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# Fast liquid crystal end-less polarisation controller for first order PMD compensation

Laurent DUPONT\*, Jean-Louis de BOUGRENET de la TOCNAYE\*,  
Michel GADONNA\*, Thierry SANSONI\*

## Abstract

*We present the principle of a fast liquid crystal end-less polarisation controller for first order polarisation mode dispersion compensation (PMD). We demonstrate how this device can be used as a variable and rotatable wave-plate and the resulting advantages to optimize the complexity of polarisation tracking algorithms. We give some experimental results obtained with an electro-clinic homeotropically aligned liquid crystal cell used as a variable and rotatable wave-plate. We discuss then the performance and the way to improve the device characteristics in order to meet the current operational PMD compensation requirements.*

**Key words:** Optical fiber transmission, Wave dispersion, Light dispersion, Wave polarization, Optical polarization, Signal convertor, Liquid crystal device.

## CONTRÔLEUR DE POLARISATION RAPIDE À CRISTAUX LIQUIDES POUR LA COMPENSATION DE PMD DU PREMIER ORDRE

### Résumé

*Cet article expose le principe d'un contrôleur de polarisation rapide, sans fin, pour la compensation dynamique de dispersion de mode de polarisation (PMD). On montre de quelle façon un tel composant peut-être utilisé comme une lame de phase variable à axe tournant, et les avantages qui en résultent pour l'optimisation des algorithmes de recherche de l'état de polarisation. On présente quelques résultats expérimentaux obtenus à partir d'une cellule à cristal liquide électrocline, alignée de manière homéotrope et utilisée comme lame de phase variable, à axe tournant. On discute ensuite les performances d'un tel composant et de quelle façon il est possible d'améliorer ses caractéristiques de manière à répondre aux spécifications exigées aujourd'hui par un système de compensation de PMD.*

**Mots clés :** Transmission fibre optique, Dispersion onde, Dispersion optique, Polarisation onde, Polarisation optique, Convertisseur signal, Dispositif cristal liquide.

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\* GET/ENST Bretagne Département d'Optique, Technopôle de Brest-Iroise, BP 832, 29280 Brest CEDEX, France

## Contents

- I. *Introduction*
- II. *Principle of first order PMD compensation*
- III. *Various optical solutions*
- IV. *Principle of homeotropic liquid crystal endless rotator*
- V. *First experimental results: optical behaviour of smectic A and smectic C\* plates*
- VI. *Discussion and trends*
- References*

## I. INTRODUCTION

Electro-optic states of polarisation convertors are currently very attractive elements both for transmission systems and optical fibre sensors. This paper focuses here on the first application and more precisely on their uses to mitigate polarisation mode dispersion, in fibre long haul transmission systems. Polarisation mode dispersion presents a major impairment for multi-gigabit systems deployment and its effect on direct detection systems through pulse spreading and depolarisation, results generally in severe performance degradations [1]. In addition, temporal drifts of PMD cause the biggest problems and the greatest challenges since the compensator dynamically must adapt to the changing transmission fibre properties. We restrict here on the first order optical PMD system compensation involving the use of high speed optical polarisation controllers. We briefly discuss the main optical arrangements and the major technologies and then we propose an illustration using high speed liquid crystal materials minimizing the number of control parameters.

## II. PRINCIPLE OF FIRST ORDER PMD COMPENSATION

Polarisation mode dispersion results from the fact that the propagation constant for the two eigen-modes of a fibre become distinct during the propagation, when the circular symmetry of the core is broken by stress or geometrically induced birefringence [2]. A single uniformly distributed perturbation on a short section of fibre creates two orthogonally polarised modes along the directions of the stress induced symmetry, called principal states of polarisation. For long optical long fibre span, random polarization mode coupling between each section has to be considered. Polarisation components simultaneously launched along these two principal states arrive at the fibre end section at different times. This is called differential group delay (DGD). PMD is characterised for a given optical frequency by two time dependent parameters: principal states of polarisation and DGD. These two parameters represent the first order polarisation mode dispersion. For long fibre spans, the evolution of PMD with the distance is fairly slow and the random probability density function of DGD is Maxwellian [3]. Therefore, PMD is difficult to assess or measure. Whereas group velocity dispersion is deterministic, PMD characteristics vary in time and frequency. Hence it is better to speak of mitigation than cancellation. The proposed and investigated methods to mitigate PMD can be divided into three main categories: electrical, optical and by use of robust modu-

lation formats. We focus here on the optical approach. Most of the practical optical (and also electrical) PMD compensation systems consist of three parts: the compensating element, the error signal, and the control algorithm, the compensating element being made itself of a birefringent element before the receiver, preceded by a polarisation controller (Figure 1) [4]. A feedback loop featuring a control algorithm optimizes performance by setting the mitigator into one of two possible operating points. The first cancels DGD by setting the polarisation controller so that the line's slow polarisation state coincides with the fast polarisation state of the birefringent element and vice versa. In this case, DGD of the birefringent element should be adjustable.

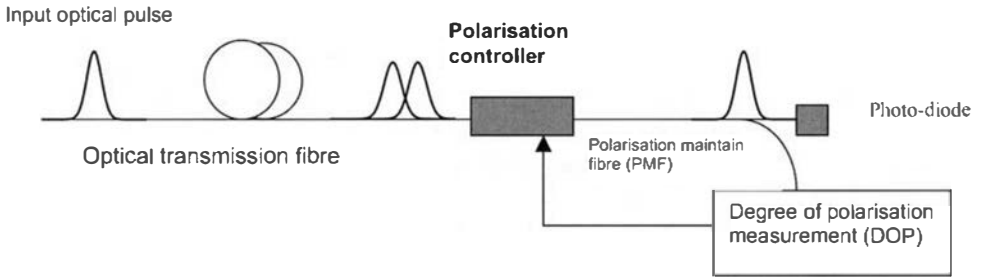


FIG. 1. – Optical methods to mitigate polarisation mode dispersion.  
The algorithm is based on degree of polarisation optimisation.

*Méthodes optiques pour atténuer la dispersion de polarisation.  
L'algorithme est basé sur l'optimisation de degré de polarisation.*

The second acts on principal states of polarisation of the entire path (line fibre and mitigator) to impose that the input polarisation state coincide with one of principal polarisation states. In this case even if the total DGD is not cancelled its effect is reduced. All of these considerations concern only first order PMD, we restrict here.

As displayed Figure 1 optical first order PMD mitigators use a combination of birefringent elements (the PMF and the polarisation controller). One section of polarisation maintaining fibre (PMF) requires one control, the polarisation controller (PC) with a simple algorithm leading to potentially fast response, if the other elements are fast enough (interface, Stokes parameters detector and PC). This configuration is of little flexibility to compensate higher order PMD (assuming several section of PMF separated by several PC). Clearly an important issue is a trade-off between flexibility and operation speed. High speed operations are critical to ensure tracking of fast dispersion transients [4]. System speeds depends not only on the complexity and implementation of the control algorithm but also on the component which gain to be as fast as possible. For instance, the polarisation controller must be able to control polarisation variations as high as 50 revolutions of the polarisation state of the signal around the Poincaré sphere within 1 sec.

An another useful feature is that the polarisation convertor, for use in optical communications, is required to convert a time-varying arbitrary state of polarisation to another, pos-

sibly time-varying arbitrary state of polarisation, without the need to reset the device, i.e. the control must be endless.

### **III. VARIOUS OPTICAL SOLUTIONS:**

Various techniques, optical configurations and materials can be used to provide polarisation converters, LiNbO<sub>3</sub> waveguides, Faraday rotators, rotating wave-plates, and electro-optic crystals. We focus here on the most commonly used, both regarding technologies and optical configurations. The most useful way of classifying optical compensators is, however, via the number of degree of freedom (DOF), i.e. the number of elements that are controlled by the control algorithm. The DOF is generally a good estimate of the complexity and hence the cost of the compensator. Basically two degrees of freedom are needed to transform any polarisation state to any each other. However for functionality and technology reasons, (e.g. endless control), more parameters are used. This is discussed in the next section.

#### **III.1. Waveguided TE-TM mode converters:**

It is basically a pure waveguide approach. To obtain arbitrary polarisation transformation, the control of both TE-TM mode conversion and differential phase shift are required. Structures have been reported and realized in which rapidly alternating mode conversions and phase shifts effectively provide a distributed phase shift over the guide [5, 6]. First realisations have been demonstrated with LiNbO<sub>3</sub> materials. Three independent voltage controls allow providing a dynamic endless polarisation conversion.

The second approach is based on free-space wave-plate combinations. In this frame, there are three equivalent ways to perform any arbitrary polarisation transform. The first uses three wave-plates with variable electrically-controllable birefringence and fixed optical axes, the second three wave-plates with rotatable axes (typically illustrated by liquid crystals) and fixed birefringence, and the third combining two variable and rotatable wave-plates. Let us now describe rapidly their advantages and limitations.

#### **III.2. Stack of fixed orientations and variable wave-plates:**

This configuration has been extensively described [7, 8]. One can demonstrate that arbitrary polarisation transformation can be achieved (see demonstration on Poincaré sphere of Figure 2.b), with only three fractional wave-plates such that the relative orientations of these plates are 45° with respect to one another [8]. By changing the applied voltages, one can control the amount of rotation with respect to each axis and then address

any location on the Poincaré sphere. Both PLZT (Pb-La-Zr-Ti ceramic) and Liquid crystal can be used.

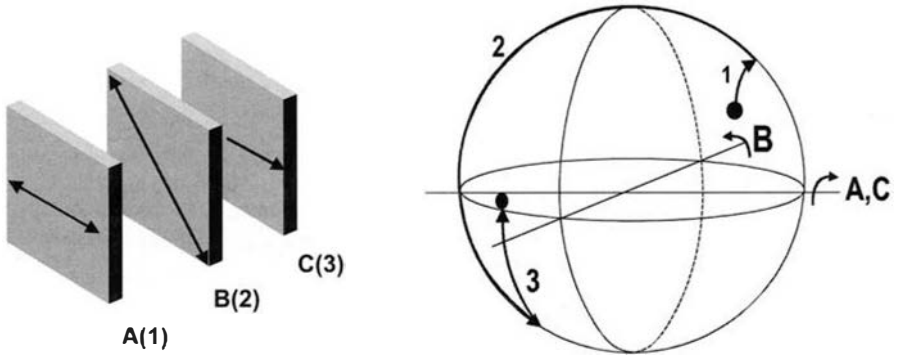


FIG. 2. – a) Wave-plates orientation and b) polarisations transformation principle with 3 variable wave-plates.

*a) L'orientation des lames biréfringentes b) Principe de transformation des états de polarisation avec trois lames biréfringentes.*

Polarisation control using such a technique needs three parameters and endless control can be achieved but assuming a sophisticated addressing scheme of the three wave-plates in contrast to the next approach which is fundamentally end-less.

### III.3. Stack of rotatable fractional wave-plates:

Three wave-plates are again required but in contrast to the previous case, their birefringence is fixed (respectively quarter, half and quarter wave-plates) whereas their principal axis can be rotated (see Figure 3). As previously one can easily demonstrated that any arbitrary polarisation can be addressed. This configuration can be implemented using various technologies (PLZT [9], LC [10], LiNbO3 [11]).

This technique needs a particular electrode schemes in order to create a rotating electric field. With PLZT it generally uses the four sides of the bulk material (see Figure 4a) and with liquid crystal the electrodes are etched on the glass substrate as depicted in figure 4b.

A vertically aligned (SmC layers are parallel to the substrate) LC layer is sandwiched between two glass substrates (see Figure 5-6). LC molecules incline parallel to the substrate. In this configuration, LC layers work as an, optically uniaxial medium retarder. Its retardation

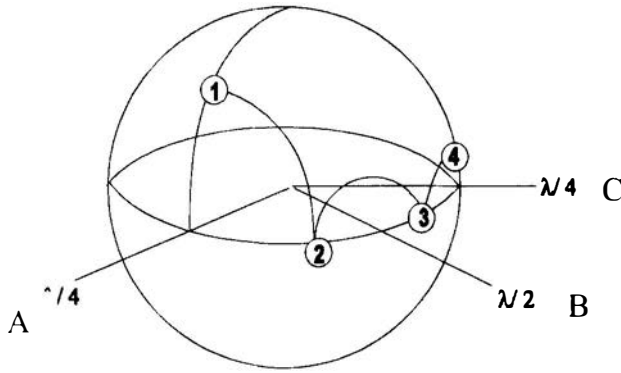


FIG. 3. – Principle of polarisation transformation using three wave-plates ( $\lambda/4$ ,  $\lambda/2$ ,  $\lambda/4$ ).  
*Principe de transformation des états de polarisations avec les lames ( $\lambda/4$ ,  $\lambda/2$ ,  $\lambda/4$ ).*

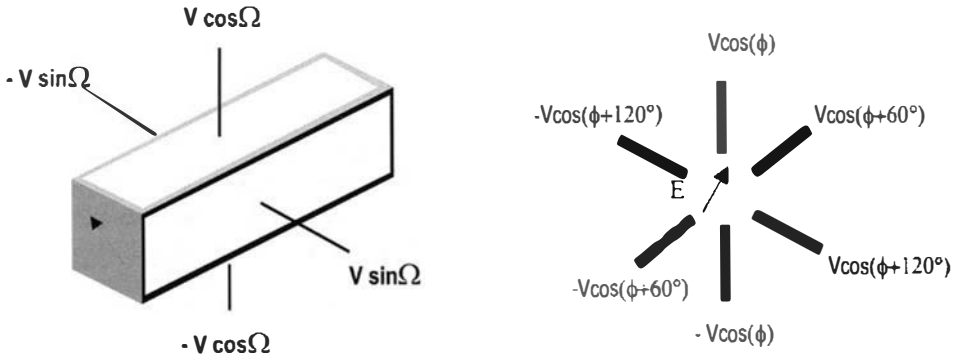


FIG. 4. – a) Electrodes implementation for a PLZT wave-plate and associated voltages.  
 b) Electrodes implementation on the substrate for liquid crystal wave-plate.

*a) L'implantation des électrodes pour les lames PLZT et les tensions associées –  
 b) L'implantation des électrodes sur le substrat pour les lames à cristaux liquides.*

depends on the direction, of the magnitude of the applied field, of the cell gap and the birefringence value  $\Delta n$ . Then the principal axis of the rotatable wave-plate depends on the direction of the applied field. In order to rotate the electric field vector, in the plane parallel to the substrates, radial electrodes (6, 8 and more) are etched on the glass substrate. Because the cell is thin, it is possible to engrave the electrodes on the glass substrate which authorizes

more complex designs. Polarisation control using such a technique (PLZT or LC) needs again three parameters but endless control can be achieved easily in contrast to previously.

### **III.4. Variable and rotatable wave-plate case**

This case is a combination of previous ones. One can demonstrate the same results when using only one cell from which both the axis and the birefringence can be modified. In this case the variable and rotatable wave-plate is controlled by two parameters, the strength and the direction of the applied voltage (for PLZT), the applied voltage value and orientation (for LC). Continuous alteration of these parameters produces a continuous change in polarisation such that the device is able to convert an arbitrary input polarisation into a desired output polarisation but with a significant gain in control parameter and then in speed for the monitoring algorithm. Similarly both PLZT and LC solution have been proposed [12, 13]. However, to obtain the endless control of the device, at least two variable and rotatable wave-plates are necessary. The phase shift magnitude and the non-blocking behaviour (concerning phase shift) are managed by the monitoring algorithm.

Indirectly the birefringence adjustment can be used to enable a better control in the c) case. When a liquid crystal polarisation controller is made using rotatable fractional wave-plates, it is crucial for the plates to be precisely half-wave or quarter-wave as required. Clearly it is difficult to achieve in any conventional way (for instance Lefebvre fibre loops) . The present device has the advantage that the half-wave or quarter-wave plate condition can be achieved very precisely by simply adjusting the magnitude of the drive voltage. In this way, a very flexible and rapid polarisation controller can be manufactured.

Free-space wave-plate solutions have generally higher coupling efficiency to fibre than LiNbO<sub>3</sub> waveguides and lower polarisation dispersion losses. Among them, liquid crystal solutions present a lot of advantages, such as simplicity, low voltage control, good package, no moving parts, no mechanical fatigue and to be low cost (compared to LiNbO<sub>3</sub> approaches). However, they suffered for a long time, from a lack of speed, which has been improved considering other liquid crystal or composite materials and/or special electrical addressing schemes, as it will be described in the next section.

## **IV. PRINCIPLE OF HOMEOTROPIC LIQUID CRYSTAL ENDLESS ROTATOR**

The use of electroclinic materials is interesting because providing switching time improvement of a few orders of magnitude with respect to standard nematic materials. The birefringent materials used are smectic A and smectic C\* ferroelectric liquid crystal in homeotropic configuration confined between two glass plates [14]. In this configuration, molecular layers are oriented parallel to the substrate. This orientation is obtained by using specific surfactant such as Silane. In the smectic A phase the birefringence is induced by the electric field. The smectic C\* exhibits a spontaneous birefringence. In both case,

the polar coupling between material and the in-plan electric field induces rotatable wave-plate, with or without phase shift control for respectively, smectic A and smectic C\* (see Figure 5).

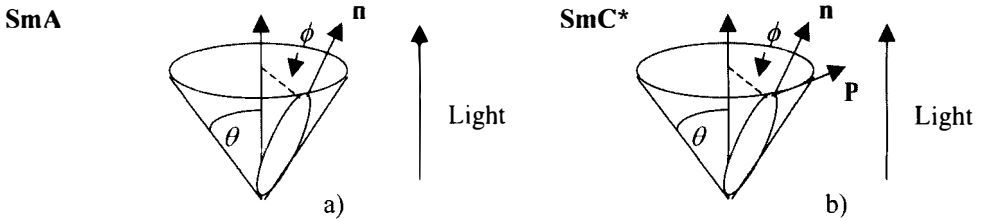


FIG. 5. – Liquid crystal is uniaxial crystal. The index ellipsoid is represented in geometry of a) Smectic A phase and b) Smectic C\* phases.

*Le cristal liquide est un matériau uniaxe. L'ellipsoïde des indices est représenté dans la géométrie de a) la phase smectique A et b) la phase smectique C\*.*

With the electroclinic effect, geometrical relations between the principal neutral axis of the index ellipsoid  $\mathbf{n}$  and the electric field  $\mathbf{E}$  is  $\vec{n} \times \vec{z} = \alpha \vec{E}$  and  $|\alpha \vec{E}| = \theta$ , with  $\alpha$  is the electroclinic coefficient. With smectic C\*  $\theta$  is constant and the spontaneous polarisation  $\mathbf{P}$  is parallel to  $\mathbf{E}$ .

In the case of polarization controller with rotatable fractional wave-plates, smectic C\* is a more useful liquid crystal for obvious functionality reasons (the first, is that birefringence is maintained without electric field – due to presence of steady states). In contrast, for a controller used as a variable and rotatable wave-plate, smectic A is preferable.

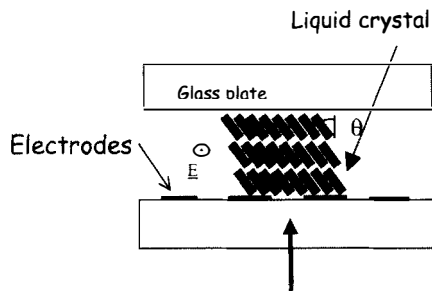


FIG. 6. – Geometry of liquid crystal cell.

*Géométrie de la cellule cristal liquide.*

The orientation of electric field and then of neutral axis is controlled by star – like electrodes (See figure 6). Typical thickness of liquid crystal are  $\approx 20$  and  $40 \mu\text{m}$  for respectively quarter and half wave-plate [13]. To obtain a large permeation length of electric field within the liquid crystal, thick electrodes are used. The thickness of copper electrodes is  $8 \mu\text{m}$  and they are realised by Liga\* process. Separations between opposite electrode are between  $20\text{-}30 \mu\text{m}$ .

## V. FIRST EXPERIMENTAL RESULTS: OPTICAL BEHAVIOUR OF SMECTIC A AND SMECTIC C\* PLATES:

The polarisation controller should have a short response time (a few  $10\mu\text{s}$ ) and should provide endless control. Two liquid crystals have been studied in two different configurations (smectic A and smectic C\*). We determined the optical characteristics of liquid crystals by two ways. First, we apply a sweep frequency of rotating the electric field that determines the rotating response time, second, we apply an electric pulse (0-V) within the liquid crystal that determines the birefringence modulation response time. By rotating both the in-plane electric field direction and its amplitude, we controlled the polarization change and then the intensity change through the polarizer (see figure 7). With a uniform rotating frequency  $f$ , the signal detected has a frequency four times higher ( $4f$ ). The optical response gives both the induced birefringence (see figure 7) and the response time.

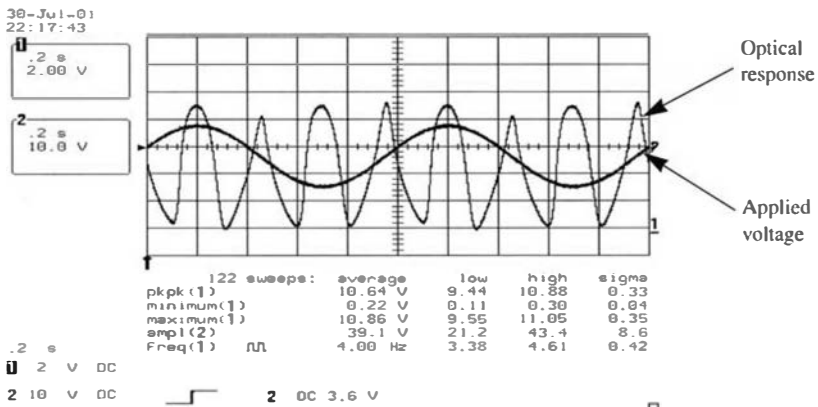


FIG. 7. – Oscillogram of the optical response.

*Oscillogramme de la réponse optique.*

The Jones matrix of the rotatable birefringent plate is:

$$\mathcal{R}(\theta) \begin{pmatrix} \exp(i \Delta \phi / 2) & 0 \\ 0 & \exp(-i \Delta \phi / 2) \end{pmatrix} \mathcal{R}(-\theta)$$

Where  $\Delta\phi$  is the phase shift of the birefringent material and  $\mathcal{R}(\theta)$  is the rotation matrix of  $\theta$  angle between the neutral axis of the birefringent material and the input polarization. By measuring the amplitude the light passing through the wave-plate by setting it between two polarizers, it is straightforward to calculate the induced phase shift by the formula:

$$\Delta\phi = 2 \sin^{-1} \left( \sqrt{\frac{I_{max}^{\perp}}{I_{max}^{\parallel}}} \right)$$

Where  $I_{max}^{\parallel}$  is the maximum intensity with polarizer parallel to the input polarizations and  $I_{max}^{\perp}$  is the maximum of intensity with polarizer crossed w. r. to the input polarizations. Then two types of liquid crystal materials and electrodes implementations have been considered.

### V.1. Electro-clinic wave-plate:

The birefringent material used is a smectic A liquid crystal (w415) of the Alkenyl family (provided by the University of Colorado at Boulder) in a homeotropic configuration and confined between two glass plates of 0.7 mm thickness with thin ITO electrodes. This material has a giant electroclinic effect at room temperature (smectic A phase: 23 – 32 °C) and the given induced tilt angle is 18° for 10V/μm. The cell thickness of 18 μm is obtained by a joint of cement including 18 μm spacers. The maximum measured phase shift is  $\Delta\phi = 0.41 \pi$  rad. for high electric field value (10V/μm) at a 1.55 μm operating wavelength. This low value of phase shift (below the typical index modulation values of smectic A liquid crystals) is the proof of the decrease in electric field magnitude in the thickness of liquid crystal. Therefore, the use of thick electrode is absolutely necessary in this case (see Figure 8). Moreover, the response time is strongly dependent of the temperature: 1 ms near smectic C\* – smectic A phase transition and less than 100 μs near smectic A – Isotropic phase transition.

### V.2. Smectic C\* wave-plate:

Smectic C\* liquid crystal wave-plates have also been studied and realized with thick copper electrodes [15]. The liquid crystal used is the ZLI-4655-100 and shows a good homeotropic orientation (see Figure 9). The cell thickness is 40 μm. The measured phase shift is close to  $\pi$ . In this case, thick electrodes are used to obtain a homogenous response time of liquid crystal in the thickness. The obtained response time is less than 100 μs with an electric field of 10V/μm at room temperature (150 V between to opposite electrodes).

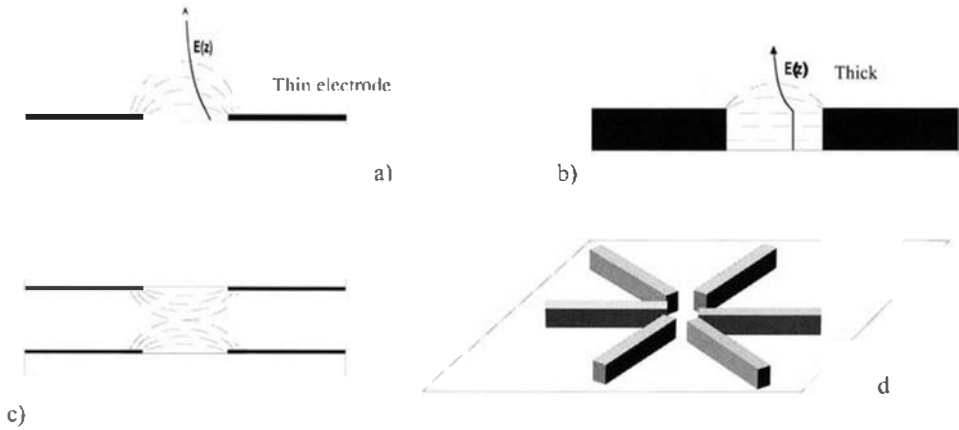


FIG. 8. – Decrease of the transverse electric field with thin electrode (a), and thick (b) electrodes. c) View of double thin electrodes. d) cross-section of thick electrodes system.

*Évolution de l'intensité du champ électrique avec des électrodes fines (a) et épaisses (b).  
c) Vue en coupe avec des électrodes fines. d) Vue générale des électrodes épaisses.*

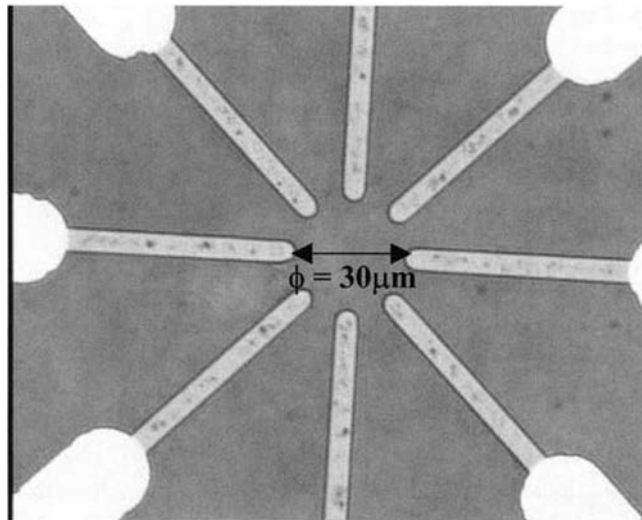


FIG. 9. – Microscope view of homeotropic liquid crystal with star-like thick ( $8\ \mu\text{m}$ ) copper electrodes (with courtesy of Highwave Optical Technology).

*Vue microscopique de l'orientation du cristal liquide avec les électrodes épaisses ( $8\ \mu\text{m}$ ) en cuivre.*

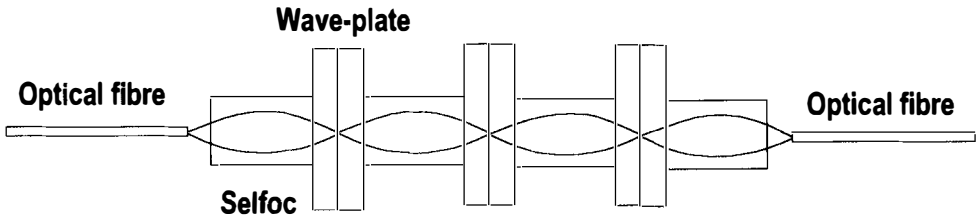


FIG. 10. – Principle of optical coupling wave-plate cells.

*Principe du couplage optique des lames.*

In both smectic cases the driving electronics has been made up by Analog amplifiers that applied phase-shifted voltages on each electrode. Electronics is monitored via a Digital-Analog Converter (National Instrument) driven by a PC. The optical system uses selfoc fibres collimating the optical beam within the polarisation controller aperture (see Figure 10).

Other types of fibres, such as extended mode fibres, can be advantageously used in such a system. Another option consists in using the device in reflection. The main advantage is to reduce the required thickness and to cancel double refraction which can occur with some material and optical configurations. In contrast, for instance, to the nematic rotatable wave-plate (rotatable fractional case), where the directors in the bulk are parallel to the glass, under an electric field, with smectic A, the directors make an angle  $\theta$  (Figure 5) to the normal resulting in double refraction under normal incidence. Double refraction also occurs in configuration (rotatable fractional and rotatable variable cases), where both director orientation and inclination are operating. Reflective devices enable to bypass this problem, but require the additional use of a circulator.

As an illustration here, double refraction results in a beam steering of a few degrees (typically  $5-6^\circ$ ), for a beam with a polarisation in the tilt plane. This results in a significant loss in the output fibre coupling when using single mode fibre (about 3dB). However, this point can be easily mitigated when using beam coupling into an extended mode fibre (typically  $40\mu\text{m}$ ).

## VI. DISCUSSION AND TRENDS:

In both cases thick electrodes are recommended to obtain a  $\pi$  phase shift for electro-clinic and to obtain homogenous response time for the smectic C\*. In addition, this arrangement prevents generally from residual polarisation dispersion loss sources due to the better homogeneity of the applied field and then liquid crystal orientation. Thermal control with a Peltier module is also required in particular for the smectic A wave-plates which have a critical behaviour near the transition temperature. Using smectic C\* phases could be an interesting solution for a fractional wave-plate: the birefringence is high and can be weakly adjusted

with temperature. Moreover, the wave-plate characteristics remain in the absence of applied electric field. This feature can provide in some case a decisive operational advantage.

Compared to other materials (nematic, PLZT and LinB03), the above solutions have the main advantage of exhibiting a good response time, a good trade-of between low voltage supply and short material thickness, enabling very compact and low loss systems. However, the alignment of such materials needs a particular attention. Therefore, other solutions have been suggested using, for instance, fast nematic liquid crystals [16] or nano-PDLC composite liquid crystal materials [17]. However, if both solutions gain in speed and are easier to manufacture, they require significantly higher voltages ( $> 20$  Volts /  $\mu\text{m}$ ). These high voltage values result generally in severe optical aperture limitations, then making more difficult the device pigtailling, collimation and packaging as well as mitigation of double refraction when it occurs (as mentioned above). This is probably the most serious practical advantage of low voltage solutions such as smectic A and C\* solutions over current competitors.

Of course, considerations on device choice cannot be only restricted to material aspects but also to algorithm optimisation. This is the reason why variable and rotatable wave-plates are preferred, because reducing the number of control parameters and then simplifying the algorithm. However, the use of polarisation controllers cannot be restricted only to the frame of PMD compensation, its potential applications include other domains such as polarisation analysis, scrambling and de-multiplexing for which fast response times are often required.

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