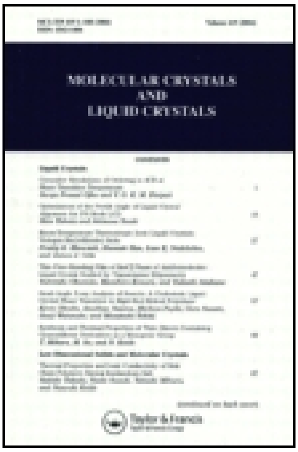

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From First to Fourteen Optics of Liquid Crystals Meeting, Geometrical Optics Approximation to 2 × 2, and Optical Bistability to Multi-Domain Vertical Alignment LCDs

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From First to Fourteen Optics of Liquid Crystals Meeting, Geometrical Optics Approximation to 2 × 2, and Optical Bistability to Multi-Domain Vertical Alignment LCDs

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As a liquid crystal researcher, I was delighted to attend the first Optics of Liquid Crystals meeting, chaired by Professor Santamato and held in Napoli, Italy 25 years ago in 1986. Over the ensuing years, I was fortunate to present papers at following OLC meetings, and had the opportunity to serve in organization and advisory committees. To celebrate the OLC's 25th year anniversary, I have provide commentary on the early OLC meetings followed by a review on the optical field induced Freedericksz transition and the intrinsic optical bistability, geometrical optics approximation, generalized geometrical optics approximation and the 2 × 2 matrix, and also the progress in the wide-viewing angle LCDs and multi-domain vertical alignment LCDs.

Keywords Multi-domain; optical bistability; optics modeling; viewing angle

1. Introduction

As de Gennes wrote in his well-known textbook, "Liquid crystals are beautiful and mysterious. I am fond of them for both reasons" [1]. We, his many readers, feel the same attraction. As LC optics researchers, we all have the great joy of performing research and witnessing developments in liquid crystal (LC) optics, manifesting from their very large optical anisotropy, and using low external field to induce large optical effects. The LC electro-optical effects have been used extensively to create useful LC devices and large display revenues. LCs are unique, useful and important materials that provide us many interesting scientific research opportunities and industrial applications.

Consequently, it is important and appropriate to hold the international topical meetings on optics of liquid crystals (OLC), as Prof. Santamato had initiated and successfully held the first OLC in 1986 in Napoli, Italy. I was delighted to participate in the first OLC. Over the ensuing years, I was fortunate to attend the following OLC meetings and had the opportunity to serve in organization and advisory committees.

To celebrate the OLC's 25th year anniversary, I will provide commentary on the early OLC meetings followed by a review on the optical field induced Freedericksz transition (OFT) and the intrinsic optical bistability (OB), geometrical optics approximation (GOA),

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generalized geometrical optics approximation (GGOA) and the 2 × 2 matrix, and also the progress in the wide-viewing angle liquid crystal displays (LCDs) and multi-domain vertical alignment (MVA) LCDs.

2. First OLC to Fourteen OLC

2.1. First OLC (1986) to Fourteen OLC (2011)

Professor Santamato and his team from the University of Napoli and University della Calabria are heroes for the first OLC [2]. I first learned about it from Prof. Y. R. Shen with whom we collaborated on the enhancement of intrinsic OB in NLC using external magnetic field [3]. Later, I was invited by Prof. Santamato to give a talk [4, 5]. The attendees for both the first and fourteen OLC meetings were Prof. Zel'dovich [6, 7], Abbate [8, 9, 10], Ong [4, 5, 11], Simoni [12, 13, 14] Soileau [15, 16], and Umeton [12, 13, 17].

As of today, it is still an exciting and pleasant memory of having attended and giving eight invited talks in these fourteen OLCs. We have made and witnessed many good progresses in the optics of LCs.

2.2. Major Events in the Last 25 Years in LC Optics Applications

Abbate delivered a historical overview of OLC meetings from the first to the thirteen as the forum for 25 years of scientific achievements [10].

The followings are the summary of some of the major events in the last 25 years in LC optics applications in my views.

LCDs are the most important applications based on LC electro-optical properties. In 2011, LCDs were widely used in consumer and professional applications. In 1986, the commercially available LCD products are smaller than 10-in in size, and limited small LCD manufacturing lines exist that produced small pocket size LC TV using MIM deceives. The LCD revenue is less than US$4.4B mainly on the passive LCDs using TN and Guest-Host LCDs [18, 19]. There was no LC TV or microdisplay LCDs that required an optical enlargement system such as magnifying lens or projection systems to view the contents of the LCD. Gen 1 TFT/LCD lines with a substrate size of around 30 × 40-cm were introduced in early 1990s. LCD revenue grew rapidly in 2000s as TFT/LCD improved the performance and cost, displaced the lower-cost technologies (mainly CRT), and created new portable applications.

Today, the LCD market size has been greatly expanded to ∼US$90B, mainly on TFT/LCDs using TN, wide-viewing angle TN, IPS/FFS and MVA LCDs. The TFT/LCD has continued to expand their share in small-medium, LC TV and also microdisplay market. More than 250 million units of LC TV have been shipped in 2011. 70-in LC TV is available from Sharp for a retails price of US$8000. Gen 10 TFT/LCD lines are available with a substrate size of 285 × 305-cm in Sharp Corp in Japan. Microdisplays with a 0.26-in panel size, 2.8 × 8.4 μm dot size and VGA resolution for the electronics view-finder applications are now available from Kopin Corp, and a 0.74-in panel size, 4.06 × 4.06-μm dot size and 4096 × 2160 native-resolution for the 3-panel projection applications are now available from Sony Electronics. Pico-projectors using microdisplays for the portable mobile phone, PDA, tablet and notebook PCs applications were also recently introduced into the market.3D LCD is also becoming available for mobile phone, LC TV and monitor.

The LC TV is growing from 242M unit in 2010 to ∼270M units in 2011, with a growth rate 12%. For 2010, the LCD revenue was US$89B with 9.78% growth. It was a profitable year for many LCD manufacturers. However, this inspired the large LCD market, and 2011 resulted in a large operation loss for many LCD manufacturers due to an oversupply in the large LC TV and monitor segments. Samsung's LCD business unit had a profit of $1,745M in 2010 but a big loss of $670M in 2011; LGD had a profit of $1,149M in 2010 but a big loss of $$821M in 2011; AUO had a profit of $350M in 2010 but a big loss of $1,922M in 2011. Thus these three TFT/LCD manufacturers had a big profit of $3,244M in 2010 but a big loss of $3,414M in 2011. CMI and Sharp also have a big loss of $3.7B and $4.3B respectively. Thus the five leading LCD vendors experienced a total loss of $9.89B in 2011.

The large operation loss in 2011 on LCD business is mainly from the LC TV price decline and oversupply where the demands are 270 M units, which are considerably smaller than the LC TV production capacity of 500M units. A few more Gen 7 – 10 facilities are in construction and planning stages. 2011 was, however, a good year for small-medium size LCDs, which continued to provide bigger revenue and profit margin. For Taiwan, IEK ITIS marketing data showed that the trend, where the large size LCD revenues in 2010–2012 are $31,858M, $25,163M and$27,352M; small-medium size LCD revenues in 2010–2012 are $4,998M, $5,778M and $6,283M; and passive TN and STN LCDs revenues in 2010–2012 are $699M, $547M, and $536M, respectively.

For mobile phones, the number of globally shipped units grew from 1329 million in 2010 to 1610 million in 2011, with a growth rate of 21%. For smart phones, the shipped units grew from 280 million in 2010 to 450 million in 2011, with a growth rate of 61%. The number of tablet PCs grew from 15.7M in 2010 to ∼58M in 2011, with a growth rate 269%. Retina displays with a pixel per inch (PPI) of 320 and higher are now available for smart phones and tablet PCs. In 2011, new emerging market surpassed the developed market where new products and process technologies continue to prevail. These high-quality LCDs with a thin, low-weight, low-power, compact, high contrast ratio, high resolution and wide-viewing angle performance are significantly impacting society and our daily life.

There was great progress in LCD market penetration between 1986 and 2011, including the replacement of CRT completely, the push of plasma panels to have very large size segment of more than 40-in size, the supertwist nematic (STN)/LCD was born in 1985 and the monochromatic STN was introduced into the market in later 1980s. Color STN was introduced in early 1990s. STN had grown to be a major LCD technology for the use in palm size mobile phones, game and NB PC, now obsolete and used mainly for special low-power applications such as low-end mobile phone. Passive TN/LCD is still in use for low-end applications, guest-host LCDs is mainly obsolete, MIM growth in late 1980s and now obsolete, and TFT/LCD started in late 1980s and now it is the king of all displays.

The LCD is becoming widely accepted as the positive result from improved LCD performance and the continued efforts from the extensive R&D, manufacturing and applications. The major advantages for advanced LCDs are high contract ratio, symmetrical and wide-viewing angle, fast response time, and high resolution, in additional to the regular advantages of low power-consumption, thin, compact, lightweight, and sufficiently life time. These make LCD appropriate for the portable, home and industrial application and enable for smart phone, NB, tablet PC, GPS and PDA products.

3. Advances in Optical Bistability

3.1. Old Optical Bistability

At the first OLC conference in the 1986, a major subject was the OFT and the associated gigantic non-linear optical effects, as discussed by Tabiryan and Zel'dovich, Shen, Arakelyan, Janossy, Khoo, Ong, Santamato, Simoni and Zolot'ko [1]. One of the exciting subjects was the intrinsic OB by the first order Freedericksz transition, as discussed by Tabiryan, Zel'dovich and Ong [20, 21]. In 1986, we reported the experimental observations of the magnetic field enhanced OB [22] that inspired Wu and Chen to demonstrate electric field enhanced OB in 1988 [23].

Tabiryan and Ong studies showed that for a homeotropically orientated NLC cell, the magnetic and electric field induced Freedericksz transition (hereafter referred to as MFT and EFT, respectively) are second-order, in which increasing field resulting in continuous changes in the NLC spatial orientation, and only for certain NLCs, OFT can be first-order, in which increasing field resulting in discontinuous changes in the NLC spatial orientation. However, with an external DC field, the first-order OFT can be enhanced or suppressed [20, 21, 24, 25]. Furthermore, with an additional optical field, the otherwise second-order MFT and EFT in a homeotropically or parallel orientated cell can become first-order and bistable [26].

The first-order transition criterion can be obtained by three approaches: examining the solution of the director orientation, examining the total free energy using the Landau model for the phase transition, and examining the total torque [4, 21, 22]. We will discuss the total free energy approach, followed by the total torque approach.

The total free energy is the sum of the LC deformation energy and the electromagnetic field energy. In terms of the maximum deformation angle in the cell, θ_m, the total free energy F_T, near the threshold transition, can be expressed as

$$F \approx -C\,\theta_m^2 + \frac{1}{2}B\,\theta_m^4 + \frac{1}{3}G\,\theta_m^6 + \cdots\cdots O\left(\theta_m^8\right), \qquad (1)$$

where $F = (2d/\,k_{33}\pi^2)\,F_T$, for MFT, $C = H/H_{th} - 1$, $B = k_{11}/4\,k_{33}$, $H_{th} = (\pi/d)\sqrt{K_{33}/\mu a}$; for EFT, $C = V/V_{th} - 1$, $B = (k_{11}/k_{33} + v)/4$, $V_{th} = 2\pi\sqrt{K_{33}/|\varepsilon_a|}$; for OFT, $C = I/I_{th} - 1$, $B = (k_{11}/k_{33} - 9u/4)/4$, $I_{th} = (ck_{33}/n_o\,u)\,(\pi/d)^2$; $\varepsilon_a = \varepsilon_\parallel - \varepsilon_\perp$, $u = 1 - (n_o/n_e)^2$, G is a constant depending on the applied field, n_o and n_e are the ordinary and extraordinary index of refraction, $\varepsilon_\perp$ and $\varepsilon_\parallel$ are the perpendicular and parallel dielectric constants respectively.

From the Landau theory, C determines the threshold field, and the sign of B determines the order of the transition: If $B \geq 0$, the transition is a second-order occurring at the threshold field; If $B < 0$, the transition is a first-order occurring at the rising and falling threshold fields. For MFT and EFT, B is always positive and the transition is always second-order. For OFT, B can be positive or negative, thus OFT can be either second order or first order, depending on NLC. Thus, the OB criterion is $B < 0$ and reduces to the following form:

$$\frac{k_{11}}{k_{33}} + \frac{9}{4}\left(\frac{n_o}{n_e}\right) - \frac{9}{4} < 0. \qquad (2)$$

We now consider the total torque approach. In term of the maximum deformation angle in the cell, the total torque Γ_T, near the threshold transition, can be expressed as

$$\Gamma \approx C\,\theta_m - 2B\theta m^3 + \cdots\ O(\theta_m{}^5). \qquad (3)$$

Where $\Gamma = \Gamma_T(k_{33}\pi^3/2\ d^2)$. Thus the feedback from the third-order term, $\theta_m{}^3$, is always negative for MFT and EFT, but can be positive for OFT if $B < 0$, i.e., if the optical and electric anisotropies are sufficiently large. This shows that the OFT can have a first-order transition because in orientating the NLC director, OFT can have positive feedback from high-order terms for large optical and elastic anisotropies.

3.2. New Optical Bistability with Dichroic Dye with Negative Dichorism

We had realized another OB in a homeotropic NLC using dye with negative dichorism where the absorption for the extraordinary wave is smaller than that for the ordinary wave [27–29]. Consequently, larger absorption results in the homeotropic state than the small tilted LC state. Thus optical torque becomes larger with a larger LC deformation. Consequently, when the Freedericksz transition occurs, LC will reorient to a larger tilted state, and a first order transition occurs.

Similar to the OFT for NLC without dyes, the first-order transition criterion can be obtained by three approaches: examining the director orientation, total free energy and total torque. The first two approaches require the solution for the NLC director. However, we could obtain a simple first-order transition criterion by considering the optical torque. The reorientation optical torque can be written in terms of LC deformation angle θ as

$$\Gamma_{\mathrm{Opt}} = \frac{1}{2}(un_{\mathrm{o}}/\mathrm{c})\,\mathrm{I}\sin 2\theta/(1-\mathrm{u}\sin^2\theta)^{3/2}, \quad (4)$$

$$\mathrm{I}(\theta, \mathrm{n_o}, \mathrm{n_e}) = I_{\mathrm{o}}\exp[-2\mathrm{k}\,\mathrm{Im}(\Phi)\,\mathrm{d}], \quad (5)$$

$$\Phi = \mathrm{n_o n_e}/\sqrt{n_o^2\sin^2\theta + n_e^2\cos^2\theta}, \quad (6)$$

where $\mathrm{k} = 2\pi/\lambda$, λ is the wavelength of the light, $\mathrm{n_o}(= \mathrm{n_{or}} + \mathrm{i}n_{\mathrm{o}}^*)$ and $\mathrm{n_e}$ $(= \mathrm{n_{er}} + \mathrm{i}n_{\mathrm{e}}^*)$ are the complex ordinary and extraordinary refractive indices. For the first-order transition to occur, we need a positive feedback from high-order terms so that when the OFT happens at the threshold intensity, we can have a discontinued first-order transition to a large LC deformations. For LC with considerably absorptive dichroic dyes, the optical absorption part in the optical intensity [$\mathrm{I}(\theta, \mathrm{n_o^*}, \mathrm{n_e^*})$term] would play a major impact on the feedback from high-order term in the optical torque than the normal optical torque [$\sin 2\theta/(1-\mathrm{u}\sin^2\theta)^{3/2}$ term].

We now consider the feedback from high-order terms in the optical field intensity. For small LC deformation angle θ and normal LC dye material where the imaginary parts of the refractive indices are much smaller than the real parts of the refractive indices ($\mathrm{n_{or}} \gg \mathrm{n_o^*}$, $\mathrm{n_{er}} \gg \mathrm{n_e^*}$), the optical intensity is reduced to the following form:

$$\mathrm{I}(\theta, \mathrm{n_o}, \mathrm{n_e}) = \mathrm{I_o}\exp\left\{-2\,\mathrm{kd}\left[\mathrm{n_o^*} + \theta^2\left(2\mathrm{n_{or}^3}\,\mathrm{n_e^*} - 3\mathrm{n_{or}^2 n_o^* n_{er}} + \mathrm{n_o^* n_{er}^3}\right)/2\mathrm{n_{er}^3}\right]\right\}. \quad (7)$$

A first-order transition and OB will occur if the term associating with θ^2 becomes negative. Thus the first-transition criterion is as follows:

$$\mathrm{n_o^*} > 2\mathrm{n_o^3 n_e^*}/\left(3\mathrm{n_o^2 n_e^*} - \mathrm{n_e^3}\right). \quad (8)$$

For a typical LC with $\mathrm{n_o}\sim\mathrm{n_e}$, the first-order transition criteria become the following simple form:

$$\mathrm{n_o^*} > \mathrm{n_e^*}. \quad (9)$$

We have found that there is a suitable dye, BD6(Beam Engineering for Advanced Measurements Co.), with parameters that meet Eqs. (7) and (8). Thus, experimentally, we could observe this kind of intrinsic OB using existing dye material. During examination of the dichroic dye BD6, there are other advantages from the larger negative dichroism at green wavelength of 532-nm. We can have a larger optical torque when the OB occurs, and a smaller thermal effect from the smaller absorption with a larger LC tilted state. Beside the dyes with a negative dichroic ratio, we could also consider dichroic dye with a negative order parameter and positive dichorism.

In the actual experiment using dye materials, one major difficulty was the optical absorption. The threshold intensity for OFT is inversely proportional to the LC cell gap square, thus for a thinner cell, we have less optical absorption but a higher threshold intensity, whereas for a thicker cell, we have a lower threshold intensity but a larger optical absorption. To reduce the optical intensity and thermal effects, we could add an external vertical electric field using LC with negative dielectric anisotropy or add external magnetic field along the horizontal direction [24, 25]. These external DC fields help to reorient the LC, thus can reduce the threshold intensity needed for the OFT.

4. GOA to GGOA and 2 × 2 Matrix

In the last 25 years, there have been many good achievements in both the optical modeling and characterizations. We now have a sufficiently accurate optical modeling for the LC electro-optical properties for the 1D, 2D and 3D LCDs.

In the first OLC, we presented the geometrical optics approximation (GOA) for the extra-ordinary wave in a planer LC structures and applied the results to model the Guest-Host LCDs [5, 30]. Later, we extended the GOA to a generalized geometrical optics approximation (GGOA) for the complete wave propagation with arbitrary oblique incident angle in the complete general LC structures. We first presented the results for the normal incidence in a uniformly twisted nematic (TN) LC structures and used it to model the optical properties for the off-state TN LCDs in 1987 [31]. Later, we had successfully obtained the GGOA solution for the complete wave propagation with arbitrary oblique incidence angle in the general LC structures and used it to model the electro-optical properties for the TN and GH LCDs in 1988–1989 [32, 33]. We consider a layered-inhomogeneous media whose dielectric properties depend on the z-axis and are constant in the xy-plane. The xz-plane is defined as the plane of incidence. in the z-axis. In the GGOA formulism, all solutions are expressed in the form

$$E(x, z) = A(z) \exp [ik\,\phi(z)z + ikp\,x], \tag{10}$$

where A(z) is a slow-varying function in z, p is a constant depending on the incident angle and refractive index of the incident medium. We used 2 × 2 formalism in the derivation for the GGOA formalism, and expressed the final solution in the integral form. The integral solution is more elegant, but more difficult to use. We have also expressed the solution in the 2 × 2 form and applied the results for the GGOA and 2 × 2 modeling of the electro-optical properties for the TN and GH LCDs for general LC and oblique incident angles. That is, the 2 × 2 matrix and GGOA are both based on the same principle [Eq. (10)], used a 2 × 2 matrix form in the derivation, except that the final solution is expressed in the 2 × 2 matrix form for the 2 × 2 matrix, and is expressed in the integral solution for GGOA [34]. For the numerical modeling, it is easier to use the 2 × 2 matrix form [34, 35].

There are a few important works on the Berreman 4 × 4 propagation matrix. Wohler obtained the exact expression for the local propagation matrix [36, 37]. We showed that the 4 × 4 propagation matrix for layered inhomogeneous anisotropic media reduces to the Abeles 2 × 2 propagation matrix method for layered inhomogeneous isotropic media when the anisotropic medium becomes isotropic [38, 39]. We also obtained an alternative derivation of the 4 × 4 propagation matrix formalism [40].

5. Single Domain LCDs vs. Multi-Domain VA (MVA) LCDs

5.1. Progress in Wide-Viewing-Angle LCDs

Limited viewing-angle performance is one of the key limitations of conventional LCDs and has received major attention in LCD development. There were no wide-viewing angle (WVA) LCDs in 1986, but there has been major progress since, and now WVA LCDs are used everywhere for many current LCDs, from small-medium size to large size LCD monitor and LC TVs.

Specifically, since 1997, achievements in the WVA LCDs have been significant not only for large size LC TV, but also for the small-medium size mobile phone, PDA, notebook, and other portable applications. The wide availability of low-cost, 160-degree (with a contrast ratio >10) viewing angle cone and 300–3000 high contrast-ratio LCDs has enlarged LCD applications and market penetration, and has effectively eliminated the CRT for portable and monitor applications, created new applications, and pushed the high-performance plasma displays out to only the very large size ($>$47-in) market segment.

Wide viewing-angle (WVA) LCD development history can be summarized into 3 major phases:

1.	Searching for good WVA LCDs:	1980–1993
2.	Bringing R&D into production of WVA LCD:	1993–1998
3.	Product and Performance Improvement	
A.	Improvement on WVA LCDs:	1999 –
B.	Searching for new WVA LCDs:	2005 –
C.	Fast LC for 3D LCDs:	2010 –
D.	WVA for very high PPI $\sim$250–400:	2010 –

There are four major WVA LCDs: WVA twisted nematic (TN), multi-domain vertical-alignment (MVA), in-plane switching (IPS), and optically compensated bend (OCB) modes. Competition between these technologies has enhanced the progress in their performance, cost, and yield. In addition, improved materials and driving schemes were also developed to sustain this development. It was a great excitement and satisfaction in developing WVA TN and MVA LCDs for the last twenty years.

5.2. WVA TN

I reported the WVA TN using a negative birefringence optical compensation film in 1992, and FujiFilm researchers brought it into production in 1997 with their special negative birefringence hybrid discotic LC materials [41, 42]. In the standard TN operation, the optical black state is the field-on state where the positive birefringence LC is close to the vertical orientation. Thus a negative birefringence optical compensation film with a vertical or close to vertical orientation can be used to reduce the light leakage in the TN optical black state, hence improving the contrast ratio and viewing angle. The use of a negative birefringence optical compensation film to reduce the light leakage in the optical black state was first used by Clerc for the vertical alignment LCD [43]. It is the simplest method to fabricate WVA TN, with the replacement of the polarizer with a WVA polarizer containing the optical compensation film. This offers a high yield, low-cost, and effective method to greatly improve the viewing angle performance for conventional TN/LCDs. Nearly every TFT/LCD manufacturer for the small-medium LCD panels uses it. Most recently, because of the low cost advantages and improvement on the compensation film, WVA TN is also used for the low end LC TV (≤30-in).

5.3. MVA with Protrusion Geometry

The most widely used MVA uses protrusion geometry. In 1992, I also reported the MVA using protrusion geometry, and Fujitsu researchers brought it into production in 1997 [44, 45, 46]. It is the most widely used WVA LCDs for LC TV, made by many manufacturers. MVA LCDs offer a perfect optical black state under crossed polarizer geometry. However, MVA using protrusion geometry have a considerably lighter leakage at the optical dark states, lower transmission, are more complex and have higher manufacturing costs. Thus there are considerable efforts devoted to new WVA LCDs without the protrusion geometry.

5.4. AIFF MVA without Protrusion Geometry and Without ITO Slits

In 2005, I reported a new amplified intrinsic fringe field (AIFF) controlled MVA AIFF MVA that used no protrusion and no ITO slits in both the TFT and CF substrates [47]. We have successfully fabricated lower-cost superior performance AIFF MVA LCDs in 2006 for small-medium size LCDs for use in GPS and smart phones and brought them into production in 2009. AIFF MVA results in a very high-yield, high transmission, high contrast-ratio, and WVA. We had also successfully fabricated a 26-in WXGA (1366xRGBx768 pixels, 140.5 um by 421.5 um dot size) LC TV with AIFF MVA technology [48]. Most recently, we have successfully fabricated ultra high resolution retinal displays with 4.3-in, WXGA (1280×768, PPI = 347). The yield remains high. In contrast, the yield for retina displays in other LCD technologies is considerably lower. The high-yield for retina displays is a key manufacturability factor and our AIFF MVA can successfully maintain a high-yield and high performance.

The AIFF MVA design eliminates the need for both protrusions and ITO slits in both the TFT and ITO substrates, and also does not require special UV process and PI rubbing, while using standard IC, VA LC, and PI process materials.

The intrinsic fringe fields are weak in normal direct view LCDs and vary depending on the display driving scheme and applied voltage. In the AIFF MVA, we need to amplify the fringe field in each dot and yet minimize interference from the fringe field from the surrounding color dots. To amplify and control the intrinsic fringe field, we introduced a few special pixel designs and layouts, including checkerboard pattern of dot polarities, polarized associated dots, additional polarized associated dots, polarity extension portions, fringe field amplifying regions, embedded polarity regions, extra-planar fringe field amplifiers, extra-planar fringe field amplifiers with sliced common electrodes, and embedded fringe field amplifiers [47, 48]. The major competitive advantages for AIFF MVA are that they have high-yield, high-transmission and low-cost. To the best of my knowledge, the transmission and yield are considerably higher than other LCD modes, such as PVA, PSVA, protrusion MVA, ASV, IPS and AFFS. The high transmission is important not only to reduce the panel power consumption, and also to reduce the cost and power for the backlight. The AIFF MVA high-transmission and high-yield for high pixel density are consistent with the small-medium size LCD trends for ultra-high-resolution retina display and low-power-consumption Green LCDs. We use no protrusion and no ITO slits in both TFT and CF substrates, these are two key factors for high transmission and high yield, and also greatly reduce the times to complete the product R&D and to mass production.

AIFF MVA high-transmission and high-yield are consistent with the trends for ultra-high-resolution retina display and low-power-consumption Green LCDs, in particular, for retina displays with a very high pixel density, our high-performance and high-yield further enhance our competitiveness.

Summary

There has been significant progress in LC optics R&D and application in the last 25 years, from the first OLC to the fourteen OLC. We all witnessed and benefited from the progress in LC optics. As an LC optics researcher, I am fortunate and excited to participate in some of the exciting LC optics projects, including the OFT and OB, LC optics formalism, modeling and characterization, and LCD viewing angle improvement.

It is great to be LC optics researchers, as we are needed. We have made contributions to the LC science and technology, and to the society.

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References

[1] De Gennes, P. G. (1974). *The Physics of Liquid Crystals*, Oxford University Press: Oxford, UK.
[2] Proceedings of the international topical meeting on optics of liquid crystals, *Mol. Cryst. Liq. Cryst. 143*, 1–144, E. Satamato as Guest Editor (1987).
[3] Karn, A., Arakelian, S. M., Shen, Y. R., & Ong, H. L. (1986). *Phys. Rev. Lett. 57*(4), 448.
[4] Ong, H. L. (1987). *Mol. Cryst. Liq. Cryst. 143*, 31–38.
[5] Ong, H. L. (1987). *Mol Cryst. Liq. Cryst. 143*, 83–88.
[6] Zel'dovich, B. Ya., Sukhov, A. V., & Tabiryan, N. V. (1987). *Mol. Cryst. Liq. Cryst. 143*, 7–16.
[7] Zel'dovich, B. Ya. (2011). *14th International Topical Meeting Optics of Liquid Crystals*, Book of Abstract, Yerevan, Armenia paper T-4.
[8] Santamato, E., Abbate, G., & Maddalena, P. (1987). *Mol Cryst. Liq. Cryst. 143*, 45–56.
[9] Santamato, E., Abbate, G., Maddalena, P., & Sasso, A. (1987). *Mol. Cryst. Liq. Cryst. 143,* 113–122.
[10] Abbate, G. (2011). *14th International Topical Meeting Optics of Liquid Crystals*, Book of Abstract, Yerevan, Armenia paper I-22.
[11] Ong, H. L. (2011). *14th International Topical Meeting Optics of Liquid Crystals,* Book of Abstract, Yerevan, Armenia paper I-15.
[12] Simoni, F., & Umeton, C. (1987). *Mol. Cryst. Liq. Cryst. 143*, 39–44.
[13] Bartolino, R., Umeton, C., Ye, F., & Simoni, F. (1987). *Mol. Cryst. Liq. Cryst. 143*, 61–66.
[14] Simoni, F., et.al. (2011). *14th International Topical Meeting Optics of Liquid Crystals*, Book of Abstract, Yerevan, Armenia paper I-7.
[15] Soileau, M. J., et. al., (1987). *Mol. Cryst. Liq. Cryst. 143*, 139–143.
[16] Soileau, M. J. (2011). *14th International Topical Meeting Optics of Liquid Crystals*, Book of Abstract, Yerevan, Armenia paper I-39.
[17] Umeton, C. (2011). *14th International Topical Meeting Optics of Liquid Crystals*, Book of Abstract, Yerevan, Armenia paper PL-1.
[18] All the LCD revenue data were reported by HIS iSuppl, DisplaySearch, Topology Research Institute respectively.

[19] For 1990, the total flat panel display revenues was US$3.3B and US$4.4B in current and constant US$. Thus the LCD revenue in 1984 should be less than $4.4B.
[20] (a) Zel'dovich, B.Ya Tabiryan, N. V., & Chilinaryan, Yu. S. (1981). *Sov. Phys. JETP 54*, 32; (b) Zel'dovich, B. Ya., & Tabiryan, N. V., (1984). *Sov. J. Quantum Electron. 14*, 1599; (c) Zel'dovich, B. Ya., & Tabiryan, N. V. (1985). *Sov. Phys. Usp. 28*, 1059; (d) Zeldovich, B. Ya., Nersisyan, S. R., & Tabiryan, N. V. (1985). *Sov. Phys. JETP*, *61*(4), 712–718.
[21] Ong, H. L. (1983). *Phys. Rev.* A *28*(4), 2393.
[22] Karn, A., Arakelian, S. M., Shen, Y. R., & Ong, H. L. (1986). *Phys. Rev. Lett. 57*(4), 448.
[23] (a) Chen, S.-H., & Wu, J. J. (1988). *Appl. Phys. Lett. 52*, 1998; (b) Wu, J. J., & Chen, S.-H. (1989). *J. Appl. Phys. 66*, 1065; (c) Wu, J. J., Ong, G.-S., & Chen, S.-H. (1988). *Appl. Phys. Lett. 53*, 1999.
[24] (a)Nersisyan, S. R., & Tabiryan, N. V. (1983). *Opt. Spectrosc. 55*, 469; (b) Nersisyan, R., & Tabiryan N. V. (1984). *Mol. Cryst. Liq. Cryst.*, *1 16*(1,2), 111–114; (c) Tabiryan, N. V. (1985). *Opt. Spectrosc. 58*, 697; (d) Asatryan, K. E., et. al., (1989). *Sov. Phys. JETP 68*, 315.
[25] Ong, H. L. (1985); *Phys. Rev.* A *31*(5), 3450 (1985). *Appl. Phys. Lett. 46*(9), 822.
[26] Ong, H. L. (1986) *Phys. Rev. A 33*(5), 3550; (1986). *IEEE Trans. Electron Devices*, *ED-33*, 1195
[27] Ong, H. L. (1990). *Bull. Amer. Phy. Soc. 35*(3), 728.
[28] Asatryan, K. E., Galstyan, T. V., & Petrosyan, L. G. (1991). *Opt. Spectrosc. 71*(3), 275.
[29] Babayan, E. A., et. al., (2010). *Phys. Rev.* E *82*, 61705.
[30] Ong, H. L. (1988). *J. Appl. Phys. 63*(4), 1247.
[31] (a) Ong, H. L. (1987). *Appl. Phys. Lett. 51*(18), 1398; (b) (1988). *J. Appl. Phys. 64*(2), 614; (c) (1988). *J. Appl. Phys. 64*(10), 4867.
[32] Ong, H. L., "Electromagnetic fields in layered-inhomogeneous uniaxial media: complete generalized geometrical optics approximation" (IBM internal publications, unpublished, 1987–1989).
[33] Ong, H. L.: "A New Formulation for Wave Propagation in Layered-inhomogeneous Anisotropic Media: Generalized Geometrical-Optics Approximation," Wave Phenomena: Theoretical, Computational, and Practical Aspects, edited by Lam, L., Morris, H. C., 249 (Springer Verlag, New York 1989).
[34] (a) Ong, H. L. (1991). *Appl. Phys. Lett. 59*(2), 155; (b) Ong, H. L. (1991). *Jap. J. of Appl. Phys. Lett. 30*(6A), L1028; (c) Ong, H. L., IDRC' (1991). 73; (d) (1993). *J. Opt. Soc. Am. A 10*(2), 283.
[35] (a) Lien, A. (1990). *Appl. Phys. Lett. 57*, 2767; (b) SID '(1991), 586; (c) (1997). *Liquid Crystals*, *22*(2), 171–175.
[36] Berreman, D. W. (1972). *J. Opt. Soc. Am. 62*, 502–510.
[37] Wohler, H., Haas, G., Fritsch, M., & Mlynski, D. A. (1988). *J. Opt. Soc. Am. A 5*, 1554–1557.
[38] Abeles, F. (1950). *Ann. Phys. (Paris) 5*, 596–640.
[39] Ong, H. L. (1991). *J. Opt. Soc. Am. A 8*(2), 303.
[40] Ong, H. L. (1990). *Optics Comm. 76*, 302.
[41] Ong, H. L. (1992). *Japan Display'92*, 247.
[42] Mori, H., et. al., (1997). *Jpn. J. Appl. Phys. 36*, 143.
[43] (a) Yamauchi, S., et. al., (1989). *SID* '1989, 378; (b) Clerc, J. F. (1991). *SID'91*, 758; (c) Yamamoto, T. et. al., (1991). *SID'91*, 762.
[44] Ong, H. L. (1992). *SID'92*, 405.
[45] (a) Koike, Y., et al. (1997). *IDW'97*, 159; (b) Takeda, A., et. al. (1998). *SID'98*, 1077.
[46] For a review on MVA with protrusion geometry, see Okamoto, K., IDW'08 1535 (2008).
[47] (a) Ong, H. L., & Chou, J. (2005). *EuroDisplay'05*, 564; (b) Ong, H. L., et. al., (2006). *IDW'06*, 205; (c) Ong, H. L., et. al., (2007). *IDW'07*, 1569; (d) Ong, H. L., & Chou, J. (2011). *SID'11*, 58–61.
[48] Ong, H. L., Chou, J., Wang, X. Y., Qiao, Y. B., Chiu, Y. W., Chung, D. C., & Jen, T. S., *IDW'10*, 1083–1086.