NOVEL FAST FERROELECTRIC LIQUID CRYSTAL MODES BASED ON NANO-SCALE PHOTOALIGNING TECHNOLOGY

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Abstract
Fast ferroelectric liquid crystal devices (FLCD) are achieved through the application of nano-scale photo aligning (PA) layers in FLC cells. The novel photoaligned FLC devices may include field sequential color (FSC) FLC with a high resolution, high brightness, low power consumption and extended color gamut to be used for PCs, PDAs, switchable goggles, and new generation of switchable 2D/3D LCD TVs, as well as photonics elements such as voltage controllable lenses, light converters, beam steering devices, light modulators, diffraction gratings etc. The FSC FLC micro display is now one of the most advanced technologies for pico-projectors.

1. Nano-scale photoalignment technology.

Photoalignment has been studied as a means of aligning liquid crystal layers for quite some time. It has many advantages over conventional rubbing of polymers in that it is clean and controllable [1, 2]. Large area processing with good uniformity is also readily achievable. Generally speaking, there are four types of photoalignment materials and photoalignment mechanisms: (1) cis-trans isomerization of certain dyes, (2) photo-induced polymerization of specific monomers, (3) photo-degradation of polymers, (4) photo-induced reorientation of linear chain molecules. At HKUST, we concentrate on photoalignment of azodyes that are based on photo-induced reorientation [1,2]. These materials can have strong anchoring properties and requires relatively low light dosages for alignment. Anchoring energy of 10^{-4} J/m^2 can be obtained with light dosage as little as 0.1 J/m^2. It has been successfully applied to align various liquid crystals.

Conventional alignment based on mechanical rubbing of polyimides is already well established in manufacturing of large area liquid crystal displays. Thus the introduction of photoalignment makes sense only if it can provide additional advantages over conventional rubbing. In this paper, we shall demonstrate several new ferroelectric liquid crystal modes that are capable of fast switching and are thus useful for applications to fast shutters and field sequential color displays.

2. Fast respond time ferroelectric liquid crystal modes

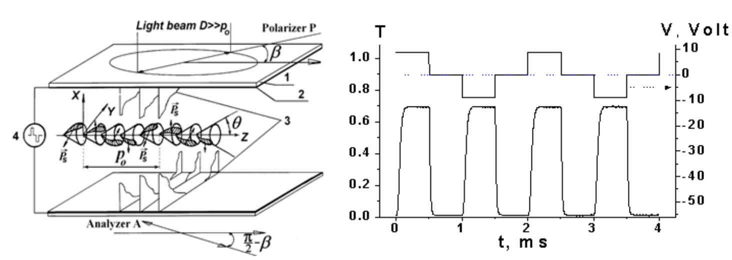
The response time of liquid crystal displays (LCD) is still inferior to competing flat panel display technologies, such as plasma display panels (PDP) or organic light emitted diodes (OLED). The target LC cell response time for a field sequential color (FSC) and 3D displays should be less than 1 ms (240 Hz frame frequency) to provide a high resolution, low power consumption and extended color gamut. Fast switching ferroelectric liquid crystal (FLC) displays (FLCD) is a good candidate for the new generation of field sequential color and 3D LCD. FLC based on nano-Scale photoaligning technology can provide a high contrast, and extremely fast switching time for a very low applied voltage.

2.1 DHF mode

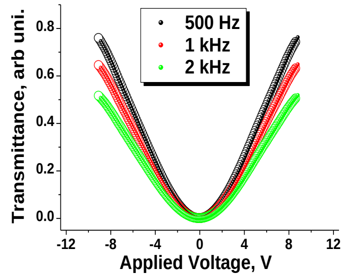
We have obtained some good results in studying DHF effect [2-4]. In particular, a high quality dark state of DHF FLCD has been obtained as well as V-shape switching with a high frequency (Fig.1). Two inherent properties of DHF-FLC have been observed (Fig. 1b): (i) similar to NLC cells, the electro-optical response is insensitive to the driving voltage polarity, but the response time is two orders faster as compared with NLC, i.e. $\tau^{on}_{0.1-0.9} \cong 80\mu s$, $\tau^{off}_{0.1-0.9} \cong 60\mu s$; (ii) the response exhibits perfect V-shaped mode obtained for the case of rectangular alternating applied voltage pulses shown in Fig. 1a. As is illustrated in Fig. 1b, the electro-optical response frequency is twice higher than the driving voltage frequency. The cell was controlled by the voltage waveform appropriate for FSC displays (Fig.1b)). Figure 1c shows that the cell light transmission is continuously tunable for each color field independently at both voltage polarities.

Thus V-shaped electro-optical response is shown to be an inherent property of a DHFLC cell under a special choice of the applied rectangular alternating electric field waveform, frequency, and the cell geometry. In contrast to other known V-shaped FLC modes, the discovered V-shaped switching is observed in a broadband frequency range including one kilohertz, and not at a certain characteristic frequency. Frequency independent V-shaped DHFLC switching allows increasing drastically (up to 1 kHz) the operating frequency of FSC LCD cells.

A DHFLC FSC display cell with red, green and blue light emitting diodes (LED's) forming sequential fields of backlight around 200 μs duration of each color has been elaborated [6]. The cell was controlled by the voltage waveform appropriate for FSC displays (Fig.2a). LED's were placed in the position labeled in Fig.1a as "light beam diameter is much larger than helix pitch $D>>p_0$" and synchronized to the driving voltage pulses with the specially designed software. Figure 2a shows that the cell light transmission is continuously tunable for each color field independently at both voltage polarities. A view of basic and intermediate colors transmitted by the FSC cell at color frame frequency 1 kHz is illustrated in Fig. 2b-2i



(a) (b)



(c)

Figure 1. DHFLC V-shape switching with a gray scale. From left to right: (a) DHFLC structure placed between crossed polarizers at $\beta = 0$; (b) the electro-optical response of DHFLC cell; (c) V-shaped DHFLC light transmission at three frequencies of operating voltage [2-4].

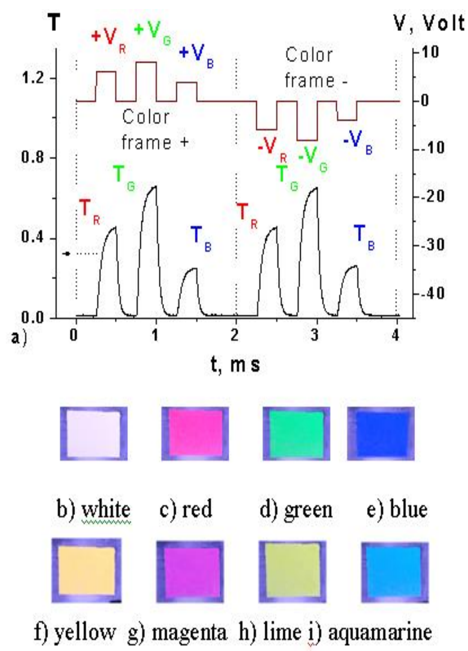


Figure 2. a) Bottom is the electro-optical response of the DHFLC placed between crossed polarizers at β=0; T_R, T_G and T_B are transmissions of the primary red, green and blue lights. Top is driving voltage applied to the DHFLC and synchronized sequentially with corresponding red, green and blue light emitting diodes; b) - e) basic colors, f) – i) intermediate colors displayed by the DHFLC cell as a result of sequential colors processing [2-4].

The photograph of the prototype and handling software has been shown in Fig. 3. A model of FSC display cell with red, green and blue light emitting diodes (LED's) forming sequential fields of backlight around 200 μs duration of each color has been elaborated. Colors can be selected from platform on computer and transfer to device using wireless communication. Typical pictures of different colors displayed on the FSC FLC prototype are shown in Fig.3 [2-4].

Figure 3. From left to right: Wireless controller connected to PC, right is portable FLCD device; FSC colors realized by our FLC device [2-4].

2.2 ESH mode

We have discovered a new electrooptic mode, which we called Electrically Suppressed Helix (ESH) mode [2,5,6]. The mode is characterized by a high contrast ratio and very fast electrooptic response and is highly suitable for FSC and 3D applications. DHF mode exists at $V \leq V_c = 0.4$V and the helix is completely suppressed by electric field at V≥1V, see Fig. 4 right part and linear dependence of the inverse response time at V>1V in Fig. 4, where the response time has absolutely the same behavior as in SSFLC mode. Despite of these similarities, it should be emphasized that at $V > V_c$, strictly speaking, there is no SSFLC mode but an electro-optical mode with completely electrically suppressed helix arises (ESH-mode). It would seem that between SSFLC and ESH modes there is only a formal difference in initial conditions (the helix is suppressed by surfaces in SSFLC, but this does not happen with ESH), as the dynamics of a completely identical. Actually, the presence of helix without applied voltage is the cause of the unique high alignment quality in ESH-mode (see top right insertions in Fig. 4). The contrast ratio in ESH mode is more than 12000:1 up to 1 kHz at ±1.5V and up to 2 kHz at ±3V; the light transmission is about of maximum in this case, see insertion to Fig. 6.

The unique high alignment quality, however, is observed only if the helix elastic energy is comparable but obligatory not less than the anchoring energy normalized to d_{FLC}:

$$Kq_0^2 \geq \frac{2W_Q^0}{d_{FLC}} \quad (1) \quad ,$$

where W_Q^0 is a coefficient the anchoring energy. We have measured $W_Q^0 = 4{\cdot}10^{-4}$ J/m^2 just for the cell whose properties are illustrated in Figs. 5, 6, thus confirming the validity of inequality (1), when outstanding alignment quality (top right insertions in Fig. 4) is observed.

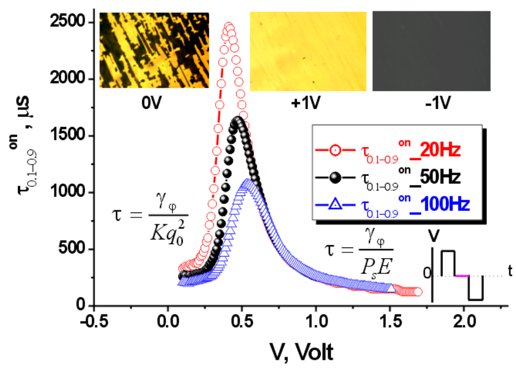


Figure 4. Dependence of switching on time of 1.5 μm cell filled with the FLC-595 [5]. Insertions: bottom right is the driving voltage waveform; top the FLC layer textures between crossed polarizers, horizontal scale of all images is 200 μm; top left - the voltage is not applied, top right - textures at +1V and -1V [2,5,6].

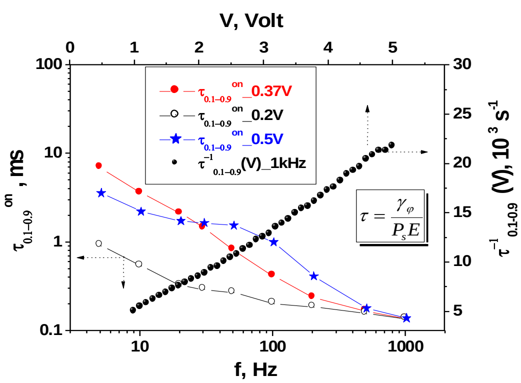


Figure 5. The frequency dependencies of the response time at different voltages under condition V≤0.5V; (•) - linear dependence of the inverse response time $\tau_{0.1-0.9}^{-1}(V)$ at V>1 V [2,5,6].

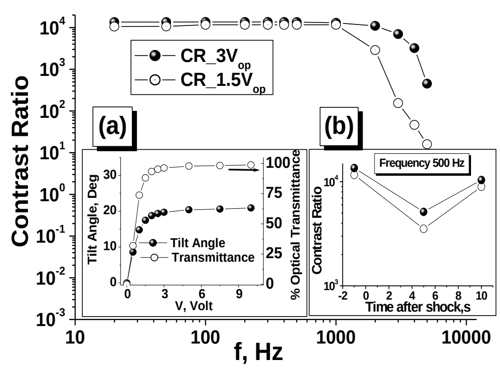


Figure 6. Dependencies of the contrast ratio on driving voltage frequency at V=1.5V and V=3V. The FLC-595 [2,5-7] layer thickness is 1.5μm, no SiO_2 layers, measurements have been carried out at T=22°C, wavelength λ=0.63 μm.

Insertion left: Dependencies on voltage: measured tilt angle and the cell light transmission in comparison with transmission of empty cell placed between crossed polarizers.

Insertion right: Contrast ratio dependence on time after the application of mechanical shock.

A very uniform FLC alignment exists just only in ESH-mode when $V > V_c$ (right top insertion in Fig. 4) while at $V<V_c$ it is worse because the FLC layer is divided into two-domain helical structures with the domains principal axes deployed at an angle around double FLC tilt angle 2θ. When observed with a polarizing microscope, these helical domains are perceived as homogeneous dark and light areas with their characteristic sizes around 10-50 μm, see left top insertion in Fig. 4. The domains are completely suppressed by a weak electric field $E_c<E<1V/\mu m$ (right top insertion in Fig. 4) thus forming perfect chevron-free alignment in ESH-mode.

In addition to this the shock stability has also been found good for the ESH mode. The contrast ratio was measured with time after removing the mechanical pressure. The contrast can be restored in very short time after removal of mechanical pressure (Fig.6). The electro-optical response manifests evident saturation at 500 Hz and ±1.5V with the response time $\tau_{0.1\text{-}0.9}$ =130 μs (Fig. 4).

The possible applications of FLC ESH mode include FSC FLC with a high resolution, low power consumption and extended color gamut, which can be used in the screens of portable PCs, mobile phones, PDAs. FSC FLC microdisplays, which is now one of the most advanced technologies for pico-projectors can be also made.

2.3 Ferroelectric liquid crystal diffraction mode

We suggest an alternative approach to fabricate ferroelectric liquid crystal (FLC) gratings characterized by high frequency saturated electro-optical (EO) modulation, low driving voltage, high diffraction efficiency, and high contrast ratio. Such gratings are very promising for applications in a variety of fast photonic and display devices. Recently, we have proposed an EO mode (the so-called electrically suppressed helix (ESH) mode) that offers good alignment quality, high contrast ratio, and low driving voltage [8,9]. Owing to the good quality of FLC alignment, we can apply the patterned alignment method to generate the periodic distribution of refractive index and thus the switchable grating. We produced a switchable FLC grating based on patterned alignment domains that provides good optical quality with contrast more than 7000:1 for the first diffraction order and diffraction efficiency about 68%. In addition, since the response time is faster than 20 μs at E=6V/μm, we can provide optically saturated electrooptical (EO) modulation at high frequency up to 5 kHz.

We have found that the alignment quality of FLC can be drastically improved provided that the helix pitch, P, is shorter than the FLC cell thickness, d, and the elastic energy of the FLC helix is comparable with the FLC anchoring energy. Our FLC grating cell has been prepared to meet this condition. The FLC FD 4004N from DIC (Japan) having spontaneous polarization Ps = 61 nC/cm^2 and tilt angle θ ~22.05^0 was chosen and sulfonic azo-dye (SD1) was used for the photoalignment [8,9].

The exposure of the SD1 substrate by the linearly polarized light with the wavelength 450 nm results in the alignment direction perpendicular to the polarization plane of the incident light. The anchoring energy strength of SD1 layer can be easily controlled by varying the exposure dose. The aligning directions of SD1 can also be changed by secondary irradiation with linearly polarized light of the same wavelength but with different polarization azimuth. These features of SD1 enable us to write, erase, and rewrite the alignment with any desirable preferences even with multi domain alignment.
In order to provide the periodic distribution of refractive indexes, the FLC has been aligned in two orthogonal planar alignment regions by mean of two step UV exposures. The exposure energy was fixed at 3 J/cm^2 giving the anchoring energy $4.03 \cdot 10^{-4}$ J/m^2. The cell thickness was maintained at d=1.5 μm and the anchoring energy was evaluated using the well known voltage coercivity method [8,9]. In the first step of alignment process, the alignment has been made in the one direction and then after the cell was assembled. The cell has been exposed again through mask with UV light having orthogonal polarization azimuth to the polarization azimuth of the first step exposing light. This technology creates the two alignment domain simultaneously on both aligning surfaces without any mutual shifting. Thus, no precise adjustment is required here for all patterns, which makes the fabrication simple and precise.
The schematic diagram of the cell structure that illustrates two orthogonal alignment regions and the optical microphotographs is shown in Fig. 7 [8,9].

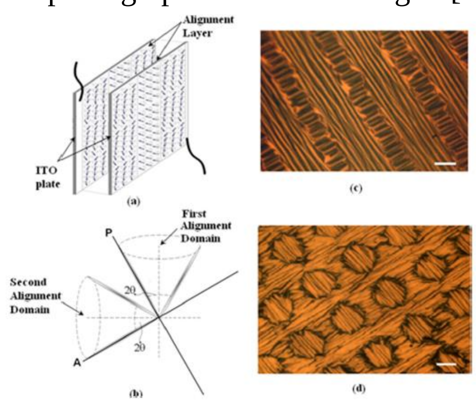


Figure 7. (a) FLC grating cell with two orthogonally aligned domains,where the smectic layer normals arranged to be parallel to the substrate are perpendicular to each other; (b) Orientational structure in the adjacent domains and the geometry of crossed polarizers (P and A stand for the polarizer and the analyzer, respectively); (c)–(d) Optical microphotographs of 1D and 2D FLC gratings taken at V=10 V. The length of the white marker is 15 μm [8,9].

Fig. 7 (a) illustrates two different overlapped alignment regions having mutually perpendicular alignment directions. Fig. 7 (b) illustrates the optics of the two alignment domains in between two crossed polarizer with one switching position parallel to either polarizer or analyzer. It can be seen that no diffraction occurs in the dark state when the switching position of the two alignment domain is either parallel to the polarizer or analyzer. However, the diffraction appears for the other switching position where the optic axis for these two domains makes an angle 2θ and 90^0-2θ for the polarizer, where θ ~22.05^0 is the FLC tilt angle. Figs. 7 (c) and 7 (d) represents the optical microphotographs of the FLC grating structure for 1D and 2D patterns made through the crossed polarizers at the electric field E=6V/μm. The period of both gratings is P_g =50 μm, which, if necessary, can be reduced down to 1 μm provided that the FLC helix pitch is sufficiently small. The diffraction profile for 1D and 2D grating is shown in Figs. 8(a) and 8(b), respectively [8,9]. Fig. 8(c) shows the dark state of the FLC grating, which is the same for both 1D and 2D structures. This figure demonstrates that the good optical quality is combined with the high contrast between diffractive and non-diffractive states. The corresponding intensity profiles are plotted in Figs. 8(d) and 8(e) for 1D and 2D grating, respectively. These figures also illustrate good diffraction efficiency of our FLC grating.

In Fig. 9, we present the results for the transmittance of the first diffraction order, which is plotted as a function of voltage in both the bright and dark states [8,9]. It can be seen that both curves reach the regime of saturation at voltages higher than 2 V [8,9]. Similar voltage dependence was also observed for the transmittance of the zero order (see insert in Fig. 3). The diffraction efficiency is thus independent of the electric field higher than 1.3V/μm.

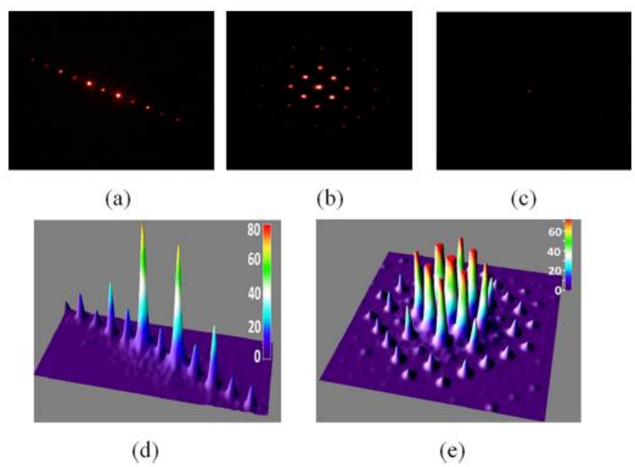


Figure 8. Diffraction profiles of FLC grating: (a) the diffractive state of 1D grating; (b) the diffractive state of 2D grating; (c) the black state, which is same for both gratings. (d) and (e) Intensity profile measured at the voltage V=5V for 1D and 2D gratings, respectively [8,9].

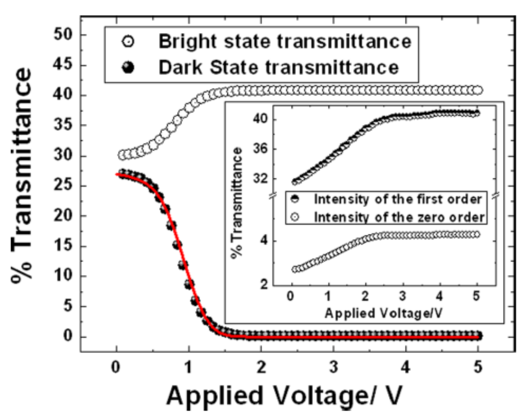


Figure 9. Electric field dependence of the transmittance for the first diffraction order. Insert shows the bright state transmittance of the first and zero diffraction orders as a function of voltage. Solid line represents the theoretical estimations [8,9].

The results on the dynamics of the FLC grating are shown in Fig. 10 [8,9]. The electric field dependence of the response time of the first diffraction order is similar to the one for the planar aligned FLC cell. It reaches the maximum value at the critical field of unwinding and decreases when the electric field further increases. At the electric field of 10 V, the response time is about 20 μs. Such fast response time enables us to drive the device up to very high driving frequency f=5 kHz. Insert in Fig. 10 presents the EO response of the first diffraction order measured at frequency of 5 kHz. It is clearly characterized by the optically saturate bright and dark states with high contrast. Since the contrast ratio for FLC cell with ESH mode is typically very high, similarly high contrast has been observed for the first diffraction order. The contrast ratio for the first order (i.e., the ratio of the I_{max}/I_{min} for the first order) is more than 7000:1 at the electric field of the 6V/μm.

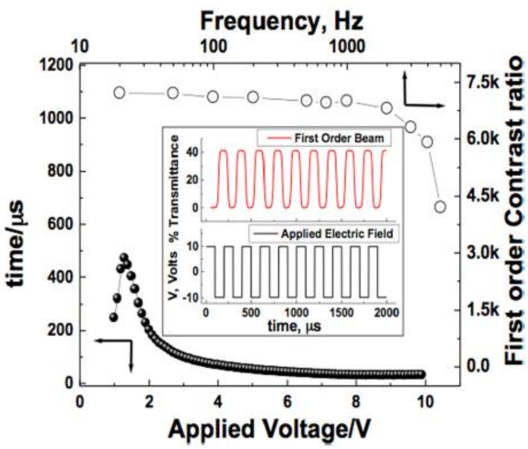


Figure 10. Voltage dependence of the response time at driving frequency of 500 Hz (solid circles) and frequency dependence of the first order contrast ratio at the fixed applied voltage V=10V (open circles). Insert shows time dependence of the applied voltage (bottom) and the EO response of the first diffraction order (top) at the wavelength λ=632nm and at the operational frequency f=5 kHz [8,9].

As is expected, the contrast ratio decreases in the high frequency region because the period has to be long enough to reach the optically saturated state. The response time of our grating is 20 μs and, therefore, the contrast ratio does not show a pronounced decrease up to the frequency of 2 kHz. Even though it is considerably reduced at higher frequencies, the contrast ratio for the first diffraction order is 4200:1 at f=5 kHz.

The new fast FLC mode is a fast switchable grating based on ferroelectric liquid crystals and orthogonal planar alignment by means of photo alignments. Both 1D and 2D gratings have been constructed. The proposed diffracting element provides fast response time of around 20 μs, contrast of 7000:1 and high diffraction efficiency, at the electric field of 6V/μm. The saturated electro-optical (EO) states up to very high frequency (~5 kHz) are the real advantage of the proposed switchable grating, which opens several opportunities to improve the quality of existing devices and to find new applications e.g., projection displays, micro-displays, beam steering devices, and other photonic and adaptive optic elements like optical interconnect.

3. Summary

Fast ferroelectric liquid crystal devices (FLCD) are achieved through the application of nano-scale photo aligning (PA) layers in FLC cells. The novel photoaligned FLC devices may include field sequential color (FSC) FLC with a high resolution, high brightness, low power consumption and extended color gamut are envisaged. The FSC FLC micro display is now one of the most advanced technologies for pico-projectors.

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The development of novel photoaligned fast ferroelectric LCD based on Deformed Helix Ferroelectric (DHF) and Electrically Suppressed Helix (ESH) mode is discussed. A high quality dark state of DHF FLCD has been obtained as well as V-shape switching with a high frequency. A fast response time and a high contrast ratio in ESH mode was observed.Â In this regard, we developed a method based on photoalignment technology, using a sulfonic azo-dye to align composites of liquid crystal polymer and semiconductor nanorods. The method retains the benefits of photoalignment technology, such as a high order parameter and a low pre-tilt angle and fabricates composites with highly anisotropic properties. Ferroelectric Liquid Crystal Display. Mitsuhiro Koden *1 Keisaku Nonomura *1 Hirofumi Katsuse *1 P. A. Gass *2 J. C. Jones *3 A. Graham *3. Syuhji Miyoshi *1 Michiyuki Sugino *1 Akira Tagawa *1 M. J. Towler *2 C. V. Brown *3 M. J. Bradshaw *3.Â Key technologies for the Ï„-Vmin mode FLCDs (Ferroelectric Liquid Crystal Displays) were developed.Â Combining these key technologies with digital gray scale method (2 bits spatial dither and 3 bits temporal dither), a 6"-prototype color FLCD with 240x320 dots, 262,000 colors (64 gray levels for each color) was fabricated. Introduction. Since Clark and Lagerwall 1) invented the basic principle of ferroelectric liquid crystal displays (FLCDs), much effort has been devoted to the development of FLCDs, aiming at practical applications. 2), 3). Keywords â€” Feroelectric liquid crystal, FLC LCD, FLC alignment, plasma-beam alignment, ion-beam alignment. DOI # 10.1889/JSID16.10.1075 In the present paper, we consider a novel approach for 1 Introduction the surface stabilization of FLC films.Â The bistable tive mesogens and semiconducting LC used in optical films switching in these materials, coined as ferroelectric liquid and surface electronics.14 This technique provides excellent crystals (FLC), was realized in thin cells in which the helical alignment uniformity of LC on a macroscopic and micro- structure was suppressed.