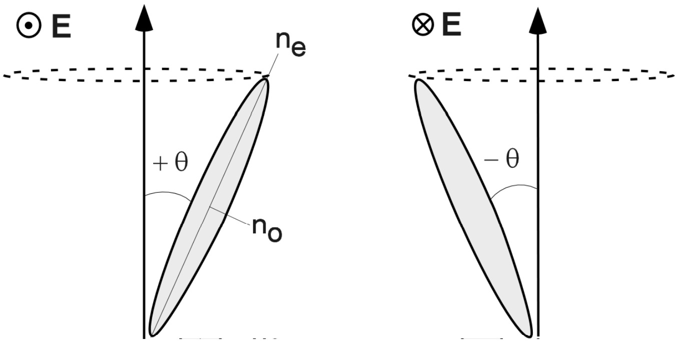

Figure 5 Switching of a FLC molecule due to the torque induced by a DC-field with opposite polarity.

The LC material is forced to enter a preferred orientation in an optical cell by using alignment layers on the glass substrate. The alignment layer usually consists of a polymer where scratches have been imposed in a specific direction (rubbing directions). In a FLC cell the molecules are aligned parallel to the glass surfaces and the surface forces stabilises the molecules. A thin cell thickness is required (d = 1–10 μm) to keep the molecules aligned. Transparent indium tin oxide (ITO) electrodes are deposited onto the glass substrate and work as electrical connectors.

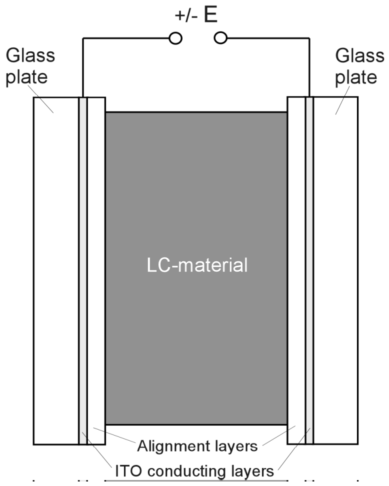

Figure 6 Schematic layout of a FLC cell for an optical modulator (transmissive). Note, the thickness of the LC, alignment and ITO layers are exaggerated.

Drive voltages of the order 5 to 10 V are used to control nematic LC, while FLC generally require drive voltages between 10 to 50 V. The response times observed for FLC materials are between 20 to 50 μs. Nematic materials are considerably slower limited by a recovery time about 20 ms. Another interesting property of FLC is the presence of *optical bi-stability*, that is, the molecules remain in their state after the field has been removed. This is an important property for optical communication applications. Ferroelectric liquid crystals are sensitive for chemical degradation due to non-symmetric electrical fields and DC-compensation of the applied field is necessary to prevent long-term damage of the optical modulator.

The optical response and properties of FLC and nematic LC can be qualitatively studied using the Jones formalism [2]. When light is propagated through a FLC cell the effective refractive index is altered between the two states. If we assume that linearly polarised light along the molecular axis (in the $+\theta$ state) passes through the cell the extraordinary refractive index is experienced by the light. Altering the polarity of the field switches the molecule to the $-\theta$ state and phase retardation is obtained. The phase retardation for single-passage through the modulator can be written as [3]

$$\Gamma = \frac{2\pi \Delta n d}{\lambda} \tag{Eq. 1}$$

where Δn is the bi-refringence, λ the wavelength and d the thickness of the cell. Commercial FLC materials usually have a tilt angle $2\theta = 45^\circ$. Choosing the thickness of the cell so $\Gamma = \pi$ produces a 90° rotation of the polarisation after the light has propagated through the cell. Hence, if the FLC cell is placed between crossed polarisers an intensity modulator is obtained (Figure 7).

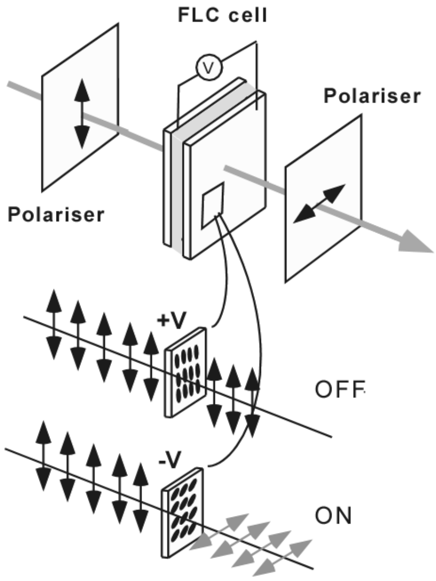

Figure 7 Principle for a FLC optical modulator placed between crossed polarisers.

The important design parameters of a FLC optical modulator is defined in Eq. 1 above. If the optical modulator does not fulfill the design criteria the contrast ratio is decreased. The effective refractive index determines the modulation properties of the modulator. Non-ideal thickness, for example, introduces a partial circular polarised component lowering the contrast ratio. Considering a FLC modulator in combination with a corner cube retroreflector only one polariser is required to obtain an intensity modulator if the optical cell is designed to correspond to a $\lambda/4$-wave retarder.

Development of new methods for fast optical modulators based on LC technology are currently studied at University of Cambridge. Using electroclinic LC materials mixed with chloride-compounds have resulted in time responses below microseconds (160 ns). The modulators are fabricated using a Fabry-Perot geometry providing contrast ratios of the order 1:6–7. These new materials provide potential for fabrication of fast optical intensity modulators. FLC optical modulators have been studied for retroreflective free-space optical communication in a balloon experiment by US Air force [4]. The retromodulator consisted of an array of FLC modulators between crossed polarisers connected to corner cubes. Data rates up to 20 kbit/s were demonstrated over long ranges.

3.2.2. Manufacturing of Liquid Crystal Modulators

The FLC cell used in the modulator is manufactured from an empty glass cell. Conductors are attached and the cell is filled with liquid crystals. The conductors are connected to the ITO conducting layers, which produces the electric field over the crystals. The most robust method for attaching the conductors is to use conducting two-component glue. Alternatively, the conductors can be pressed against the cell and soldered. This attachment tends to break, however.

Empty cells[4] with gap thickness 4 µm and 6 µm are used. Each cell is placed upon a temperature stage and heated to 90 °C. The liquid crystals are easy-handled, being almost solid at room temperature. Some crystals are entered from the outer

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[4] E.H.C. Co., Tokyo, Japan: Standard cell, type Y, ITO, surface treated with polyimid, rubbing direction 0°

edges of the cell. Due to the high temperature, the crystals melt and are pulled into the gap by the capillary forces.

For monitoring the filling of the cells and the different phases of the crystals, the temperature stage and cell is placed in a polarising microscope. The temperature is lowered to room temperature at a cooling rate of 2 °C min^{-1}. Simultaneously it is possible to study the different phases of the crystals and the way domains appear in each phase. An alternating voltage is applied to the cell during the entire cooling process in order to make the alignment of the molecules easier. Table 2 summarises facts about the cells manufactured.

Table 2 Cell designations and corresponding thickness and crystal filling

Designation	**Thickness (μm)**	**Liquid crystal**
J	6	unknown
B	6	FELIX-017/100 [6]
C1	6	ZLI-4654-100 [5]
C2	6	ZLI-4851-100 [5]
C3	6	FELIX-017/100 [6]
C4	6	FELIX-018/100 [6]
D1	4	FELIX-017/100 [6]
D2	4	FELIX-018/100 [6]

3.2.3. Performance Factors

The performance of the FLC modulators is tested by measuring the transmission properties of the modulator. Main factors affecting the response are

- frequency of the drive voltage, which determines the communication speed,
- amplitude of the drive voltage, affecting the orientation of the liquid crystal molecules; and
- the cell temperature, which determines the actual phase of the liquid crystal.

A series of measurements were carried out to characterise the modulator with respect to these factors. Of particular interest were

- the edge rising time of signal; and
- the contrast between highest and lowest signal level.

3.2.4. Experimental Set-Up for Characterisation

The modulator was mounted on an optical bench with the FLC cell between two polarisers. The 6-μm cell was mounted in a temperature stage; the 4-μm cell was not. Figure 8 and Figure 9 show the set-up. A function generator [7] was used to generate a square voltage of variable frequency and amplitude. A high-voltage amplifier [8] was

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[5] Merck KGaA, Darmstadt, Germany: Licristal, ferroelectric smectic mixture.

[6] Hoechst AG, FELIX Ferroelectric Liquid Crystals

[7] Rhode & Schwarz, Function Generator, 10 mHz … 20 MHz, AFG

[8] Voltage amplifier F20A. FLC Electronics.

employed to deliver the appropriate voltage to the cell. The light went through the modulator and the irradiance was measured by a photodetector [9]. The response was analysed with an oscilloscope [10].

The cells (C1–C4) were inserted, the polarisers were adjusted for best signal contrast, and measurements were made for different combinations of the frequency and amplitude of the drive voltage, and the cell temperature.

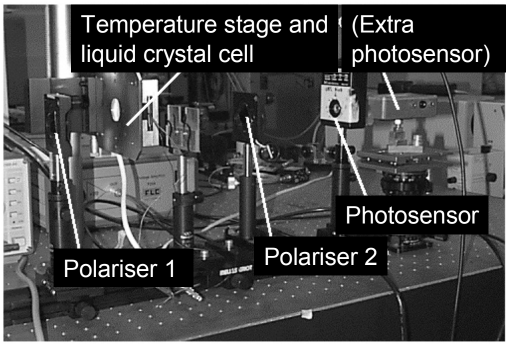

Figure 8 Experimental set-up for performance measurements of FLC modulator (cell thickness 6 µm).

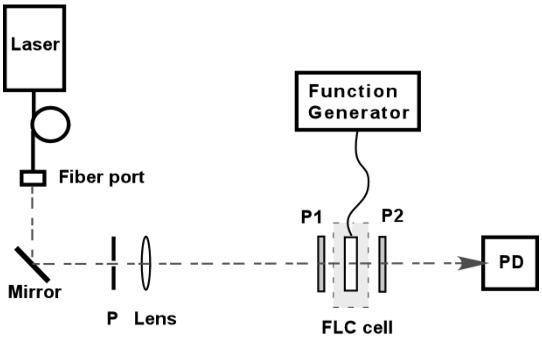

Figure 9 Overview of the experimental set-up. P is a pinhole, P1 and P2 are polarisers and PD is the photodetector.

The set-up for the 4-µm cells (D1, D2) was similar to the one above. However, the cell and polarisers were closely positioned in a common mount. No temperature stage was used in this case, allowing only room temperature to be considered.

3.2.5. Experimental Results

The experimental results showed that the 6-µm cells should be used at higher temperatures than room temperature to achieve a good temporal response. At room temperature, only cell C4 exhibits a fairly good contrast of 2.2, although the ideal square wave was transformed into a sinusoidal wave.

The optical response is sufficient for communication rates above 20 kbit/s for all 6-µm cells if they are heated to 40–50 °C. The response is better at higher drive voltages. The best results were obtained for the cells C3 and C4, which have a contrast of 3–4, applying the voltage ± 40 V. Figure 10 is a typical example.

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[9] Large area IR photoreceiver (2033). New Focus, Inc. 800 to 1750 nm.

[10] Digital Oscilloscope Le Croy LC 534A.

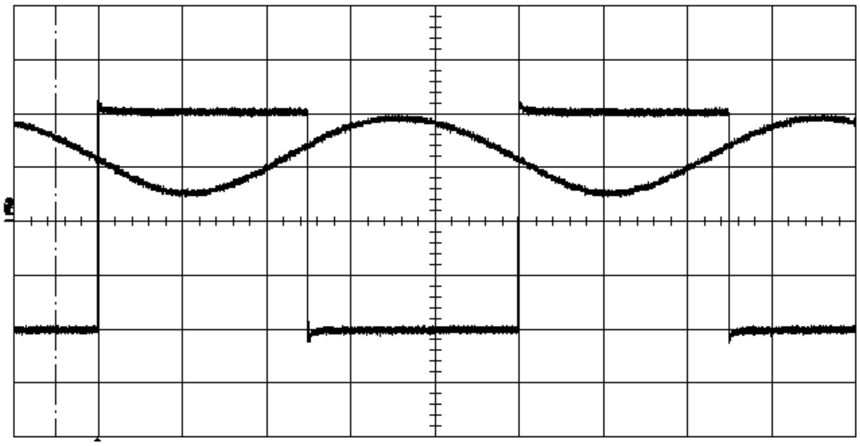

Figure 10 Drive voltage (square trace) and detector response when using cell C3 in modulator. Drive parameters: cell temperature 40 °C, voltage ±40 V and frequency 20 kHz.

An increased frequency decreases the contrast of the modulator. The cell C3 showed the best properties; a contrast of 2.0 at 45 kHz (Figure 11).

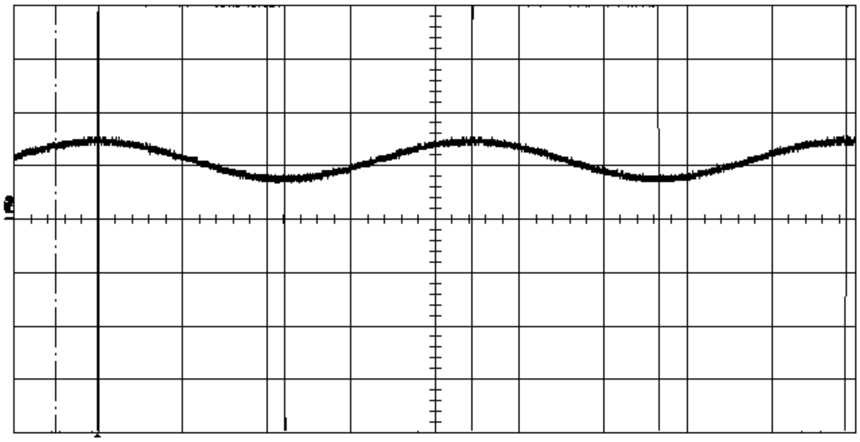

Figure 11 Drive voltage (square, clipped trace) and detector response when using cell C3 in modulator. Drive parameters: cell temperature 40 °C, voltage ±80 V and frequency 45 kHz.

The optical response follows the drive voltage as the frequency is lowered to 5 kHz; see Figure 12. In this particular situation, the voltage and temperature are medium high, that is, ± 40 V and 40–50 °C. All cells C1–C4 were tested and the contrast was greater than 2.4. A maximum contrast of 10.7 was obtained for cell C3.

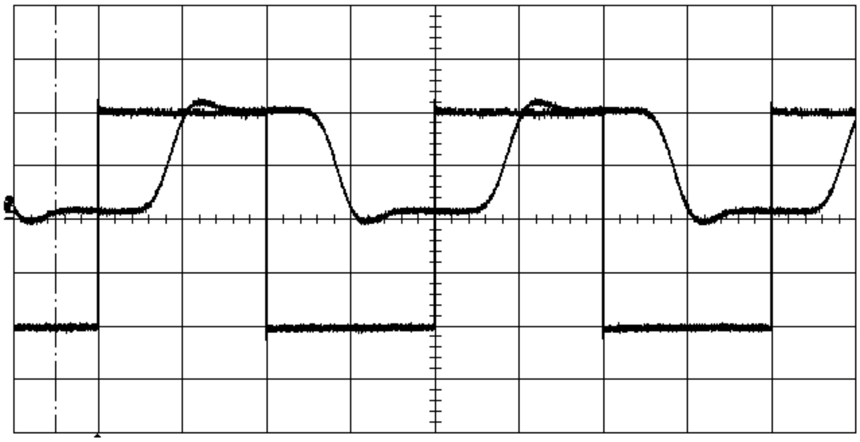

Figure 12 Drive voltage (square trace) and detector response when modulating with cell C3. Drive parameters: cell temperature 40 °C, voltage ±40 V and frequency 5 kHz.

A higher temperature, 60–70 °C, makes no differences to the response.

The 4-µm cells D1 and D2 responded to frequency- and amplitude variations similar to the 6-µm cells. However, they showed a better contrast. For example, at 10 kHz, cell D1 had a contrast of 2.9 for ±20 V and 4.2 at ±60 V. The contrast decreased at higher frequency and for 30 kHz it was 1.5 and 2.2, respectively.

The agreement between the response and the drive signal largely depends on the rise and fall time of the modulator. At low drive frequencies, the response will be square, whereas at high frequencies the modulator is not able to switch fully, resulting in a sinusoidal response. The distorted response typically emerges above 20 kHz. Increasing the drive frequency results in lowered contrast due to incomplete switching of the liquid crystal molecules. Moreover, the modulated waveform will be delayed with respect to the modulating signal. The time lag can be as high as one period. This could be explained by the inertia of the liquid crystal, particularly the viscosity. To improve the time response it is necessary to shorten the rise and fall time. Increasing the amplitude of the drive voltage towards ±80 V or raising the temperature to about 40–50 °C will improve the response. In fact, the viscosity of the liquid crystal is temperature dependent.

4. Transceiver

The transceiver consists of components for transmitting a laser beam and receiving the beam after modulation. The components are depicted in Figure 13 and Figure 14. A schematic layout of the transceiver is shown in Figure 1.

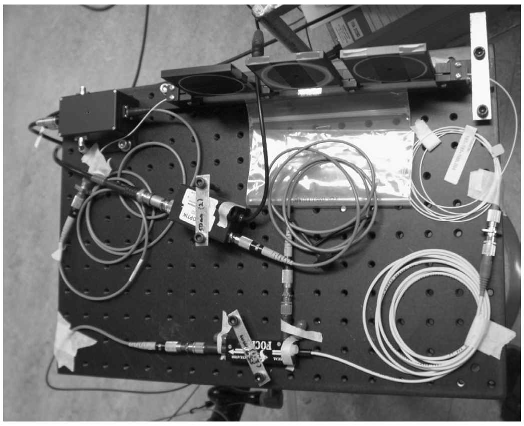

Figure 13 Photograph showing the laser and detector components of the transceiver.

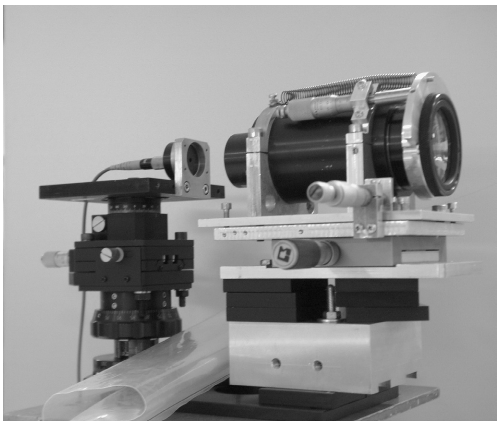

Figure 14 The fibre coupling port and beam expander of the transceiver.

A semiconductor laser[11] of 1.55 µm wavelength and 1.3 mW power is used as a power source. The laser light is coupled into a short, permanent mount optical fibre (pigtail). Therefore the laser can easily be exchanged to another one with different power (or wavelength). The light passes through a polarisation controller. This controller works as a quarter, a half and a quarter wave retarder in series. It can alter the polarisation state by changing the phase difference between different laser modes in the fibre. The purpose is to assure that the beam is not linearly polarised when it hits the modulator: a linearly polarised beam can be attenuated and difficult to modulate if the direction of polarisation do not coincide with the first polariser. An optical circulator directs the beam into a fibre that is connected to a fibre coupling port. It contains a lens, which collimates the beam. Leaving the port, the beam diameter is 0.5 mm. A beam expander is situated in close connection to the port. The beam expander has a ×10 magnification, which enlarges the beam diameter to 5 mm. It also collects the beam, after modulation and reflection, and compresses it. The light is then transferred to the fibre by the fibre port. Meeting the circulator a second time, it is directed to a detector.

The fibre-based solution provides a flexible system: the transceiving optics is separated from the laser and detector and can be operated freely. It is also easy to change or insert new components, since components pigtailed with fibres are common.

A difficulty with the fibre system is to achieve efficient optical coupling from fibre to air and vice versa. The alignment of the fibre port and the beam expander is complicated and crucial if irradiance losses are to be avoided. The actual non-optimised optics and its simplified mounting complicate the performance. In addition, single mode fibres with small core diameters (about 9 µm) are used. Multimode fibres, which are thicker (about 50 µm), facilitate the beam transition and can improve the system handling.

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[11] ACREO: Semiconductor laser (distributed feedback laser) DFB 2766 B

5. All Fibre Optic Links

We have considered an alternative way to establish the free space optical link based on direct coupling of the laser beam into a fibre. Some preliminary tests were initiated but not concluded during the course of this year for reasons explained below. Indeed, a retroreflector-based modulator has got the advantage of a large aperture and a comparably large field of view making it particularly useful on platforms that might become hard to stabilise. Moreover, the condition of retroreflection is truly fulfilled whereas fibre based solution can only emulate this property. But, it will be difficult if not impossible to construct devices able to match the modulation speed in reach with fibre optic components. To better take advantage of the bandwidth available in the optical link it is thus desired to couple the light into an optical fibre e.g. such as in Figure 15.

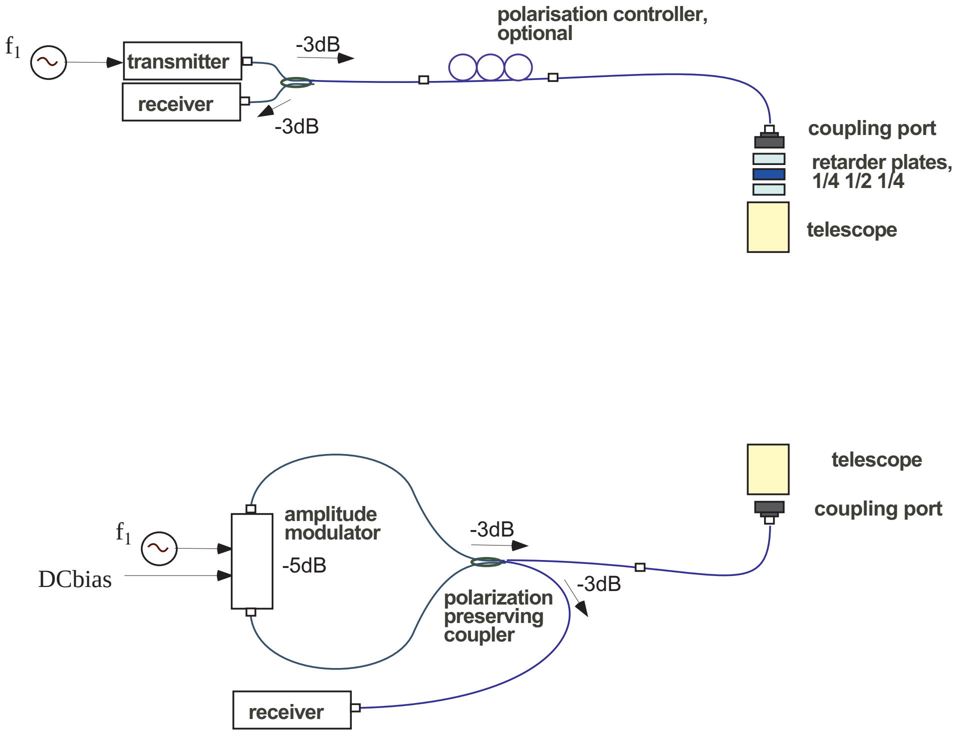

Figure 15 Free space optical communication link, with one passive end, based on fibre optics. A fibre loop is used to redirect the incident light to the transmitter. An external modulator in the loop is used to modulate the light with the communication signal from this end. A receiver picks up communication signals transmitted from the other end.

The link depicted in Figure 15 has only one active side from which the light is transmitted and resembles the retroreflector link in that respect. Although the second side, a fibre optic loop replacing the retromodulator, is being passive it will act as if it was transmitting a laser beam while the communication link is established. There are possibly two advantages with this configuration compared to other fibre optic solutions of this kind. Firstly, the loop can by no means transmit light unless light is incident on the port. It acts truly as a mirror. Secondly, the loop does not require electrical power apart from the signal modulation and the DC bias. The receiver can be located in the mother craft and linked by the fibre. The scheme includes polarisation components which are required only if the modulator is polarisation dependent. This was the case for the equipment set up in the laboratory. The polarisation dependence could be a considerable disadvantage for mobile systems moving with respect to each other. In a real situation polarisation independent devices, commercially available, ought to be preferable.

A serious disadvantage related to the optical fibres may become the limited field of view for such systems. Particularly, if single mode optical fibres are to be used for which a typical field of view (depending on the aperture) is less than 50 μrad. Consequently, a highly stable platform will be required in order to keep the line of sight directed onto the transmitting side. It may not be possible to stabilise a port mounted on a buoy type of platform to a required level. This is still a matter of investigation.

In fact, this was a problem already in the laboratory while trying to operate the link in Figure 15. It was possible for us to establish a link but it required careful adjustments and aligning of the optics. To obtain an effective link, a more accurate laboratory work to the optical arrangements would be needed. Coupling of remote laser light into optical fibre is currently being studied in another project on free space optical communication at our department. We are currently awaiting the conclusions from that work.

A way to increase the field of view of the fibre coupling ports is to use fibres with larger core diameters, multimode fibres. It does also simplify the coupling into the fibre. Single mode fibres are attractive in this application since most of the developed external components are compatible only with single mode fibres. The allowed communication distance within the fibre is certainly also much larger for single mode fibres which could be another reason to select single mode fibres.

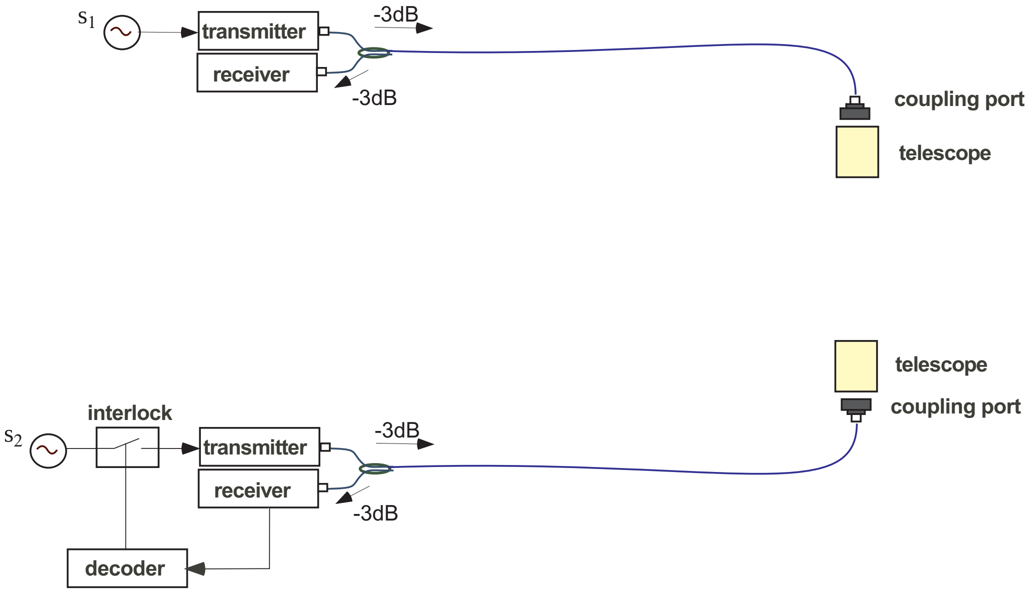

Figure 16 Free space optical communication link, with two transceiver ends, based on fibre optics. Interlock electronics can be used to ascertain that transmission of signals does not occur unless a known counterpart unlocks the link.

We do not now of any high-speed external modulators for multimode fibres. Thus the use of multimode fibre may require another approach. As was previously noted the difference between the light transmitted by the loop mirror and light that would be transmitted by a local laser are not obvious. In fact, all visible light properties could be made the same by the use of a local laser, e.g. beam divergence, wavelength and intensity. The optical phase cannot be made the same, at least not the correlation properties of the reflected light. This is important only if a coherent communication is to be considered. The main difference lies in that an active device is required on both sides. But since the light is coupled directly into the fibre it may very well be guided long distances prior to detection. Hence, the transceiver unit could be hosted by the mother craft. Figure 16 shows a scheme based on this concept. A coupling port, fibre link, transmitter, receiver and auxiliary electronics are used in place of the retromodulator system. An interlock function can be used to assure that light is not transmitted unless the receiver detects a signal that may include coding. An advantage is that a minimum of equipment has to be carried by the buoy, in principle only the coupling optics. Another advantage could be that multimode fibres can very well be used between the input port and the transceiver. Approximately, a factor of 10 of larger field of view is obtained if a standard multimode fibre is used instead of a single mode fibre. Use of special fibres can further increase the field of view. Available fibres with core diameters up to 1 mm would allow for a field of view as large as 10 mrad. However, mode dispersion in large core fibres will limit the bandwidth*range product. A possible way to circumvent this problem, at least for the communication channel going in the direction away from the sub seaside, is to use separate fibres for the communication in either direction. A single mode fibre for the transmitter allows for a high bandwidth while the bandwidth in the multimode channel is sufficient for the communication link to the sub sea platform. The output coupling port, denoted collimator, is much easier to construct than a single mode input coupling port since less precision is required.

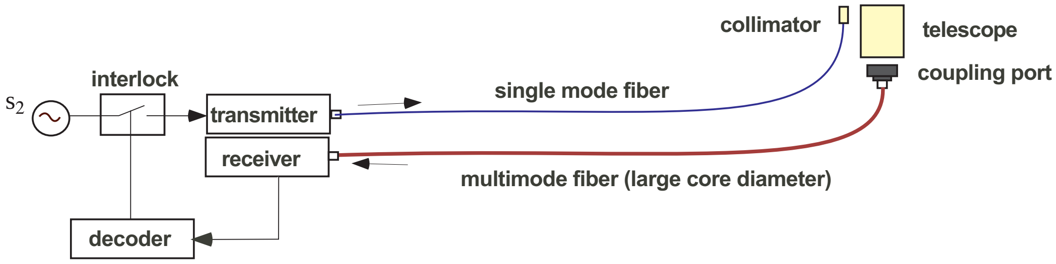

Figure 17 Optional transceiver solution for the free space optical communication link. This solution uses a multimode fibre in the receiving direction to allow for a larger field of view. A single mode fibre allows for high-speed communication in the transmitter direction.

6. Discussion and Conclusions

The preliminary result from our test of a retrocommunication link is that the technique works as predicted and that there is a potential for an even better performance. It has been demonstrated that a 100 characters text message can be transferred with

- a transmission rate of 10 kbit/s over 8 m.

Evaluation of critical subsystems has been performed as well. In the first place we have obtained

- performance data for a FLC-modulator of our own design; and also
- experience of a fibre-based transceiver.

The transmission rate depends partly on the switch characteristic of the FLC cell. Of importance is the choice of the liquid crystal type and the local temperature. The achievable rate is dependent on the signal-to-noise ratio, limited by attenuation in the link; by positioning of the retromodulator; and by the vibrations that the retromodulator is subject to. The laser beam divergence in free-space largely determines the attenuation. Also, misalignment of the fibre port and the beam expander causes attenuation.

As the distance between the transceiver and the retromodulator is increased, it will be necessary to control the laser beam shape to prevent power losses. In addition, a narrow beam requires higher tracking ability-especially if there is a relative motion between the transceiver and the retromodulator.

Some efforts that would enhance the communication performance are listed below:

- modulator with new FLC material with better and faster switch characteristic
- adjustment of polarisator angles and FLC cell thickness
- temperature control of the modulator
- use of one-polarisator retromodulator
- use of a beam expander with adapted transmission properties.

Our further research will include tests of the angle dependence of the retromodulator. It could also be useful to construct computer models for simulating the system and for designing parts, like the retromodulator.

7. References

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