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Review

Photoaligning and Photopatterning—A New Challenge in Liquid Crystal Photonics

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Abstract: Photoalignment possesses obvious advantages in comparison with the usually "rubbing" treatment of the substrates of liquid crystal display (LCD) cells. The application of the photoalignment and photopatterning nanotechnology for the new generation of photonic and display devices will be reviewed.

Keywords: liquid crystals; photonics; display; photoalignment; photopatterning

1. Introduction

Liquid crystal (LC) displays and photonic devices based on nanosized novel photoalignment and photopatterning materials, including passive elements for fiber optical communication used in the program FTTH (fiber-to-the-home) are becoming increasingly important. FTTH (fiber-to-the-home) is a form of fiber optic communication delivery in which the fiber extends from the central office to the subscriber's living or working space. Fiber configurations that bring fiber right into the building can offer the highest speeds, delivering voice, video and data, since Gigabit and Terabit Ethernet can be efficiently used. The implementation of this technology will lead to a number of passive optical elements, such as switches, filters, attenuators, polarization rotators and controllers, which can be efficiently implemented using nano-size (2–15 nm layer) novel photoalignment and photopatterning LC technology. Fast switching photoaligned LC cells with microsecond and sub-microsecond switching time should replace the currently used micro-electro-mechanical (MEM) switching devices with millisecond switching time presently used in FTTH systems.

Despite a certain drop in the fiber optical component market within the last three years, the need for reliable passive optical components is still very strong and will continue to grow in the long run. Certain liquid crystal (LC) components, such as LC-based coaxial variable optical attenuators, polarization controllers and phase retarders, have already appeared in the market [1–3]. Recently, Vescent Photonics (USA) announced the LC Waveguides as a new electro-optic technology platform for a variety of applications, such as interferometers, beam steerers, tunable filters and lasers, *etc*. [2]. Photoalignment and photopatterning technology can make a sufficient contribution to the new classes of such devices. Photoalignment possesses obvious advantages in comparison with the usually "rubbing" treatment of the substrates of liquid crystal display (LCD) cells. Possible benefits for using these techniques include [1]:

(i) Elimination of electrostatic charges and impurities, as well as mechanical damage of the surface;
(ii) A controllable pretilt angle and anchoring energy of the liquid crystal cell, as well as its high thermo and ultraviolet (UV) stability and ionic purity;
(iii) New advanced applications of LC in fiber communications, optical data processing, holography and other fields, where the traditional rubbing LC alignment is not possible, due to the sophisticated geometry of the LC cell and/or high spatial resolution of the processing system;
(iv) Ability for efficient LC alignment on curved and flexible substrates;
(v) Manufacturing of new optical elements for LC technology, such as patterned polarizers and phase retarders, tunable optical filters, polarization non-sensitive optical lenses, with voltage controllable focal distance, *etc.*

Photoalignment and photopatterning is a key technology, which will be briefly considered in this review. Some recent examples of photonic LC devices based on this technology will also be provided.

2. Results and Discussion

Fiber optical communication systems (dense wavelength division multiplexing (DWDM) components) based on photoaligned LC cells, enable the production of switches, filters, attenuators, equalizers, polarization controllers, phase emulators, beam steering devices and other fiber optical components.

2.1. Liquid Crystal (LC) Switches

Switches for optical fiber networks are increasingly important. LC switches show certain advantages in comparison with micro-electro-mechanical (MEM) switches, commonly used for the same purpose, such as (i) fast switching time; (ii) low controlling voltages and power consumption and (iii) higher reliability and working time [1]. However, wavelength dependence of the response times and thermal drift of the characteristics of LC switches should be avoided [1]. We have pioneered several LC electro-optical modes, which can be used for producing LC switches for optical fiber networks, shown below [1].

2.1.1. Deformed Helix Ferroelectric (DHF) Effect in Ferroelectric LCs (FLCs)

The switching time, less than 10 μs, at the controlling voltage of 20 V can be provided, which is temperature independent over a broad temperature range [4,5]. The deformed helix ferroelectric (DHF) LC cells are the basis of fast responding modulators and optical filters, which are applicable in fiber optical communication systems. High operation speed is achieved for DHF-ferroelectric LC (FLC) at low driving voltages. The DHF effect is also less sensitive to the surface treatment and more tolerant to cell gap inhomogeneity. The DHF effect in a photoaligned FLC cell allows the implementation of a "natural", *i.e.*, dependent on voltage amplitude, grey scale, both linear and quadratic in voltage [5]. Recently, we have discovered a new fast V-shaped DHF-FLC for new active-matrix LCD and optical data processing devices, which is "nematic-like", *i.e.*, independent of voltage sign, takes place at very low voltages (<5 V) and provides a continuous gray scale with the switching times of about 60–80 μs, which is more than an order of magnitude faster than in nematic LC [6,7].

2.1.2. Volume-Stabilized (VS) FLC Mode

In this case, the FLC helix pitch may be infinite and plays no role. The V-shape curve is obtained by (i) using FLC with a high spontaneous polarization to produce multi-stable switching of two domain structures [8] and (ii) polymer stabilization of FLC structure [9]. The photoalignment technique enables us to produce highly uniform FLC cells over a sufficiently large surface area. Recently, we have obtained a very effective new volume-stabilized (VS) FLC mode, which we called ESH (electrically suppressed helix) mode [10,11]. The switching times were 130 μs at the voltage of ±7 V with the contrast ratio of 8000:1 [10,11].

2.1.3. The LC Switches Can Use the Effect of Total Internal Reflection in Nematic LC [12]

The total internal reflection switch operates only for one light polarization (TE, *i.e.*, Transfer Electric mode), and the most promising is the vertical aligned nematic (VAN) configuration, made by a photoalignment [12]. The switching time of 1 ms can be easily obtained in this case for the switching pulse amplitude of 5 V [12].

2.1.4. A Bistable Ferroelectric LC Optical Switch

Both bistability and fast FLC switching was shown with a typical response time of 100 μs from TE to TM (Transverse Magnetic) state and *vice versa*. A very low power consumption device with a rather satisfactory optical quality based on the photoalignment technique was developed as a result [13].

2.1.5. A Bypass Optical Switch

A bypass optical switch based on two nematic liquid crystal cells with a switching time less than 200 μs was demonstrated using two temperature-stabilized photoaligned nematic LC (NLC) birefringent cells [14]. Two subsequent NLC cells with crossed optical axes compensate the relaxation of NLC birefringence if turned off simultaneously. Thus, the switching speed of a two-cell switch can be as fast as the NLC cell turn-on times. The cells can be specified to a certain fiber wavelength by adjusting the cell gap thickness.

2.1.6. LC Switch to Control Light Beams in a Plane of LC Layers

It was shown experimentally that the direction of the light beam can be considerably changed by refraction and reflection of light at the sharp boundaries between the regions with different orientations created by photoalignment [15]. LC switching can be controlled by the electric field. Certain ways were proposed for optimization insertion loss and crosstalk of the 1 × 2 switcher for real photonic applications. Using different photoalignment templates, it is possible to create a N × M switch and other different optical processing data elements, e.g., attenuators. There are a number of ways to optimize such types of LC devices, including application of fast operating ferroelectric liquid crystal layers, which can provide the operation times in the microsecond range.

2.2. LC Polarization Controllers, Rotators and Variable Optical Attenuators

2.2.1. Polarization Controllers

Polarization controllers are elements that can transfer any input state of polarization (SOP) to the desired one, thus controlling the unpredictable polarization change or drift, which comes from the polarization-dependent components of the fiber optical system. These elements can be made with the three subsequently placed LC cells, which exhibit the effect of electrically controlled birefringence (ECB) with a homogeneous initial orientation [16]. Typical switching times are dependent on the LC material and on the order of 10 ms for the wavelength $\lambda = 1.3$ μm [16].

2.2.2. Polarization Rotators

Polarization rotator is an LC element that can rotate the linear polarized light in the output of the LC system to any desirable angle, while still keeping the linear polarization at the output [17]. The LC configuration proposed by us consists of the polarizer and two LC homogeneous cells placed at 45° with respect to each other (one with the a voltage controllable phase change and the other fixed as a quarter wave plate [17]). The configuration can rotate the light polarization state at any angle between 0° and 90°, dependent on voltage.

2.2.3. Variable Optical LC Attenuators

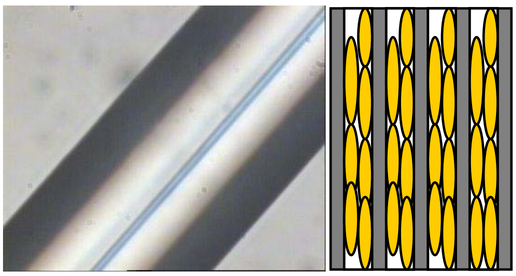
Variable optical LC attenuators (VOA) have the typical attenuation range of 30 dB for the driving voltage of 12 V at 1525–1575 nm wavelength range [1–3], with the response time of about 10–30 ms. Some of them are based on the light scattering of LC cells filled with a polymer network (PN-LCD). The light from the input fiber was scattered as a result of the refractive index mismatching of the LC and the polymer when no voltage was applied, and it was passed through the PN-LC layer as a result of the refractive index match of the LC and the polymer, when a voltage was applied.

2.3. LC Photonics Devices

2.3.1. Photonic Crystal Fiber

Photonic crystal fiber (PCF) is a glass or polymer fiber with an array of microscopic air holes running along the length of the fiber. The waveguide properties of such a fiber can be controlled by introducing an additional material into the air holes [18,19]. LC is suitable for that purpose, because its refractive index can be easily tuned by an electric field or temperature. The technique of photo-configurable alignment of LC in glass microtubes and in photonic crystal fiber was developed (Figure 1) [18,19]. Good homogeneous alignment was detected with polarized microscopy and Fourier transform infrared spectroscopy (FTIR) methods. The presented technique of alignment is based on proper developed photoaligning azo-dye materials [20] and is promising as a non-contact method for LC orientation in complex photonic crystal structures. Figure 1 presents the glass tube of inner diameter 4 µm treated with the photoaligning sulfonic azo-layer (SD1) and filled with uniform nematic LC orientation without point defects or linear disclinations. The order parameter S of LC has been obtained from FTIR spectroscopy data and has demonstrated good alignment quality. The presented technique can be used as a non-contact method of LC alignment in complex photonic crystal structure. New thin porous films with LC filling will also be investigated, taking into account practical applications in electrically controlled optical attenuators and polarization-independent optical switches [21].

Figure 1. High-quality liquid crystal (LC) alignment in microtubes (photonic crystal holes) [18].

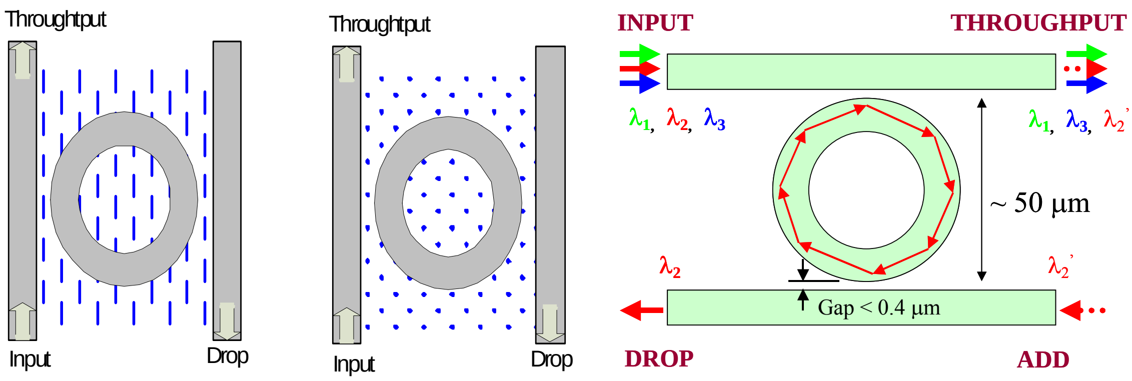


2.3.2. LC Filters

An electrically tunable micro-resonator using photoaligned liquid crystal as cladding layers, where a photoalignment layer on the device surface defined the orientation of the liquid crystal molecules, and the transmission property of the waveguide-coupled micro-resonator that was electrically tuned by varying the cladding refractive index under an applied electric field in the vertical direction was demonstrated [19,22]. The liquid crystal cladding refractive index is then varied according to the applied voltage, and subsequently, the microresonator resonance wavelengths were tuned. Based on our initial measurements, the FSR (free spectral range) wavelength shift within the range of 20 nm was obtained, which is comparable with a thermo-optic effect. The new voltage controllable Si-based add drop filters are envisaged, based on this principle (Figure 2).

Remnant high efficiency polarization gratings were created in nematic liquid crystal cells by layers of azo-dye molecules deposited on the cell substrates and exposed to “interfering” beams with opposite circular polarizations [23]. The diffraction picture was controlled by an electric field applied across the LC cell. The obtained polarization gratings can be used for electrically controlled discrimination and detection of polarized components of light. All molecules of LC are reoriented to a uniform homeotropic state at high voltage, and there is no more modulation of LC alignment in the cell. Applications in LC optical switches and filters are envisaged.

Figure 2. Electrically tunable microresonators using photoaligned LCs as the cladding layers, LC molecules switch between homogeneous (parallel) and homeotropic (perpendicular) orientation [22].

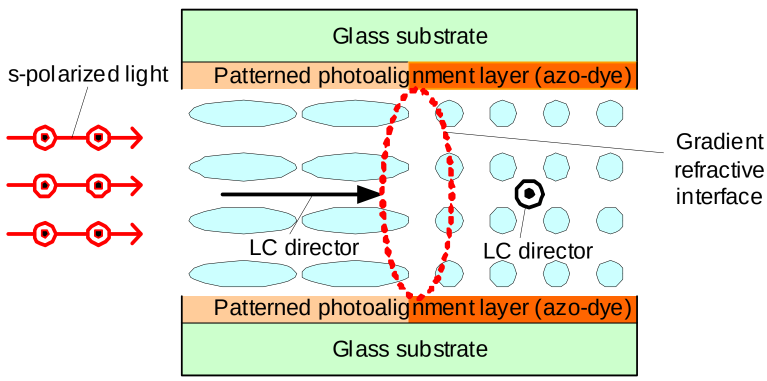


2.4. Novel LC Display Devices Based on Photoaligning and Photopatterning Technology

2.4.1. ORW Technology

Optical rewritable technology (ORW), pioneered by us [17,20,24–27], can be successfully used for Photonics applications. The modern LC materials with improved technological properties provide a real opportunity for an optimization of LC devices. To the best of our knowledge, there are no publications made by other groups on the application of optically rewritable technology for photonics devices, such as light controllable LC plane waveguides, LC polarization-dependent elements, such as lenses and wave plates, LC polarization rotators and polarization controllers, light and voltage controllable diffraction gratings for optical filters, *etc.* One of the examples of such applications is shown in Figure 3.

Figure 3. Formation of refractive interface for S polarized light by nematic liquid crystal inside the bulk of the LC cell [24].



Using ORW photoalignment techniques, the smooth collimating refractive interface can be written by light in front of the waveguide immerged into LC [24]. Such passive LC structure is stabilized by the photoalignment layers and does not need applied voltage to operate. It can out-couple the S polarized light, coming from the waveguide, into a collimated beam inside the LC bulk for further processing, while the P polarized light can be guided by matching polarization, maintaining the LC waveguide [24]. We suggest the polarization-independent design of the LC photonic device that can convert both polarization components out-coupled from the polarization-independent waveguide to one polarization for the further process of light by the polarization-dependent LC structure for routing or other purposes. The novel design consists of polarization maintaining LC waveguides, a LC polarization-dependent passive lens and an active half wave plate (HWP). Optically rewritable (ORW) LC displays are also envisaged. They do not require a current conducting layer, are highly tolerant to the cell gap non-uniformity, very cheap in production and, thus, highly appropriate for plastic LCD [26] (Figure 4). Plastic card displays, outdoor advertisements and price labels in supermarkets, as well as security applications using ORW E-paper are envisaged (Figure 5).

Figure 4. Electrically tunable LC lens, based on photoalignment technology [28].

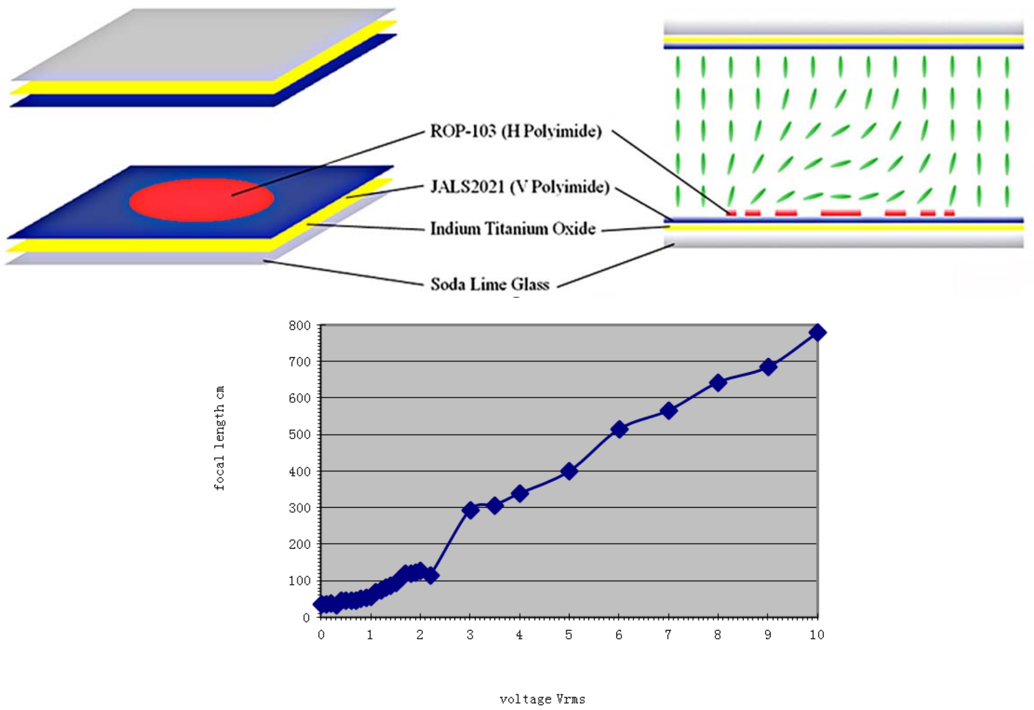
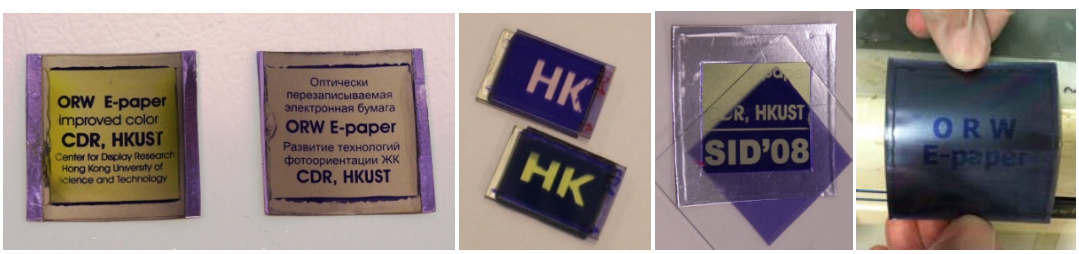


Figure 5. Images of optically rewritable (ORW) LC display [24–27].



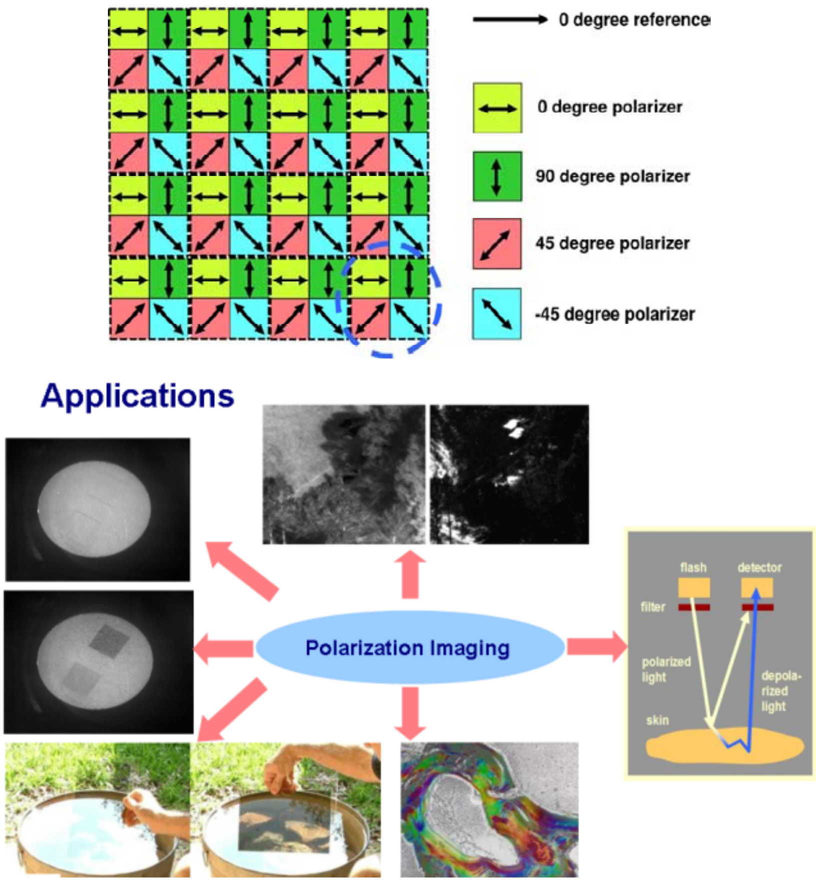
2.4.2. Tunable LC Lenses

A tunable-focus liquid crystal (LC) lens can be achieved using stacked alignment layers (Figure 4) [28]. The stacked alignment layer is made of photo-aligned polymer on top of a rubbed polyimide. The focal length of the LC lens can be worked out according to the retardation profile, and it is electrically tunable from 37 cm (without voltage) to infinite length (Figure 4). Applications in digital cameras and 2D/3D switchable LCD are envisaged. Our recent research shows that the stacked alignment layer is not necessary, as variable pretilt angle can be made by varying the exposure energy on a single photoalignment layer [28].

2.4.3. Micro-Patterned Polarizer Sensor Displays

A thin photo-patterned micropolarizer array for complementary metal-oxide-semiconductor (CMOS) image sensors can be made for simultaneous detection of all four Stokes parameters of an output optical image (Figure 6) [29–31]. A 2 μm pitch is achieved by using UV light to define the orientation of the micropolarizer elements. Reported experimental results validate the concept of high performance photoaligned LC micropolarizer arrays with major principal transmittance of ~80% and an extinction ratio as high as ~3200 (35 dB).

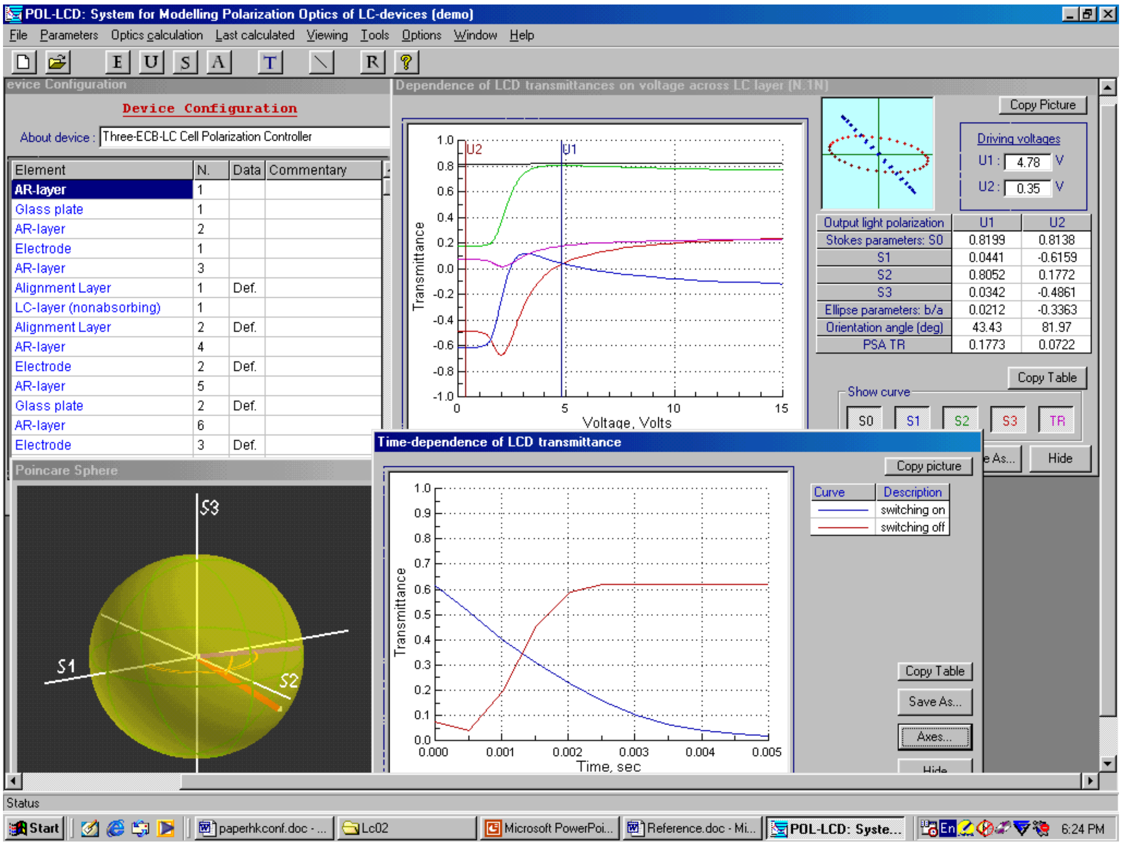
Figure 6. A thin photopatterned micropolarizer array for complementary metal-oxide-semiconductor (CMOS) image sensors for simultaneous detection of all four Stokes parameters of output optical image, including "invisible objects" (constant transmission or reflection and no color) [29–31].



2.5. Optimization Software

We have also developed a special software that enables us to optimize various LC cell configurations to get perfect switching of the polarization plane of the input light to the required switching angle [19]. The software can be used to find an appropriate LC electro-optical mode, LC cell configuration and driving regime with fast switching time and low controlling voltage for applications to fiber optical systems. The LC polarization controller must be able to transfer any input state of the light polarization to any output state, which is shown by the corresponding trajectory on the Poincare sphere (Figure 7).

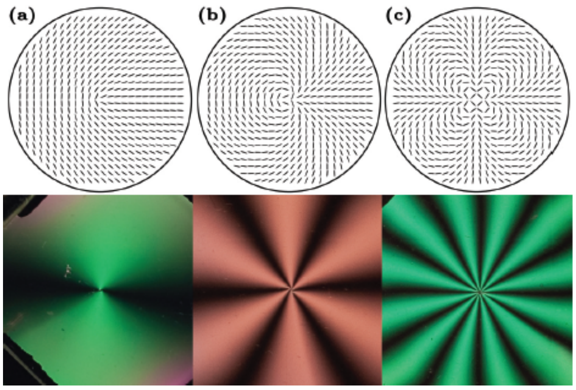
Figure 7. The example of a polarization controller, based on three subsequently placed LC cells, developed and optimized using our new software POL (polarization)-LCD [19].



2.6. Electrically Tunable q-Plates

Recently, we used a photoalignment technology to fabricate electrically tunable liquid crystal q-plates with various topological charges for generating optical vortex beams with definite orbital angular momentum (OAM) per photon [32]. We carried out several tests on our q-plates, including OAM tomography, finding excellent performances. These devices can have useful applications in general and quantum optics. The azo-dye materials showed a very high resolution capability of LC alignment in these experiments (Figure 8).

Figure 8. High resolution LC patterns for switchable q-plates made by photoalignment [32].

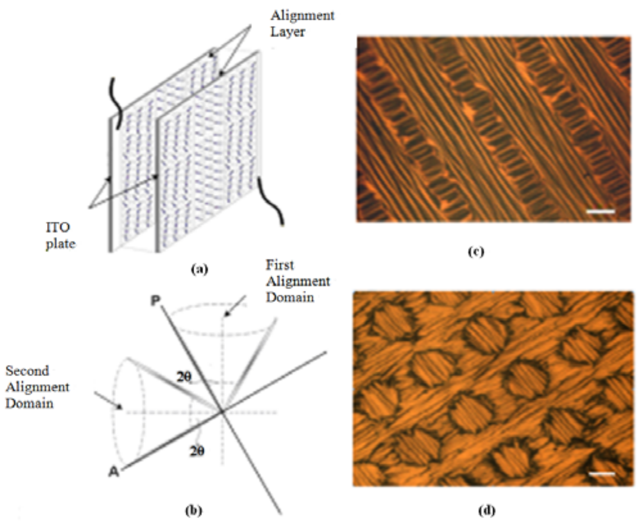


2.7. Electrically Tunable FLC Grating

Fast grating based on FLC has been realized by first utilizing both intrinsic material properties and second by deploying two orthogonally aligned FLC domains. The natural diffracting efficiency is not suitable for any practically application, thus the chiral nanotube has been introduced in the pure FLC matrix (concentration of 0.5 wt %) that results in increase in the diffraction efficiency, while the response time and power consumption is the same as the pure FLC [33].

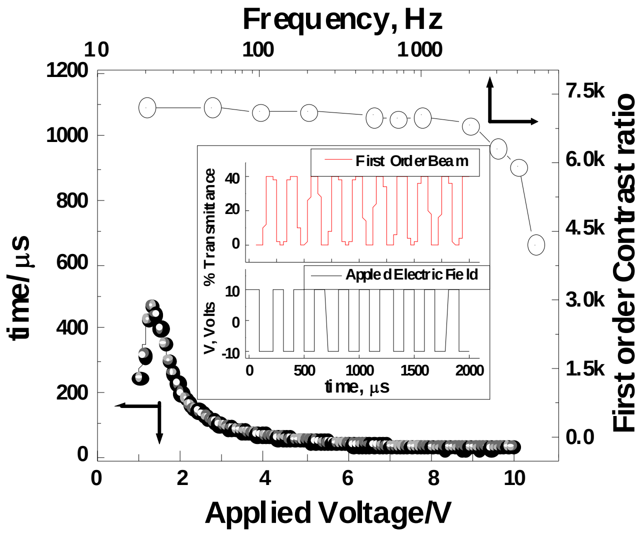
Another FLC grating based on orthogonally aligned FLC domain (Figure 9) for both one dimensional (1D) and two dimensional (2D) structure has been realized by photoalignment [34].

Figure 9. (**a**) The ferroelectric LC (FLC) grating cell having two alignment domains, wherein alignment directions are mutually perpendicular to each other and smectic layers are perpendicular to the substrate; (**b**) simple illustration of the molecular orientation in different alignment domains with respect to the crossed polarizer; P is the polarizer and A is the analyzer and (**c**) and (**d**) are the optical micro photograph of the 1D and 2D grating FLC cells, respectively, at the applied electric field of 10 V. The white marker in the photographs represents the length of 10 μm [34].



These gratings are based on the electrically suppressed helix (ESH) mode mentioned above and provides a very high contrast (7000:1) and diffraction efficiency (>70%) and fast response (10~50 μs) at a very low electric field (Figure 10). Moreover, these elements manifest saturated electro-optical states, up to 5 kHz of high frequency [34].

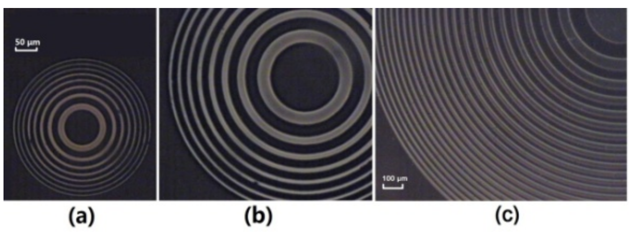
Figure 10. The response time dependence on applied voltage at a driving frequency of 500 Hz (solid legends). The frequency dependence of the first order contrast ratio at the fixed applied voltage at 10 V (open legends). The insertion represents the electro-optical response of the FLC grating cell, the bottom is the applied voltage and the top represents electro-optical response for the first order diffracted beam of wavelength λ = 632 nm at the operational frequency f = 5 kHz [34].



2.8. Electrically and Optically Tunable Fresnel Lens

Fresnel lens have been developed by deploying nematic liquid crystals on the alternative twisted nematic (TN) and planar aligned domain by means of photoalignment [35]. The micrograph of the structure under crossed polarizers has been presented in Figure 11, where the white rings represent the TN domains, while the dark regions are the planar aligned area. These elements provide very high efficiency, ~42%, that can be further improved, and the switching time for the 3 μm thick cell is ~6.7 ms, which is relatively fast in comparison to existing switchable grating LC devices. The response time can be further improved by deploying FLC instead of nematic LC.

Figure 11. Optical microphotograph of the designed Fresnel zone lens under crossed polarizers [35]. (**a**) LC Fresnel zone lens (lens I) with the focal length of 3.2 mm; (**b**) the zoomed-in version of (**a**); (**c**) LC Fresnel zone lens (lens II) with the focal length of 50 mm.



3. Conclusions

Further work in the field of new LC photonics and display devices based on nanosized photoalignment and photopatterning technology is needed. New working prototypes ready for packaging are highly desirable. We believe that photoalignment and photopatterning technology will replace rubbing in the very near future [36].

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Conflict of Interest

The author declares no conflict of interest.

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