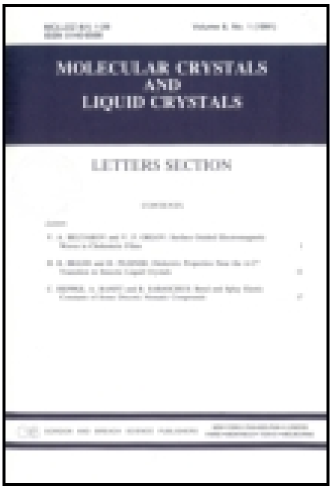

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Ferroelectric Liquid Crystal Cells for Advanced Applications in Displays and Photonics

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Ferroelectric Liquid Crystal Cells for Advanced Applications in Displays and Photonics

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Ferroelectric Liquid Crystals (FLC) are discussed for various applications in displays and photonics. We have considered new FLC electrooptic modes based on photoalignment technology: deformed helix ferroelectric (DHF) FLC, Electrically Suppressed Helix (ESH) and Voltage Controllable Diffraction (VCD) FLC Mode. New FLC display and photonics devises such as field sequential color (FSC) FLC displays, switches, grating, Fresnel lens, Circular Dammann (CD) grating are discussed. Certain comparison between ferroelectric and nematic LC devices is provided.

Keywords Ferroelectric liquid crystals; photonics; displays; photoalignment

1. Introduction

Fast tunable photonic elements are one of the hot research topics these days. Thus, liquid crystals have become attractive for applications such as diffractive optics, adaptive optics, or optical metrology. While nematic liquid crystal (LC) devices are the dominant technology, because of its easy manufacturing, devices based on ferroelectric liquid crystals (FLC) have grown in importance because they can switch up to 100 times faster than standard nematic LC at the cost of less power consumption. FLC have found applications in diffractive optics for the generation of digital holograms, adaptive beam steering systems, and polarization gratings. Additionally, high-speed communication systems, producing elements (such as switches, attenuators, polarization rotators) demand extremely fast response, stable, low loss, operable over a wide temperature range, and that require small operating voltages and extremely low power consumption. Thus, fast switching FLC is a good candidate for the new generation of photonic and display devices, which proved to be better in response time, than usually used nematic LC. However the FLC are less popular for real applications because of difficult alignment process.

The photoalignment technology enables to solve the key problems usually faced in FLCD applications, such as (i) quality of FLC alignment on sufficiently large surface area; (ii) appropriate adjustable anchoring energy and pre-tilt angle; (iii) low losses in the alignment layers due to their small thickness etc.

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2. FLC Electrooptical Modes

Electrooptical switching in ferroelectric liquid crystals (FLC) is much faster than in nematic liquid crystals (LC) [1]. Slower response of nematic LC is mainly due to the relatively large decay times, which in FLC case can be very short in sufficiently high electric fields E. Actually due to the linear electrooptical response there is no difference in "on" τ_{on} and "off" τ_{off} times in FLC, which results in a very fast switching times:

$$\tau_{on} = \tau_{off} \sim \gamma_{\varphi}/P_s E,$$

where γ_{φ} is a rotational viscosity, P_s-spontaneous polarization and E is the applied electric field. The typical response time may be 20 μs for the applied electric field $E = \pm 7-8\ V/\mu$, which is about ± 10 V for 1.5 μ FLC cell [2].

The following electrooptical effects in FLC can be used in fast optical switching.

1. Deformed helix ferrroelectric (DHF) effect [1]. High operation speed is achieved for DHF-FLC at low driving voltages. This takes place because a slight distortion of the helix near the equilibrium state results in a considerable change in the transmission. The DHF effect is also less sensitive to the surface treatment and more tolerant to the cell gap in homogeneity. As follows from experiment and qualitative estimations, the effective LC birefringence value Δn_{eff} is approximately twice as low as $\Delta n = n_{\parallel} - n_{\perp}$ in the full FLC switching (Clark-Lagerwall mode) [3]. The DHF effect allows the implementation of a "natural," i.e., dependent on voltage amplitude, grey scale both linear and quadratic in voltage.
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 [4]; (ii) polymer stabilization of FLC structure [5].
   Some new perspective methods of LCD addressing is color sequential LCD. The driving of such color sequential LCD includes three sub-frames. The response time of the LCD needs to be very fast in order to fit the field sequential driving method. Suppose that are 60 frames per second, then there is 16.67 ms per frame. Each sub-frame will have 5.5 ms. Again, each sub-frame has to further divide into three parts. The first one is the data loading time which is about 0.5 ms. Secondly, it comes to the LC response time which is about 2.1 ms. Finally, the total LED illumination time is around 2.9 ms. However, typical response rate of LCD is about 240 frames per second [5] and increases twice, when 3D time sequential addressing is used, so the LC response time should be about 8 times shorter, i.e. about 250 μsec, which is really a challenge.
   Polymer stabilization of FLCs exhibiting a continuous gray scale V-shaped switching free from zigzag defects producing a high contrast ratio, and a high-speed response below 400 μs, called PSV-FLCD was developed by Kobayashi et al. [5]. The advantages for PSV-FLCD are (i) a continuous gray scale capability for full color displaying by dissolving the bistability; (ii) uniaxal alignments causing a pure dark state; (iii) the capability of unwinding helical structure in smectic C* phases by polymer stabilization. The materials used in PSV-FLCD are mixtures composed of conventional and newly synthesized FLC mixtures and several newly synthesized photo-curable monomers. PSV-FLCD are fabricated with a unique process combining a UV-light exposure for a formation of polymeric nanostructures stabilizing

FLC alignment and an applying ac voltage for a creating uni-axial orientation exhibiting a dark state without zigzag defects. By this process, a biaxial orientation based on bistable switching in FLC displays changes into a uni-axial orientation exhibiting V-shaped switching to be possible to produce a continuous gray scale [5]. In order to accommodate the polymer-stabilized FLCD to active matrix (thin film transistor-TFT) driving, the reduction of operating voltage within 10 volts was provided as well as suppression of temperature variation in operating voltage, in which the variation is within 3 mV/°C in the range from –5°C to 50°C, resulting in successful demonstration of a TFT driving field sequential full color type featured by a high-resolution of SVGA (800 × 600 pixels) in a small size of 4 inch diagonal display without color filter. The novel PSV-FLCDs show the fast response times below 400 μs at 25°C, even in a gray scale. In the lower temperature of operation, PSV-FLCs exhibits a fast response time less than 1000 μs even at −5°C. The new FLC materials with a lower birefringence should be developed to increase the FLC cell gap for achromatic black/white switching required for color sequential FLC displays [1].

3. Another electro-optical mode is electrically suppressed helix ferroelectric liquid crystals (ESHFLC). In this case the helix of the FLC is smaller than the FLC layer thickness and the anchoring energy of the cell is obligatory less than the elastic energy of the helix. The ESHFLC is characterize by very high contrast ratio (∼10000:1), very fast response time (10∼50 μs) at very small electric field [6]. Special optimal value of FLC anchoring energy is required to realize this mode [1].

3. FLC Display and Photonics Devices

Fast FLC elements can be also successfully used in other display and Photonics LC devices, such as tunable cladding in Mach-Zehnder interferometers [7], fiber-optic and waveguide switches [8, 9], bistable FLC–on- silicon (FLCOS) micro-displays with double brightness for ultra-miniature projector products (pico-projectors) [10], and fast bistable microlens arrays based on a birefringent layer and FLCs [11].

There are three different approaches that underline the most popular methods used for producing the diffractive profile. These are based on: (1) deploying the patterned electrode [12]; (2) defining two or more different alignment regions [13]; and (3) utilizing the intrinsic diffractive properties of LC like the grating based on alternate twisted nematic (TN) and planar alignment (PA) photoalignment [14] and cholesteric LC [15].

Most of such gratings are slow and show low diffraction efficiency and low contrast ratio. They also require rather high driving electric field. On the other hand, there are several methods such as the fringe field effect and the guest host effect that have been suggested to increase the speed of the nematic LC devices [16–21]. In these methods, however, the response time is typically limited to 1 ms.

Several efforts to improve the response time are still in progress. Most notably, the polymer-stabilized blue phase liquid crystal that has been proposed last year shows high diffraction efficiency with the response time at about 400 μs but at the expense of high driving voltage [21]. We have recently disclosed a fast switchable grating based on three electrode driving scheme device comprising nematic LC with the response time of 150 μs at the electric field $E = 20$ V/μm [13].

In an alternative approach that uses the flexoelectric effect in short pitch cholesteric LCs the response time is limited to 200 μs [20]. This technology, however, has several material issues and a very complicated fabrication procedure. As a matter of fact, some of

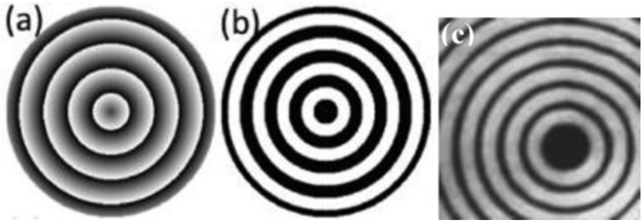

Figure 1. Two dimensional (2D) binary phase patterns for (a) Linear axicon, (b) Binary axicon, (c) the optical micrograph of the CD grating [27–29].

the recently proposed diffraction grating elements that show good optical quality combined with fast switching speed generally requires high driving voltages. Due to some fundamental limitations, the latter cannot be reduced much [22].

Ferroelectric LC (FLC) diffractive elements have an edge on all of the existing technology because of their fast switching speed and low power consumption. There are, however, a number of problems that considerably complicate deploying FLC as a diffractive element. There are two known possible approaches to realize FLC diffractive element. The first one uses the diffractive properties of FLC arising from the periodicity of the ferroelectric domains, which strongly depends on the spontaneous polarization, P_s. In this case, high diffraction efficiency can only be achieved in materials with large values of P_s. But, the high P_s, is known to produce other defects that have a destructive effect on the quality of the diffractive profile [23–24].

Great effort has already been done to realize the Fresnel lens based on patterned electrode, polymer dispersed nematic liquid crystals and dye doped liquid crystals etc. [25–26]. However, all of these systems are characterized by the low efficiency, complicated fabrication procedure. The response time is limited by tens of ms and the maximum achieved efficiency is around 23% [25–26].

Another important photonic element is Dammann (CD) grating. A grating can generate one-dimensional spots and two-dimensional rectangular spots but not a circular pattern. The CD grating can generate circular equal intensities profile at various orders in the far field (Fig. 1). The first CD grating structure was proposed in 2003 [27]. CD grating is very useful for applications e.g., laser processing of materials, laser micromachining, and high-intensity laser fusion, and optical trapping etc. Several efforts have been made to make these elements tunable by electric field, however the manufacturing process is very difficult and expensive [28–29].

All of above-mentioned elements are characterized by difficult manufacturing, high power consumption and extremely slow response, typically limited to few tens of milliseconds [25–29]. At the same time the photoalignment provides easy fabrication of such structures and in association of FLC these elements could find application in various modern photonic devices [2, 4, 6, 12–14]. FLC alignment on sufficiently large surface is always a big issue, as in order to avoid screening the switching field by charges, one has to use thin orienting layers with high dielectric permittivity and sufficiently thick FLC cells with a low spontaneous polarization. Moreover, the FLC anchoring energy cannot be very high, and in order to avoid the defects a sufficiently large pretilt angle on the surface should be obtained. Usual polyimide (PI) layers, prepared by a common rubbing technology can hardly solve the problem [1].

We have produced an extensive work studying optical and electrooptical response of FLC, as well as developing new FLC materials with advanced surface alignment. We have also made a good progress in formulating new photoalignment materials that are potentially capable of being used in photo-aligning technology for LCD [30–34].

1. The aligning materials developed at HKUST are based on photo-polymerized and cross-linked dye photosensitive layers, that enable (i) high order parameter > 0.8; (ii) excellent alignment quality of LCD with a high contrast ratio in TN, VAN, π-BTN and FLC modes; (iii) high temperature stability up to 230°C suitable for LCD manufacturing; (iv) UV-stability due to the polymerization and cross-linking effect in dye layers; (v) perfect adhesion and high azimuthal and polar anchoring energy, i.e. $> 10^{-4}$ J/m^2, which is the same as the anchoring of the rubbed polyimide (PI) layer; (vi) excellent sensitivity with a minimum energy of 150 mJ/cm2 for a non-polarized obliquely incident light and 20 mJ/cm2 for polarized light, allowing roll to roll processing of retardation films and polarizers; and (vii) the value of voltage holding ratio (VHR) for the photo-aligned LC cell (>99% at 80°C) and residual DC voltage (<50 mV) was found to be even better than those for rubbed PI layers [32].
2. The high uniformity of FLC layer was obtained by a photo-alignment with asymmetric boundary conditions, when only one aligning layer at the boundary is used [2, 32–34]. Moreover, the azo-dye photo-aligning layer can be easily adjusted to be thin enough, so as to suppress the depolarizing fields, which is practically impossible in the case of rubbed polyimide (PI) layers. However, the asymmetry of FLC configuration creates certain problems with the steadiness of FLC bistable switching and multiplex addressing of passive matrix FLCD.

We have suggested certain ways to overcome these problems. We proposed a new principle of a FLCD multiplex addressing with a grey scale and considered its limitations due to the dependence of FLC material parameters on temperature [30]. A new concept of the passive matrix FLCD with a memorized grey scale was elaborated. Intrinsic grey scale generation and stabilization in FLCD have been proposed and investigated [30, 31]. Study of the FLC samples shows that the switching process takes place through the formation and evolutions of domains formation. Dynamic current and electrooptical response in FLC testing cell are discussed as a criterion of memorized grayscale generation for FLC display. Grayscale stability for different crosstalk effects under a passive multiplex driving scheme was demonstrated. For the FLC display, the dark state is fixed here as a basic one, while the gray levels depend on the writing voltage with a fixed duration time [30]. The bright state can also be selected as a reference state of the FLCD. The images can be saved for infinitive time without any power supply. The contrast ratio could even be increased if better FLC mixtures, smaller cell gap, and compensation films are used. A criterion for reliable bistability was derived dependent on FLC hysteretic behavior in an electric field. An optimal (about 3–5 nm) azo-dye layer thickness that provided both the highest multiplex operation steadiness and the best contrast ratio of FLC display cells were found [31]. A 160×160 passive matrix addressed bistable reflective FLC display was demonstrated with the driving voltage of 13 V and 5 μm cell gap with four grey levels [30].

However, the display quality needs further improvement in terms of (i) elimination of the sticking effect; (ii) realization of bi- and multi-stable switching with the memorizing of the gray level for a low voltage driving; (iii) improvement of the contrast ratio and quality of FLC alignment on sufficiently large surface areas with achromatic (black/white) switching; and (iv) increasing FLCD resolution. The success in this development can be guaranteed by a proper choice of the photoalignment (PA) layer (preferably low-polar), ITO coating, FLC material and driving scheme. The potential market includes the screens of mobile phones, smart cards, PDA, electronic books, etc., where an extremely low power of operation is required.

Another possibility is a fast switching FLC with V-shape switching, i.e. a number of gray scales, which can be used, e.g. for field sequential colors (FSC) FLC LCD. In this case, we need FLC with a sufficiently low spontaneous polarization and fast switching. Ideally, we need FLC with a spontaneous polarization $P_s < 10$ nC/cm^2 and response time of 100 μs for the applied electric field E<2 V/μm. At the same time, FLC should be mechanically stable (shock free) and without any hysteresis in the electrooptical response. One of the possibilities is a volume stabilized (VS) mode with a very low viscosity of FLC and a polymer network to enable monostable V-shape switching (PSV- FLCD) [5]. However, our preliminary investigations showed that the hysteresis almost inevitable in electrooptical switching in this case. Further investigations are necessary to understand the PSV- FLCD advantages more in detail.

Another opportunity is the application of the deformed helix ferroelectric (DHF) effect [35]. We have already obtained some good results in this direction. In particular, a high quality dark state of DHF FLCD has been obtained as well as V-shape switching with a high frequency. High frequency hysteretic free electrically controlled 0–2π phase modulation of the light has been obtained using a very short helix pitch (less than 400 nm) DHF FLC. The electrically controlled 0–2π hysteretic free phase modulation was achieved at the driving voltage frequency till 4 kHz and the voltage amplitude of 32 V. The application of fast V-shaped DHF-FLC for new active-matrix LCD and optical data processing devices is envisaged. Further work is needed in this direction to decrease the driving voltage and to decrease the FLC cell thickness. However, the latter is possible, if we are able to increase the FLC anchoring energy produced by a photoalignment layer.

We have also obtained certain promising results in photonics applications of FLC [36–38]. We developed half-wave retarder based of DHF-FLC cell [36]. Birefringence and thickness of DHF FLC cell were optimized to obtain 90° rotation of the light polarization. The switching time, less than 10 μs at controlling voltage of 20 V can be provided, which is temperature independent over the broad temperature range. We believe that DHFLC cell is a promising device to build the optical switches for telecommunication systems due to their high speed of operation and independence from temperature. Also, the system of two DHF cells with helix axes crossed at 90° is considerable to realize the optical switches operating at arbitrary light wavelengths in the visible and infrared spectrum.

FLC switches show certain advantages in comparison with MEM switches, commonly used for the same purpose, such as (i) fast switching time; (ii) low controlling voltages and power consumption; (iii) higher reliability and working time [37–39]. We developed a bistable FLC switch [37]. The developed switch exhibits a perfect bistable 90° FLC reorientation. The FLC alignment has been provided with the photo-alignment technique. We obtained the bistable polarizing plane switching characterized by ellipticity of 0.07 with steady keeping of the switched states without any power consumption from several milliseconds up to several days while the switching time was about 100 μs. A very low power consumption 90° polarization rotator with a high optical quality was demonstrated.

For the fast grating based on FLC has been realized by 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 we have introduced chiral nanotube in the pure FLC matrix (concentration of 0.5% wt/wt) that results in increment in the diffraction efficiency, while the response time and power consumption is

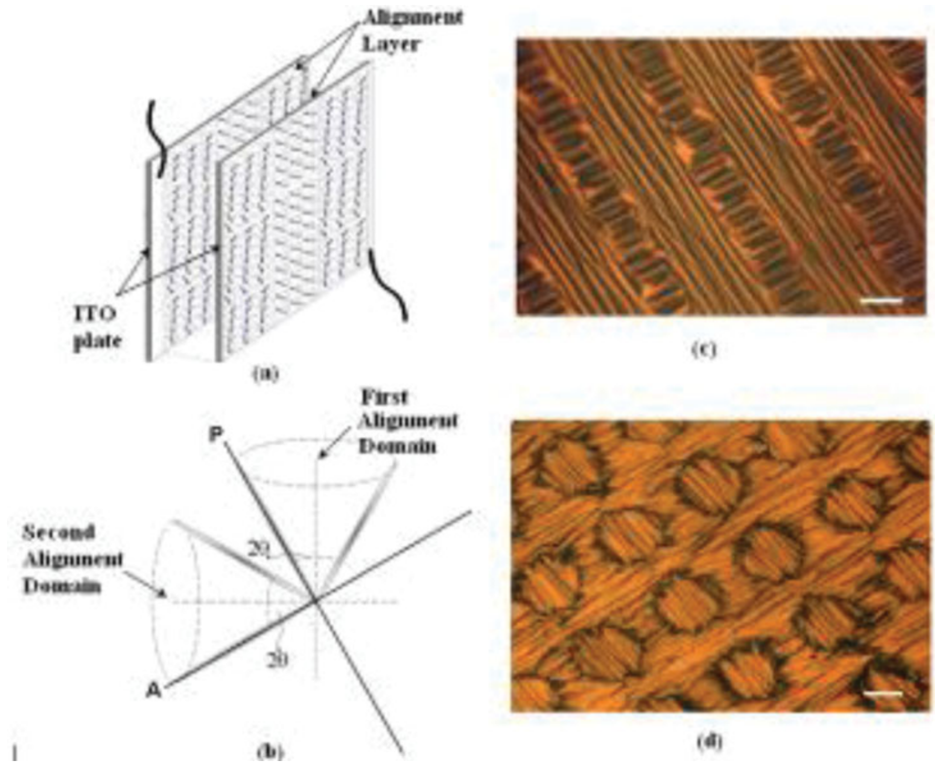

Figure 2. (a) The FLC grating cell having two alignment domains wherein alignment direction are mutually perpendicular to each other and smectic layers are perpendicular to the substrate, (b) Simple illustration of the molecular orientation in different alignment domains with respect to the crossed polarizer, P is the polarizer and A is the analyzer. (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 [40].

the same as the pure FLC [16]. Another FLC grating based on orthogonally aligned FLC domain (Fig. 2) for both 1 D and 2D structure has been realized by photoalignment [40].

Figure 3 represents the intensity profile for the bright and dark state for 1D and 2D FLC grating elements. These grating are based on the ESH mode that gives very high contrast (7000:1) and diffraction efficiency (>70%) and fast response (10~50 μs) at very low electric field (Fig. 4). Moreover, these elements manifest saturated electro-optical states up to 5 kHz of high frequency [40, 41].

Optically rewritable ferroelectric liquid-crystal grating was also developed [41]. The electrically switchable and optically rewritable grating structure based on FLC with ultra-fast switching speed and high diffraction efficiency at small electric field was developed. A response time of 50 μs at 6.67 V/μm has been achieved. High efficiency for the first order is around 65% for 1D and 2D gratings (Fig.4) with contrast ratio greater than 7000:1. Moreover, further optimization of the exposure energy and of the FLC parameters provides us an opportunity to achieve a grating pitch less than 2 μm and a higher contrast ratio. The proposed grating can be erased and rewritten optically for a different grating vector with simple steps. The fabrication process and the optical rewriting procedure is relatively

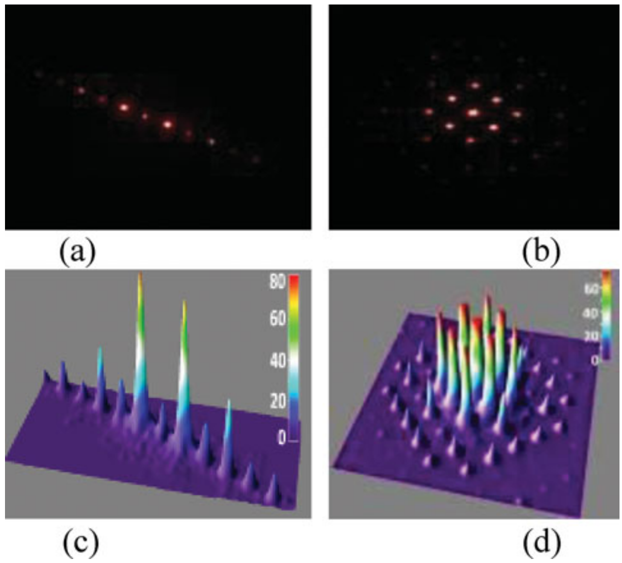

Figure 3. The diffraction profile of the proposed grating (a) the diffractive state of the 1D FLC grating, (b) diffractive state of the 2D grating while (c) represents the black state which is same for both gratings. (c) and (d) represent the intensity profile of the 1D and 2D grating respectively at the electric field of 5 V [40, 41].

simpler, fast and easy. We believe this method has a great potential to find application in projection display, pico-projectors and various photonic elements.

In addition to this, we have developed a special software for an advanced design of new FLCD prototypes [42, 43]. Certain new FLCD prototypes can be optimized using our

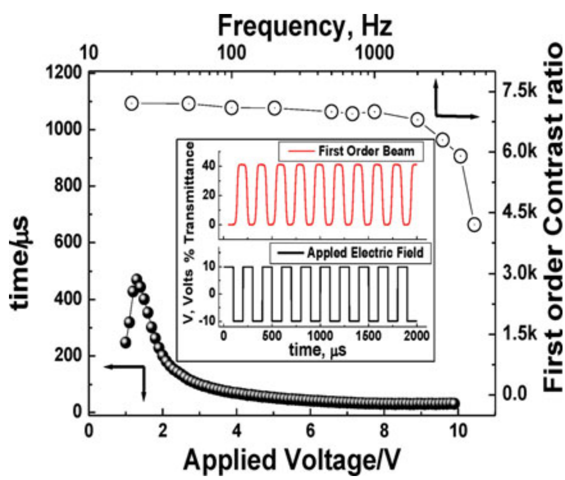

Figure 4. The response time dependence on applied voltage at driving frequency of 500 Hz (solid legends). The frequency dependence of the first order contrast ratio at the fixed applied voltage at 10 V (open legends). The insertion represents the electro-optical response of the FLC grating cell, bottom is the applied voltage and top represents electro-optical response for the first order diffracted beam of wavelength (λ) = 632 nm at the operational frequency (f) of 5 kHz [40]

software, including the optimization of FLC configuration as well as the optical scheme. We found a way of implementation of various bistable FLCD with achromatic [39] and full color birefringent switching without color filters [42].

4. Conclusion

The comprehensive investigation of fast photoaligned ferroelectric liquid crystal displays and photonics devices is needed, including the following main items: (i) further fundamental study of the new appropriate electro-optical modes used for switching such as deformed helix ferroelectric (DHF) or electrically suppressed helix (ESH) FLC mode as well as voltage controllable diffraction (VCD) FLC mode; (ii) understanding of physical mechanisms of FLC interaction with a photoaligned surface of different photosensitive nature (diffusion, photo-crosslinking, photo-degradation) to produce a stable alignment with a controllable anchoring energy and pretilt angle over sufficiently large surface area; (iii) the development of new fast responding FLC materials with fast switching and a sufficient number of switchable gray levels; elaboration of fast response optical FLC elements for photonics applications, such as grating, CD grating and Fresnel lens, and beam steering devices; (v) investigations of regimes of operation to allow to use efficient addressing of FLCs; (vi) further development of the software module, taking into account real FLC parameters with further optimization of FLC optical and electrooptical performance for different electro-optical modes.

The existing photonic element like grating, Circular Dammann (CD) grating and Fresnel lens are a bit slow, required very high electric field and fabrication procedure is very difficult. Thus these elements need further improvement in terms of (i) the elimination of the sticking effect; (ii) the realization of a hysteresis free electro-optical modulation with a low voltage driving; (iii) the improvement of the contrast ratio and quality of FLC alignment on sufficiently large surface areas with achromatic (black/white) switching; fast response time and (iv) the increment of resolution for pitch of different FLC photonic elements up to 10 micron. Fist three aims will be achieved by optimizing FLC and photoalignment material and physical parameter to get the high quality alignment and contrast ratio. To increase the resolution up to 10 micron for pitch, photolithography or the interference beam will be used depending on the requirement.

Thus developed fast and low power consuming FLCs can also be used for the field sequential color (FSC) FLC micro-displays, which is now one of the most advanced technologies for pico-projectors can be also made on the basis of new materials and electro-optical modes in FLC. The modulators and switches based on fast responded FLC are envisaged in DWDM elements of optical communication systems, such as switches, filters, attenuators, equalizers, beam steering device and tunable lens etc are envisaged.

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